First results from the MicroBooNE search for a low energy excess

Nick Kamp for the MicroBooNE Collaboration
Lepton-Photon 2021

More MicroBooNE @ Lepton-Photon:
A Deep Learning Search of Dark Tridents at the MicroBooNE Experiment by Luis Mora
Recent neutrino cross-section results from MicroBooNE by Wenqiang Gu
Astroparticle and Beyond the Standard Model Capabilities and Results from MicroBooNE by Anyssa Navrer-Agasson
This talk examines the MiniBooNE anomaly: an excess of electron neutrino-like events in a predominately muon neutrino beam.

Tested by the follow-up MicroBooNE experiment, a liquid argon time-projection chamber situated on the same beam-line.

Presented today: MicroBooNE’s first results exploring the nature of the MiniBooNE low energy excess.
Outline

1. The MiniBooNE anomaly
2. The MicroBooNE experiment
3. MicroBooNE’s first results
Outline

1. The MiniBooNE anomaly
2. The MicroBooNE experiment
3. MicroBooNE’s first results
The MiniBooNE Excess

**Electrons:** “fuzzy” rings from multiple scattering

4.8σ excess observed in the electron-like channel

Cherenkov limitations:
- Electrons/photons indistinguishable
- No hadronic information

PRD 103, 052002
The MiniBooNE Excess

Electrons: “fuzzy” rings from multiple scattering

4.8σ excess observed in the electron-like channel

One really needs a robust experimental test of the MiniBooNE anomaly, which requires a detector capable of providing more detailed event-by-event information.

Cherenkov limitations:
- Electrons/photons indistinguishable
- No hadronic information
Outline

1. The MiniBooNE anomaly
2. The MicroBooNE experiment
3. MicroBooNE’s first results
The Liquid Argon Time Projection Chamber (LArTPC)
MicroBooNE

- 85 metric ton active mass LArTPC
- O(mm) spatial resolution
- Reconstructs hadronic activity
- Photon/electron discrimination
- Important contributions to our understanding of LArTPCs:
  - Electric field distortions from space charge effects
    P. Abratenko et al 2020 JINST 15 P12037
  - Noise characterization/filtering
    R. Acciarri et al 2017 JINST 12 P08003
  - Neutrino-Ar cross sections
    Phys. Rev. Lett. 123, 131801
  - GENIE event generator tuning
    arXiv 2110.14028 (submitted to PRD)
  - Data-driven detector uncertainties
    arXiv 2111.03556 (submitted to EPJ-C)
  - + more!
The MicroBooNE Dataset

• Data taken from 2015-2021
• The analyses covered today consider the first ~7e20 protons-on-target (~1/2 of the full dataset)
Outline

1. The MiniBooNE anomaly
2. The MicroBooNE experiment
3. MicroBooNE’s first results
What is tested in MicroBooNE’s first results?

Three independent analyses have targeted $\nu_e$ final states, testing whether the excess is due to an enhancement of $\nu_e$ interactions?

Another analysis has searched for an enhancement of NC $\Delta \rightarrow N\gamma$ events.

MicroBooNE has not yet performed a generic single photon search—stay tuned!
The Simplified LEE Model

- MicroBooNE focused on a simplified, phenomenological model for an excess of low-energy $\nu_e$ events based on MiniBooNE results.
- MiniBooNE observation is unfolded under a $\nu_e$ assumption to obtain LEE model weights as a function of true neutrino energy.
- Weights are applied to MicroBooNE simulated intrinsic CC $\nu_e$ events—same treatment for all electron analyses.

MiniBooNE inputs:
PRL 121, 221801 (2018)

Unfolding method:
MICROBOONE-NOTE-1043-PUB
Electron Neutrino Searches

2-body CCQE Sample
- Exclusive signal
- $1e1p$ final state
- Leverages deep learning-based reconstruction and 2-body scattering kinematics

Pion-less Sample
- Semi-inclusive signal
- Two final states: $1e0p0\pi$ and $1eNp0\pi$ ($N>1$)
- Leverages Pandora-based reconstruction

Inclusive Sample
- Fully-inclusive signal
- $1eX$ final state
- Leverages Wire-Cell reconstruction
**νₜμ Sideband Samples**

### 2-Body CCQE Analysis

- **ΣData/ΣPred = 1.08 ± 0.13**
- **MicroBooNE 6.67 x 10^20 POT**

**νₜμ CCQE 1µ1p**

- Data / Pred for ν₂μ CCQE (3369.27)
- Neutrino Background (699.15)
- BNB OffVtx (313.08)
- Cosmic Background (97.77)
- Systematic Error (Data 4848)

### Inclusive Analysis

**νₜμ CC**

- **MicroBooNE**
- **νₜμ CC inclusive**
- **νₜμ CCπ⁰**

### Pion-less Analysis

- **νₜμ selection**
- **MicroBooNE 2.13 x 10^20 POT**
- Dirt (Outside TPC) ν₂μ CC
- NC ν
- Cosmics
- νₜμ CC
- BNB Data

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N. Kamp  
Lepton-Photon; 11 January 2022
\( \nu_\mu \) Constraint Strategy

• The BNB flux and cross section of \( \nu_\mu \) events in MicroBooNE are highly correlated with that of \( \nu_e \) events

• Thus, the \( \nu_\mu \) sideband samples can be used to perform a data-driven constraint on the prediction and uncertainties in the \( \nu_e \) signal channel of each analysis
Electron Neutrino LEE Results

2-Body CCQE Analysis

MicroBooNE 6.67 \times 10^{20} POT

1e1p

2110.14080

Inclusive Analysis

MicroBooNE 6.369 \times 10^{20} POT

1eX

2110.13978

Pion-less Analysis

1eNp0\pi (N>0)

2110.14065

Summary of results: arXiv:2110.14054
**νe LEE Results: Electron Angle**

### 2-Body CCQE Analysis

- **Data/Pred:** \( \Sigma Data/\Sigma Pred = 0.93 \pm 0.15 \text{(sys)} \pm 0.19 \text{(stat)} \)
- **MicroBooNE:** \( 6.67 \times 10^{20} \text{ POT} \)
- **Result:** \( 1e1p \)

### Inclusive Analysis

- **Data POT:** \( 6.369 \times 10^{20} \)
- **BNB data:** \( 368.0 \)
- **Result:** \( 1eX \)

### Pion-less Analysis

- **Result:** \( 1e0p0pi (N>1) \)
- **Result:** \( 1e0p0pi \)

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**Legend:**
- \( \nu_e \) CCQE (20.5)
- \( \nu_e \) CC other (3.7)
- Background (2.8)
- Systematic Error
- Data (25)

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**Graphs:**
- **Left:** 2-body CCQE analysis
- **Right:** Inclusive analysis
- **Bottom left:** Pion-less analysis

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**References:**
- [MicroBooNE](#)
- [LEE](#)
- [BNB](#)
\( \nu_e \) LEE Results: Hadronic Energy

### 2-Body CCQE Analysis

**MicroBooNE** 6.67 x 10^{20} POT

\( \sum \frac{\text{Data}}{\text{Pred}} = 0.93 \pm 0.14 \text{ (sys)} \pm 0.19 \text{ (stat)} \)

**1e1p**

\[ \text{1e1p} \quad 2110.14080 \]

**Data/\text{Pred}**

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Data/\text{Pred}</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>100</td>
<td>1.0</td>
</tr>
<tr>
<td>150</td>
<td>1.5</td>
</tr>
<tr>
<td>200</td>
<td>2.0</td>
</tr>
<tr>
<td>250</td>
<td>2.5</td>
</tr>
<tr>
<td>300</td>
<td>3.0</td>
</tr>
<tr>
<td>350</td>
<td>3.5</td>
</tr>
<tr>
<td>400</td>
<td>4.0</td>
</tr>
<tr>
<td>450</td>
<td>4.5</td>
</tr>
<tr>
<td>500</td>
<td>5.0</td>
</tr>
</tbody>
</table>

### Inclusive Analysis

**MicroBooNE**

\( \sum \frac{\text{Data}}{\text{Pred}} = 0.93 \pm 0.14 \text{ (data)} \pm 0.19 \text{ (pred)} \)

**1eX**

\[ \text{1eX} \quad 2110.13978 \quad \text{Unconstrained FC} \]

**Data/\text{Pred}**

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Data/\text{Pred}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>40</td>
<td>1.0</td>
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<tr>
<td>60</td>
<td>1.5</td>
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<tr>
<td>80</td>
<td>2.0</td>
</tr>
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<td>100</td>
<td>2.5</td>
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<td>120</td>
<td>3.0</td>
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<tr>
<td>140</td>
<td>3.5</td>
</tr>
<tr>
<td>160</td>
<td>4.0</td>
</tr>
<tr>
<td>180</td>
<td>4.5</td>
</tr>
</tbody>
</table>

### Pion-less Analysis

**MicroBooNE** 6.86 x 10^{20} POT

**1eNp0\pi \nu_e \text{ selection}**

\[ \text{1eNp0\pi (N>1)} \quad 2110.14065 \]

**Entries / 0.05 GeV**

<table>
<thead>
<tr>
<th>Leading Proton Kinetic Energy (GeV)</th>
<th>Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>0.2</td>
<td>1.5</td>
</tr>
<tr>
<td>0.3</td>
<td>2.0</td>
</tr>
<tr>
<td>0.4</td>
<td>2.5</td>
</tr>
<tr>
<td>0.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Electron LEE Model Tests

- Most analyses observe a deficit of electron neutrino events at the lowest energies, inconsistent with a MiniBooNE-like excess.
- Scale the LEE model by a signal strength parameter -> limit on the electron neutrino contribution to the MiniBooNE excess.

![Graph showing electron-like analyses and LEE enriched regions with data from MicroBooNE and predictions with and without eLEE.](arXiv:2110.14054)
What about the Photons?

- MicroBooNE has also performed a Pandora-based analysis searching for an excess of NC $\Delta \rightarrow N\gamma$ events.
- From MiniBooNE: a scaling of the NC $\Delta \rightarrow N\gamma$ rate by a factor of 3.18 would explain the MiniBooNE anomaly [1].

See 2110.00409 for more details on this analysis!

[1] (MiniBooNE Collaboration) PRD 103, 052002
Single Photons: $\Delta \rightarrow N\gamma$

This analysis has also looked for $\Delta^0 \rightarrow n\gamma$ decays with a $1\gamma0p$ final state.
$\Delta \rightarrow N\gamma$ Search Results

- A scaling of NC $\Delta \rightarrow N\gamma$ rate by a factor of 3.18 is ruled out at the 94.8% CL
- World-leading limit on the effective branching ratio for $E_\nu < 1$ GeV by more than an order of magnitude [1]

$$B_{\text{eff}}(\Delta \rightarrow N\gamma) < 1.38\% \ (90\%\ CL)$$

<table>
<thead>
<tr>
<th>1$\gamma$1p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstr. bkgd.</td>
</tr>
<tr>
<td>Constr. bkgd.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1$\gamma$1p</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC $\Delta \rightarrow N\gamma$</td>
</tr>
<tr>
<td>LEE ($x_{MB} = 3.18$)</td>
</tr>
</tbody>
</table>

[1] (T2K collaboration) 1902.03848
MicroBooNE’s Full First Results

• MicroBooNE has investigated the LEE in several final states

• Results suggest that the MiniBooNE excess is not primarily due to either low-energy $\nu_e$ CC interactions or NC $\Delta \rightarrow N\gamma$ interactions
MicroBooNE’s Full First Results

• MicroBooNE has investigated the LEE in several final states
• Results suggest that the MiniBooNE excess is not primarily due to either low-energy $\nu_e$ CC interactions or NC $\Delta \rightarrow N\gamma$ interactions

What else could explain the MiniBooNE Excess?
Theoretical Landscape

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - [14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141
- New resonance matter effects
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
- Decay of heavy sterile neutrinos produced in beam
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
- Decay of axion-like particles
- A model-independent approach to any new particle
## Theoretical Landscape

See Anyssa Navrer-Agasson’s talk on Wednesday and Luis Mora’s poster from Monday more details!

<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>
</tr>
</thead>
<tbody>
<tr>
<td>eV Sterile $\nu$ Osc</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed Osc + Sterile $\nu$</td>
<td>✓ [7]</td>
<td>✓ [7]</td>
<td>✓ [7]</td>
<td>✓ [7]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sterile $\nu$ Decay</td>
<td>✓ [13,14]</td>
<td>✓ [13,14]</td>
<td>✓ [13,14]</td>
<td>✓ [13,14]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dark Sector &amp; Z’ *</td>
<td>✓ [2,3]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>More complex higgs *</td>
<td></td>
<td>✓ [10]</td>
<td>✓ [10]</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Axion-like particle *</td>
<td></td>
<td>✓ [8]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM $\gamma$ production</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

*Requires heavy sterile/other new particles also

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N. Kamp

Lepton-Photon; 11 January 2022
Summary

• The analyses presented today address the MiniBooNE anomaly by searching for a corresponding signal in the MicroBooNE detector.

• Overall, recently-released MicroBooNE results disfavor both $\nu_e \text{CC}$ and NC $\Delta \rightarrow N \gamma$ as the primary source of the MiniBooNE excess.

• A search for NC $\Delta \rightarrow N \gamma$ events disfavors an enhancement necessary to explain the MiniBooNE LEE at the $\sim 95\% \text{ CL}$.

• Three searches for $\nu_e \text{CC}$ interactions in multiple final state topologies disfavor explanations of the MiniBooNE LEE consisting entirely of excess $\nu_e$ events at the $\sim 2-3\sigma \text{ CL}$.

• This is just the first phase of MicroBooNE and SBN results that will test an array of BSM explanations for the MiniBooNE LEE anomaly.
Backups
The MiniBooNE Experiment

- 800-ton mineral oil Cherenkov detector
- Situated along Fermilab’s Booster Neutrino Beam
  - Neutrino energies ~500 MeV
  - ~540 m from the beryllium target
  - ~70 m downstream from MicroBooNE
Photon/Electron Discrimination

- **Photons**
  - Trunk dE/dx ~ 2 x MIP
  - Gap ~ photon radiation length

- **Electrons**
  - Trunk dE/dx ~ 1 x MIP
  - No gap for electrons
Electron Neutrino Results

- Three analyses which the same input data but have been developed independently, each using different reconstruction tools
- You can find the full suite of papers at: http://ubdllee.org
Constraint Strategy

• Each analysis uses larger $\nu_\mu$-based sample(s) to constrain the prediction and uncertainty on their $\nu_e$ signal channel

• **Flux:** both species of neutrinos come from the same beam, from decays of the same population of hadrons

• **Cross-section:** both interact with argon nuclei via the weak interaction
Blindness Strategy

- Each analyses was performed in a blind manner
- Data was examined in sideband samples not sensitive to the LEE model before moving on to the signal region
- Signal region: highest $\nu_e$ likelihood and lowest neutrino energy

Example Near Sideband 1e1p Analysis: “almost signal-like” sample
Single Photons: $\Delta \rightarrow N \gamma$

1γ1p Channel

$4^0\text{Ar}$ → $p \rightarrow \Delta^+$

$\nu_\mu$ → Short proton candidate with Bragg peak

1γ0p Channel

$4^0\text{Ar}$ → $n \rightarrow \Delta^0$

$\nu_\mu$ → No proton-like activity behind EM shower (Neutrons non-ionizing)
Single Photons: $\Delta \rightarrow N\gamma$

**$1\gamma 1p$ Channel**

**$1\gamma 0p$ Channel**
2γ Sideband Channels

Correlation Matrix

Leverage large correlations between the 2γ sideband and 1γ signal channels to constrain the 1γ prediction and uncertainty.
$\Delta \rightarrow N\gamma$ Search Results

### 1$\gamma$1p

<table>
<thead>
<tr>
<th>Category</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC $\Delta \rightarrow N\gamma$</td>
<td>27.0 ± 8.1</td>
</tr>
<tr>
<td>LEE ($x_{MB} = 3.18$)</td>
<td>+4.88</td>
</tr>
</tbody>
</table>

Unconstrained: 20.5 ± 3.6

16 Data Events Observed

### 1$\gamma$0p

<table>
<thead>
<tr>
<th>Category</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC $\Delta \rightarrow N\gamma$</td>
<td>165.4 ± 31.7</td>
</tr>
<tr>
<td>LEE ($x_{MB} = 3.18$)</td>
<td>+6.55</td>
</tr>
</tbody>
</table>

Unconstrained: 145.1 ± 13.8

153 Data Events Observed
Δ → Nγ Search Results

1γ1p

\[
\begin{array}{c}
\text{Unconstr. bkgd.} & 27.0 \pm 8.1 \\
\text{Constr. bkgd.} & 20.5 \pm 3.6 \\
\text{NC Δ → Nγ} & +4.88 \\
\text{LEE (x_{MB} = 3.18)} & +15.5 \\
\end{array}
\]

16 Data Events Observed

1γ0p

\[
\begin{array}{c}
\text{Unconstr. bkgd.} & 165.4 \pm 31.7 \\
\text{Constr. bkgd.} & 145.1 \pm 13.8 \\
\text{NC Δ → Nγ} & +6.55 \\
\text{LEE (x_{MB} = 3.18)} & +20.1 \\
\end{array}
\]

153 Data Events Observed

• Statement about ruling out LEE model
• Statement about improvement on branching ration limit
$\Delta \rightarrow N\gamma$ Search Results

![Graph showing distribution of $W$ in NC $\Delta \rightarrow N\gamma$ (arb. units).]

- Distribution of $W$ in NC $\Delta \rightarrow N\gamma$ (arb. units)
- GENIE v3.0.6 $W$ dependence
- Mean GENIE $B_{\text{eff}}$
- MiniBooNE LEE model ($x_{MB} = 3.18$)
- MicroBooNE 90% CL sensitivity
- MicroBooNE 90% CL exclusion

$B_{\text{eff}} \Delta \rightarrow N\gamma$ (%)

$W$, Invariant Mass of Resonance (GeV/$c^2$)
The Bigger Picture

• This is consistent MiniBooNE, who have shown that kinematics of their excess events do not look like $\nu_e$ CC or NC $\Delta \rightarrow N\gamma$

• The community has developed other theories, mostly involving other BSM sources of photon-like events in MiniBooNE

• Future MicroBooNE results will probe these possibilities further

\[
\{d, m_N\} = \{2.8 \times 10^{-7} \text{ GeV}^{-1}, 376 \text{ MeV}\}
\]

\[
\nu(p, n) \rightarrow \bar{N}(p, n)
\]

\[
\nu A \rightarrow NA
\]

\[
\nu_\mu \rightarrow \nu_e
\]

\[
\{\Delta m^2, \sin^2(2\theta)\} = \{1.3 \text{ eV}^2, 6.9 \times 10^{-4}\}
\]

MiniBooNE Data

PRD 103, 052002 (2021)

PRD 104, 095005 (2021)
## Signal-enhanced region comparison

<table>
<thead>
<tr>
<th></th>
<th>$1e1p$</th>
<th>$1eN\pi0\pi$</th>
<th>$1e0\pi0\pi$</th>
<th>$1eX$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_\nu$ (MeV)</td>
<td>200-500</td>
<td>150-650</td>
<td>150-650</td>
<td>0-600</td>
</tr>
<tr>
<td>Predicted, no eLEE</td>
<td>8.8 ± 3.0</td>
<td>30.4 ± 6.1</td>
<td>19.0 ± 5.3</td>
<td>69.6 ± 9.4</td>
</tr>
<tr>
<td>Predicted, w/ eLEE</td>
<td>18.5 ± 4.4</td>
<td>39.0 ± 6.8</td>
<td>22.3 ± 5.7</td>
<td>104 ± 12</td>
</tr>
<tr>
<td>Observed</td>
<td>6</td>
<td>21</td>
<td>27</td>
<td>56</td>
</tr>
</tbody>
</table>

## Final fit results

<table>
<thead>
<tr>
<th></th>
<th>$1e1p$</th>
<th>$1eN\pi0\pi$</th>
<th>$1e0\pi0\pi$</th>
<th>$1eX$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_\nu$ (MeV)</td>
<td>200-1200</td>
<td>150-1550</td>
<td>150-1550</td>
<td>0-2500</td>
</tr>
<tr>
<td>$p$ ($\chi^2_x = 0$)</td>
<td>$1.4 \times 10^{-2}$</td>
<td>0.18</td>
<td>0.13</td>
<td>0.85</td>
</tr>
<tr>
<td>$p$ ($\Delta \chi^2 &lt; \text{obs.}$, w/ eLEE)</td>
<td>$1.6 \times 10^{-4}$</td>
<td>$2.1 \times 10^{-2}$</td>
<td>0.93</td>
<td>$9.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$x$ observed, $1\sigma$</td>
<td>[0.00, 0.08]</td>
<td>[0.00, 0.41]</td>
<td>[1.91, 8.10]</td>
<td>[0.00, 0.22]</td>
</tr>
<tr>
<td>$x$ observed, $2\sigma$</td>
<td>[0.00, 0.38]</td>
<td>[0.00, 1.06]</td>
<td>[0.77, 24.3]</td>
<td>[0.00, 0.51]</td>
</tr>
<tr>
<td>$x$ expected upper limit, $2\sigma$</td>
<td>0.98</td>
<td>1.44</td>
<td>4.64</td>
<td>0.56</td>
</tr>
</tbody>
</table>
Neutrinos

- Oscillations between three flavor states imply small but nonzero masses

\[
\begin{bmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{bmatrix} = 
\begin{bmatrix}
U_{e1} & U_{\mu 1} & U_{\tau 1} \\
U_{e2} & U_{\mu 2} & U_{\tau 2} \\
U_{e3} & U_{\mu 3} & U_{\tau 3}
\end{bmatrix}
\begin{bmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{bmatrix}
\]

\[P(\nu_\alpha \rightarrow \nu_\beta) = \left| \langle \nu_\beta(t) | \nu_\alpha(t) \rangle \right|^2 = \left| \sum_i U_{\alpha i} U_{\beta i}^* e^{-i m_i^2 L / 2E} \right|^2 \approx \sin^2(2\theta) \sin^2 \left( 1.27 \Delta m^2 \frac{L}{E} \right)\]

Two-Neutrino Approximation

(Normal Ordering)
Neutrinos

- Oscillations between three flavor states imply small but nonzero masses
- Mixings and mass splittings well-measured by accelerator, reactor, atmospheric, and solar experiments

\[
\begin{align*}
\nu_e & \quad \nu_\mu & \quad \nu_\tau \\
\nu_1 & \quad \nu_2 & \quad \nu_3 \\
m_1^2 & \quad m_2^2 & \quad m_3^2 \\
(\text{Normal Ordering})
\end{align*}
\]

![Graphs and diagrams related to neutrino oscillations and mass splittings](image-url)
Neutrino Sector Anomalies

- Difficult to explain within the standard three-neutrino oscillation paradigm

- Explanations often invoke oscillations with a fourth “sterile” neutrino*

  *tension in global picture

---

Short Baseline Accelerator

**LSND**

**MiniBooNE**

**Reactor**

**Gallium**

---

*Data (stat err.)

- $\nu_e$ from $\mu^-$
- $\nu_e$ from $K^+$
- $\nu_e$ from $K^0$
- $\pi^+$ misid
- $\Delta \rightarrow N_l$
- dirt
- other
- Constr. Syst. Error
- Best Fit

---

**PRD 64, 112007**

**PRD 103, 052002**

---

1101.2755

2109.11482
The MiniBooNE Detector

**Electrons**: “fuzzy” rings from multiple scattering

**Muons**: “clean” rings from long, straight tracks

**Neutral Pions**: two rings from decay to two photons
The MiniBooNE Excess

Cherenkov limitations:

- Electrons/photons indistinguishable
- No hadronic information

The excess could be…

1. Mis-modeled photon background?
2. Electron-like (e.g. sterile-driven oscillations?)
3. More exotic new physics?
The MiniBooNE Excess

Cherenkov limitations:

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- No hadronic information

The excess could be…

1. **Mis-modeled photon background?**

2. Electron-like (e.g. sterile-driven oscillations?)

3. More exotic new physics?

Neutral Pion and dirt backgrounds constrained *in situ*; disfavored by radial/timing distributions of excess

**Delta decay background** would need be scaled by factor of ~3 to explain excess; disfavored by recent MicroBooNE results (spoiler alert)
The MiniBooNE Excess

Cherenkov limitations:

- Electrons/photons indistinguishable
- No hadronic information

The excess could be...

1. Mis-modeled photon background?
2. Electron-like (e.g. sterile-driven oscillations?)
3. More exotic new physics?

A single sterile neutrino model does not fit the excess well at the lowest energies and smallest electron scattering angles.

It also also difficult to reconcile the single sterile neutrino model with data from other neutrino experiments (see 1906.00045)
The MiniBooNE Excess

Cherenkov limitations:

- Electrons/photons indistinguishable
- No hadronic information

The excess could be...

1. Mis-modeled photon background?
2. Electron-like (e.g. sterile-driven oscillations?)
3. More exotic new physics?

A model with one eV-scale sterile (driving oscillations) and one dipole-portal MeV-scale sterile (facilitating decays to photons) can explain MiniBooNE and also relieve tension in the global picture.

Models involving dark sector decays to collimated e^+e^- paired have also been explored in the literature.
The MiniBooNE Excess

Cherenkov limitations:

• Electrons/photons indistinguishable

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The excess could be...

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Models involving dark sector decays to collimated $e^+e^-$ paired have also been explored in the literature.

One really needs a robust experimental test of the MinBooNE anomaly, which requires a detector capable of providing more detailed event-by-event information.

$\nu(p, n) \rightarrow N(p, n)$
$\nu A \rightarrow N A$
$\nu_{\mu} \rightarrow \nu_e$
$\{\Delta m^2, \sin^2(2\theta)\} = \{1.3 \text{ eV}^2, 6.9 \times 10^{-4}\}$
$\{d, m_N\} = \{2.8 \times 10^{-7} \text{ GeV}^{-1}, 376 \text{ MeV}\}$
MicroBooNE

- Designed to directly address the MiniBooNE anomaly
- Harnesses the imaging power of liquid argon time projection chamber (LArTPC) technology to observe detailed pictures of neutrino interactions
The MicroBooNE Detector
What is tested in MicroBooNE’s first results?

We DON'T Test: Sterile Neutrino Models

Despite what the press release from Fermilab says, MicroBooNE has never fit the data with a sterile model.

Why?
We've known the effect is not 3+1 for some time.
If it isn't simple 3+1, what model should you use?
→ Instead, measure the $\nu_e$ content, then find the right model.
• We will go through the 2-body CCQE analysis as an example (see http://ubdllee.org for more details)
The CCQE Analysis in a Nutshell

- This analysis uses novel image-based deep learning algorithms alongside traditional reconstruction algorithms to isolate a highly-pure sample of electron neutrinos in the MicroBooNE detector.

- We focus on charged-current quasi-elastic (CCQE) interactions creating one electron and one proton (1e1p) in the final state.

- These requirements give strong kinematic and topological handles on event selection.
CCQE 1e1p Motivation

- The QE cross section is dominant around the peak of the MiniBooNE excess (200-500 MeV)
- The QE cross section is also better understood than other neutrino interactions
CCQE $1e1p$ Motivation

- Simple topology: one track from the proton and one electromagnetic shower from the electron

- Kinematic handles:
  - Forward-going protons
  - CCQE-consistent reconstructed energy
  - Bjorken $x$ near unity

\[ E_{\nu}^{\text{range}} = K_p + K_{\ell} + M_\ell + M_p - (M_n - B), \]
\[ E_{\nu}^{QE-p} = \left( \frac{1}{2} \right) \frac{2 \cdot (M_n - B) \cdot E_p - ((M_n - B)^2 + M_p^2 - M_\ell^2)}{(M_n - B) - E_p + \sqrt{(E_p^2 - M_p^2)} \cdot \cos \theta_p}, \]
\[ E_{\nu}^{QE-\ell} = \left( \frac{1}{2} \right) \frac{2 \cdot (M_n - B) \cdot E_\ell - ((M_n - B)^2 + M_\ell^2 - M_p^2)}{(M_n - B) - E_\ell + \sqrt{(E_\ell^2 - M_\ell^2)} \cdot \cos \theta_\ell}. \]
Deep Learning Motivation

- LArTPC data come in the form of high-resolution images of charged particles
- MicroBooNE spatial resolution: \(3 \times 3.3\) mm
- This lends itself to the use of image-based deep learning algorithms like convolutional neural networks (CNNs)
Analysis Chain

Semantic Segmentation via SparseSSNet

Cosmic Tagging

Vertex and Track/Shower Reconstruction

Particle Identification via MPID

1e1p Selection  \( \pi^0 \) Selection  1\( \mu \)1p Selection

Statistical Results
Analysis Chain

- Semantic Segmentation via SparseSSNet
- Cosmic Tagging
- Vertex and Track/Shower Reconstruction
- Particle Identification via MPID
- CNN-based
- 1e1p Selection
- \( \pi^0 \) Selection
- 1\( \mu \)1p Selection
- Statistical Results
SparseSSNet

Phys. Rev. D 103, 052012

• We use the Sparse Semantic Segmentation Network to perform pixel-level labeling of LArTPC images

• Built using sparse convolutions, more efficient given the sparse nature of our data  arXiv 1706.01307

One-hot Labels

Track
• Highly ionizing particle (protons)
• Minimum ionizing particle (muons, charged pions)

Shower
• EM shower (electrons, photons)
• delta (knock-on electrons)
• Michel electrons (from muon decay)
SparseSSNet

Phys. Rev. D 103, 052012

Accuracy

<table>
<thead>
<tr>
<th></th>
<th>Test</th>
<th>Intrinsic $\nu_e$</th>
<th>Full-BNB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track</td>
<td>0.992</td>
<td>0.992</td>
<td>0.998</td>
</tr>
<tr>
<td>Shower</td>
<td>0.996</td>
<td>0.859</td>
<td>0.823</td>
</tr>
</tbody>
</table>
Analysis Chain

Semantic Segmentation via SparseSSNet

Cosmic Tagging

Vertex and Track/Shower Reconstruction

Particle Identification via MPID

1e1p Selection

π⁰ Selection

1μ1p Selection

Statistical Results

CNN-based

CNN-based
Cosmic Rejection

Phys. Rev. Applied 15, 064071

- Cosmic muons are a pernicious background for our near-surface detector
- We remove the bulk of cosmic muons using tools from the Wire-Cell reconstruction software leveraging for example, charge-to-light matching
Analysis Chain

- Semantic Segmentation via SparseSSNet
  - Cosmic Tagging
    - Vertex and Track/Shower Reconstruction
      - Particle Identification via MPID
        - 1e1p Selection
        - \(\pi^0\) Selection
        - 1\(\mu\)1p Selection
          - Statistical Results
Vertex Reconstruction

P. Abratenko et al 2021 JINST 16 P02017

- Search for two prongs of charge emanating from the same 3D-consistent vertex

- Use SparseSSNet pixel labels to partition into “track-track” (1µ1p) events and “track-shower” (1e1p) events

- Vertex resolution < 1 cm
Track Reconstruction

P. Abratenko et al 2021 JINST 16 P02017

• Build up a set of 3D points associated with each track via an iterative stochastic algorithm

• Output is used to reconstruct the direction and energy of protons and muons
Shower Reconstruction

• In the collection plane: use SparseSSNet to mask out everything but shower-like pixels

• Encapsulate shower-like pixels within a cone

• Convert charge within cone to a reconstructed shower energy

• Capable of reconstructing two showers from the same vertex
Shower Reconstruction

arXiv 2110.11874

• Validate charge-to-energy conversion using two standard candles:
  • \(\pi^0\) invariant mass
  • Michel energy cutoff

Charge-to-energy [MeV/Q]

MicroBooNE 5.28 \times 10^{19} POT Simulation Normalized to Data

Electron Energy [MeV]

Events / 10 [MeV]

MicroBooNE 6.67 \times 10^{20} POT Simulation Normalized to Data

n^0 mass [MeV/c^2]

Events / 16 [MeV/c^2]

Data/Pred

MicroBooNE
Analysis Chain

- Semantic Segmentation via SparseSSNet
  - CNN-based
  - Cosmic Tagging
    - Vertex and Track/Shower Reconstruction
    - Particle Identification via MPID
      - CNN-based
      - 1e1p Selection
      - $\pi^0$ Selection
      - 1$\mu$1p Selection
    - Statistical Results
MPID

- Multi Particle IDentification network
- Outputs likelihood that a particle exists in a given LArTPC image

<table>
<thead>
<tr>
<th>Particle</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>0.89</td>
</tr>
<tr>
<td>e^-</td>
<td>0.95</td>
</tr>
<tr>
<td>γ</td>
<td>0.85</td>
</tr>
<tr>
<td>μ^-</td>
<td>0.06</td>
</tr>
<tr>
<td>π^±</td>
<td>0.17</td>
</tr>
</tbody>
</table>

MicroBooNE Simulation
Analysis Chain

1. Semantic Segmentation via SparseSSNet
2. Cosmic Tagging
3. Vertex and Track/Shower Reconstruction
4. Particle Identification via MPID
5. 1e1p Selection
6. \(\pi^0\) Selection
7. 1\(\mu\)1p Selection
8. Statistical Results

CNN-based
1e1p Sample

Selection Criteria

1. Broad data quality requirements
   • e.g. forward-going proton

2. Ensemble of boosted decision trees
   • 19 kinematic variables (e.g. electron/proton energies and angles)
   • 4 topological variables (e.g. fraction of SparseSSNet-labeled shower pixels)
   • Accept/reject based on the average score

3. Particle content requirements
   • e.g., low MPID muon/photon scores
1e1p Background Fits

- Due to the purity of this analysis, the simulation samples we use to assess the non-$\nu_e$ background to the 1e1p analysis are have large statistical errors.

- In order to address this, we employ an empirical Landau+linear fit to the backgrounds (leveraging information from a looser BDT cut).
1e1p Sample

- Final sample is dominated by $\nu_e$ CCQE events, with 76% purity and 6.6% efficiency
- This is by design—we optimize for purity at the expense of efficiency in this exclusive analysis
\( \pi^0 \) Sample Motivation

- Interactions with a \( \pi^0 \) in the final state are the main background to the 1e1p sample

\[
\text{clean } \nu_\mu \text{ CC} \pi^0 \quad \text{and} \quad 1e1p\text{-like } \nu_\mu \text{ NC} \pi^0
\]
Small deficit observed (within systematic error)

Use a data-driven method to reweight the $\pi^0$ prediction in true momentum space

These weights are applied to $\pi^0$ events in both the 1e1p and 1µ1p samples
1µ1p Sample

- We isolate a sample of $\nu_\mu$ 1µ1p events in the final state to constrain the $\nu_e$ 1e1p prediction and uncertainties

Selection Criteria

1. Broad data quality requirements
2. Ensemble of boosted decision trees
3. Require high MPID proton score to reject cosmics

- Final selection has 77.3% purity and 4.3% efficiency for $\nu_\mu$ CCQE events
- Small excess at lower energies (within systematic error)
Uncertainties on the Prediction

- This analysis considers uncertainties on the prediction due to the following five sources:
  1. Neutrino beam flux model (BNB, shared with MiniBooNE)
  2. Neutrino–nucleus interaction model (GENIE)
  3. Hadron re-interaction model for protons, π⁺, and π⁻ (GEANT4)
  4. Detector response model
  5. Finite statistics in event samples used to form the prediction

![MicroBooNE Simulation](image)
Neutrino Interaction Uncertainties

- MicroBooNE has developed a custom theory-driven tune of the GENIE v3 event generator based on fits to T2K CC0\pi cross section data
  - Tuning focused on CCQE and MEC interaction channels, gives updated parameter values and uncertainties
- For this analysis, most important parameters are for CCQE model and final-state interactions (FSI)
  - FSI matter because they can change relationship between CCQE, 1\ell1p, and two-body scattering kinematics
Detector Response Uncertainties

- MicroBooNE is the first LArTPC neutrino experiment to include comprehensive detector response uncertainties

- Sources of detector response uncertainty considered:
  - Wire response as a function of position and angular orientation
    arXiv 2111.03556 (2021)
  - Local deviations in the TPC electric field (space charge effect)
    JINST 15, P07010 (2020) and JINST 15, P12037 (2020)
  - Electron–ion recombination
    JINST 15, P03022 (2020)
  - Light parameters — light yield, attenuation, Rayleigh scattering length

- Uncertainties are evaluated by comparing the nominal simulation to simulation samples where the detector response is modified
Constraining 1e1p Prediction

Our $\nu_e$ and $\nu_\mu$ events have much in common, so measurement of $\nu_\mu$ can constrain expectations for intrinsic $\nu_e$ events

- Flux: both species of neutrinos come from the same beam, from decays of the same population of hadrons
- Cross-section: both interacting with argon nuclei via the weak interaction

\[
p \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow \bar{\nu}_\mu \rightarrow e^+ \quad \text{measured}
\]

\[
e^+ \rightarrow \text{constrained}
\]
Constraining 1e1p Prediction

• Constraint procedure leverages the fact that the joint 1e1p+1μ1p covariance matrix describes a multivariate Gaussian distribution and conditions the 1e1p prediction on the 1μ1p observation.

• Constrained 1e1p prediction depends on the joint covariance matrix and the 1μ1p observation compared to its prediction.

\[
\Sigma = \begin{pmatrix}
\Sigma_{ee} & \Sigma_{e\mu} \\
\Sigma_{\mu e} & \Sigma_{\mu\mu}
\end{pmatrix}
\]

\[
\mu^e, \text{ constr.} = \mu^e + \Sigma^{e\mu} (\Sigma^{\mu\mu})^{-1} (x^\mu - \mu^{\mu})
\]

\[
\Sigma^{ee, \text{ constr.}} = \Sigma^{ee} - \Sigma^{e\mu} (\Sigma^{\mu\mu})^{-1} \Sigma^{\mu e}
\]

where \(x^\mu\) is the 1μ1p observation, and \(\mu^\mu (\mu^e)\) is the 1μ1p (1e1p) prediction.
Constraining 1e1p Prediction

- Result is a ~6% increase in the number of expected 1e1p events, and a substantial reduction in the systematic uncertainties
  - Analysis sensitivity is limited by data statistics, $\mathcal{O}(50\%)$ per bin
  - The constrained 1e1p prediction and uncertainties are inputs to all statistical tests for quantifying and interpreting results
Staged Unblinding

- This was a blind analysis
- We successively opened data at lower neutrino energies and higher BDT scores
- Our analysis was frozen before unblinding the data in the signal region:
  - Neutrino energy 200—500 MeV
  - BDT ensemble average score > 0.95
Staged Unblinding

0.7 < BDT Score < 0.95

• Used as a final check before unblinding signal region
• Also validates the background fitting procedure
Result

MicroBooNE 6.67 \times 10^{20} \text{ POT}

- CC \nu_e (25.8)
- Fitted Background (3.2)
- Pre-Constraint Prediction
- LEE (11.6)

Data/Pred

Constrained Uncertainties

$E_\nu [\text{MeV}]$
Result

\[ \Sigma_{\text{data}} / \Sigma_{\text{pred}} = 0.86 \pm 0.06 \text{ (sys)} \pm 0.19 \text{ (stat)} \]

MicroBooNE $6.67 \times 10^{20}$ POT

- Data (25)
- CC $\nu_e$ (25.8)
- Fitted Background (3.2)
- Pre-Constraint Prediction
- LEE (11.6)
Goodness-of-Fit Tests

• Compare observation to predictions using a goodness-of-fit test with the combined Neyman–Pearson $\chi^2$ test statistic [1]
  • $H_0$ prediction is intrinsic CC $\nu_e$ and misidentified backgrounds
  • $H_1$ prediction adds in the LEE signal model prediction

• Observe tension with both $H_0$ and $H_1$ predictions, but more with $H_1$

[1] Ji, Xiangpan et al. 1903.07185
Goodness-of-Fit in Other Variables

- Observe less tension with $H_0$ in most other variables than in $E_\nu$
- Similar features in reconstructed electron-based QE energy as $E_\nu$
- Other variables don’t apply the background fit or 1$\mu$1p constraint
Simple Hypothesis Tests

- Perform simple hypothesis tests using a $\Delta \chi^2$ test statistic
- Value of the $\Delta \chi^2$ for data observation is $-11.08$, which is on the low side of both the $H_0$ and $H_1$ distributions
- Probability of a lower value is 0.020 for $H_0$ and $1.6 \times 10^{-4}$ for $H_1$
Simple Hypothesis Tests

- Given that the observation is an apparent under-fluctuation of $H_0$, also apply the CL$_s$ method [1] to the simple hypothesis test results.
- CL$_s$ value is $p_{H_1}/p_{H_0} = (1.6 \times 10^{-4})/(0.020) = 0.080$, which leads us to reject of $H_1$ in favor of $H_0$ with a significance of $2.4\sigma$.

eLEE Signal Strength Fit

• For the final statistical test, allow LEE signal strength $x_{\text{eLEE}}$ to float

• Obtain confidence intervals using the Feldman–Cousins procedure
  \[ \text{PRD 57, 3873 (1998)} \]

• Observation rules out $x_{\text{eLEE}} = 0.38$ at 2\(\sigma\) C.L.
  • Compared to expected upper limit for $H_0$ at 2\(\sigma\) C.L. of $x_{\text{eLEE}} = 0.98$
The 3+1 Model

- Explanations of these anomalies often invoke oscillations with a fourth neutrino mass eigenstate ~1 eV
- Invisible Z width measurements mean this state must be mostly sterile
- Facilitate oscillations at shorter baseline than those involving active neutrinos
3+1 Model Tension

\[ P(\nu_\mu \rightarrow \nu_e) = 4 |U_{e4}|^2 |U_{\mu4}|^2 \sin^2 \left( 1.27 \Delta m^2 \frac{L}{E} \right) \]

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4 |U_{\mu4}|^2 (1 - |U_{\mu4}|^2) \sin^2 \left( 1.27 \Delta m^2 \frac{L}{E} \right) \]

\[ P(\nu_e \rightarrow \nu_e) = 1 - 4 |U_{e4}|^2 (1 - |U_{e4}|^2) \sin^2 \left( 1.27 \Delta m^2 \frac{L}{E} \right) \]

Lack of muon neutrino disappearance* in tension with electron neutrino appearance/disappearance anomalies!

\*up to some IceCube hints
IceCube and the 3+1 Model


M. Moulai Thesis. 2110.02351 (2021)
Sterile Neutrinos in MicroBooNE

- The external neutrino community has already recast MicroBooNE’s first results from the electron-like excess search into bounds on a single sterile neutrino model.

- MicroBooNE is working on an internal sterile neutrino analysis—stay tuned!
New Genie Tune

arXiv:2110.14028
What do and don't we test with the Oct 27 result?

We DO Test:
Is the MiniBooNE excess likely due to 100% $\nu_e$ interactions?

We DON'T Test:
Is any fraction due to photons? (Stay tuned for our generic photon search)

We DO Test:
Is some fraction due to $\nu_e$ interactions?
MiniBooNE at Fermilab

- 800-ton mineral oil Cherenkov detector
- Situated along the Booster Neutrino Beam (BNB)
  - Neutrino energies ~500 MeV
  - MicroBooNE detector sits ~70 m upstream of MiniBooNE
The MiniBooNE Experiment

- 800-ton Cherenkov detector at Fermilab’s Booster Neutrino Beam
- Designed to test oscillation interpretation of LSND:

\[
\frac{L_{\text{LSND}}}{E_{\text{LSND}}} \sim \left[ \frac{30 \text{ m}}{30 \text{ MeV}} \right] \quad \frac{L_{\text{MB}}}{E_{\text{MB}}} \sim \left[ \frac{500 \text{ m}}{500 \text{ MeV}} \right]
\]

LSND Collaboration, PRD 64 112007. 2001

The MiniBooNE Detector

- Mineral oil (CH$_2$) detector medium
- 1520 photo-multiplier tubes
- Remarkable stability over the 17 year lifetime

Michel Electron Energy  $\nu_\mu$ CCQE Muon Energy  $\pi^0$ Mass Peak

[Graphs showing energy distributions for Michel electron, CCQE muon, and $\pi^0$ mass peaks]

Physics Motivations for Short Baseline Oscillation and Decay Searches:

For 25 years, anomalies have been observed at short baseline.

The simplest model to explain this is "3+1"
Hard to explain through issues with SM backgrounds or nuclear effects.

**Updated MiniBooNE neutrino oscillation results with increased data and new background studies**

A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration)
Phys. Rev. D 103, 052002 – Published 8 March 2021

![Graph showing MiniBooNE 4.8σ excess](image)

**An Altarelli Cocktail for the MiniBooNE Anomaly?**

Vedran Brdar (Fermilab and Northwestern U), Joachim Kopp (CERN and JGU Mainz)

We critically examine a number of theoretical uncertainties affecting the MiniBooNE short-baseline neutrino oscillation experiment in an attempt to better understand the observed excess of electron-like events. We re-examine the impact of fake charged current quasi-elastic (CCQE) events, the background due to neutral current $\pi^0$ production, and the single-photon background. For all processes, we compare the predictions of different event generators (GENIE, GIBUU, NUANCE, and NuWro) and, for GENIE, of different tunes. Where MiniBooNE uses data-driven background predictions, we discuss the uncertainties affecting the relation between the signal sample and the control sample. In the case of the single-photon background, we emphasize the large uncertainties in the radiative branching ratios of heavy hadronic resonances. We find that not even a combination of uncertainties in different channels adding up unfavorably (an "Altarelli cocktail") appears to be sufficient to resolve the MiniBooNE anomaly. Varying the radiative branching ratios of the $\Delta(1232)$ and $N(1440)$ resonances by $\pm 2\sigma$, however, reduces its significance from $4\sigma$ to less than $3\sigma$. We finally investigate how modified background predictions affect the fit of a 3+1 sterile neutrino scenario. We carefully account for full four-flavor oscillations not only in the signal, but also in the background and control samples. We emphasize that because of the strong correlation between MiniBooNE's $\nu_e$ and $\nu_\mu$ samples, a sterile neutrino mixing only with $\nu_\mu$ is sufficient to explain the anomaly, even though the well-known tension with external constraints on $\nu_\mu$ disappearance persists.
NC $\pi^0$ background — MC predictions

(a) 

NC $\pi^0$ background — data-driven predictions

(b)
**Effect of 2γ1p constraint**

### Constraint has two effects:
- **Overall drop in expected backgrounds** by 24.1%
- **Reduction in systematic uncertainty** (29.8% → 17.8%)

Use high statistics NC π⁰ 2γ1p sample to **constrain** the NC π⁰ backgrounds in signal rich 1γ1p sample.
Uncertainties on the Prediction

• This analysis considers uncertainties on the prediction due to the following five sources:
  ‣ Neutrino beam flux model (BNB, shared with MiniBooNE)
  ‣ Neutrino–nucleus interaction model (GENIE)
  ‣ Hadron re-interaction model for protons, $\pi^+$, and $\pi^-$ (GEANT4)
  ‣ Detector response model
  ‣ Finite statistics in event samples used to form the prediction

• Uncertainties are incorporated using covariance matrix formalism applied to the analysis bins in reconstructed neutrino energy
  ‣ Diagonals contain variances of expected number of events in the bin, off-diagonals contain covariances between pairs of bins

• Correlations encoded in off-diagonal entries of covariance matrix are used to constrain the $1e1p$ with the $1\mu1p$ observation
MicroBooNE GENIE Tune

- MicroBooNE uses GENIE v3 with the G18_10a_02_11a model set
- Model parameters tuned are CCQE $M_A$, strength of the RPA effect, MEC normalization, and MEC shape in $q^0$–$q^3$ space
- Uncertainties are updated along with parameter values

![Graph showing $\nu_e$ CC inclusive total cross section](image-url)
Detector Response Uncertainties

• Detector variation samples suffer from limited statistics, which leads to statistical fluctuations affecting systematic uncertainties.

• This analysis uses a kernel density estimator (KDE) smoothing algorithm to mitigate statistical fluctuations.

• Smoothed spectra from each detector variation are used to compute the associated systematic uncertainty.

![Unsmoothed](graph1.png)  ![KDE Smoothed](graph2.png)
Uncertainties on the Prediction

- Diagonal of the fractional covariance matrix contains the same information as the total lines in the plots on the previous slide.
- Off-diagonals contain information about correlations between the contents of analysis bins, which are used for constraining $1\text{e}1\text{p}$

$$F_{ij} = \frac{\sigma_{ij}^2}{N_i N_j}$$

$$\rho_{ij} = \frac{\sigma_{ij}^2}{\sigma_i^2 \sigma_j^2}^{1/2}$$
Goodness-of-Fit Tests

- Compare observation to predictions using a goodness-of-fit test with the combined Neyman–Pearson $\chi^2$ test statistic
  - $H_0$ prediction is intrinsic CC $\nu_e$ and misidentified backgrounds
  - $H_1$ prediction adds in the LEE signal model prediction

- Observe tension with both $H_0$ and $H_1$ predictions, but more with $H_1$

<table>
<thead>
<tr>
<th>Range</th>
<th>Nominal Predictions</th>
<th>Constrained Predictions</th>
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</thead>
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<tr>
<td></td>
<td>$H_0$</td>
<td>$H_1$</td>
</tr>
<tr>
<td></td>
<td>$\chi^{2}_{\text{CPN}}$/dof</td>
<td>p-value</td>
</tr>
<tr>
<td>200–500 MeV</td>
<td>6.06/3</td>
<td>0.138</td>
</tr>
<tr>
<td>200–1200 MeV</td>
<td>23.02/10</td>
<td>0.024</td>
</tr>
<tr>
<td>200–500 MeV</td>
<td>7.91/3</td>
<td>0.075</td>
</tr>
<tr>
<td>200–1200 MeV</td>
<td>25.28/10</td>
<td>0.014</td>
</tr>
</tbody>
</table>

2.5σ tension 3.6σ tension
Other MicroBooNE LEE Analyses

- All channels except 1e0p0\(\pi\) rule out LEE signal strength needed to explain the MiniBooNE anomaly at the \(\sim 2\sigma\) C.L. or greater
- All channels except 1e0p0\(\pi\) also see an apparent under-fluctuation of the \(H_0\) prediction, therefore set better limits than expected
  - To varying degrees — 1e1p CCQE analysis is most significant example

Electron-Like Analyses

Photon-Like Analysis

- Distribution of \(W\) in NC \(\Delta\rightarrow N_y\) (arb. units)
- GENIE v3.0.6 \(W\) dependence
- Mean GENIE \(B_{\text{eff}}\)
- MiniBooNE LEE model (\(x_{MB} = 3.18\))
- MicroBooNE 90% CL sensitivity
- MicroBooNE 90% CL exclusion

\(114 = x_{MB} = 3.18\) excluded at 94.8% CL
Cosmic Rejection

Phys. Rev. Applied 15, 064071

- Cosmic muons are a pernicious background for our near-surface detector
- We remove the bulk of cosmics using tools from the Wire-Cell reconstruction software leveraging 3D event reconstruction, charge-to-light matching, and dQ/dx fitting
Vertex Reconstruction

P. Abratenko et al 2021 JINST 16 P02017

- Search for two prongs of charge emanating from the same 3D-consistent vertex

- Use SparseSSNet pixel labels to partition into “track-track” (1mu1p) events and “track-shower” (1e1p) events

- Vertex resolution < 1 cm
### Background breakdown

<table>
<thead>
<tr>
<th>Interaction Channel</th>
<th>Predicted Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ resonant $\pi^0$</td>
<td>1.26</td>
</tr>
<tr>
<td>$\nu_\mu$ resonant $\pi^\pm$</td>
<td>0.21</td>
</tr>
<tr>
<td>$\nu_\mu$ CCQE</td>
<td>0.14</td>
</tr>
<tr>
<td>$\nu_\mu$ other</td>
<td>0.19</td>
</tr>
<tr>
<td>Off-vertex</td>
<td>0.93</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event Topology</th>
<th>Predicted Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1\mu N \pi^0$</td>
<td>0.57</td>
</tr>
<tr>
<td>$0\mu N \pi^0$</td>
<td>1.09</td>
</tr>
<tr>
<td>$1\mu 1p$</td>
<td>0.14</td>
</tr>
<tr>
<td>Off-vertex</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Backup Slides

\[ \sum \frac{\text{Data}}{\sum \text{Pred}} = 0.93 \pm 0.15 \text{ (sys)} \pm 0.19 \text{ (stat)} \]

MicroBooNE $6.67 \times 10^{20}$ POT
Backup Slides

\[ \sum_{\text{Data}} / \sum_{\text{Pred}} = 0.95 \pm 0.15 \text{(sys)} \pm 0.20 \text{(stat)} \]

MicroBooNE $6.67 \times 10^{20}$ POT

- LEE (10.0)
- $\nu_\mu$ CCQE (19.1)
- $\nu_\mu$ CC other (3.3)
- Background (2.8)
- Systematic Error
- Data (24)
Backup Slides

\[ \frac{\text{Data}}{\text{Pred}} = 0.93 \pm 0.15 \text{ (sys)} \pm 0.19 \text{ (stat)} \]

MicroBooNE $6.67 \times 10^{20}$ POT

- LEE (10.0)
- $\nu_e$ CCQE (20.5)
- $\nu_e$ CC other (3.7)
- Background (2.8)
- Systematic Error
- Data (25)
Ran Itay, SLAC | The Two Body CCQE Exclusive Analysis Using Deep-Learning-Based Reconstruction

Backup Slides

\[ \sum \frac{\text{Data}}{\sum \text{Pred}} = 0.96 \pm 0.17 \text{ (sys)} \pm 0.20 \text{ (stat)} \]

MicroBooNE $6.67 \times 10^{20}$ POT

\[ \chi^2_{\text{NDF}} / 5.25/10 \]

\[ p_{\text{val}} : 0.76 \]

- LEE (10.0)
- $\nu_e$ CCQE (19.0)
- $\nu_e$ CC other (3.3)
- Background (2.8)
- Systematic Error
- Data (24)
Backup Slides

\[ \sum_{\text{Data}} / \sum_{\text{Pred}} = 0.93 \pm 0.14 \text{(sys)} \pm 0.19 \text{(stat)} \]

MicroBooNE 6.67 \times 10^{20} \text{ POT}

\[ \chi^{2}_{\text{NDF}} / \text{NDF} = 5.77/10 \]
\[ \rho_{\text{val}} = 0.80 \]

- LEE (10.0)
- \( \nu_e \) CCQE (20.5)
- \( \nu_e \) CC other (3.7)
- Background (2.8)
- Systematic Error
- Data (25)
Ran Itay, SLAC | The Two Body CCQE Exclusive Analysis Using Deep-Learning-Based Reconstruction

\[ \frac{\Sigma_{\text{data}}}{\Sigma_{\text{MC}}} = 0.93 \pm 0.19 \]

\[ \chi^2_{\text{NDF}} / \text{NDF} = 5.77 / 10 \]

\[ \rho_{\text{val}} = 0.80 \]

---

### Backup Slides

![Graph showing POT Normalized Count vs. Energy (MeV)](attachment:image.png)

- \( \nu_e \) CCQE (20.5)
- \( \nu_e \) Other (3.7)
- \( \nu_\mu \) CCQE (0.1)
- \( \nu_\mu \) Res \( n^+ \) (0.2)
- \( \nu_\mu \) Res \( n^0 \) (1.3)
- Off Vertex (0.9)
- \( \nu_\mu \) Other (0.2)
- Unfolded MB Excess (10.0)
- Data (25)

---

123 10/27/21 Ran Itay, SLAC | The Two Body CCQE Exclusive Analysis Using Deep-Learning-Based Reconstruction
Backup Slides

\[ \sum_{\text{Data}} / \sum_{\text{Pred}} = 0.93 \pm 0.14 \text{ (sys)} \pm 0.19 \text{ (stat)} \]

MicroBooNE 6.67 \times 10^{20} \text{ POT}

\[ \chi^2_{\text{NP/NDF}} = 3.99/8 \]

\[ p_{\text{val}} = 0.86 \]

- LEE (10.0)
- \( \nu_e \) CCQE (20.5)
- \( \nu_e \) CC other (3.7)
- Background (2.8)
- Systematic Error
- Data (25)
\[ \frac{\text{Data}}{\text{Pred}} = 0.93 \pm 0.19 \text{ (sys)} \pm 0.19 \text{ (stat)} \]

MicroBooNE 6.67 \times 10^{20} \text{ POT}

\[ \chi^2_{\text{NP}} / \text{NDF}: 5.77 / 10 \]
\[ \rho_{\text{val}}: 0.86 \]
Backup Slides

\[ \frac{\Sigma \text{Data}}{\Sigma \text{Pred}} = 0.93 \pm 0.14 \text{ (sys)} \pm 0.19 \text{ (stat)} \]

MicroBooNE 6.67 \( \times 10^{20} \) POT

\[ \chi^2_{NP}/NDF: 0.72/2 \]

\[ p_{\text{val}}: 0.70 \]
\[ \frac{\sum \text{Data}}{\sum \text{Pred}} = 0.90 \pm 0.15 \text{(sys)} \pm 0.22 \text{(stat)} \]

MicroBooNE $6.67 \times 10^{20}$ POT

$\chi^2_{NP}/\text{NDF}: 9.74/10$

$p_{\text{val}}: 0.57$

- LEE (10.0)
- $\nu_e$ CCQE (15.2)
- $\nu_e$ CC other (2.2)
- Background (2.6)
- Systematic Error
- Data (18)
Backup Slides

$\frac{\Sigma_{\text{Data}}}{\Sigma_{\text{Pred}}} = 0.93 \pm 0.15 \text{ (sys)} \pm 0.19 \text{ (stat)}$

MicroBooNE 6.67 $\times 10^{20}$ POT

$\chi^2_{\text{NP}}/\text{NDF}: 15.74/10$

$p_{\text{val}}: 0.15$

Data/Pred vs Bjorken X (Nucleon Rest Frame)
\[ \frac{\sum \text{Data}}{\sum \text{Pred}} = 0.93 \pm 0.15 \text{ (sys)} \pm 0.19 \text{ (stat)} \]

MicroBooNE 6.67 \times 10^{20} \text{ POT}
Backup Slides

\[ \frac{\sum \text{Data}}{\sum \text{Pred}} = 0.95 \pm 0.15 \text{ (sys)} \pm 0.20 \text{ (stat)} \]

MicroBooNE 6.67 \times 10^{20} \text{ POT}

- LEE (10.0)
- \( \nu_e \) CCQE (19.1)
- \( \nu_e \) CC other (3.3)
- Background (2.8)
- Systematic Error
- Data (24)
Backup Slides

**Hadron** MicroBooNE Simulation

**Detector** MicroBooNE Simulation

**Total** MicroBooNE

**Flux**

**XS**
Backup Slides

\[ \frac{\sum \text{Data}}{\sum \text{Pred}} = 1.08 \pm 0.14 \]

MicroBooNE $6.67 \times 10^{20}$ POT

- BNB $\nu_\mu$ CCQE (3322.23)
- Neutrino Background (694.07)
- BNB OffVtx (307.43)
- Cosmic Background (94.52)
- Systematic Error
- Data (4781)
Backup Slides

\[
\frac{\Sigma \text{Data}}{\Sigma \text{Pred}} = 1.07 \pm 0.14
\]

MicroBooNE 6.67 x 10^{20} POT

- BNB \(v_\mu\) CCQE (3029.09)
- Neutrino Background (581.66)
- BNB OffVtx (212.07)
- Cosmic Background (79.87)
- Systematic Error
- Data (4176)
Backup Slides

\[ \sum \frac{\text{Data}}{\sum \text{Pred}} = 1.08 \pm 0.13 \]

MicroBooNE 6.67 \times 10^{20} \text{ POT}

- BNB \( \nu_\mu \) CCQE (3369.27)
- Neutrino Background (699.15)
- BNB OffVtx (313.08)
- Cosmic Background (97.77)
- Systematic Error
- Data (4848)

BDT Ensemble Score Average

Event Count

Data/Pred
Updated MiniBooNE Electron-Like Excess with the Complete Dataset

APS April Meeting 2021
Nick Kamp for the MiniBooNE Collaboration
Overview

• Brief review of the MiniBooNE experiment
• Updated electron-like excess results with the complete neutrino mode dataset (18.75E20 protons-on-target)
• Explorations of the excess in different channels:
  • 2D energy/angle correlations
  • Timing distribution
  • Radial distribution
Overview

• Brief review of the MiniBooNE experiment

• Updated electron-like excess results with the complete neutrino mode dataset (18.75E20 protons-on-target)

• Explorations of the excess in different channels:
  • 2D energy/angle correlations
  • Timing distribution
  • Radial distribution
The MiniBooNE Experiment

• The MiniBooNE experiment uses a Cherenkov detector to measure the interactions of neutrinos produced in the Booster Neutrino Beam (BNB)

• Designed to look for muon-to-electron neutrino oscillations $L/E \sim 1$ (units) to test the oscillation interpretation of the LSND excess

LSND Collaboration, PRD 64 112007. 2001

The Booster Neutrino Beam

- The Booster Neutrino Beam (BNB) is created by irradiating a beryllium target with 8 GeV protons
- Neutrinos produced predominately by the charged meson decay
- The MiniBooNE detector sits 541 m away from the BNB target

The MiniBooNE Detector

- Mineral oil (CH$_2$) detector medium (high $n$, low Cherenkov threshold)
- 1520 photo-multiplier tubes covering the inner surface of the spherical detector
- Remarkable stability in the detector response over the 17 year lifetime

Michel Electron Energy

$\nu_\mu$ CCQE Muon Energy

$\pi^0$ Mass Peak

![Graphs showing Michel Electron Energy, CCQE Muon Energy, and $\pi^0$ Mass Peak for different data sets.](image-url)
The MiniBooNE Detector

**Electrons:** “fuzzy” rings from multiple scattering

**Muons:** “clean” rings from long, straight tracks

**Neutral Pions:** two rings from decay to two photons
Overview

• Brief review of the MiniBooNE experiment

• **Updated electron-like excess results with the complete neutrino mode dataset (18.75E20 protons-on-target)**

• Explorations of the excess in different channels:
  • 2D energy/angle correlations
  • Timing distribution
  • Radial distribution
Final Electron-Like Excess

- With the complete dataset, the excess of electron-like events is 4.8 sigma: \(638.0 \pm 52.1\) (stat) \(\pm 122.2\) (sys) events.
- Excess is consistent across the different run periods.
Oscillation Interpretation

- eV-scale oscillation parameter space consistent with LSND allowed region
- Additional excess above best fit at lowest energies
Overview

• Brief review of the MiniBooNE experiment
• Updated electron-like excess results with the complete neutrino mode dataset (18.75E20 protons-on-target)

• Explorations of the excess in different channels:
  • 2D energy/angle correlations
  • Timing distribution
  • Radial distribution
Electron Angle / Energy

- Significant portion of the excess in the low electron visible energy / scattering angle region of phase space
- In the most forward peaked region, the excess extends to higher visible energy
Timing Distribution

- The excess is contained within the expected 8 ns window around the beam bunch timing structure.
- Disfavors interpretations involving external neutrinos or beam-off events.
- Note: timing information available for second run period only.
Radial Distribution

- Shape fits to the radial distribution disfavor explanations of the excess involving external events or neutral pions

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Multiplicative factor</th>
<th>$\chi^2/\text{ndf}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC $\Delta \rightarrow N\gamma$ Background</td>
<td>3.18</td>
<td>10.0</td>
</tr>
<tr>
<td>External Event Background</td>
<td>5.98</td>
<td>44.9</td>
</tr>
<tr>
<td>$\nu_e$ &amp; $\bar{\nu}_e$ from $K^0_L$ Decay Background</td>
<td>7.85</td>
<td>14.8</td>
</tr>
<tr>
<td>$\nu_e$ &amp; $\bar{\nu}_e$ from $K^{\pm}$ Decay Background</td>
<td>2.95</td>
<td>16.3</td>
</tr>
<tr>
<td>$\nu_e$ &amp; $\bar{\nu}_e$ from $\mu^{\pm}$ Decay Background</td>
<td>1.88</td>
<td>16.1</td>
</tr>
<tr>
<td>Other $\nu_e$ &amp; $\bar{\nu}_e$ Background</td>
<td>3.21</td>
<td>12.5</td>
</tr>
<tr>
<td>NC $\pi^0$ Background</td>
<td>1.75</td>
<td>17.2</td>
</tr>
<tr>
<td>Best Fit Oscillations</td>
<td>1.24</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Example of a $\pi^0$ mis-ID
Conclusion

• The MiniBooNE excess has increased to 4.8 sigma following an analysis of the full 17-year dataset (18.75E20 POT)

• The excess has been explored in a number of new channels, indicating:
  • Preference for low visible energy / scattering angle
  • Consistency with the beam bunch timing
  • Inconsistency with events coming from outside the detector volume (via the radial distribution cut)

• More details can be found in Phys. Rev. D 103, 052002

• The associated data release for this analysis can be found at www-boone.fnal.gov/for_physicists/data_release/nue2020/
Backups
Radial Fits
Forward-Peaked Events
<table>
<thead>
<tr>
<th>Process</th>
<th>Neutrino Mode</th>
<th>Antineutrino Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ &amp; $\bar{\nu}_\mu$ CCQE</td>
<td>107.6 ± 28.2</td>
<td>12.9 ± 4.3</td>
</tr>
<tr>
<td>NC $\pi^0$</td>
<td>732.3 ± 95.5</td>
<td>112.3 ± 11.5</td>
</tr>
<tr>
<td>NC $\Delta \to N\gamma$</td>
<td>251.9 ± 35.2</td>
<td>34.7 ± 5.4</td>
</tr>
<tr>
<td>External Events</td>
<td>109.8 ± 15.9</td>
<td>15.3 ± 2.8</td>
</tr>
<tr>
<td>Other $\nu_\mu$ &amp; $\bar{\nu}_\mu$</td>
<td>130.8 ± 33.4</td>
<td>22.3 ± 3.5</td>
</tr>
<tr>
<td>$\nu_e$ &amp; $\bar{\nu}_e$ from $\mu^\pm$ Decay</td>
<td>621.1 ± 146.3</td>
<td>91.4 ± 27.6</td>
</tr>
<tr>
<td>$\nu_e$ &amp; $\bar{\nu}_e$ from $K^\pm$ Decay</td>
<td>280.7 ± 61.2</td>
<td>51.2 ± 11.0</td>
</tr>
<tr>
<td>$\nu_e$ &amp; $\bar{\nu}_e$ from $K^0_L$ Decay</td>
<td>79.6 ± 29.9</td>
<td>51.4 ± 18.0</td>
</tr>
<tr>
<td>Other $\nu_e$ &amp; $\bar{\nu}_e$</td>
<td>8.8 ± 4.7</td>
<td>6.7 ± 6.0</td>
</tr>
<tr>
<td>Unconstrained Bkgd.</td>
<td>2322.6 ± 258.3</td>
<td>398.2 ± 49.7</td>
</tr>
<tr>
<td>Constrained Bkgd.</td>
<td>2309.4 ± 119.6</td>
<td>400.6 ± 28.5</td>
</tr>
<tr>
<td>Total Data</td>
<td>2870</td>
<td>478</td>
</tr>
<tr>
<td>Excess</td>
<td>560.6 ± 119.6</td>
<td>77.4 ± 28.5</td>
</tr>
<tr>
<td>0.26% (LSND) $\nu_\mu \to \nu_e$</td>
<td>676.3</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Bunch Timing

[Diagram showing the process from Be Target to MiniBooNE Detector, with options for Dark Matter Production and Neutrino Production, connected by Fiber Optic to DAQ, and a data distribution graph with MC and Data statistics.]