Latest Results from the MicroBooNE Experiment

Tanaz Angelina Mohayai, Indiana University
For the MicroBooNE Collaboration
TAU2023, Dec. 7, 2023
Exploiting the long- to short-baseline oscillation experiments to unravel the remaining puzzles in $\nu$ physics

- Do neutrinos oscillate differently than anti-neutrinos? Which neutrino is the lightest?
- Do we understand everything about neutrino interactions?
- Are there more than 3 types of neutrinos?
- What Beyond Standard Model physics can we search for in $\nu$ experiments?
Exploiting the long- to short-baseline oscillation experiments to unravel the remaining puzzles in $\nu$ physics

- Do neutrinos oscillate differently than anti-neutrinos? Which neutrino is the lightest?

- Do we understand everything about neutrino interactions?

- Are there more than 3 types of neutrinos?

- What Beyond Standard Model physics can we search for in $\nu$ experiments?
Neutrino Oscillations

- Neutrino oscillations considered one of the strongest pieces of evidence of BSM physics
  - Modeled with various parameters, mixing angle, $\theta_{ij}$, mass splitting squared term, $\Delta m^2_{ij}$, CP violating term, $\delta_{CP}$, baseline, $L$, and neutrino energy, $E_\nu$

  simplified 2 flavor probability, e.g. $\nu_e$ appearance probability, $P(\nu_\mu \rightarrow \nu_e)$

  $$\sin^2(2\theta) \sin^2(1.27\Delta m^2_{21} / E)$$
## Neutrino Oscillation Parameters

<table>
<thead>
<tr>
<th>NuFIT 5.2 (2022)</th>
<th>Normal Ordering (best fit)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bfp $\pm 1\sigma$</td>
</tr>
<tr>
<td></td>
<td>$3\sigma$ range</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$0.303^{+0.012}_{-0.011}$</td>
</tr>
<tr>
<td>$\theta_{12}/^\circ$</td>
<td>$33.41^{+0.75}_{-0.72}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.572^{+0.018}_{-0.023}$</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$</td>
<td>$49.1^{+1.0}_{-1.3}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$0.02203^{+0.00056}_{-0.00059}$</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$</td>
<td>$8.54^{+0.11}_{-0.12}$</td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$</td>
<td>$197^{+42}_{-25}$</td>
</tr>
<tr>
<td>$\frac{\Delta m^2_{21}}{10^{-5} \text{ eV}^2}$</td>
<td>$7.41^{+0.21}_{-0.20}$</td>
</tr>
<tr>
<td>$\frac{\Delta m^2_{3\ell}}{10^{-3} \text{ eV}^2}$</td>
<td>$+2.511^{+0.028}_{-0.027}$</td>
</tr>
</tbody>
</table>
Oscillation Probability

- Based on current oscillation parameters:
  - No oscillations expected for 1 GeV neutrinos, at baselines $< 100$ km, i.e. the survival probability $\approx 1$ & appearance probability $\approx 0$
  - Oscillations at baseline $< 100$ km could suggest larger splitting due to an additional 4$^{th}$ neutrino

![Example of oscillation probability of ~1 GeV neutrinos](credit: E. Worcester)
MiniBooNE at Short-baseline

- A Cherenkov detector that operated for 17 years
- Observed a large excess of events at low energies:
  - If due to **electrons**, then could constitute a possible evidence for $\nu_e$ appearance at short-baselines
  - Could also be due to **background photons**

Baseline: ~500 m, avg neutrino energy: ~800 MeV

4.8σ significance Yet to be resolved
MiniBooNE at Short-baseline

- A Cherenkov detector that operated for 17 years
- Observed a large excess of events at low energies:
  - If due to **electrons**, then could constitute a possible evidence for $\nu_e$ appearance at short-baselines
  - Could also be due to **background photons**

**specifically, distinguishing between photons and electrons** is a challenge in a Cherenkov detector like MiniBooNE
MicroBooNE employs a liquid-argon time projection chamber, LArTPC which can more efficiently make the distinction between electrons and photons, using topological and dE/dx information.

arXiv:2110.14065v3
for the first time, a long-baseline (1300 km) oscillation experiment will use argon as its nuclear target for precision studies of $\nu$ oscillations
Challenges of Future Precision Experiments

- Future precision experiments, e.g. DUNE, require few percent uncertainties
  - Includes uncertainties on neutrino interactions, detector systematics, & flux
  - Ultimate sensitivity in DUNE achieved only via a robust constraint on these, particularly dominant uncertainties from neutrino interactions
  - Leverage existing LArTPC experiments to address the current scarcity of data on argon

![Graph showing DUNE sensitivity](arXiv:2103.13910)
Fermilab Short-baseline Program

- MicroBooNE is the pioneer LArTPC in this program, operated from 2015 to 2021 in the same $\nu$ beam as MiniBooNE.
- Combined with SBND and ICARUS, its goals are to investigate short-baseline oscillations both in appearance and survival modes, neutrino-argon interaction cross-sections, advancements in LArTPC detector physics, and BSM signature searches.
MicroBooNE Detector

- 170 tonne LArTPC
- World's largest dataset of neutrino interactions on argon
Working Principle of the Detector

[Diagram showing the working principle of a detector, with text credits to B. Yu and J. Asaadi]
The Beam

Booster $\nu$ beam
MicroBooNE, SBN program

MicroBooNE

NuMI $\nu$ beam
NOvA, MINERvA, MINOS+

Main Injector
proton energy: 120 GeV

DUNE $\nu$ beam
(planned)

Booster
proton energy: 8 GeV
Low-energy Excess/sterile neutrino searches

neutrino-argon interactions

advancing LArTPC Detector Technology

BSM Searches in a LArTPC
Two channels were investigated:
- $1\gamma 1p$ and $1\gamma 0p$

Achieved the most stringent constraint on neutrino-induced $\text{NC } \Delta \rightarrow N\gamma$ on any nuclear target

Rules out photons from $\text{NC } \Delta \rightarrow N\gamma$ as the cause of the LEE, 94.8% C.L.
Two channels were investigated:

1$\gamma$1p and 1$\gamma$0p

Achieved the most stringent constraint on neutrino-induced NC $\Delta \rightarrow N\gamma$ on any nuclear target

Rules out photons from NC $\Delta \rightarrow N\gamma$ as the cause of the LEE, 94.8% C.L.

Looking ahead: more photon searches are underway including inclusive single-photon and Coherent photon searches

MicroBooNE NOTE-1104-PUB
MicroBooNE NOTE-1102-PUB
MicroBooNE NOTE-1103-PUB
Is there an excess in $\nu_e$ that can point to oscillations at short baselines?
Rejects electrons as the sole explanation of the LEE at > 97% CL

**Legend**
- MicroBooNE Observed
- Non-$\nu_e$ background
- Intrinsic $\nu_e$
- Total, no eLEE ($x = 0.0$)
- Total, w/ eLEE ($x = 1.0$)

**Graph**
- **Events Observed / Predicted (no eLEE)**
- **1e1p CCQE**
- **1eNp0π**
- **1e0p0π**
- **1eX**

**References**
- Phys. Rev. Lett. 128, 241801 (2022)
Future Prospects of the LEE Searches

- Only runs 1-3 have been explored for LEE searches so far, more results underway with the remaining data!
- A combined analysis using NuMI and BNB is underway, better sensitivity to other experimental results (mainly due to degeneracy mitigation) expected.
MicroBooNE Physics Program

- Low-energy Excess/sterile neutrino searches
- Neutrino-argon interactions
- Advancing LArTPC Detector Technology
- BSM Searches in a LArTPC
MicroBooNE Cross-section Program – Overview

μBooNE

CC inclusive
• 1D $\nu_\mu$ CC inclusive @ BNB  
• 1D $\nu_\mu$ CC $E_\nu$ @ BNB  
  *Phys. Rev. Lett. 128, 151801 (2022)*
• 3D CC $E_\nu$ @ BNB  
  *arXiv:2307.06413*, submitted to PRL
• 1D $\nu_e$ CC inclusive @ NuMI  
  *Phys. Rev. D105, L051102 (2022)*
  *Phys. Rev. D104, 052002 (2021)*

CC0π
• 1D $\nu_e$ CCNp0π @ BNB  
  *Phys. Rev. D 106, L051102 (2022)*
• 1D & 2D $\nu_\mu$ CC1p0π Transverse Imbalance @ BNB  
  *Phys. Rev. Lett. 131, 101802 (2023)*
  *Phys. Rev. D 108, 053002 (2023)*
• 1D & 2D $\nu_\mu$ CC1p0π Generalized Imbalance @ BNB  
  *arXiv:2310.06082*, submitted to PRD
• 1D $\nu_\mu$ CC1p0π @ BNB  
  *Phys. Rev. Lett. 125, 201803 (2020)*
• 1D $\nu_\mu$ CC2p @ BNB  
  *arXiv:2211.03734*
• 1D $\nu_\mu$ CCNp0π @ BNB  
  *Phys. Rev. D102, 112013 (2020)*

Pion production
• $\nu_\mu$ NCπ$^0$ @ BNB  
  *Phys. Rev. D 107, 012004 (2023)*
MicroBooNE CCQE-like Topology: $1\mu 1p0\pi$

- First transverse kinematic imbalance measurement on argon target
- Data favors including FSI (Final State Interaction) models in generators

[Graph showing data and models comparison]

arXiv:2301.03700, accepted by PRL
arXiv:2301.03706, accepted by PRD
Event selections mostly selects MEC (Meson Exchange Current) events
Model tension when angle between the two protons is small

arXiv:2211.03734
low-energy Excess/sterile neutrino searches

neutrino-argon interactions

advancing LArTPC Detector Technology

BSM Searches in a LArTPC
Advancing LArTPCs

- Latest papers include achieving ns timing resolution (Phys. Rev. D 108, 052010) and investigating the presence of Rn daughters in a sizable LArTPC.
- Demonstrating particle calorimetry and identification at the lowest energies recorded in a single-phase neutrino LArTPC, as important input to MeV-scale astrophysics searches in future DUNE.
MicroBooNE Physics Program

- Low-energy Excess/sterile neutrino searches
- Neutrino-argon interactions
- Advancing LArTPC Detector Technology
- BSM Searches in a LArTPC
BSM Searches

- Many of these scenarios predict overlapping $e^+e^-$ final states which can be used for the LEE searches

![Graph showing $\theta^2$ vs. HPS mass [MeV] with various data points and interpretations.](chart.png)
Summary

Leveraging the most extensive $\nu$-Ar dataset available, MicroBooNE is providing vital input to upcoming precision oscillation experiment, DUNE, in the context of $\nu$-Ar interaction cross sections, LArTPC detector advancements, and rare/exotic physics searches.

The flagship MicroBooNE analyses aimed at resolving the MiniBooNE LEE anomaly so far rules out NC $\Delta \rightarrow N\gamma$ backgrounds and dismisses the notion that electron events from $\nu e$ entirely account for the MiniBooNE LEE.

★ We have only used ~half of the BNB data set so far; stay tuned for results from all BNB data sets as well as combined BNB+NuMI beam!
Additional Slides
Level of Neutrino Interaction Uncertainty Today

<table>
<thead>
<tr>
<th>Type of Uncertainty</th>
<th>$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-K Detector Model</td>
<td>1.5</td>
</tr>
<tr>
<td>Pion Final State Interaction and Rescattering Model</td>
<td>1.6</td>
</tr>
<tr>
<td>Neutrino Production and Interaction Model Constrained by ND280 Data</td>
<td>2.7</td>
</tr>
<tr>
<td>Electron Neutrino and Antineutrino Interaction Model</td>
<td>3.0</td>
</tr>
<tr>
<td>Nucleon Removal Energy in Interaction Model</td>
<td>3.7</td>
</tr>
<tr>
<td>Modeling of Neutral Current Interactions with Single $\gamma$ Production</td>
<td>1.5</td>
</tr>
<tr>
<td>Modeling of Other Neutral Current Interactions</td>
<td>0.2</td>
</tr>
<tr>
<td>Total Systematic Uncertainty</td>
<td>6.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$\nu_e$ Signal (%)</th>
<th>$\nu_e$ Bkg. (%)</th>
<th>$\bar{\nu}_e$ Signal (%)</th>
<th>$\bar{\nu}_e$ Bkg. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-sections</td>
<td>+4.7/-5.8</td>
<td>+3.6/-3.4</td>
<td>+3.2/-4.2</td>
<td>+3.0/-2.9</td>
</tr>
<tr>
<td>Detector model</td>
<td>+3.7/-3.9</td>
<td>+1.3/-0.8</td>
<td>+0.6/-0.6</td>
<td>+3.7/-2.6</td>
</tr>
<tr>
<td>ND/FD diffs.</td>
<td>+3.4/-3.4</td>
<td>+2.6/-2.9</td>
<td>+4.3/-4.3</td>
<td>+2.8/-2.8</td>
</tr>
<tr>
<td>Calibration</td>
<td>+2.1/-3.2</td>
<td>+3.5/-3.9</td>
<td>+1.5/-1.7</td>
<td>+2.9/-0.5</td>
</tr>
<tr>
<td>Others</td>
<td>+1.6/-1.6</td>
<td>+1.5/-1.5</td>
<td>+1.4/-1.2</td>
<td>+1.0/-1.0</td>
</tr>
<tr>
<td>Total</td>
<td>+7.4/-8.5</td>
<td>+5.6/-6.2</td>
<td>+5.8/-6.4</td>
<td>+6.3/-4.9</td>
</tr>
</tbody>
</table>

- From existing experiments, T2K and NOvA, the dominant sources of uncertainties are cross sections/neutrino interactions.
● Pioneering achievement in demonstrating $\mathcal{O}(1\text{ ns})$ timing resolution

★ Introduces a novel cosmic-rejection technique for distinguishing neutrino interactions arriving in approximately 2 ns pulses in the BNB

**Phys. Rev. D 108, 052010**
Neutrino Interactions

- We expect a specific range of energies in neutrino experiments:
  - Each experiment will be sensitive to a specific interaction type and a specific set of nuclear effects, affecting what we see in the detectors.