MicroBooNE's Sterile Oscillation and Low-Energy Excess Results

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On behalf of the MicroBooNE Collaboration

2nd Short-Baseline Experiment-Theory Workshop

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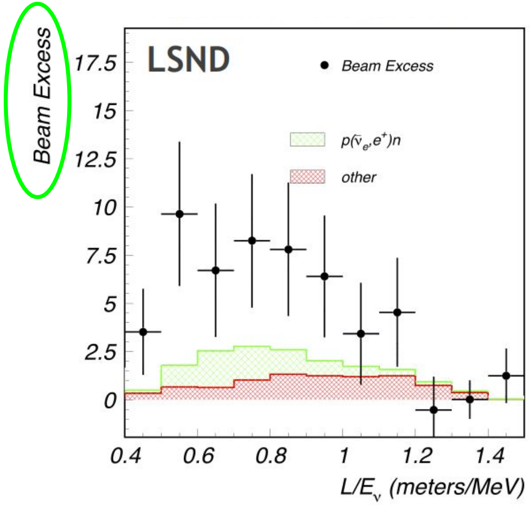
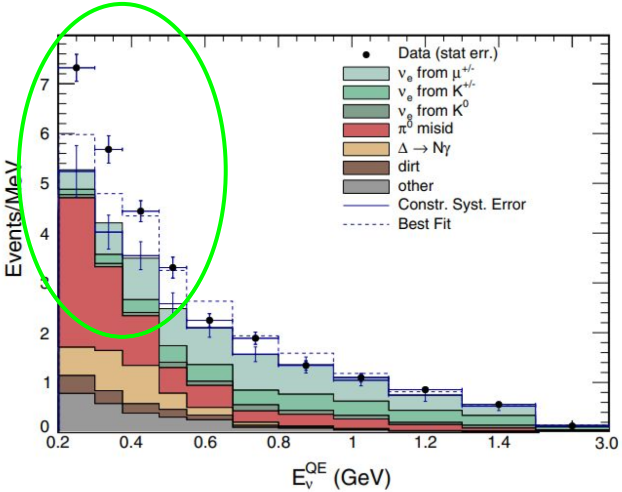
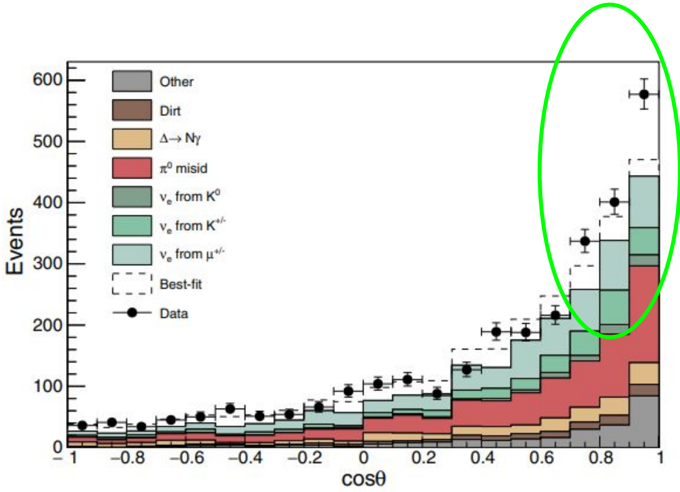
Low Energy Excess Anomalies

- In 1995, LSND saw an excess of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation events at energies ~50 MeV
- MiniBooNE was built at a similar L/E as LSND to test this anomaly
- With data collected from 2002 to 2019, sees a 4.8σ excess of ν_e candidate events
  - energies of about 200-800 MeV
  - forward-going angles



Phys. Rev. D. 64, 112007 (2001)



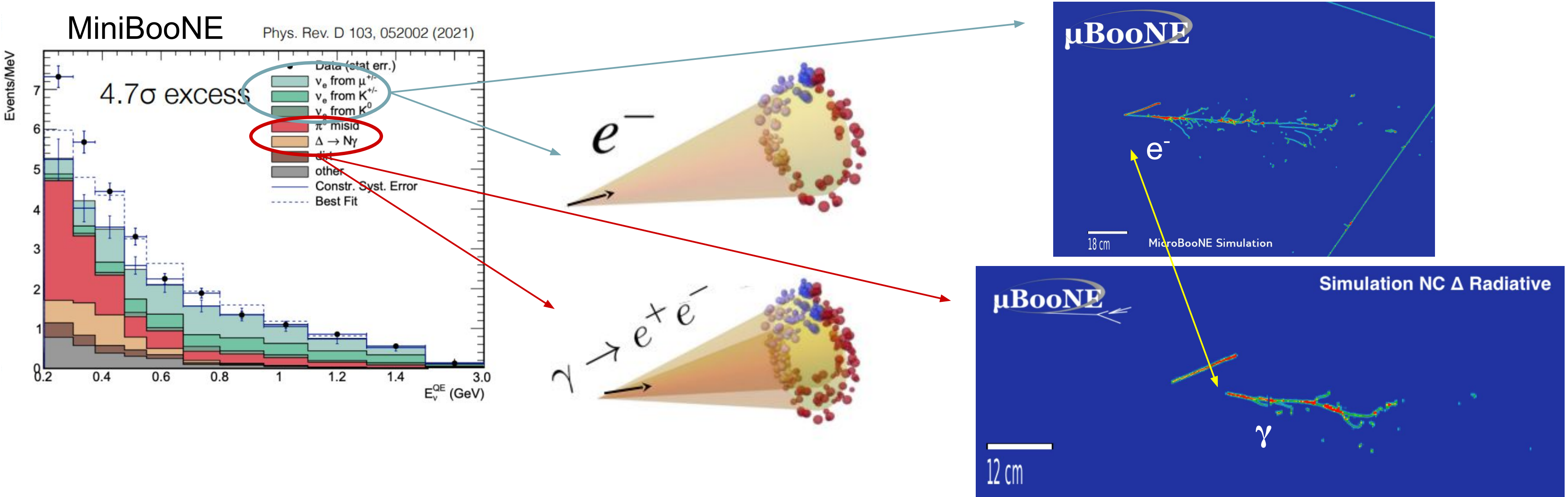


Phys. Rev. D 103, 052002 (2021)

Testing the LEE with LArTPCs

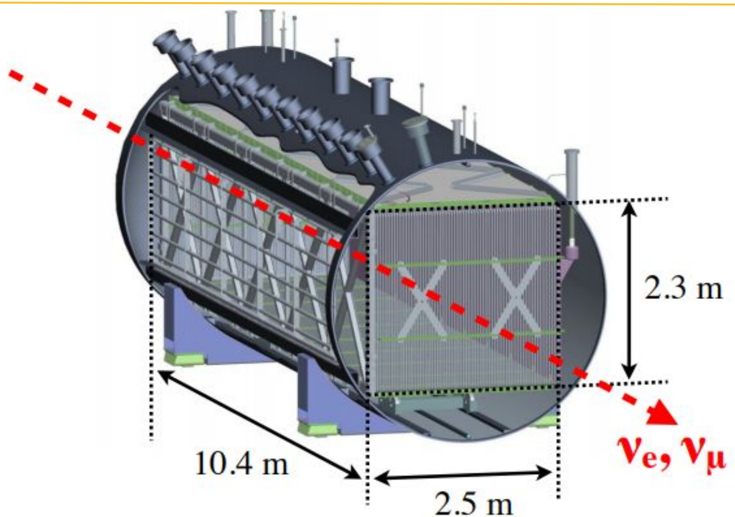
- However, MiniBooNE, as a cherenkov detector, can not distinguish between e^- and γ
- A Liquid Argon Time Projection Chamber (LArTPC) **can** distinguish these, allowing us to probe into the nature of the excess.

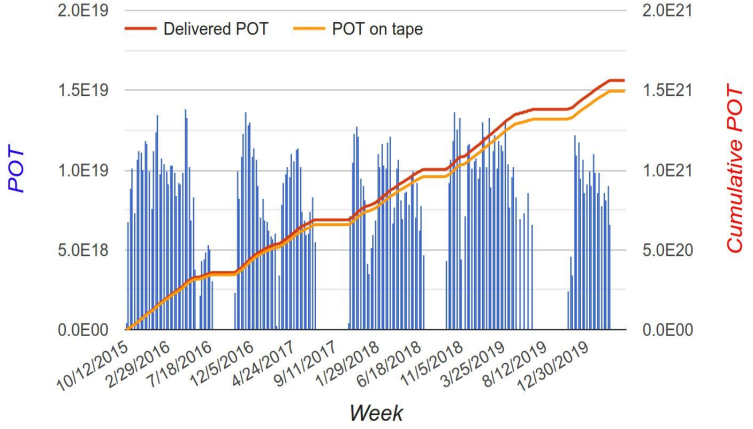
MiniBooNE **MicroBooNE (LArTPC)**



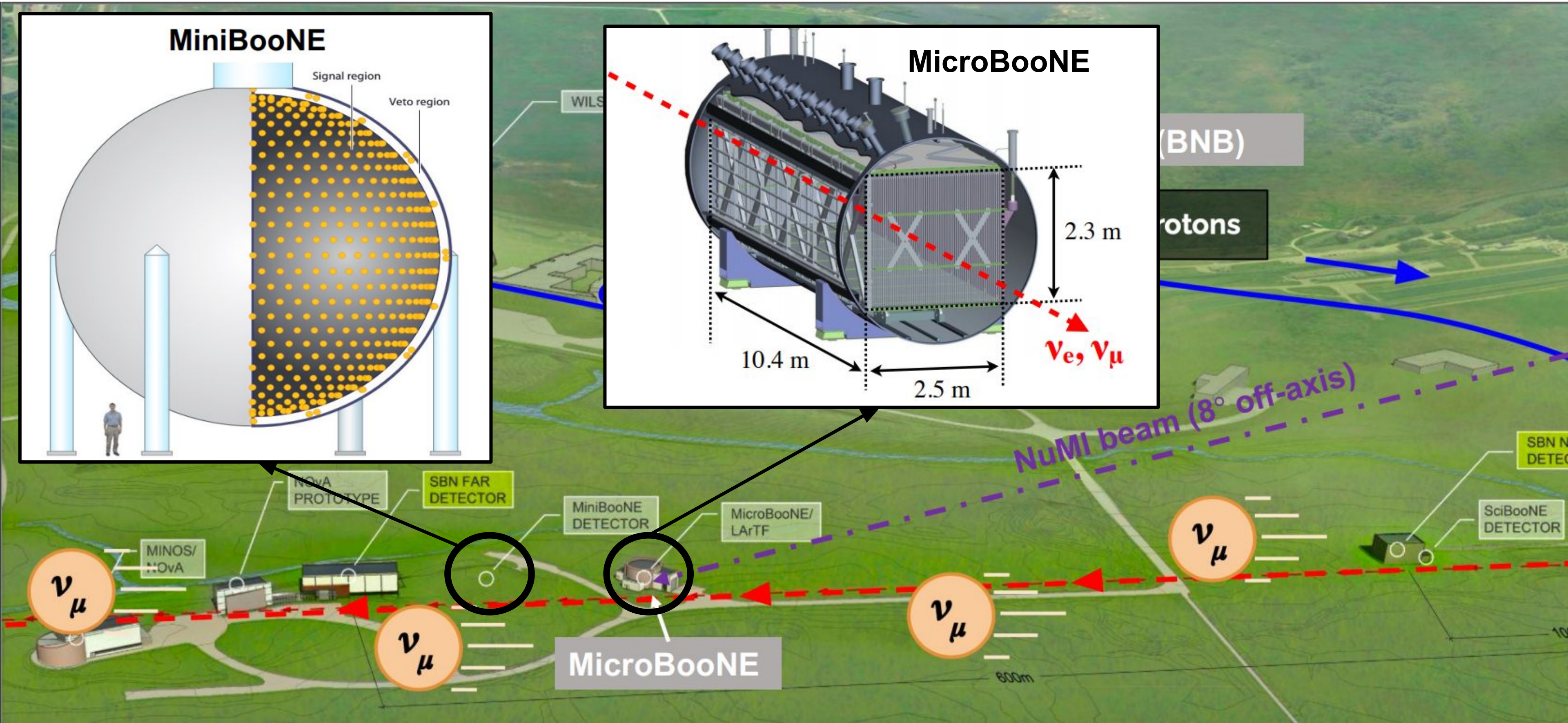
MicroBooNE

- MicroBooNE is a surface-level, 85 tonne LArTPC neutrino experiment
- On the Booster Neutrino Beam (BNB) at Fermilab
  - neutrino energy peak: ~700 MeV
- 470m downstream from the neutrino production target
- Collected data 2015 - 2021
  - ~0.5M neutrino events
  - Largest neutrino-argon data set
- Being decommissioned
  - parts are being reused for other experiments like SBND and DUNE
- Primary design goal is to understand the LEE anomaly seen by MiniBooNE



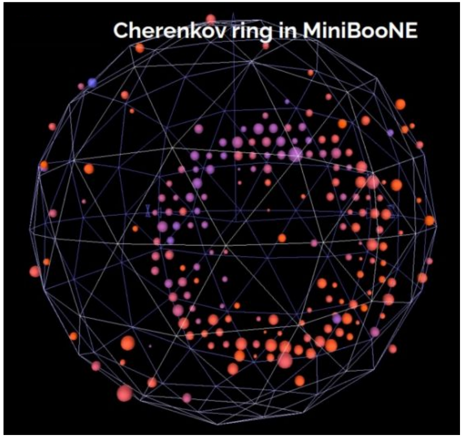


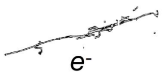
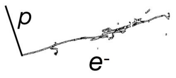
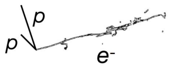
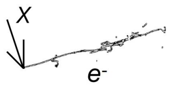
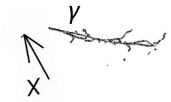
MicroBooNE


MiniBooNE
Signal region
Veto region
MicroBooNE
2.3 m
10.4 m
2.5 m
ν_e, ν_μ
(BNB)
rotons
NuMI beam (8° off-axis)
WILS
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS/ NOvA
SciBooNE DETECTOR
ν_μ
MicroBooNE
600m

Possible Anomaly Channels

First series of results (½ the MicroBooNE data set)



1e0p	1e1p	1eNp	1eX	1γ0p	1γ1p	1γX
						

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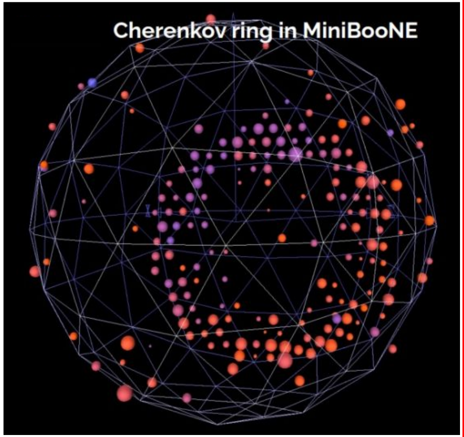
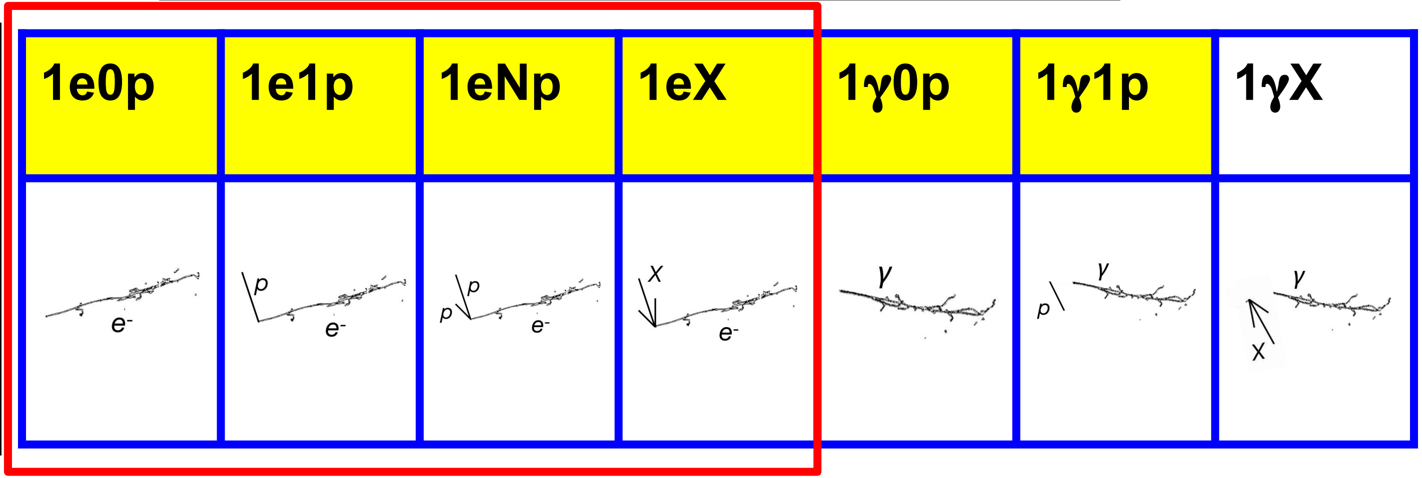
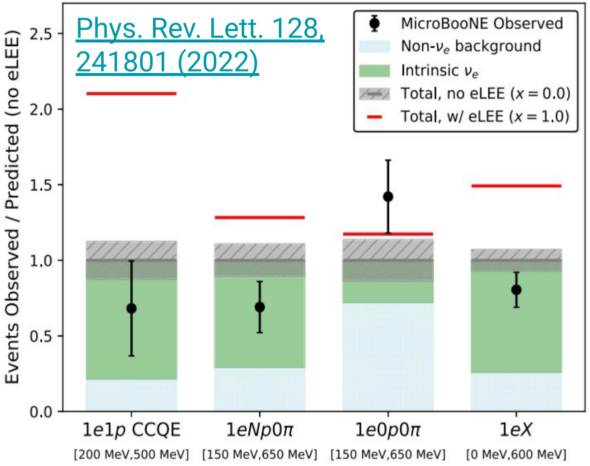


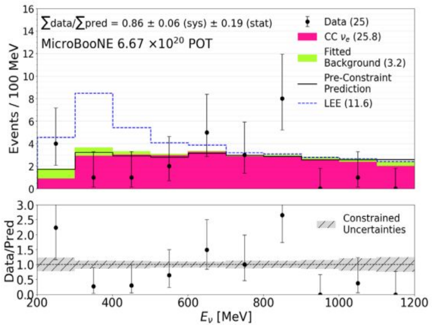


First Results: Electrons

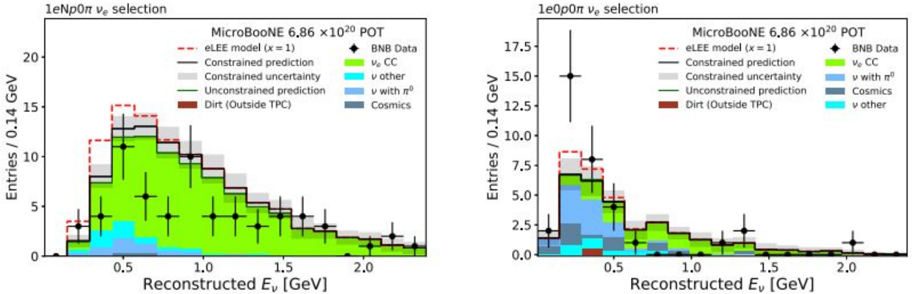
- Used about half of MicroBooNE's collected dataset
- 3 ν_eCC searches for four event classes (1e0p, 1e1p, 1eNp, 1eX)



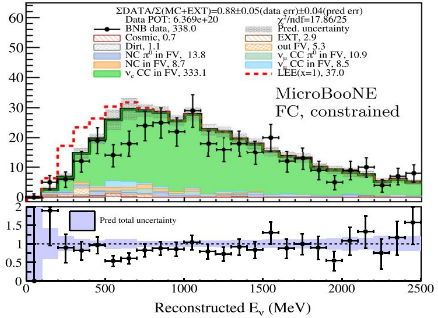
Phys. Rev. D **105**, 112003 (2022)



Phys. Rev. D **105**, 112004 (2022)

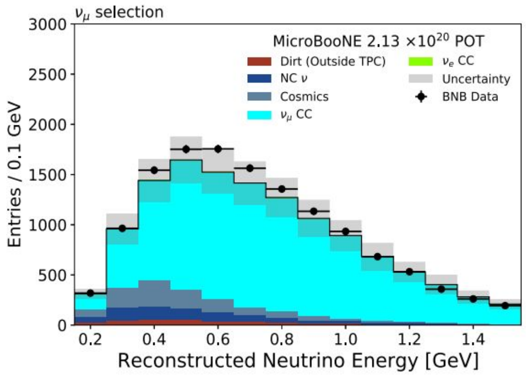


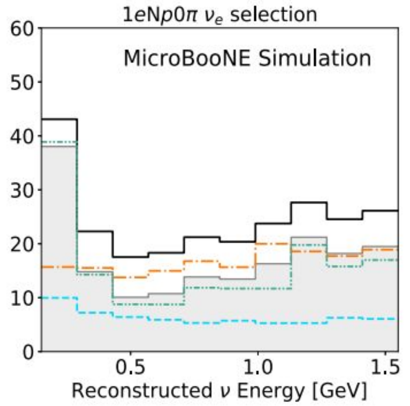
Phys. Rev. D **105**, 112005 (2022)

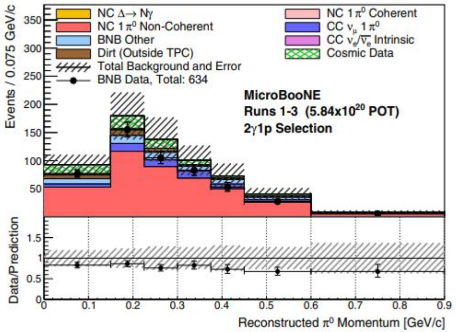


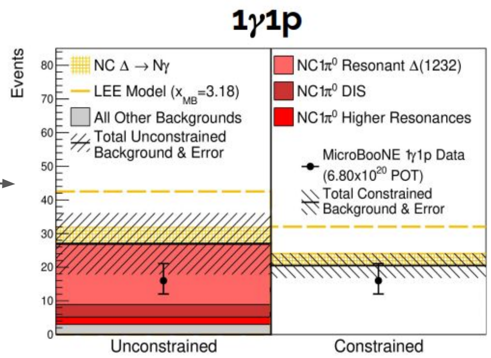
Aside: Constraints

- Without a near detector, MicroBooNE needs a way to reduce uncertainties on these rare events
- Leverage ν_μ and ν_e correlations
  - Common flux parentage
  - Lepton universality
- High-statistics ν_μ sidebands, joint covariance matrix
  - ν_μ measurement constrains ν_e prediction and reduces uncertainty
- Similar concept applies for other interactions
  - For instance: NC $\Delta \rightarrow N\gamma$ result uses a "2 photon sideband" for constraint that leverage the correlations with NC π^0 events, which are also the main background





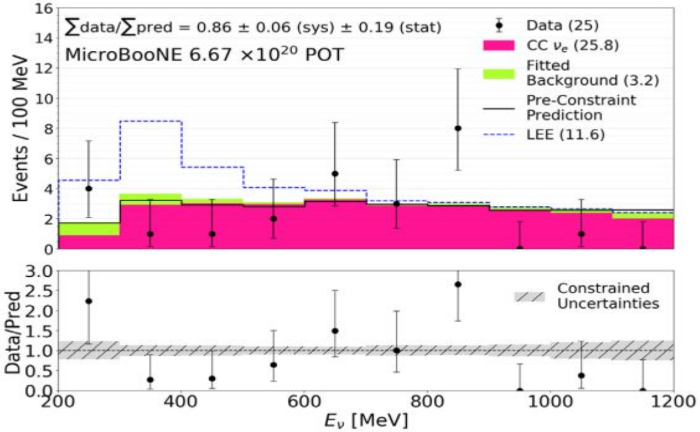


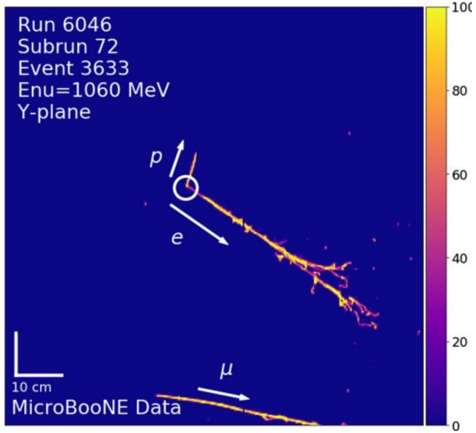


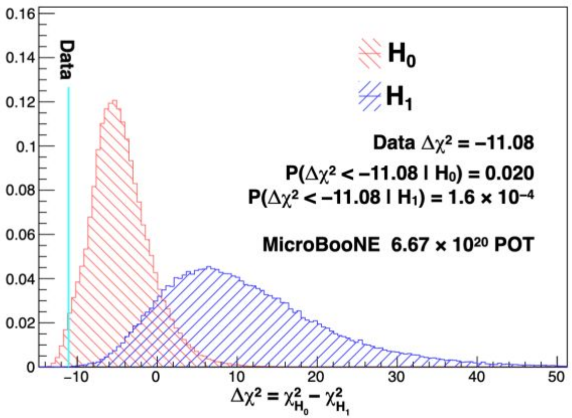
Phys. Rev. D **105**, 112003 (2022)

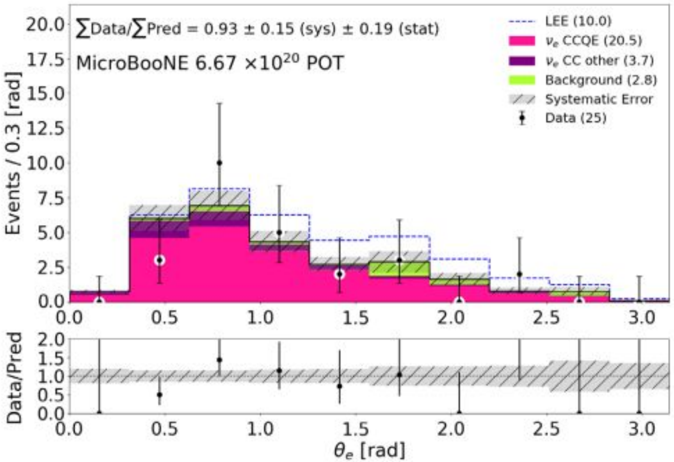
First Results: 1e1p

- CCQE-like events
- Utilizes deep learning tools (SparseSSNet) for reconstruction and event selection
- Rejects LEE at > 95% CL
  - prefers no LEE with a significance of 2.4σ





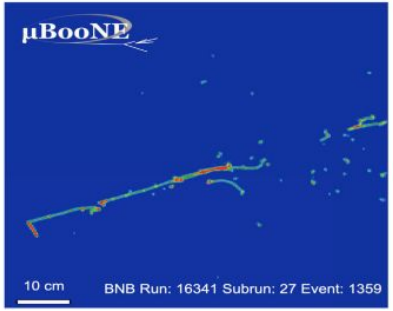


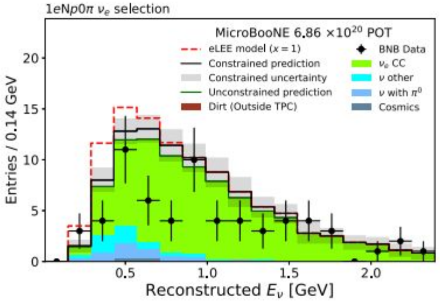


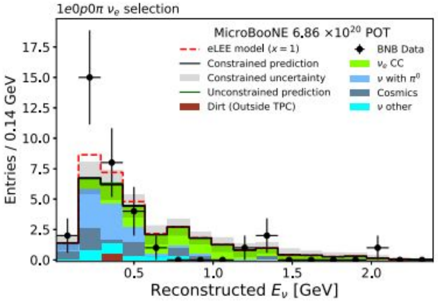
Phys. Rev. D **105**, 112004 (2022)

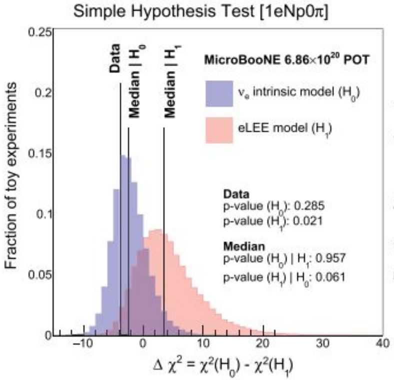
First Results: Pion-less

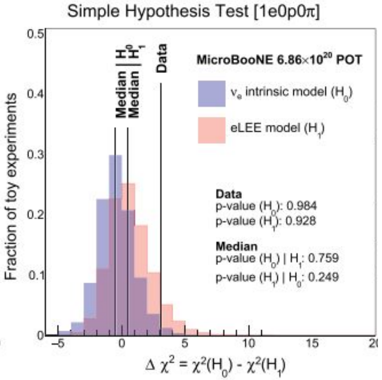
- Separated into 1e0p0pi and 1eNp0pi
- Uses Pandora reconstruction framework
- 1eNp channel excludes the LEE hypothesis at 97.9% C.L.
- Less sensitive 1e0p channel shows no strong preference for either LEE or no LEE hypothesis

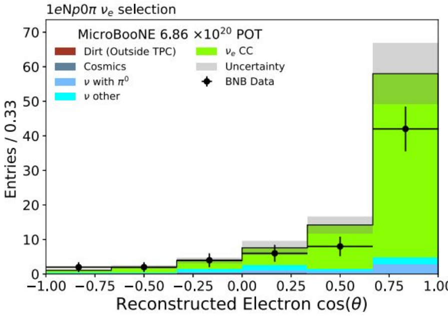


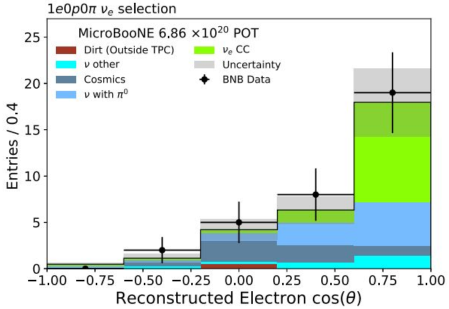






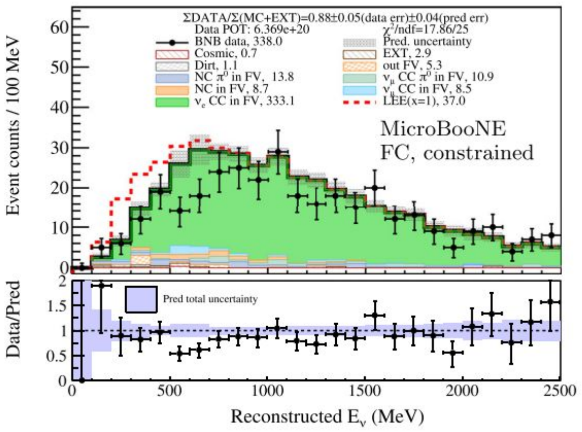


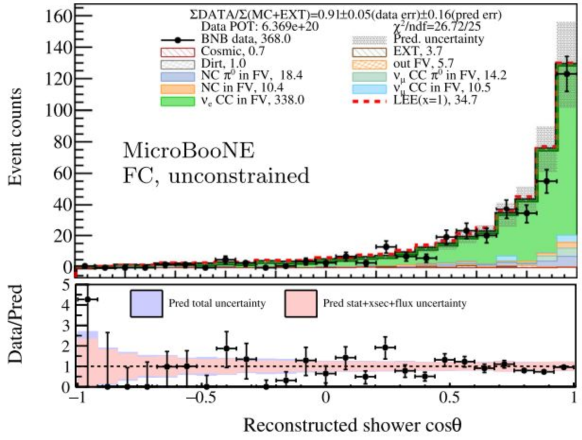


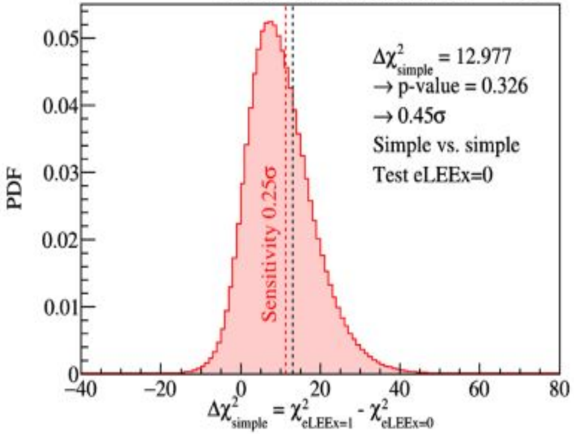


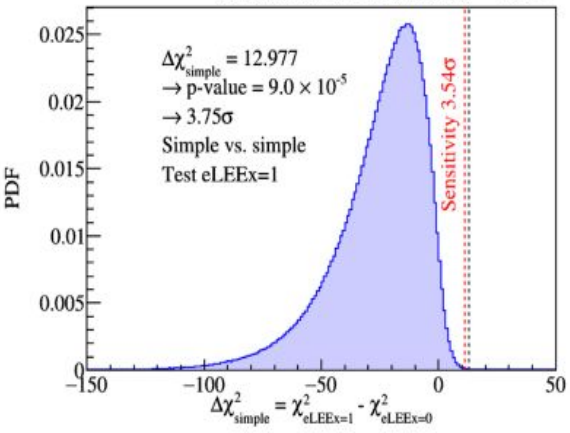
First Results: Inclusive ν_eCC (1eX)

- all ν_eCC-like events, no restriction on final state particles
- Uses Wire-Cell reconstruction framework
- Rejects LEE at > 99.7% CL
  - prefers no LEE with a significance of 3.75σ



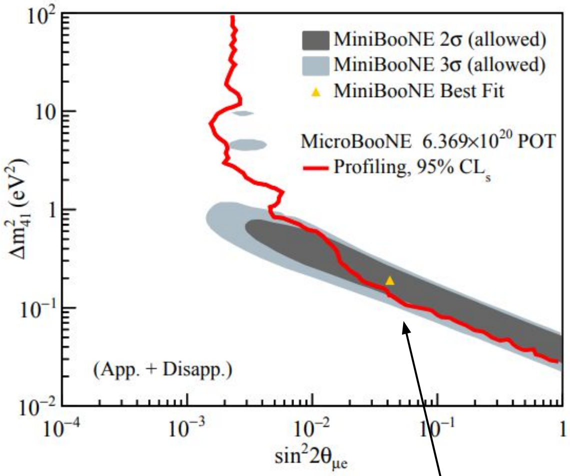


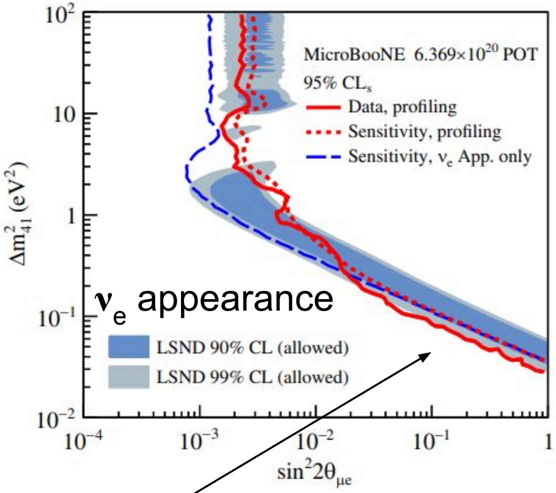




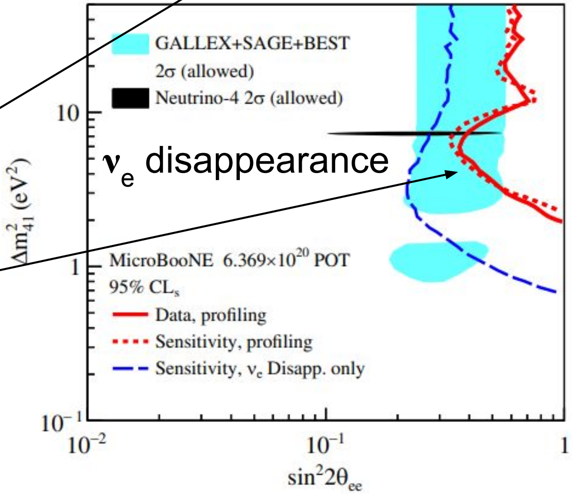
3+1 Oscillations

- Use the data from the first results to perform a 3+1 sterile neutrino oscillation analysis



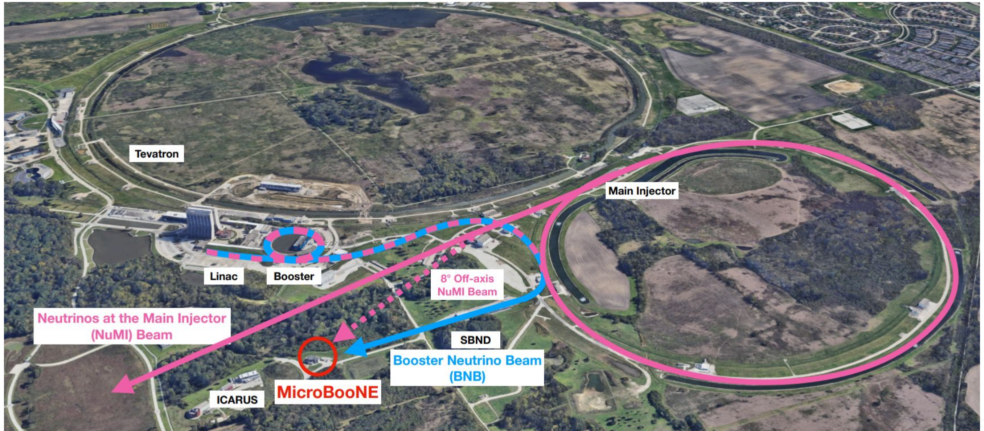


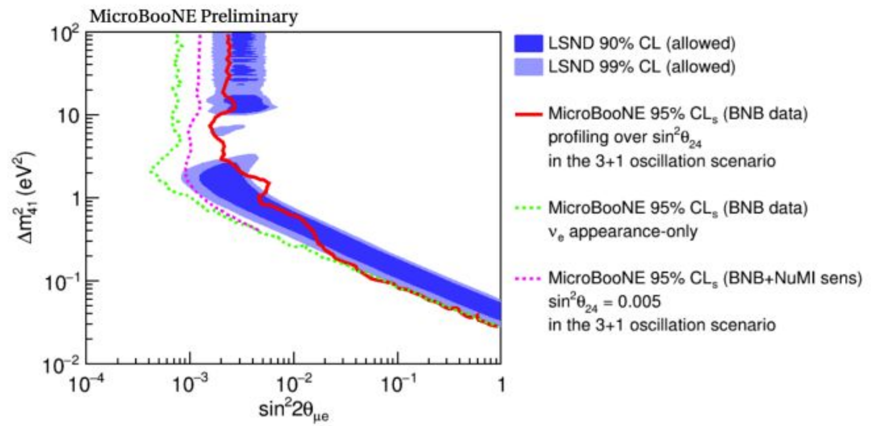
- Simultaneously considering appearance and disappearance effects
- Saw no evidence for 3+1 sterile neutrino oscillations
- For $\nu_\mu \rightarrow \nu_e$, excludes parts of the MiniBooNE and LSND allowed regions
- For $\nu_e \rightarrow \nu_e$, excludes part of the allowed regions from gallium experiments

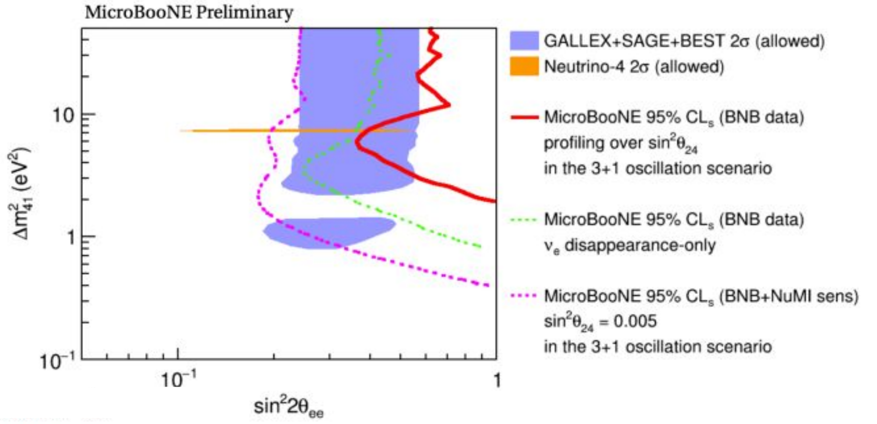


Improving the Sensitivity: BNB+Numi

- In addition to the on-axis BNB beam, MicroBooNE sees the NuMI beam at an off-axis angle of 8°
  - more than doubles statistics
- Intrinsic flux and ν_μ to ν_e ratio in NuMI is quite different from the BNB
  - addition of NuMI events helps to break the degeneracy of the appearance and disappearance effects

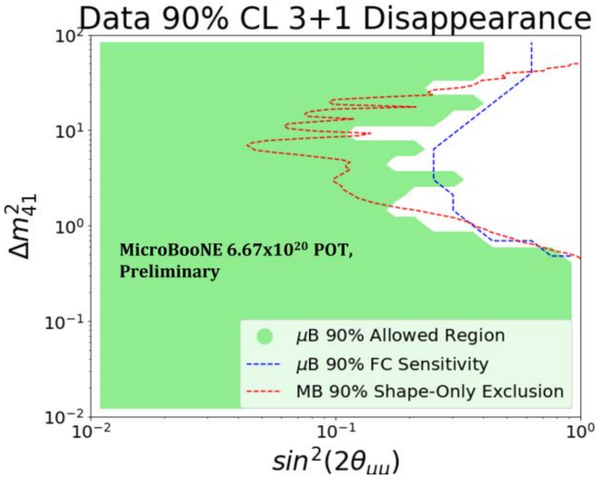


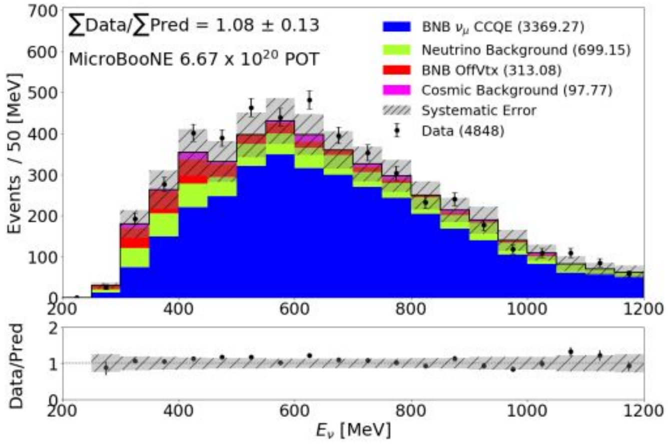


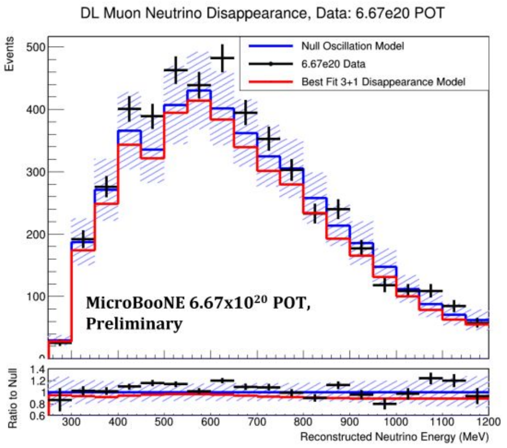


ν_μ Disappearance

- Using the Deep Learning CCQE ν_μ selection, which was used as a constraint in the 1e1p analysis
- Muon neutrino spectrum data is consistent with prediction
- Dataset is used to produce exclusion contour for muon neutrino disappearance

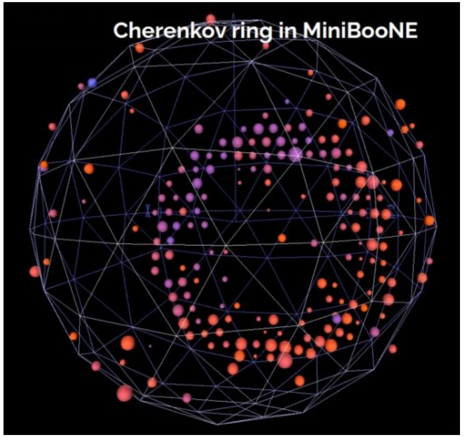


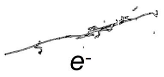
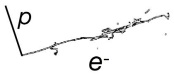
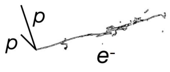
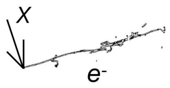
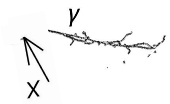




Possible Anomaly Channels

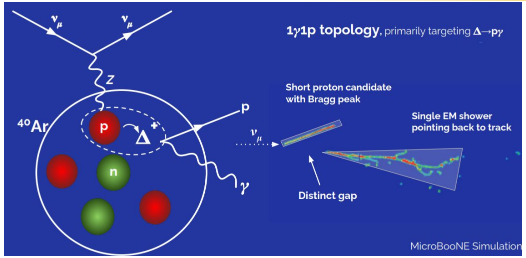
First series of results (½ the MicroBooNE data set)

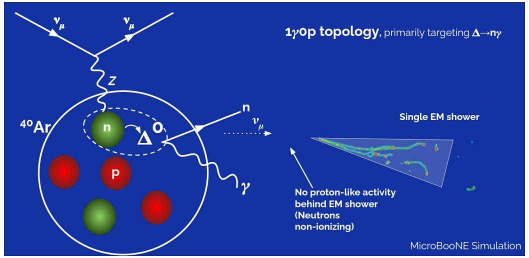


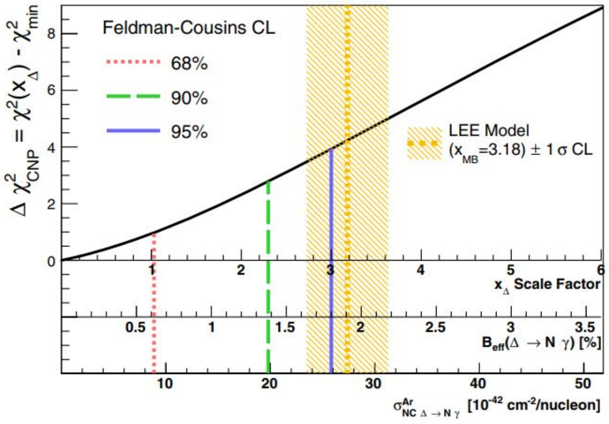
1e0p	1e1p	1eNp	1eX	1γ0p	1γ1p	1γX
						

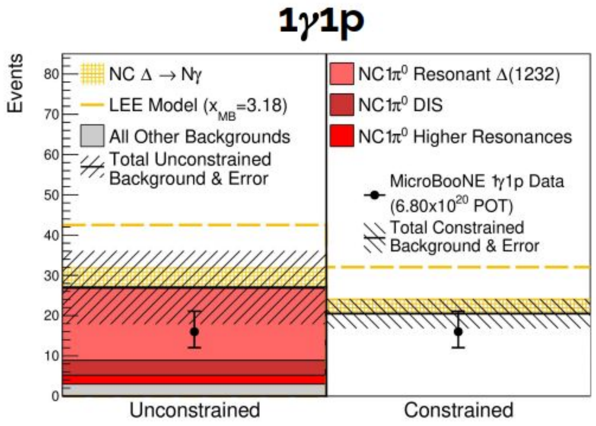
First Results: NC $\Delta \rightarrow N\gamma$

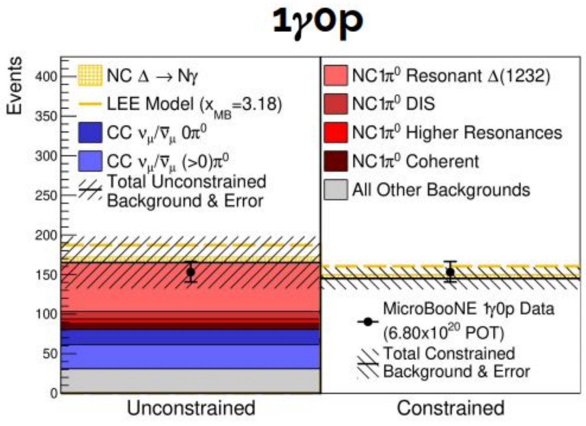
- Single photon search for NC $\Delta \rightarrow N\gamma$
  - $1\gamma 0p$, $1\gamma 1p$
- Rules out photons from NC $\Delta \rightarrow N\gamma$ as the cause of the LEE at 94.8% C.L.
- Higher purity/more sensitive $1\gamma 1p$ channel dominates





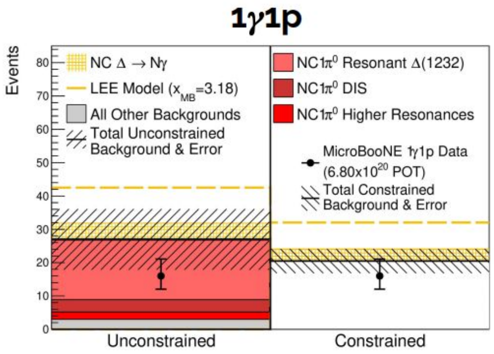


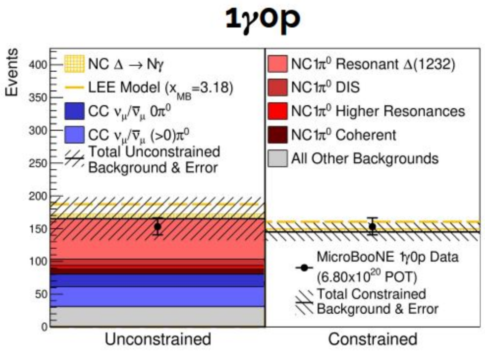


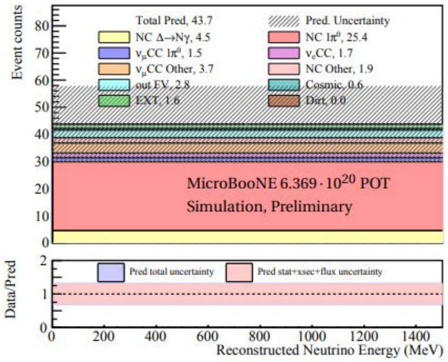


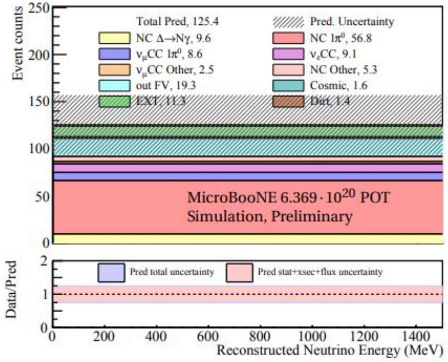
Expanding Results: NC $\Delta \rightarrow N\gamma$

- Expanded NC $\Delta \rightarrow N\gamma$ search
- Incorporates Wire-Cell reconstruction in addition to previous Pandora-based results
  - largely orthogonal -> almost doubles statistics
- In particular, additional 1g0p selection has more sensitivity
- Expand the original 1D NC Δ scaling LEE analysis to 2D (0p vs 1p)









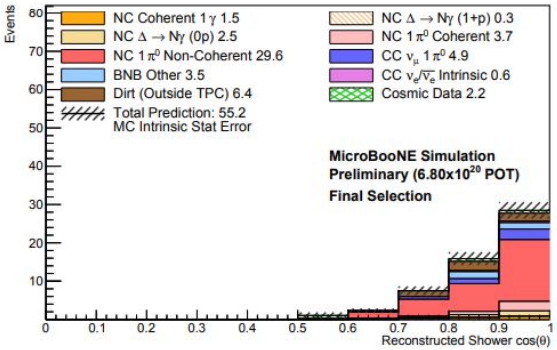
Coherent Photon

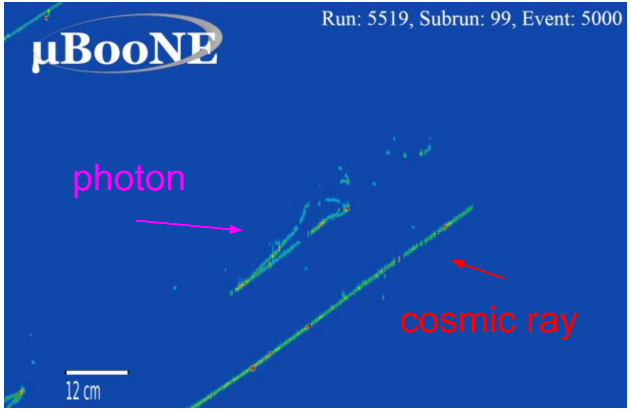
- Coherent-like single-photon production search
- building on the previous $1\gamma0p$ result
  - Subdominant NC 1γ background, never been measured experimentally
- expect ~10 events in three years of MicroBooNE data
- increased sensitivity to "coherent-like" events
  - Standard Model predicted process

    (E. Wang, L. Alvarez-Ruso, and J. Nieves, Phys. Rev. C 89, 015503 (2014))

$$\nu(\overline{\nu}) + \mathrm{Ar}_{gs} \rightarrow \nu(\overline{\nu}) + \mathrm{Ar}_{gs} + \gamma$$

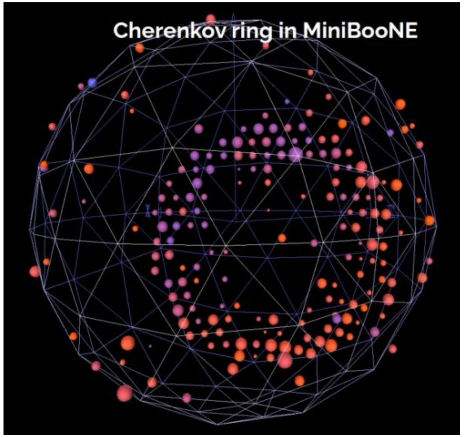
  - forward-going photons
  - no visible hadronic activity
    - improvements in proton identification for better event selection



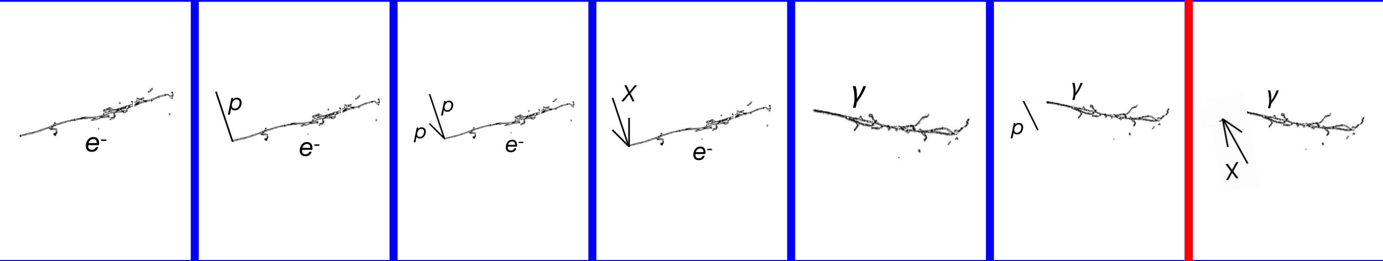


Possible Anomaly Channels

First series of results (½ the MicroBooNE data set)

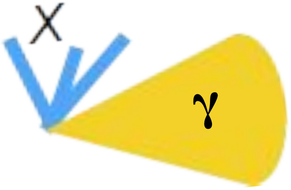


1e0p	1e1p	1eNp	1eX	1γ0p	1γ1p	1γX

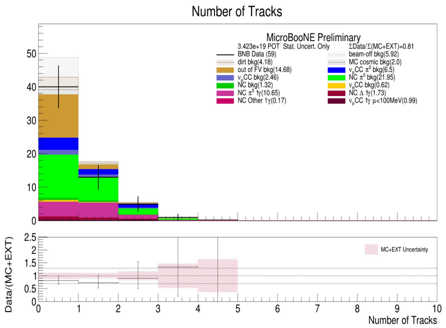


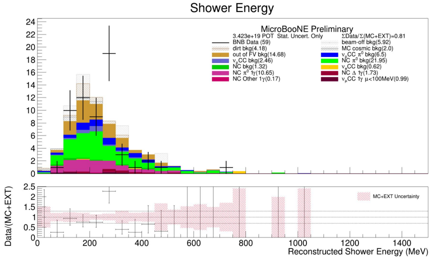
Inclusive Photon Search

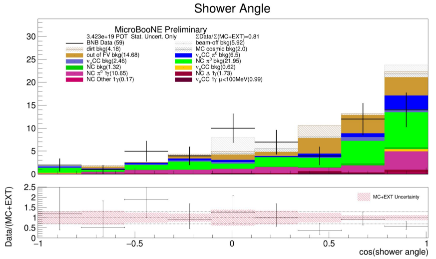
- Only current photon result is the NC $\Delta \rightarrow N\gamma$ ($1\gamma0p$, $1\gamma1p$) channel
- Cover the remaining unexplored single photon phase-space
- Inclusive single photon ($1\gamma X$)
    - more general "single photon-like" final states
        - one photon or highly overlapping di-photon or e^+e^-
    - no dependence on model or requirement on hadronic activity

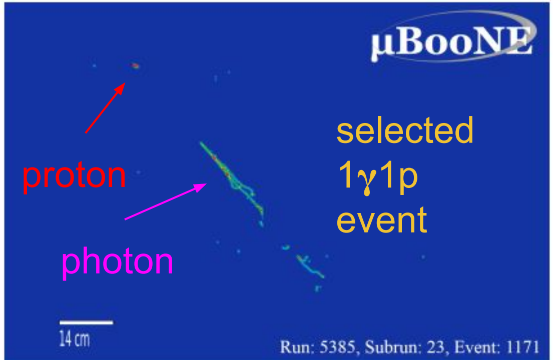


~2% of full dataset, no systematic errors



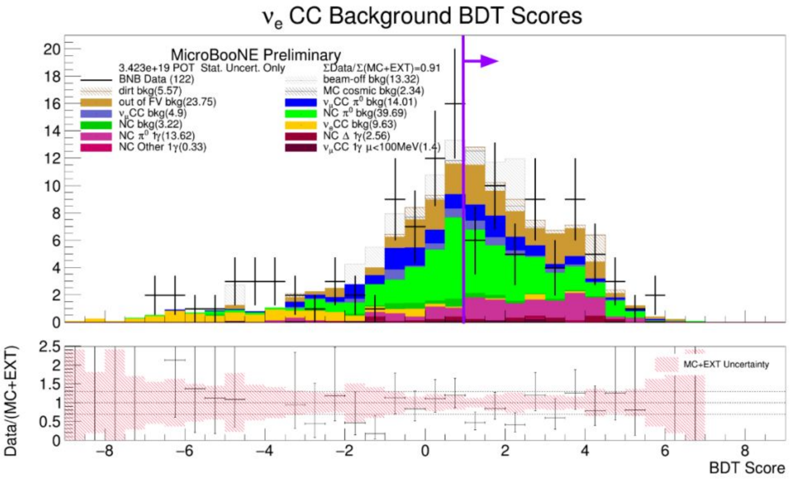


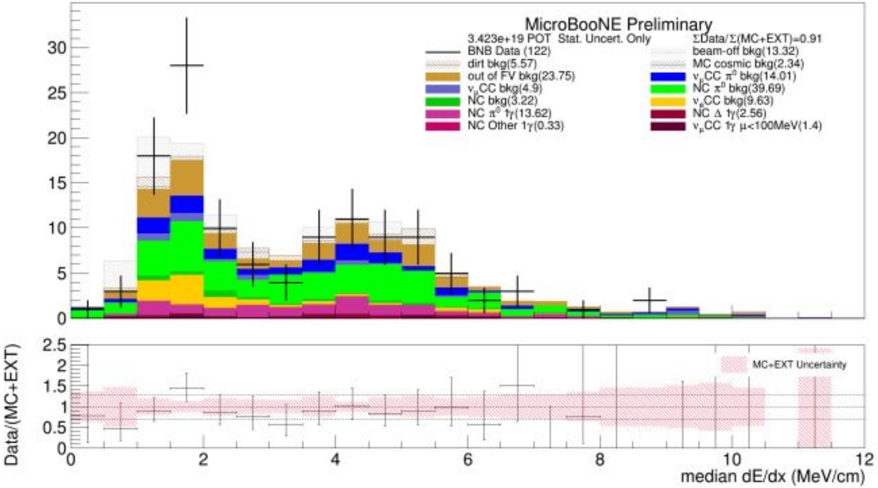




Single Shower

- Can use inclusive photon analysis to look at a "single shower" result by not cutting out the ν_eCC events
- More like MiniBooNE
- Direct comparisons of single electron and single photon events using the electron/photon separation variables

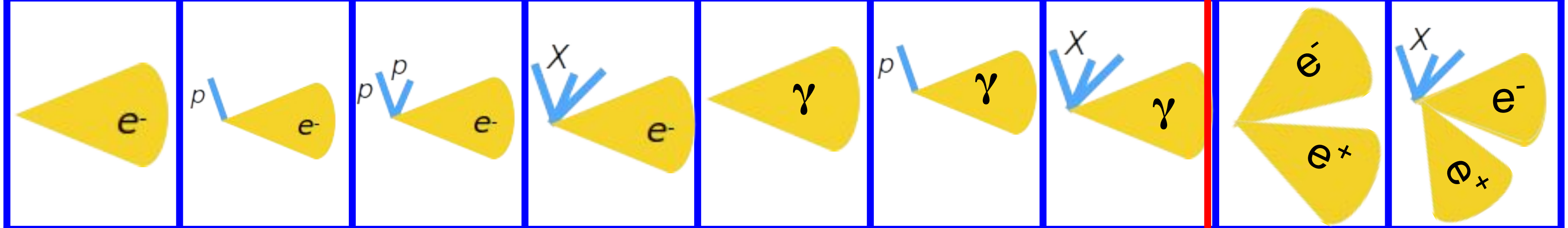




Exploring Further Channels

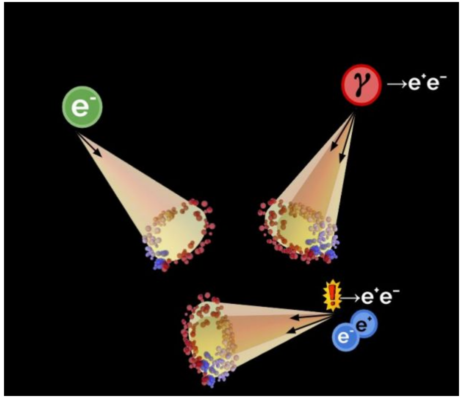
First series of results (½ the MicroBooNE data set)

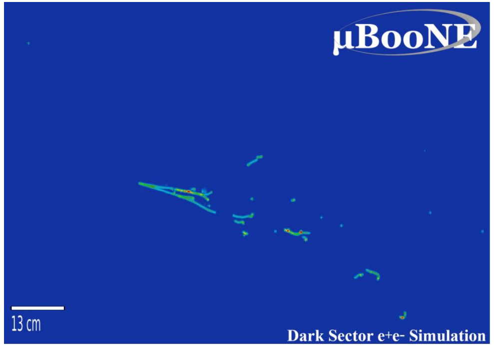
1e0p	1e1p	1eNp	1eX	1γ0p	1γ1p	1γX	e^+e^- + nothing	e^+e^-X

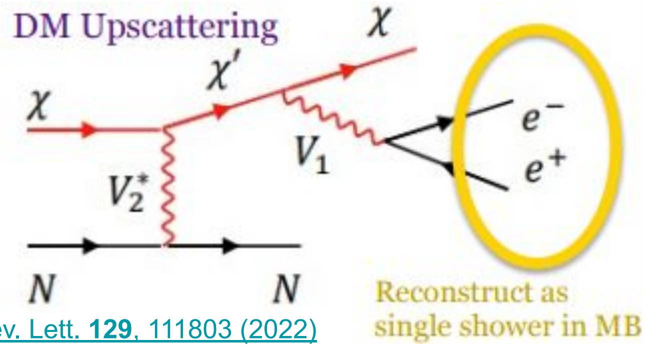


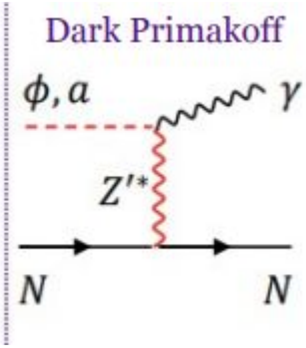
Other BSM Explanations

- A number of proposed BSM scenarios beyond sterile neutrinos
- Overlapping e^+e^- final states will mimic a single shower topology
- Models include dark neutrinos, heavy neutral leptons, new scalars, dark matter, and many more

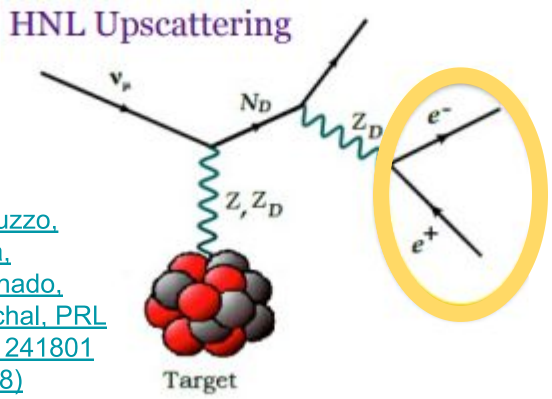








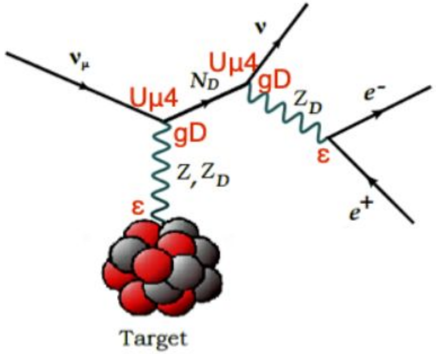
Phys. Rev. Lett. **129**, 111803 (2022)

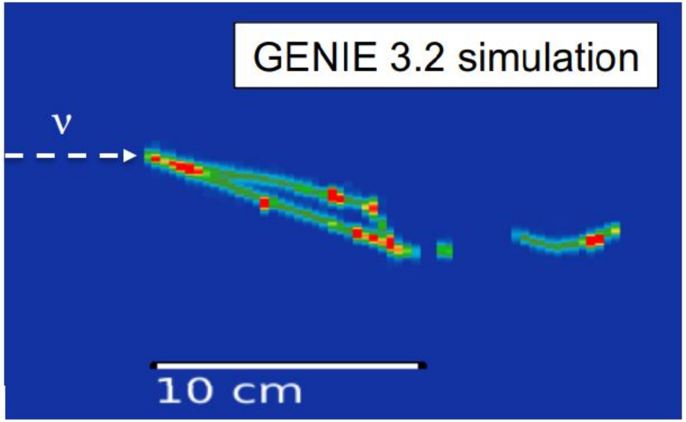


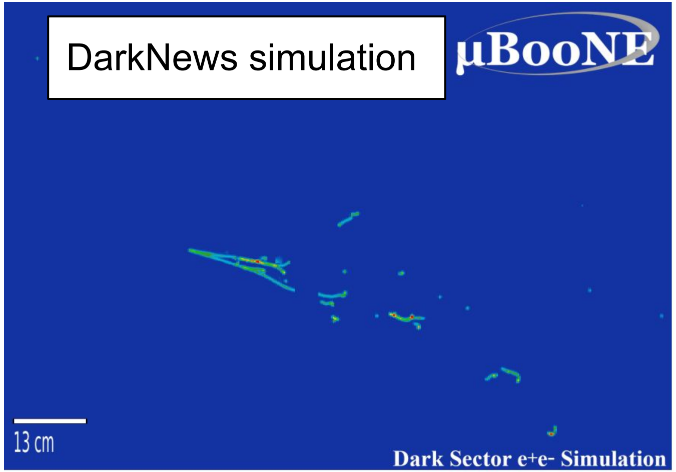
Bertuzzo, Jana, Machado, Funchal, PRL 121, 241801 (2018)

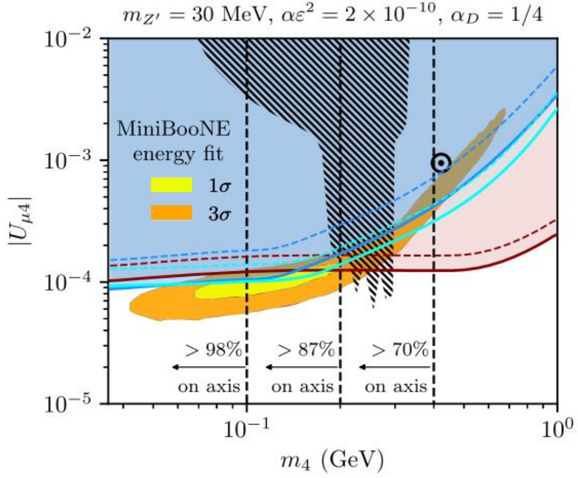
e+e- Searches

- Some searches for e+e- explanations already underway
- Looking for dark neutrino/dark photon models using different generators and reconstruction paradigms









arXiv:2308.02543

Phys. Rev. Lett. 123, 261801 (2019)

Summary

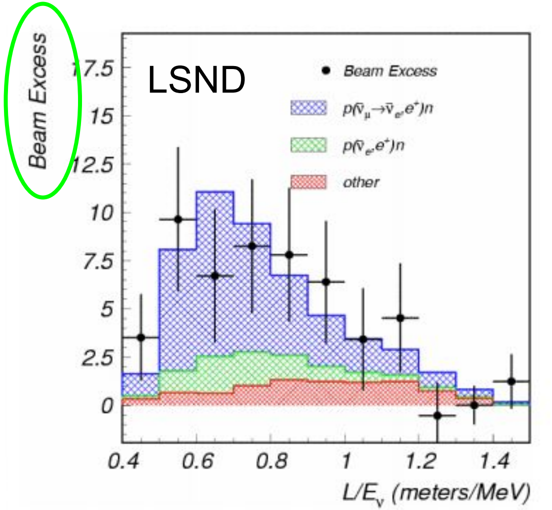
- The MicroBooNE experiment was designed to test the nature of the excess of single electromagnetic shower events seen by MiniBooNE
- The current set of results from MicroBooNE uses half the MicroBooNE dataset and disfavor electrons and NC $\Delta \rightarrow N\gamma$ photon backgrounds as an explanation for the MiniBooNE LEE
  - Efforts to expand these results to the full MicroBooNE dataset are ongoing
- Additionally, we have performed a sterile neutrino oscillation fit and expect to improve this fit in the near future with the inclusion of data from the NuMI beam
- A number of new MicroBooNE LEE analyses, particularly for single photon and e+e- final states, are underway

Thank You!

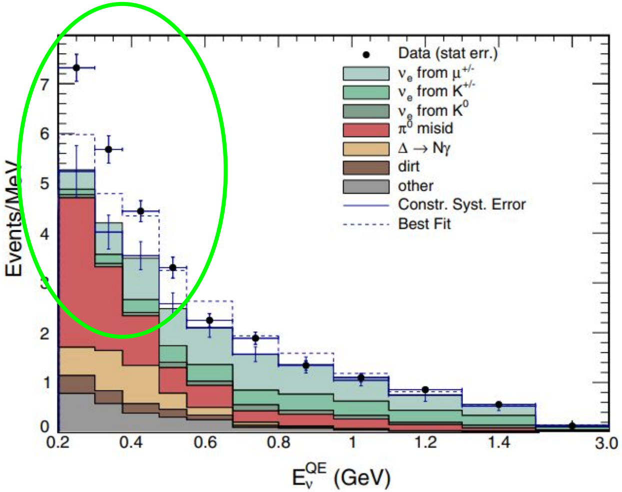
Backup

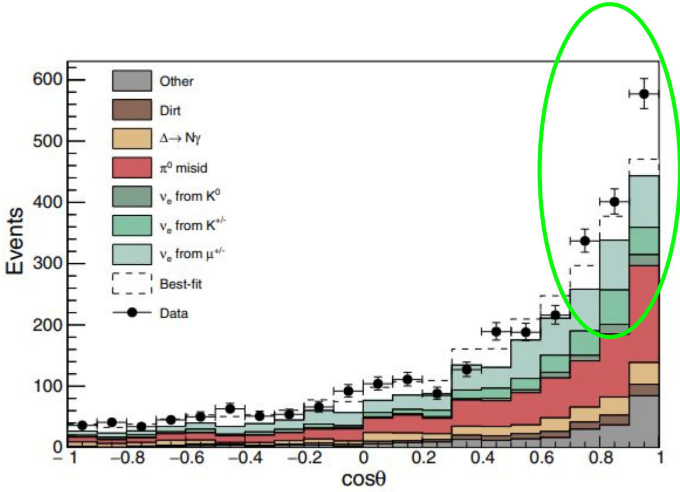
Low Energy Excess Anomalies

- In 1995, LSND saw an excess of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation events at energies ~50 MeV
- MiniBooNE was built at a similar L/E as LSND to test this anomaly
- With data collected from 2002 to 2019, sees a 4.8σ excess of ν_e candidate events
  - energies of about 200-800 MeV
  - forward-going angles



Phys. Rev. Lett. 75, 2650 (1995)



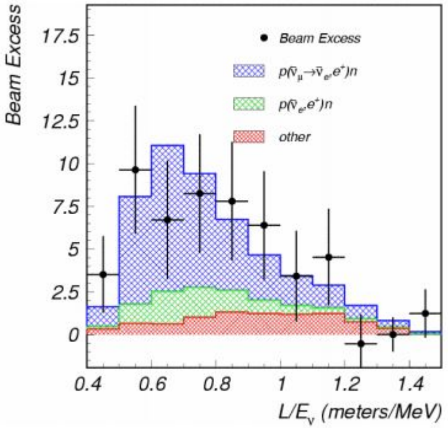


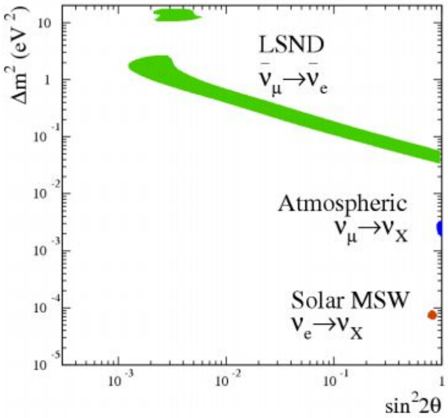
Phys. Rev. D 103, 052002 (2021)

Sterile Neutrinos: LSND Appearance Signal

- Liquid Scintillator Neutrino Detector at Los Alamos National Laboratory
- μ^+ decay-at-rest experiment - looking at $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ oscillation events
- 30m baseline, 0.8 GeV neutrino beam energy
- Excess of 87.9 ± 22.4 ± 6.0 events consistent with $\bar{\nu}_e$ + p $\longrightarrow$ e^+ + n above expected background

- If interpreted in a 2 neutrino oscillation model then most favored oscillation region is a band in Δm^2 in the ~eV^2 range
- If excess is truly electron anti-neutrinos from oscillation then could be evidence of a 3+N sterile neutrino theory

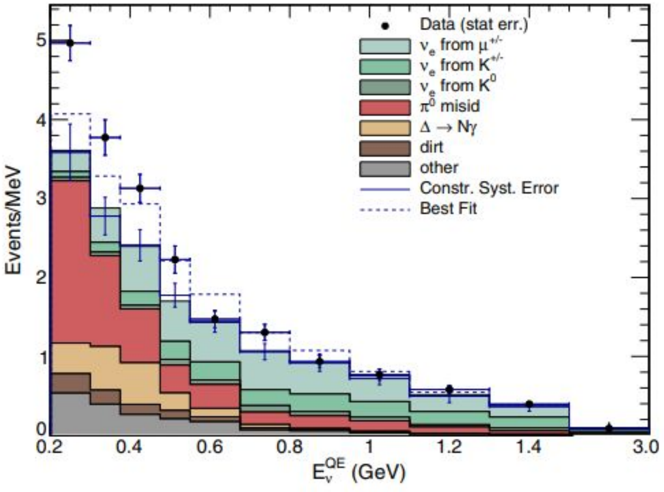




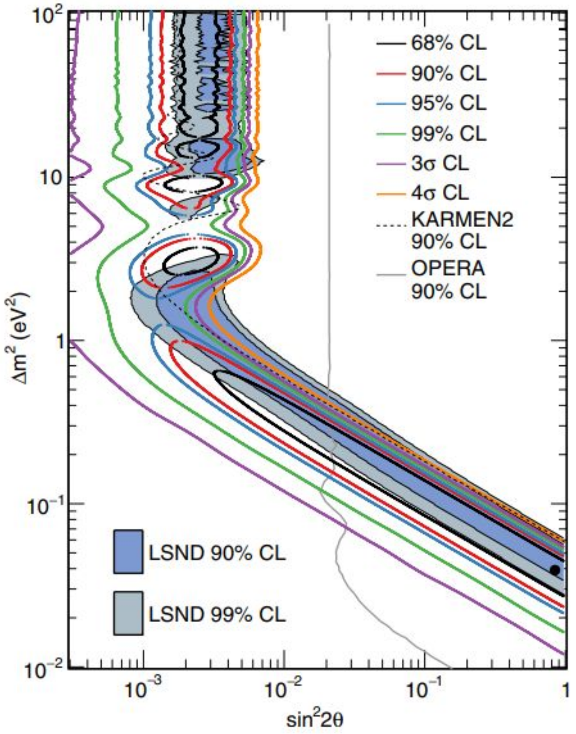
[C. Athanassopoulos et al., Phys. Rev. Lett. 75, 2650 (1995); 81,1774(1998); A.Aguilar et al., Phys. Rev. D64, 112007(2001)]

Sterile Neutrinos: MiniBooNE Low Energy Excess

- Spherical Mineral Oil (CH2) Cherenkov Detector at Fermilab
- Booster Neutrino Beam provides (mostly muon) neutrinos
- Total electron neutrino + anti-neutrino CCQE excess of **460.5 ± 99.0** events with respect to expectation (2018 result)
  - **4.7σ** excess
  - 12.84×10^{20} POT in neutrino mode
  - 11.27×10^{20} POT in anti-neutrino mode
- Neutrino and anti-neutrino fits consistent with LSND allowed regions

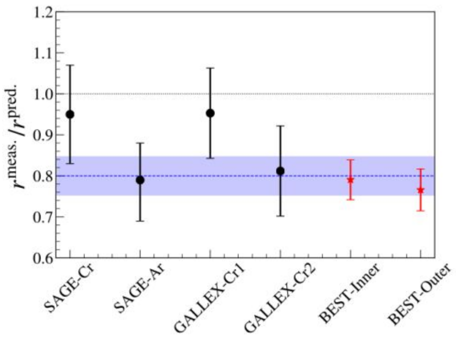


$\nu + \bar{\nu}$ mode



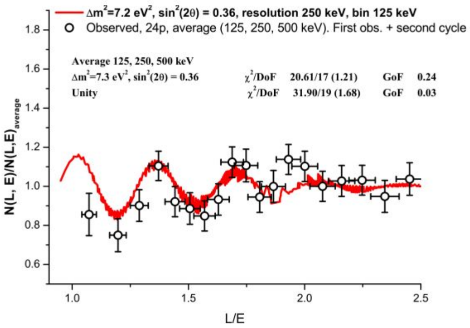
Other Short-Baseline Anomalies

- BEST and other gallium experiments see a deficit that could be explained by $\nu_\mu \to \nu_e$ oscillations
- Neutrino-4 sees an oscillation as a function of distance/energy that could be explained by $\nu_e \to \nu_{\mu,\tau,s}$ oscillations



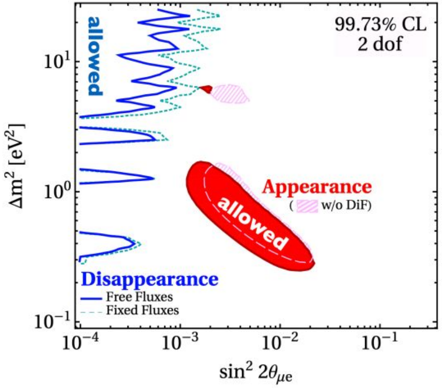
BEST

Phys. Rev. C 105, 065502 (2022)



Neutrino-4

Phys. Rev. D 104, 032003 (2021)

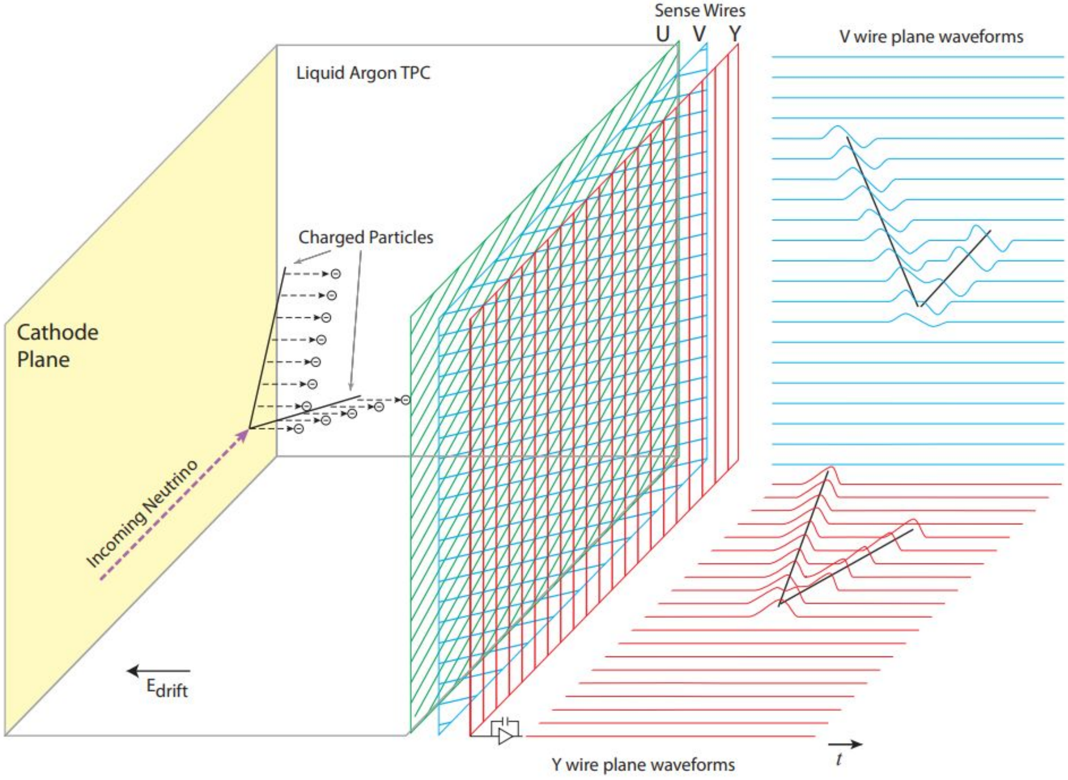


3+1 Global Fit

J. High Energ. Phys. 2018, 10 (2018)

MicroBooNE

- 3 planes of wires (vertical, +60°, -60°) with 3mm spacing
- 32 PMTs collect light from flash at time of interaction
- Charged particle trajectory reconstructed using the known positions of the anode plane wires and the recorded drift time of the ionization



3+1 Neutrino Oscillations

- With three active neutrinos and one sterile neutrino, the PMNS matrix can be extended to 4x4 using the following parameterization:

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

- For short baselines, only the sterile neutrino oscillation will be relevant, and the survival probability is:

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}} \cdot \sin^2(2\theta_{\alpha\beta}) \cdot \sin^2\left(1.267\frac{\text{GeV}}{\text{eV}^2\text{km}}\frac{\Delta m^2_{41} L}{E}\right)$$

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:** $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14}\sin^2\theta_{24}$

ν_e Appearance/Disappearance Cancellation

$$N_{\nu_e \text{ at detector}} = N_{\nu_e \text{ in beam}} \cdot P_{\nu_e \to \nu_e} + N_{\nu_\mu \text{ in beam}} \cdot P_{\nu_\mu \to \nu_e}$$

$$= N_{\nu_e \text{ in beam}} \left[1 + \boxed{\left(\frac{\sin^2 \theta_{24}}{R_{\nu_e/\nu_\mu}} - 1 \right)} \cdot \sin^2 2\theta_{14} \cdot \sin^2 \left(1.267 \frac{\text{eV}^2\text{km}}{\text{GeV}} \frac{\Delta m_{41}^2 L}{E} \right) \right]$$

- The number of ν_e at MicroBooNE is mostly unaffected by oscillations when $\sin^2 \theta_{24}$ approaches R_{ν_e/ν_μ}, the ratio of intrinsic ν_e to ν_μ in the beam

BNB R_{ν_e/ν_μ}: ~0.005

NuMI R_{ν_e/ν_μ}: ~0.04