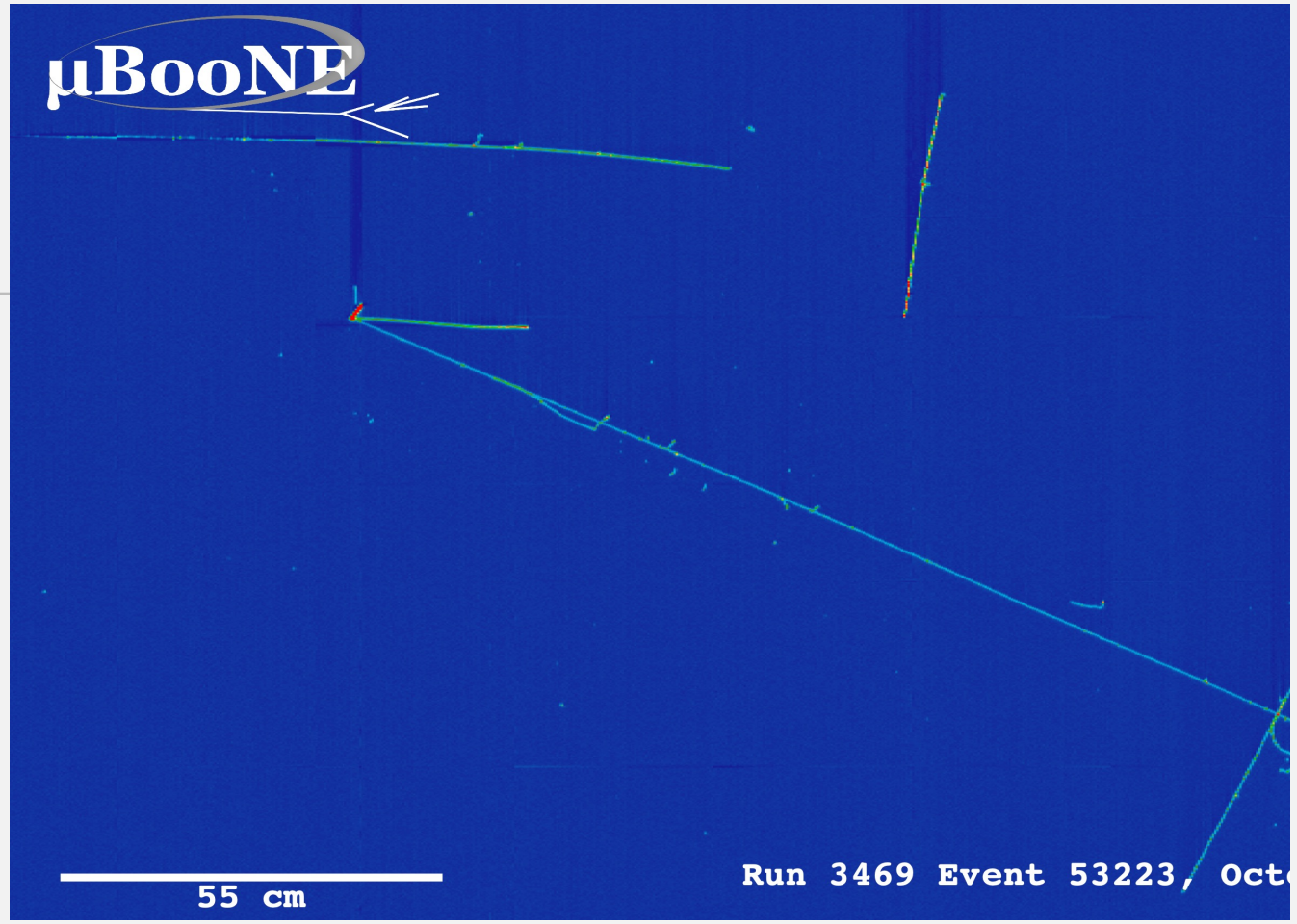
Recent MicroBooNE results

Jaroslaw Nowak

for the MicroBooNE Collaboration

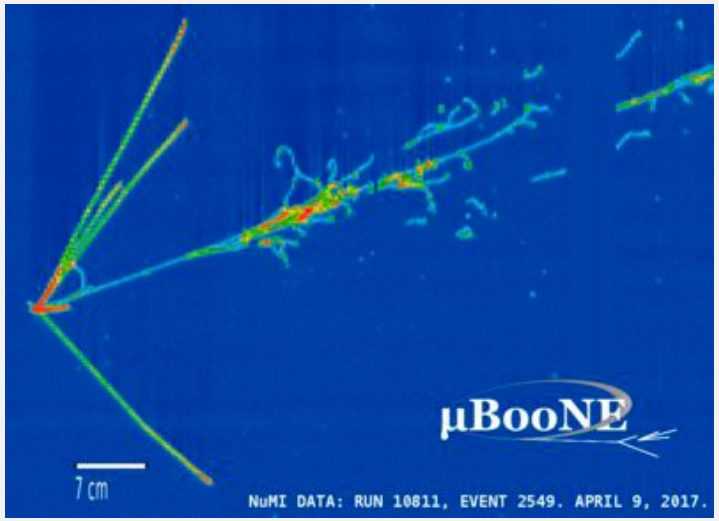
Lancaster University

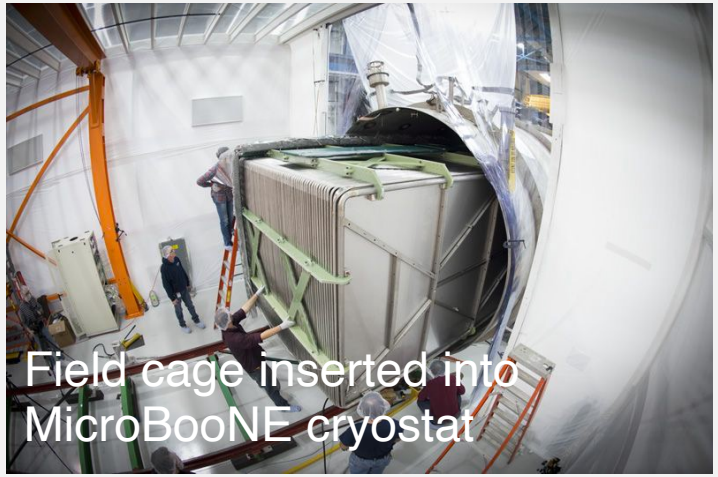


MicroBooNE has harnessed the **power of LArTPC detector technology** to make valuable new precision measurements

- World's first high-statistics precision cross-section measurements on argon
- Detailed initial **investigations into MiniBooNE anomaly**
- Further **searches for new physics**

MicroBooNE is also **laying the groundwork for future LArTPC detector SBN programme** and multi-kt neutrino experiment DUNE




Field cage inserted into MicroBooNE cryostat

MicroBooNE: 85-tonne active mass LArTPC

JINST 12 P02017 (2017)

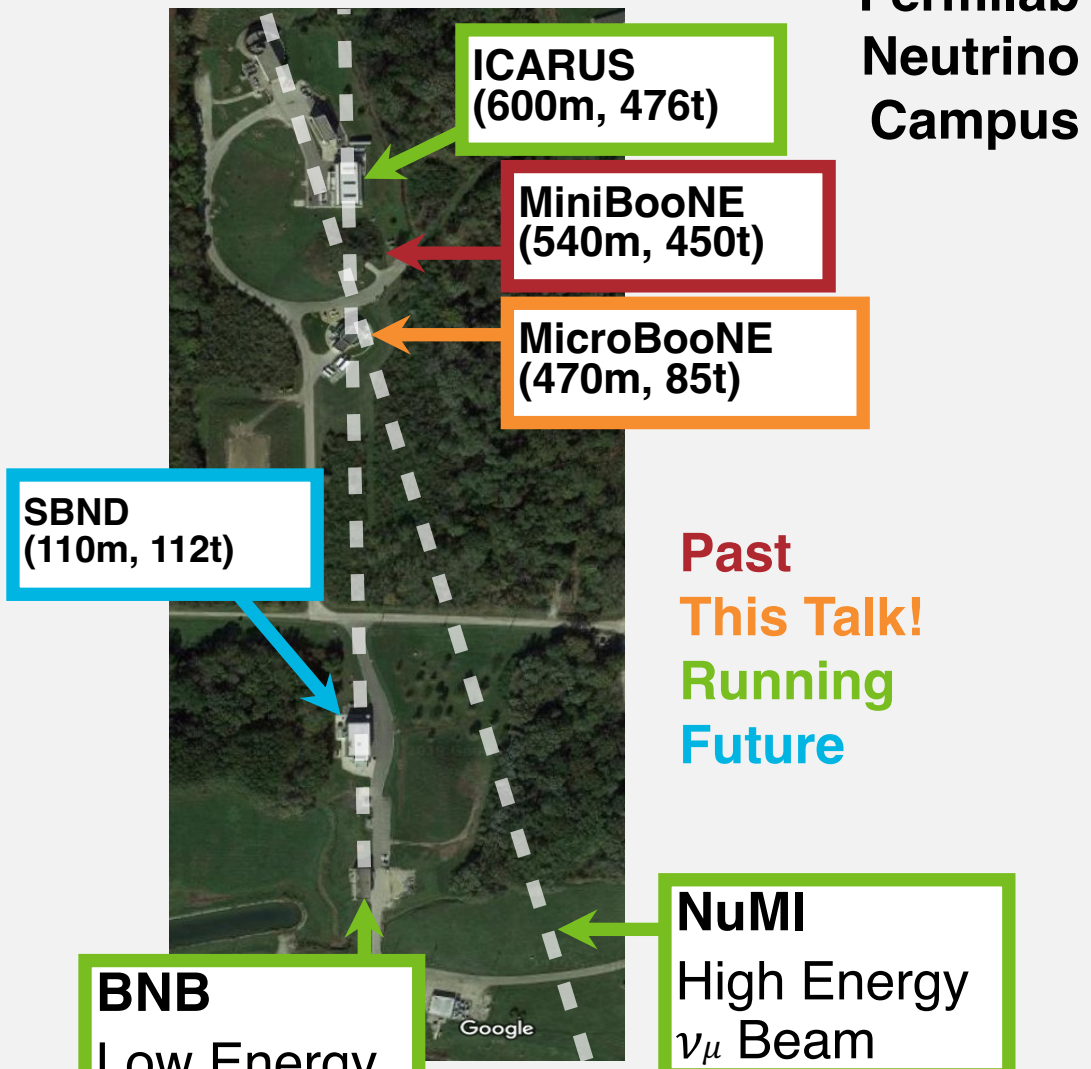
Sits in **two neutrino beams** at Fermilab:

- BNB (on-axis, $<E_{\nu\mu}>$=800 MeV) and
- NuMI (off-axis, $<E_{\nu e}>$=650 MeV)

Completed 5 years of beam physics data-taking: **world's largest dataset of neutrino interactions on argon**

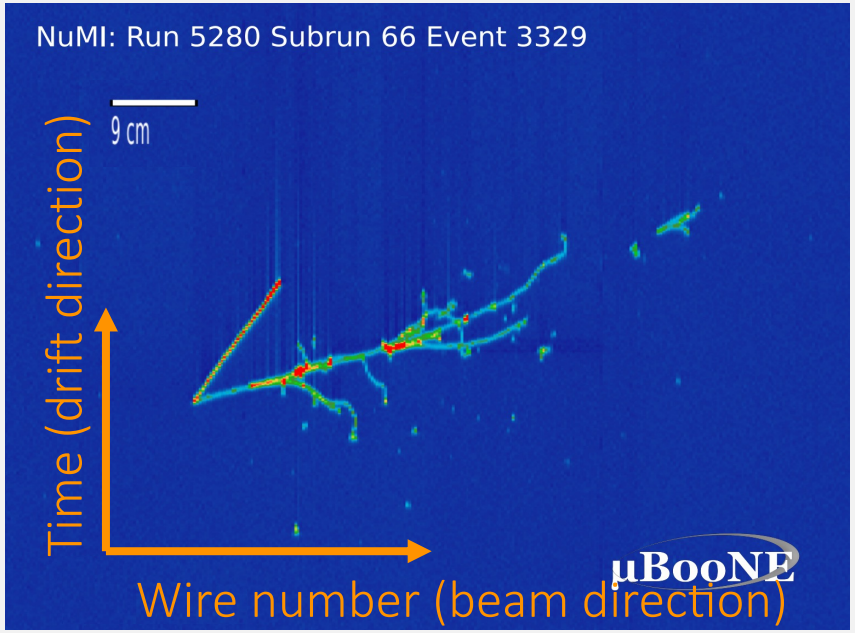
Several post-operations R&D studies

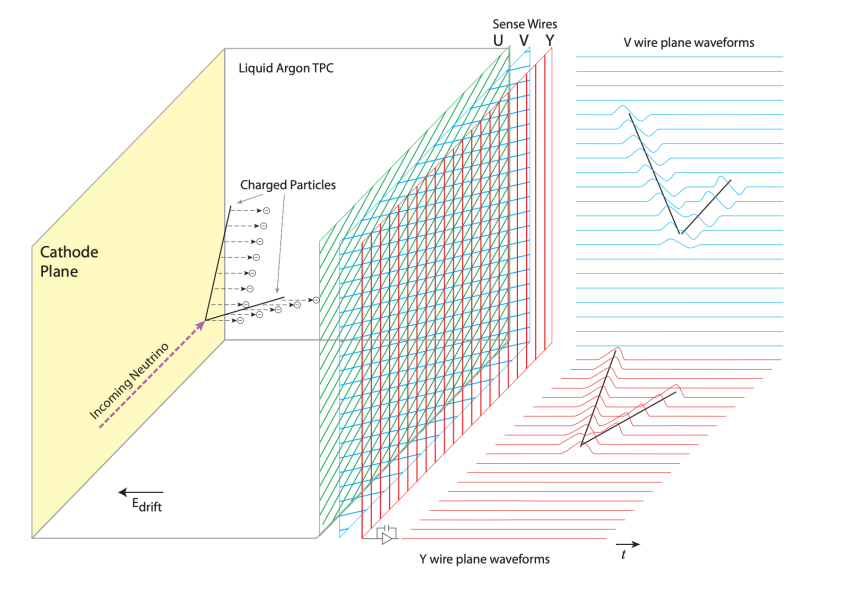
Thank you to Fermilab Accelerator Division, Cryogenics team, and Operations team!

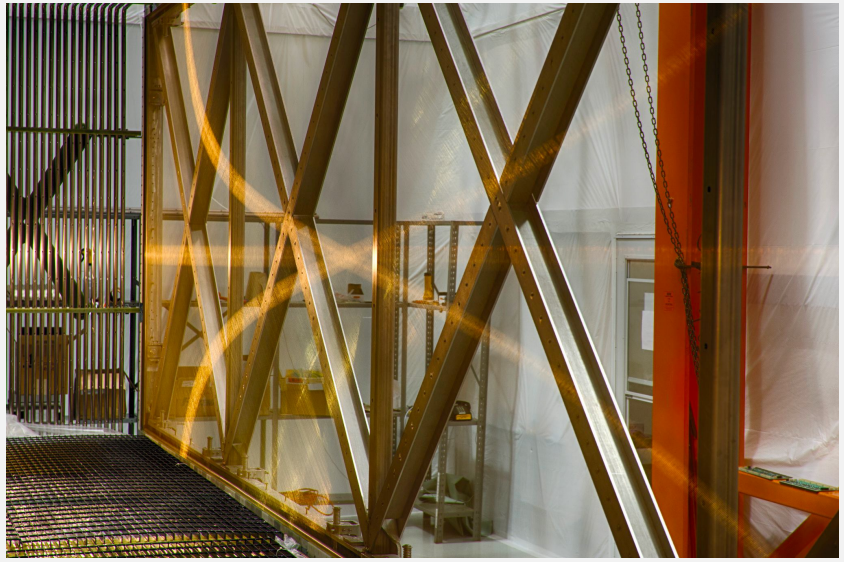


Liquid argon time projection chamber

- Fully-active tracking calorimeter
- **32 PMTs** collect light from flash at time of interaction
- **3 planes** of wires (vertical, +60°, -60°) with **3mm spacing**
  - ➢ mm-level resolution, low thresholds, excellent particle identification







JINST 12 P02017 (2017)

MicroBooNE's scientific and technical accomplishments

2017 2018 2019 2020 2021 2022

Differential cross section measurement of charged current ve\nu_{e}ve interactions without final-state pions in MicroBooNE
Search for long-lived heavy neutral leptons and Higgs portal scalars decaying in the MicroBooNE detectorv
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 ve 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

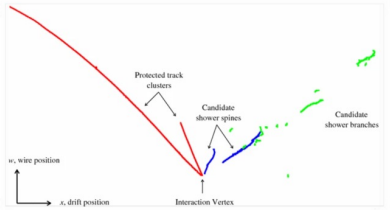
50 publications
>75 public notes
>50 PhD MicroBooNE theses

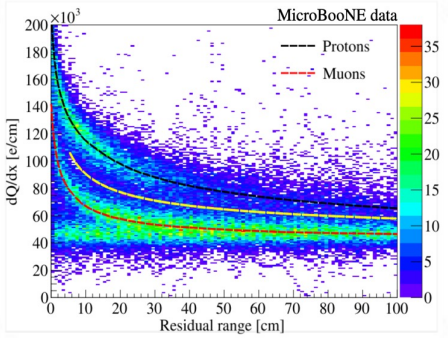
UNDERSTANDING LArTPCs AND DEVELOPING TECHNIQUES

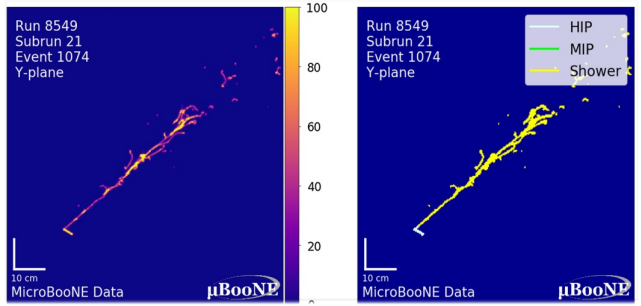
- MicroBooNE has contributed to significant advances in LArTPC detector physics, modelling, and reconstruction
- Post-operations R&D studies are just beginning to bear fruit

Reconstruction

Eur. Phys. J. C 78, 82 (2018)
JINST 17 P01037 (2022)
Phys. Rev. D 103, 052012 (2021)
and more

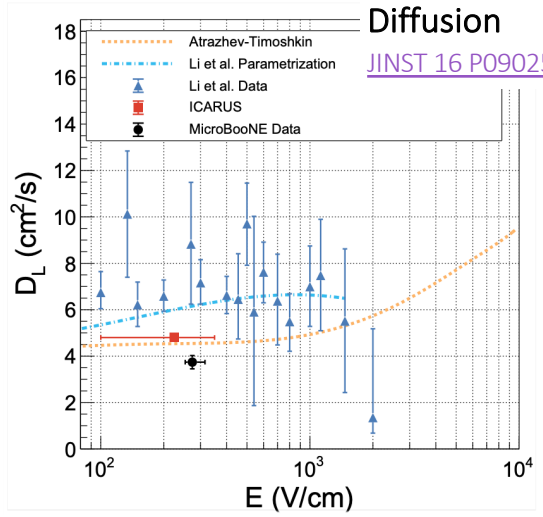






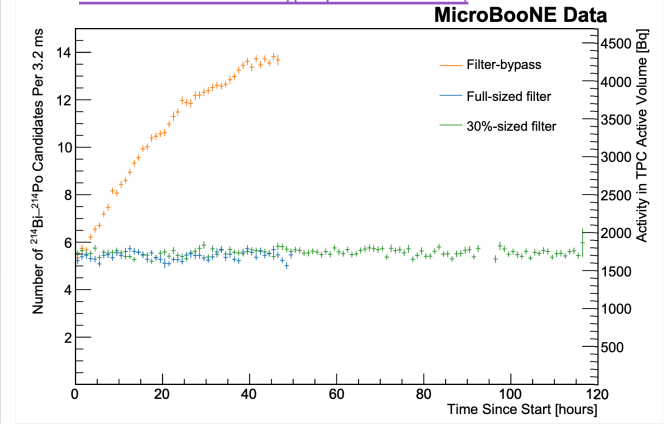
Electron Diffusion

JINST 16 P09025 (2021)



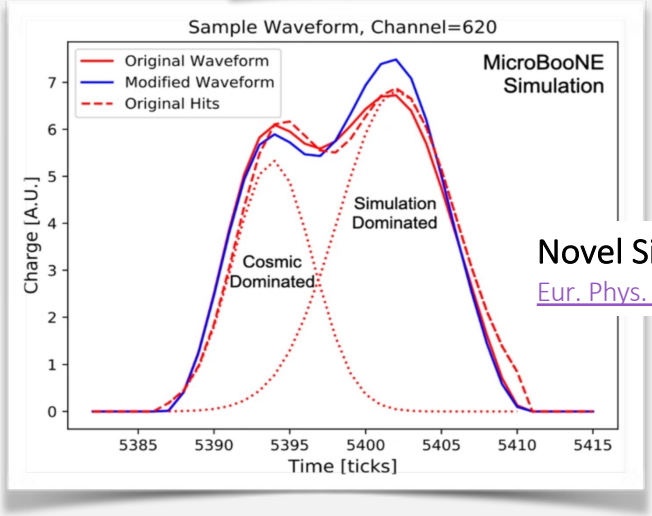
Radon Mitigation

arXiv:2203.10147 [physics.ins-det]



Novel Sim. Modification

Eur. Phys. J. C 82, 454 (2022)

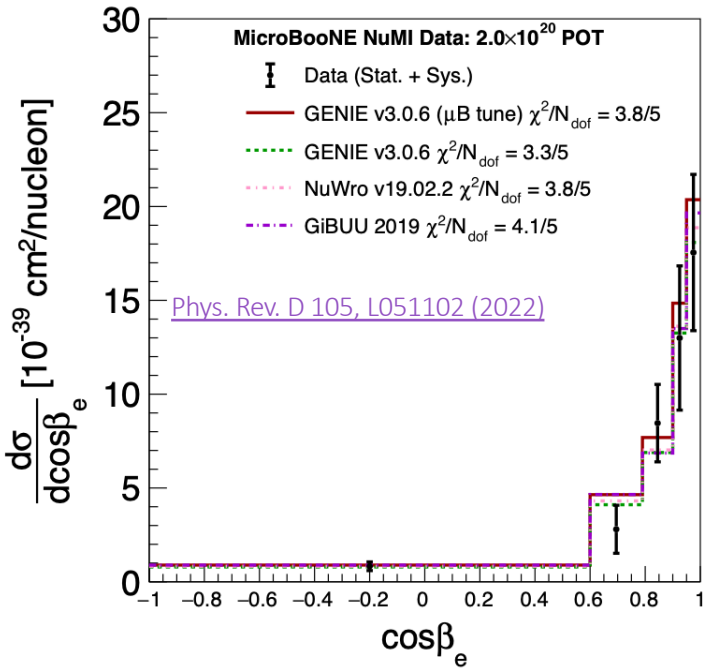


Understanding ν-Ar interactions

Charged-current Inclusive measurements

ν_e CC inclusive

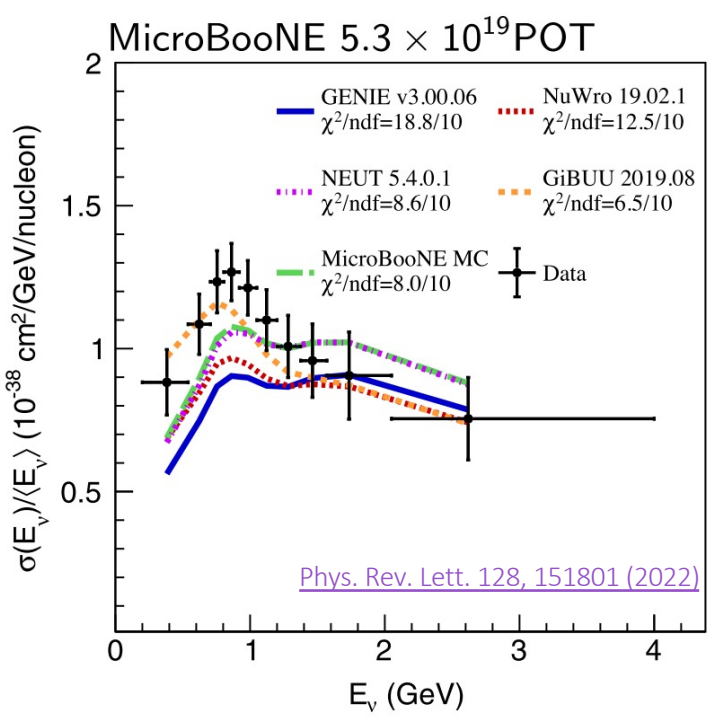
- first measurement on argon as a function of scattering angle and electron energy
- excellent overall test of neutrino-nucleus generator



ν_μ CC inclusive

- first measurement on argon as a function of neutrino energy and energy transfer
- enabled by extensive validation of missing energy model
- stringent test of hadronic part of the interaction

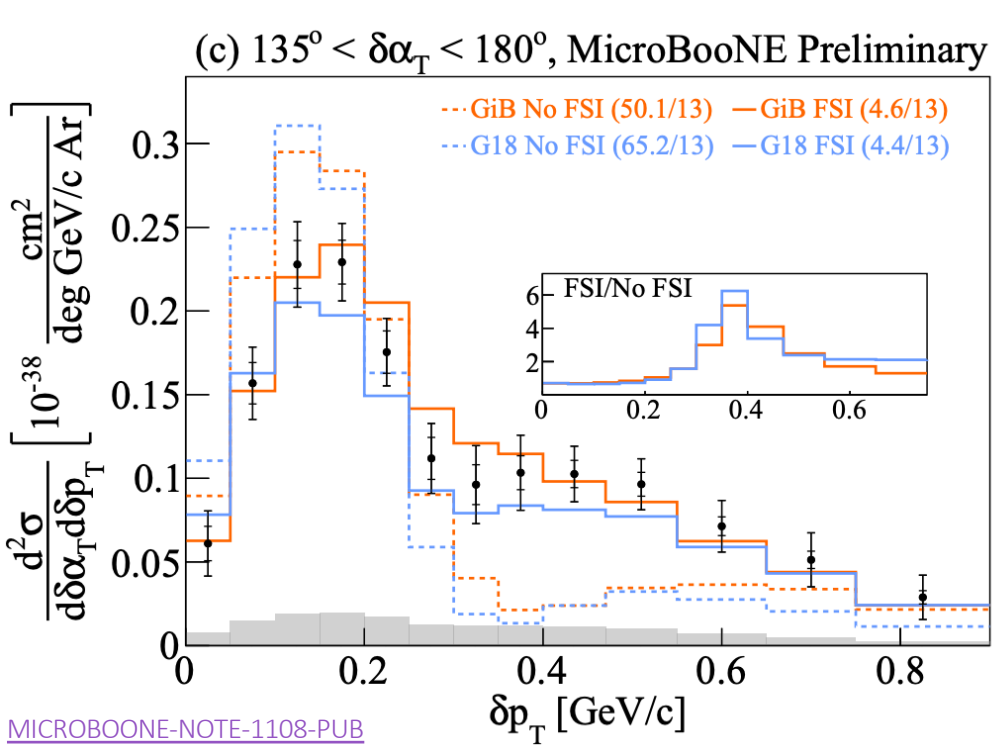
More to come: higher statistics, multi-differential



Exclusive channels, differential cross-sections

ν_μ CC0π1p Transverse Variables

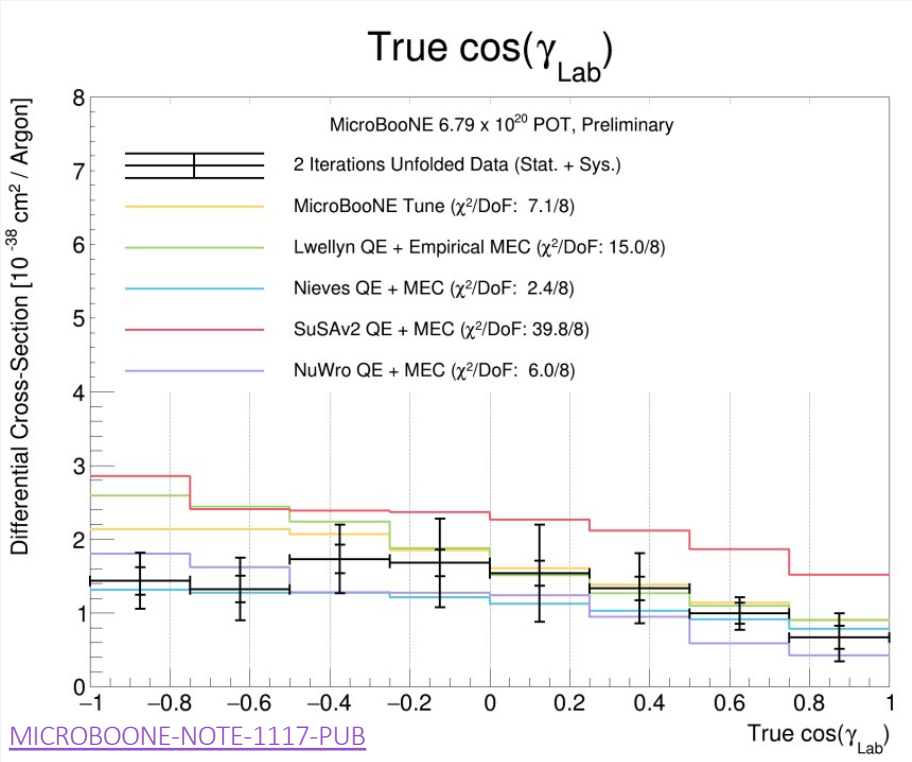
- first double-differential cross section in these variables on argon
- especially sensitive to nuclear effects



MICROBOONE-NOTE-1108-PUB

ν_μ CC0π2p

- first ever direct measurement of 2-proton cross section
- dominated by 2p2h/MEC processes



MICROBOONE-NOTE-1117-PUB

Neutral current neutral pion production

Important background to ν_e searches in LArTPCs (MicroBooNE and future experiments: DUNE, SBN)

- $\pi^0 \rightarrow \gamma\gamma$ looks like ν_e if one photon missed

First NCπ^0 measurement on argon with <E_ν>~1 GeV

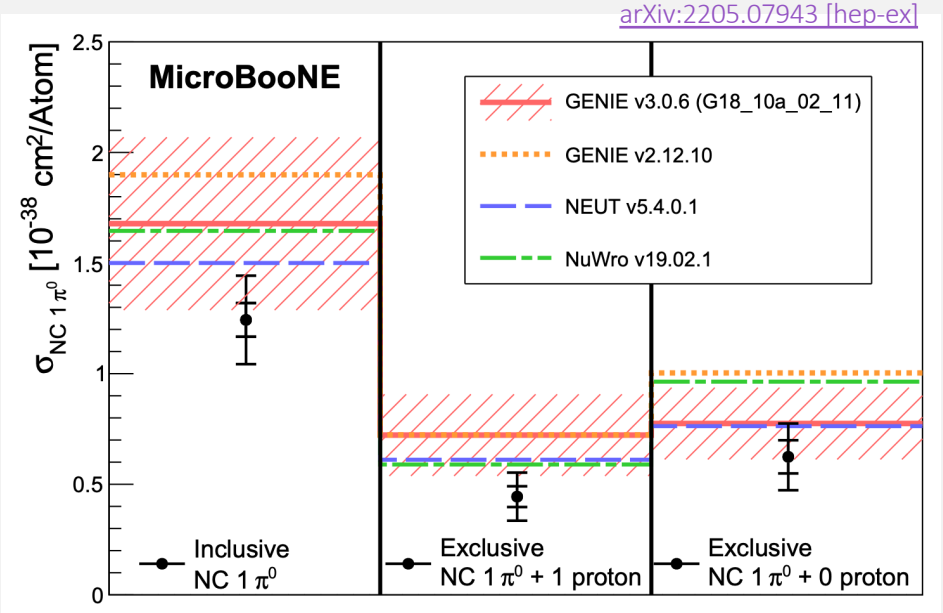
- separated into 0p and 1p channels
- deficit observed compared to all models

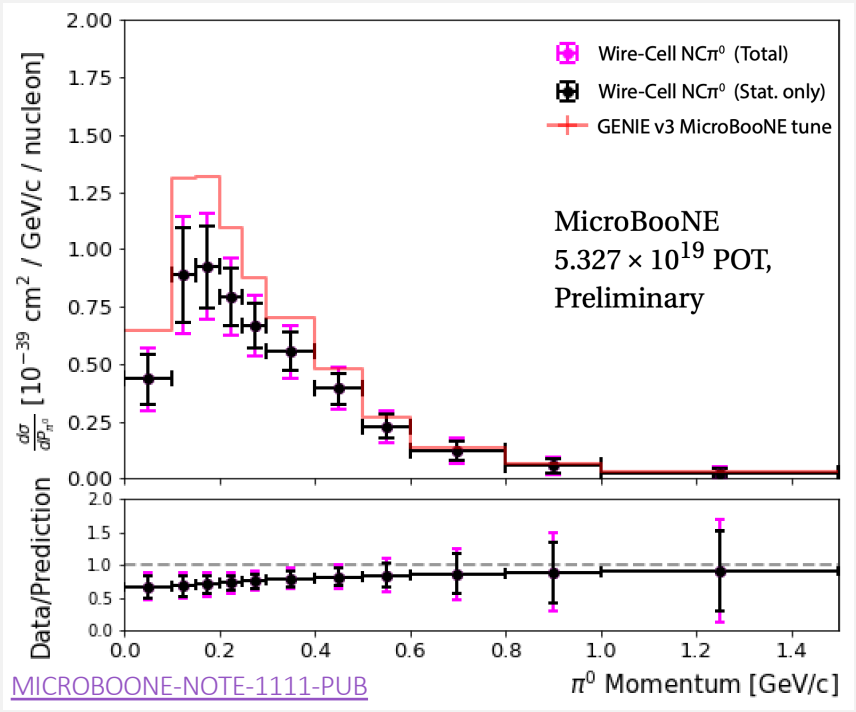
Differential cross-section measurement well under way

- current result limited by statistics (only few % of available data used)

CCπ^0 measurement in progress, along with more rare searches e.g. hyperon production

arXiv:2205.07943 [hep-ex]

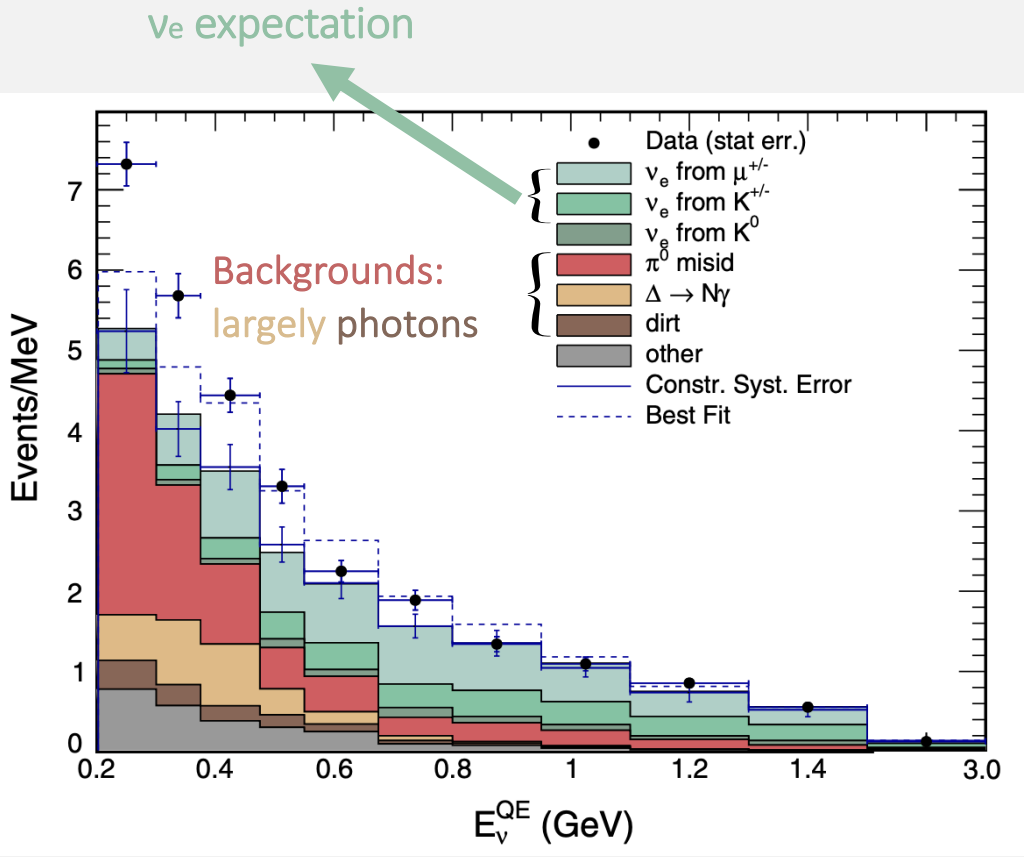




MICROBOONE-NOTE-1111-PUB

Searching for new physics

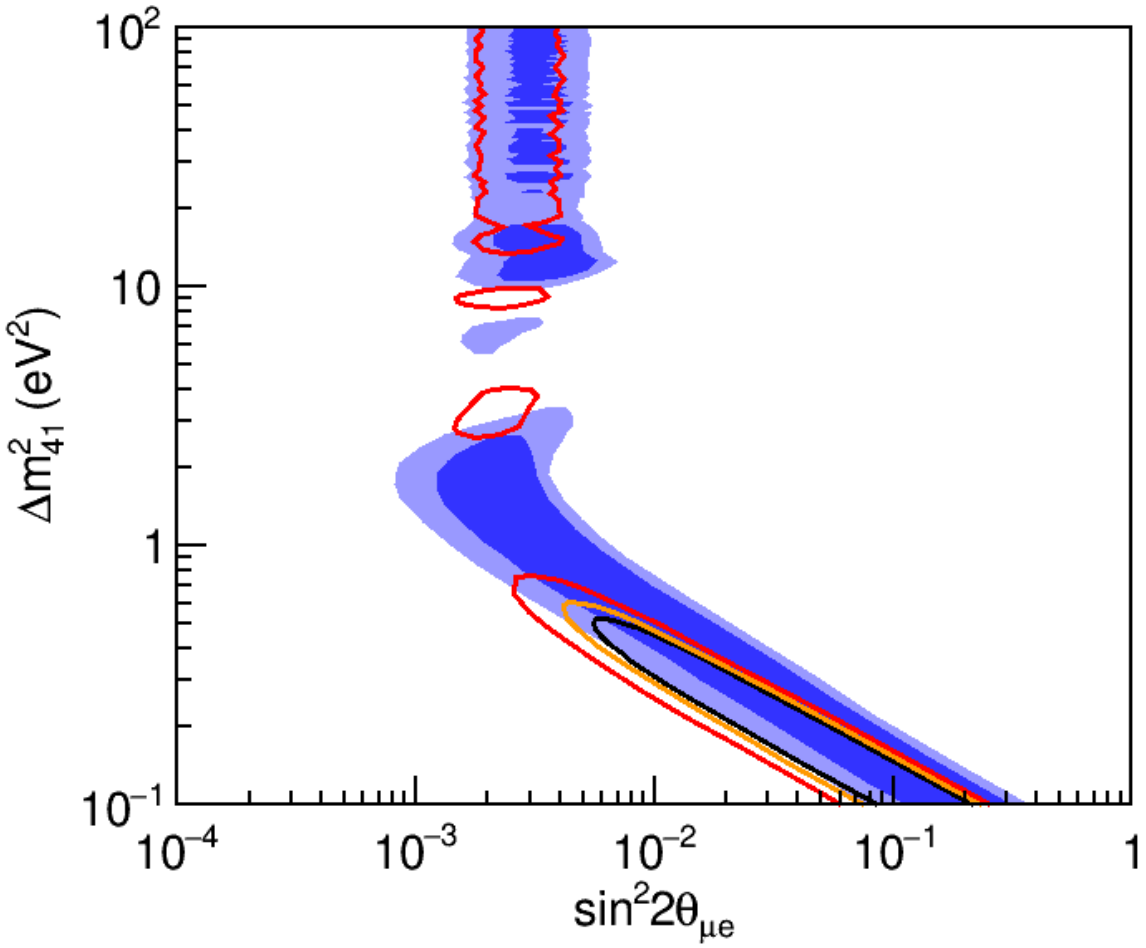
The MiniBooNE low-energy excess (LEE)

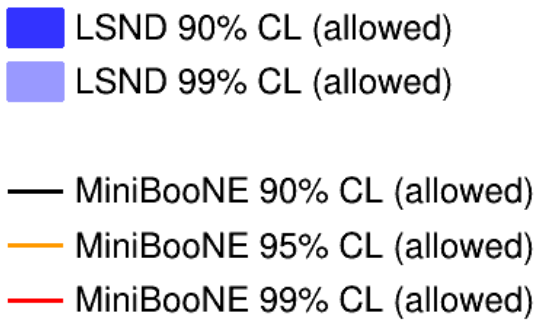


- 4.8σ excess of measured ν_e and $\bar{\nu}_e$ over prediction, focused at low energy
- Consistent with prior results from the LSND experiment: combined significance of 6.1σ
- Source of excess not known:
  - could be ν_e
  - photons look identical to electrons in MiniBooNE detector
  - or something else?

Phys. Rev. D 103, 052002

The MiniBooNE low-energy excess (LEE)



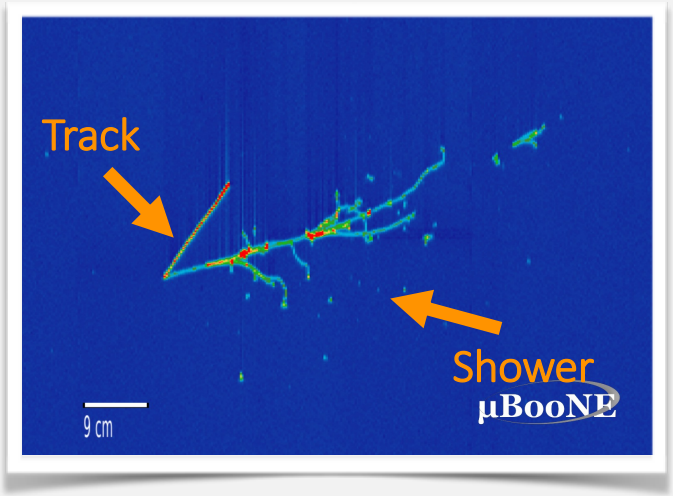


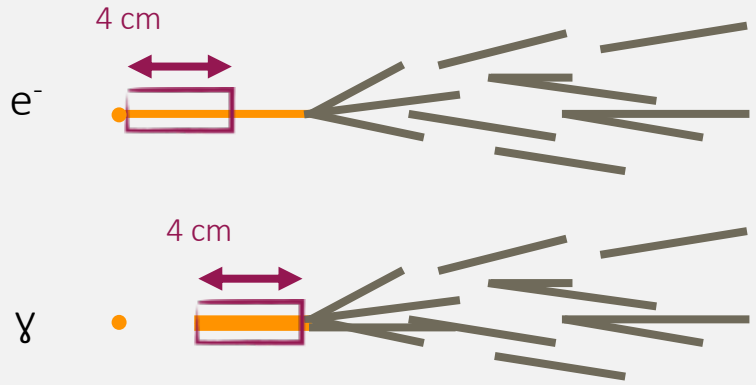
- If interpreted as ν_e appearance through a two-flavour neutrino oscillation, best fit $\Delta m^2 = 0.04$ eV^2
- Not consistent with any known neutrino flavour → new "sterile" neutrino?

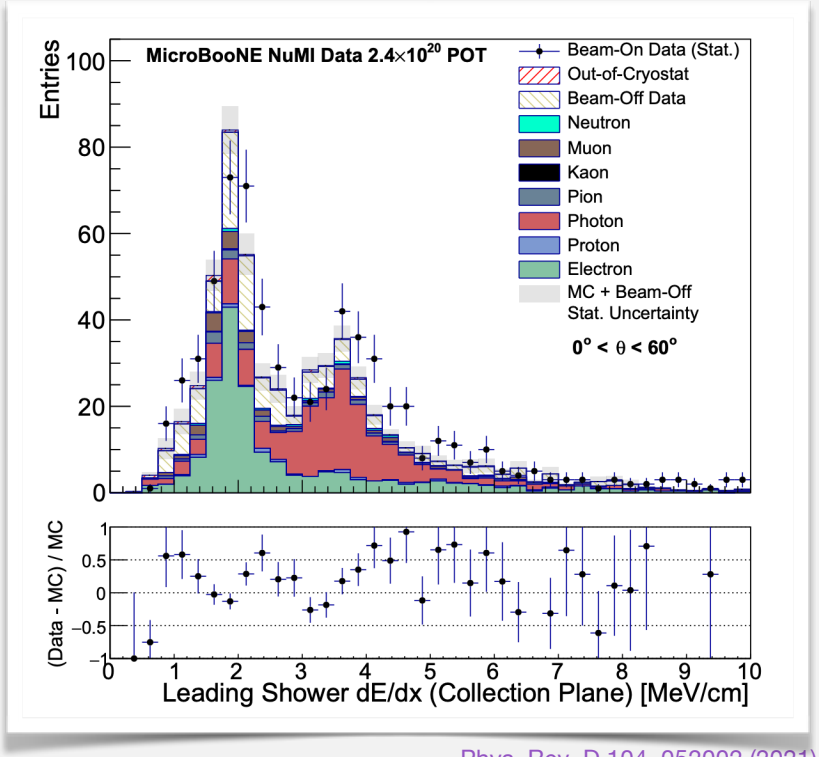
Phys. Rev. D 103, 052002

LArTPC STRENGTH: electrons and photons

- Electrons and photons produce showers in LArTPCs
- Distinguish using dE/dx at start of shower and start point







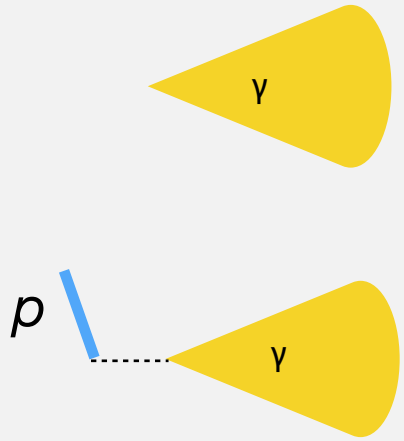
Phys. Rev. D 104, 052002 (2021)

First investigation of the MiniBooNE low-energy excess

Photon search

Target Δ→Nɣ:

1ɣ0p and 1ɣ1p



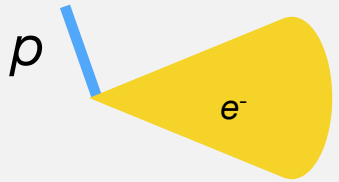
Phys. Rev. Lett. 128, 111801

Phys. Rev. Lett. 128, 241801

Electron searches

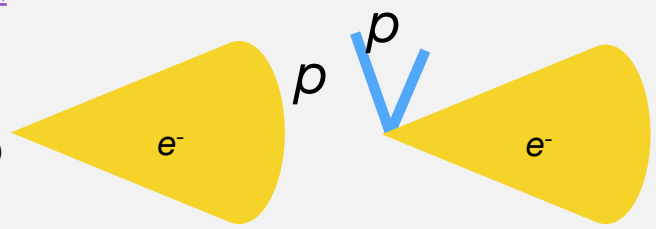
Phys. Rev. D 105, 112003

CCQE-like: 1e1p



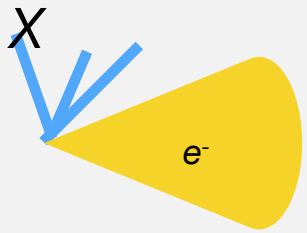
Phys. Rev. D 105, 112004

CC0π:
1e0p and 1eNp



Phys. Rev. D 105, 112005

Inclusive: 1eX

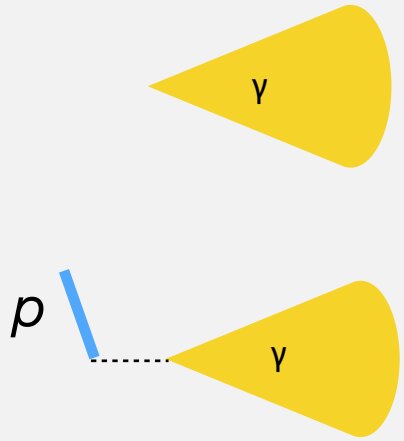


First investigation of the MiniBooNE low-energy excess

Photon search

Target Δ→Nɣ:

1ɣ0p and 1ɣ1p



Phys. Rev. Lett. 128, 111801

Phys. Rev. Lett. 128, 241801

Electron searches

Phys. Rev. D 105, 112003

CCQE-like: 1e1p

Phys. Rev. D 105, 112004

CC0π: 1e0p and 1eNp

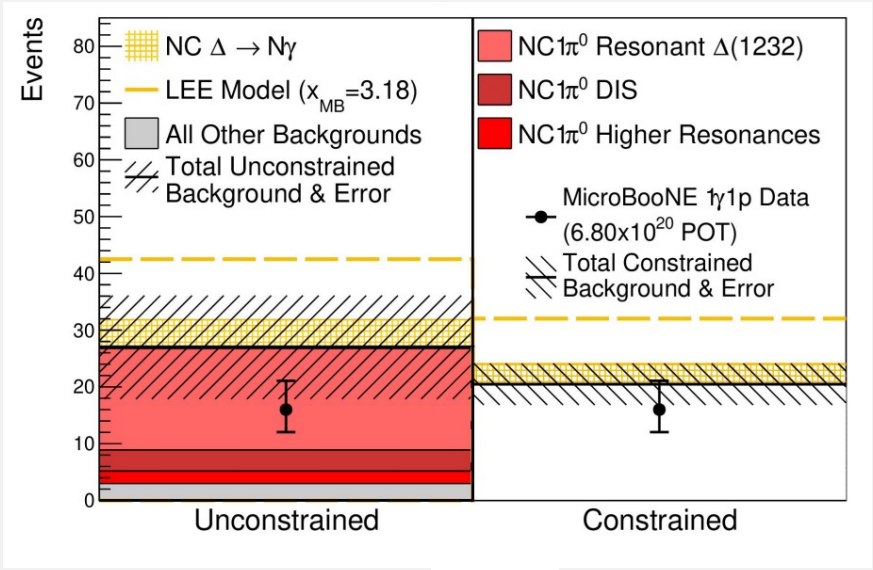
Phys. Rev. D 105, 112005

Inclusive: 1eX

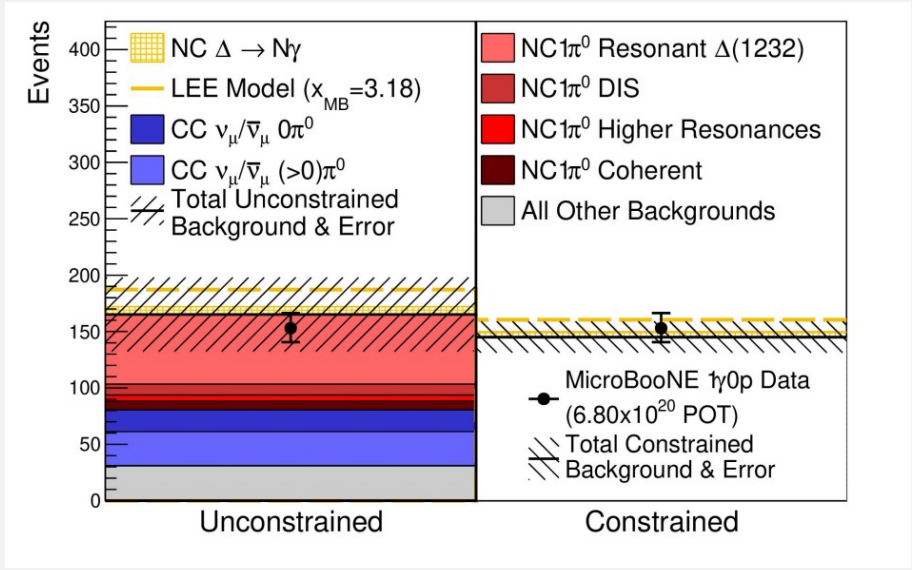
NC-Δ single photon search

Phys. Rev. Lett. 128, 111801

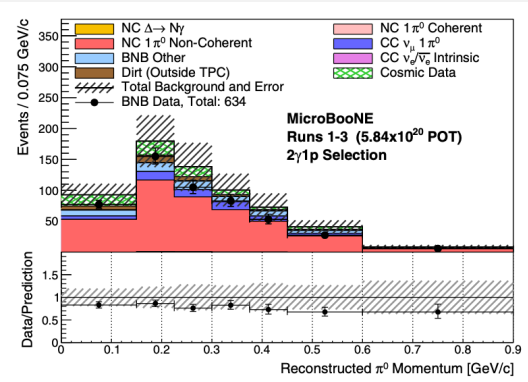
π^0-rich sample → constraint on backgrounds in signal region



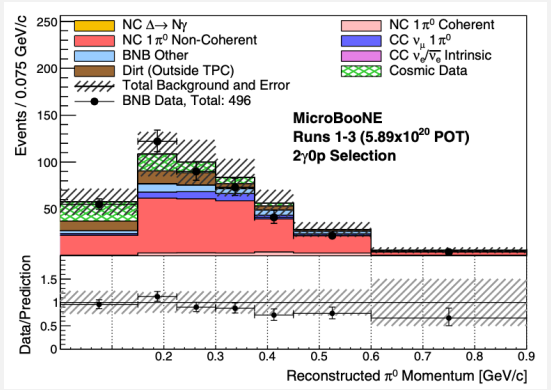
1ɣ1p



1ɣ0p



2ɣ1p



2ɣ0p

No evidence of an excess in either sample

Reject Δ→Nɣ x3.18 increase as explanation of excess at 94.8% CL

First investigation of the MiniBooNE low-energy excess

Photon search

Target Δ→Nγ:
1γ0p and 1γ1p

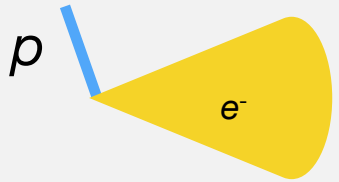
Phys. Rev. Lett. 128, 111801

Phys. Rev. Lett. 128, 24180

Electron searches

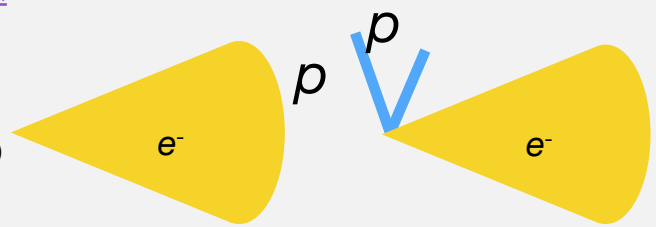
Phys. Rev. D 105, 112003

CCQE-like: 1e1p



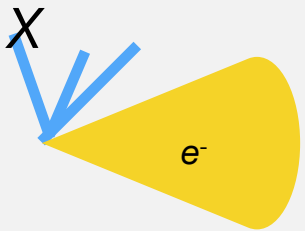
Phys. Rev. D 105, 112004

CC0π:
1e0p and 1eNp



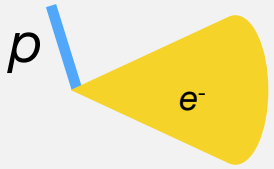
Phys. Rev. D 105, 112005

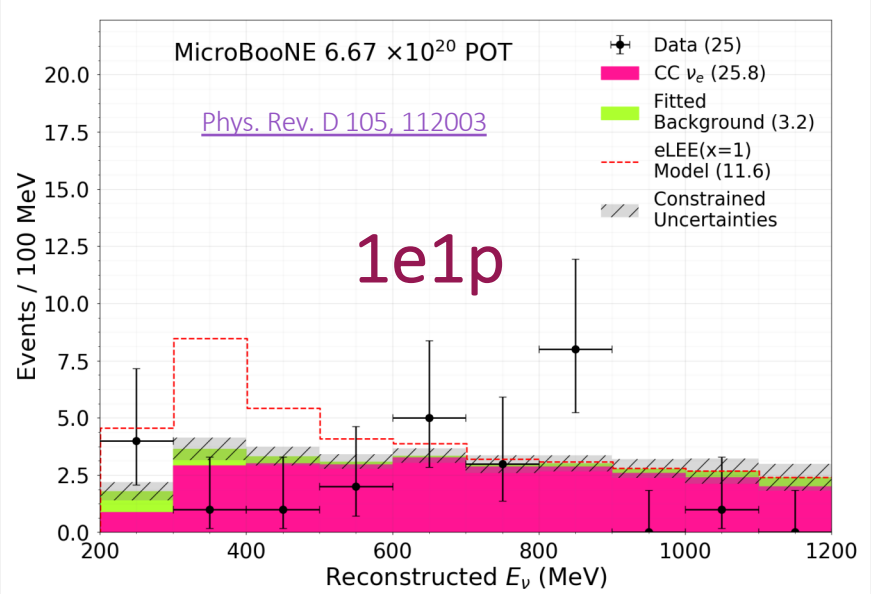
Inclusive: 1eX

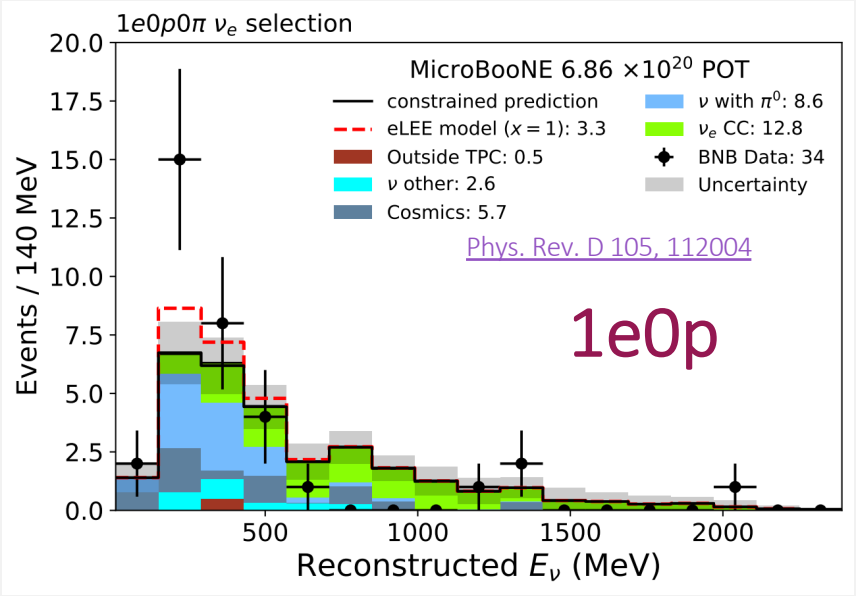


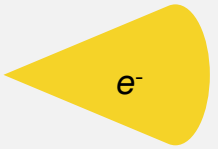
νe SEARCH

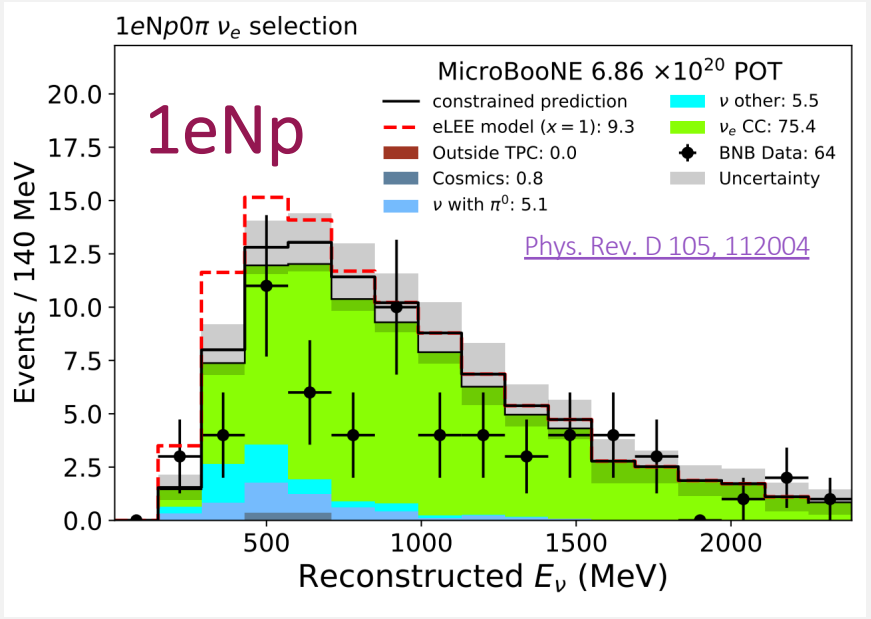
Phys. Rev. Lett. 128, 241801

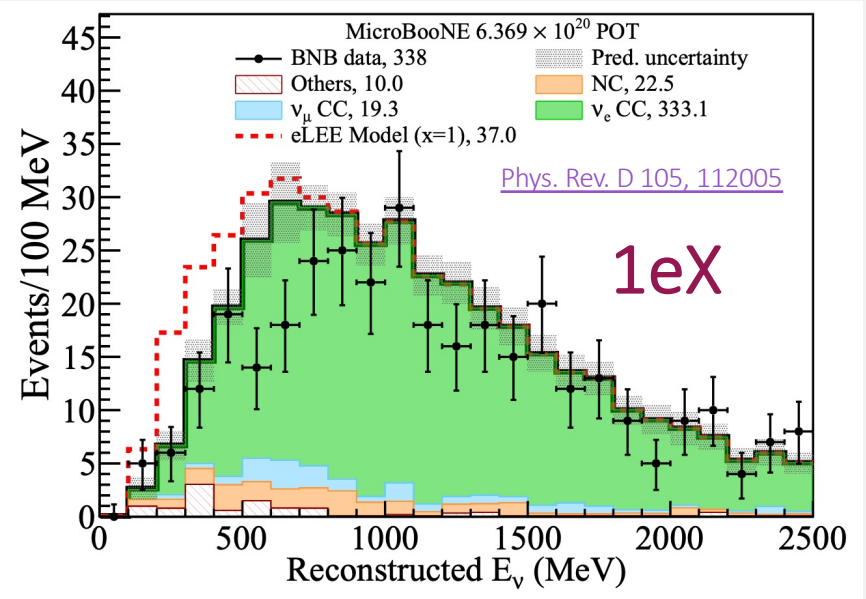


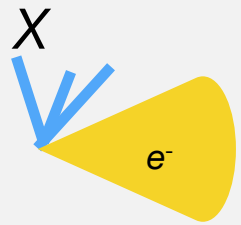


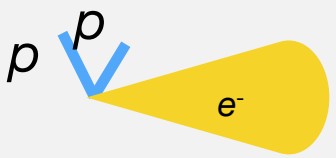






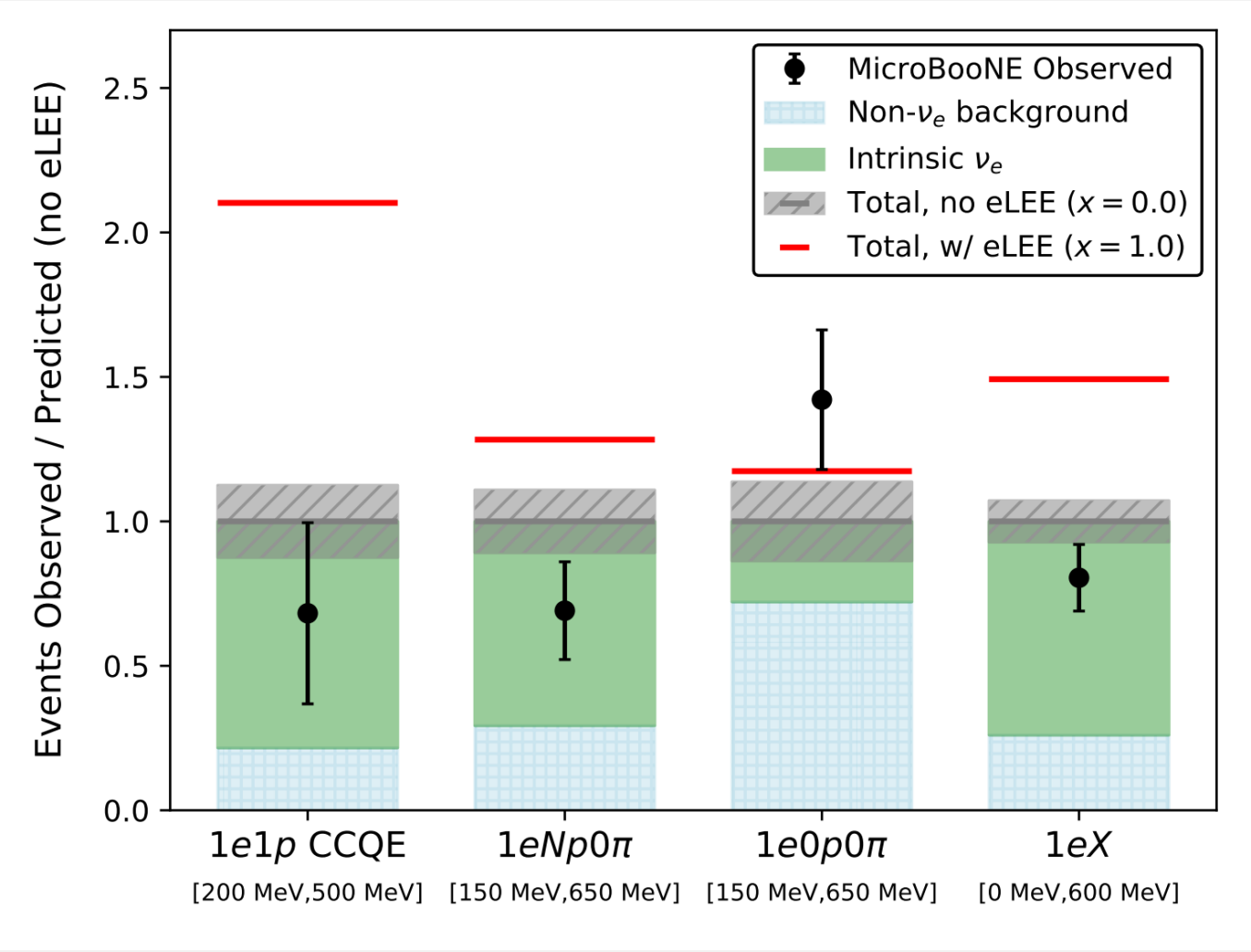






Phys. Rev. Lett. 128, 241801

ν_e SEARCH



Three high-purity analyses reject ν_e interactions as sole source of excess at >97% CL

Both initial hypotheses rejected

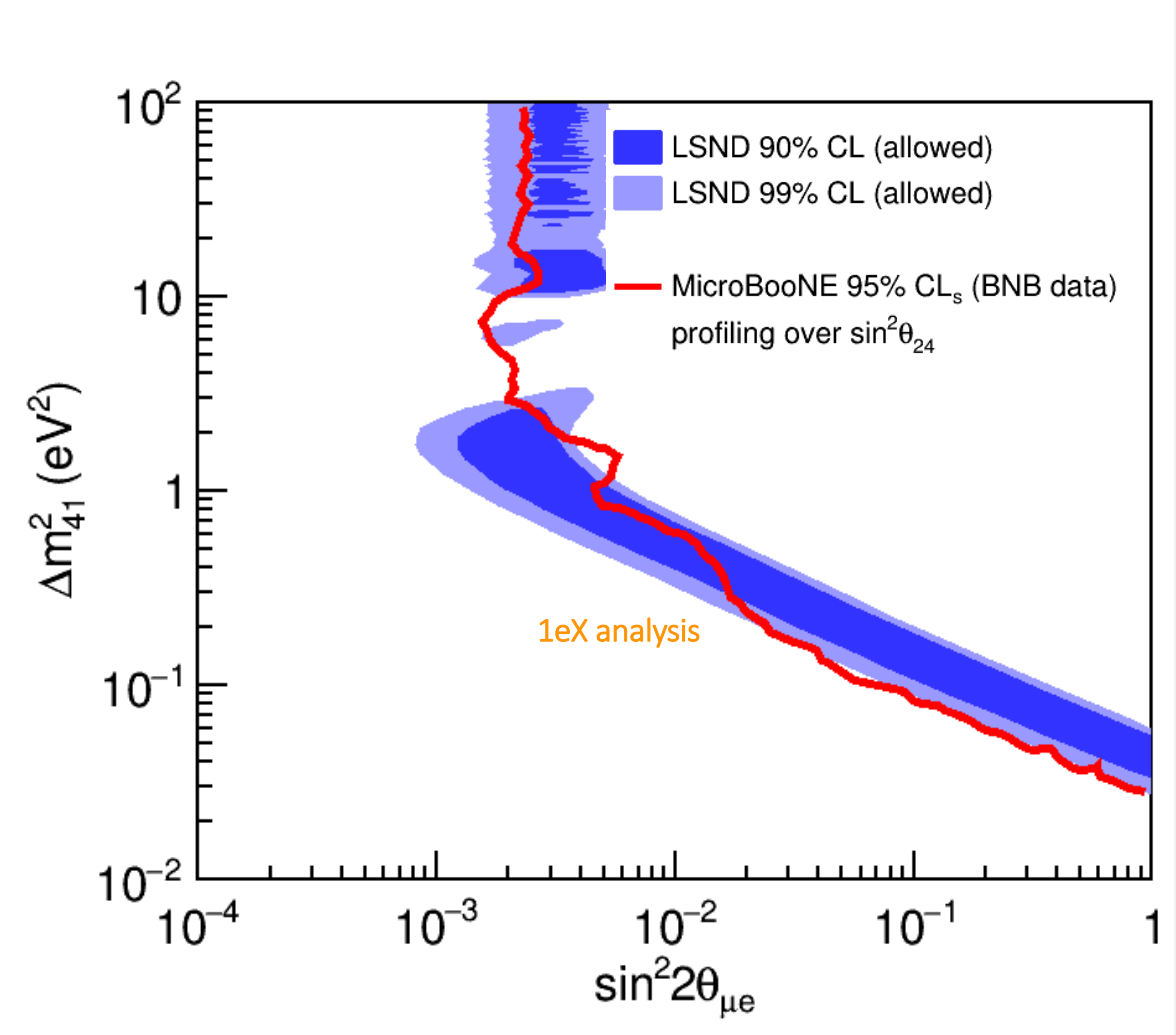
- Single photon from $\Delta \rightarrow N\gamma$:
- Single electrons

The future searches will include

- Other 1γ events
- e^+e^- events

Oscillation hypothesis

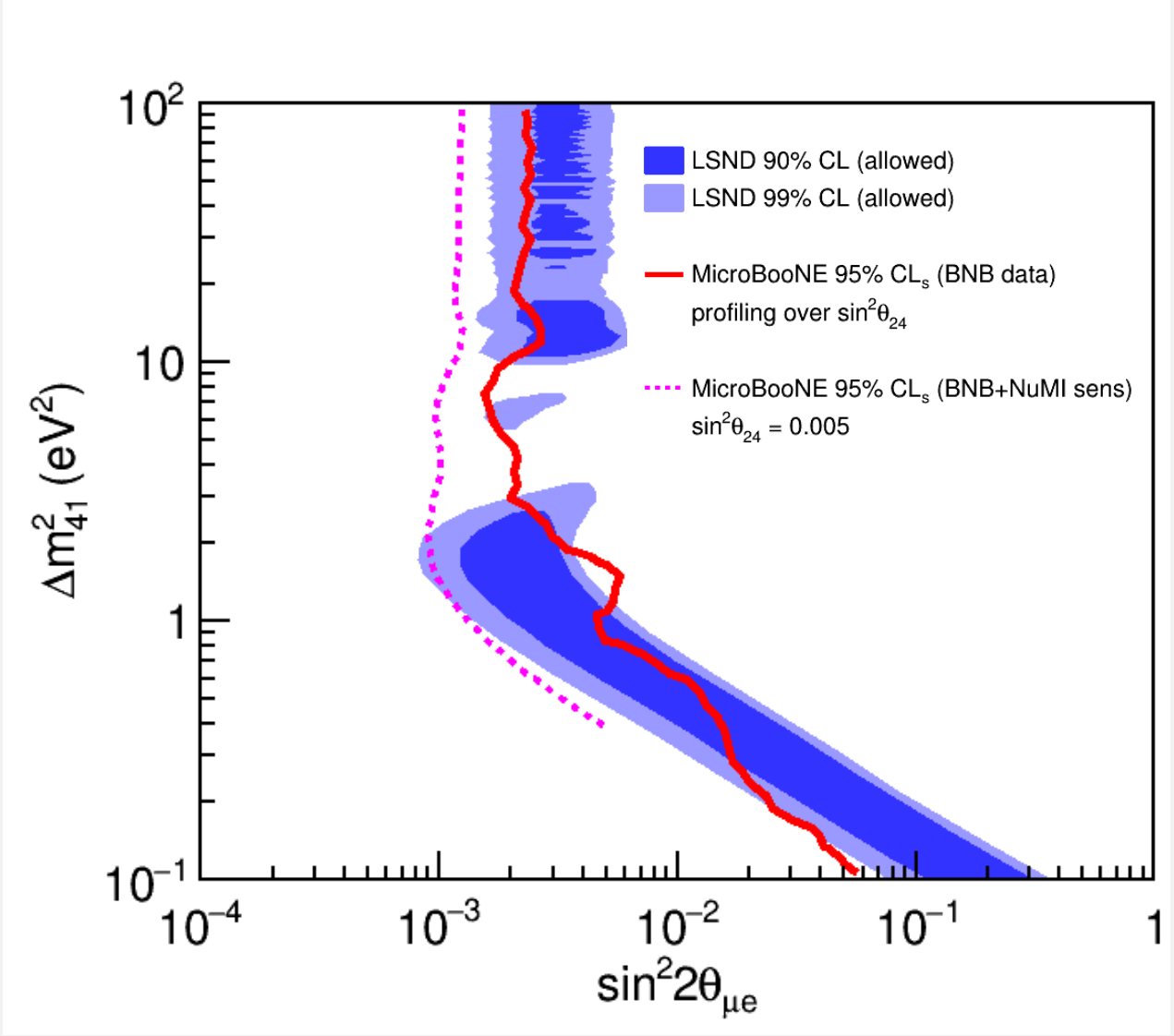
- What does this mean for the sterile neutrino hypothesis?
- We haven't seen evidence of an excess → place constraints on oscillation phase space for a new neutrino flavour.



Future prospects: BNB+NuMI

- Combining both data sets → significantly improved sensitivity
  - BNB $R_{ve/\nu\mu}$: 0.005
  - NuMI $R_{ve/\nu\mu}$: 0.04

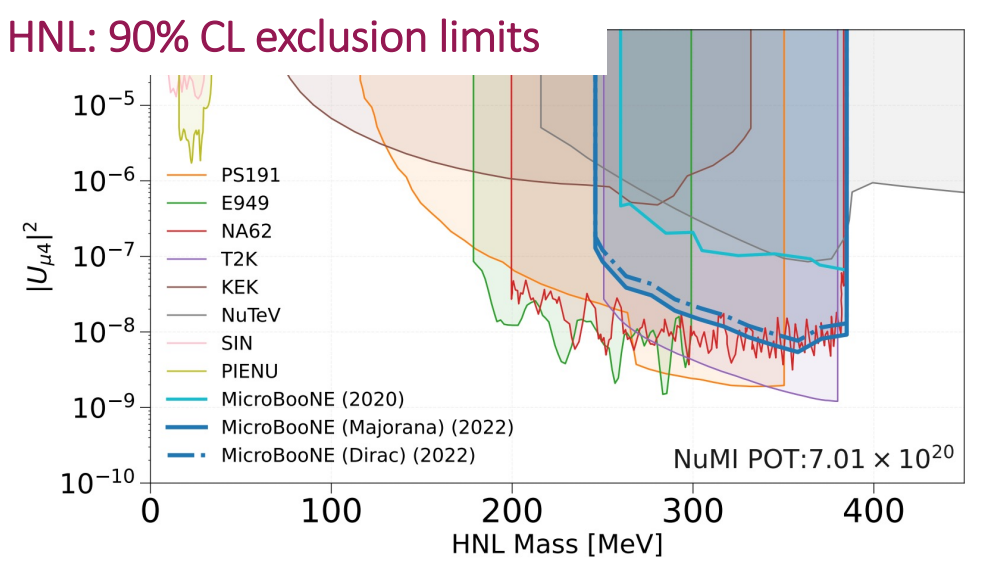
→ Upcoming BNB + NuMI analysis will be sensitive to full LSND allowed regions

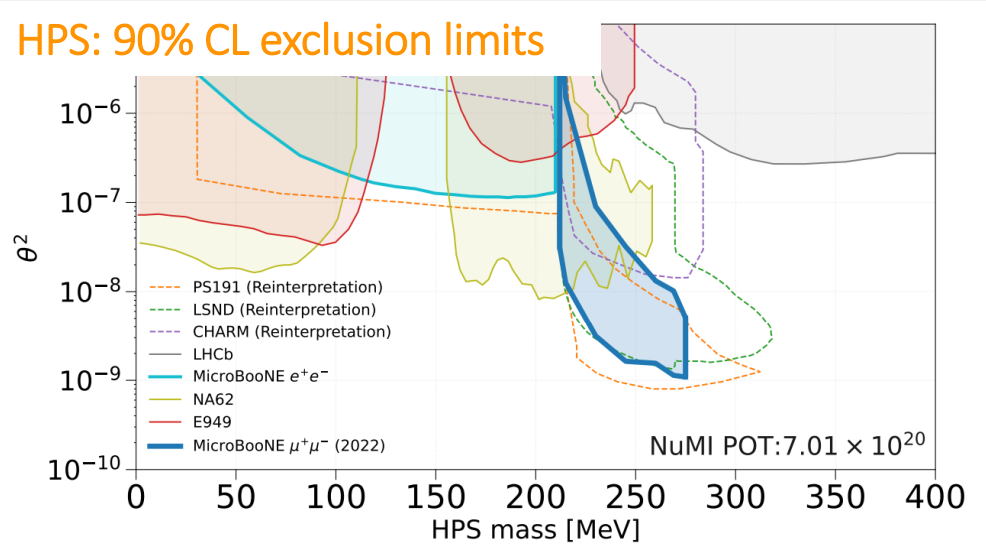


SEARCHING FOR OTHER NEW PHYSICS SIGNATURES

arXiv:2207.03840 [hep-ex]

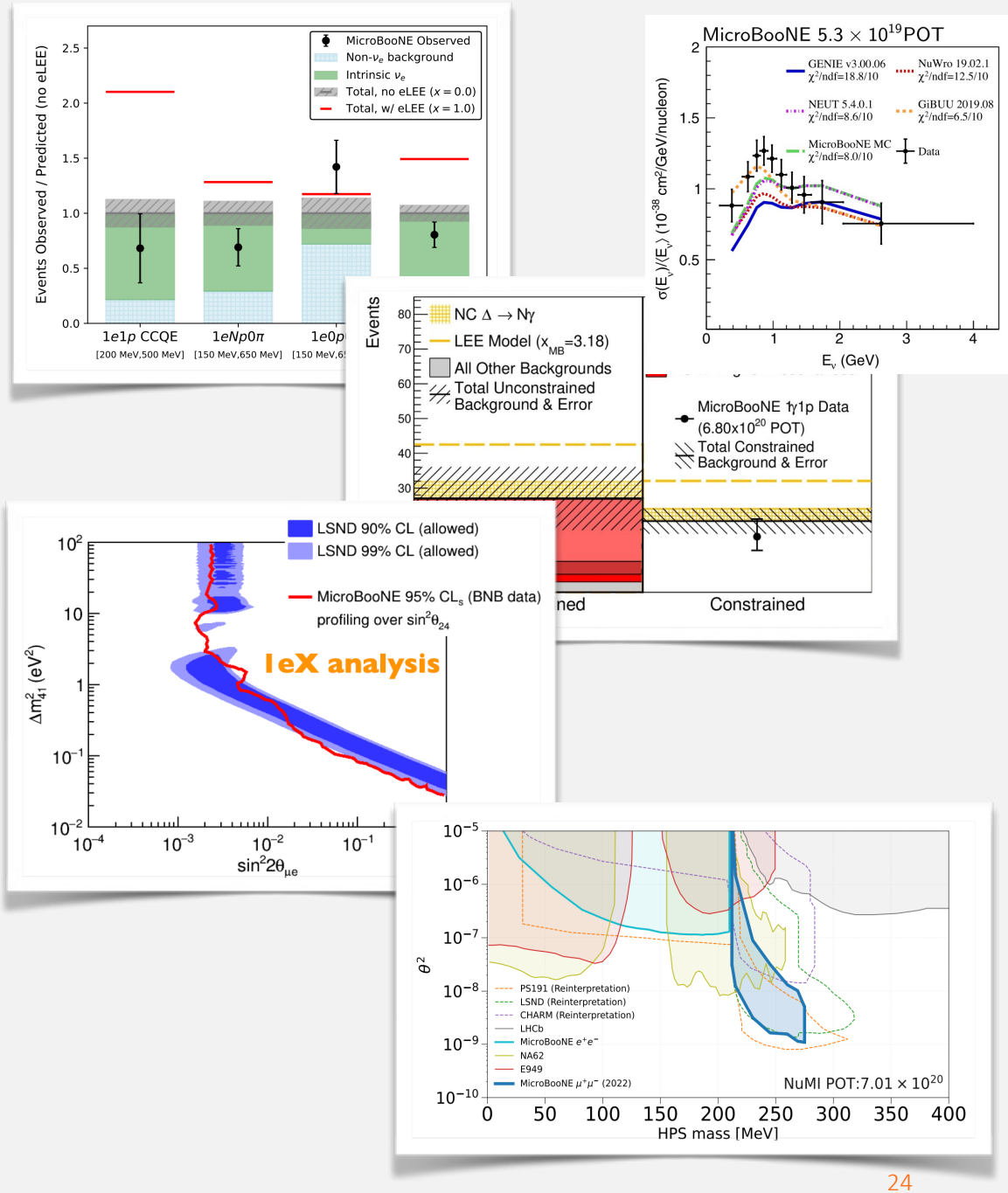
- Search for **heavy neutral lepton (HNL) decays to $\mu^{\pm}\pi^{\pm}$**
  - similar sensitivity to NA62
  - order of magnitude improvement on previous MicroBooNE results
- Search for **Higgs portal scalar (HPS) decays to $\mu^{+}\mu^{-}$**
  - complementary to previous $e^{+}e^{-}$ MicroBooNE search
  - First constraints on scalar-Higgs mixing angle θ in this mass range from a dedicated experimental search





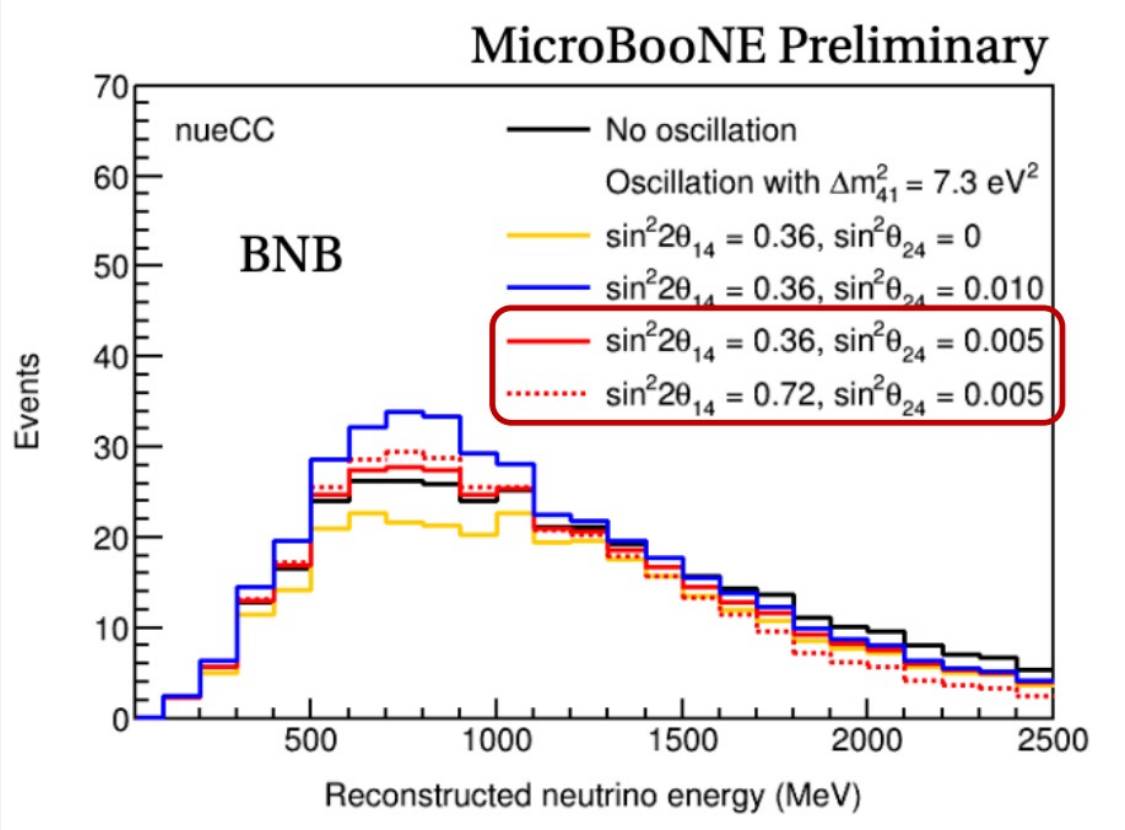
Summary

- MicroBooNE has harnessed the full power of LArTPC detector technology to make important new precision measurements
- Detailed initial investigations into MiniBooNE anomaly show no evidence for an excess in pure ν_e and NCΔ 1γ channels
- Exclusion limits set and further investigations underway
- Many more precision cross-sections measurements underway.



THANK YOU

Oscillation parameter degeneracy



ν_e disappearance

ν_e appearance

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

$$= N_{\text{intrinsic } \nu_e} [1 + (R_{\nu_\mu/\nu_e} \sin^2\theta_{24} - 1) \sin^2 2\theta_{14} \sin^2 \frac{\Delta m^2_{41} L}{4E}]$$

Cancellation if $\sin^2\theta_{24} = R_{\nu e/\nu\mu}$ (ratio of ν_e to ν_μ in beam)

→ about 0.005 in BNB

→ about 0.04 in NuMI

1μ1p disappearance exclusion limits

- Use **1μ1p sample** (98% pure ν_μ) to search for **ν_μ disappearance** in BNB
- Data consistent with no oscillation → set Feldman-Cousins **exclusion limits**

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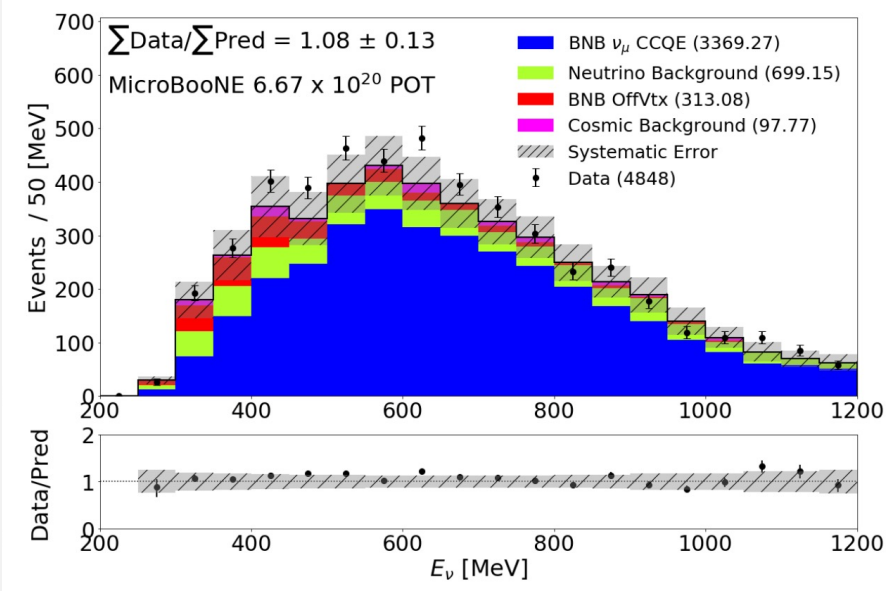
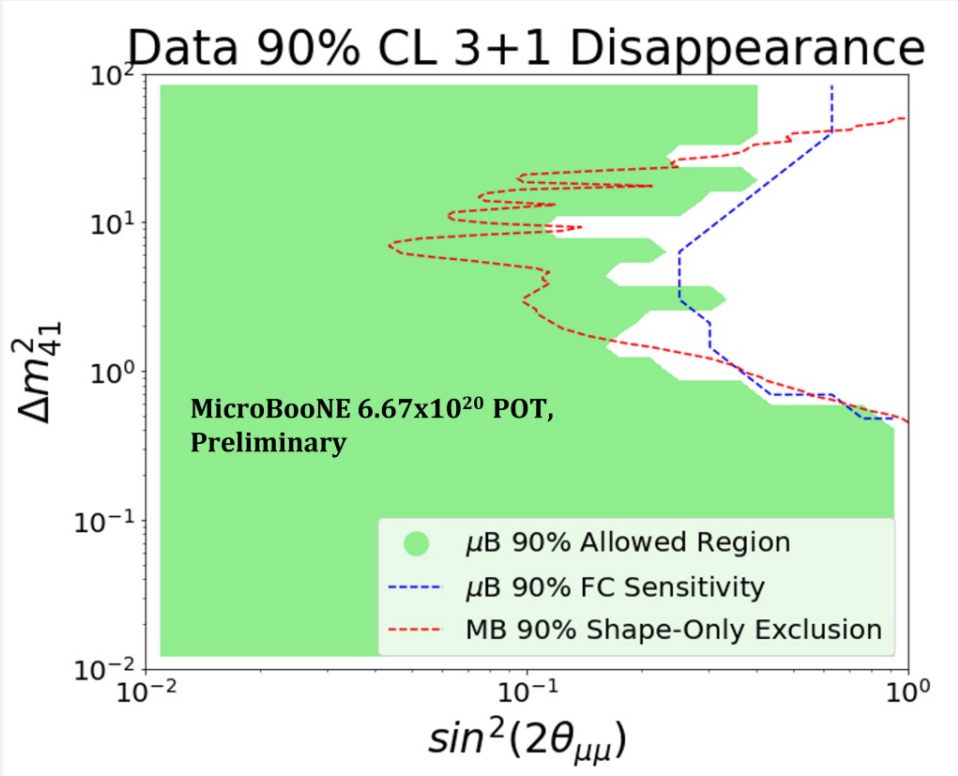
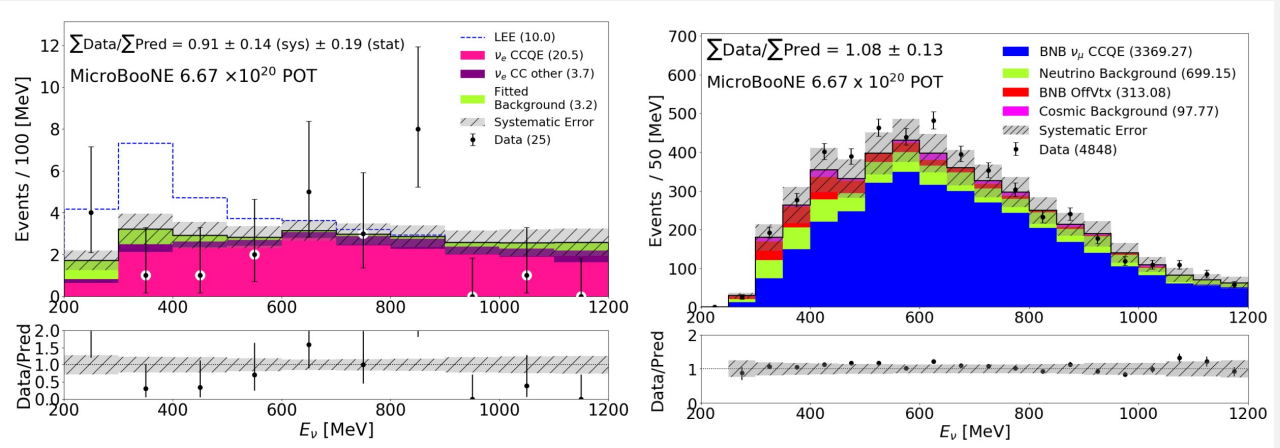
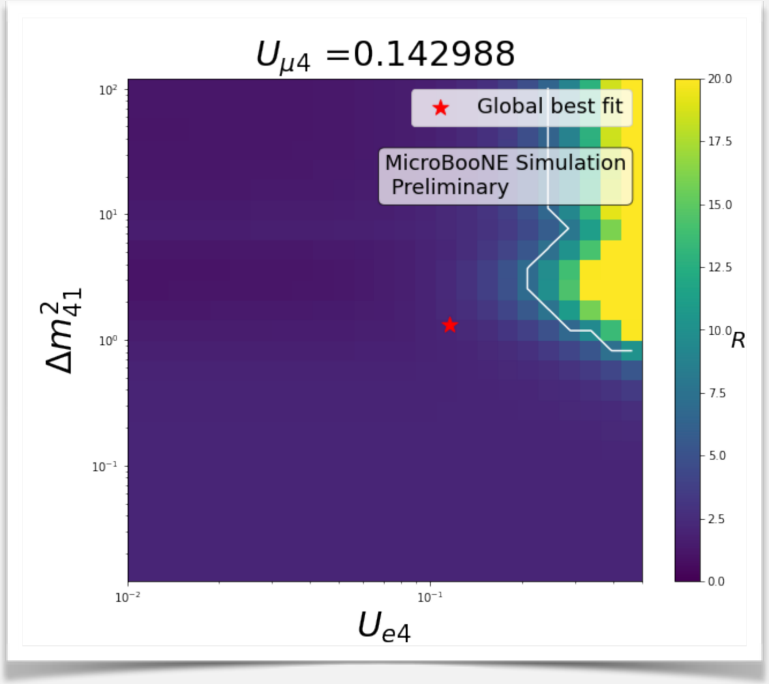




Future 3+1 1e1p and 1μ1p oscillation analysis

- Full 3+1 analysis (as done for inclusive selection) also in progress using **1e1p and 1μ1p samples**
- **Exclusion sensitivity** (assuming no oscillation) using **Wilks' theorem** has been found
- **Feldman-Cousins treatment in progress** for full oscillation results - coming soon!





What does this mean?

- 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)*
- 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)*
- 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

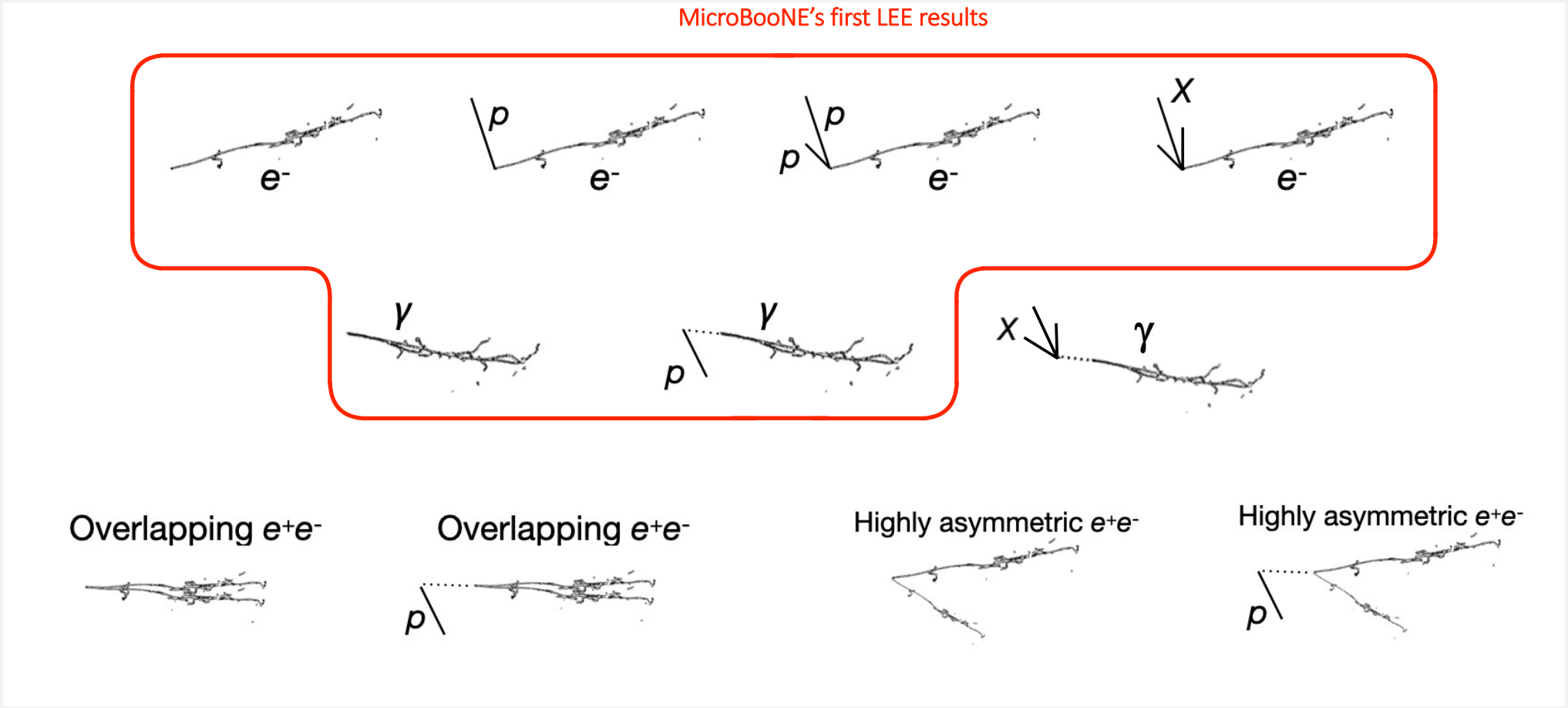
Produces e^+e^- pairs

Caution: not an exhaustive list!

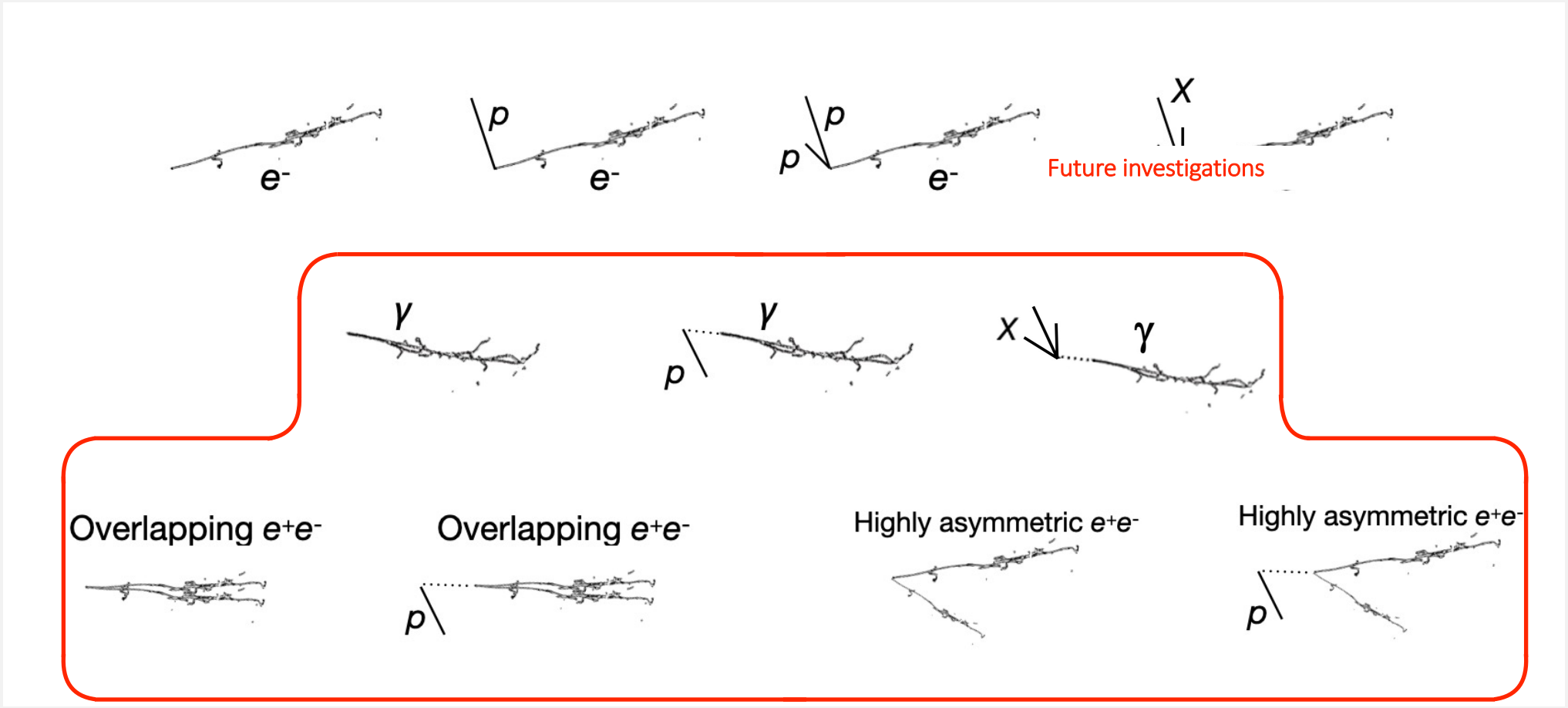
This is meant to be representative only

More information: see P. Machado, Fermilab PAC, November 2021

What does this mean?



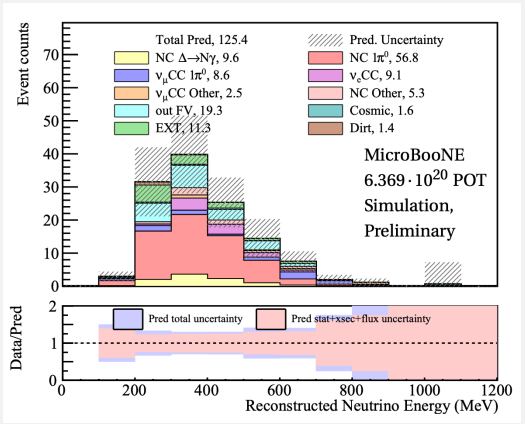
Future investigations



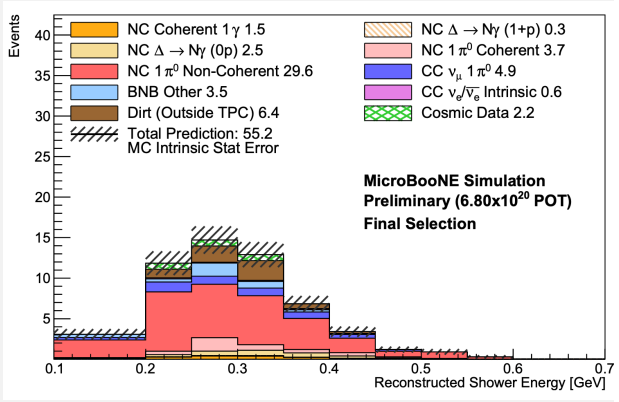
Future investigations

MICROBOONE-NOTE-1104-PUB
MICROBOONE-NOTE-1103-PUB
MICROBOONE-NOTE-1102-PUB

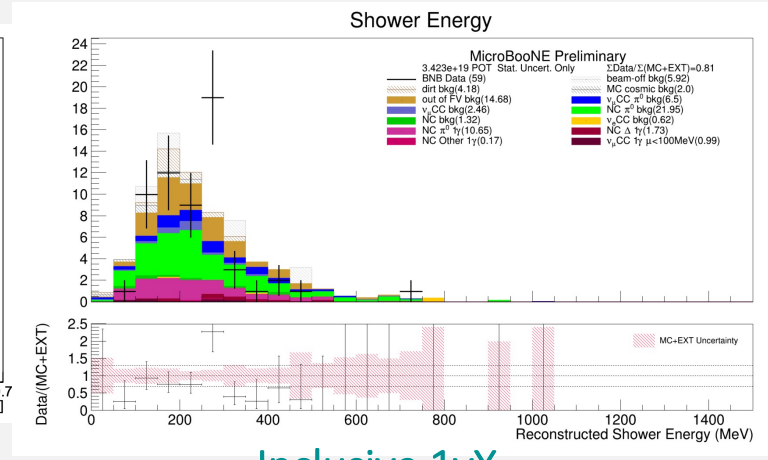
- Further investigations will expand photon-like searches and investigate e^+e^- final states - some preliminary results shown below:
  - **Further investigation of NC Δ model**: independent reconstruction, more sensitivity to potential excess in 1ɣ0p channel
  - **NC-Coherent 1ɣ targeted search**: forward-going photons with no visible hadronic energy
  - **Inclusive 1ɣ search**: generic test of single photon production
- Even more on the way!



1ɣ0p

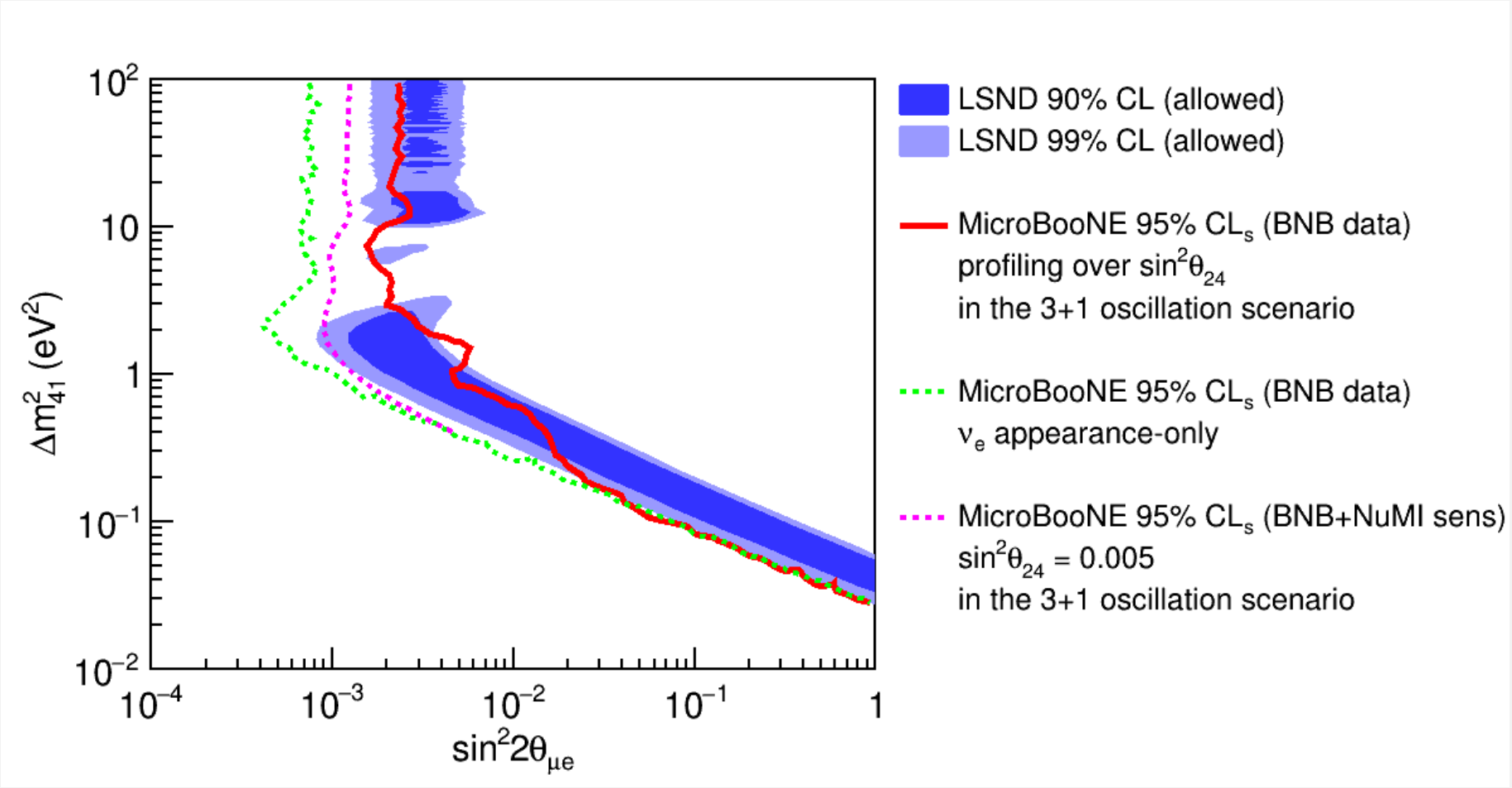


Coh-1ɣ0p

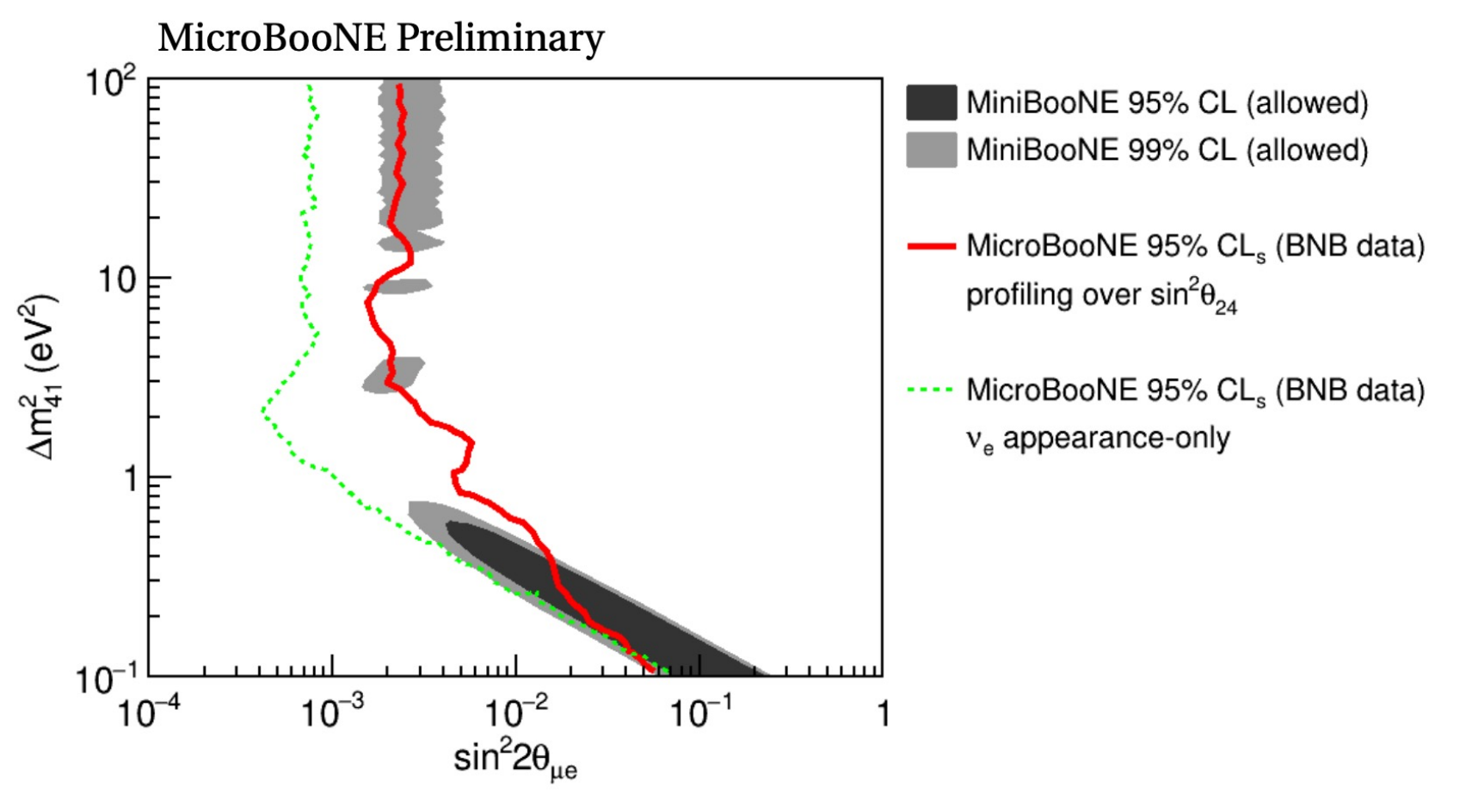


Inclusive 1ɣX

Oscillation parameter degeneracy



Oscillation parameter degeneracy



Future investigations

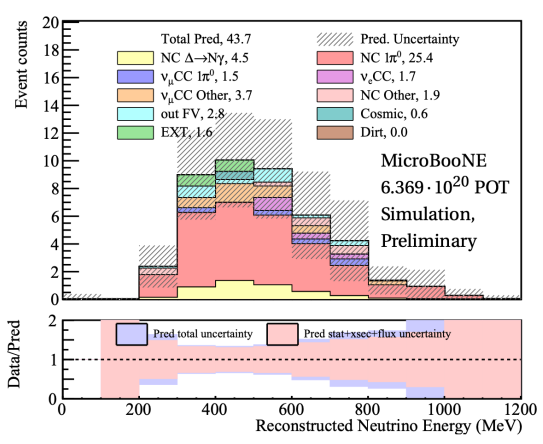
MICROBOONE-NOTE-1104-PUB
MICROBOONE-NOTE-1103-PUB

Further investigation into NCΔ 1ɣ model:

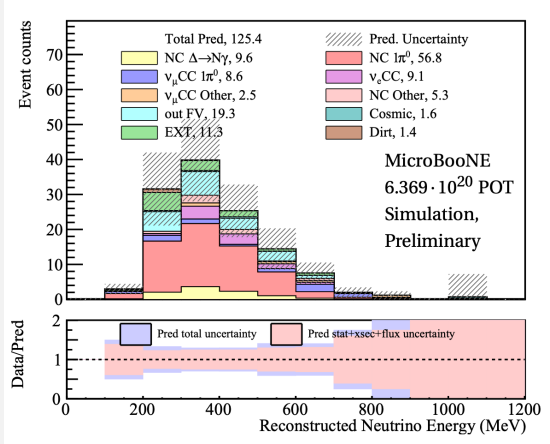
- ❑ Independent reconstruction
- ❑ Larger phase space (including charged pions and multiple protons)
- ❑ More sensitive to potential excess in 1ɣ0p channel

Coherent-like single ɣ search:

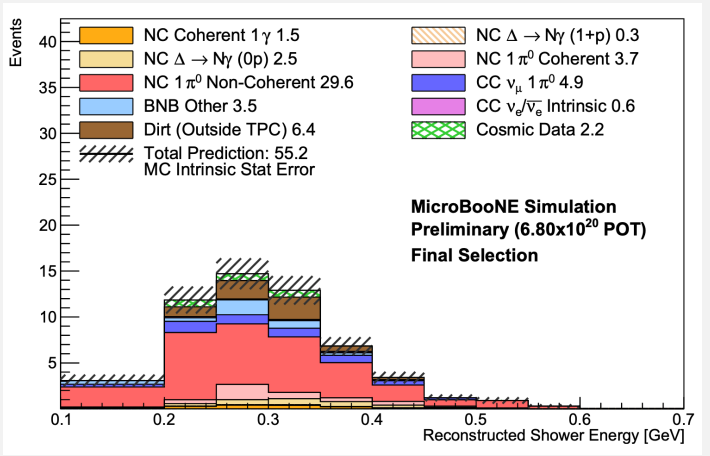
- Focus on forward-going photons with no visible hadronic energy
- More sensitive to potential excess in forward-going and 1ɣ0p channel



1ɣNp (N≥1)



1ɣ0p

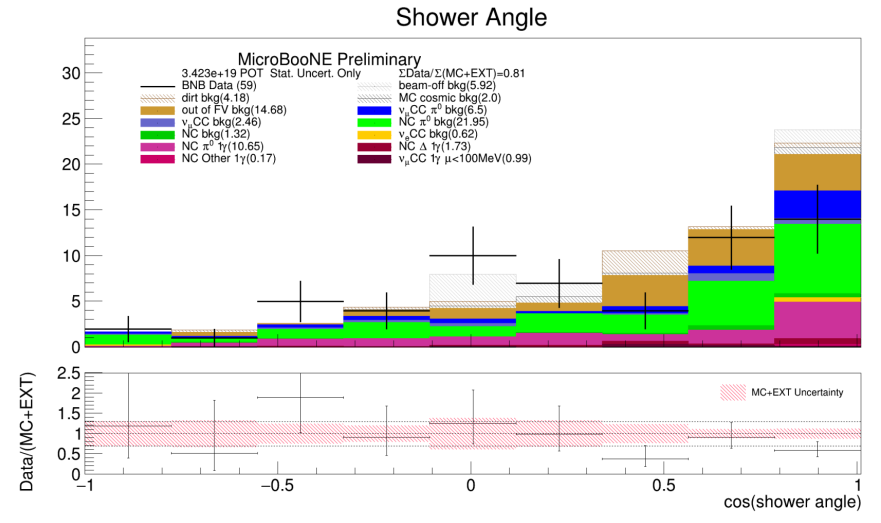


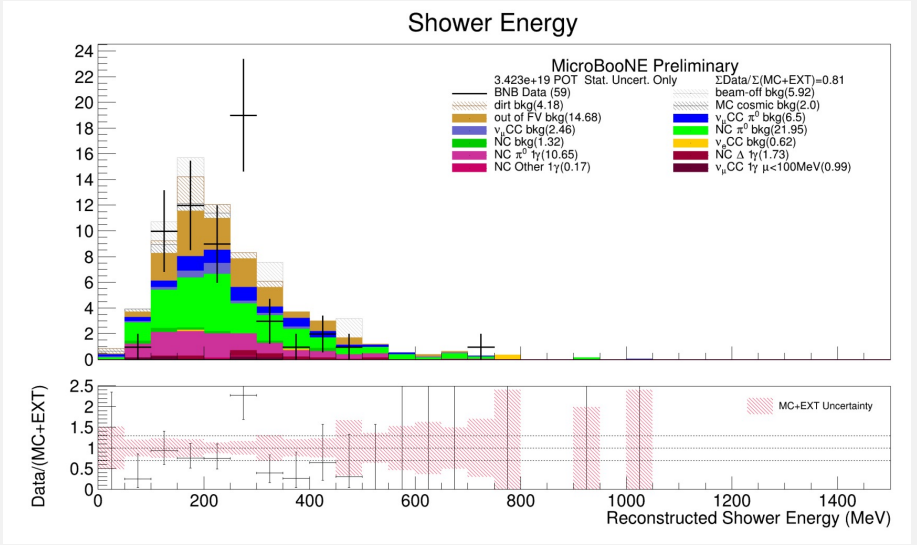
Coh-1ɣ0p

Future investigations

Inclusive single γ selection

- ❑ Broader search beyond specific NC Δ model
- ❑ Inclusive signal definition: no electrons and exactly one photon with KE>20 MeV. No muons with KE>100 MeV, but any number of hadrons allowed
- ❑ Generic test of Standard Model prediction for single-photon events





Single photon search

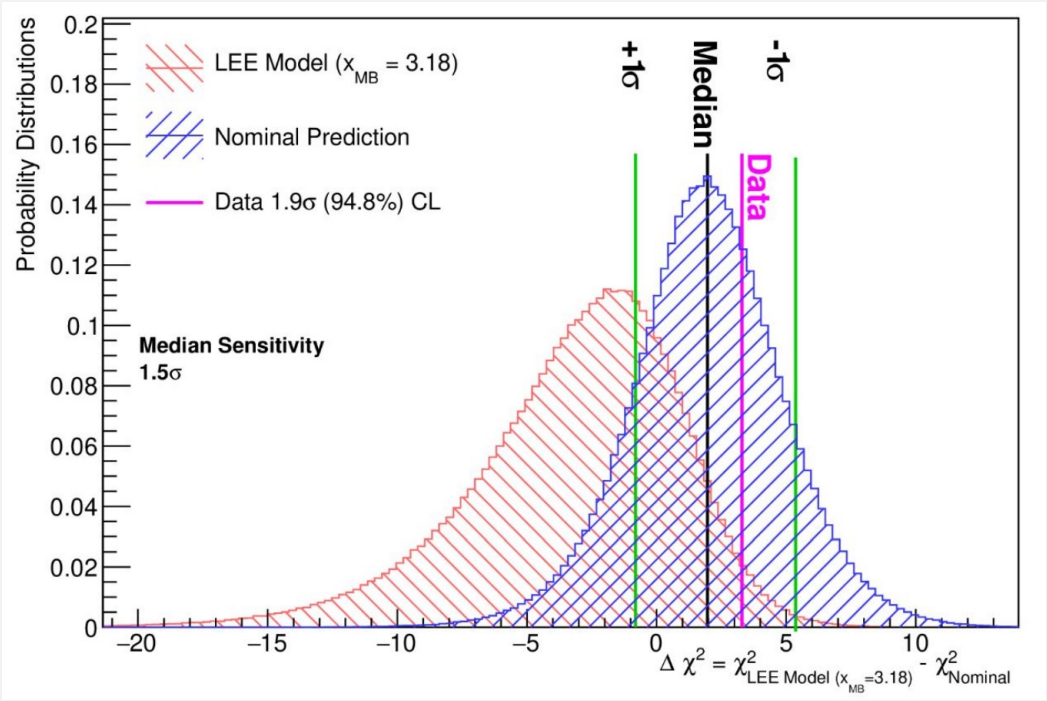
- Simple hypothesis test: use combined Neyman-Pearson χ^2 as test statistic

Nucl. Inst. Meth. A 961 (2020) 163677

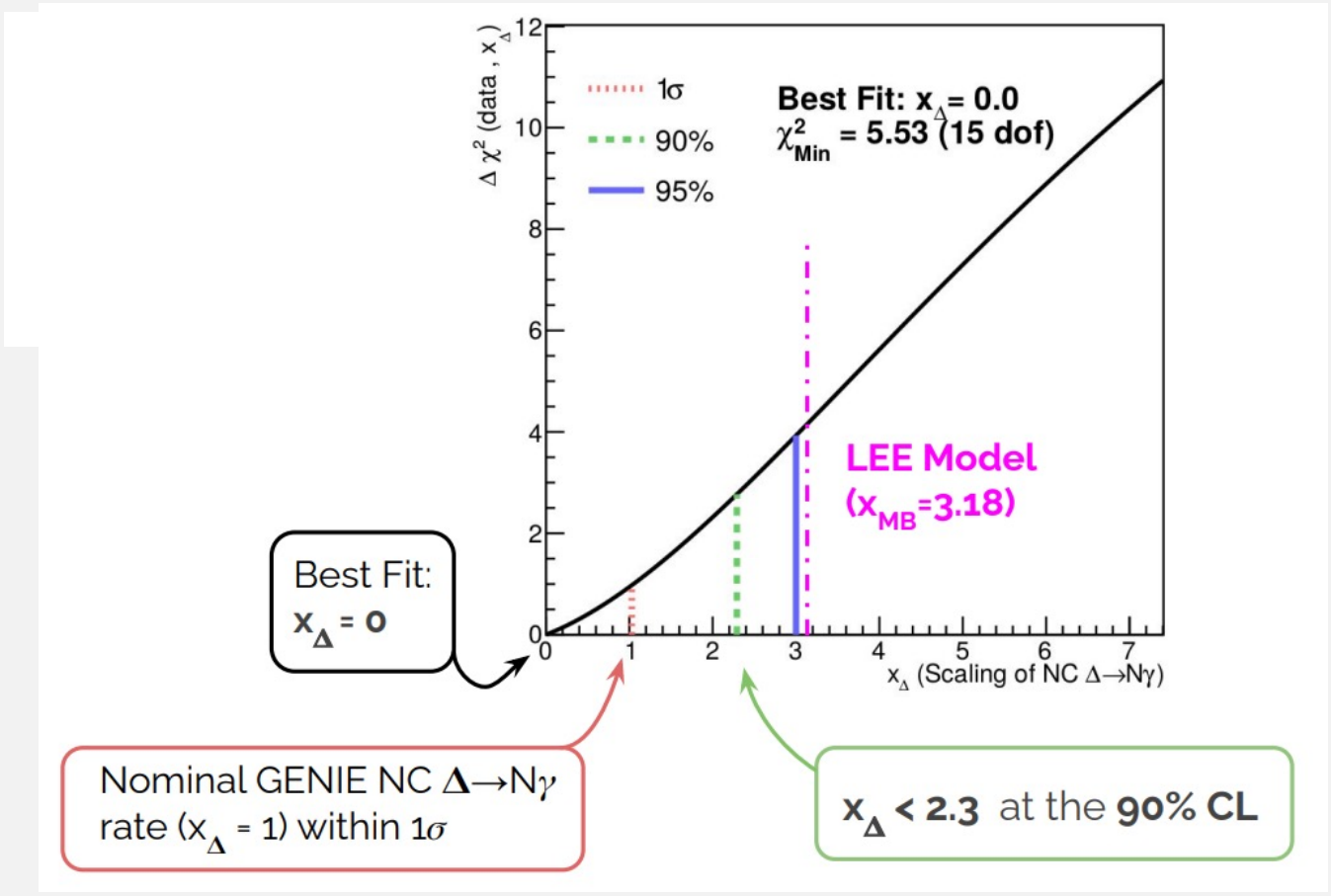
- Data consistent with nominal $\Delta \rightarrow N\gamma$ prediction

- Data **rejects LEE model hypothesis** in favour of nominal prediction at **94.8% CL**

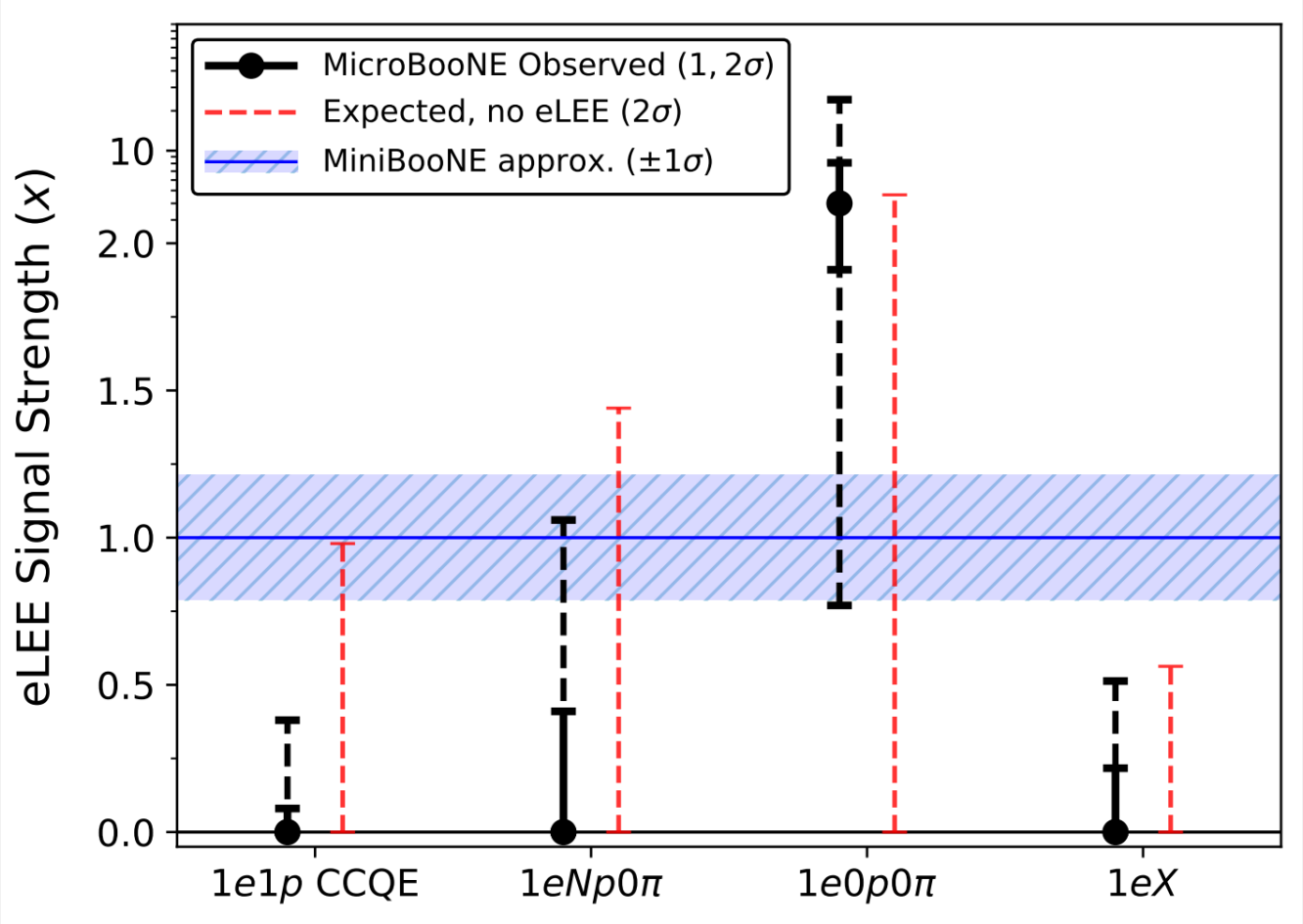
arXiv:2110.00409 [hep-ex]

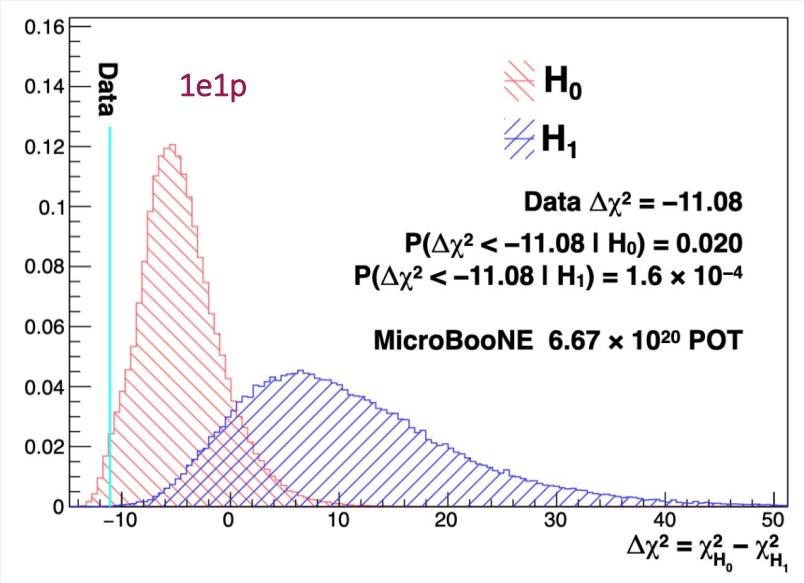


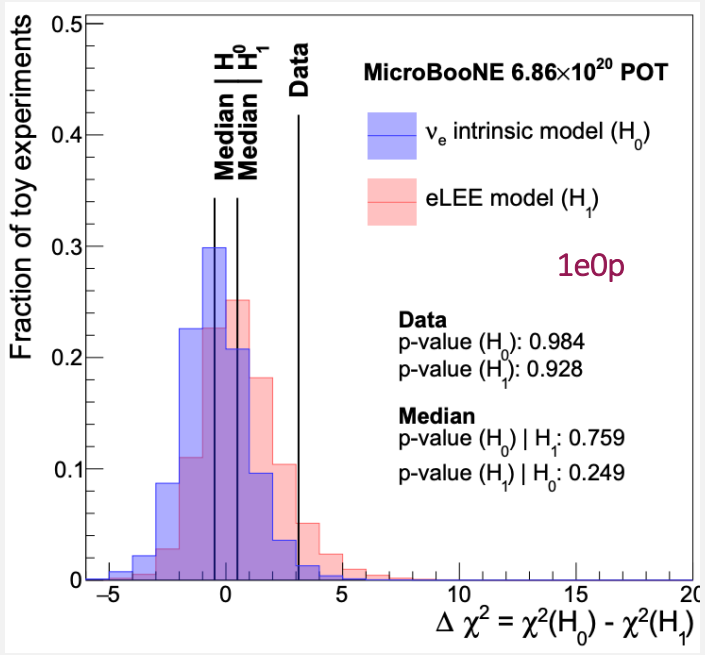
single photon search

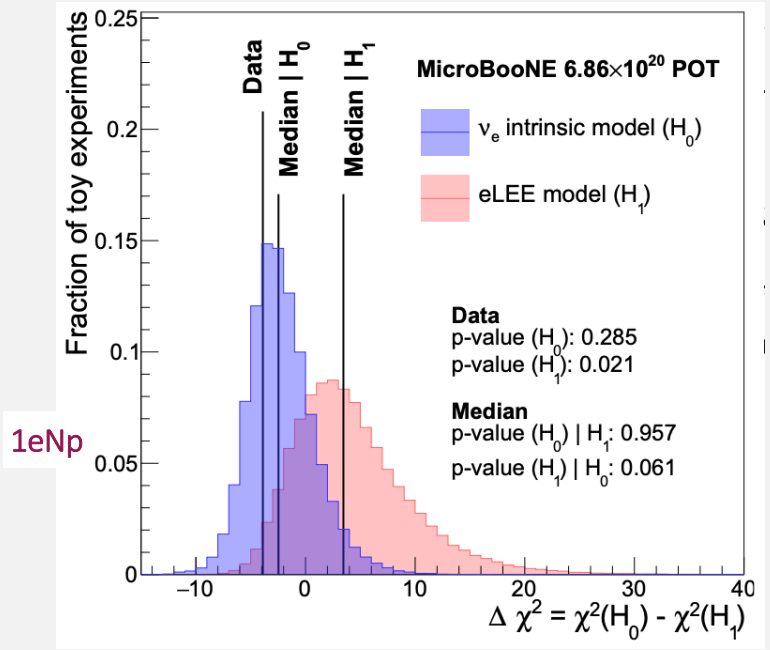


Slide credit: Mark R-L


MicroBooNE Observed (1, 2σ)
Expected, no eLEE (2σ)
MiniBooNE approx. (±1σ)
eLEE Signal Strength (x)
10
2.0
1.5
1.0
0.5
0.0
1e1p CCQE
1eNp0π
1e0p0π
1eX







assuming $eLEE_{x=0}$ hypothesis is true