Status of the MicroBooNE 
Low Energy Excess Search

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1. History of Low Energy Neutrino Anomalies
2. MicroBooNE Detector
3. Anomaly Search Strategies
4. Results
5. Summary
Anomalies at Short Baselines

LSND

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

$$\bar{\nu}_\mu \overset{\text{oscillation}}{\rightarrow} \bar{\nu}_e + p \rightarrow e^+ + n$$
$$n + p \rightarrow d + \gamma$$
MiniBooNE

- Cherenkov detector
  - Signal is a single electromagnetic shower; $e^-/\gamma$ indistinguishable
  - No sensitivity to protons
- Latest results give a 4.5σ excess in $\nu_e$-like events at low energies (200 MeV – 600 MeV)

Excess can be a result of photonic background (red, beige, brown)

\[
\nu_u \rightarrow \nu_e + n \rightarrow e^- + p \\
\nu_e + C \rightarrow 1eXp0\pi
\]

Overlapping $e^-/e^+$

\[\gamma \text{ vs. } e^- \text{ Cherenkov rings}\]

\[\text{PRL 121, 221801 (2018)}\]
MicroBooNE

- Uses a Liquid Argon Time Projection Chamber (LArTPC) as the detector technology
  - $e^-/\gamma$ separation
- Investigate and characterize the nature of the MiniBooNE excess
- Two Beamlines:
  - BNB: On Axis
  - NuMI: Off Axis
MicroBooNE

• Uses a Liquid Argon Time Projection Chamber (LArTPC) as the detector technology
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• Two Beamlines:
  ➢ BNB: On Axis
  ➢ NuMI: Off Axis
• Part of the Short Baseline Neutrino (SBN) Program (See Matt Toups talk tomorrow!) along with ICARUS (Biswaranjan Behera)
Status of MicroBooNE

- Taking neutrino data since October 2015; now the longest-running LArTPC detector
- Detector has operated smoothly, with 96% detector + DAQ uptime
- Currently have about 500k neutrino interactions recorded in MicroBooNE
MicroBooNE LArTPC

Drift Time

Wire Number

Color indicates charge deposited

Z-axis (Beam Direction)

17 cm

X-axis (Drift Direction)

Color shows deposited energy

NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.
Tracks: Protons, Muons, Pions

Color shows deposited energy

X-axis (Drift Direction)

Z-axis (Beam Direction)

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

Electromagnetic Showers: electron-like

Color shows deposited energy

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

X-axis (Drift Direction)

Z-axis (Beam Direction)

17 cm
$e^-/\gamma$ Separation in LArTPCs

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

- Gap between the neutrino interaction vertex and the start of the shower
- Amount of energy deposited per unit length in the trunk of the shower — $e^-$ is one MIP, $\gamma \to e + e^-$ is two MIPs

MICROBOONE-NOTE-1054-PUB
How to Resolve the LEE Anomaly

Understand the Detector
- Signal Processing
- Calibrate Detector Response

Understand $\nu$-Ar Interactions
- Explore low energy $\nu$-Ar scattering
- Test models

Constrain Systematics
- Flux
- Cross Section
- Detector

Search for the Excess
- Define channel
- Develop selection
- Search for anomalous excess
How to Resolve the LEE Anomaly

Understand the Detector
• Signal Processing
  ➢ JINST 12, P08003 (2017)
  ➢ JINST 13, P07006 (2018)
  ➢ JINST 13, P07007 (2018)
• Calibrate Detector Response
  ➢ arXiv:1907.11736

Constrain Systematics
• Flux
• Cross Section
• Detector

Search for the Excess
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Previous talk by Sebastien Prince
MicroBooNE is pursuing two main signal hypotheses:

- Electrons from $\nu_e$
- Photons from $NC \Delta \to N\gamma$

For each signal hypothesis, a few possible channels

For $\nu_e$:

- $\nu_e + Ar \to e^- \ (1e0p)$
- $\nu_e + Ar \to e^- + Np \ (1eNp)$
- $\nu_e + Ar \to e^- + X \ (\text{inc.})$
- Etc...

For $NC \Delta \to N\gamma$:

- $\nu + Ar \to \gamma \ (1\gamma0p)$
- $\nu + Ar \to \gamma + 1p \ (1\gamma1p)$
- Etc..

Unfolding method described in MICROBOONE-NOTE-1043-PUB
Search for the Excess

**Electron-Like Searches**

**WireCell Reconstruction**

Tomographic reconstruction
3D Imaging -> 3D Reco

3D Space Point Creation

Clustering

**Deep Learning Reconstruction**

Uses CNNs for PID and track/shower pixel labels

**Photon-Like Searches**

**Pandora Multi-Algorithm Reconstruction**

Clustering charge independently on each wire-plane before matching across planes to make a 3D reconstructed object

2D Imaging -> 2D Reco -> 3D Reco

*MicroBooNE-Note-1040-PUB*

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JINST 12, P03011 (2017)

PRD 99, 092001 (2019)

EPJC 78, 182 (2018)
Low Energy Excess Strategies

Photon-Like Search

- Shower detached from the neutrino vertex
- Shower $dE/dx$ of two MIPs

Electron-Like Search

- Shower attached at the neutrino vertex
- Shower $dE/dx$ of one MIP
Photon-Like Search

- One of the larger backgrounds at MiniBooNE
- $NC \Delta \rightarrow N\gamma$ never observed in neutrino scattering, uncertainty in the measured cross section.
- Investigating $1\gamma 1p$ and $1\gamma 0p$ to maximize statistics
- Major Challenge is the $NC \pi^0$ backgrounds:  
  - Second Shower difficult to reconstruct
- Using Boosted Decision Trees to distinguish signal from cosmics and other backgrounds

MICROBOONE-NOTE-1041-PUB
$\nu_e CC$ Topologies

- One Electron and at Least One Proton
  
  $\nu_e + Ar \rightarrow 1eNp0\pi$

- Only One Electron
  
  $\nu_e + Ar \rightarrow 1e0p0\pi$

- One Electron Inclusive
  
  $\nu_e + Ar \rightarrow 1eXpX\pi$

- Tracks available means easier time finding vertex
- Main channel for sensitivity
- MiniBooNE signal: $\nu_e + C \rightarrow 1eXp0\pi$
- Single shower search
- Shower $dE/dx$ helps distinguish signal from background
- Constrain event migration $1eNp0\pi \leftrightarrow 1e0p0\pi$
- Proton Uncertainties:
  - Reconstruction
  - Multiplicity
  - Kinematics
- Tracks available means easier time finding vertex
- Channel with highest statistics
- Constrains high energy intrinsic $\nu_e$
BNB $\nu_e CC$ Search

- Initial representation of $1eNp0\pi$ selection
  - Efficiency: 46% and Purity: ~1%
  - High level of cosmic activity present
- Additional improvements are in development:
  - Cosmic Ray Tagger for cosmic backgrounds
  - More signal samples, improved reconstruction
- Cross-check sidebands on 3.5% of the total BNB data

\[ \nu_\mu CC \text{ enriched sideband} \]

\[ \chi^2 / \text{n.d.f.} = 1.00 \]
\[ \text{Data} / (\text{MC} + \text{EXT}) = 1.01 \]

\[ \chi^2 / \text{n.d.f.} = 0.45 \]
\[ \text{Data} / (\text{MC} + \text{EXT}) = 0.95 \]
NuMI $\nu_e CC$ Search

- Signal events pile up at NuMI beam geometry (at $\theta \approx 20^\circ$ and $\varphi \approx 8^\circ$)
- Efficiency: 9%, Purity: 40%

MICROBOONE-NOTE-1054-PUB
νμ and νe have much in common:

- Flux: both species of neutrinos come from the same beam, from decays of the same populations of hadrons
- Cross-Section: Both neutrinos interact with argon nuclei
$\nu_\mu$ Constraining Uncertainties

- Booster Neutrino Flux Prediction at MicroBooNE
- BNB $\nu_\mu$ selection used to supplement $\nu_e$ search
- High statistics for BNB $\nu_\mu$ flux can be used to constrain low statistics of the $\nu_e$ sample
- High correlation between neutrino species at low energies

Correlation matrix for the true neutrino energies of the BNB including cross-species correlations

MICROBOONE-NOTE-1031-PUB
MicroBooNE has made significant progress towards analyses that will test the electron- or photon-like nature of the MiniBooNE excess

- Explicit selections targeting both electron and photon channels
- NuMI events used to test shower reconstruction tools
- \( \nu_\mu \) sample is being used to constrain flux and cross section systematic uncertainties

Look forward to more results in the near future!
¡Muchas Gracias!