New Results from MicroBooNE

Pip Hamilton

on behalf of the MicroBooNE collaboration
Overview

• **MicroBooNE’s Physics Mission**
  - LArTPC Reconstruction
  - Cross-Section Studies
  - Seeking the Low-Energy Excess

• **New Neutrino Cross-Section Results**
  - Charged Particle Multiplicity Study
  - Charged Current $\pi^0$ Cross-Section
  - Charged Current Inclusive Cross-Section

• **Progress Towards $\nu_e$ Appearance**

• **Conclusions**
MicroBooNE’s Physics Mission
LArTPC Reconstruction

- LArTPCs give bubble chamber-like image resolution, with much higher data rates (at short baselines).
  - Images of interactions have lots of fine detail features.
  - Reconstruction must be automated.
- MicroBooNE provides LArTPC data of the volume and quality needed to develop reconstruction techniques for future LArTPC neutrino detectors (e.g. SBND, DUNE).
  - Shared LArSoft reconstruction software.
- MicroBooNE uses multiple reconstruction approaches to explore which techniques are optimal for neutrino interaction analyses.
  - Wire Cell
  - Pandora
  - Deep Learning
Larger detectors such as DUNE (and longer exposures on existing experiments such as NOvA and T2K) are moving us ever further into the systematically limited regime of neutrino oscillation measurements.

Reconstructing the neutrino energy is highly dependent on our understanding of neutrino-nucleus cross-sections.

MicroBooNE offers the opportunity to perform high-statistics cross-section measurements on Ar.

- High resolution imaging ⇒ access to many exclusive channels, providing strong test of nuclear models.
- Comparative lack of data on Ar.
- Ar is a large nucleus!
Seeking the Low-Energy Excess

- The MiniBooNE low-energy excess is not going away.
  - $\nu_e$ appearance at short baseline $\Rightarrow$ sterile neutrinos $\Rightarrow$ new physics?

- MicroBooNE sits in the same beam, at approximately the same baseline.

- With LArTPC imaging capabilities, MicroBooNE has an enhanced ability to distinguish backgrounds.

The MiniBooNE neutrino mode data, showing the persistent excess at $E^{QE}_\nu < 0.5$ GeV.

Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment, arXiv:1805.12028
New Cross-Section Results from MicroBooNE
New Cross-Section Results

MicroBooNE has recently produced 3 cross-sections:

- Charged Particle Multiplicity
- CC-$\pi^0$
- CC-inclusive

All are cut-based selections addressing similar challenges:

- Cosmic mitigation
- Vertex identification
- Containment

http://venu.physics.ox.ac.uk
Charged Particle Multiplicity

- MicroBooNE’s first published physics result!
- The number of charged particles ejected from a neutrino interaction provides a powerful probe of nuclear models.
  \[ \rightarrow \text{an important measurement for improving neutrino generators} \]

Charged Particle Multiplicity

- Results consistent with GENIE models (default, MEC, TEM) within $2\sigma$ – require more statistics for stronger model discrimination.
- Results favour lower multiplicities.

CC-Inclusive Cross-Section

- First and simplest cross-section channel to measure.
- Provides benchmark to other experiments.
- Direct bearing on DUNE oscillation signal.
CC-Inclusive Cross-Section

- Selection detailed in public note MICROBOONE-NOTE-1045-PUB, 2018
- Double differential cross-section coming soon!
CC-\(\pi^0\) Cross-Section

\(\nu_\mu \rightarrow \mu \rightarrow W \rightarrow \Delta^+ \rightarrow \pi^0 \rightarrow \gamma \gamma\)

\(\pi^0\) production is a critical background for low-energy excess searches: produces EM showers similar to \(\nu_e\) appearance signal.

\(\Rightarrow\) this measurement is a good test of our shower reconstruction.

MicroBooNE has measured the first CC-\(\pi^0\) cross-section on Ar.
CC-\(\pi^0\) Cross-Section

- Selected events correctly reproduce expected \(\pi^0\) invariant mass.
- Selection described in public note MICROBOONE\-NOTE-1032-PUB, 2018

\[ \langle \sigma_{\nu\mu}^{\nu cc\pi^0} \rangle_\Phi = (1.94 \pm 0.16 \text{ [stat.]} \pm 0.60 \text{ [syst.]}) \times 10^{-38} \text{ cm}^2 \text{ Ar} \]

\(\pi^0\) mass = 135 MeV
Progress Towards $\nu_e$ Appearance
Progress Towards $\nu_e$ Appearance

- Multiple complementary analyses.
- Blind search developing analyses on 4% of collected BNB data.
- Cross-check against large sample of open NuMI data.
  - Higher $\nu$ energy
  - Off-axis
- We want to perform our cross-section measurements first to ensure we have a good understanding of our signal and background channels.

The $\nu_e$ appearance signal comes in many forms
Progress Towards $\nu_e$ Appearance

- Multiple complementary analyses.

<table>
<thead>
<tr>
<th>$\nu_e$ analyses</th>
<th>Single photon analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1e1p (Deep Learning)</td>
<td>1$\gamma$0p (Pandora)</td>
</tr>
<tr>
<td>1eNp (Pandora)</td>
<td>1$\gamma$1p (Pandora)</td>
</tr>
<tr>
<td>1e inclusive (Pandora, WireCell)</td>
<td></td>
</tr>
</tbody>
</table>

Recent Public Notes:
- R. Soleti, Electron-neutrino reconstruction in MicroBooNE using the Pandora pattern reconstruction, MICROBOONE-NOTE-1038-PUB, 2018
- R. Murrells, Search for NC single photon events in MicroBooNE, MICROBOONE-NOTE-1041-PUB, 2018
- M. Ross-Lonergan, MicroBooNE tests of the MiniBooNE low-energy excess, MICROBOONE-NOTE-1043-PUB, 2018
Example events selected by the 1eNp analysis show good reconstruction of EM showers.

See public note (MICROBOONE-NOTE-1038-PUB)

3 selected $\nu_e$ candidate events
Progress Towards $\nu_e$ Appearance

Sideband checks show good data-MC agreement:

- Photon-enhanced $\nu_e$ CC
- $\mu$-enhanced $\nu_e$ CC

$\chi^2$/n.d.f. = 0.71
Data / (MC + EXT) = 0.90

$\chi^2$/n.d.f. = 0.45
Data / (MC + EXT) = 0.95
Progress Towards $\nu_e$ Appearance

Analyses so far have shown us where we need to improve:

- **Cosmic removal**: we are improving our cosmic removal algorithms while simultaneously integrating a new cosmic ray tagger system to the detector itself.

- **Particle identification**: more robust & sophisticated PID methods are being implemented.

- **Reconstruction efficiency**: effort is being focused on improving reconstruction efficiency at low energies.

- **Machine learning**: these techniques have shown great promise and are being developed further.

We aim to perform an end-to-end analysis with these improvements, validated on the NuMI sample, before publication.
Conclusions

- MicroBooNE is providing valuable $\nu$-Ar interaction data for the SBN programme and other LArTPC detectors (e.g. DUNE).
  - First cross-section results are out:
    - $\nu_\mu$ CC inclusive
    - CC$\pi^0$
    - Charged particle multiplicity
  - Many more underway.

- Automated LArTPC event reconstruction has been demonstrated on MicroBooNE data and is growing more sophisticated.

- We have performed our first fully automated $\nu_e$/single $\gamma$ selections, and are making improvements towards a complete low-energy excess analysis.

- Much of our work is documented on a rapid timescale on our public notes page: http://microboone.fnal.gov/public-notes/
Thank You!
Backups
BNB Flux

MicroBooNE Simulation

\[ \frac{\nu}{\text{POT/GeV/cm}^2} \]

![Graph showing BNB Flux with energy vs. flux for different neutrino types (\(\nu_\mu\), \(\bar{\nu}_\mu\), \(\nu_e\), \(\bar{\nu}_e\))](image)
CC-Inclusive Track Reconstruction Efficiency
CC-$\pi^0$ Shower Reconstruction Efficiency

**Reconstruction efficiencies:**
- 62% for leading CC-$\pi^0$ shower
- 50% for subleading CC-$\pi^0$ shower
- 80% above 300 MeV

**Selection efficiencies:**
- 1 shower: 771 events
  Efficiency 17%, purity 53%
- 2 showers: 224 events
  Efficiency 6%, purity 64%
Physics Results

PUBLICATIONS


PUBLIC NOTES

- “First measurement of muon neutrino charged-current neutral pion production in LArTPC”, MICROBOONE-NOTE-1032-PUB, 2018
- “First measurement of muon neutrino charged-current inclusive cross-section measurement in MicroBooNE”, MICROBOONE-NOTE-1045-PUB, 2018
- “Towards measurements of nuclear effects in MicroBooNE”, MICROBOONE-NOTE-1046-PUB, 2018
- “Electron-neutrino reconstruction in MicrobooNE using the Pandora pattern reconstruction”, MICROBOONE-NOTE-1038-PUB, 2018
- “Search for NC single photon events in MicroBooNE”, MICROBOONE-NOTE-1041-PUB, 2018
- “MicroBooNE tests of the MiniBooNE low-energy excess”, MICROBOONE-NOTE-1043-PUB, 2018
- “Booster Neutrino Flux Prediction at MicroBooNE”, MICROBOONE-NOTE-1031-PUB, 2018
Detector Physics Results

PUBLICATIONS

- “Ionization Electron Signal Processing in Single Phase LAr TPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation”, arXiv:1802.08709, accepted by JINST

PUBLIC NOTES

- “A Method to Extract the Charge Distribution Arriving at the TPC Wire Planes in MicroBooNE”, MICROBOONE-NOTE-1017-PUB, (2016)
- “Noise Dependence on Temperature and LAr Fill Level in the MicroBooNE Time Projection Chamber”, MICROBOONE-NOTE-1001-TECH, (2016)
Reconstruction and Calibration Results

PUBLICATIONS


PUBLIC NOTES

- “Vertex finding and reconstruction for contained two-track events in the MicroBooNE detector”, MICROBOONE-NOTE-1042-PUB, 2018
- “Towards automated neutrino selection at MicroBooNE using tomorgraphic event reconstruction”, MICROBOONE-NOTE-1040-PUB, 2018
- Hunting muon neutrinos in microboone with deep learning techniques, MICROBOONE-NOTE-1051-PUB, 2018
- “Reconstruction Performance Studies with MicroBooNE Data in Support of Summer 2018 Analyses”, MICROBOONE-NOTE-1049-PUB, 2018
- “Detector Calibration using through going and stopping muons in the MicroBooNE LArTPC”, MICROBOONE-NOTE-1048-PUB, 2018
- Proton Track Identification in MicroBooNE Simulation for Neutral Current Elastic Events, MICROBOONE-NOTE-1025-PUB, 2017
- "A Comparison of Monte-Carlo Simulations and Data from MicroBooNE”, MICROBOONE-NOTE-1014-PUB, 2017