First Results from MicroBooNE's Low Energy Excess Search

Guanqun Ge  Columbia University

on behalf of the MicroBooNE Collaboration

7th Symposium on Neutrinos and Dark Matter in Nuclear Physics
May 21st 2022
Outline

The Short-Baseline anomalies

MicroBooNE detector

Photon and Electron searches

Summary
The Liquid Scintillator Neutrino Detector (LSND)

**LSND** was a short-baseline liquid scintillator experiment at Los Alamos National Laboratory which took data from 1993-1998.

LSND used an extremely pure beam of $\bar{\nu}_\mu$ from $\pi^+$ decay to search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

$\bar{\nu}_e$ undergoes inverse beta decay

$$\bar{\nu}_e p \rightarrow e^+ n$$

3.8$\sigma$ excess observed suggesting neutrino oscillations occur with $\Delta m^2$ of 0.2~10 eV$^2$

Extra heavier neutrino?
The MiniBooNE experiment

MiniBooNE is a short-baseline mineral oil Cherenkov experiment at Fermi national accelerator laboratory, with its main goal to test for neutrino mass at $\Delta m^2 \sim 1\text{eV}^2$.

MiniBooNE is exposed to a different beam - Booster Neutrino Beam - which is on average $O(10)$ higher energy but has similar $L/E$ to LSND of $\sim 1\text{m}/\text{MeV}$.

$\bar{\nu}e p \rightarrow e^+ n$

$\nu_e n \rightarrow e^- p$

MiniBooNE ran collecting data for 17 years between 2002-2019, with periodic data releases.
The MiniBooNE Low Energy Excess (LEE)

Combining the MiniBooNE neutrino and antineutrino data, the overall significance of the excess is $4.8\sigma$.
Neutrino mode only

Both photon and electron produce fuzzy Cherenkov ring in MiniBooNE detector

→ In need of detector that can distinguish electrons from photons!
MicroBooNE! liquid argon time projection chamber 85 tonne of active mass on-axis 470m downstream the BNB

Guanqun Ge, Columbia U. | NDM 2022
MicroBooNE!

MicroBooNE
liquid argon time projection chamber
85 tonne of active mass
on-axis 470m downstream the BNB

BNB in neutrino mode > 99% $\nu_\mu/\bar{\nu}_\mu$, with
~0.5% $\nu_e$

$\nu_\mu$: 93.65%
$\bar{\nu}_\mu$: 5.79%
$\nu_e$: 0.51%
$\bar{\nu}_e$: 0.05%

arXiv:2110.13978
The main scientific goals of MicroBooNE:

- resolve the source of the MiniBooNE low-energy excess
- measure neutrino-argon interaction cross sections
- search for astrophysical phenomena and exotic physics

Meghna Bhattacharya: Recent neutrino cross-section results from MicroBooNE [Friday session]

Ivan Lepetic: Searching for Beyond the Standard Model Physics with MicroBooNE [Monday session]
MicroBooNE has completed its 5 years physics run from 2015-2020, with beam delivery corresponding to $O(10^{21})$ protons-on-target (POT), yielding the largest neutrino-argon interaction dataset!

In total 5 run periods, the result presented today is based on data collected during **Runs 1-3** (first 3 years of data corresponding to $6.8 \times 10^{20}$ POT)
By identifying the conversion distance of photon shower and higher deposited energy per length $dE/dx$, MicroBooNE is able to distinguish photon showers from electron showers.
MicroBooNE has investigated the explanation of MiniBooNE low-energy excess in two interpretations:

- Excess is photon, or
- Excess is electron

Both searches were developed using MicroBooNE open data (10% of whole Runs 1-3 dataset), and frozen before the full Runs 1-3 dataset was unblinded.
Excess is Photon

- $\pi^0$ misidentified background is constrained in-situ
- $\Delta$ radiative decay $\Delta \rightarrow N\gamma$ is not directly constrained

Flat scaling of 3.18 for neutral current $\Delta \rightarrow N\gamma$ events will be able to cover the excess
Photon search: Neutral Current $\Delta \to N\gamma$


Two topologies in MicroBooNE detector
Neutral Current $\Delta \rightarrow N\gamma$ Search

This is a very rare and elusive neutrino process.

In the whole Runs 1-3 data we expect only: 124.1 NC $\Delta \rightarrow N\gamma$ events

and need to be picked out from

$\sim$110,000 Single shower backgrounds

This analysis uses boosted decision trees (BDT)'s to target the key backgrounds to the NC $\Delta \rightarrow N\gamma$ signal. Leverage the kinematics and correlations of the $\Delta \rightarrow N\gamma$ decay products.
Neutral Current $\Delta \rightarrow N\gamma$ Search

1$\gamma$1p

1$\gamma$1p backgrounds are dominated by NC $\pi^0$ (89%), with negligible contributions from cosmics, dirt, intrinsic $\nu_e$ and CC$\pi^0$'s.

This is a 97.2% pure photon sample with electron rejection at 99.8% relative to all 1 track 1 shower events.

<table>
<thead>
<tr>
<th>Process</th>
<th>1$\gamma$1p</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC $\pi^0$ Non-Coherent</td>
<td>24.0</td>
</tr>
<tr>
<td>NC $\pi^0$ Coherent</td>
<td>0.0</td>
</tr>
<tr>
<td>CC $\nu_\mu$ 1$\pi^0$</td>
<td>0.5</td>
</tr>
<tr>
<td>CC $\nu_e$ and $\bar{\nu}_e$</td>
<td>0.4</td>
</tr>
<tr>
<td>BNB Other</td>
<td>2.1</td>
</tr>
<tr>
<td>Dirt (outside TPC)</td>
<td>0.0</td>
</tr>
<tr>
<td>Cosmic Ray Data</td>
<td>0.0</td>
</tr>
<tr>
<td>Total Background</td>
<td>27.0</td>
</tr>
<tr>
<td>NC $\Delta \rightarrow N\gamma$</td>
<td>4.88</td>
</tr>
<tr>
<td>LEE ($x_{MB} = 3.18$)</td>
<td>15.5</td>
</tr>
</tbody>
</table>

Overall 1$\gamma$1p NC $\Delta \rightarrow N\gamma$ efficiency 3.9%

Rejected 99.98% backgrounds, relative to all single reconstructed shower events.
Without the proton to help tag the vertex, the $1\gamma 0p$ selection has a lower NC $\Delta \rightarrow N\gamma$ purity and a more diverse category of backgrounds (Still very much NC $\pi^0$ dominant).

Despite this is is still a 83.2% pure photon sample with electron rejection is at 87.6%

Overall $1\gamma 0p$ NC $\Delta \rightarrow N\gamma$ efficiency **5.2%**

Rejected **99.8% backgrounds**, relative to all single reconstructed shower events
Dedicated $2\gamma$ Sample

To constrain the dominant background, and validate energy reconstruction, we have developed dedicated $\pi^0$ selection

- Negligible contributions from NC $\Delta \to N\gamma$
- High statistics (1130 candidate NC $\pi^0$ data events)
Final Result

**1γ1p**

- NC $\Delta \rightarrow N\gamma$
- LEE Model ($x_{MB}=3.18$)
- All Other Backgrounds
- Total Unconstrained Background & Error

**1γ0p**

- NC $\tau^0$ Resonant $\Delta(1232)$
- NC $\tau^0$ DIS
- NC $\tau^0$ Higher Resonances
- MicroBooNE $1\gamma1p$ Data ($6.80 \times 10^{20}$ POT)
- Total Unconstrained Background & Error

**Constraint** from $\pi^0$ sample has

- Overall drops expected backgrounds in $1\gamma1p$ by **24.1%**
- Reduces systematic uncertainty in $1\gamma1p$ from **29.8% → 17.8%**
Elevate this normalization scaling to a continuous parameter, $x_{\Delta}$, and perform a fit to extract the best fit and classical confidence intervals, via the Feldman-Cousins procedure.\(^\dagger\)

Nominal GENIE NC $\Delta \rightarrow N \gamma$ rate ($x_{\Delta} = 1$) within 1$\sigma$

$x_{\Delta} < 2.3$ at the 90% CL

\(^\dagger\)Phys. Rev. D 57, 3873 (1998)
- Unfold MiniBooNE result and attribute the difference between the data and simulation to an excess of $\nu_e$ in the beam
- Apply energy-dependent weights to the rate of intrinsic $\nu_e$ event prediction in MicroBooNE
Electron Search

Assume enhancement of intrinsic $\nu_e$ events as a function of true $\nu$ energy

Expected $\nu_e$ charge current events in the MicroBooNE detector with (without) $\nu_e$-like excess for Runs 1-3 data.

MicroBooNE Simulation

Scaled to $6.4 \times 10^{20}$ POT
- MC prediction without LEE
- LEE ($x=1$) prediction

Event counts / 100 MeV

True $E_\nu$ (MeV)

Unfolded MiniBooNE LEE Model

arXiv:2110.14080
MicroBooNE has 3 analyses targeting different event topologies and developed with different reconstruction techniques!
Electron Search

MicroBooNE has 3 analyses targeting different event topologies and developed with different reconstruction techniques!

1e0p0π

1eNp0π (N >= 1)

Pandora Reconstruction
MicroBooNE has 3 analyses targeting different event topologies and developed with different reconstruction techniques!
Electron Search: DL based, exclusive

1e1p

The overall selection efficiency for $\nu_e$ CCQE events is \( \sim 6.6\% \)

highly pure (75\%) $\nu_e$ CCQE events

$\sum_{\text{Data}/\Sigma_{\text{Pred}} = 0.91 \pm 0.14 \text{ (sys)} \pm 0.19 \text{ (stat)} \quad \text{MicroBooNE} \quad 6.67 \times 10^{20} \text{ POT}$
Electron Search: DL based, exclusive

highly pure (75%) $\nu_e$ CCQE events

the overall selection efficiency for $\nu_e$ CCQE events is $\sim 6.6\%$

Because of low statistics (caused by small $\nu_e$ component of $\sim 0.5\%$ in the beam), high statistic $1\mu1p$ sample is used to constrain the background and systematic uncertainties in 1e1p measurement.
Electron Search: DL based, exclusive

\[ \frac{\Sigma \text{Data}}{\Sigma \text{Pred}} = 0.91 \pm 0.14 \text{ (sys)} \pm 0.19 \text{ (stat)} \]

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

- LEE (10.0)
- \(\nu_e\) CCQE (20.5)
- \(\nu_e\) CC other (3.7)
- Fitted
- Background (3.2)
- Systematic Error
- Data (25)

Because of low statistics (caused by small \(\nu_e\) component of \(\sim 0.5\%\) in the beam), a high statistic \(1\mu \nu e\) sample is used to constrain the background and systematic uncertainties in the \(1e1p\) measurement.

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

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

- BNB \(\nu_e\) CCQE (3369.27)
- Neutrino Background (699.15)
- BNB OffVtx (313.08)
- Cosmic Background (97.77)
- Systematic Background (4848)
After constraint, the uncertainties on the 1e1p are dominated by the **statistical** uncertainties.
Electron Search: DL based, exclusive

- Best-fit value at LEE signal strength of $x_{\text{LEE}} = 0$
- The 90% confidence interval has an upper bound at $x_{\text{LEE}} \leq 0.25$
- The 2σ interval has an upper bound at $x_{\text{LEE}} = 0.38$
MicroBooNE rejects the hypothesis that $\nu_e$ CC interactions are fully responsible for MiniBooNE LEE at >97% CL for both exclusive (1e1p CCQE, 1eNp0π) and inclusive (1eX) event classes.
MicroBooNE's first LEE results!

These results strongly disfavour the possibility of the MiniBooNE low-energy excess being entirely due to an increased $\nu_e$ rate or enhanced single-photons from NC $\Delta \rightarrow N\gamma$ decays.
Summary

- MicroBooNE has released its first results on investigation on MiniBooNE low-energy excess.
- Data from first 3 runs disfavors excess entirely due to an increased $\nu_e$ rate or due to enhanced single-photons from NC $\Delta \rightarrow N\gamma$ decays.
- While all analyses presented today are statistics limited, data from Runs 4 and 5 is under validation and will be bring 1x more statistics.
- MicroBooNE are expanding our first results to a wider range of possible explanations, motivated by the surge in theoretical ideas.
- Watch out for new results at Neutrino 2022 and summer conferences!
Backup Slides
Neutral Current $\Delta \rightarrow N\gamma$ Search Final Result

### $1\gamma 1p$

- NC $\Delta \rightarrow N\gamma$
- NC $1\pi^0$ Non-Coherent
- BNB Other
- Dirt (Outside TPC)
- Total Background and Error
- BNB Data, Total: 16

### $1\gamma 0p$

- NC $\Delta \rightarrow N\gamma$
- NC $1\pi^0$ Non-Coherent
- BNB Other
- Dirt (Outside TPC)
- Total Background and Error
- BNB Data, Total: 153

---

Electron Search: Pandora based, semi-inclusive

1eNp0π (N>0)

- 1eNp0π yields 80% $\nu_e$ purity and 15% selection efficiency for true 1eNp0π.
- 1e0p0π yields 43% $\nu_e$ purity with lower selection efficiency of 9% for true 1e0p0π events.
- Inclusive sample of $\nu_\mu$ CC events is used to constrain $\nu_\mu$ background and systematic uncertainties.
Electron Search: WireCell based, inclusive

before constraint

- 82% purity and 46% selection efficiency for $\nu_e$ CC events
- Constraint from other 6 channels including partially contained $\nu_e$ CC sample and various $\nu_\mu$ and $\pi^0$ channels

after constraint

arXiv:2110.13978
Electron Search: summary

![Graph showing MicroBooNE observed and predicted events with and without eLEE.]

- MicroBooNE Observed
- Predicted, no eLEE ($x = 0.0$)
- Predicted, w/ eLEE ($x = 1.0$)

![Graph showing eLEE signal strength for different events.]

- MicroBooNE Observed (1, 2σ)
- Expected, no eLEE (2σ)
- MiniBooNE approx. (±1σ)

ArXiv:2110.14054

Guanqun Ge, Columbia U. | NDM 2022