Low-energy Excess and New Physics Searches with MicroBooNE

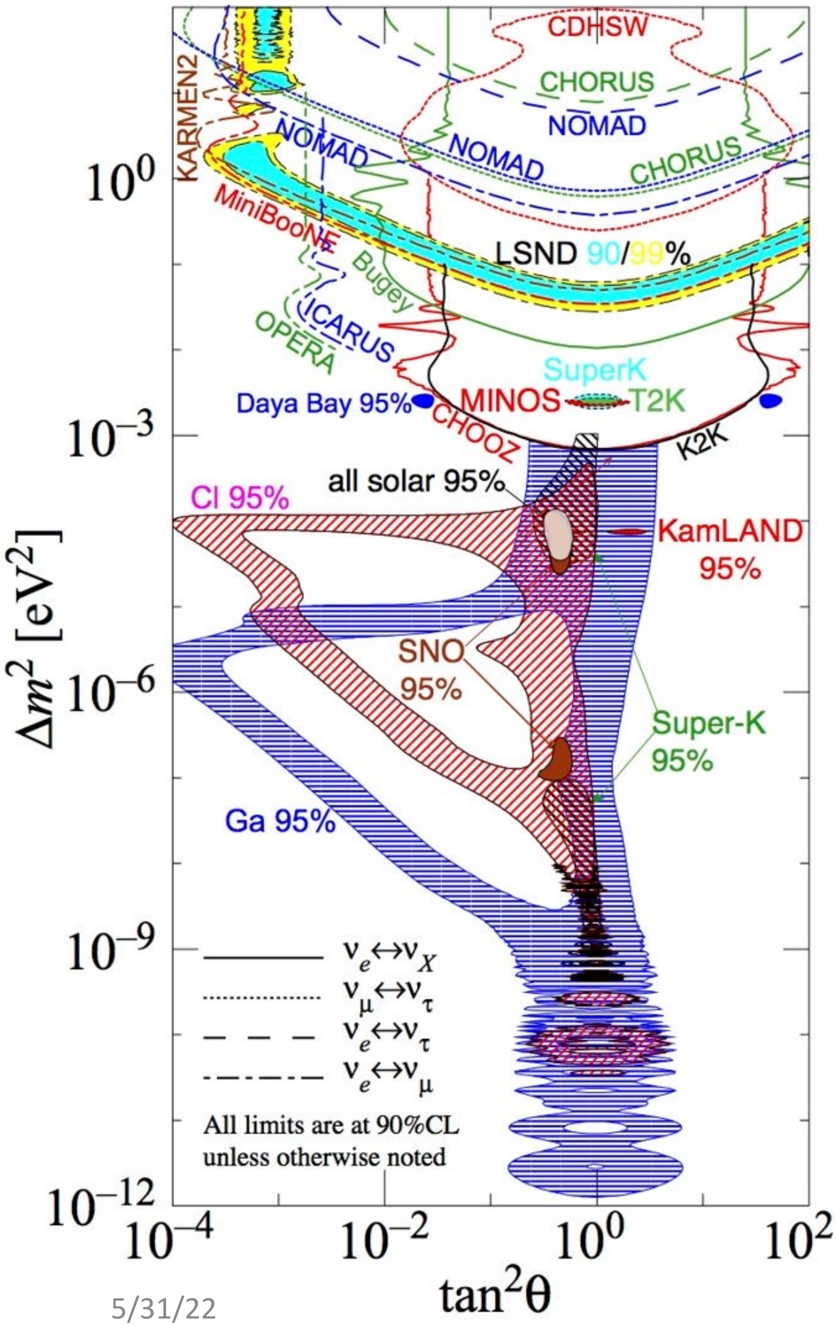
Hanyu Wei, Louisiana State University
on behalf of the MicroBooNE collaboration

NEUTRINO 2022
XXX International Conference on Neutrino Physics and Astrophysics

May 31 2022, Virtual Seoul

μBooNE
LArTPC

Credit: Hitoshi Murayama

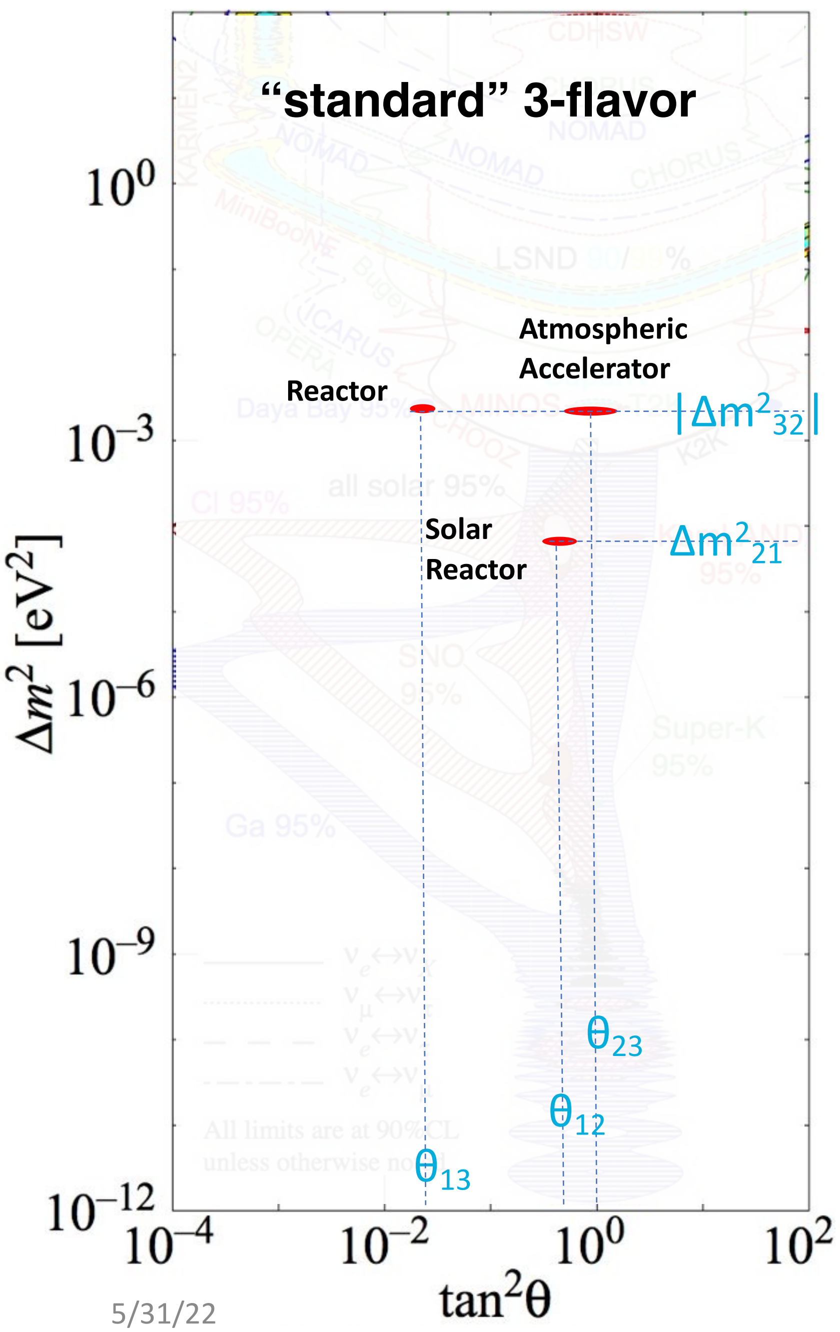


Neutrino Oscillation Experiments

> 50 years

> 30 experiments

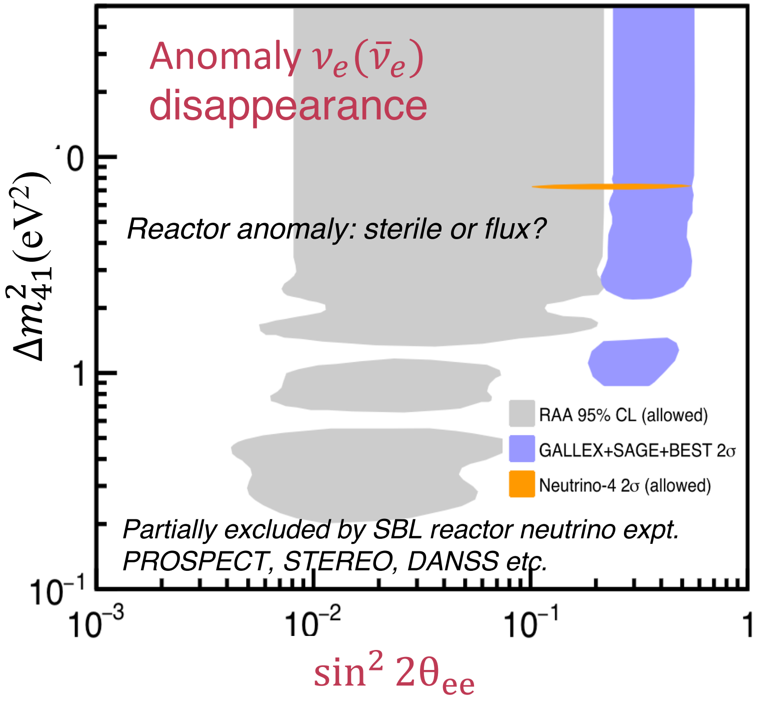
> Phase space over ten orders of magnitude



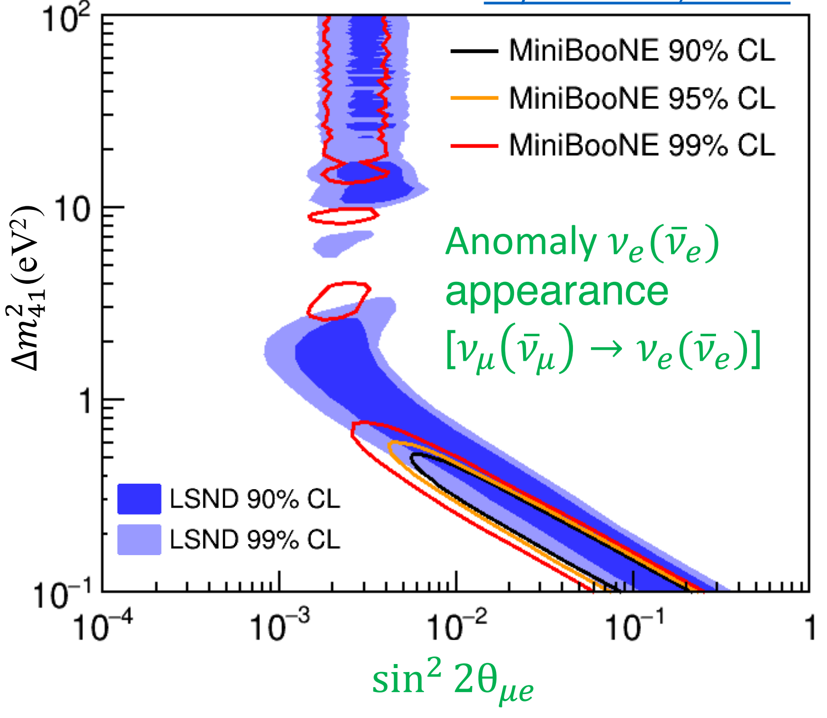
Majority of the experimental results are consistent with the "standard" three-flavor neutrino framework.

Several "anomalies" hint toward at least an additional flavor of neutrinos -- eV-scale light sterile neutrinos

Phys. Rev. D **104**, 032003
Phys. Rev. D **83**, 073006
arXiv: 2201.07364

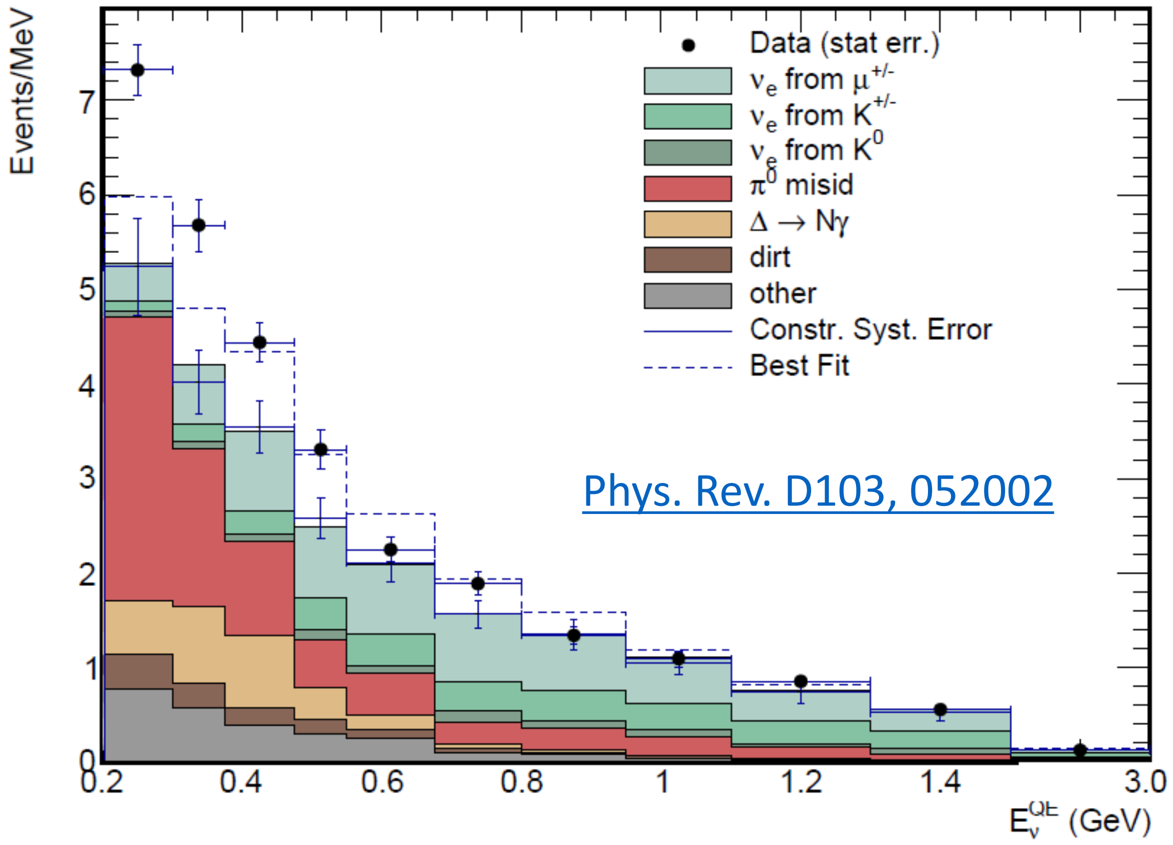


Phys. Rev. D **103**, 052002
Phys. Rev. D **64**, 112007



"anomalies": reactor, radioactive source, LSND, MiniBooNE

MiniBooNE Anomaly

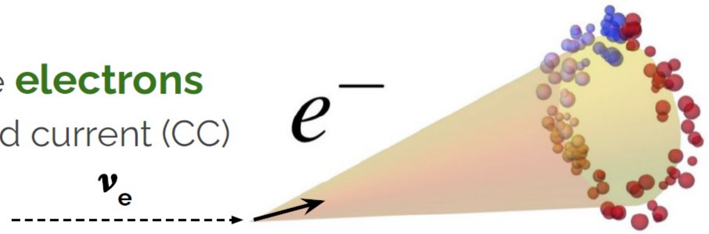


Phys. Rev. D103, 052002

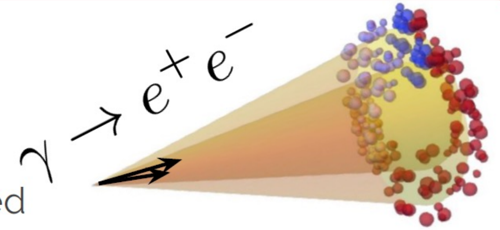
- MiniBooNE (2002-2019) observed a low-energy excess (LEE) of electromagnetic events with 4.8σ significance

MiniBooNE Cherenkov detector unable to distinguish photons and electrons, and unable to detect hadronic final-state particles below Cherenkov threshold.

It detected ν_e by the **electrons** produced in charged current (CC) interactions.



However, **photons**, that pair produce extremely collimated electron/positron pairs produced an identical Cherenkov ring



Micro Booster Neutrino Experiment

μBooNE

May 5, 2022 @ Rutgers

Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

SWISS NATIONAL SCIENCE FOUNDATION

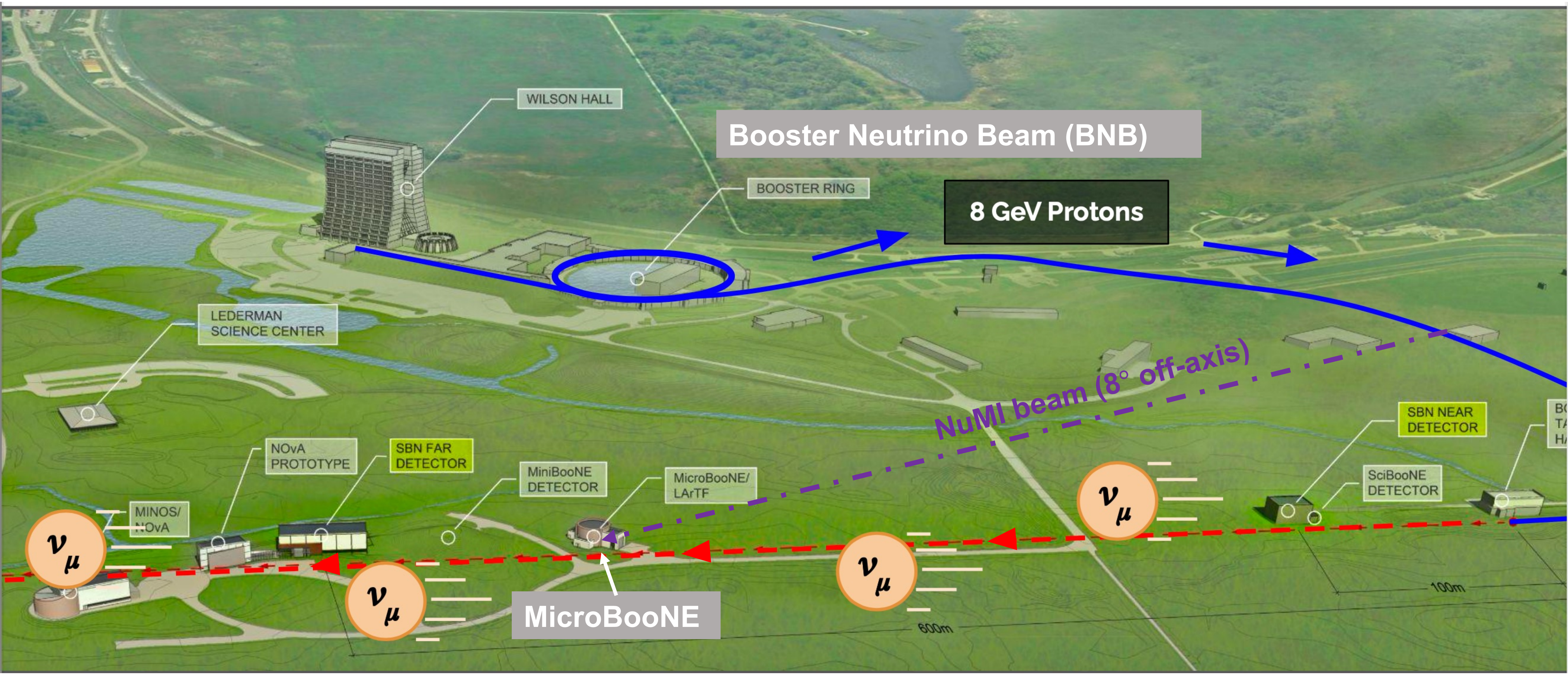
Science & Technology Facilities Council

THE ROYAL SOCIETY

European Commission

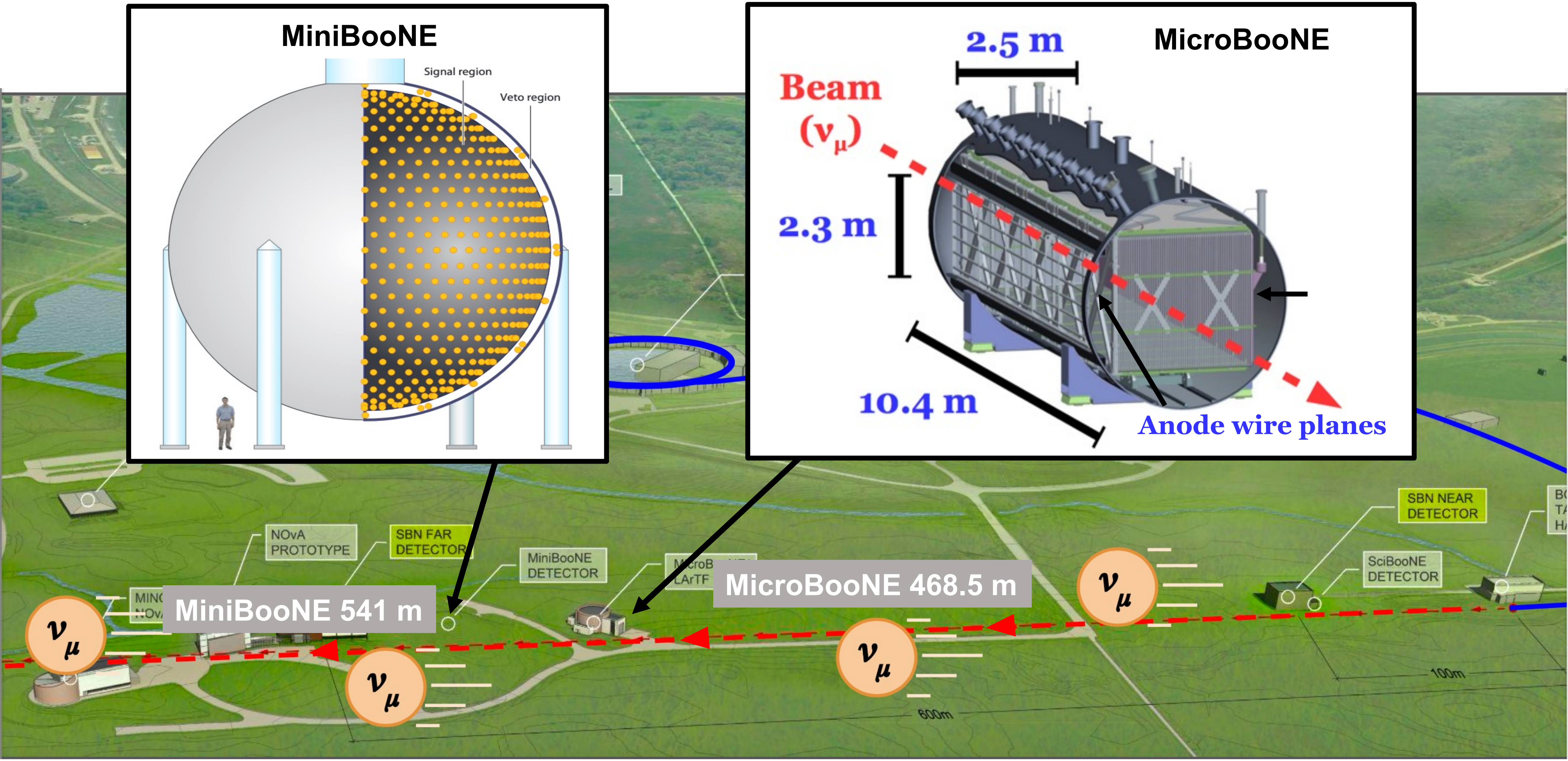
Horizon 2020 European Union funding for Research & Innovation

MicroBooNE @Fermilab



Cherenkov detector: 820 tonne mineral oil

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

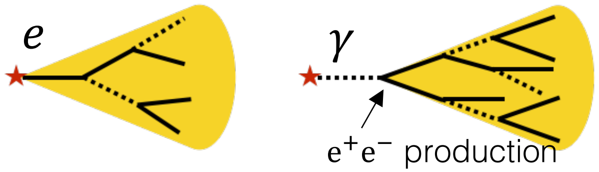


LArTPC: an enabling detector

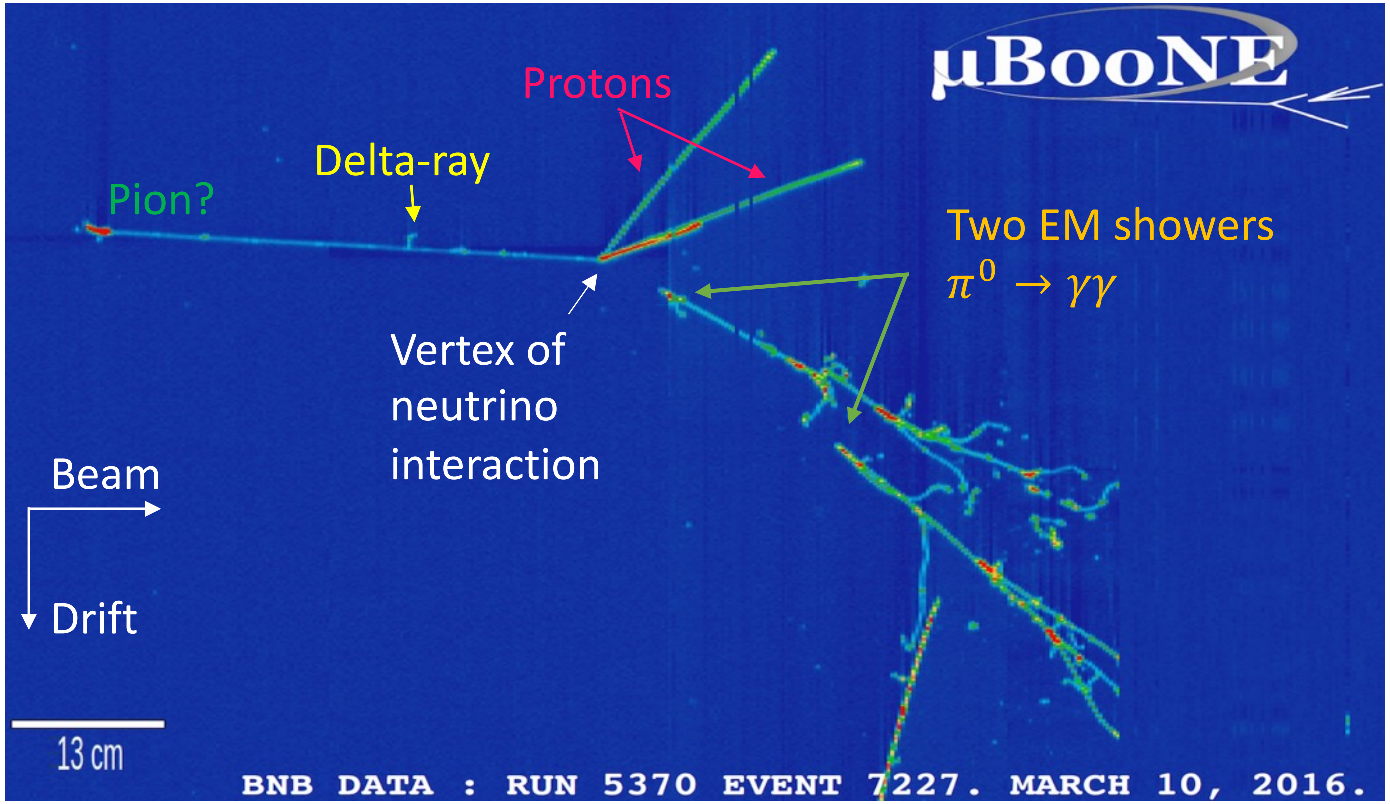
Capable of identifying different species of particles and reconstructing 3D images with fine-grained information

- Neutrino vertex
- Particle flow (mother-daughter relationship)
- Track (μ, π, p etc.) vs shower (e, γ EM cascade)

- **e vs γ (e^+e^- pair production) separation**
  - Gap between shower start point and neutrino vertex?
  - dE/dx in shower stem (1 MIP vs 2 MIPs)
  - Split of e^+e^- pair (large opening angle)



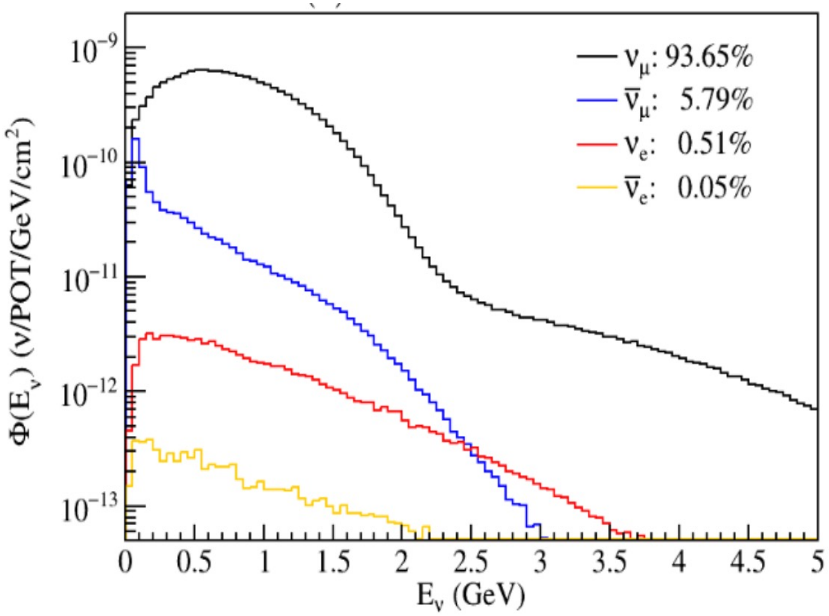
LArTPC: fully active calorimeter + high-resolution tracking



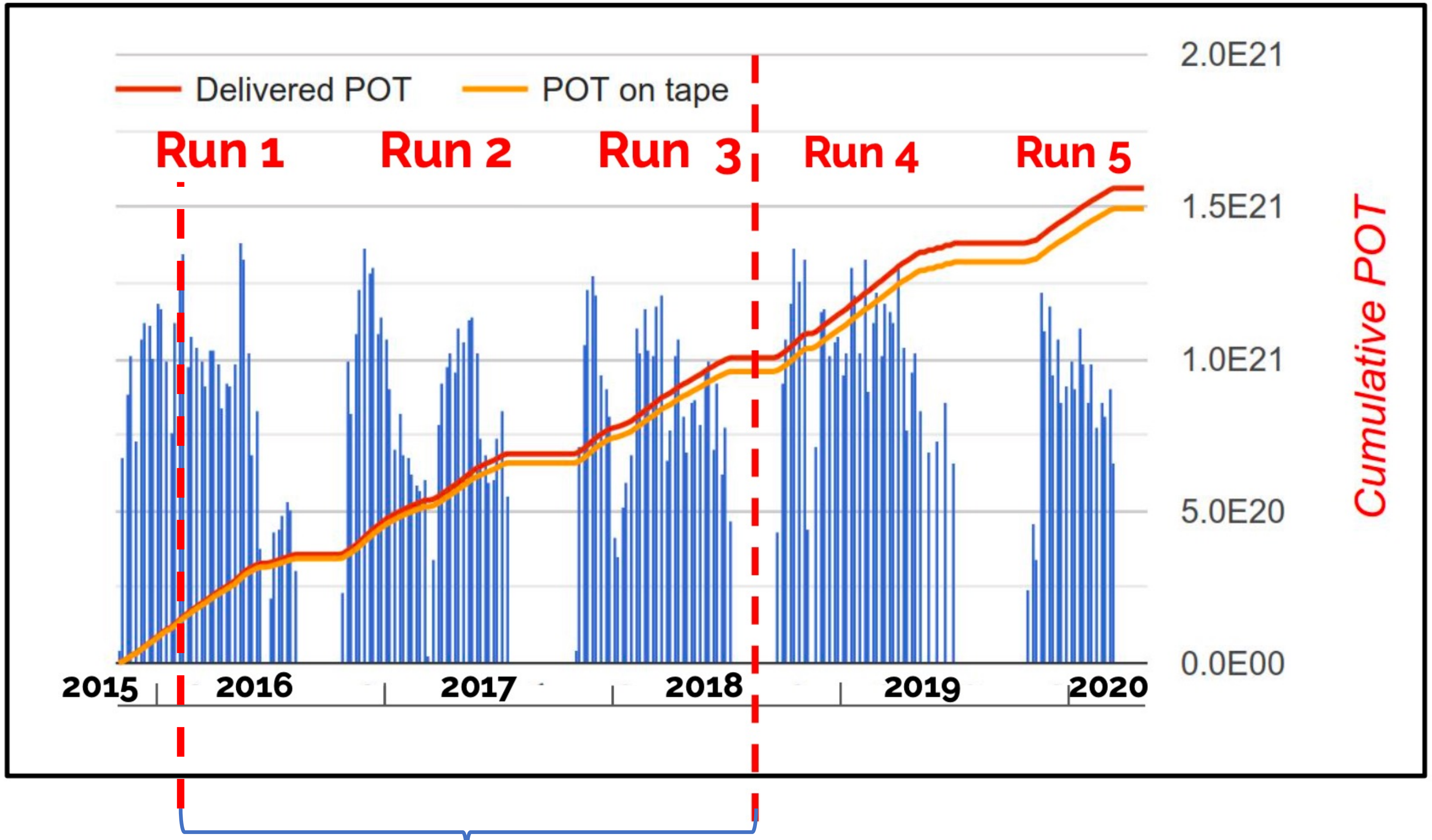
Most likely a neutral current interaction

Since turning on in 2015, MicroBooNE has amassed the **largest sample of neutrino interactions on argon in the world**

BNB neutrino flux



Neutrino-mode BNB neutrino flux from mostly from π^+/K^+ decays.
Interaction rate peaks around 0.8 GeV.

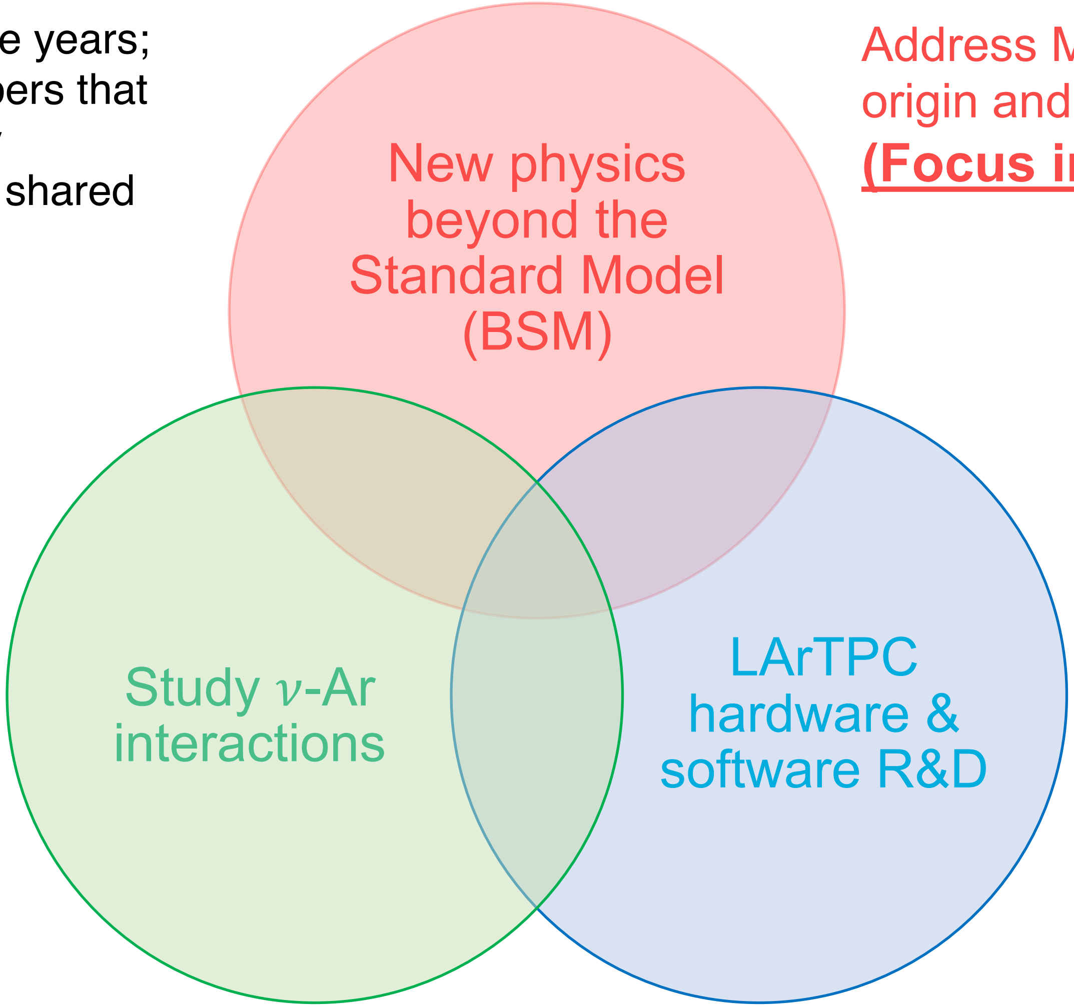


BNB data $\sim 7 \times 10^{20}$ POT in this talk

MicroBooNE's fruitful technical and scientific success

About 50 papers in the past five years; ~50% pioneering technical papers that benefit the LArTPC community
More than 70 public technotes shared with the community as we go

Address MiniBooNE low-energy excess origin and search for new physics
(Focus in this talk)

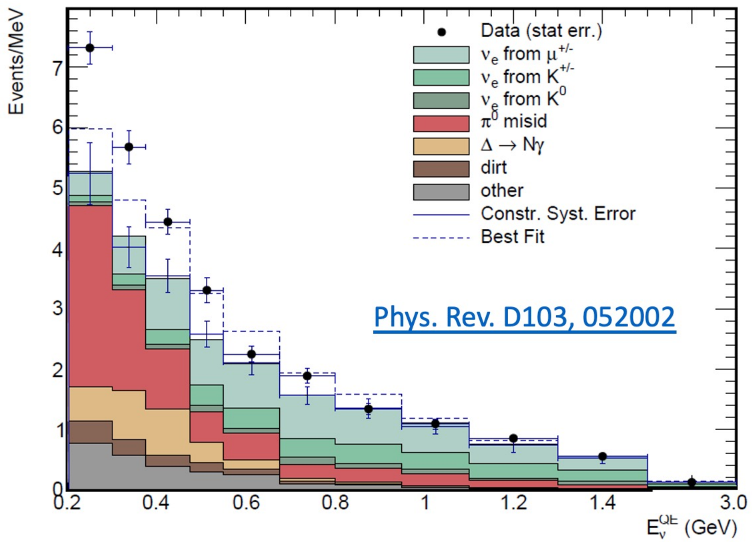


Pioneering LArTPC detector
- Long-term running cold electronics, high-purity and stable operation
- Cosmic-ray tagger, laser calibration system
- Good understanding of detector response: wire response, space charge effect, etc.
- Multiple novel & auto reconstruction techniques
- Computing challenges
- Post-operation R&D (Rn doping, HV related, etc.)

Various exclusive and inclusive cross section measurements
- Largest $\nu - Ar$ data sample
- Leveraging the excellent PID capability of LArTPC

(See Steven Gardiner's talk)

Examination of MiniBooNE LEE



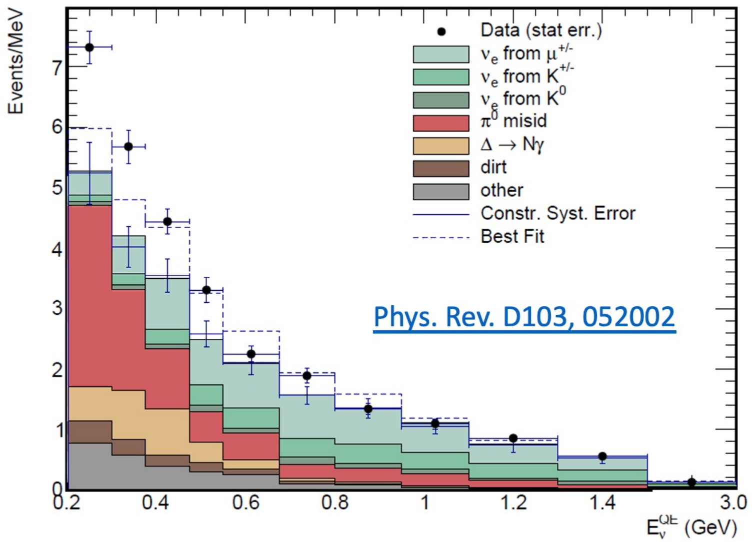
Electron-like excess (ν_e excess)

- Mismodeled/unknown process?
- Oscillation-driven excess?

Photon-like excess

- Mismodeled/unknown process producing photons, e.g. NC Δ resonance radiative decay?

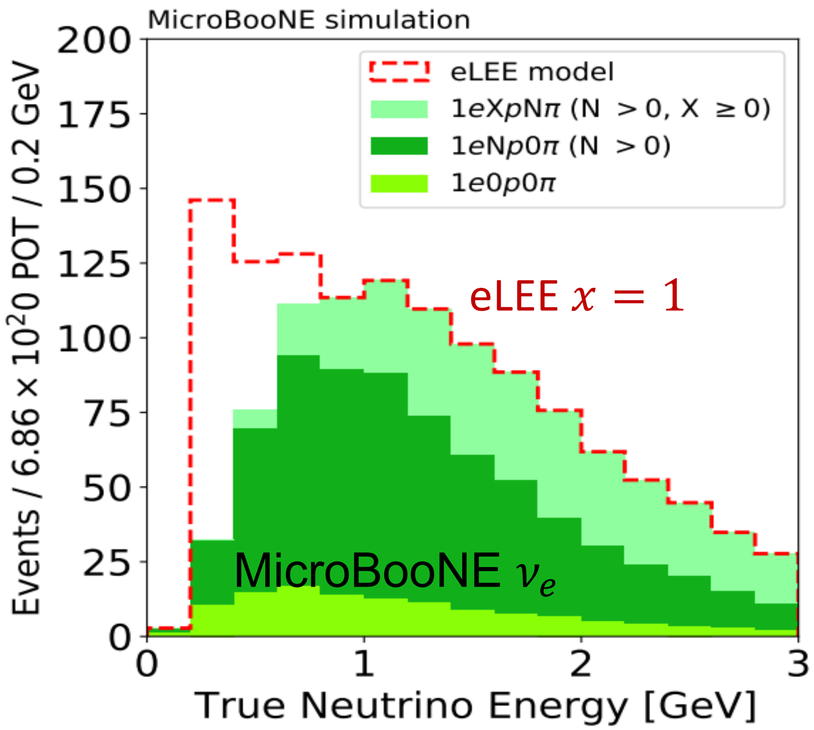
ν_e low-energy excess (eLEE) search



$$\text{MiniBooNE } x = \begin{cases} 1 \pm 0.08 \text{ (stat.)} \\ 1 \pm 0.21 \text{ (full)} \end{cases}$$

Unfolding detector response, acceptance, efficiency

Empirical eLEE model derived from MiniBooNE



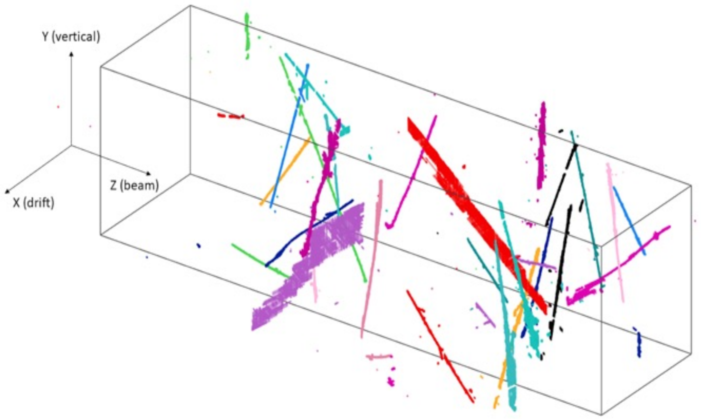
Assumption about excess: an energy-dependent enhancement of intrinsic ν_e events at low energy.

MicroBooNE public note 1043

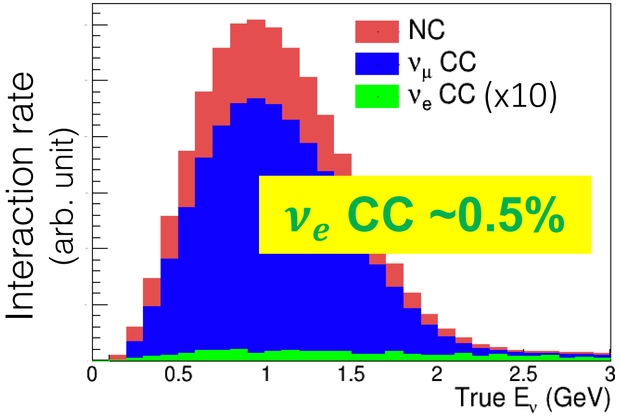
ν_e low-energy excess (eLEE) search

Extremely low initial signal-to-background ratio

High-rate cosmic-ray activity in the near-surface detector



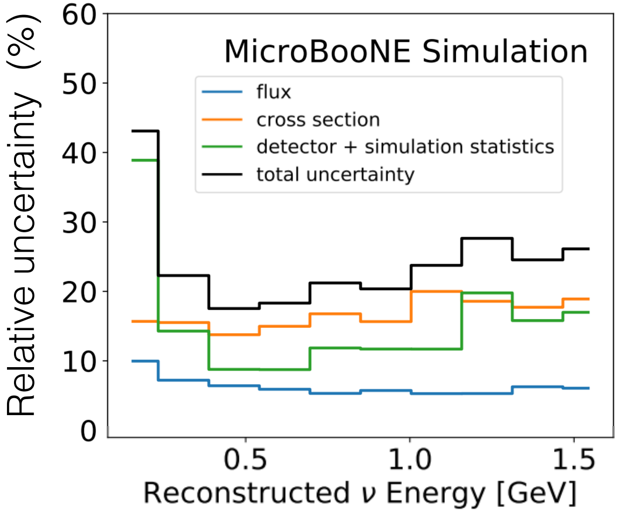
ν_μ-dominated flux
"rare" ν_e events



- ✓ **Develop advanced event reconstruction and PID algorithms to exploit LArTPC capability**

Low-precision ν_e interaction rate prediction

15-20% cross-section uncertainty
10-20% detector response uncertainty
5-10% flux uncertainty (same treatment as MiniBooNE)



- ✓ Cross-section: MicroBooNE Genie tune, Phys. Rev. D 105, 072001
- ✓ Detector systematics: data-driven, EPJC 82, 454 (2022))
- ✓ **Apply data constraints from the in-situ measurements of ν_μ and other dedicated background sidebands**

Three independent eLEE searches

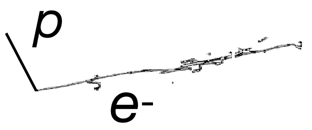
Targeting different final states with different novel reconstruction approaches developed in MicroBooNE

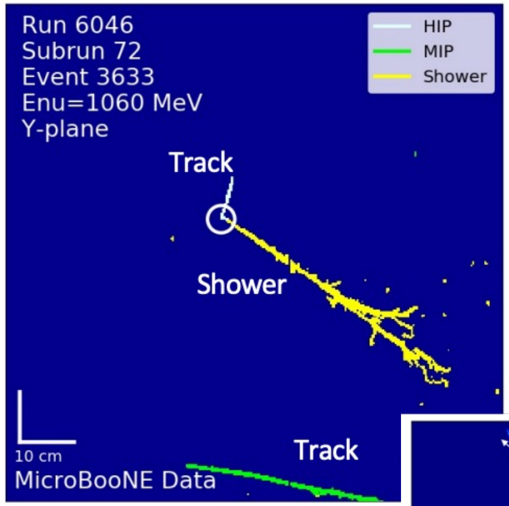
- CC quasi-elastic ν_e scattering
- CCQE dominates at low energy
- Deep-learning-based reconstruction

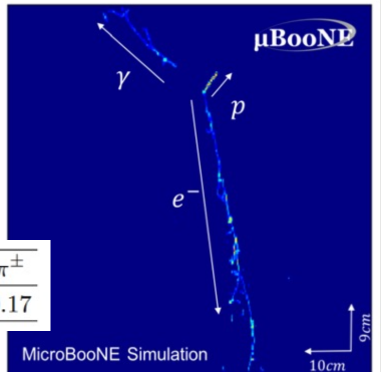
- Pionless semi-inclusive CC ν_e scattering
- MiniBooNE event topology
- Pandora-based reconstruction

- Inclusive CC ν_e scattering
- High efficiency and less model dependent
- Wire-Cell reconstruction

1e1p



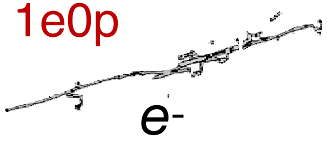




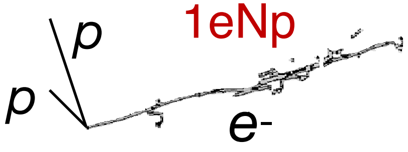
arXiv: 2110.14080 (PRD accepted)

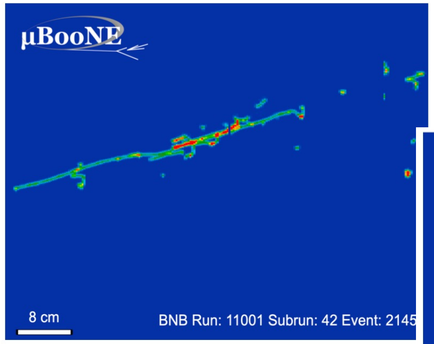
	p	e^-	γ	μ^-	$\pi^\pm$
MPID Score	0.89	0.95	0.85	0.06	0.17

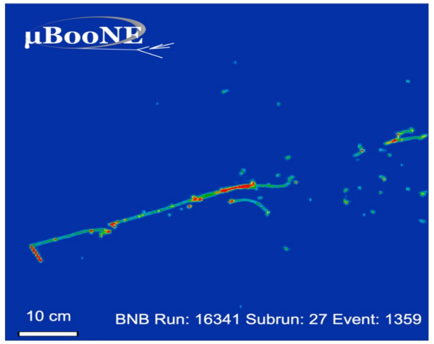
1e0p

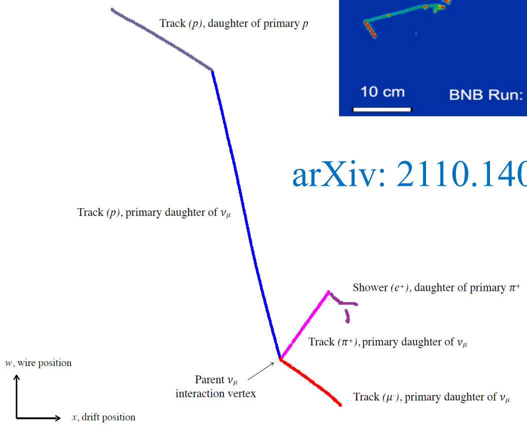


1eNp



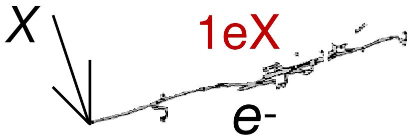


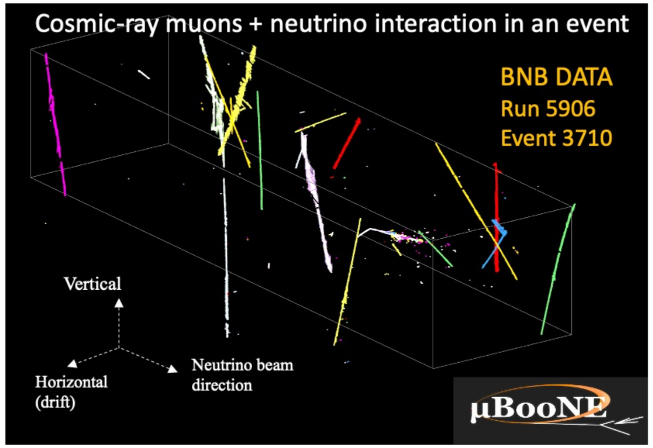


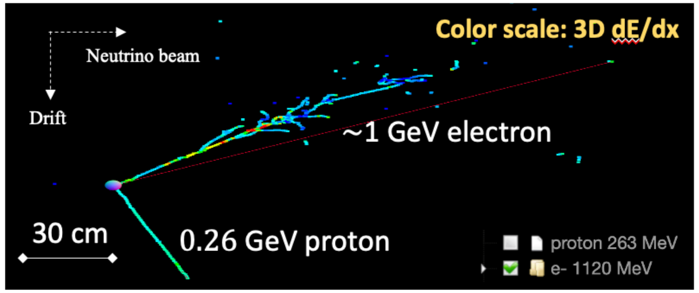


arXiv: 2110.14065 (PRD accepted)

1eX





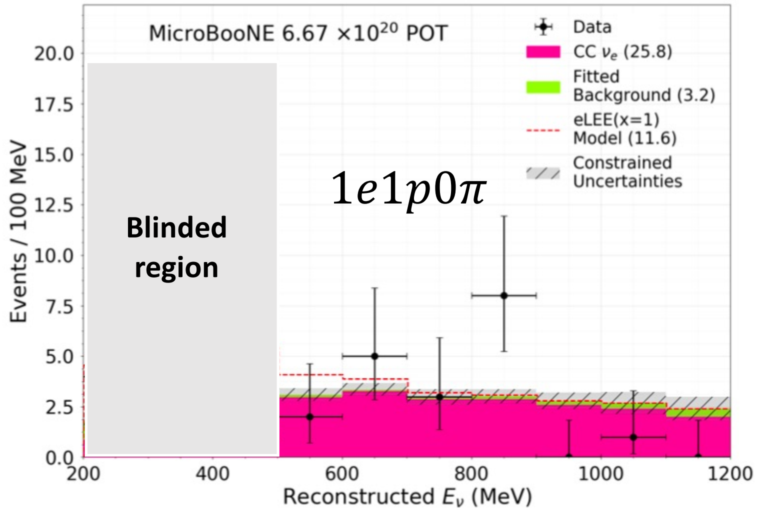


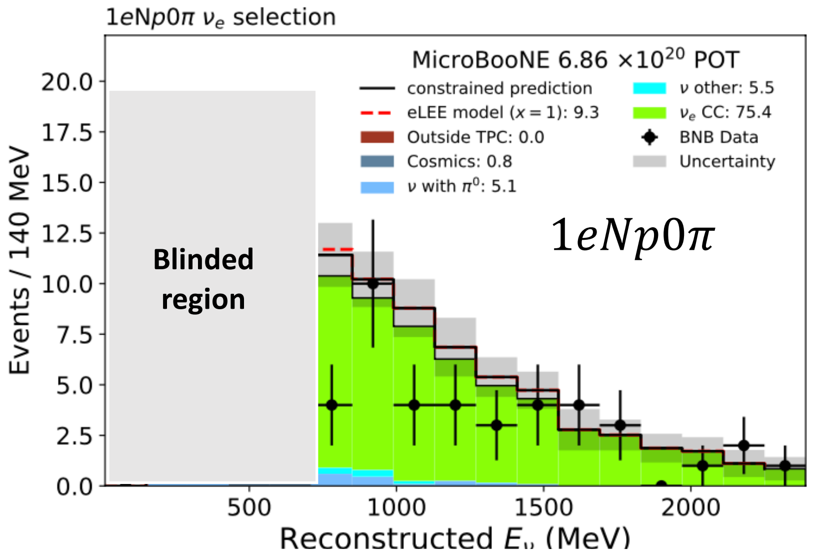
arXiv: 2110.13978 (PRD accepted)

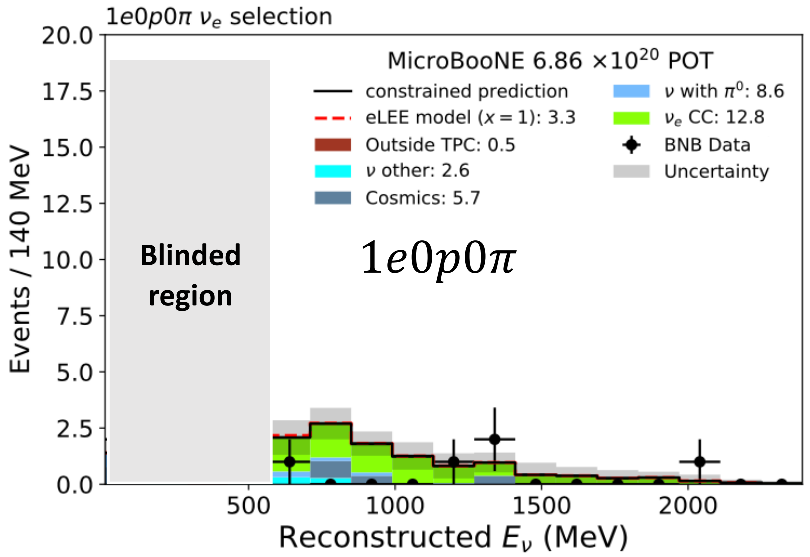
ν_e energy spectra

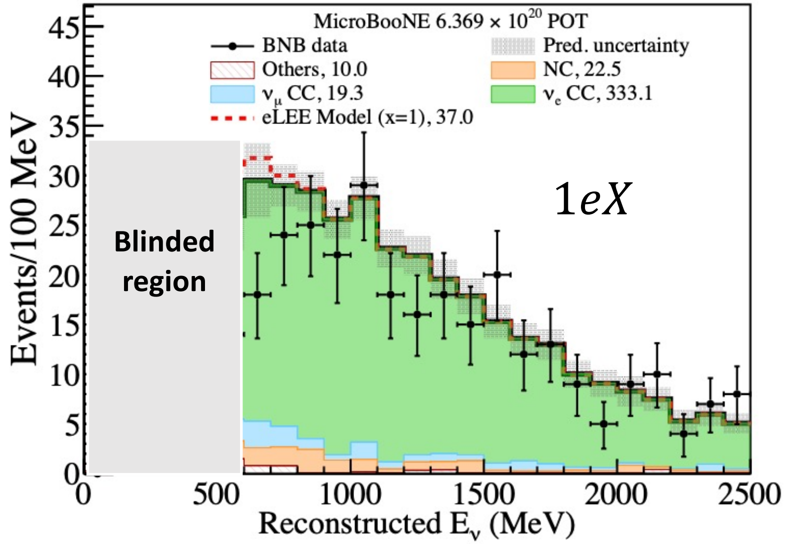
- ~80% purity
- Up to 50% efficiency of full active volume ν_e CC events (**a milestone for intrinsic ν_e selection in ν_μ-dominated accelerator neutrino beam**)

Low-energy excess
- Blind analysis (topological characteristics + kinematics sidebands)
- NuMI data validation
- Mock data study







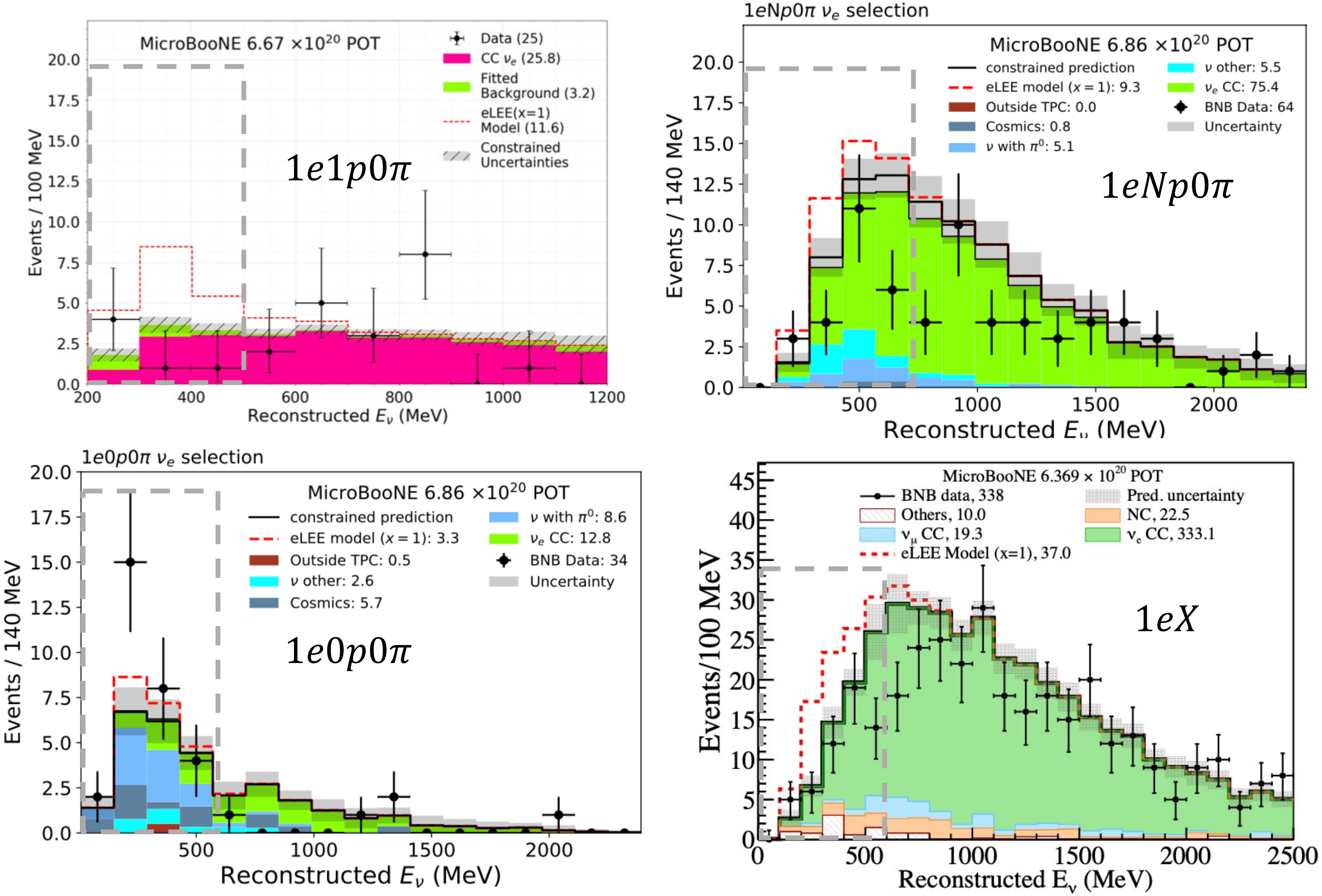


ν_e energy spectra

arXiv: 2110.14080 (PRD accepted)
arXiv: 2110.14065 (PRD accepted)
arXiv: 2110.13978 (PRD accepted)

Low-energy excess

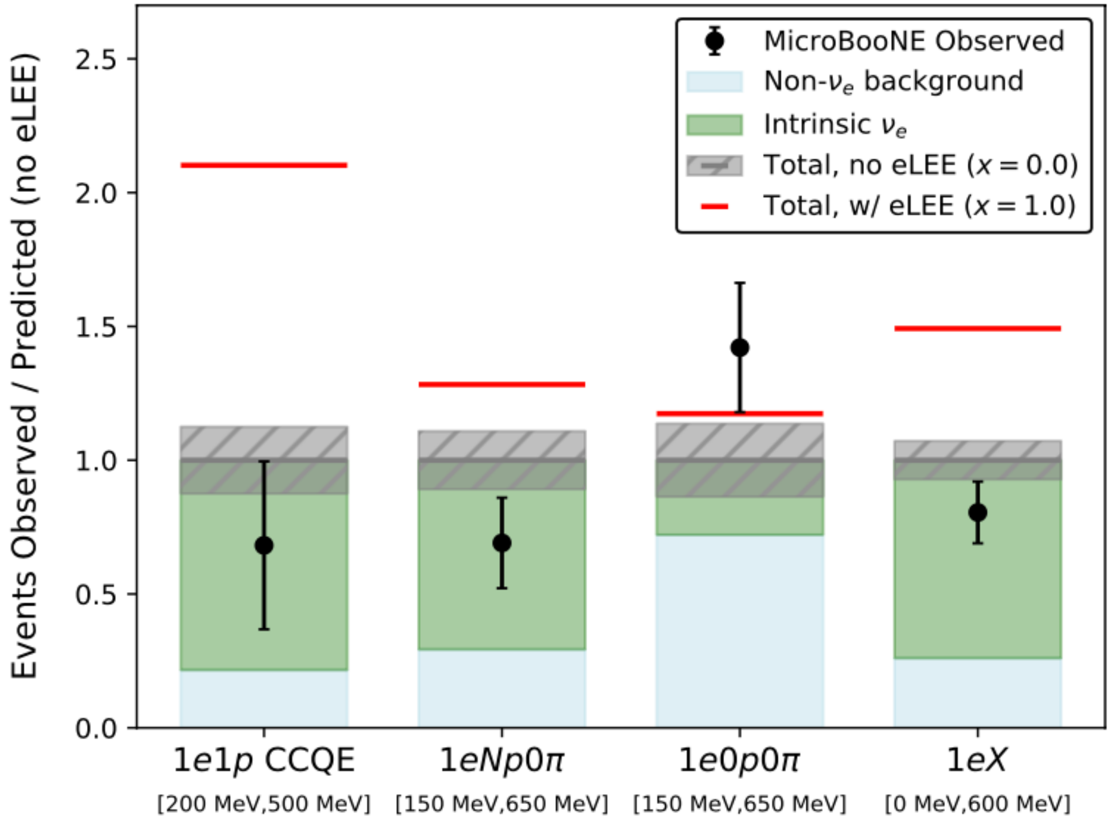
- Unblinded in summer 2021
- No observation of ν_e candidate excess in the low-energy region (except for the low- ν_e-purity $1e0p0\pi$ channel)



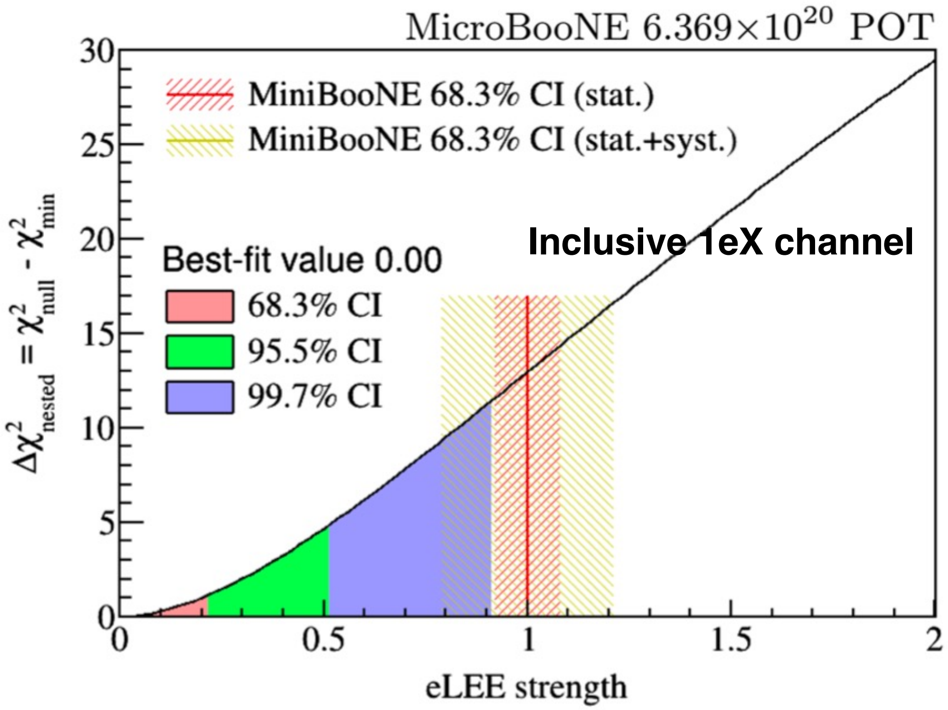
Ivan Caro, poster I-b DT14-735, "Search for an anomalous excess of charged-current electron neutrino interactions without pions in the final state with the MicroBooNE experiment"

eLEE search results

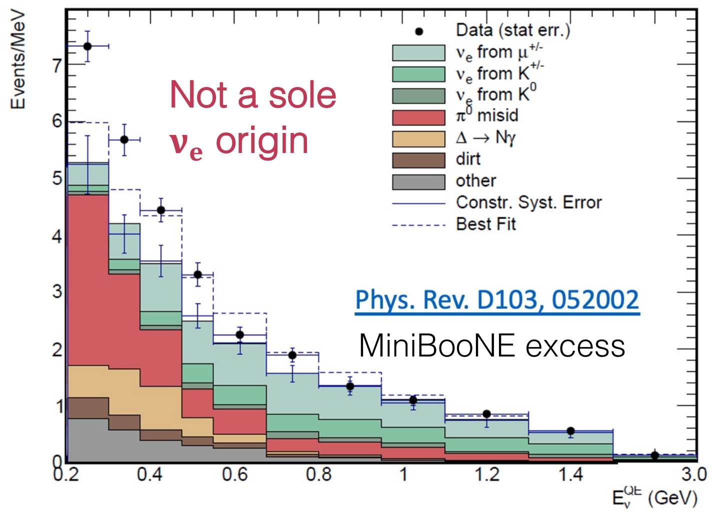
arXiv: 2110.14054 (PRL accepted)



- Observed ν_e candidate rates are statistically consistent with the predicted background rates in the LEE region
- With exception of the low- ν_e-purity $(1e0p0\pi)$ channel, the hypothesis that ν_e events are *fully responsible* for the ***median*** MiniBooNE LEE is rejected at >97% C.L.; >3σ in the inclusive channel

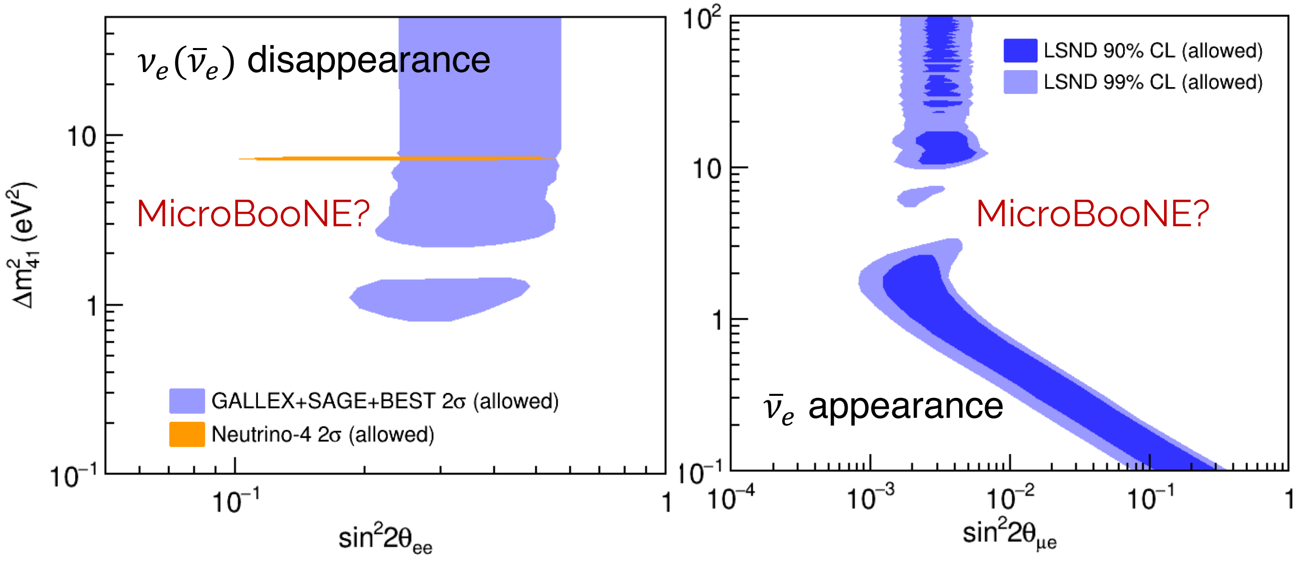


MiniBooNE excess and sterile neutrinos



- The MicroBooNE eLEE result disfavors the MiniBooNE anomaly originating from a pure ν_e excess.
- The existence of sterile neutrinos cannot be ruled out by the MicroBooNE eLEE result which is a generic low-energy ν_e excess search.

- The MicroBooNE eLEE results can be re-interpreted under a sterile neutrino oscillation hypothesis: a combination of short-baseline ν_e appearance and ν_e disappearance
- 3+1 oscillation searches using the selections in the MicroBooNE eLEE searches will be presented today for the first time.



3+1 neutrino oscillation framework

The PMNS matrix is extended to a 4 x 4 unitary matrix following the parametrization below

$$U_{PMNS} = R_{34}(\theta_{34}, \delta_{34})\ R_{24}(\theta_{24}, \delta_{24})\ R_{14}(\theta_{14}, 0)\ R_{23}(\theta_{23}, 0)\ R_{13}(\theta_{13}, \delta_{13})\ R_{12}(\theta_{12}, 0)$$

The effective mixing angles $\theta_{\alpha\beta}$ for short-baseline oscillations are defines below

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}} \cdot \sin^2 2\theta_{\alpha\beta} \cdot \sin^2(1.267 \frac{\Delta m_{41}^2 L}{E})$$

ν_e disappearance	$\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$
ν_μ disappearance	$\sin^2 2\theta_{\mu\mu} = 4\cos^2\theta_{14}\sin^2\theta_{24}(1-\cos^2\theta_{14}\sin^2\theta_{24})$
ν_e appearance	$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14}\sin^2\theta_{24}$

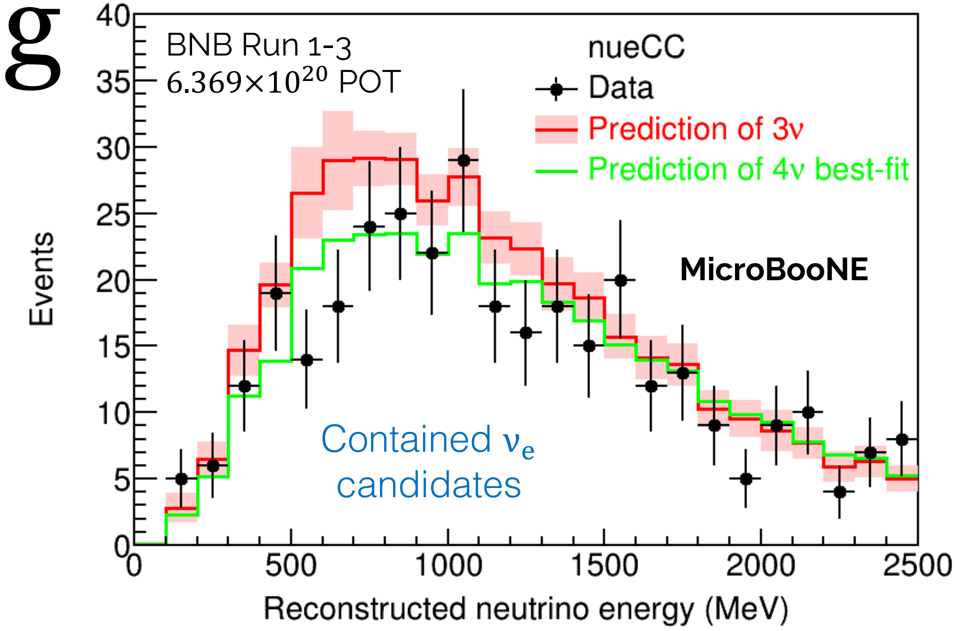
- non-zero ν_e appearance requires both ν_e and ν_μ disappearances

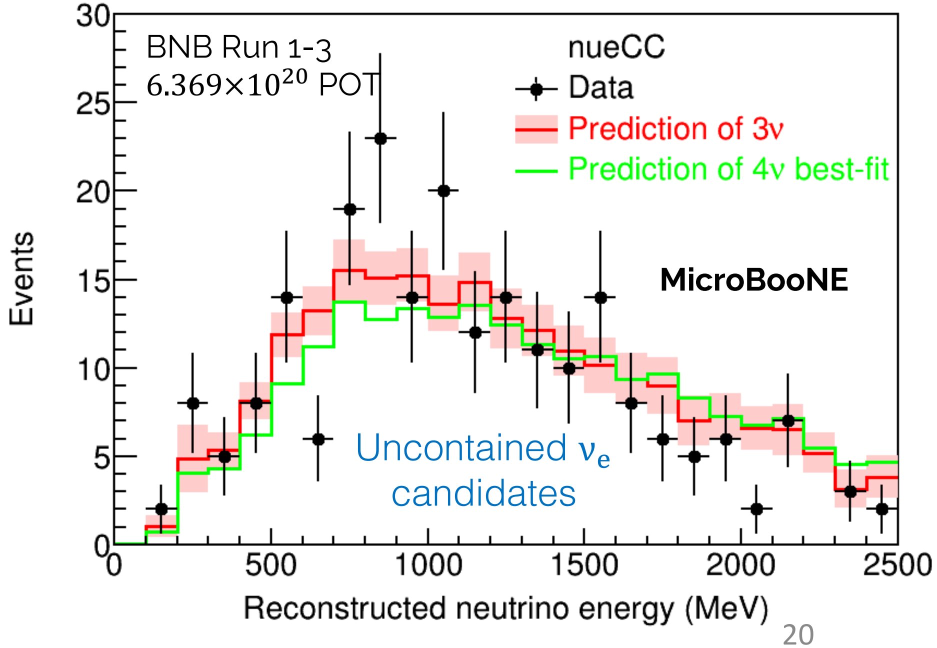
In MicroBooNE 3+1 fit:

- Oscillation effects (the above three) depending on the three oscillation parameters ($\Delta m_{41}^2, \sin^2\theta_{14}, \sin^2\theta_{24}$) are applied for all ν_e and ν_μ events
- ν_μ appearance ignored because <1% intrinsic ν_e

3+1 oscillation analysis using

- Three oscillation effects (ν_e app. ν_e/ν_μ disapp.) + simultaneous fit on the multiple selection channels including ν_eCC, ν_μCC*, and NC* **(same input as the inclusive 1eX eLEE search)**
- Validated neutrino energy reconstruction especially hadronic energy reconstruction





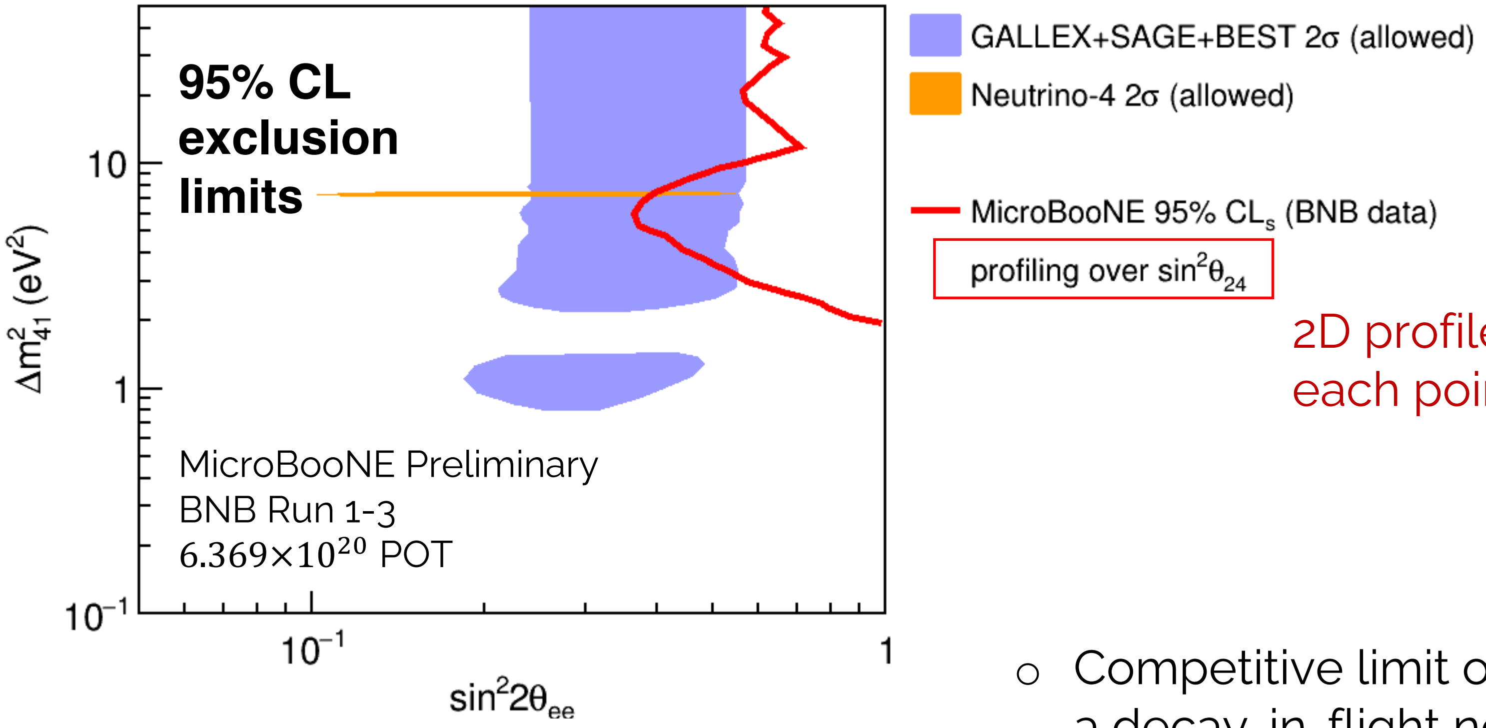
- Considering full 3+1 oscillation, **BNB Run 1-3 data was found to be consistent with the 3ν hypothesis within 1σ** following the Feldman-Cousins approach.
- **95% C.L. exclusion limits** were calculated using the frequentist **CLs method.**

* *Separate selections; not the ν_μCC or NC background in the ν_eCC selection*

MicroBooNE 3+1 oscillation analysis results

Xiangpan Ji, poster I-b DT14-753, "Search for a sterile neutrino at MicroBooNE using BNB and NuMI beams"

ν_e disappearance 2D parameter space



2D profiled result, full 3+1 analysis at each point in the parameter space

- Competitive limit on the eV-scale ν_e disappearance from a decay-in-flight neutrino source, first $\nu - Ar$ scattering data limit

MicroBooNE 3+1 oscillation analysis results

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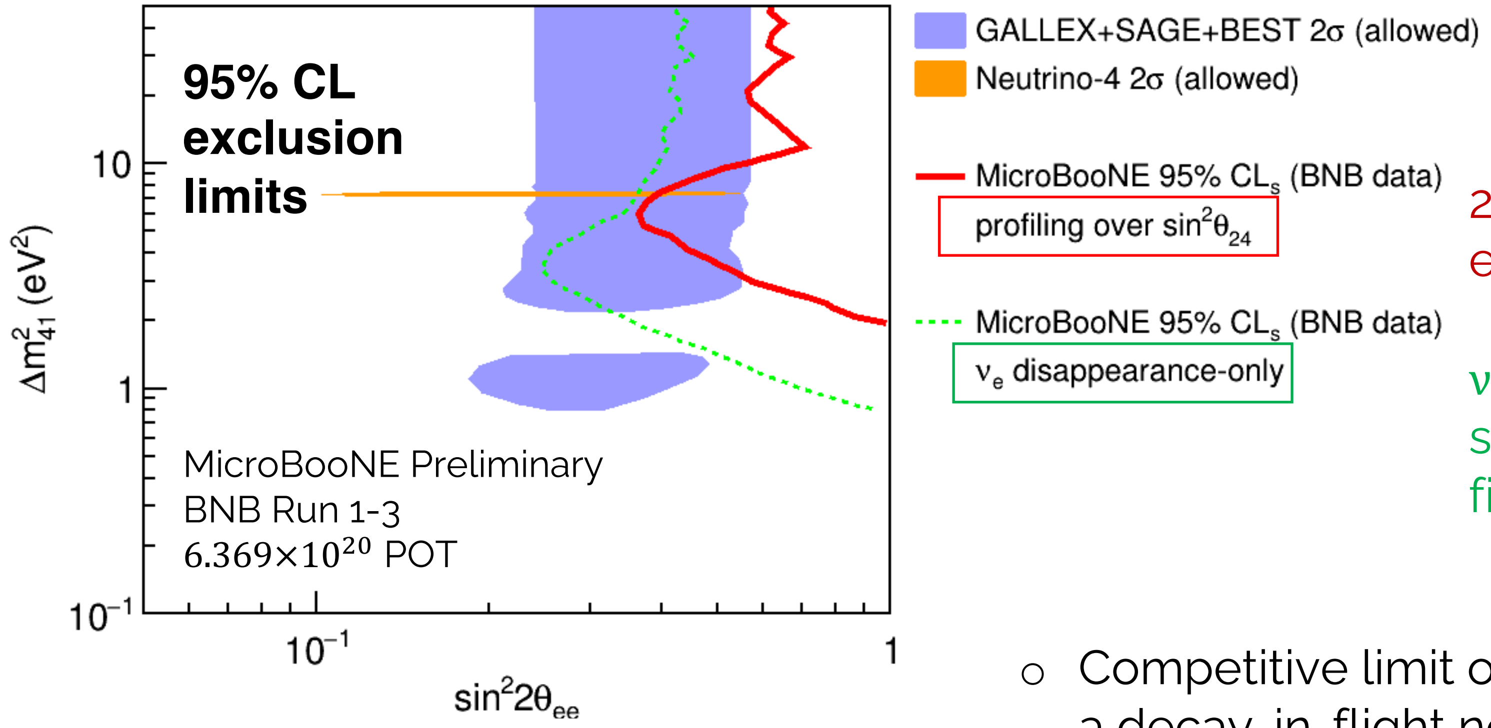
ν_e disappearance 2D parameter space



2D profiled result, full 3+1 analysis at each point in the parameter space

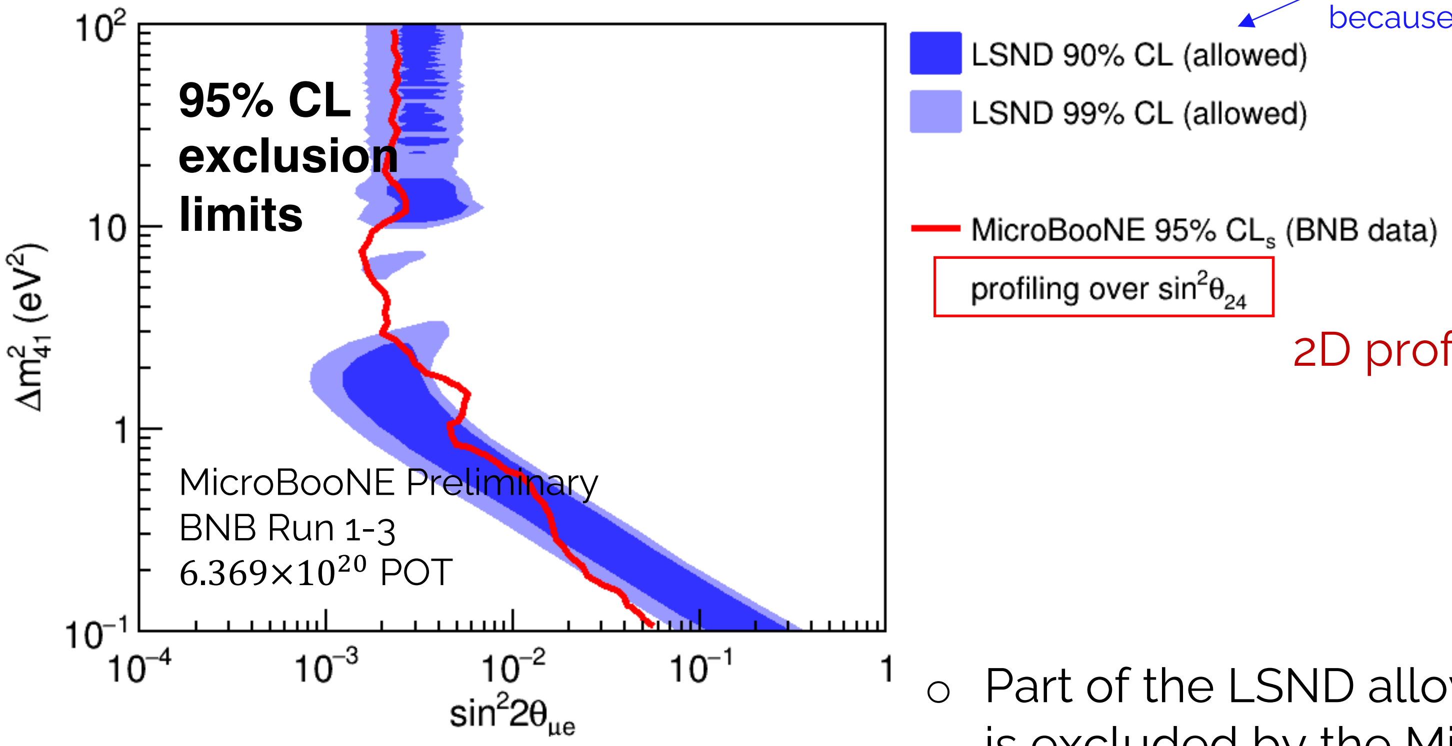
ν_e disappearance-only, more stringent limit corresponding to a fixed $\sin^2\theta_{24} = 0$

- Competitive limit on the eV-scale ν_e disappearance from a decay-in-flight neutrino source, first $\nu - Ar$ scattering data limit

MicroBooNE 3+1 oscillation analysis results

Xiangpan Ji, poster I-b DT14-753, "Search for a sterile neutrino at MicroBooNE using BNB and NuMI beams"

ν_e **appearance** 2D parameter space

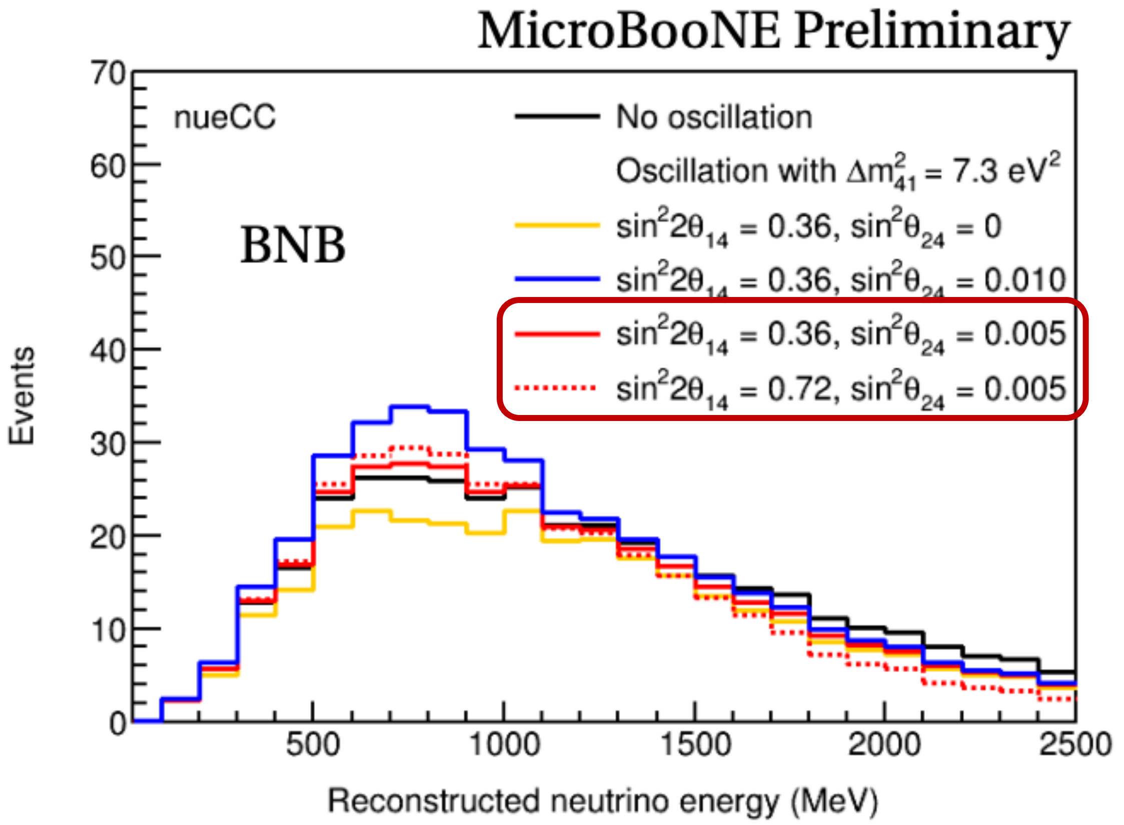


ν_e appearance-only; a reasonable approximation because of low stats. Intrinsic $\bar{\nu}_e$

2D profiled result

- Part of the LSND allowed region (not including the best-fit) is excluded by the MicroBooNE 95% CL limit
- ν_e **appearance-only** result (***see backup slide***) is not shown and it is physically not allowed in the 3+1 framework

Cancellation of ν_e appearance and ν_e disappearance -- degeneracy of oscillation parameters



ν_e disappearance ν_e appearance

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

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

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

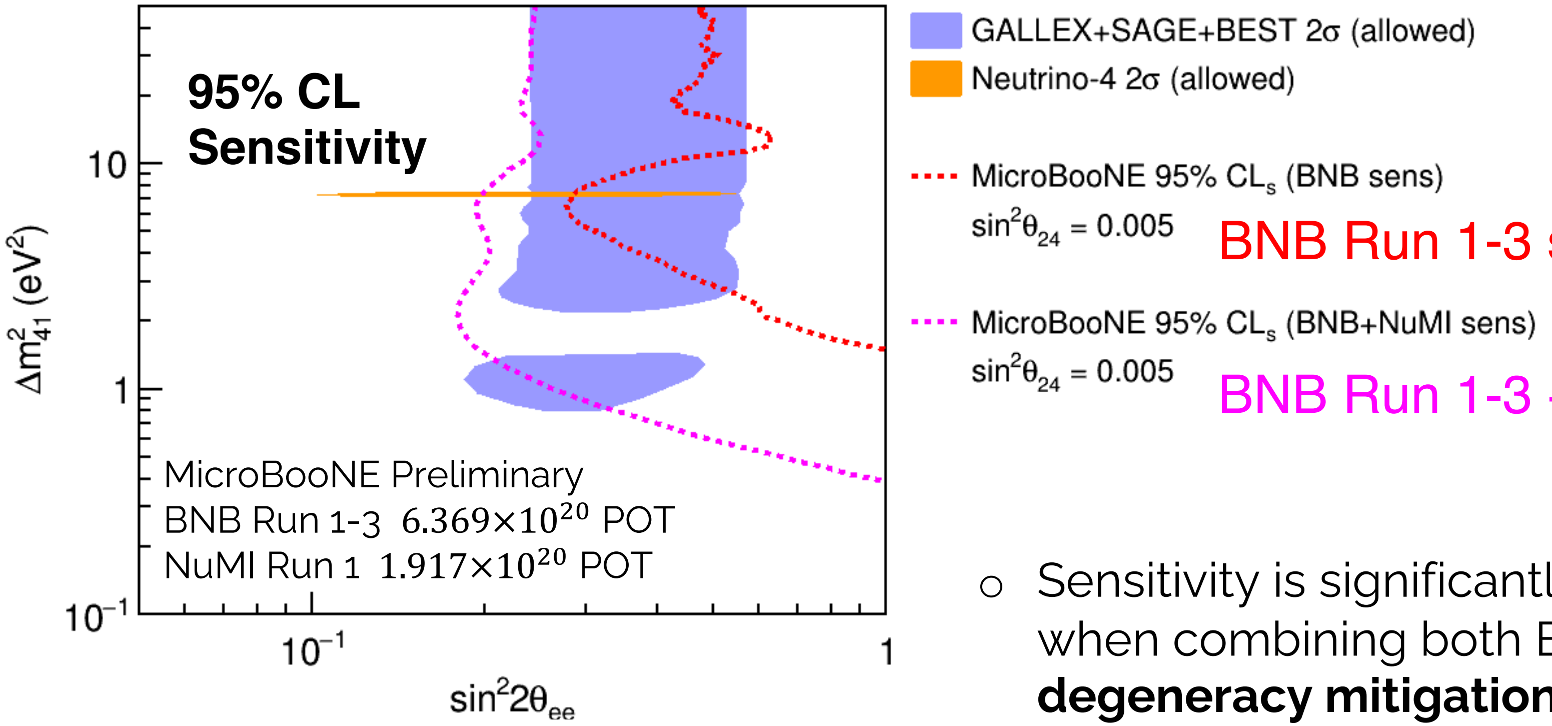
Different degeneracy points: degeneracy mitigation utilizing both

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

MicroBooNE 3+1 oscillation analysis sensitivity

Xiangpan Ji, poster I-b DT14-753, “Search for a sterile neutrino at MicroBooNE using BNB and NuMI beams”

ν_e disappearance 2D parameter space

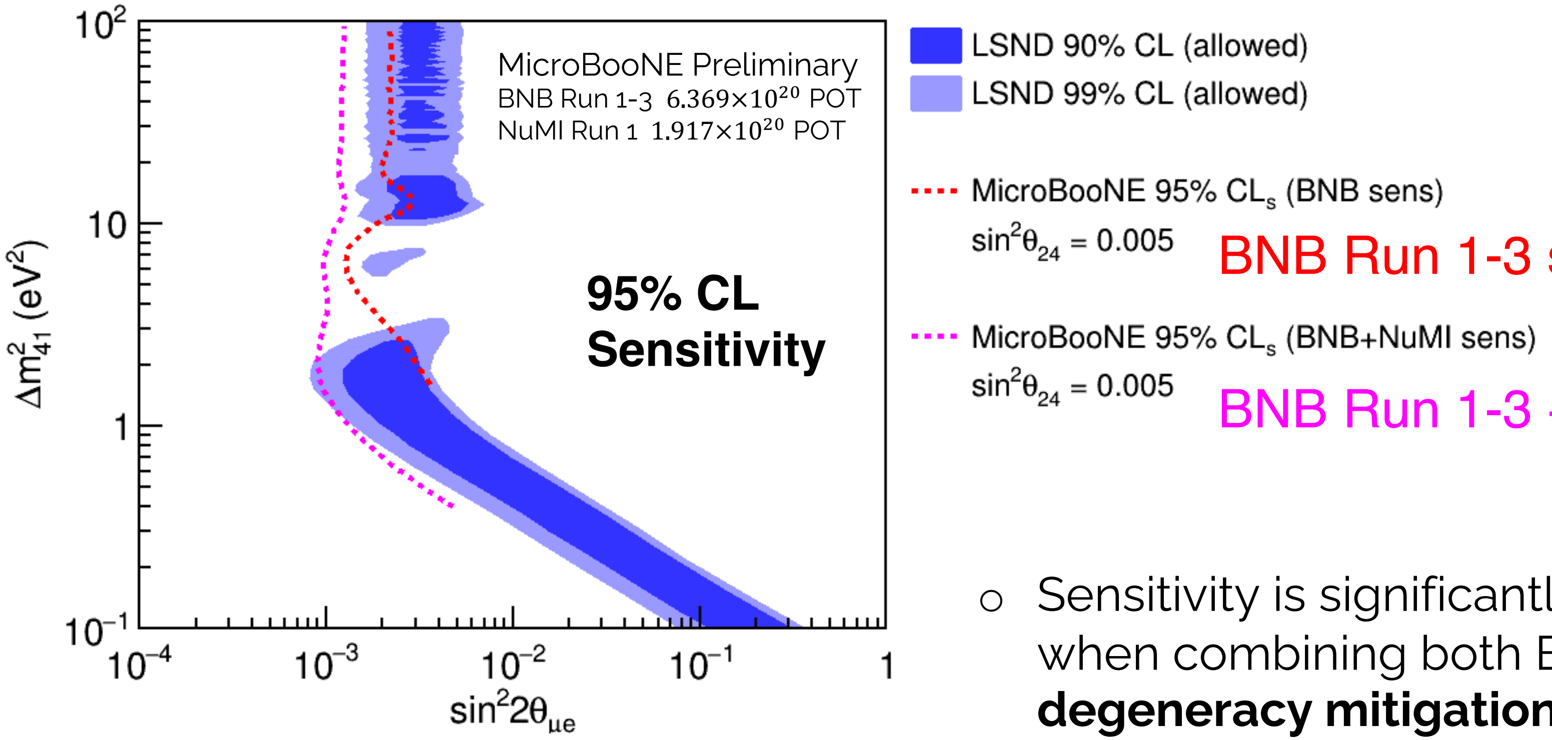


- Sensitivity is significantly improved (overall a factor of 2) when combining both BNB and NuMI (mainly due to **degeneracy mitigation**)
- BNB+NuMI data result is coming soon, expected to be sensitive to the Neutrino-4/Gallium results.

MicroBooNE 3+1 oscillation analysis sensitivity

Xiangpan Ji, poster I-b DT14-753, "Search for a sterile neutrino at MicroBooNE using BNB and NuMI beams"

ν_e appearance 2D parameter space



BNB Run 1-3 sensitivity

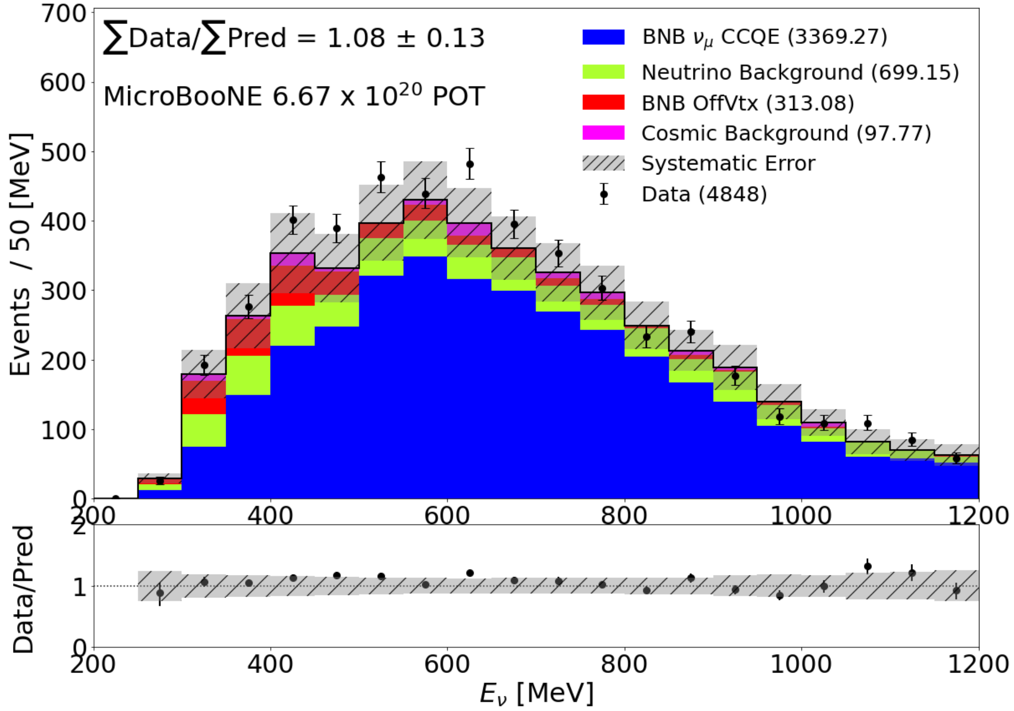
BNB Run 1-3 + NuMI Run 1 sensitivity

X-axis range changes

- Sensitivity is significantly improved (overall a factor of 2) when combining both BNB and NuMI (mainly due to **degeneracy mitigation**)
- BNB+NuMI data result is coming soon, expected to be sensitive to the LSND results.

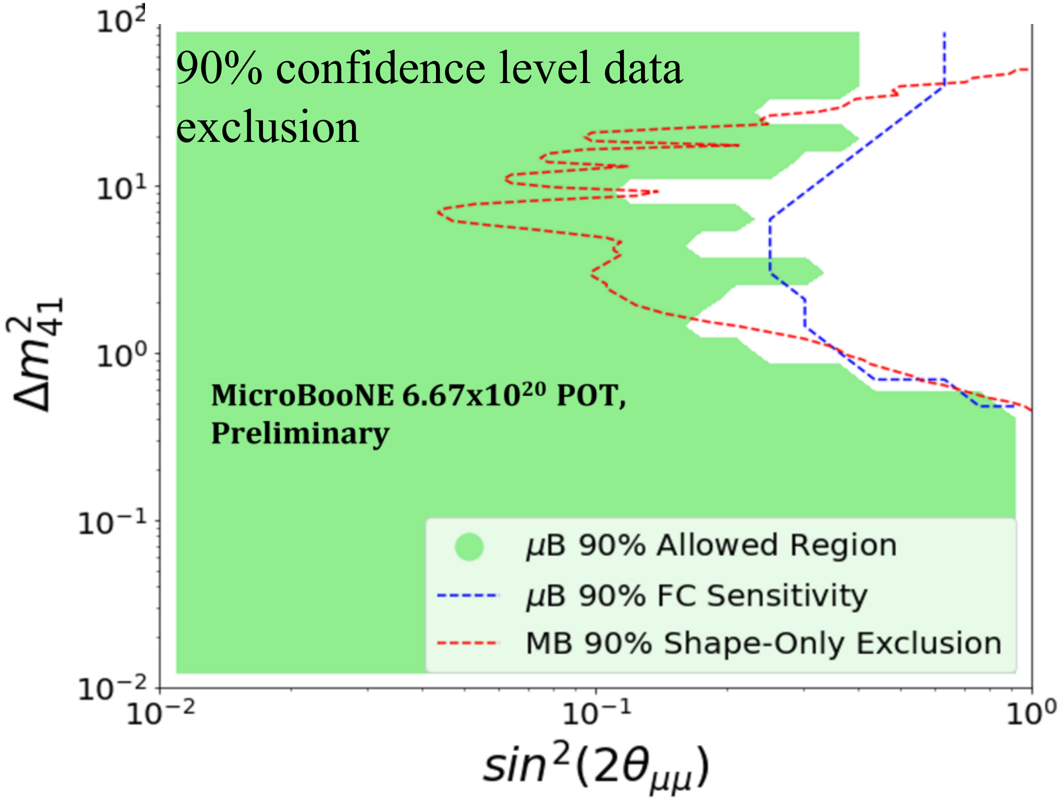
3+1 oscillation analyses using deep-learning-based ν_e / ν_μ selections

- Uses CCQE-dominated 98% pure ν_μ selection (deep-learning-based $1\mu1$p selection)
- The BNB data (Run 1-3) was found to be consistent with the 3ν (null) hypothesis
- MicroBooNE's Feldman-Cousins allowed region, compared to our sensitivity, is shown against the MiniBooNE shape-only exclusion limit



$1\mu1$p-like ν_μ CC candidates

Josh Mills, poster I-b DT14-720, "A Search for Sterile-Neutrino-Based Muon Neutrino Disappearance using the MicroBooNE Deep Learning Analysis"

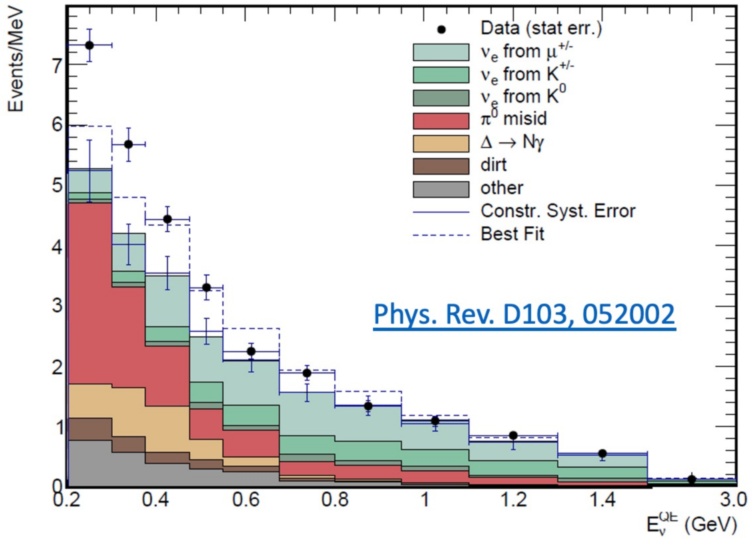


- A full 3+1 analysis using deep-learning-based ν_e and ν_μ selections is coming.

Katie Mason, poster I-b DT14-719, "Search for a 3+1 Sterile Neutrino with the MicroBooNE Experiment Using Deep-Learning-Based Reconstruction"

Examination of MiniBooNE LEE

MiniBooNE excess is still unexplained.



Electron-like excess (ν_e excess)

- Mismodeled/unknown process?
- Oscillation-driven excess?

Photon-like excess

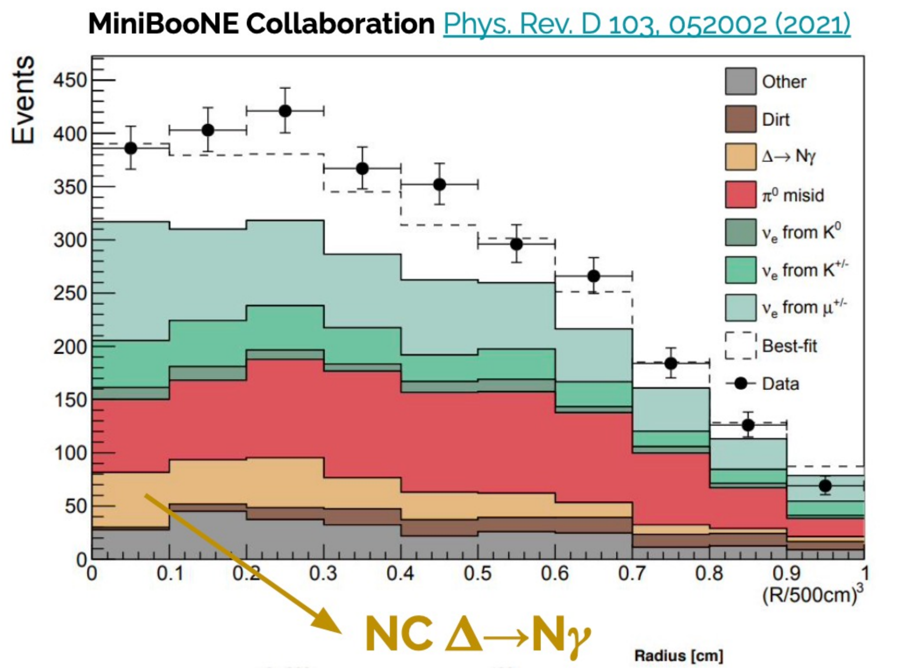
- Mismodeled/unknown process producing photons, e.g. **NC Δ resonance radiative decay**?

Search for a single-photon excess

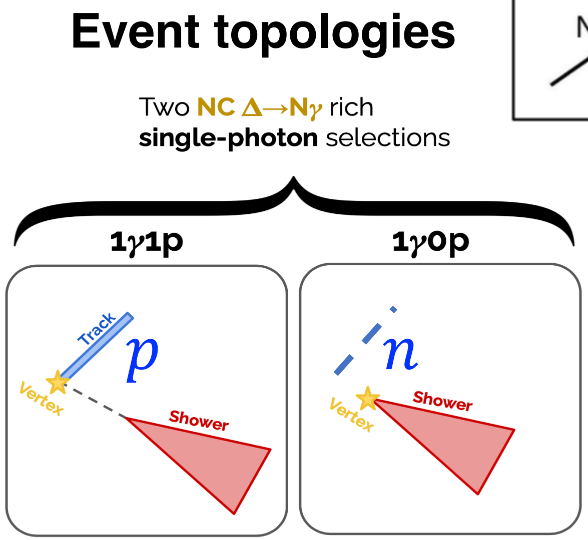
[Phys. Rev. Lett. **128**, 111801]

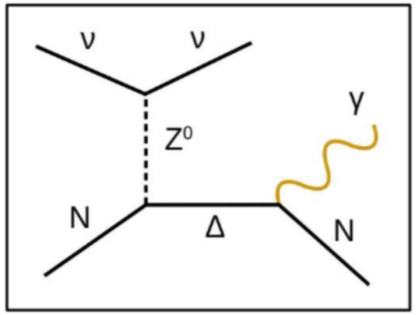
Targeting NC Δ resonance radiative decay ($\Delta \rightarrow N\gamma$)

- Standard model process
- Never been directly observed in neutrino scattering
- Previous best experimental limit at O(1 GeV) is orders of magnitude higher than the prediction



- An enhancement in NC Δ → Nγ with a multiplicative factor of **x3.18** would give good agreement with the observed MiniBooNE LEE





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

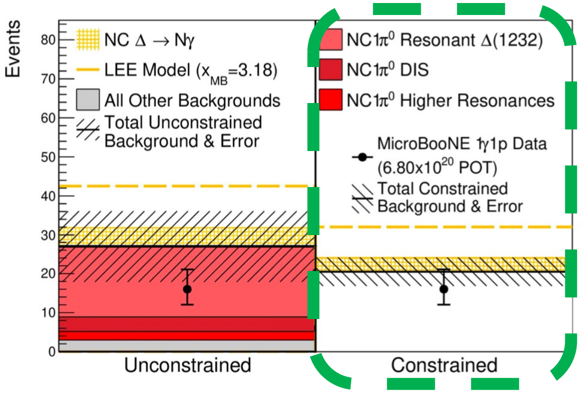
Two **NC $\Delta \rightarrow N\gamma$** rich **single-photon** selections

+

Two high-statistics **NC π^0 rich two-photon** selections

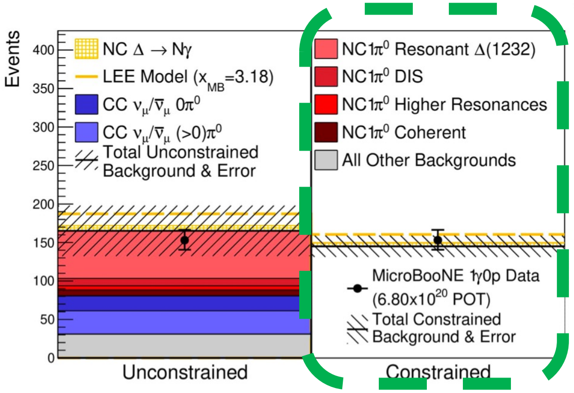
[Phys. Rev. Lett. **128**, 111801](#)

$1\gamma1p$



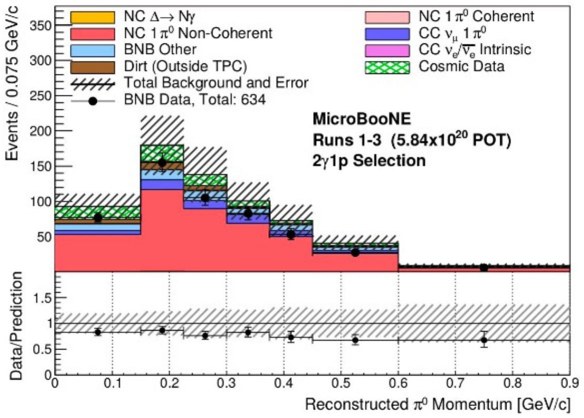
One-bin, Shower Energy from 0-0.6 GeV

$1\gamma0p$



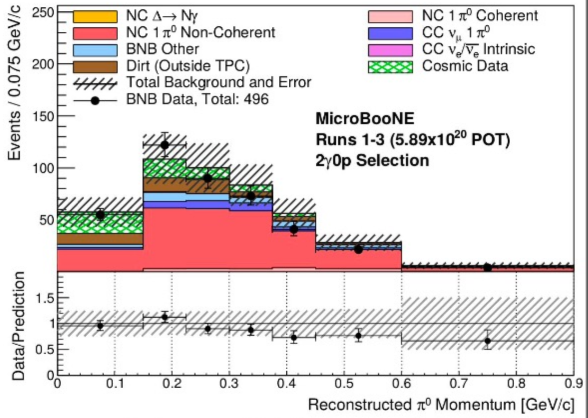
One-bin, Shower Energy from 0.1-0.7 GeV

$2\gamma1p$



7-bins, π^0 Momentum from 0-0.9 GeV/c

$2\gamma0p$

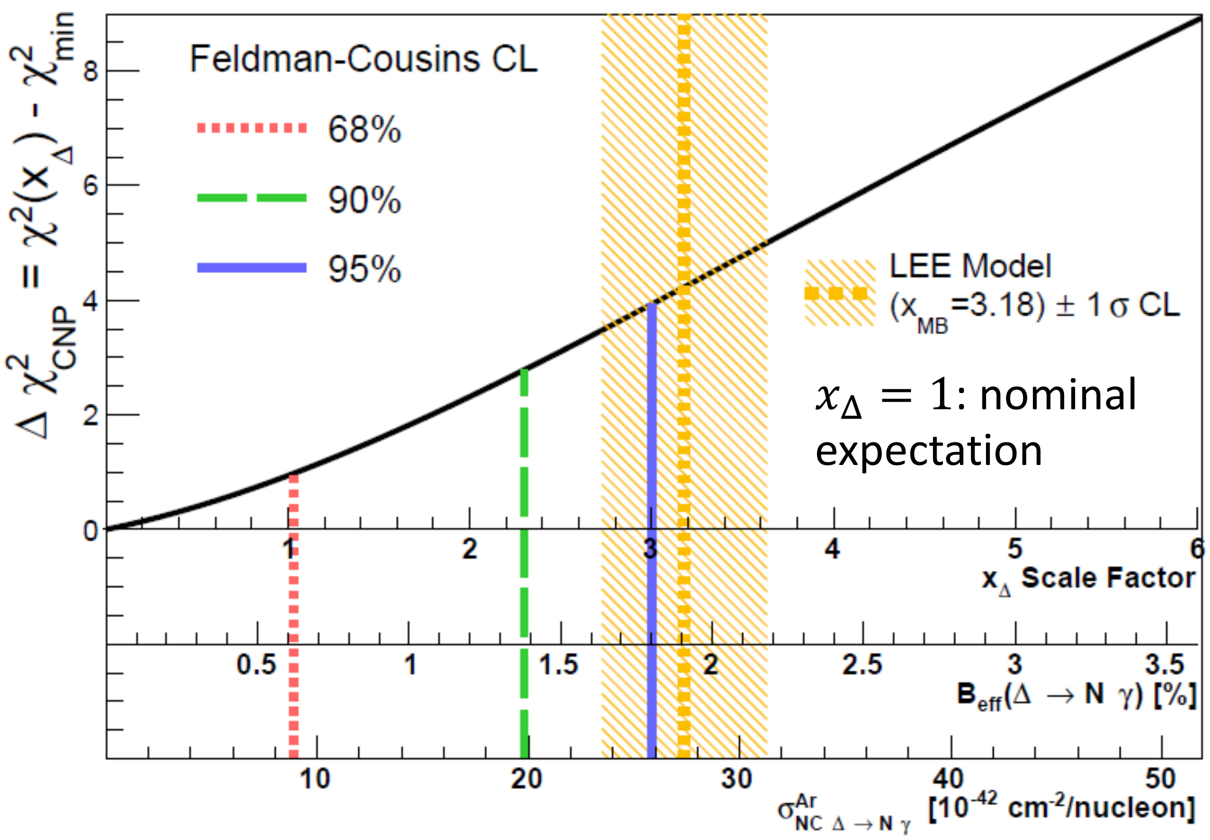


7-bins, π^0 Momentum from 0-0.9 GeV/c

NC $\Delta \rightarrow N\gamma$ search results

- This result disfavors the most suspect single-photon background as a sole source of the MiniBooNE excess
  - No evidence for an enhanced rate of single photons from NC Δ → Nγ decay above nominal expectation
  - Disfavors x3.18 NC Δ → Nγ decay at 94.8% C.L.
- One-sided bound on the normalization of Δ → Nγ was determined to be 2.3 at 90% C.L., leading to a 50-fold improvement over the previous world's best limit in the sub-GeV neutrino energy range

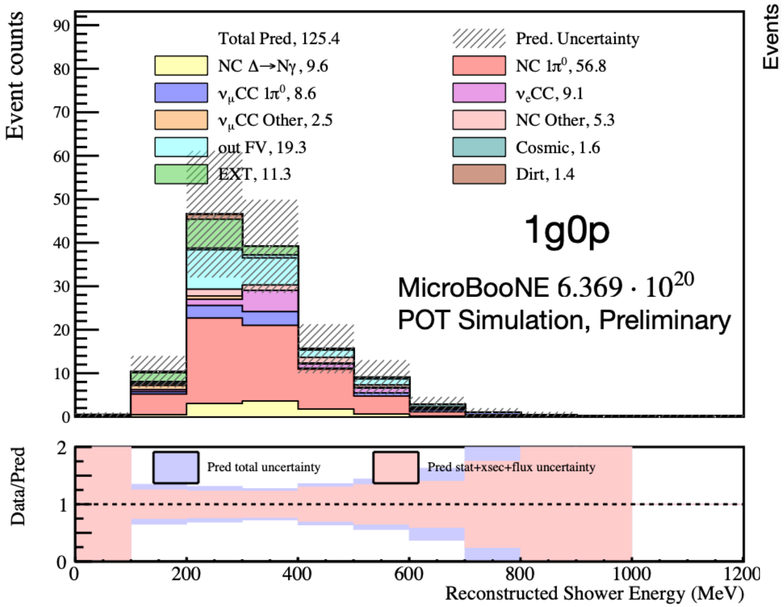
Phys. Rev. Lett. **128**. 111801



Mark Ross-Lonergan, poster IV-b MT05-767, "Search for anomalous single-photon production in MicroBooNE as a test of the MiniBooNE low-energy excess"

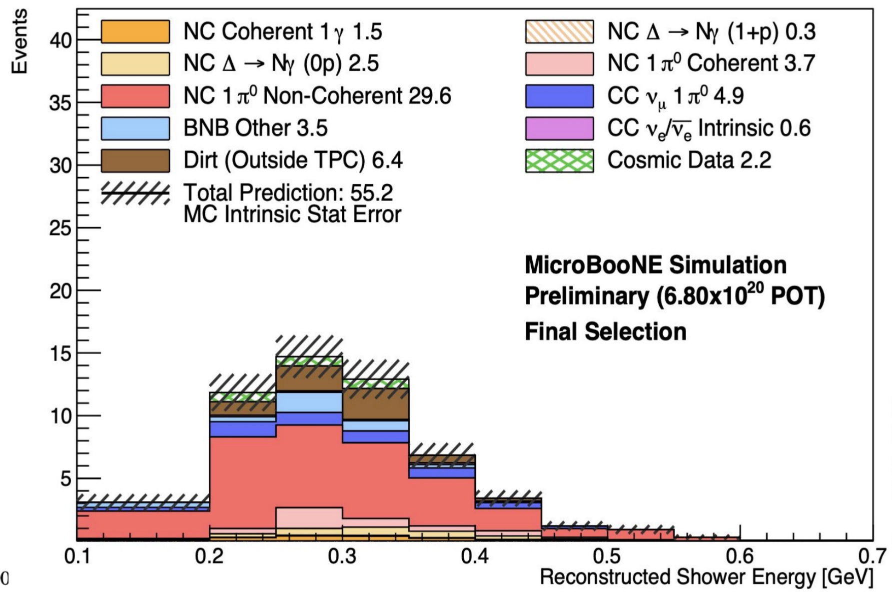
Other single-photon analyses in progress

Lee Hagaman, poster III-b MT07-764, “Progress Towards An Investigation Of The MiniBooNE Low Energy Excess Using NC Δ-Like Single Photons In MicroBooNE”



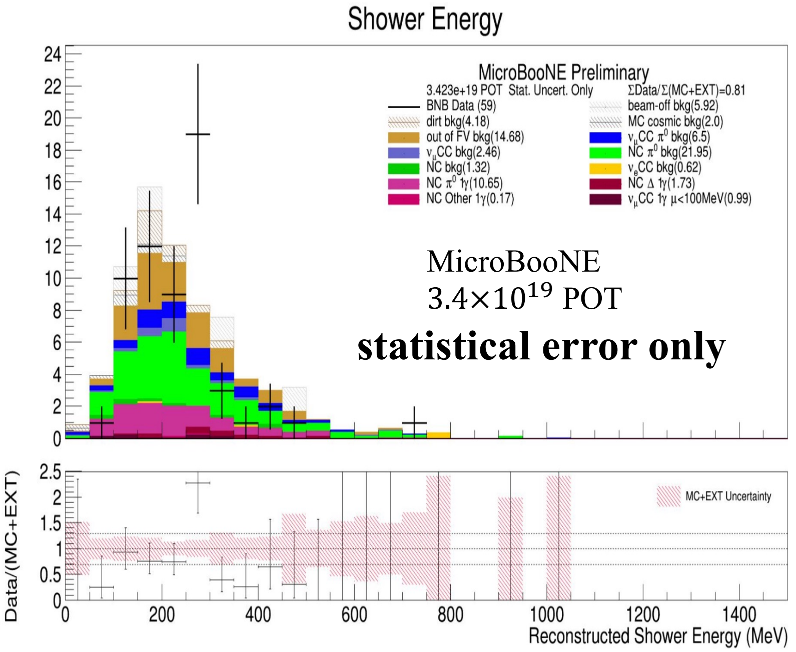
- Investigation of NC Δ-like single photons
- Improved efficiency and purity in 1g0p channel
- **More sensitive to potential excess in 1g0p channel**

Guanqun Ge, poster IV-b MT05-765, “Search for Anomalous NC Coherent-like Single-photon Production with MicroBooNE”



- Improved BDT selections focusing on forward-going, no hadronic activity single photons, i.e. NC coherent-like events
- New tools to further reject NC π^0 background and identify low-energy protons
- **Sensitive to potential excess in 1g0p and forward-going region**

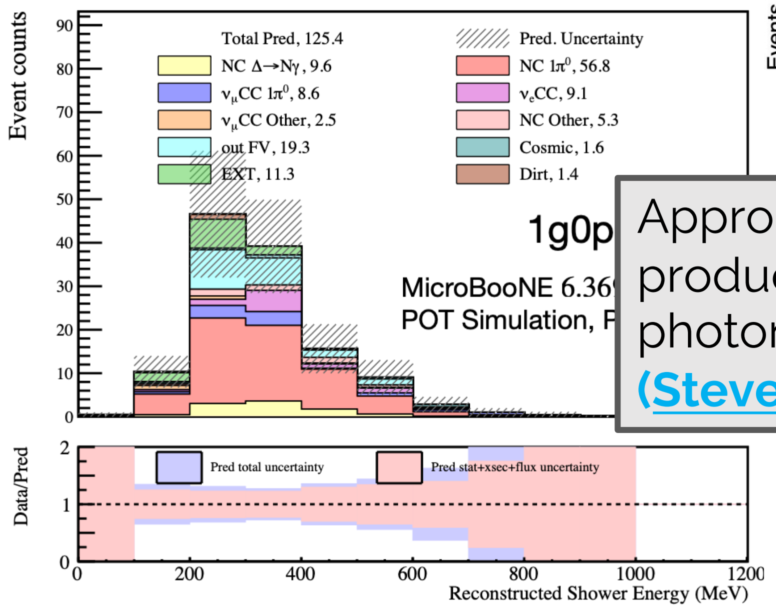
Erin Yandel, poster III-b MT07-722, “An Inclusive Single Photon Analysis in MicroBooNE”



- Investigation of a more broad and inclusive set of single-photon-like events
- A MiniBooNE-like selection and a decent efficiency of single-photon events
- **Generic test on standard model prediction of single-photon events in MicroBooNE**

Other single-photon analyses in progress

Lee Hagaman, poster III-b MT07-764, "Progress Towards An Investigation Of The MiniBooNE Low Energy Excess Using NC Δ-Like Single Photons In MicroBooNE"



- Investigation of NC Δ-like single photons
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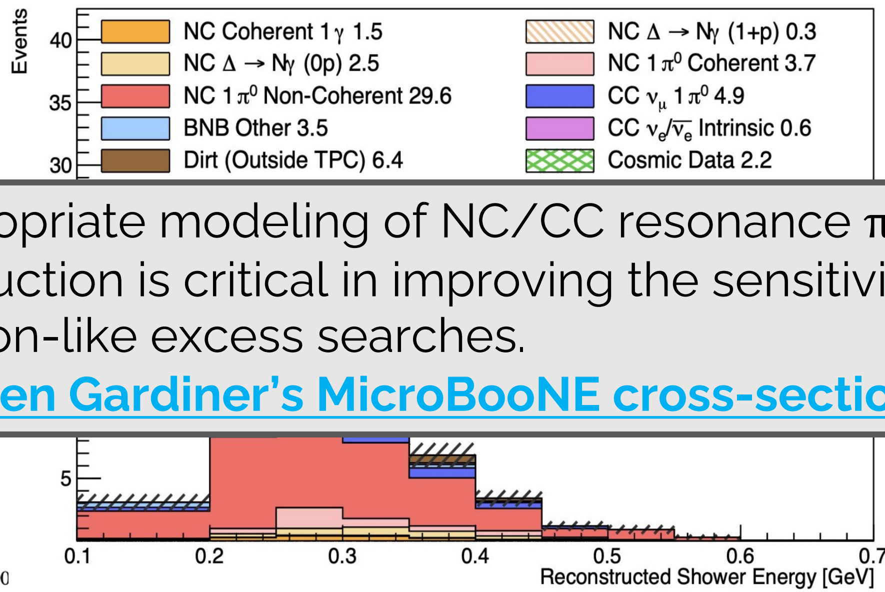
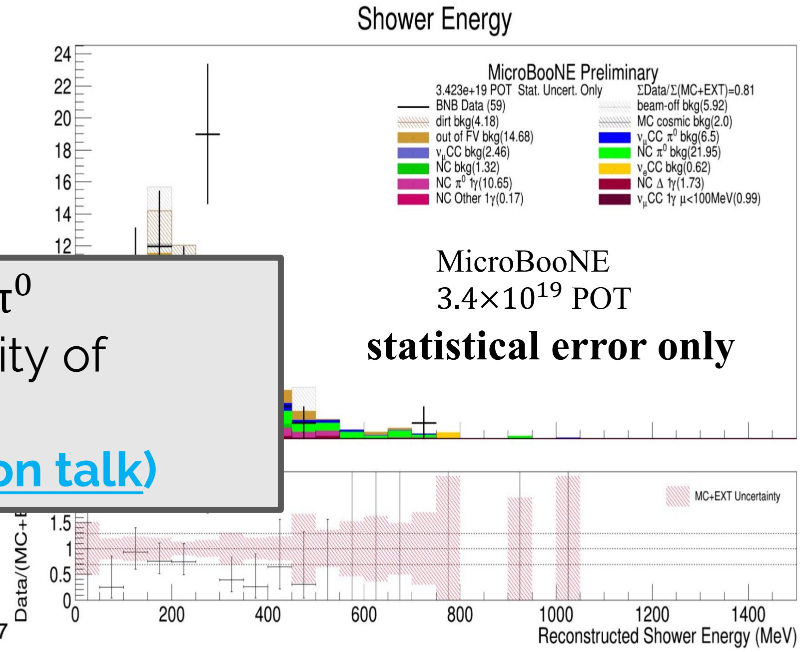
Guanqun Ge, poster IV-b MT05-765, "Search for Anomalous NC Coherent-like Single-photon Production with MicroBooNE"



- Improved BDT selections focusing on forward-going, no hadronic activity single photons, i.e. NC coherent-like events
- New tools to further reject NC π^0 background and identify low-energy protons
- **Sensitive to potential excess in 1g0p and forward-going region**

Erin Yandel, poster III-b MT07-722, "An Inclusive Single Photon Analysis in MicroBooNE"



- Investigation of a more broad and inclusive set of single-photon-like events
- A MiniBooNE-like selection and a decent efficiency of single-photon events
- **Generic test on standard model prediction of single-photon events in MicroBooNE**

Appropriate modeling of NC/CC resonance π^0 production is critical in improving the sensitivity of photon-like excess searches.
(Steven Gardiner's MicroBooNE cross-section talk)

Exotic physics searches

- [Beam] Heavy neutral lepton search [Phys. Rev. D **101**, 052001] (update coming soon)
- [Detector material] Baryon number-violating neutron-antineutron oscillation search Neutrino 2022 poster
- [Beam] Millicharged particle search in progress

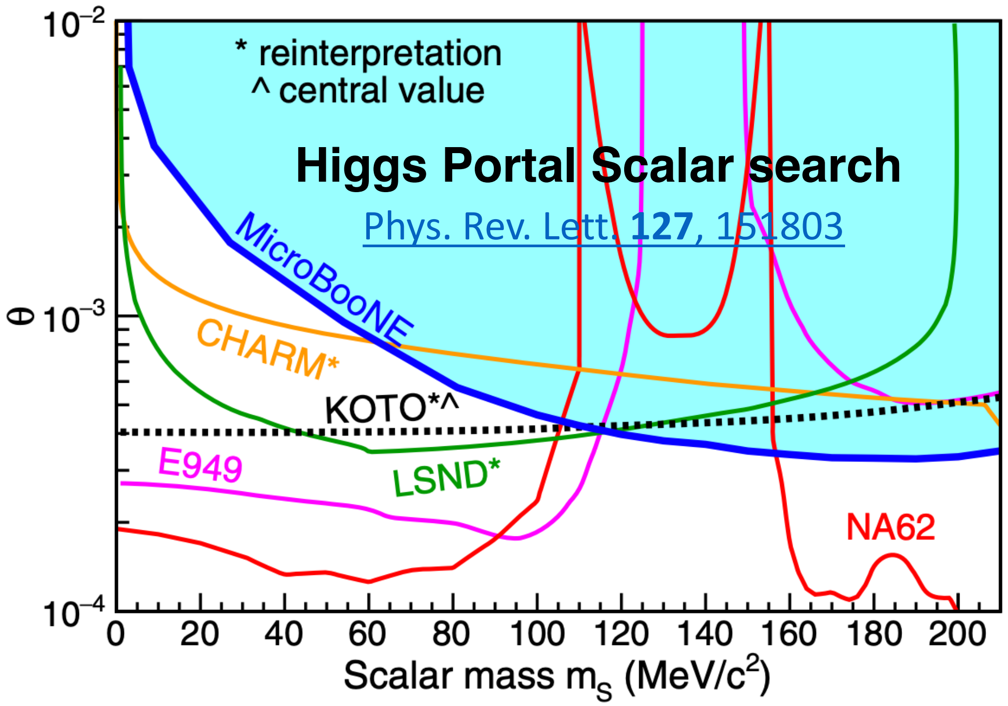
- [Beam] Higgs portal scalar limit [Phys. Rev. Lett. **127**, 151803] (update coming soon)
- [Beam] Dark trident search in progress

Pioneered e^+e^- searches for more exploration of MiniBooNE excess

Neutron-Antineutron search

70-80% efficiency in a surface LArTPC

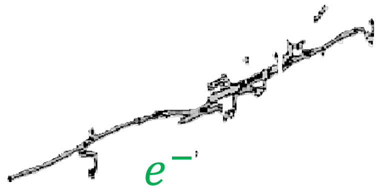
Yeon-jae Jwa, poster II-b DT15-770, "A first search for argon-bound neutron-antineutron oscillation using the MicroBooNE LArTPC"



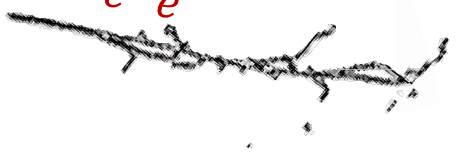
More exploration of MiniBooNE excess

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - *[13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)*
  - *[14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141*
- New resonance matter effects
  - *[5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)*
  - *[16] Alves, Louis, deNiverville, [hep-ph]2201.00876 (2022)*
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - *[7]Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470*
- Decay of heavy sterile neutrinos produced in beam
  - *[4] Gninenko, Phys.Rev.D83:015015,2011*
  - *[12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)*
  - *[15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)*
  - *[11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)*
  - *[17] Dutta, Kim, Thompson, Thornton, Van de Water [hep-ph]2110.11944*
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - *[1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)*
  - *[2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531*
  - *[3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)*
  - *[10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)*
  - *[6] Abdallah, Gandhi, Roy,Phys. Rev. D 104, 055028 (2021)*
- Decay of axion-like particles
  - *[8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)*
- A model-independent approach to any new particle
  - *[9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)*

Produces True Electrons

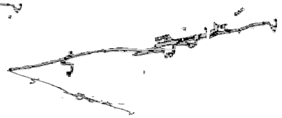


Produces True Photons



Produces e^+e^- pairs

Overlapping e^+e^-



Asymmetric e^+e^-

Evolving theory landscape …
(not an exhaustive list)

Summary

- Our first searches for low-energy excess found no evidence of excessive ν_e or NC Δ radiative decay to explain the MiniBooNE excess (eLEE result gLEE result)
  - Disfavor pure ν_e excess as a sole source of MiniBooNE excess at 3σ level
  - Disfavor pure NC Δ radiative decay as a sole source of MiniBooNE excess at about 2σ level
- Full 3+1 oscillation analyses were carried out to interpret the MicroBooNE eLEE results under a sterile neutrino oscillation hypothesis (note#1116, note#1106, note#1105)
  - The data (50% BNB dataset) was found to be consistent with 3-flavor hypothesis and exclusion limits were calculated using a frequentist approach
  - Utilizing both BNB and NuMI data, the 3+1 analysis will be sensitive to the Neutrino-4/Gallium/LSND results.
- Further investigations on MiniBooNE excess are underway (note#1102, note#1103, note#1104)
  - Expanded scope of sterile neutrino oscillations
  - Extended photon-like event searches
  - Exotic e^+e^- pair search
- Searches for other BSM particles or processes

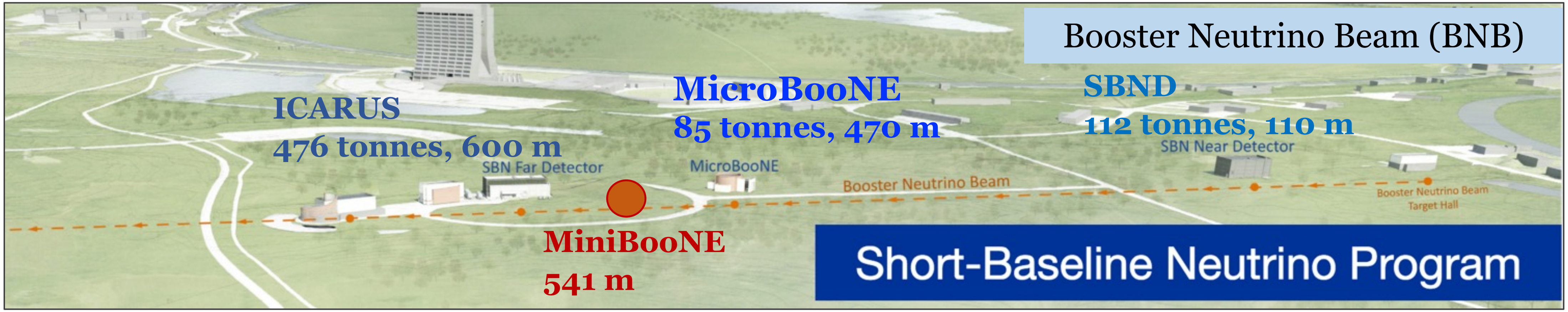
Much more coming soon!

Summary

- MicroBooNE has developed various techniques and tools to perform precision physics analyses in LArTPCs.
- The capability of exploring the MiniBooNE low-energy excess and other exotic physics will be enhanced leveraging the three detectors in the Short-Baseline Neutrino Program (SBN)
    - BNB beam: SBND, ICARUS, MicroBooNE
    - NuMI beam: ICARUS, MicroBooNE

See the next talk from A. Schukraft

- MicroBooNE laid the groundwork for the other SBN LArTPC detectors and the future mega-scale neutrino experiment DUNE



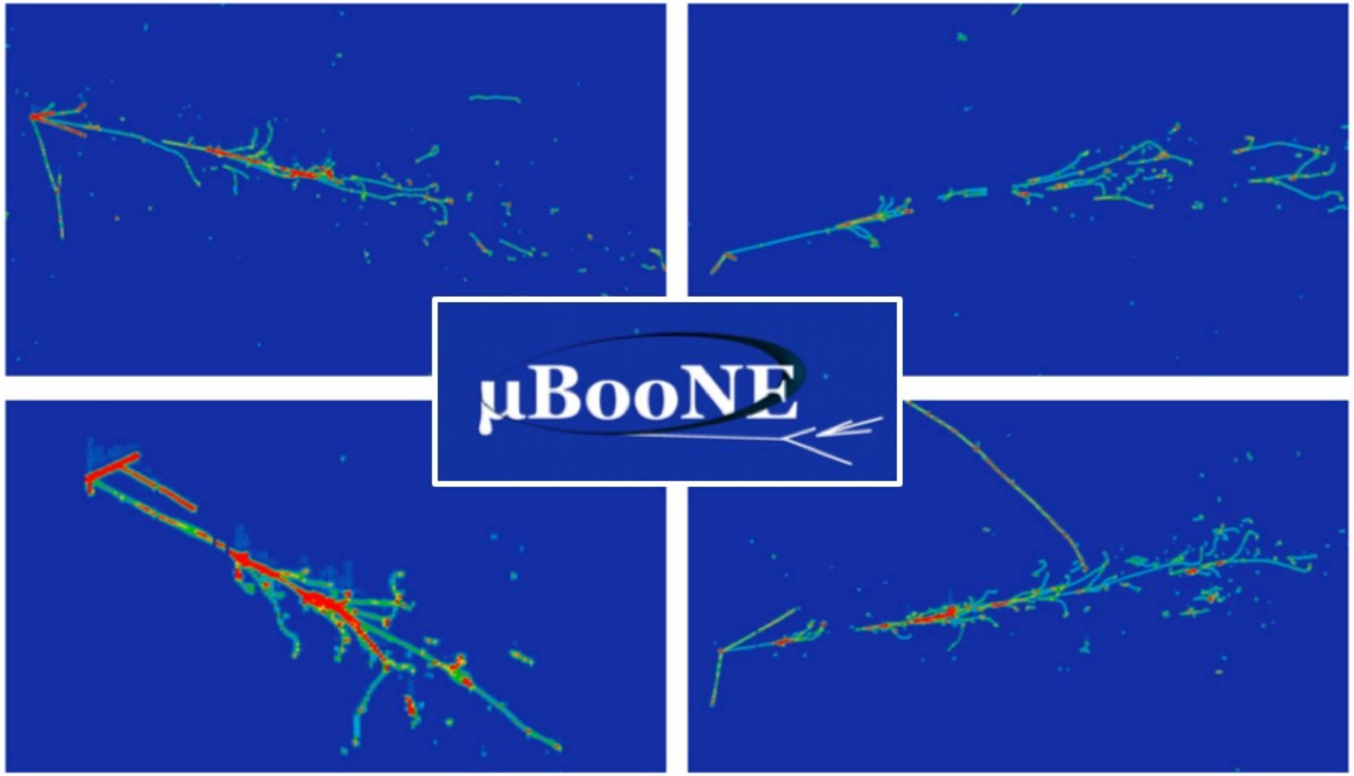
Other MicroBooNE Neutrino 2022 posters

- **K. Wresilo**, II-a DT01-725, “Impact of Improving Pandora Reconstruction in MicroBooNE: Towards Understanding the Low-Energy Excess Anomaly”
- **D. Totani**, III-b MT16-727, “Demonstration of <2 ns timing resolution for neutrino interaction in the MicroBooNE detector”
- **I. Lepetic**, IV-b MT17-703, “Observation of Radon Mitigation in MicroBooNE by a Liquid Argon Filtration System”

- **J. Barrow**, IV-b MT05-772, “Cosmic ray studies of μ-Argon interactions”
- **A. Papadopoulou**, IV-b MT05-748, “First Measurement of Differential Charged Current Quasielastic-like ν_μ–Argon Scattering Cross Sections In Kinematic Imbalance Variables With The MicroBooNE Detector”
- **S. Sword-Fehlberg**, IV-b MT05-723, “First Extraction of Single Differential Cross-Sections on ^{40}Ar for CC1μ2p0π Event Topologies in the MicroBooNE Detector”
- **L. Cooper-Troendle**, IV-b MT05-766, “Methodology of the extraction of multi-differential cross sections of charged-current ν_μ–Argon interactions in MicroBooNE using Wire-Cell ν_μ CC selection”
- **M. Bhattacharya**, IV-b MT05-773, “A Measurement of Neutrino Induced Charged Current Neutral Pion Production in the MicroBooNE Experiment”
- **S. Berkman**, IV-b MT05-734, “MicroBooNE Electron Neutrino Cross Section without Visible Pions”
- **G. Scanavini**, IV-b MT05-759, “Measurement of Neutral-Current π^0 in MicroBooNE using Wire-Cell”
- **C. Thorpe**, IV-a MT05-708, “Λ Production in MicroBooNE”
- **N. Oza**, IV-b MT05-756, “Measuring the Neutral Current π^0 Cross-section on Argon in MicroBooNE”

Technotes for the posters https://microboone.fnal.gov/public-notes/

Thank you!

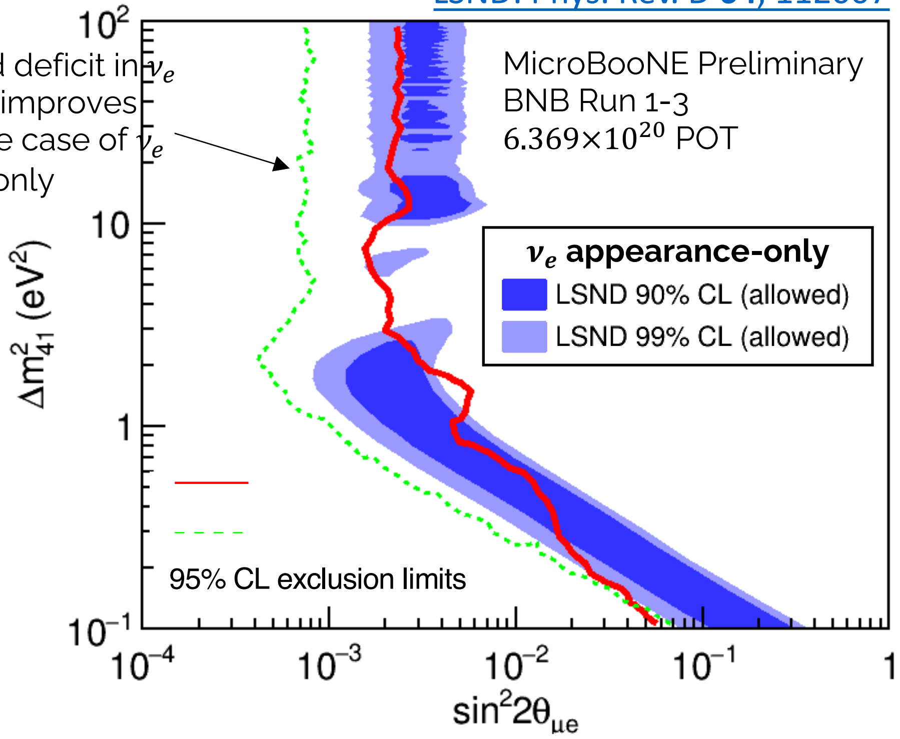


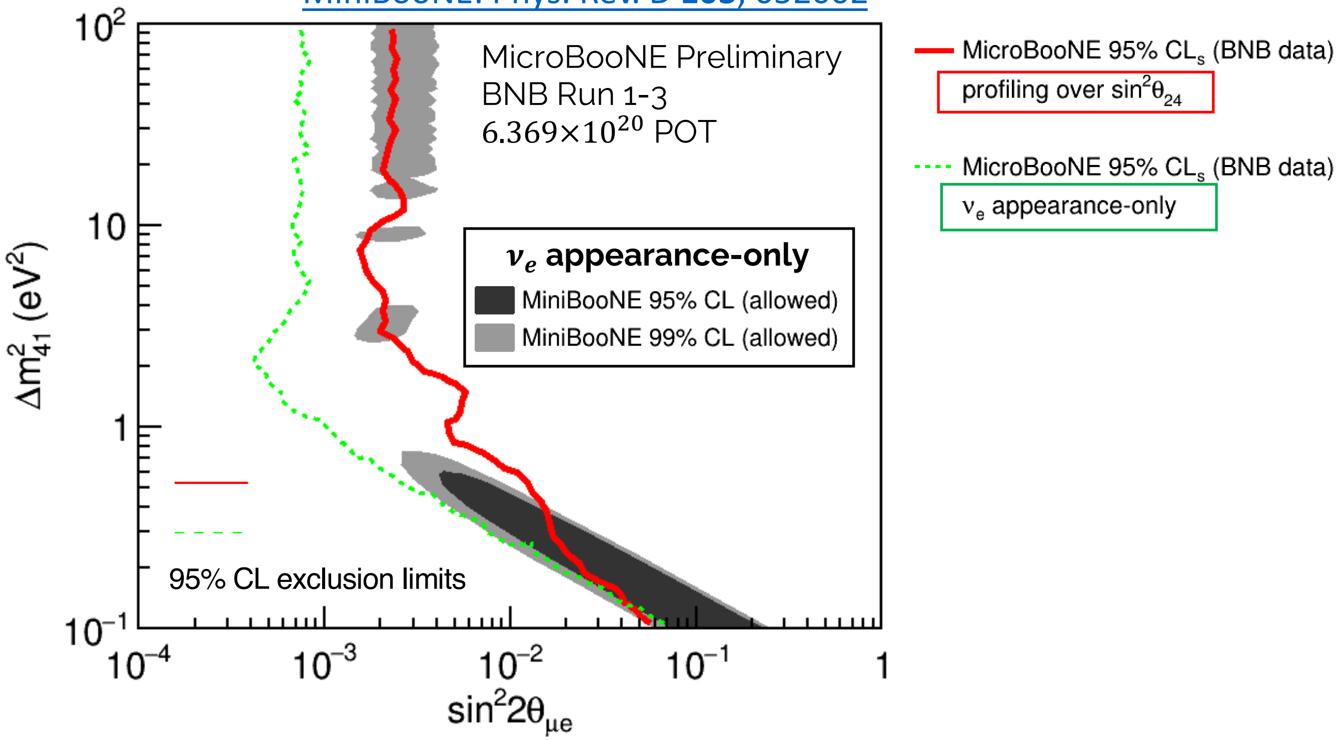
Extra slides

"3+1" versus "ν_e appearance-only" results

ν_e **appearance** 2D parameter space

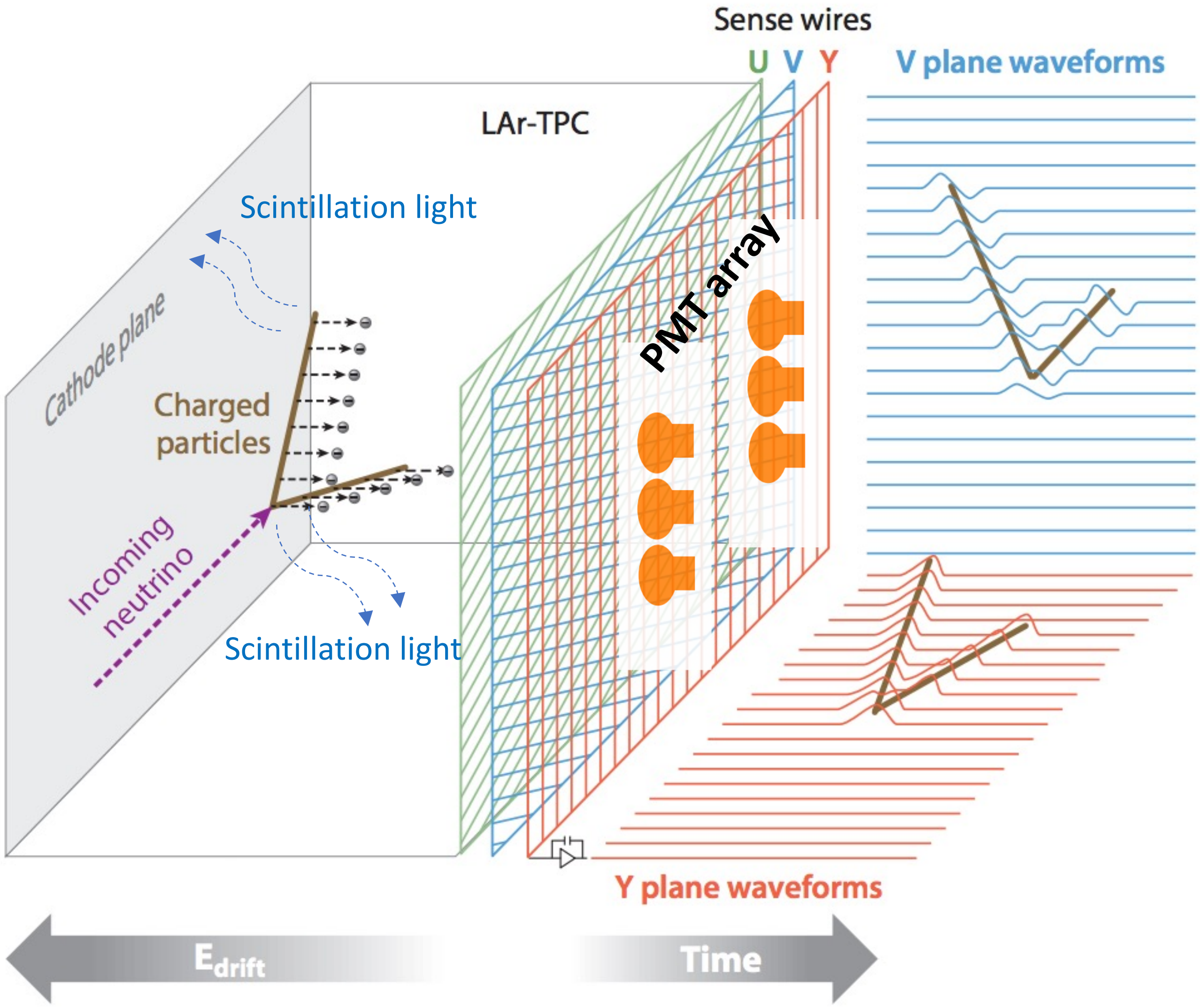
The observed deficit in ν_e considerably improves this limit in the case of ν_e appearance-only



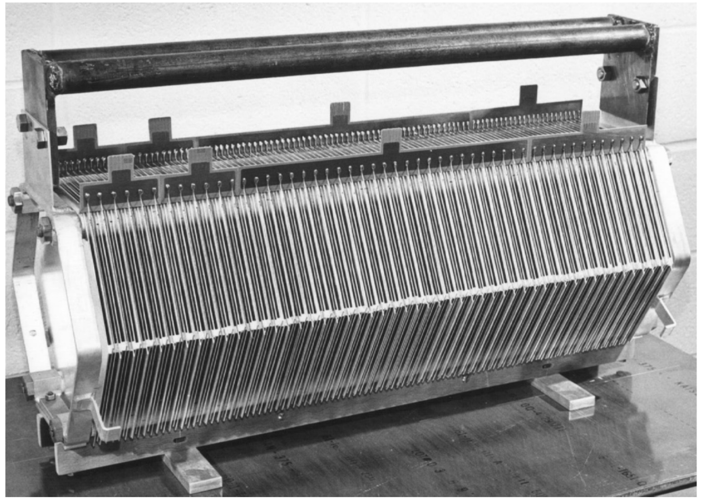


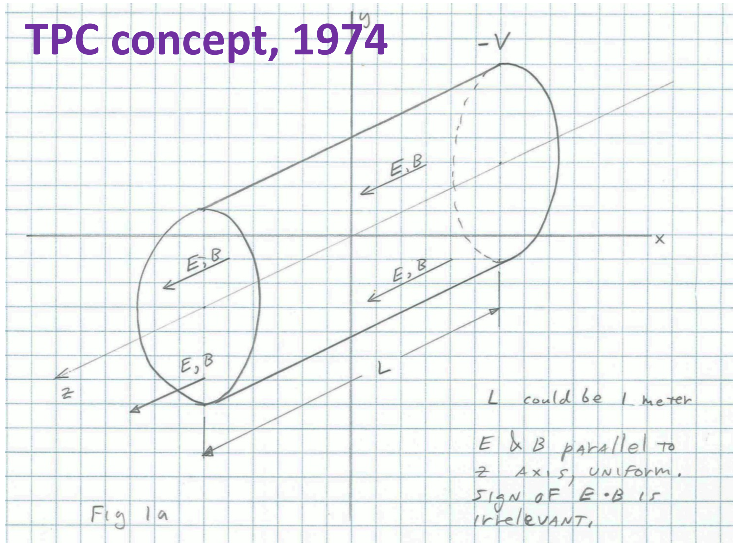
- **Caveat: ν_e appearance-only** physically not allowed in the 3+1 framework; in some case it is a reasonable approximation, like LSND (low stats. Intrinsic $\bar{\nu}_e$), but not for MicroBooNE/MiniBooNE
- Full 3+1 oscillation should be applied in any channels that serve as systematics constraints

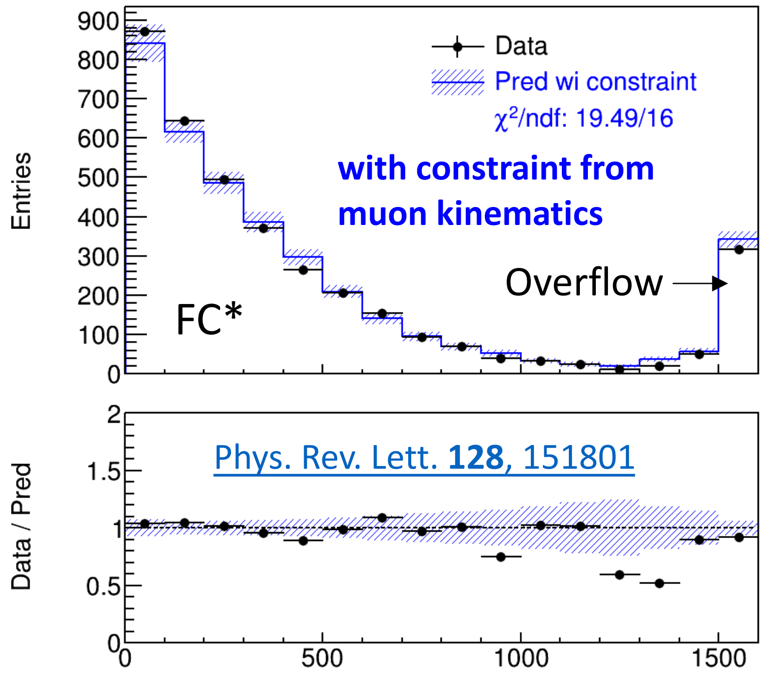
Liquid Argon Time Projection Chamber



LAr calorimeter, 1974

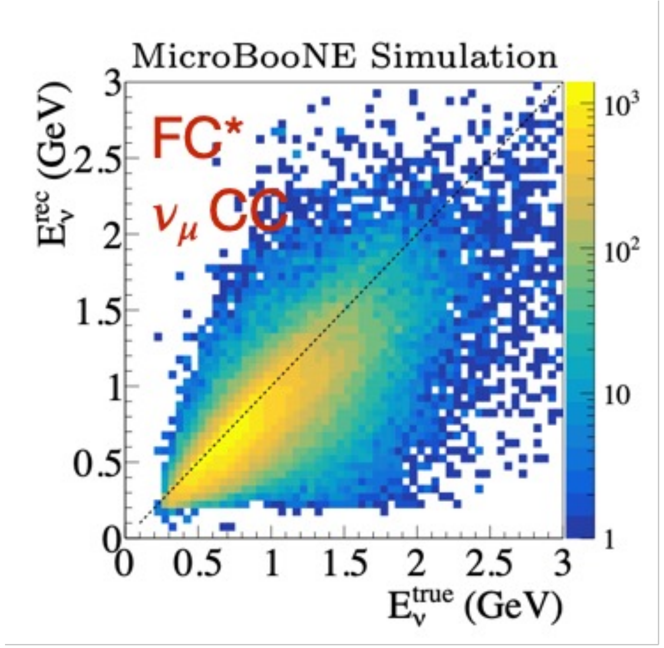


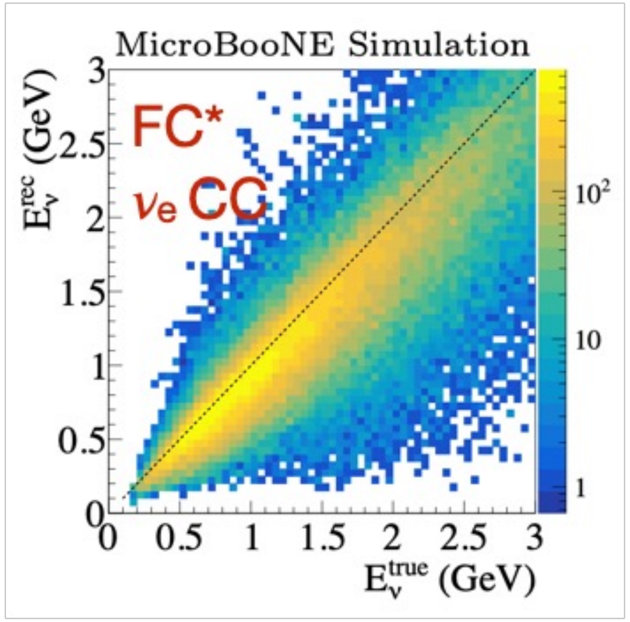




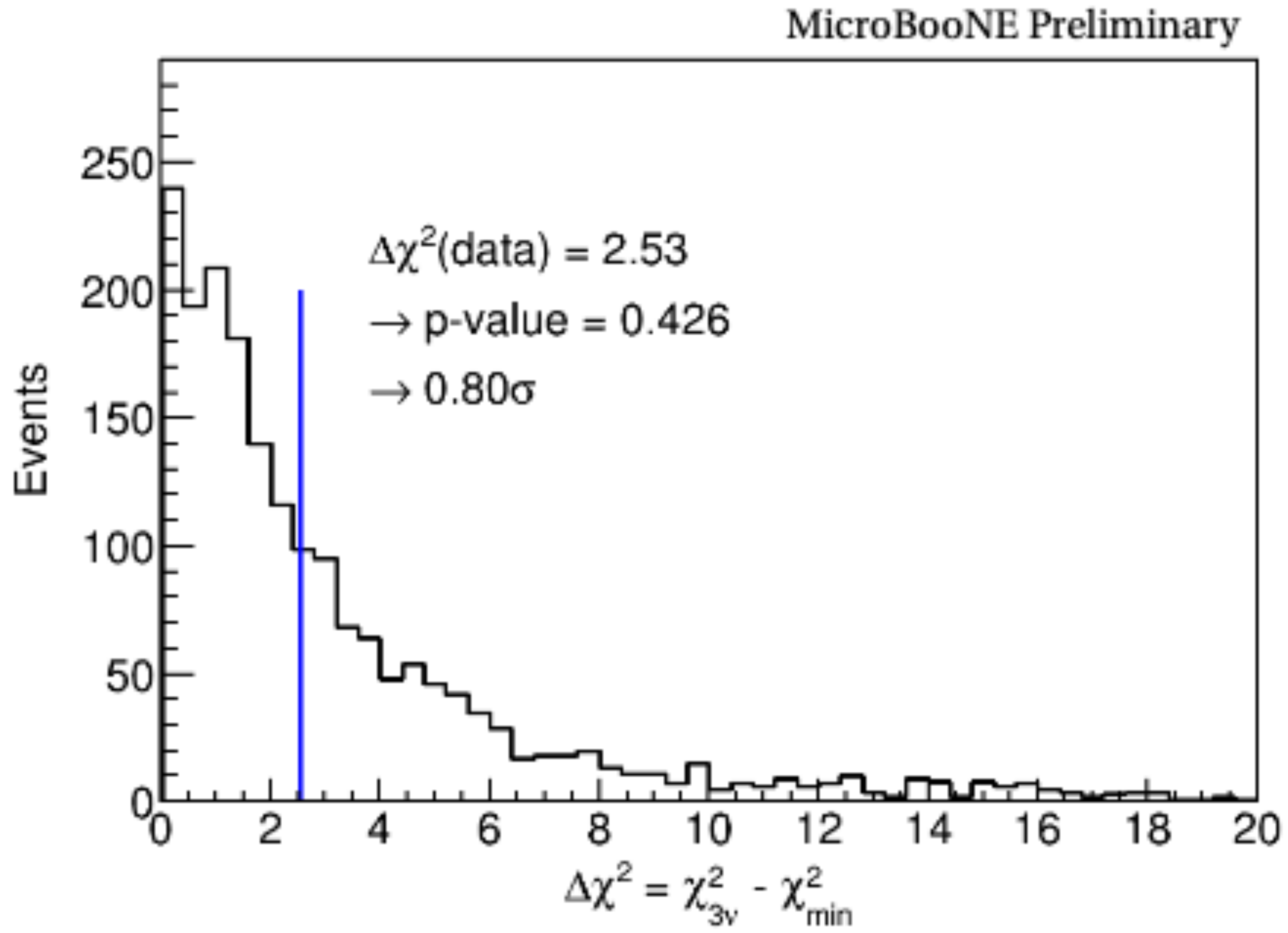
Reconstructed visible hadronic energy

Neutrino energy reconstruction primarily follows a calorimetric method





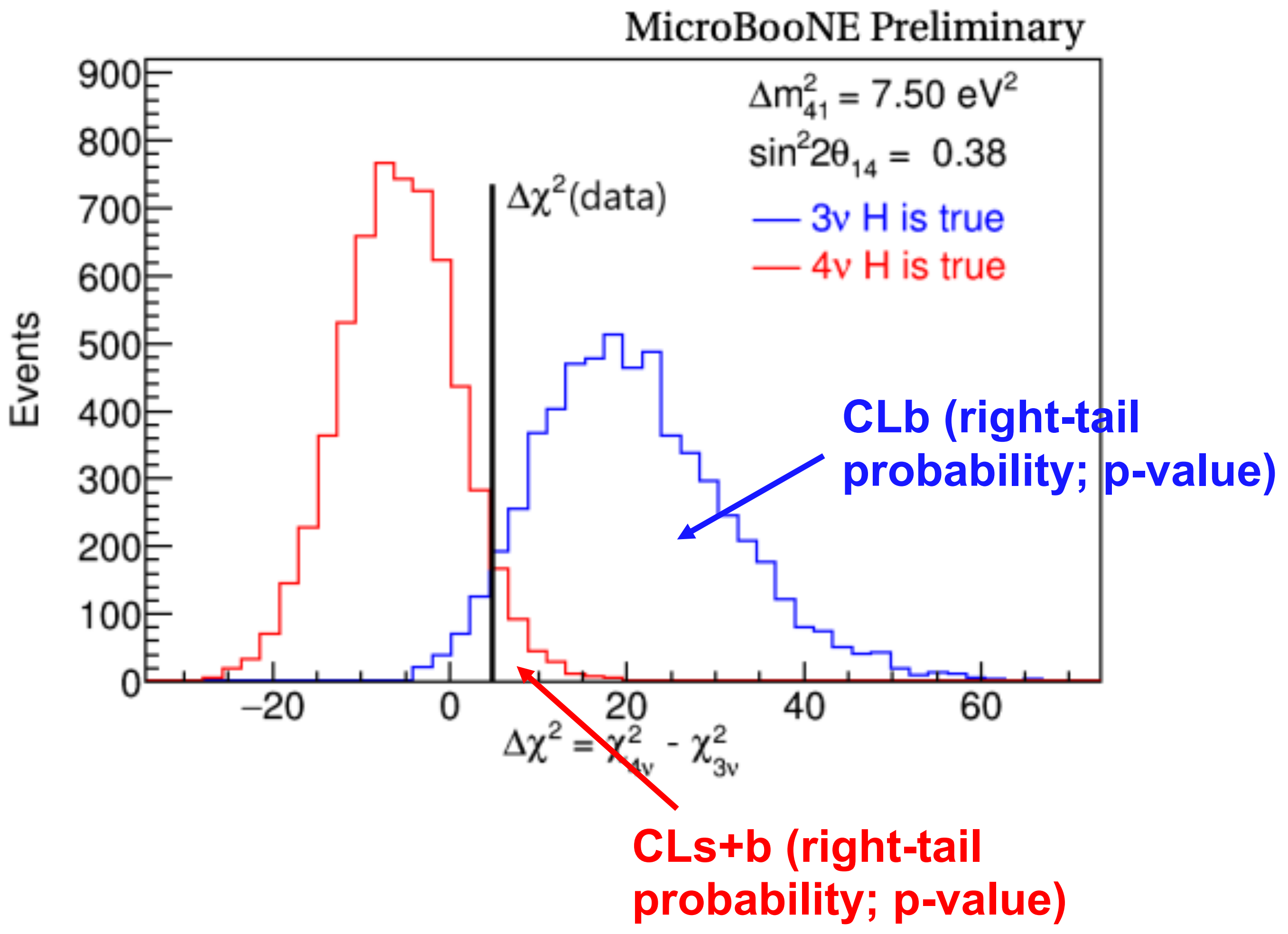
- 15-20% resolution for fully contained ν_μ CC
- 10-15% resolution for fully contained ν_e CC



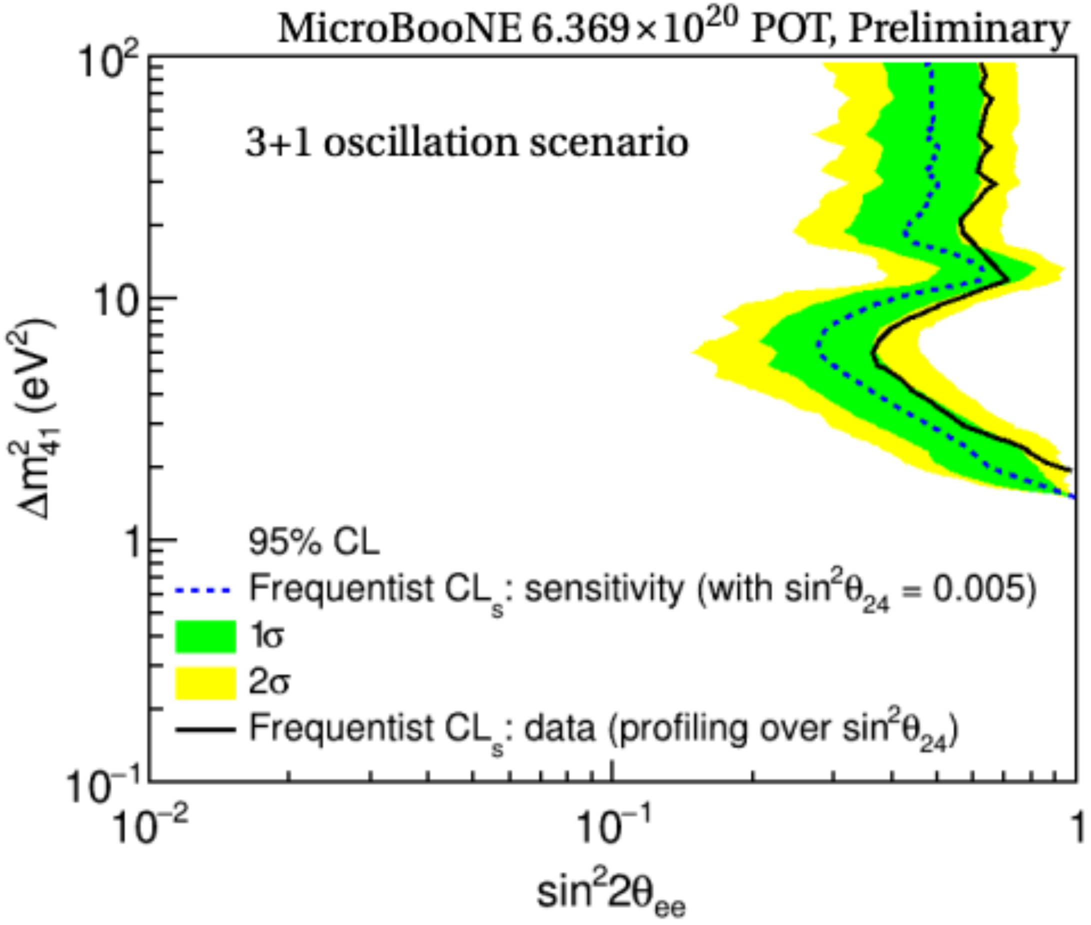
Full 3+1 data p-value following the Feldman-Cousins approach

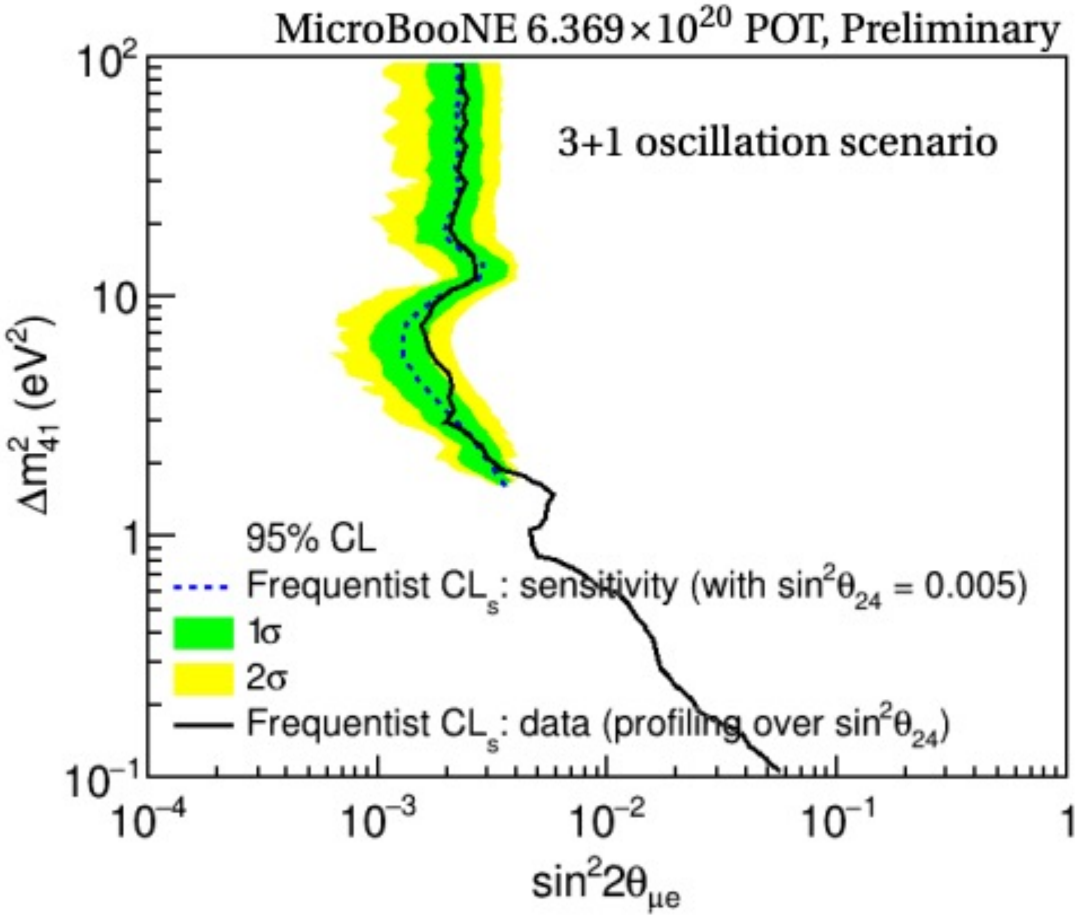
CLs method

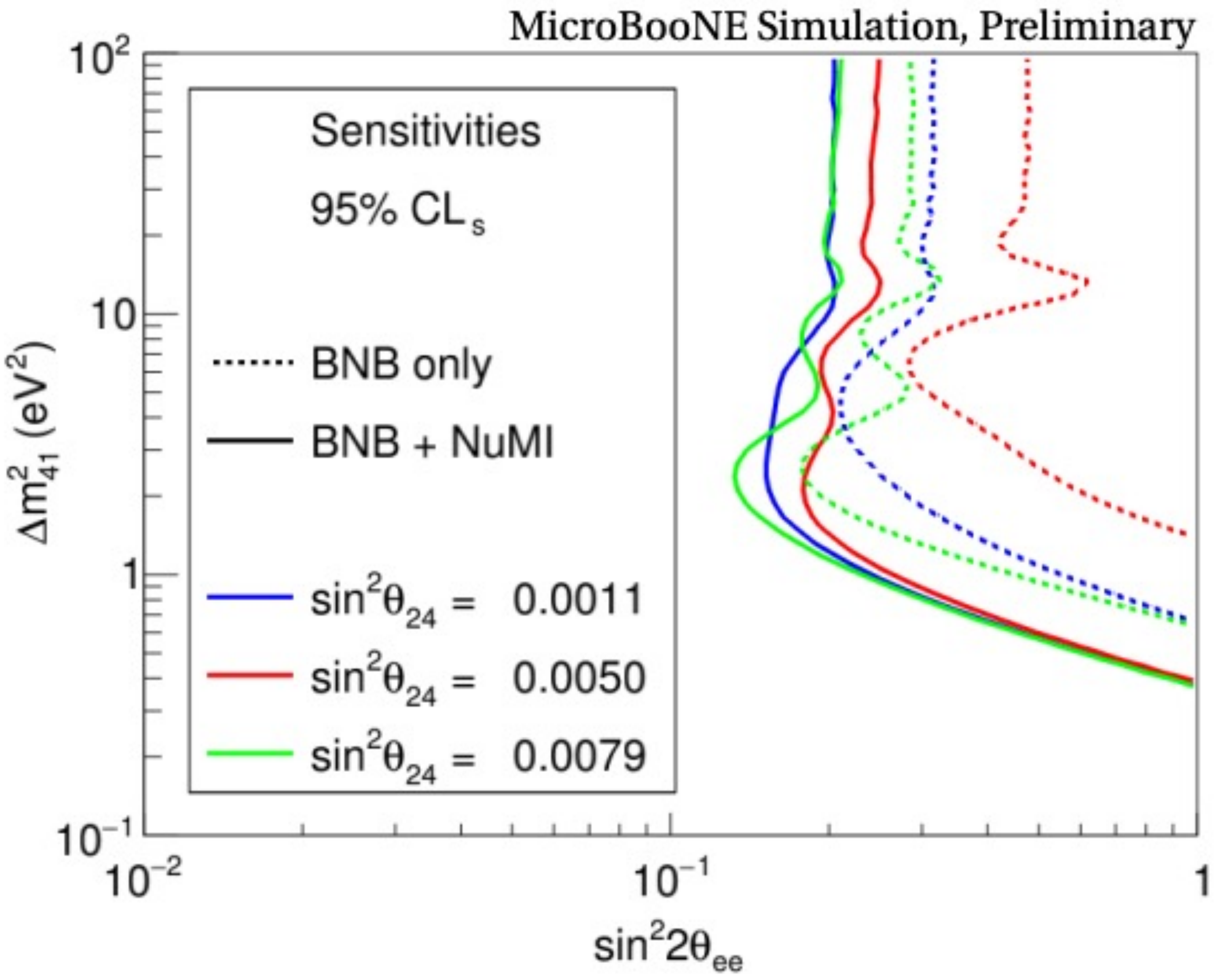
CLs = CLs+b/CLb = 1 - α (confidence level)



Full 3+1 sensitivity and data exclusion limits







BNB Run 1-3
NuMI Run 1

Degeneracy mitigation