



# Recent Results from MicroBooNE's Low Energy Excess Search

Wanwei Wu, Fermi National Accelerator Laboratory  
On behalf of the MicroBooNE Collaboration  
Phenomenology 2023 Symposium, May 8-10, 2023



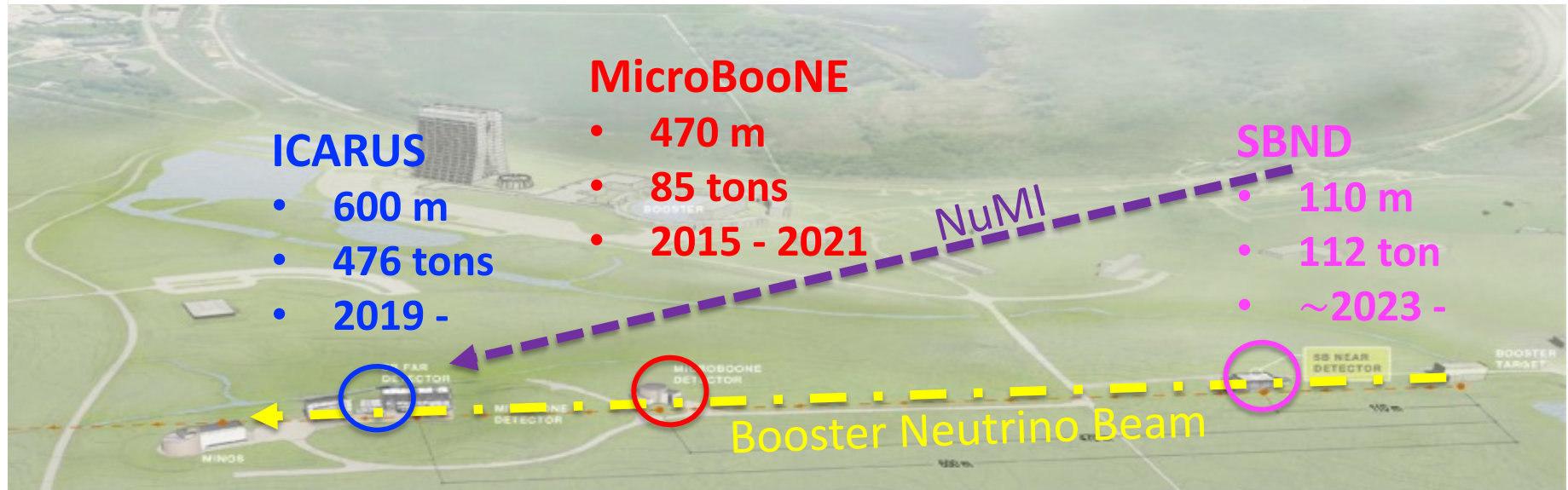
# MicroBooNE Experiment

Part of the Fermilab Short-Baseline Neutrino (SBN) program:

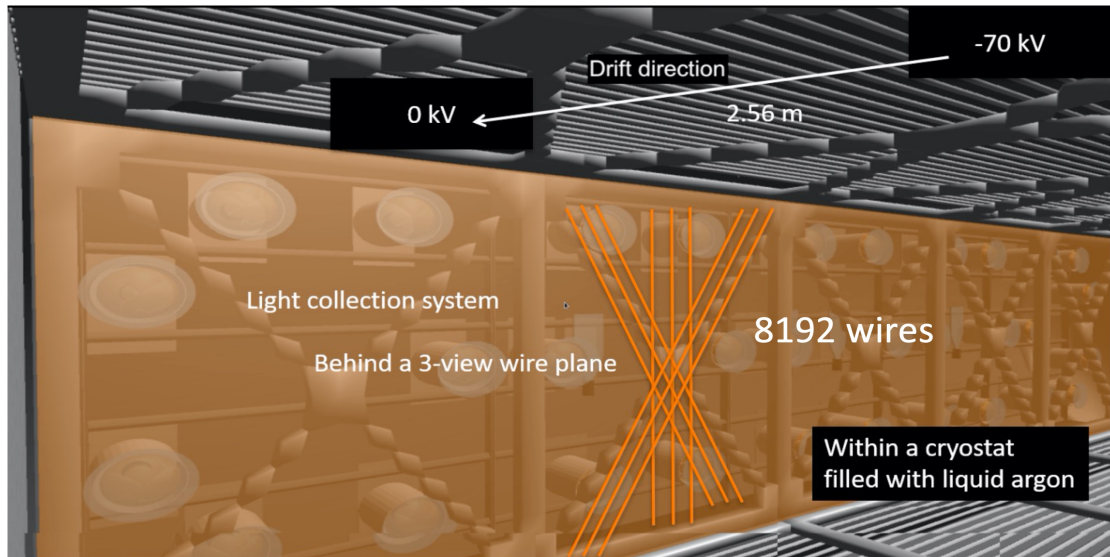
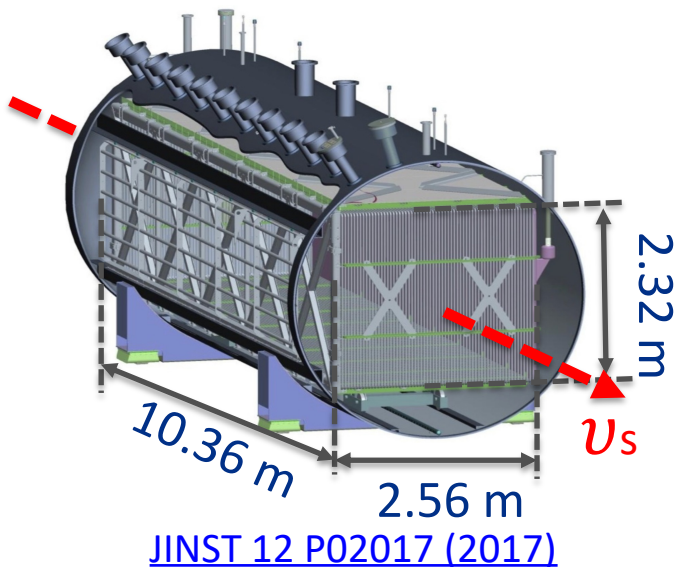
- liquid argon time projection chamber (LArTPC) detector

Major goals:

- Investigate MiniBooNE's low energy excess
- Measure the neutrino-argon cross sections
- Develop LArTPC techniques



# MicroBooNE Detector



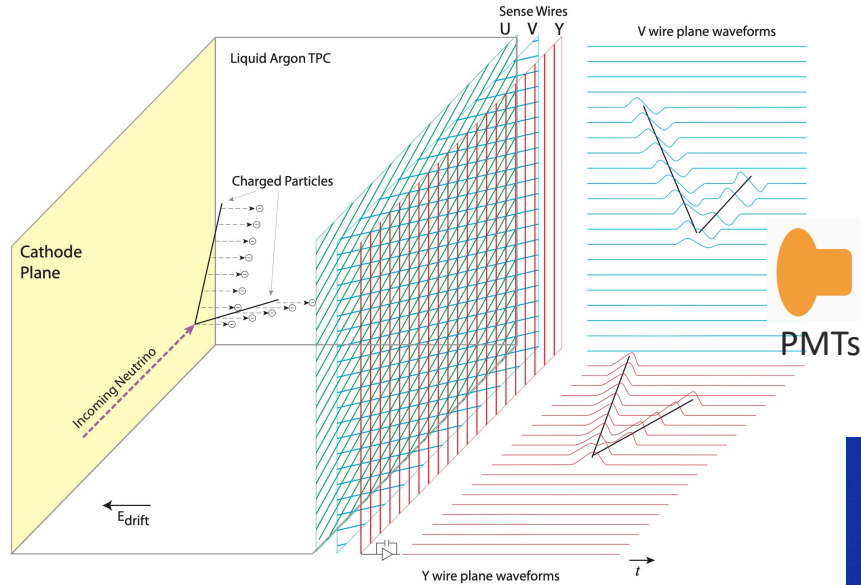
Three wire planes for charge collection:

- 3 mm plane-to-plane spacing with a 3 mm wire pitch
- Reconstruction of event and calorimetry

Light collection system

- 32 PMTs as primary subsystem
- 4 light guide paddles for R&D studies
- Mainly for trigger and event selection

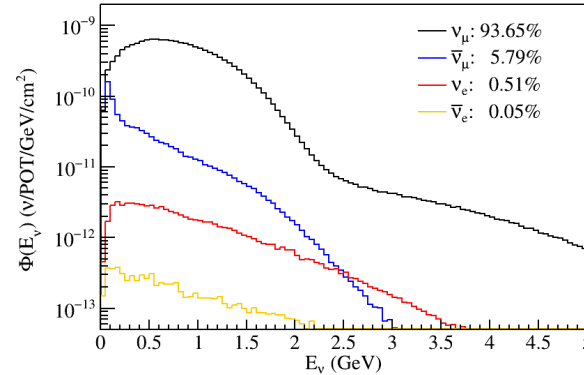
# MicroBooNE LArTPC



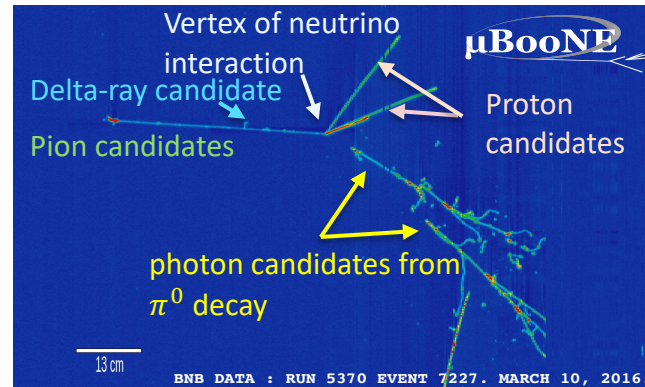
Detailed images of events:

- mm-scale spatial resolution
- sub-MeV energy threshold
- $\sim$ ns timing resolution

[Phys. Rev. D 105, 112005 \(2022\)](#)



Neutrino flux  
from BNB beam  
seen by  
MicroBooNE  
detector



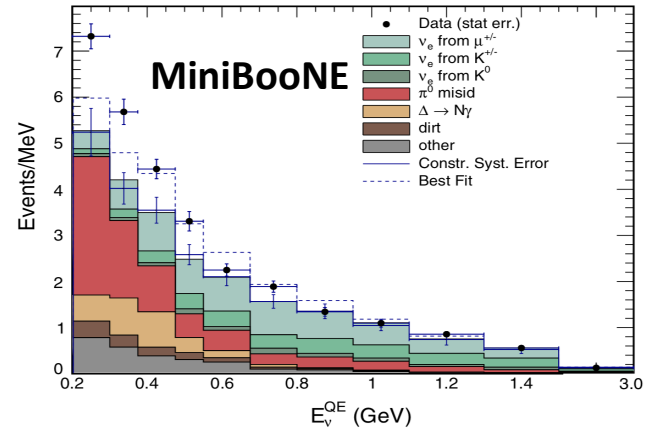
A candidate of  
neutral-current  
interaction

# MiniBooNE Low Energy Excess

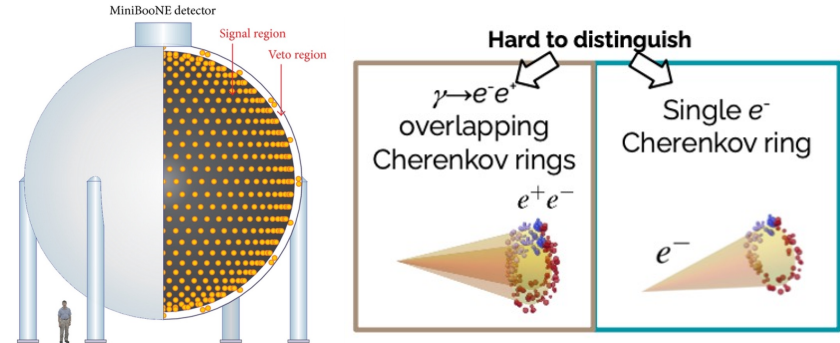
- Series of anomalous results seen at short-baselines using a variety of neutrino sources ([LSND](#), [MiniBooNE](#), [BGALLEX/SAGE](#), etc.), if caused by oscillations, are not consistent with a 3- $\nu$  picture

## MiniBooNE:

- Mineral oil Cherenkov detector**
- Measured  $\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  appearance
- Observed low energy excess (LEE):  $4.8\sigma$
- Largest background from photons ( $\pi^0$  or  $\Delta \rightarrow N\gamma$ )
- Could not distinguish between  $e^\pm$  and  $\gamma$

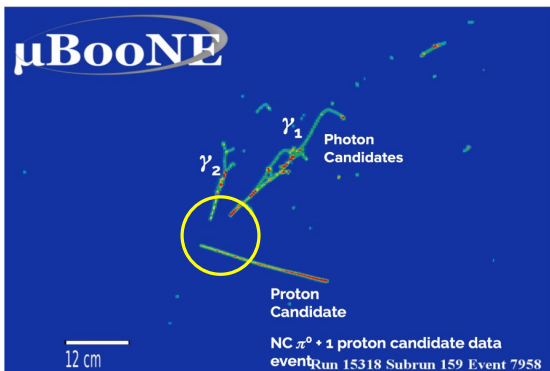
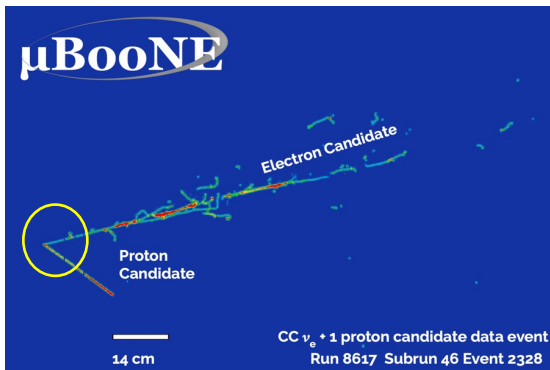


[Phys. Rev. D 103, 052002 \(2021\)](#)

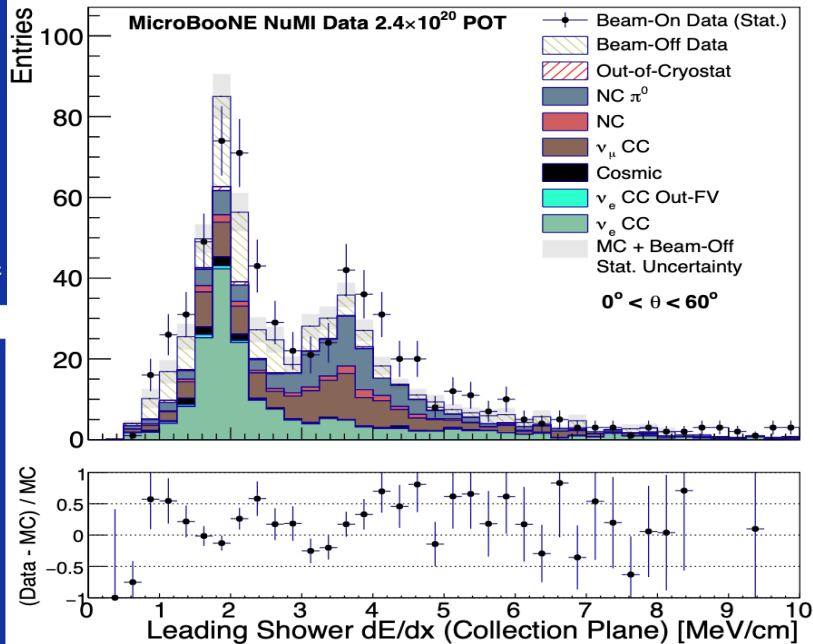


# $e/\gamma$ Separation in MicroBooNE

MicroBooNE can distinguish photon and electron by identifying the shower conversion distance and energy loss ( $dE/dx$ ) at the beginning of the shower.

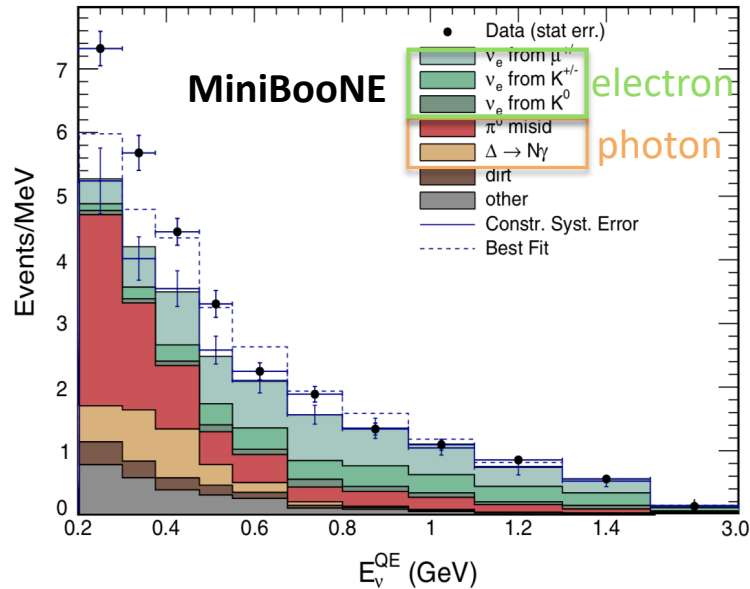


## Electron Photon shower shower



[Phys. Rev. D \*\*104\*\*, 052002 \(2021\)](#)

# MicroBooNE's Low Energy Excess Search



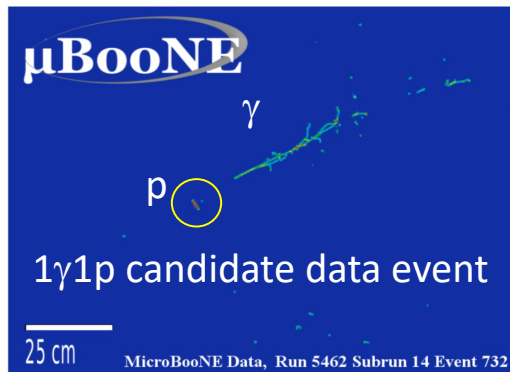
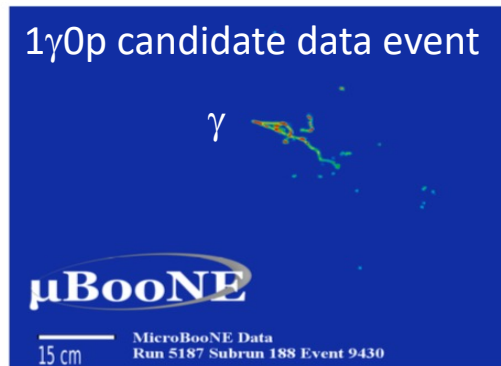
[Phys. Rev. D 103, 052002 \(2021\)](#)

MicroBooNE has investigated the explanation of MiniBooNE low energy excess (LEE) in two interpretations (focusing on four independent analyses) using Run 1-3 data ( $\sim 6 \times 10^{20}$  POT):

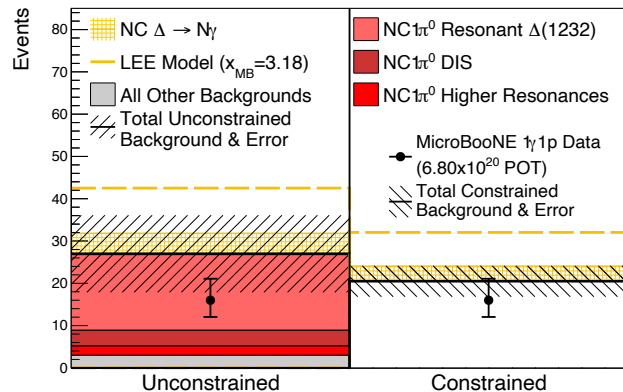
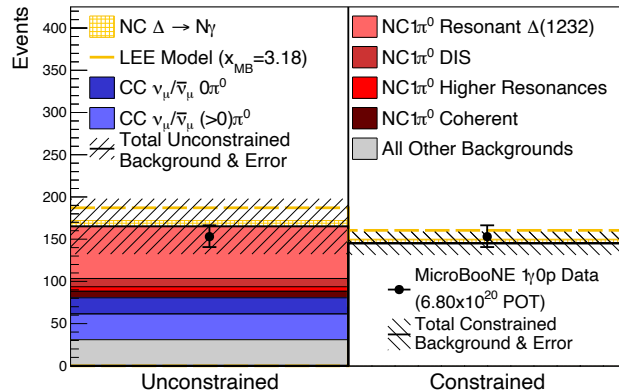
- Assuming excess is **photon**
  - Single photon analysis: targeting NC  $\Delta \rightarrow N\gamma$  hypothesis ( $1\gamma 0p$ ,  $1\gamma 1p$ )
- Assuming excess is **electron**
  - MiniBooNE-like final states ( $1eNp0\pi$ ,  $1e0p0\pi$ )
  - Restricting to quasi-elastic kinematics ( $1e1p0\pi$ )
  - All CC  $\nu_e$  final states ( $1eX$ )

# Investigation of Photon Excess

- Disfavor a candidate photon interpretation of MiniBooNE LEE as a  $x_{MB}=3.18$  enhancement of nominal rate NC  $\Delta$  radiative decay rate at the 94.8% CL



[Phys. Rev. Lett. 128, 111801 \(2022\)](#)



# Investigation of Electron Excess

## 3 $\nu_e$ analyses using different reconstructions:

- “Pandora” based:  
MiniBooNE-like final states  
( $1e0p0\pi$ ,  $1eNp0\pi$ )

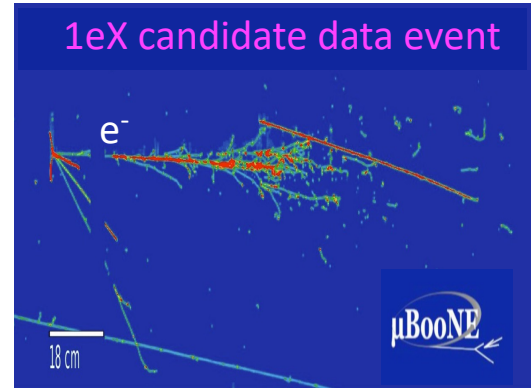
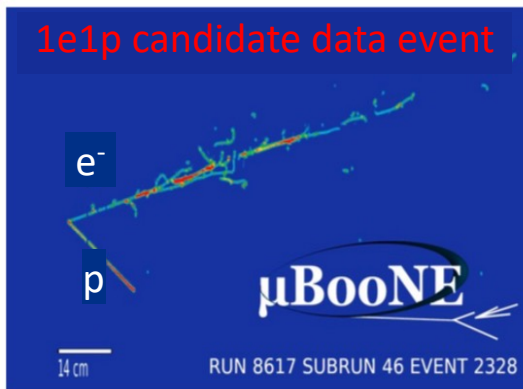
[Phys. Rev. D 105, 112004 \(2022\)](#)

- “Deep Learning” based:  
restricting to quasi-elastic  
kinematics ( $1e1p$ )

[Phys. Rev. D 105, 112003 \(2022\)](#)

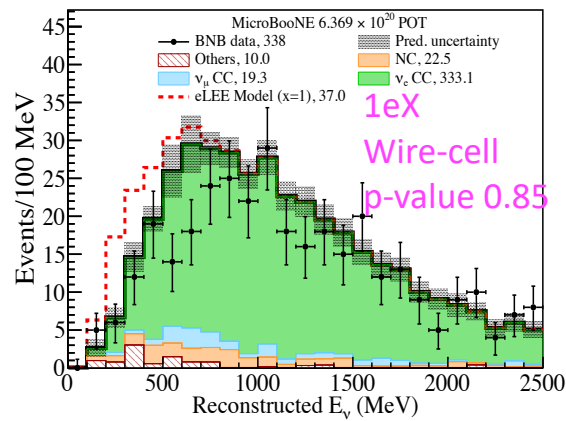
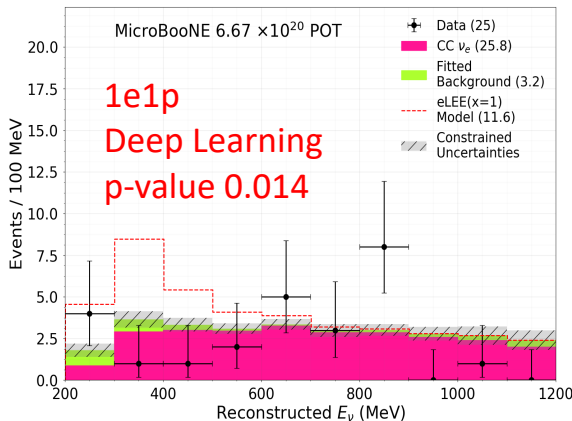
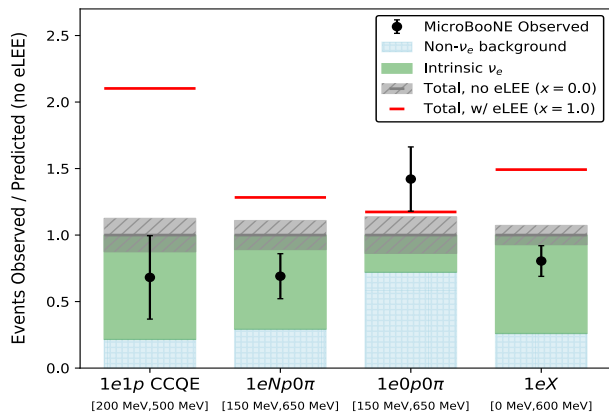
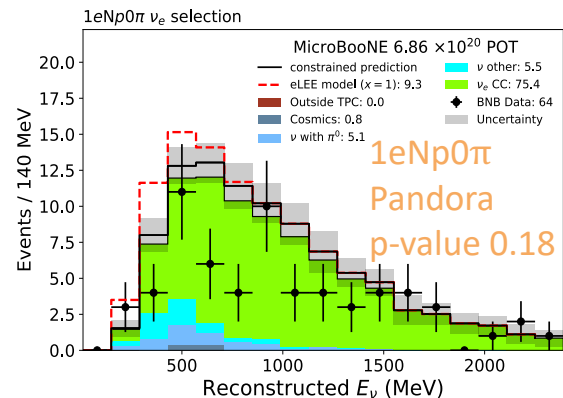
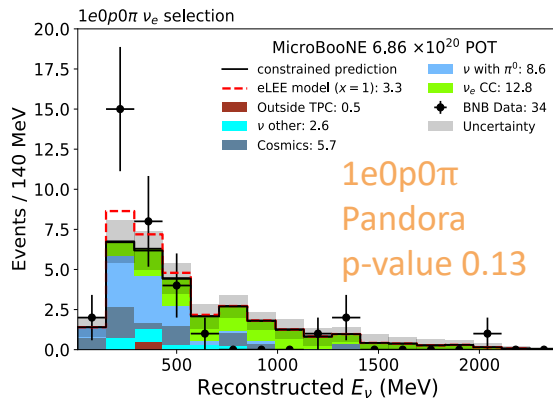
- “Wire-Cell” based:  
all CC  $\nu_e$  final states ( $1eX$ )

[Phys. Rev. D 105, 112005 \(2022\)](#)



# Investigation of Electron Excess

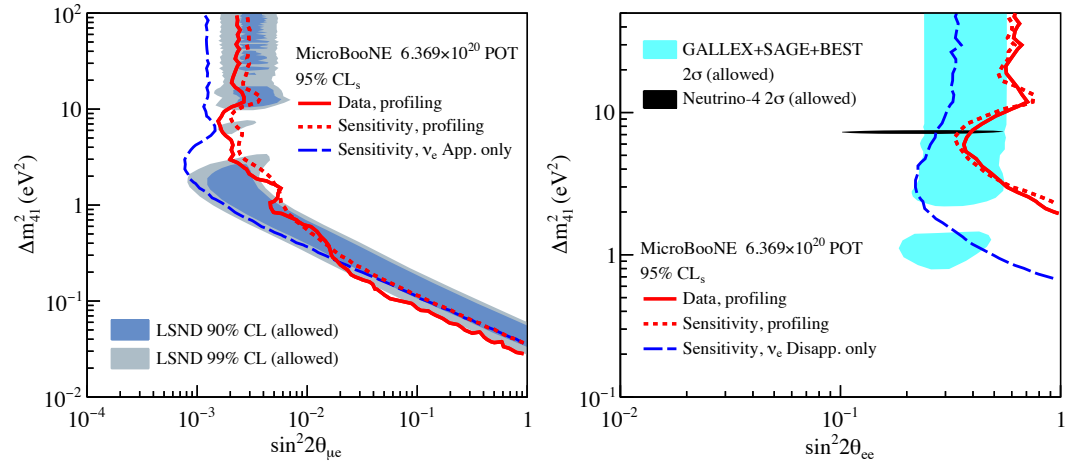
- Disfavor an interpretation of MiniBooNE's observed electron-like excess signature at >97% CL (results are found to be consistent with the nominal  $\nu_e$  rate expectations from BNB)



[Phys. Rev. Lett. 128, 241801 \(2022\)](#)

# Search for a Light Sterile Neutrino in 3+1 Model

- MicroBooNE is suitable for searching for oscillations caused by eV-scale sterile neutrinos
  - $L/E \sim \mathcal{O}(1)$  [m/MeV]
- Full 3+1 search using Run 1-3 data
  - Cancellation of  $\nu_e$  appearance and  $\nu_e$  disappearance leads to degeneracies in determining the oscillation parameters
- **No evidence of light sterile neutrino oscillation**



[Phys. Rev. Lett. 130, 011801 \(2023\)](#)

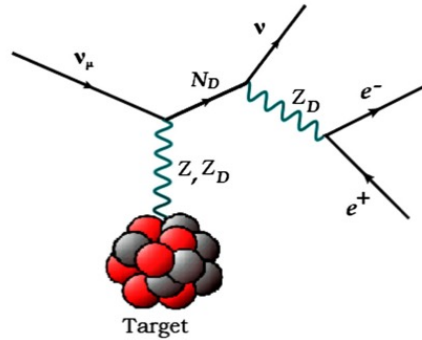
$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}} = \delta_{\alpha\beta} - (-1)^{\delta_{\alpha\beta}} \sin^2(2\theta_{\alpha\beta}) \sin^2\left(\frac{1.27 \Delta m_{41}^2 L}{E}\right)$$

# Other BSM Models

- Beyond the light sterile neutrinos, there are other BSM models which could explain the MiniBooNE anomaly, e.g.:

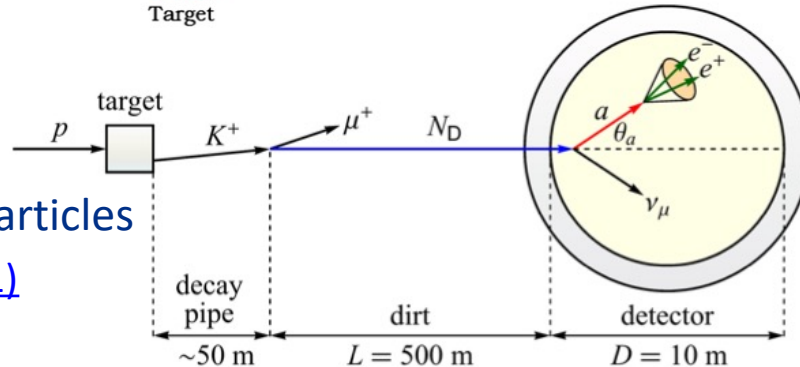
## Dark Neutrino Portal

[PRL 121, 241801 \(2018\)](#)



## Decay of axion-like particles

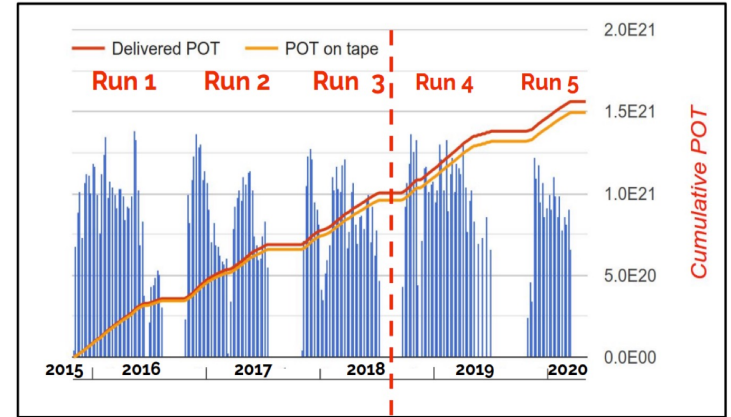
[PRD 104, 015030 \(2021\)](#)



- Rich phenomenology possibly at play at short-baselines:
  - For a comprehensive review, see the Snowmass White Paper: [arXiv:2203.07323](#).
- MicroBooNE will be probing those models.
  - New results on exotic searches, with  $e^+e^-$  focus are forthcoming.

# Summary

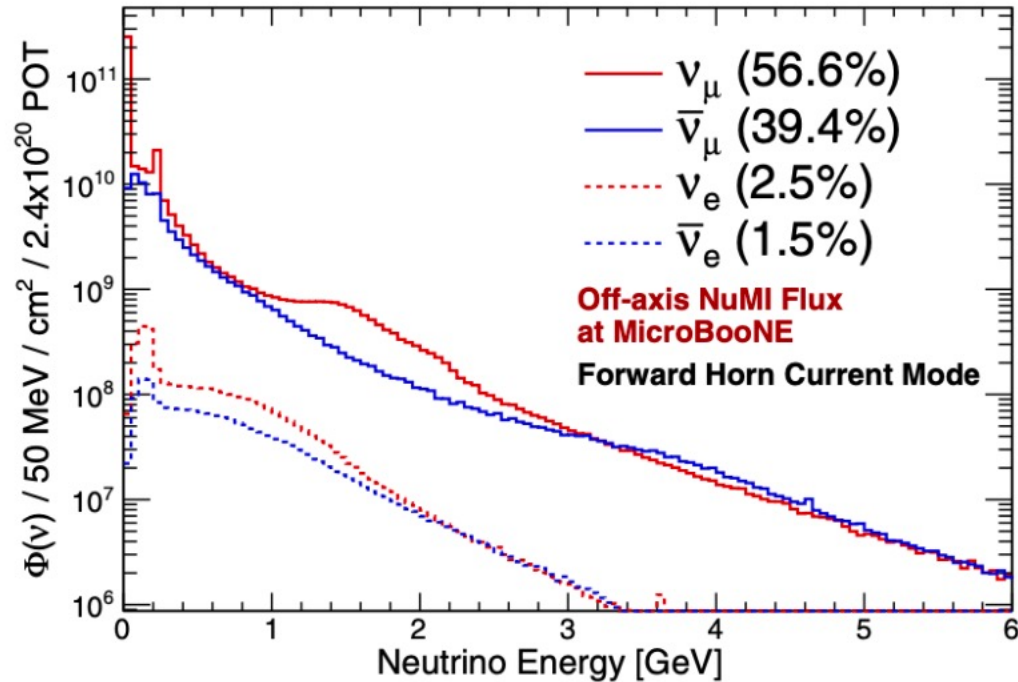
- MicroBooNE has completed its 5 years physics run. The first LEE results released use Run 1-3 data.
- So far, we do not see an excess due to enhanced single-photons from NC  $\Delta$  radiative decay or due to an increased  $\nu_e$  rate.
- Full dataset results are expected soon, which will double the statistics approximately.
- We have performed a search for eV-scale sterile neutrino oscillations in 3+1 model.
  - Presently No evidence of sterile neutrino oscillations (BNB Run 1–3 data).
  - Results can be improved in upcoming search with combining BNB and NuMI data.
- We are expanding the search for new physics with rich phenomenology:
  - New results on exotic searches, with  $e^+e^-$  focus are expected soon.



# Thank you!

# Backup

# Off-axis NuMI Flux at MicroBooNE



# MicroBooNE's Low Energy Excess Search

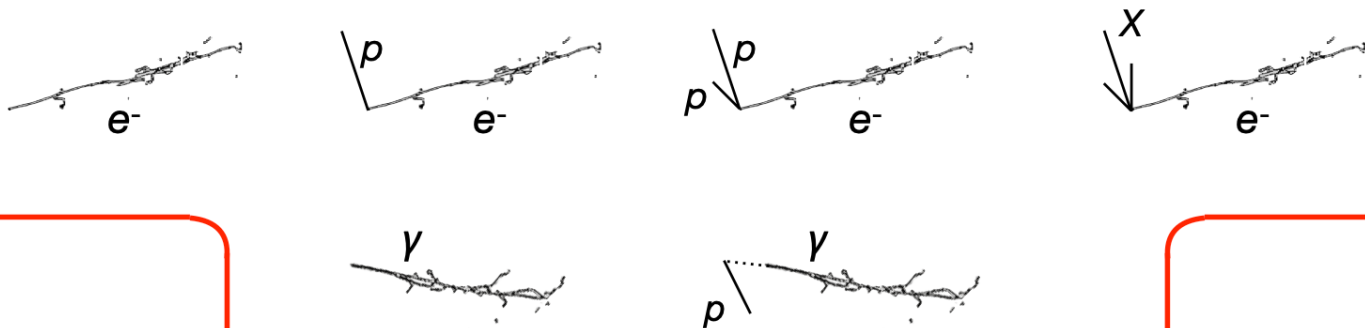
First series of results (1/2 the MicroBooNE data set)

Reco topology Models	1e0p	1e1p	1eNp	1eX	$e^+e^-$ + nothing	$e^+e^-X$	1 $\gamma$ 0p	1 $\gamma$ 1p	1 $\gamma$ X
eV Sterile $\nu$ Osc	✓	✓	✓	✓					
Mixed Osc + Sterile $\nu$	✓ <sub>[7]</sub>	✓ <sub>[7]</sub>	✓ <sub>[7]</sub>	✓ <sub>[7]</sub>			✓ <sub>[7]</sub>		
Sterile $\nu$ Decay	✓ <sub>[13,14]</sub>	✓ <sub>[13,14]</sub>	✓ <sub>[13,14]</sub>	✓ <sub>[13,14]</sub>			✓ <sub>[4,11,12,15]</sub>	✓ <sub>[4]</sub>	✓ <sub>[4]</sub>
Dark Sector & Z' *	✓ <sub>[2,3]</sub>				✓ <sub>[2,3]</sub>	✓ <sub>[2,3]</sub>	✓ <sub>[1,2,3]</sub>	✓ <sub>[1,2,3]</sub>	✓ <sub>[1,2,3]</sub>
More complex higgs *					✓ <sub>[10]</sub>	✓ <sub>[10]</sub>	✓ <sub>[6,10]</sub>	✓ <sub>[6,10]</sub>	✓ <sub>[6,10]</sub>
Axion-like particle *					✓ <sub>[8]</sub>		✓ <sub>[8]</sub>		
Res matter effects	✓ <sub>[5]</sub>	✓ <sub>[5]</sub>	✓ <sub>[5]</sub>	✓ <sub>[5]</sub>					
SM $\gamma$ production							✓	✓	✓

\* Requires heavy sterile/other new particles also

# MicroBooNE's Low Energy Excess Search

MicroBooNE's first series of LEE search results



Overlapping  $e^+e^-$



Overlapping  $e^+e^-$



Highly asymmetric  $e^+e^-$



Highly asymmetric  $e^+e^-$



Credit: M. Toups

# Short-Baseline Neutrino Anomalies

Experiment	$\nu$ Source	Channel	Significance
LSND	Accelerator (Decay-at-Rest)	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$3.8 \sigma$
MiniBooNE	Accelerator (Decay-in-Flight)	$\nu_\mu \rightarrow \nu_e$	$4.5 \sigma$
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$2.8 \sigma$
GALLEX/SAGE	e capture	$\nu_e \rightarrow \nu_x$	$2.8 \sigma$
Reactor	$\beta$ decay	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	$3.0 \sigma$

## Exploring the Sterile Neutrinos @ Short-Baseline Neutrino (SBN) program at Fermilab

- SBN will provide a conclusive verification of the sterile neutrino hypothesis
- Combined analysis of SBND, MicroBooNE, and ICARUS is expected to cover the currently allowed parameter region with  $5\sigma$  sensitivity both in appearance and disappearance channels

# Mini SBN-Theory Workshop

## Mini SBN-Theory workshop

 13 Dec 2021, 14:55 → 15 Dec 2021, 18:00 UTC

 online

**Description** Given the recent exciting developments in Fermilab's SBN Program, we are organizing the special SBN-Theory mini-workshop "Physics opportunities at the Short Baseline Neutrino Program" on **December 13-15, 2021**.

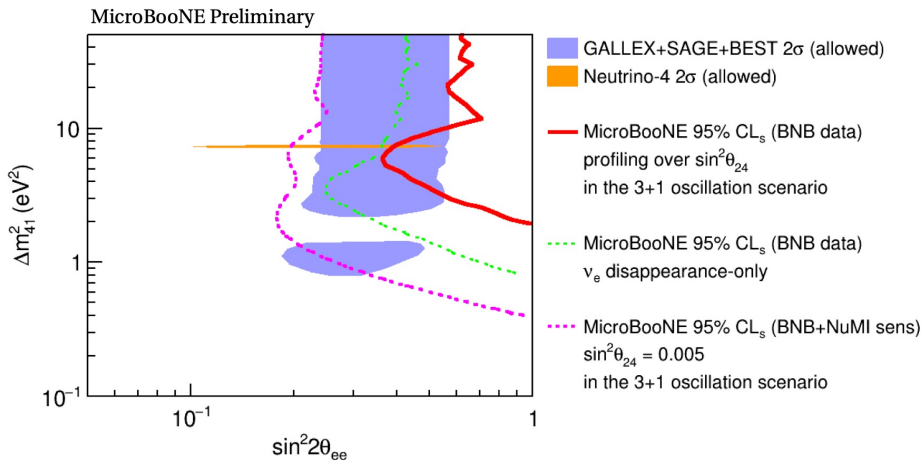
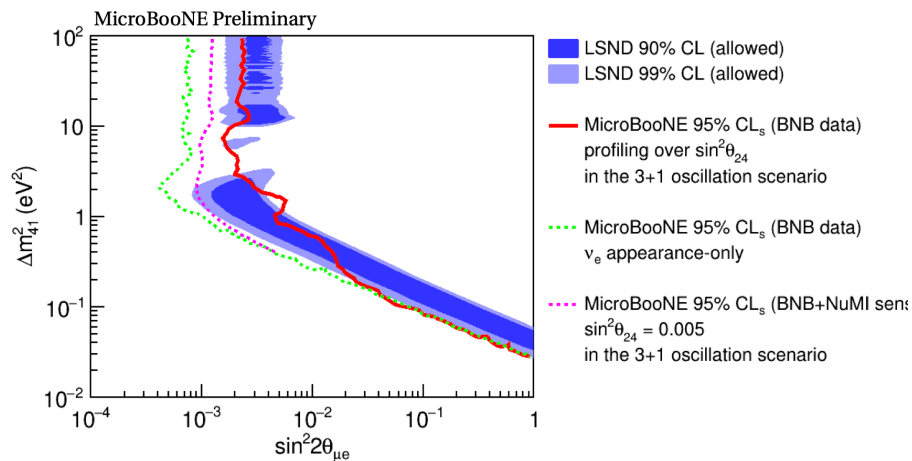
The goal of the workshop is to foster collaborations among theorists and experimentalists to discuss future searches in the SBN Program, particularly in the context of the MiniBooNE anomaly, though not limited to it.

As in other SBN-Theory events, this mini-workshop will be informal, focused on the physics, and in the intersection between theory and experiment.

We aim to get work done and to distribute tasks among participants by the end of the event.

<https://indico.ph.ed.ac.uk/event/107/>

# Search for a Light Sterile Neutrino in 3+1 Model with NuMI + BNB



[MICROBOONE-NOTE-1116-PUB](#)