Recent Results from MicroBooNE’s Low Energy Excess Search

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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

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

MicroBooNE’s Low Energy Excess Search

MicroBooNE has investigated the explanation of MiniBooNE low energy excess (LEE) in two interpretations (focusing on four independent analyses) using Run 1-3 data ($\sim6 \times 10^{20}$ POT):

- Assuming excess is photon
  - Single photon analysis: targeting NC $\Delta \rightarrow N\gamma$ hypothesis ($1\gamma0p, 1\gamma1p$)
- 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 ($1eX$)

**Phys. Rev. D 103, 052002 (2021)**
Investigation of Photon Excess

- **Disfavor** a candidate photon interpretation of MiniBooNE LEE as a x3.18 enhancement of nominal rate NC $\Delta$ radiative decay rate at the 94.8% CL

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)

**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)

Search for a Light Sterile Neutrino in 3+1 Model

- MicroBooNE is suitable for searching for oscillations caused by eV-scale sterile neutrinos
  - \( \frac{L}{E} \approx O(1) \text{ [m/MeV]} \)
- 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

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

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

\[ \Phi(v) / 50 \text{ MeV} / \text{cm}^2 / 2.4 \times 10^{20} \text{ POT} \]

- $\nu_\mu$ (56.6%)
- $\bar{\nu}_\mu$ (39.4%)
- $\nu_e$ (2.5%)
- $\bar{\nu}_e$ (1.5%)

Off-axis NuMI Flux at MicroBooNE
Forward Horn Current Mode
### MicroBooNE’s Low Energy Excess Search

<table>
<thead>
<tr>
<th>Models</th>
<th>1e0p</th>
<th>1e1p</th>
<th>1eNp</th>
<th>1eX</th>
<th>e⁺e⁻ + nothing</th>
<th>e⁺e⁻ X</th>
<th>1γ0p</th>
<th>1γ1p</th>
<th>1γX</th>
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<tbody>
<tr>
<td>eV Sterile ν Osc</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
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<tr>
<td>Sterile ν Decay</td>
<td>[13,14]</td>
<td>[13,14]</td>
<td>[13,14]</td>
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<td>[13,14]</td>
<td>[4,11,12,15]</td>
<td>[4]</td>
<td>[4]</td>
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<td>Dark Sector &amp; Z’</td>
<td>[2,3]</td>
<td>✓</td>
<td></td>
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<td>[2,3]</td>
<td>[2,3]</td>
<td>[1,2,3]</td>
<td>[1,2,3]</td>
<td>[1,2,3]</td>
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<tr>
<td>More complex higgs</td>
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<td></td>
<td>[10]</td>
<td>[10]</td>
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<td>[6,10]</td>
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<tr>
<td>Axion-like particle</td>
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<td>[8]</td>
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<td>SM γ production</td>
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</tbody>
</table>

* Requires heavy sterile/other new particles also
MicroBooNE’s Low Energy Excess Search

Overlapping $e^+e^-$

Overlapping $e^+e^-$

Highly asymmetric $e^+e^-$

Highly asymmetric $e^+e^-$

Credit: M. Toups
Short-Baseline Neutrino Anomalies

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

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

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