Five Years of MicroBooNE and Beyond in Ten Minutes

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New Perspectives
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Overview

- MicroBooNE is a neutrino experiment based at Fermilab that utilizes a liquid argon time projection chamber (LArTPC) and has been collecting data since October 2015

- This talk will provide a brief overview of the rich and exciting physics program at MicroBooNE over the last five years and beyond

- MicroBooNE’s body of work provides an important foundation for future LArTPC experiments, including SBN and DUNE
The LSND Anomaly

- LSND studied $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, using $\bar{\nu}_\mu$ from $\mu^+$ decay at rest
- Observed a $3.8\sigma$ excess of $\bar{\nu}_e$-like events, which can be interpreted as some probability of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations due to a sterile neutrino

$$P_{osc} = \sin^2(2\theta) \sin^2 \left( \frac{(m_1^2 - m_2^2) L}{4E_\nu} \right)$$

$$\Delta m_{12}^2 \equiv m_1^2 - m_2^2$$
The MiniBooNE Anomaly

- MiniBooNE is a mineral oil Cherenkov detector located in Fermilab’s Booster Neutrino Beam (BNB), which is primarily muon neutrinos

- MiniBooNE studied $\nu_\mu \rightarrow \nu_e$ appearance using $\nu_\mu$ from Fermilab’s Booster Neutrino Beam (BNB), and observed a 4.7$\sigma$ excess of $\nu_e$-like events

- Experiments have different baseline and energy but similar $L/E$ at $\sim$1 m/MeV, which suggests sterile neutrino oscillation could explain both anomalies

\[
P_{\text{osc}} = \sin^2(2\theta) \sin^2 \left( \frac{(m_1^2 - m_2^2)L}{4E_\nu} \right)
\]

\[
\Delta m^2_{12} = m_1^2 - m_2^2
\]

Similar $L/E$ means similar $P_{\text{osc}}$

Given the same $\theta$, $\Delta m^2$
The SBN Program at Fermilab

• MicroBooNE was proposed as a follow-up to MiniBooNE
  ‣ Same beam, similar baseline
  ‣ Aims to check existence of excess, whether it’s from $e^-$ or $\gamma$

• Short Baseline Neutrino (SBN) Program consists of three LArTPCs: SBND, MicroBooNE, and ICARUS

• SBN will enable $5\sigma$ coverage of LSND allowed regions under the 3+1 sterile neutrino hypothesis

• SBN will also provide an important foundation for future LArTPC experiments, such as DUNE
Taking neutrino data since October 2015, now the longest-running LArTPC detector

Detector continues to operate smoothly, with >95% detector + DAQ uptime

Over 500k neutrino interactions recorded
  ▶ More than half of this with our cosmic ray tagger (CRT) installed and taking data
Detecting Neutrinos with a LArTPC

"Design and Construction of the MicroBooNE Detector"
JINST 12, P02017 (2017)

Beam
\[ E_{\text{drift}} \]
Induction
Collection
3 mm spacing

Anode planes:
U, V, Y

Cathode

MicroBooNE Simulation Preliminary

Wire

Time
**e⁻ / γ Separation in LArTPCs**

LArTPCs offer two main ways to distinguish electrons and photons in neutrino interactions:

- **Amount of energy deposited per unit length in the trunk of the shower** — e⁻ is ~2 MeV/cm, γ → e⁺e⁻ is twice that.

- **Gap between the neutrino interaction vertex and the start of the shower**

![Diagram showing separation between electron and photon vertices with energy deposited and gap measures.](image-url)
Addressing the MiniBooNE Anomaly

MicroBooNE is pursuing two main signal hypotheses:

**Electron-Like Model**
Electron Neutrino Events

**Photon-Like Model**
NC $\Delta \rightarrow N\gamma$ Events

Unfolding method described in MICROBOONE-NOTE-1043-PUB
Addressing the MiniBooNE Anomaly

For each signal hypothesis, a few possible channels:

**Electron-Like Model**  
**Electron Neutrino Events**

- $\nu_e + \text{Ar} \rightarrow e^- + 1 \ p \ (1e1p)$
- $\nu_e + \text{Ar} \rightarrow e^- + N \ p \ (1eNp)$
- $\nu_e + \text{Ar} \rightarrow e^- + 0 \ p \ (1e0p)$
- $\nu_e + \text{Ar} \rightarrow e^- + X \ (\text{incl.})$

**Photon-Like Model**  
**NC $\Delta \rightarrow N\gamma$ Events**

- $\nu + \text{Ar} \rightarrow \gamma + 1 \ p \ (1\gamma1p)$
- $\nu + \text{Ar} \rightarrow \gamma + 0 \ p \ (1\gamma0p)$

Unfolding method described in MICROBOONE-NOTE-1043-PUB
Status of Low-Energy Excess Searches

- Have developed end-to-end analyses searching for both signal hypotheses
- Multiple complementary selections using different analysis techniques
- On the cusp of unblinding for our first results — stay tuned!
- All of this builds on important work in a number of other areas

We are here!
Detector Physics & Calibrations

- Have completed major calibration campaign
- Have measured our E-field *in situ* with cosmic ray muons and with UV laser
- Have incorporated the results of both into our current default simulation
- More exciting and important detector physics measurements to come
Novel Reconstruction Methods

• MicroBooNE is developing a number of novel reconstruction techniques applicable to LArTPC data and putting them to the test in physics analyses

• Have demonstrated the use of deep learning techniques using CNNs on LArTPC images, including for track/shower labeling and for particle identification

• Have demonstrated the WireCell 3D clustering and reconstruction, which provides powerful cosmic rejection and increased neutrino efficiency over other methods

Deep Learning Pixel Labeling
Example on a $\nu_\mu$ CC $\pi^0$ Event

WireCell 3D Reconstruction and Clustering

PRD 99, 092001 (2019)
Model Tuning & Systematics

• Recent and future results use an updated cross section model based on GENIE v3 with CCQE and CC MEC channels tuned to T2K $\nu_\mu$ CC $0\pi$ data
  ‣ New model shows better agreement with MicroBooNE data than previous results

• Have developed a novel, data-driven method for assessing detector systematics uncertainties in MicroBooNE
  ‣ Similar approach could be applied to future LArTPC experiments
Neutrino–Argon Interactions

MicroBooNE is measuring neutrino–argon interaction cross sections in a range of channels, which are critical to reduce systematic uncertainties for the SBN program and DUNE

BNB:
- $\nu_\mu$ CC inclusive
  \[ \text{PRL 123, 131801 (2019)} \]
- $\nu_\mu$ CC $\pi^0$
  \[ \text{PRD 99, 091102(R) (2019)} \]
- $\nu_\mu$ CCQE-like
- $\nu_\mu$ CC Np, 2p
  \[ \text{MICROBOONE-NOTE-1056-PUB} \]
- NC elastic
  \[ \text{MICROBOONE-NOTE-1067-PUB} \]
- CC K$^\pm$
  \[ \text{MICROBOONE-NOTE-1071-PUB} \]
- CC 1$\pi^+$
- CC coherent $\pi$
- NC $\pi^0$
- … and more!

NuMI:
- $\nu_e$ CC inclusive
  \[ \text{MICROBOONE-NOTE-1054-PUB} \]
- $\nu_e$ CCQE-like
- Kaon decay-at-rest (KDAR)

Summary

- MicroBooNE has made significant progress towards analyses that will test electron- or photon-like nature of the MiniBooNE excess, stay tuned for first results!

- The SBN program aims to conclusively address the possibility of sterile neutrino oscillations suggested by LSND and MiniBooNE

- Beyond that, MicroBooNE has a rich research program including pioneering work in detector physics, calibrations, reconstruction, systematics evaluation, and neutrino–argon interactions

- This work is foundational for the Short Baseline Neutrino Program and for future LArTPC experiments, including DUNE

Thank you!