# MicroBooNE's Tests of the MiniBooNE Low Energy Excess

Erin Yandel (UCSB)
On behalf of the MicroBooNE Collaboration

Lepton Photon 2023

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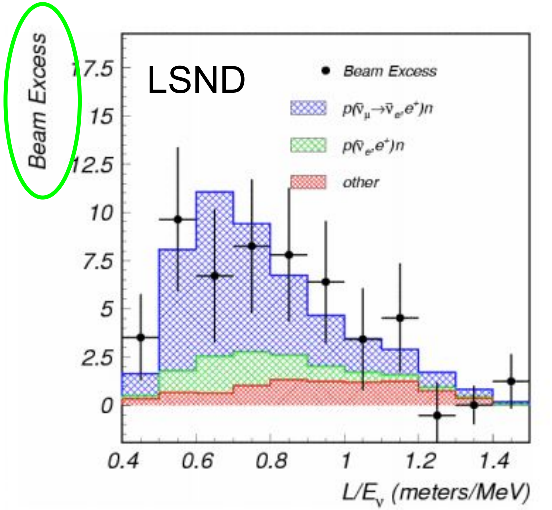
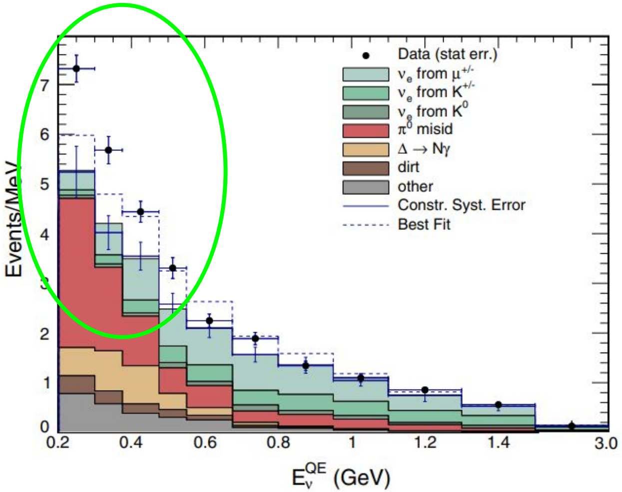
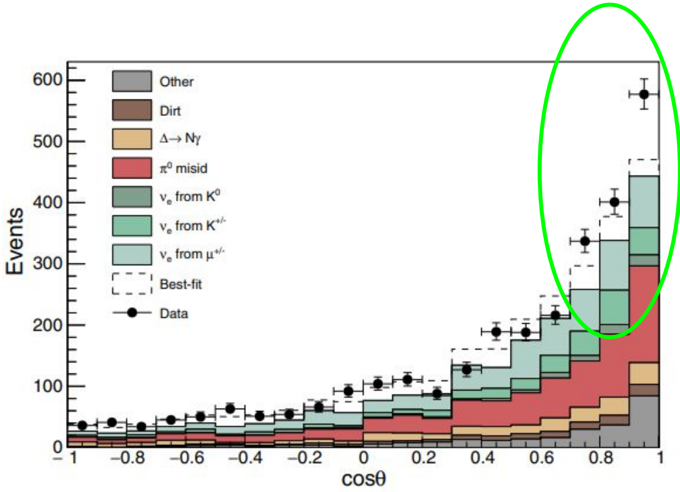
# Low Energy Excess Anomalies

- 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 $\nu_e$ candidate events
  - energies of about 200-800 MeV
  - forward-going angles




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



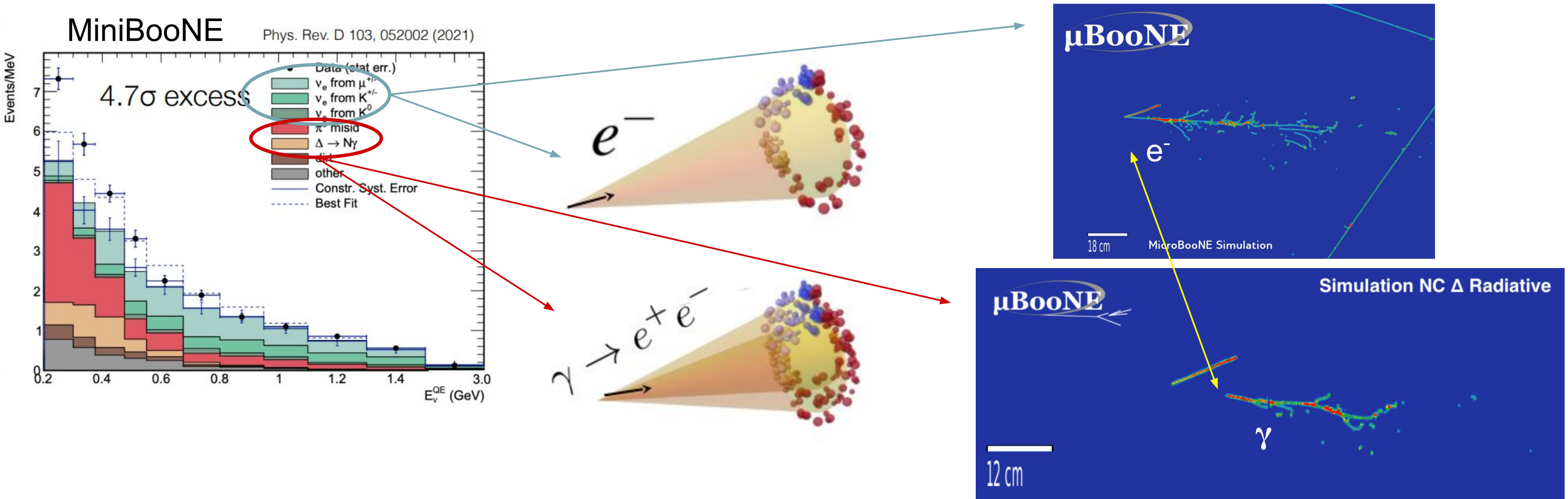




Phys. Rev. D 103, 052002 (2021)

# Testing the LEE with LArTPCs

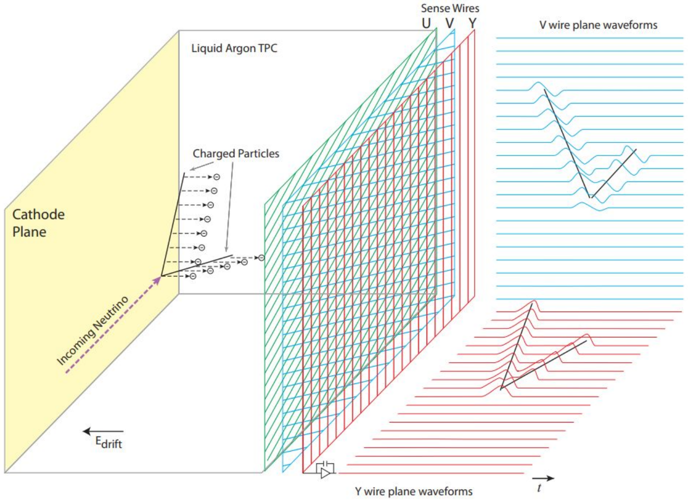
- However, MiniBooNE, as a cherenkov detector, can not distinguish between $e^-$ and $\gamma$
- A Liquid Argon Time Projection Chamber (LArTPC) **can** distinguish these, allowing us to probe into the nature of the excess.

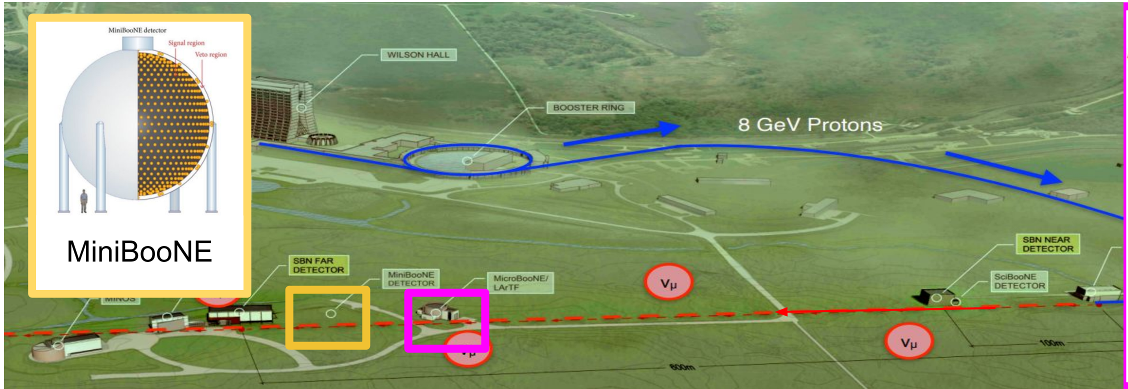
**MiniBooNE** **MicroBooNE (LArTPC)**

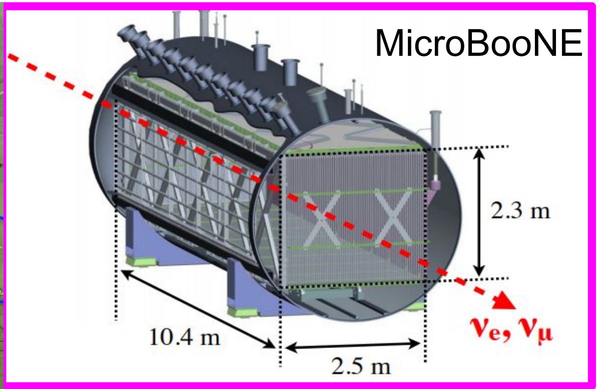


# MicroBooNE

- MicroBooNE is a surface-level, 85 tonne ($10\times2.5\times2.5$ m$^3$) LArTPC neutrino experiment on Fermilab's Booster Neutrino Beamline (BNB)
- Scintillation light (collected by 32 PMTS) and ionization charge on 3 wire planes allows for 3D reconstruction and detailed particle ID
- Collected data 2015 - 2021
- Primary design goal is to understand this LEE anomaly seen by MiniBooNE

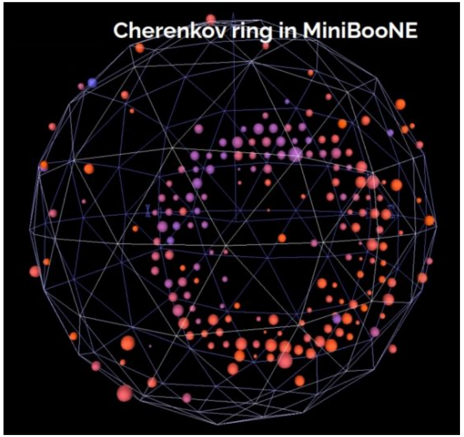


# Possible Anomaly Channels

First series of results (½ the MicroBooNE data set)




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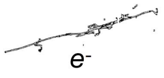
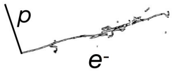
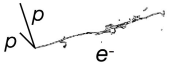
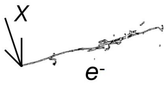
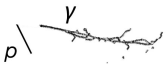
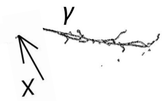
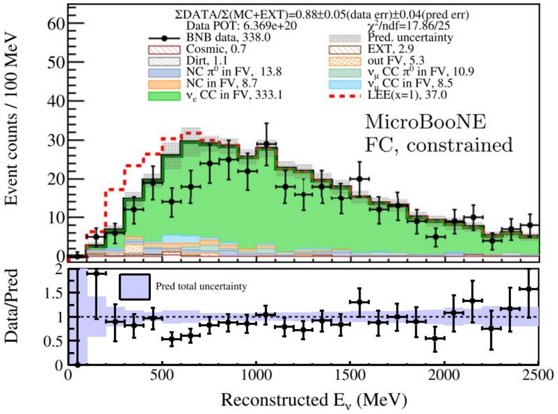
|   |   |   |   |   |   |   |

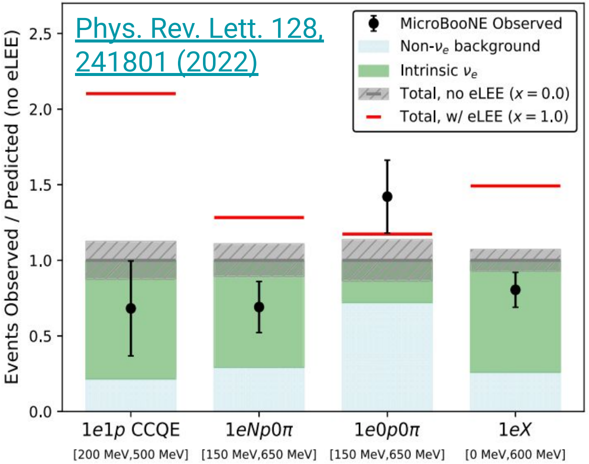
# First Results

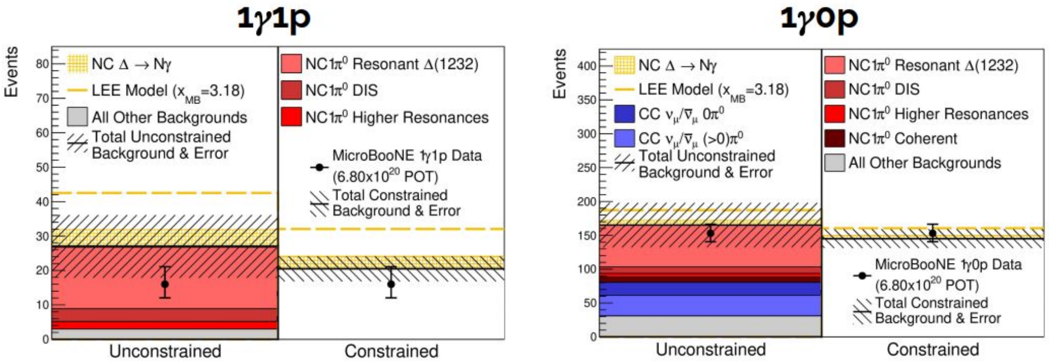
- Used about half of MicroBooNE's collected dataset
- 3 $\nu_e$CC searches for four event classes (1e0p, 1e1p, 1eNp, 1eX)
  - Rejects electrons as LEE explanation at > 97% CL
- One single photon search for NC $\Delta \rightarrow N\gamma$ (1$\gamma$0p, 1$\gamma$1p)
  - Rules out photons from NC $\Delta \rightarrow N\gamma$ as the cause of the LEE at 94.8% C.L.

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




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



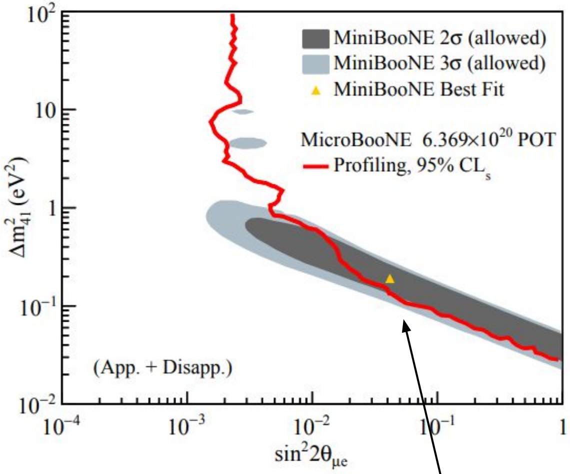



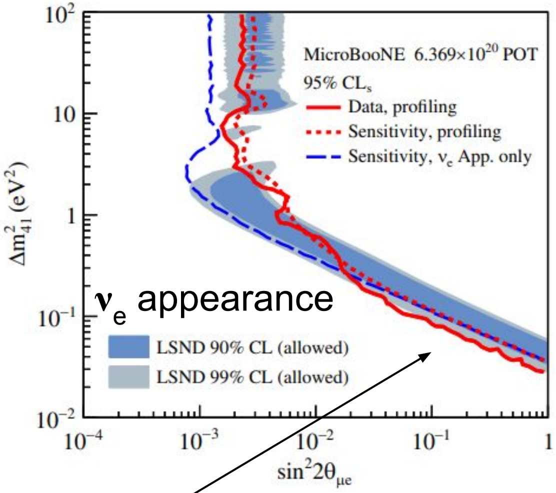

Phys. Rev. Lett. 128, 111801 (2022)

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

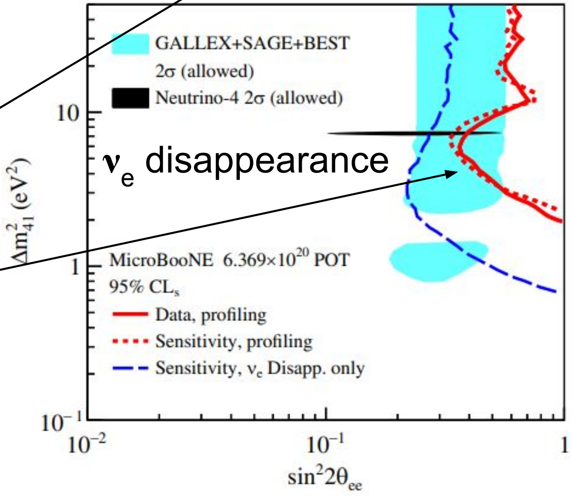
# 3+1 Oscillations

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



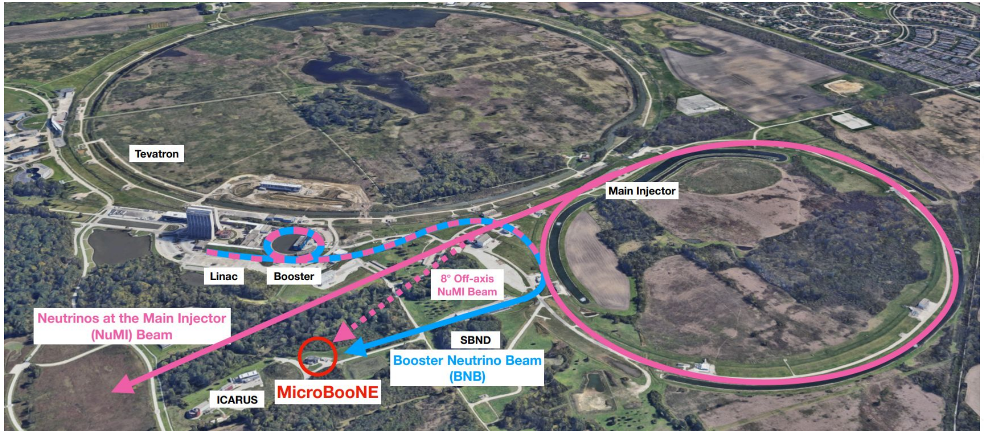



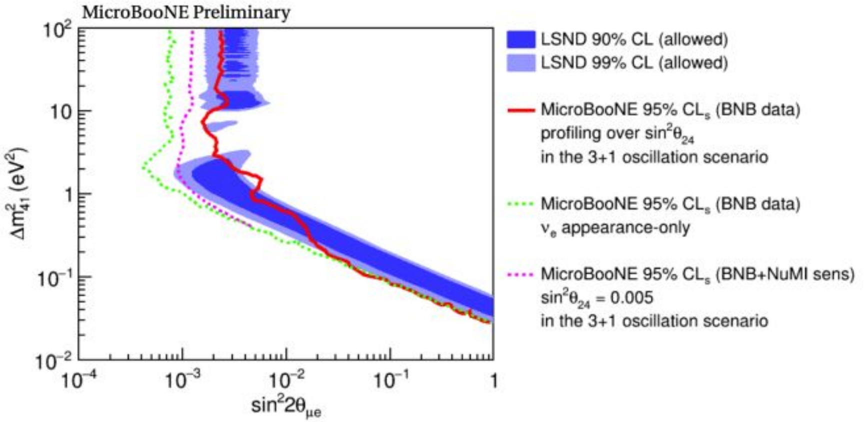

- simultaneously considering appearance and disappearance effects
- saw no evidence for 3+1 sterile neutrino oscillations
- For $\nu_\mu \rightarrow \nu_e$, excludes parts of the MiniBooNE and LSND allowed regions
- For $\nu_e \rightarrow \nu_e$, excludes part of the allowed regions from gallium experiments

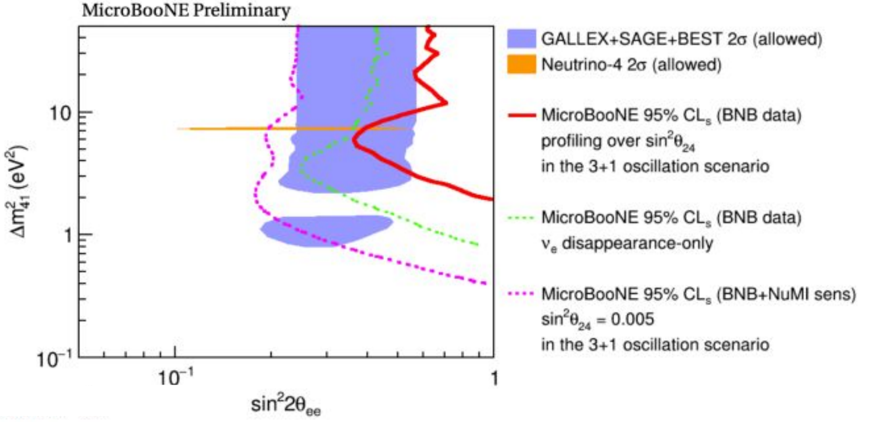


# Improving the Sensitivity: BNB+Numi

- 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 $\nu_\mu$ to $\nu_e$ ratio in NuMI is quite different from the BNB
  - addition of NuMI events helps to break the degeneracy of the appearance and disappearance effects

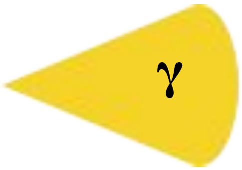


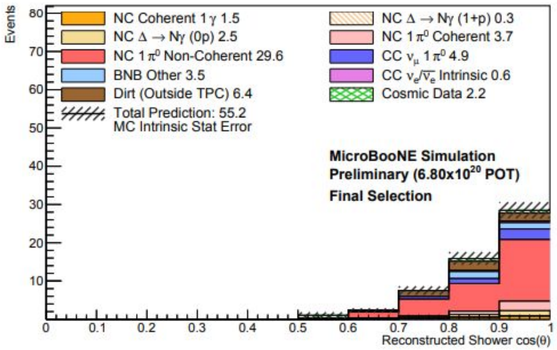



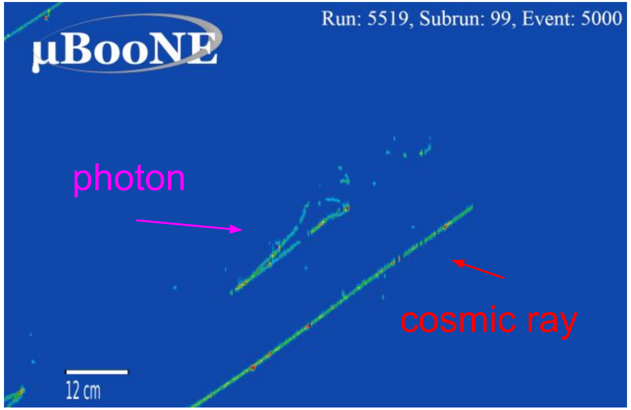



# More Photon Channels: Coherent Photon

- Coherent-like single-photon production search
- building on the previous 1$\gamma$0p result
- increased sensitivity to "coherent-like" events
  - forward-going photons
  - no visible hadronic activity
    - improvements in proton identification for better event selection
  - closely follows the expected LEE topology
- results coming soon!

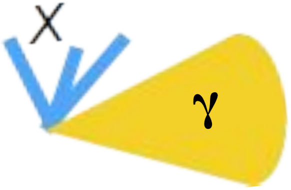


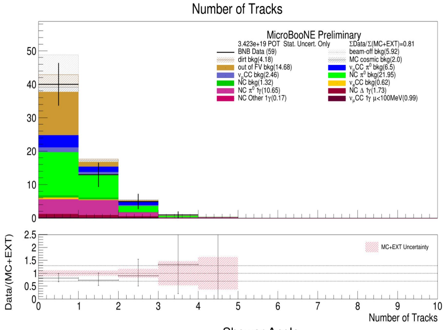



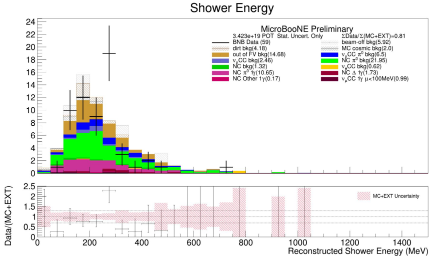
# Inclusive Photon Search

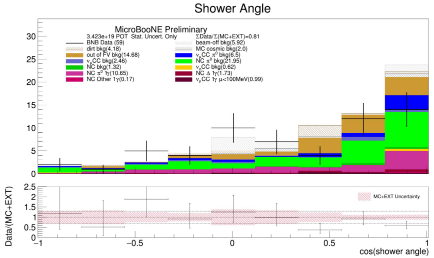
- Only current photon result is the NC $\Delta \rightarrow N\gamma$ ($1\gamma0p$, $1\gamma1p$) channel
- Cover the remaining unexplored single photon phase-space
- Inclusive single photon ($1\gamma X$)
  - more general "single photon-like" final states
    - one photon or highly overlapping di-photon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




~2% of full dataset, no systematic errors



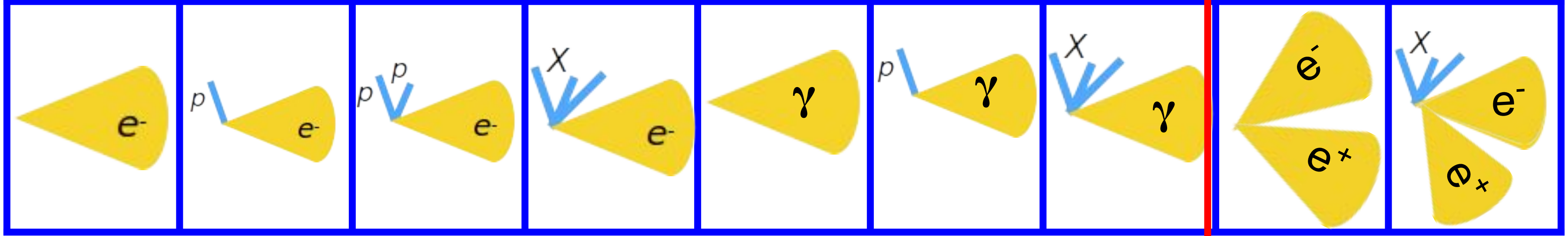





# Exploring Further Channels

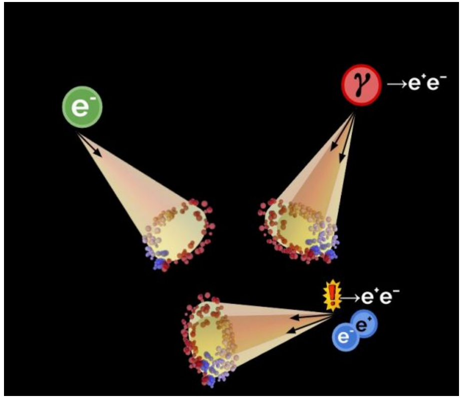
First series of results (½ the MicroBooNE data set)

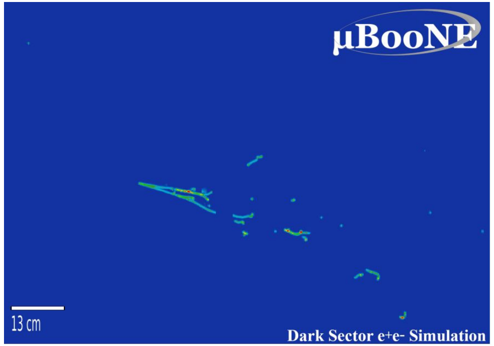
| 1e0p | 1e1p | 1eNp | 1eX | 1γ0p | 1γ1p | 1γX | $e^+e^-$ + nothing | $e^+e^-X$ |
|---|---|---|---|---|---|---|---|---|

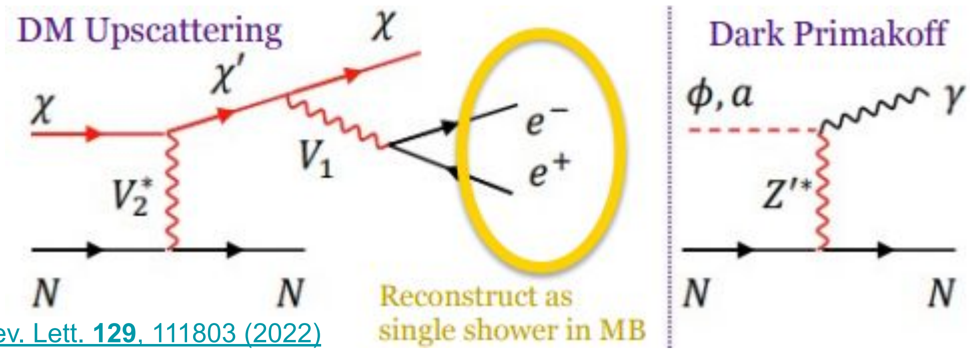


# Other BSM Explanations

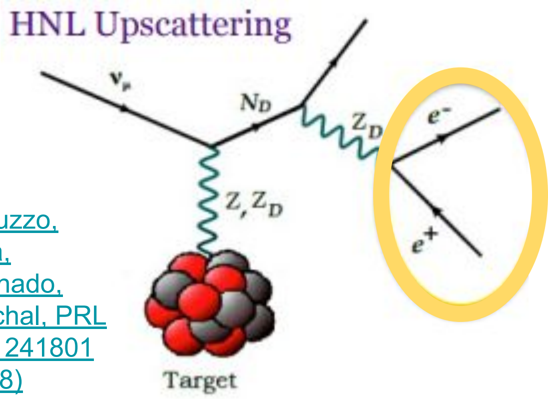
- A number of proposed BSM scenarios beyond sterile neutrinos
- Overlapping $e^+e^-$ final states will mimic a single shower topology
- Models include dark neutrinos, heavy neutral leptons, new scalars, dark matter, and many more



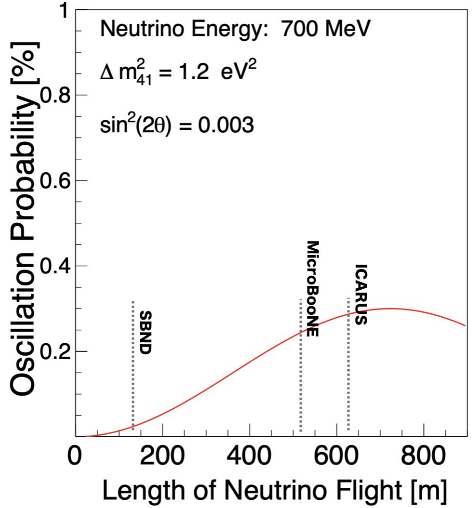

Phys. Rev. Lett. **129**, 111803 (2022)




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

# The SBN Program

- MicroBooNE is part of the Short-Baseline Neutrino (SBN) Program at Fermilab
  - 3 LArTPC detectors along the BNB
- In addition to one detector searches, a number of multi-detector oscillation analyses can be done once the near detector (SBND) turns on next year




# 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 disfavor electron and NC $\Delta \rightarrow N\gamma$ photon background as an explanation for the MiniBooNE LEE
- 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, including searches for new models and more general event topologies, are underway, with many results expected soon
- The final detector in Fermilab's SBN Program will turn on next year, allowing for more precise, multi-detector LEE and oscillation analyses

# Thank You!

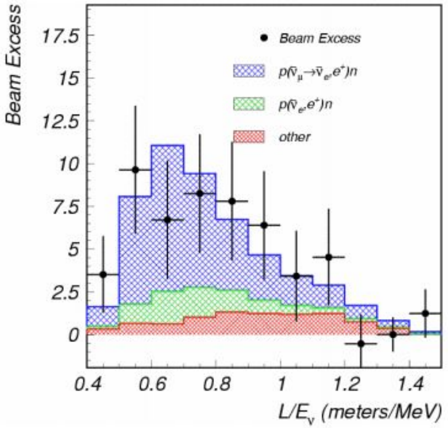

Fermilab U.S. DEPARTMENT OF ENERGY Office of Science NSF FNSNF SWISS NATIONAL SCIENCE FOUNDATION Science & Technology Facilities Council THE ROYAL SOCIETY

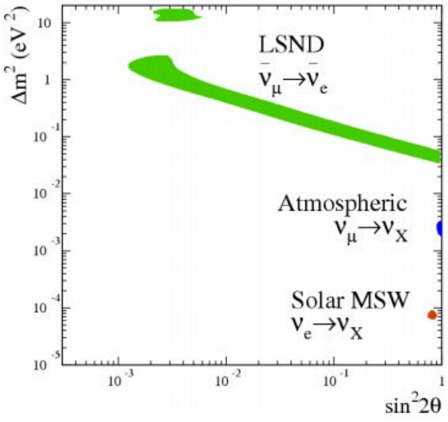
# Backup

# Sterile Neutrinos: LSND Appearance Signal

- Liquid Scintillator Neutrino Detector at Los Alamos National Laboratory
- $\mu^+$ 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 $\Delta m^2$ 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

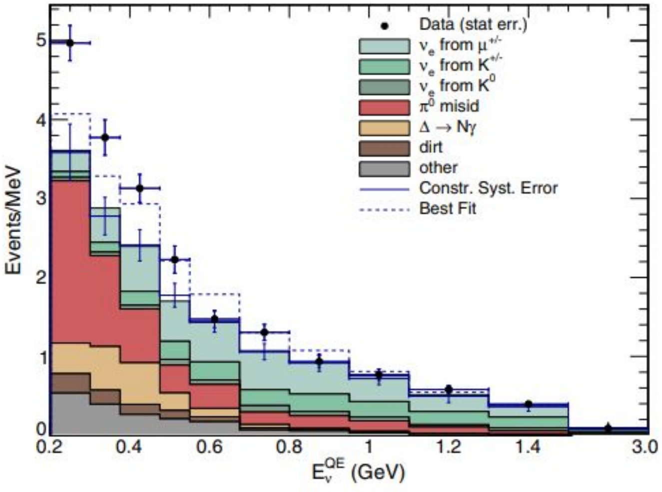


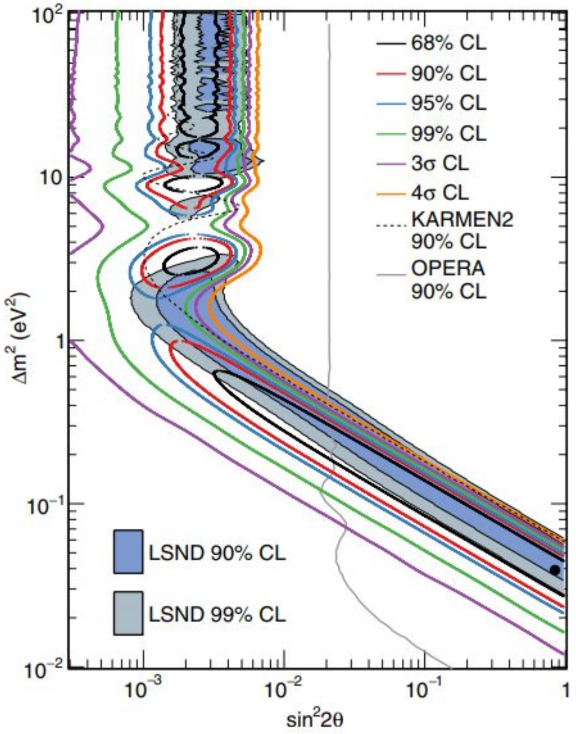

[C. Athanassopoulos et al., Phys. Rev. Lett. 75, 2650 (1995); 81,1774(1998); A.Aguilar et al., Phys. Rev. D64, 112007(2001)]

# 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
  - $12.84 \times 10^{20}$ POT in neutrino mode
  - $11.27 \times 10^{20}$ POT in anti-neutrino mode
- Neutrino and anti-neutrino fits consistent with LSND allowed regions

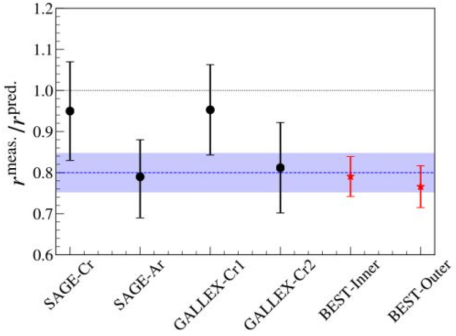



$\nu + \bar{\nu}$ mode



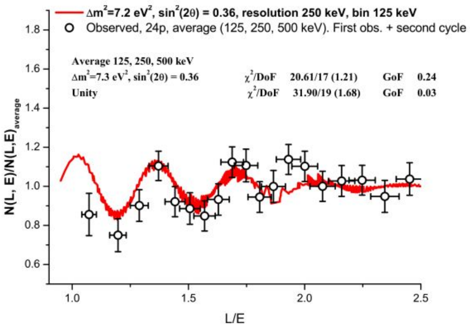
# Other Short-Baseline Anomalies

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



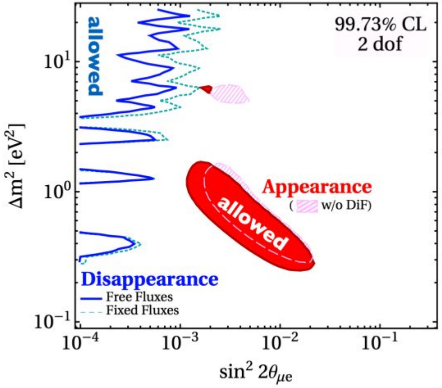

BEST

Phys. Rev. C 105, 065502 (2022)




Neutrino-4

Phys. Rev. D 104, 032003 (2021)

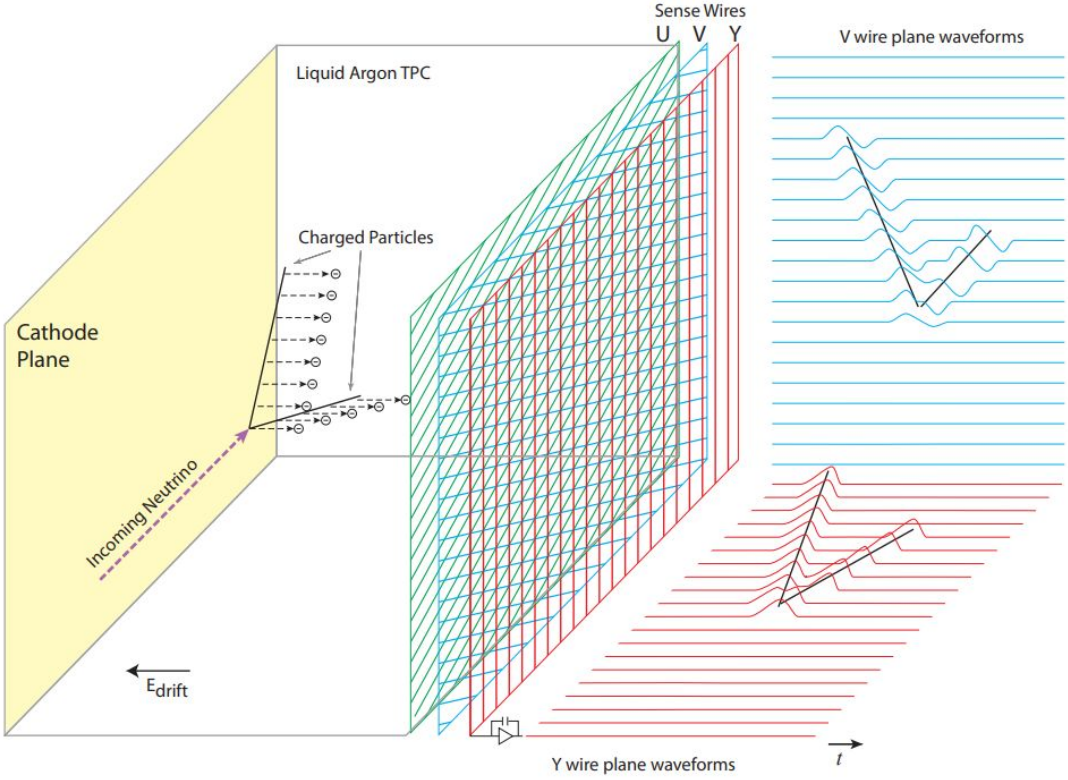



3+1 Global Fit

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:

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

$\nu_e$ **disappearance:** $\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$

$\nu_\mu$ **disappearance:** $\sin^2 2\theta_{\mu\mu} = 4\cos^2\theta_{14}\sin^2\theta_{24}(1 - \cos^2\theta_{14}\sin^2\theta_{24})$

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

# $\nu_e$ Appearance/Disappearance Cancellation

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

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

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

BNB $R_{\nu_e/\nu_\mu}$: ~0.005

NuMI $R_{\nu_e/\nu_\mu}$: ~0.04