Recent Oscillation Results from MicroBooNE.. and more

International Conference on Neutrinos and Dark Matter **(NuDM-2022)**

25-28 September 2022

Sharm El-Sheikh, Egypt- Online

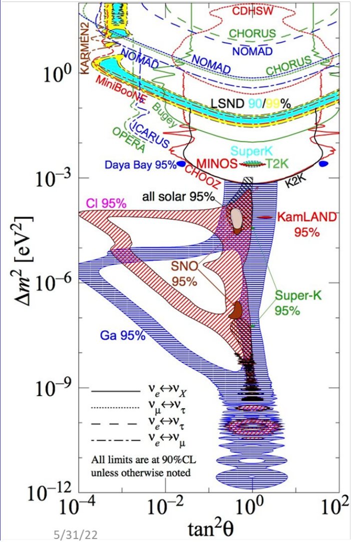
Mary Bishai (for the MicroBooNE Collaboration)

Brookhaven National Laboratory

Sep 25th,2022

The Big Experimental Picture of Neutrino Oscillations

Credit: Hitoshi Murayama



- **Over 50 years of experiments and > 30 experiments using solar neutrinos, atmospheric neutrinos, cosmogenic neutrinos, neutrinos from accelerators, reactors and radioactive sources.**
- **Experimental techniques vary - from few MeV solar to UHE neutrinos, Water/ICE Cherenkov detetors, scintillator detectors, tracking detectors ...**
- **Searches for both anamolous appearance and disappearance**

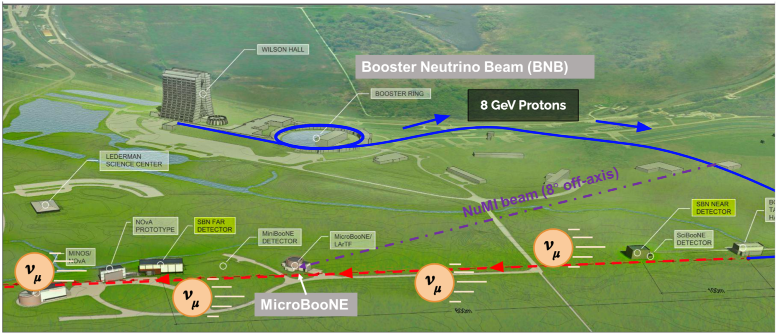
Short baseline osc. anomalies: Excess of ν_e-like signals from LSND, MiniBooNE; deficit of ν_e from radioactive source expts: GALLEX, BEST, SAGE; reactor $\bar{\nu}_e$ modulation in Neutrino-4

The MicroBooNE Experiment

MicroBooNE at Fermilab

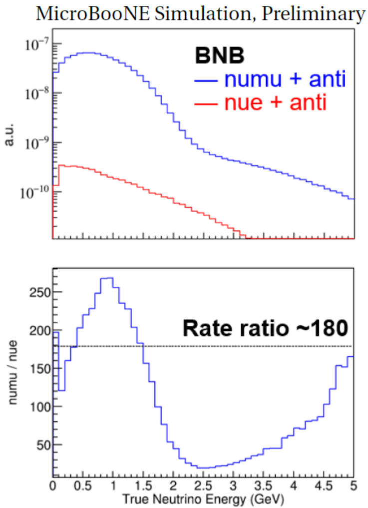
The Micro Booster Neutrino Experiment is located at Fermilab and studies $\nu_\mu \rightarrow \nu_x$ oscillations using high purity ($> 99\%$) $\nu_\mu/\bar{\nu_\mu}$ beams:

Beamline (Distance from target)	Proton beam energy	Beam timing	Peak ν energy
BNB (470m on-axis)	8 GeV	$\sim$ 5 Hz, 1.6 μs pulse	$\sim$ 800 MeV
NuMI (680 m 8° off-axis)	120 GeV	$\sim$ 0.5 Hz, 10 μs pulse	see next

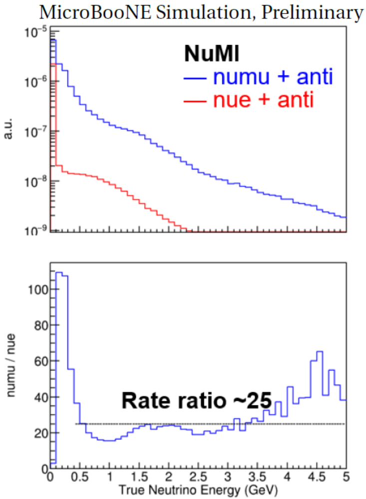


Neutrino Beams in MicroBooNE

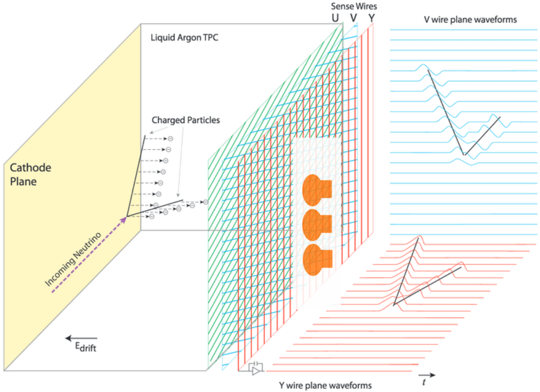
Neutrinos from the BNB



Neutrinos from NuMI



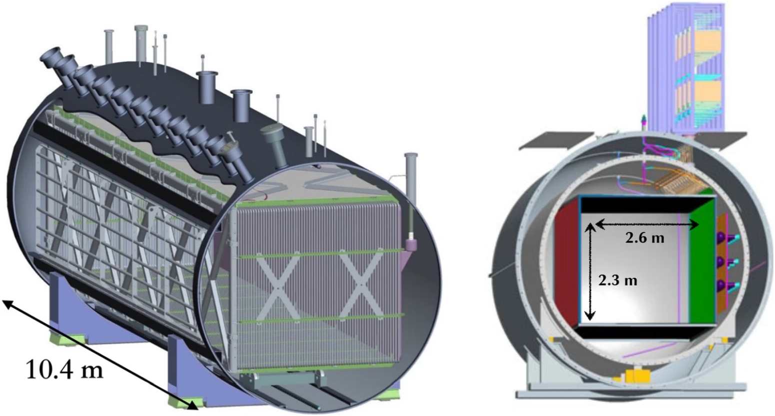
The Liquid Argon Time Projection Chamber



Ionization v = 1.6m/ms (E_{drift} = 500V/cm), Ar scintillation light 6ns (fast)/1.6 μs (slow)

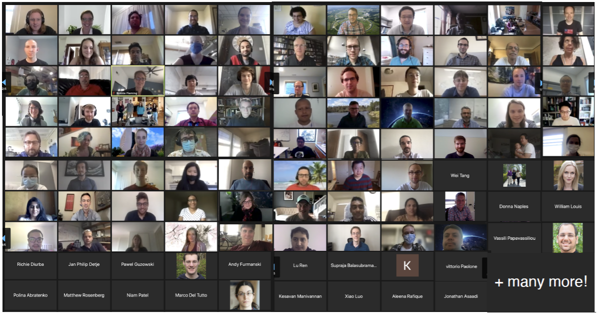
Video: Neutrino detection in a Liquid Argon Time-Projection-Chamber

The MicroBooNE Detector and Collaboration



170 ton of Liquid Argon, 85 tonne active, operated from 2015 to 2021

The MicroBooNE Detector and Collaboration



180 collaborators

40 postdocs

60 grad students

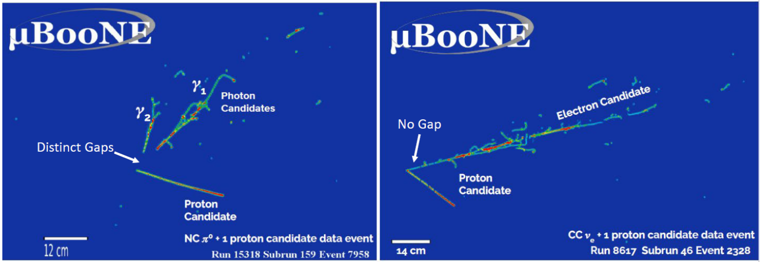
(40% international students)

36 institutions

5 countries

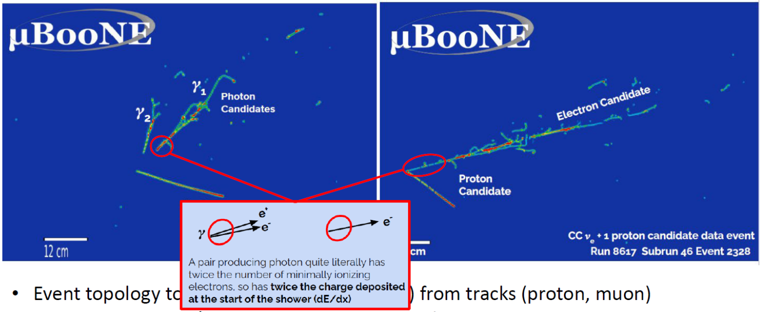
Finding Neutrinos in MicroBooNE

Imaging Neutrino Interactions in MicroBooNE



- Event topology to separate EM showers (e/γ) from tracks (proton, muon)
- Separation of e and γ : Gap Identification

Imaging Neutrino Interactions in MicroBooNE

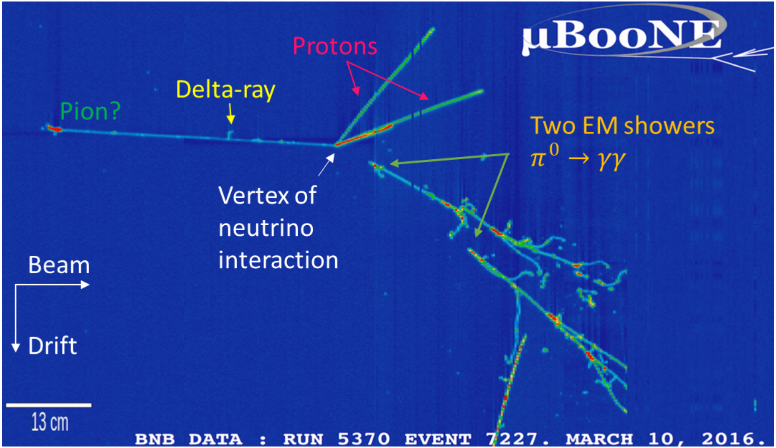


- Event topology to ...) from tracks (proton, muon)
- Separation of e and γ : Gap Identification + dE/dx
- Unique capability to identify ν_e charge-current (CC) interactions in LArTPC

12

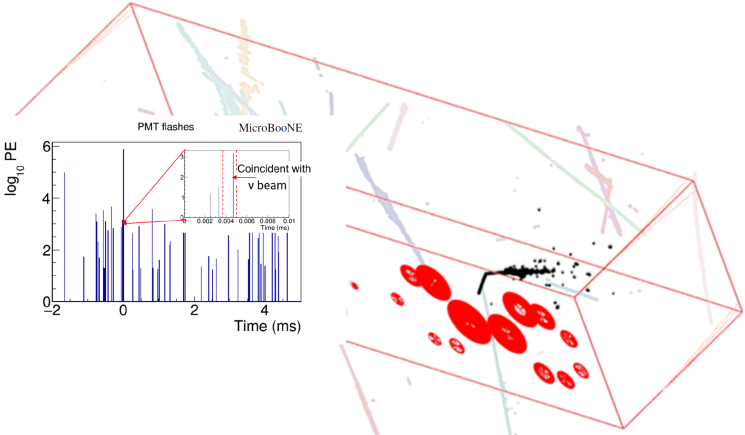
Imaging Neutrino Interactions in MicroBooNE

A NC event ?



Imaging Neutrino Interactions in MicroBooNE

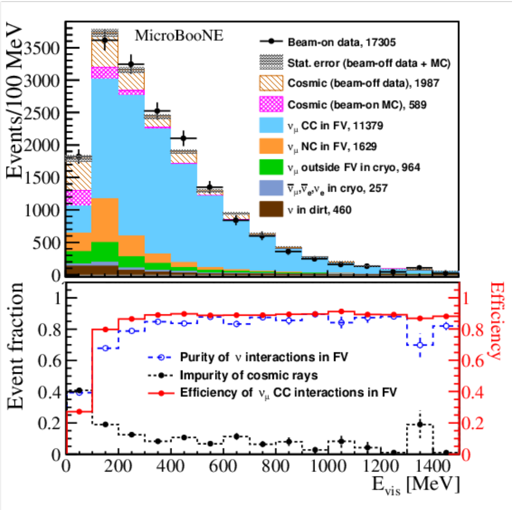
3-D ν_e data candidate after imaging, reconstruction and cosmic rejection:



Video: Wire-Cell 3-D neutrino imaging and selection in MicroBooNE

JINST 16 P06043 (2021)

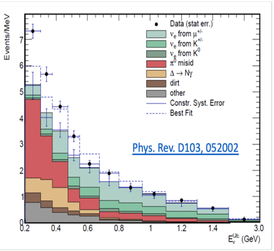
Generic Neutrino identifcation (BNB)



arXiv:2012.07928

Search for an excess of low energy ν_e events (LEE) in MicroBooNE

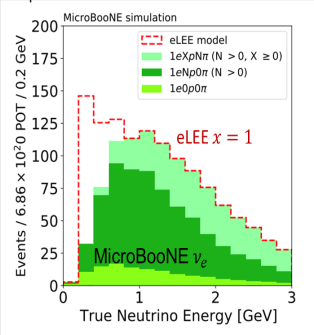
The MiniBooNE Excess in MicroBooNE



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

Unfolding detector response, acceptance, efficiency

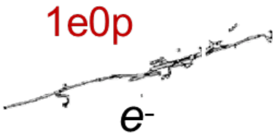
Empirical eLEE model derived from MiniBooNE

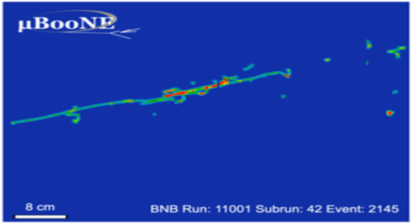


Assumption about excess: an energy-dependent enhancement of intrinsic ν_e events at low energy.

MicroBooNE public note 1043

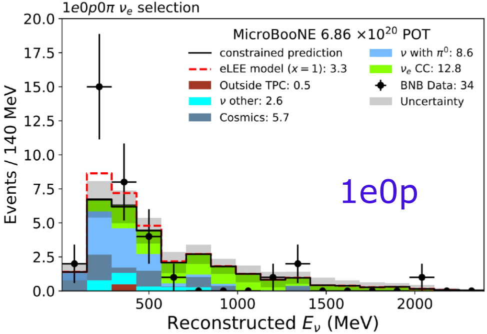
ν_e signatures in MicroBooNE



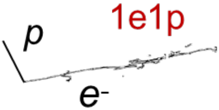


CCQE-like ν_e scattering with no visible proton and no pions- MiniBooNE event topology. Uses 2-D image reconstruction in each of 3 TPC views then combines (Pandora technique)

Phys. Rev. D 105, 112004

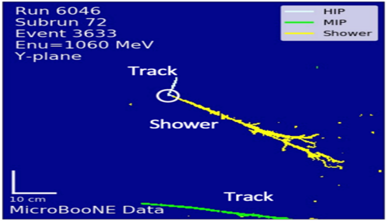


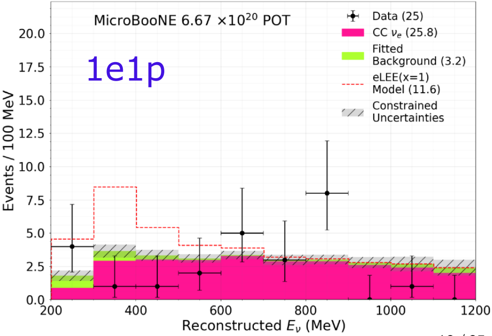
ν_e signatures in MicroBooNE



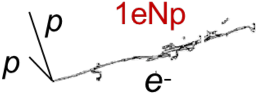
CC quasi-elastic ν_e scattering which dominates at low energy.
Deep-learning based event selection.

Phys. Rev. D 105, 112003 (



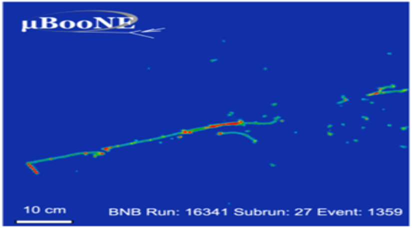


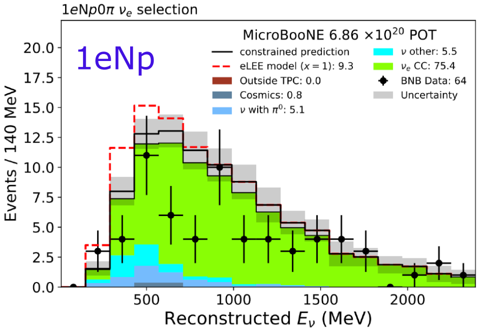
ν_e signatures in MicroBooNE



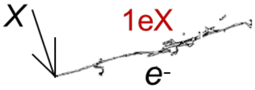
CC semi-inclusive ν_e scattering to electrons and protons. No pions in final state. Uses Pandora-based reconstruction

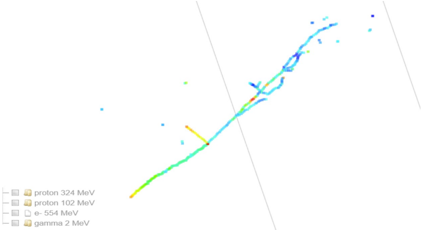
[**Phys. Rev. D 105, 112004**]





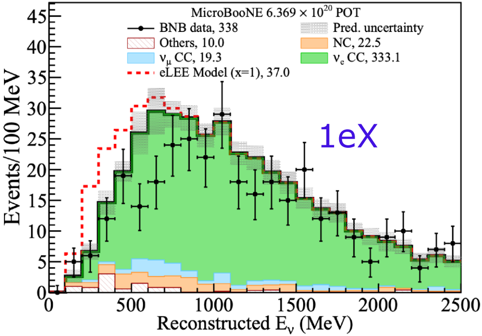
ν_e signatures in MicroBooNE



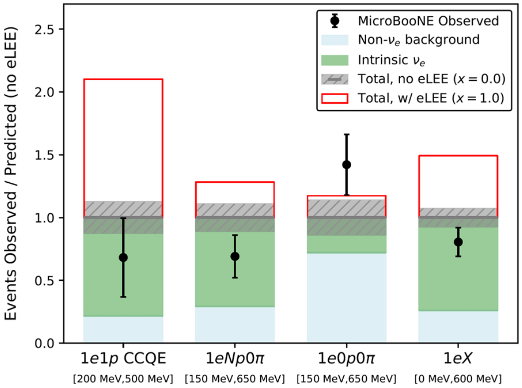


CC inclusive ν_e scattering with high efficiency and no model dependence. 3-D Wire-Cell reconstruction enhanced with Deep-learning.

Phys. Rev. D 1015, 112005



Results from MicroBooNE ν_e excess analysis:

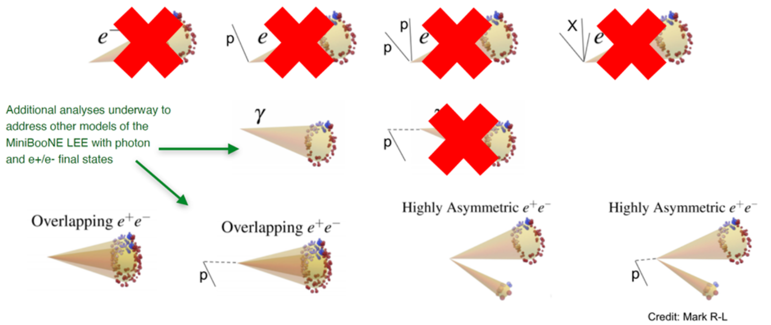


The 3 analysis with highest purity for ν_e signal reject ν_e interactions as sole source of MiniBooNE exess at $> 97\%$ C.L.

Phys. Rev. Lett 128, 241801 (2022)

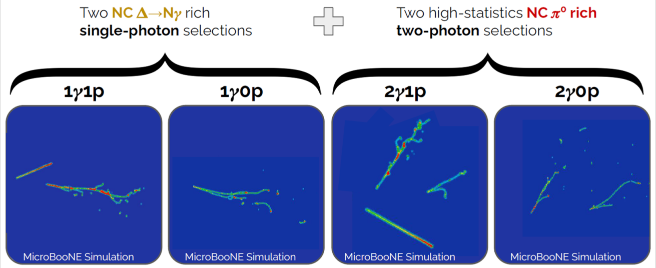
So What is the MiniBooNE Excess?

Theoretical Models of the MiniBooNE LEE



Searching for NC $\Delta \rightarrow N\gamma$

Enhancing the NC $\Delta \rightarrow N\gamma$ signal by $\times 3.18$ could be an explaination for the MiniBooNE LEE. MicroBooNE search for NC Δ:



1γ1p

Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \rightarrow N\gamma$	$+4.88$
LEE ($x_{\rm MB} = 3.18$)	$+15.5$

16 Data Events Observed

1γ0p

Unconstr. bkgd.	165.4 ± 31.7
Constr. bkgd.	145.1 ± 13.8
NC $\Delta \rightarrow N\gamma$	$+6.55$
LEE ($x_{\rm MB} = 3.18$)	$+20.1$

153 Data Events Observed

Phys. Rev. Lett 128, 111801 (2022)

No LEE observed in NC $\Delta \rightarrow N\gamma$. BR $< 1.38\%$ at 90% C.L. limit

Fit to a 3+1 Scenario using Booster Beam Data

The 3+1 Oscillation Model

Using a 3+1 framework with 4x4 unitary PMNS matrix and assuming ($m_4 >> m_3, m_2, m_1$), the short-baseline oscillation probability from flavor α to flavor β can be expressed as

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}} \cdot \sin^2 2\theta_{\alpha\beta} \cdot \sin^2\Delta_{41}, \quad \Delta_{41} = \frac{\Delta m^2_{41} L}{4E}$$

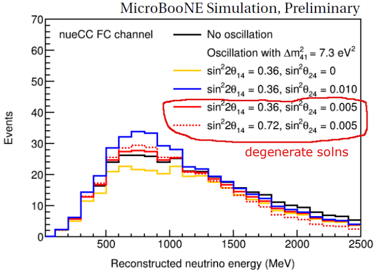
where $\delta_{\alpha\beta} = 0(\alpha \neq \beta),\ 1(\alpha = \beta)$ and $\theta_{\alpha\beta}$ is the effective mixing angle

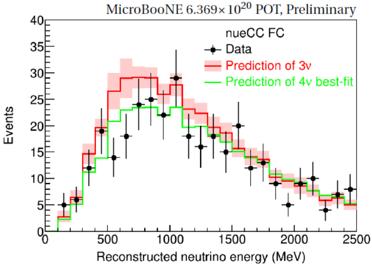
In the 3+1 oscillation analysis in MicroBooNE both ν_e appearance and ν_e/ν_μ disappearance are considered. The ν_e disappearance can cancel the appearance of ν_e events:

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

In MicroBooNE degeneracies occur when $\sin^2\theta_{24} \approx 1/R_{\nu_\mu/\nu_e} \sim 0.005$ (BNB) ~ 0.04 (NuMI)

MicroBooNE ν_e appearance from BNB using 3+1



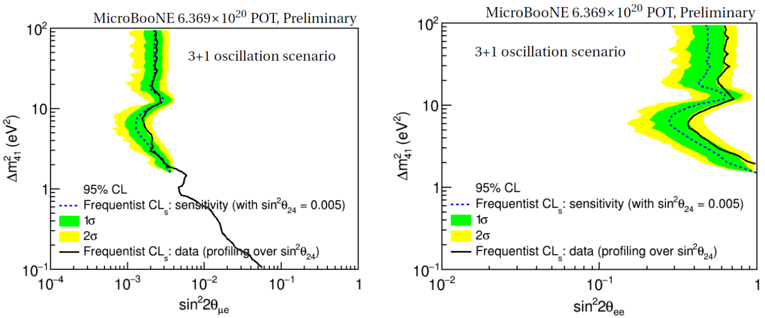


MicroBooNE data from BNB rules out ν_e as the excess observed in MiniBooNE at $> 97\%$ C.L. but on its own does not completely rule out a 3+1 scenario. Appearance and disappearance effects compete and there are degeneracies in the parameters.

MicroBooNE public note 1116

MicroBooNE ν_e appearance from BNB using 3+1

$\nu_\mu \rightarrow \nu_e$ (appearance) **$\nu_e \rightarrow \nu_e$ (disappearance)**



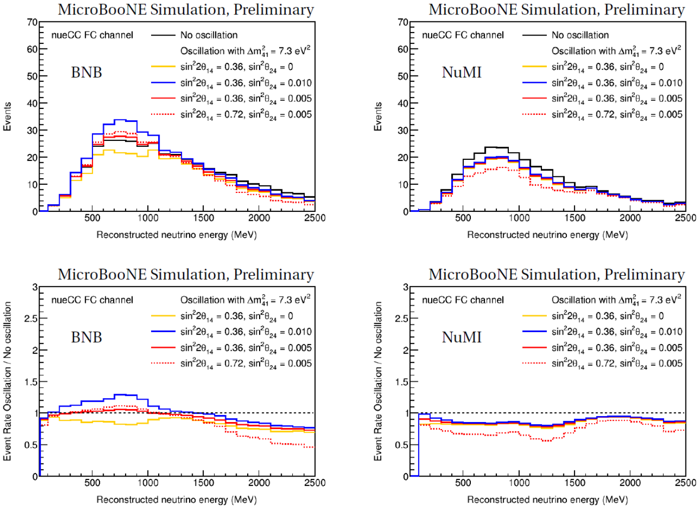
MicroBooNE data is highly consistent with the 3ν model. MicroBooNE data rules out a significant portion of the 3+1 oscillation scenario in the appearance channels. There is also exclusion of a smaller fraction of the parameter space in ν_e disappearance

[**MicroBooNE public note 1116**]

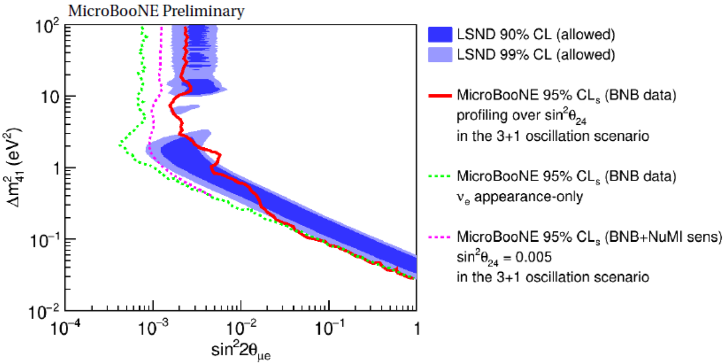
Future prospects for the 3+1 fit in MicroBooNE

Searching for oscillations with NuMI+BNB

Booster Beam ν — **NuMI Beam ν**



3+1 Sensitivites with NuMI+BNB



MicroBooNE public note 1116

Recent Oscillation Results from MicroBooNE.. and more

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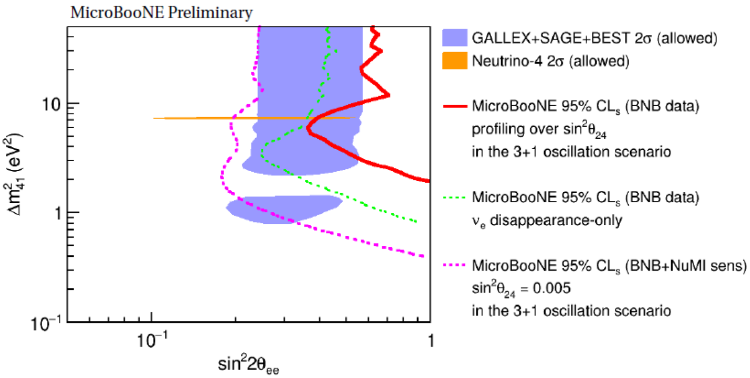
3+1 Sensitivites with NuMI+BNB



MicroBooNE public note 1116

New Physics Searches

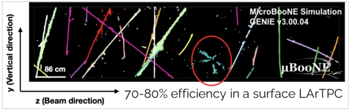
Examples of Exotic Physics Searches in MicroBooNE

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

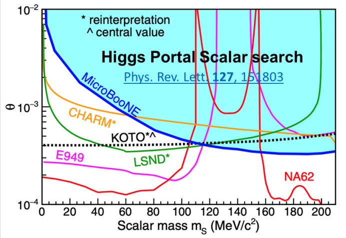
- [Beam] Higgs portal scalar limit Phys. Rev. Lett. **127**, 151803 (update coming soon)
- [Beam] Dark trident search in progress

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

Neutron-Antineutron search



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



X. Qian

Summary and Conclusions

Summary and Conclusions

- **The MicroBooNE experiment has launched the short baseline oscillation program at Fermilab with spectacular success.**
- **MicroBooNE is the first ν experiment to fully realize and exploit the power of Liquid-Argon Time Projection Chambers.**
- **MicroBooNE has excluded an excess of ν_e as a source of the MiniBooNE anomaly.**
- **A full 3+1 oscillation fit to the MicroBooNE booster beam data has been carried out taking into account both appearance and disappearance effects. The fit demonstrates that** ***MicroBooNE data are consistent with the 3ν hypotheses and provides no evidence for a sterile neutrino***
- **The MicroBooNE exclusion limit in 3+1 fit covers a large fraction of sterile neutrinos parameter space allowed by results from other experiments.**
- **Combining the Booster beam and NuMI beam data in MicroBooNE will enable the experiment to further expand the senstivity to 3+1 oscillations**