Results from the MicroBooNE Low-Energy Excess Search

Ivan Caro Terrazas - Colorado State University
On Behalf of the MicroBooNE Collaboration
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Anomalies at Short Baselines

**LSND**  *PRD 64, 112007 (2001)*
- Measure neutrino oscillations
- $\nu_\mu$ beam from pions-at-rest
- $\langle E_\nu \rangle = \sim 30 \text{ MeV}; L = \sim 30 \text{ m}$
- Excess at 3.8$\sigma$

**MiniBooNE**  *Phys. Rev. D 103, 052002*
- $\nu_\mu$ beam from accelerator
- $\langle E_\nu \rangle = \sim 500 \text{ MeV}; L = \sim 500 \text{ m}$
- Similar L/E as LSND
- Excess at 4.8$\sigma$
Anomalies at Short Baselines: MiniBooNE

• Cherenkov detector
  • Signal is a single electromagnetic shower; $e^-/\gamma$ indistinguishable
  • Only sensitive to particles above the Cherenkov threshold:
    • No sensitivity to protons
• Possible sources for the anomaly:
  • $\nu_e$ excess
  • $\Delta \rightarrow N\gamma$

\[ \nu_{\mu} \rightarrow \nu_e + n \rightarrow e^- + p \]
\[ \nu_e + C \rightarrow 1eXp0\pi \]

γ vs. $e^-$ Cherenkov rings

Phys. Rev. D 103, 052002
The MicroBooNE Experiment

• “Micro Booster Neutrino Experiment” (MicroBooNE)
• Uses a Liquid Argon Time Projection Chamber (LArTPC) as the detector technology
  • $e/\gamma$ separation
• 170-ton (89-ton active volume) LArTPC
• Sits on two beam lines:
  • BNB: On-Axis
  • NuMI: Off-Axis
Status of MicroBooNE

• Collected $\sim 1.5 \times 10^{21}$ protons-on-target (POT) from 2015 to 2021
  • Analysis shown here uses a subset of full data
• Detector operated smoothly, with 96% detector + DAQ uptime
MicroBooNE Goals

LArTPC R&D
- Noise filtering
- Signal processing
- Energy reconstruction
- Detector Calibrations

ν-Ar Cross-Sections
- Explore low energy ν-Ar scattering
- Test ν-Ar models

Exotic Physics
- Test Higgs portal model
- Dark sector
- Heavy neutral leptons

Anomaly Search
- Test MiniBooNE findings
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Anomaly Search
- Test MiniBooNE findings

See Daisy Kalra’s talks tomorrow!

This Talk

Phys. Rev. Lett. 127, 151803

Phys. Rev. D 103, 052002
LArTPC Event

NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.

Color shows deposited energy

X-axis (Drift Direction)

Z-axis (Beam Direction)

17 cm
LArTPC Event

Tracks: Protons, Muons, Pions

Color shows deposited energy

NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.
LArTPC Event

Electromagnetic Showers: electron

Color shows deposited energy

NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.
Main draw of LArTPCs is that they can separate photons from electrons
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• Fine spatial resolution
Main draw of LArTPCs is that they can separate photons from electrons
- Fine spatial resolution
- Calorimetry

Pair production from photons produces twice the number of minimally ionizing electrons, so has twice the charge deposited at the start of the shower
Anomaly Search

NCΔ Single-Photon Search

- $NC \Delta \rightarrow N\gamma$
- Shower detached from the neutrino vertex
- Single Photon
- arXiv:2110.00409, accepted by PRL

Electron Search

- Three $\nu_e$ Searches
- Shower attached at the neutrino vertex
- Single electron
  and arXiv:2110.13978 accepted to PRD
Anomaly Search

NC$\Delta$ Single-Photon Search

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Electron Search

- Three $\nu_e$ Searches
- Shower attached at the neutrino vertex
- Single electron
• Standard model process
  • Predicted Br $\Delta(1232) \rightarrow N\gamma$ is $< 1\%$
• To date, never directly observed in neutrino scattering
• Enhancement of $\Delta \rightarrow N\gamma$ signal $x3.18$ would agree with observed anomaly at MiniBooNE

arXiv:2110.00409, accepted by PRL
NCΔ Single-Photon Search: Analysis

• Utilize Pandora Multi-Algorithmic Reconstruction [EPJC 78, 182 (2018)]

• Major challenge is $NC\pi^0$ backgrounds:
  • Second shower difficult to reconstruct

• Leverage five BDTs to target key backgrounds
  • Cosmic activity, two focusing on $NC\pi^0$, $CC\nu_e$, other backgrounds from the BNB

• Backgrounds further constrained with high-purity $NC\pi^0$ sample

arXiv:2110.00409, accepted by PRL
NCΔ Single-Photon Search: Selected Events

• Signal for $\Delta \rightarrow N\gamma$: $1\gamma 1p$ and $1\gamma 0p$

$arXiv:2110.00409$, accepted by PRL
NCΔ Single-Photon Search: Results

- Disfavor NC Delta radiative decay interpretation of the MiniBooNE LEE at the 94.8% CL

arXiv:2110.00409, accepted by PRL
Anomaly Search

**NCΔ Single-Photon Search**

- \( NC \Delta \rightarrow N\gamma \)
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**Electron Search**

- Three \( \nu_e \) Searches
- Shower attached at the neutrino vertex
- Single electron
Electron Search: Analysis Topologies

- $\nu_e + Ar \rightarrow 1e1p0\pi$
  - Deep learning approach
  - Low to medium energy $\nu_e$
  - Targeting CCQE interactions

- $\nu_e + Ar \rightarrow 1eXp0\pi$
  - Pandora reconstruction
  - Low to medium energy $\nu_e$
  - Two channels: 0p and Np ($N>0$)
    - MiniBooNE signal

- $\nu_e + Ar \rightarrow 1eX$
  - Wire-Cell reconstruction
  - High statistics
  - Inclusive selection

arXiv:2110.13978, submitted to PRD

arXiv:2110.14080v2, accepted by PRD

arXiv:2110.14065, accepted by PRD
Electron Search: Constraint and Systematic Uncertainties

- Use high-statistics $\nu_\mu$ sample to constrain $\nu_e$ uncertainties
- Flux: $\nu_\mu$ and $\nu_e$ come from same beam
- Cross-Section: $\nu_\mu$ and $\nu_e$ share $\nu$-Ar interaction model
- Validate neutrino rate modeling
- Constrain uncertainties on prediction:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Reduction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1e1p0\pi$</td>
<td>2.0</td>
</tr>
<tr>
<td>$1eNp0\pi$ and $1e0p0\pi$</td>
<td>1.7</td>
</tr>
<tr>
<td>$1eX$</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Electron Search: $e^-/\gamma$ Separation – Conversion distance

- Distance between start point of shower and track
- Photon-induced showers are detached from neutrino vertex

\[ \nu_e \text{ Candidate} \]

\[ \nu_e \quad \text{No Gap} \]

\[ \nu_e \quad \text{10 cm} \]

BNB Run: 16341 Subrun: 27 Event: 1359
Electron Search: $e^-/\gamma$ Separation – $dE/dx$

- Amount of energy deposited per unit length ($dE/dx$) at start of shower
- Median of first 4 cm of shower trunk

$\nu_e$ Candidate
Electron Search: Selections

- Blind analysis: Use data that is not in the signal region to validate analysis
- Examples:
  - Each analysis employs Boosted Decision Trees (BDT):
    - Further separate $\nu_e$ from other background
    - Cut on BDT score is chosen to provide high purity

Examples:

1eνπ0ν selection

MicroBooNE 6.86 x10^{20} POT
- Dirt (Outside TPC)
- $\nu_e$ CC
- $\nu$ other
- $\nu$ with π^0
- BNB Data

1eνπ0ν selection

MicroBooNE 2.00 x10^{20} POT
- Dirt (Outside TPC)
- $\nu_e$ CC
- $\nu$ other
- $\nu$ with π^0
- NuMI Data

Shower Transverse Development [degrees]

Electron Search: Selections

- Blind analysis: Use data that is not in the signal region to validate analysis
- Examples:
  - Each analysis employs Boosted Decision Trees (BDT):
    - Further separate $\nu_e$ from other background
    - Cut on BDT score is chosen to provide high purity
Electron Search: Selected Events

RUN 8617 SUBRUN 46 EVENT 2328

14 cm

BNB Run: 9727 Subrun: 138 Event: 6929

17 cm

BNB Run: 8590 Subrun: 136 Event: 6839

11 cm

BNB Run: 11001 Subrun: 42 Event: 2145

8 cm
Electron Search: $\nu_e$ Energy Spectra

1eNp0π

1e0p0π

1eX

1e1p0π
Observations show $\nu_e CC$ event rates in agreement, or below, the predicted rate.

- We reject our simple eLEE model at >97% CL for both exclusive ($1e1p$ CCQE, $1eNp0\pi$) and inclusive ($1eX$) event classes.
- $1e0p0\pi$ shows slight excess
  - Low sensitivity
  - $\gamma$ background dominated
- We disfavor generic $\nu_e$ interactions as the primary contributor to the excess

Electron Search: Results

arXiv:2110.14054, accepted to PRL
• First search for MiniBooNE low-energy excess in MicroBooNE was performed
• No evidence for excesses of $\nu_e$ or $NC\Delta \rightarrow N\gamma$
• MicroBooNE actively pursuing new measurements to explain MiniBooNE anomaly
  • See Daisy’s Talks tomorrow!
Thank You!

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Neutrinos in the Standard Model

• Neutrinos come in three flavors in the Standard Model: electron, muon and tau
• Only neutral leptons
• Only interact via the weak interaction and gravity
• Neutrinos Oscillates:
  • Propagate as mass states, interact as flavor states
  • Produce some neutrino $\nu_\alpha$ and detect it as $\nu_\beta$
Neutrino Oscillations

Probability of detecting a neutrino of a given flavor oscillates as:

\[ P(\text{osc}) \sim \sin^2 \left( \frac{1.27 \Delta m_{ij}^2 L}{E} \right) \]

\[ \Delta m_{ij}^2 = m_i^2 - m_j^2 \]
Accelerator Neutrinos

- Accelerator neutrino experiments use a neutrino beam from the decay of (mostly) pions and kaons.
- Neutrinos categorized by distance of flight L and energy E:
  - Short-baseline experiments have $L/E \sim 1 \text{ km/GeV}$ (not sensitive to three-flavor oscillations)
  - Long-baseline experiments have $L/E \sim 10^3 \text{ km/GeV}$
Liquid Argon Time Projection Chamber (LArTPC)

- Impinging charged particles leads to ionization of argon
- Scintillation light also produced \( \sim O(ns) \)
  - Excitation (Ar*)
  - Recombination
- Ionization electrons drift according to electric field \( \sim O(ms) \)
Understanding the Detector: Modeling

Space charge effects modify local E-field

Noise filtering and signal processing improve signal-to-noise ratio

JINST 15 P07010

JINST 12 P08003
JINST 13 P07006
JINST 13 P07007
Understanding the Detector: Calibrations

MicroBooNE TPC Calibration: [JINST 15 P03022](https://jinst.science/abstract/1503.03022)
Electric Field Calibrations: [JINST 15 P07010](https://jinst.science/abstract/1507.010) & [JINST 15 P12037](https://jinst.science/abstract/1512.037)
EM Shower Calibrations: [JINST 15 P02007](https://jinst.science/abstract/1502.007), [JINST 09 P09014](https://jinst.science/abstract/0909.014) & arXiv:2110.11874

Proton dE/dx vs residual range
Key to particle ID


Invariant mass from $\pi^0 \rightarrow \gamma\gamma$
Key to electron energy scale

[JINST 15 P02007](https://jinst.science/abstract/1502.007)
Characterizing $\nu_e$ Events: Track Identification

- Likelihood function to evaluate $dE/dx$ relative to particle range
• Classification of $\nu_e$ from other background
• No weight on energy, no use of kinematics related variables

1eNp0$\pi$

1eNp0$\pi$ $\nu_e$ selection

MicroBooNE 6.86 $\times 10^{20}$ POT

- Dirt (Outside TPC)
- $\nu_e$ CC
- Cosmics
- $\nu$ other
- $\nu$ with $n^\circ$

2 BDTs
16 variables

MicroBooNE 4.05 $\times 10^{18}$ POT

- Rate (inside TPC)
- $\nu_e$ CC
- Cosmics
- $\nu$ other
- $\nu$ with $n^\circ$

1e0p0$\pi$

1e0p0$\pi$ $\nu_e$ loose selection

MicroBooNE 6.86 $\times 10^{20}$ POT

- Dirt (Outside TPC)
- $\nu_e$ CC
- Cosmics
- $\nu$ other
- $\nu$ with $n^\circ$

1 BDT
28 variables
Sidebands: Background Validation

- Blind analysis: Use data that is not in the signal region to validate analysis
- Background rich samples: Low-BDT and two shower sidebands
  - Good data-simulation agreement of selection variables
Sidebands: NuMI

- **Blind analysis**: Use data that is not in the signal region to validate analysis

- **Background rich samples**: Low-BDT and two shower sidebands
  - Good data-simulation agreement of selection variables

- **NuMI samples**:
  - High intrinsic $\nu_e$ relative to BNB
  - Selections not tuned on NuMI data: applied after frozen, before unblinding BNB data
Electron Search: Excess Model

- Unfold MiniBooNE excess under a $\nu_e$ hypothesis
  - Only considers $E_\nu$ dependence
- Apply scaling to MicroBooNE intrinsic $\nu_e$ component
Analysis Strategy

1) Event Reconstruction

2) Neutrino Event Identification and Characterization

3) Variable creation and Event Selection

4) Statistical Analysis and Signal Strength Measurement
Anomalies at Short Baselines

**LSND**

- Cherenkov detector
- Measure neutrino oscillations
- Observed a possible $3.8\sigma$ excess of $\bar{\nu}_e$-like events
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation could be associated to potential sterile neutrinos

\[
\bar{\nu}_\mu \xrightarrow{\text{oscillation}} \bar{\nu}_e + p \rightarrow e^+ + n, \quad n + p \rightarrow d + \gamma
\]
• In the Standard Model, neutrinos are created and detected via weak interactions mediated by the $W$ and $Z$ bosons
  • Charged current interactions are mediated by the $W$ boson
  • Neutral current interactions are mediated by the $Z$ boson
• Charged current interactions couple the neutrinos to their charged lepton counterparts
Neutrino Oscillations

- Neutrinos oscillate between different flavors in flight
- First observed by the Homestake experiment in the 60’s
- Oscillations confirmed by Super-Kamiokande in the 90’s

Electron Neutrinos from the Sun
Homestake Experiment – 1960’s

Muon neutrinos from the atmosphere
Super-Kamiokande - 1998

Legend
- Expected
- Measured

Expected number without oscillations
Observed number with oscillations
On the Surface Detector

- Surface LArTPC + slow e- drift → large cosmic background
- O(10) cosmic rays/event
Signal Processing Chain

Drifting Electrons

Field Response

Signal on Wire

Electronics Response

Shaped/Amplified Signal

Digitization

Signal Data Acquisition

Deconvolution

Extraction of Charge from Signal

Response Functions (Field + Electronics)

Signal Deconvolution

Estimated Sig = \frac{\text{Measured Sig.}}{\text{Resp. Func.}} \ast \text{Filter Func.}

Frequency Domain

Induced Signals on Neighboring Wires

- **1D Deconvolution**: Time Domain
- **2D Deconvolution**: Time AND Wire Domain