Recent Cross-Section Results from MicroBooNE

Joel Mousseau
University of Michigan
Studying Neutrino - Argon Cross Sections

- Cross sections are necessary for formulating a *prior* neutrino flux for disappearance / appearance measurements.

- Identify reactions / topologies that act as signals and backgrounds for a MiniBooNE-like excess.

- Provide a resource for studying advanced electroweak nuclear physics:
  - Short range correlations
  - Meson-Exchange currents
  - Random Phase Approximation

---

**Detector Spectrum**

Detectors measure rates

**Excess lies mainly in QE region**

Wideband flux gives us cross-checks in RES and MEC region.
Our LEE search relies on a measurement of inferred neutrino energy.

Same is true for measuring CP violation!
MicroBooNE Detector

- 85-ton active volume Liquid argon TPC.
- Many advantages to LArTPC:
  - Excellent position, energy resolution.
  - $4\pi$ charged particle acceptance.
  - Large argon nucleus give sensitivity to nuclear effects.

Many challenges with LArTPCs:
- Large argon nucleus give sensitivity to nuclear effects.
- Drift model requires a detailed simulation.
Charged Current Inclusive Analysis

- Cosmic rejection cuts form the basis of a *charged current inclusive* analysis, which looks for events with a neutrino induced muon and anything else.

Tracks reconstructed using the Pandora$^1$ pattern-recognition framework from (noise subtracted) wire hits.

Muon momentum measured with MCS, allows us to analyze exiting tracks (50%).

Single and double differential measurement performed in muon momentum and angle.

Hadronic energy not measured. Analysis has no dependence on multiplicity.

Charged-Current Inclusive Analysis

- First double-differential result on argon.

arxiv 1905.09694
Charged-Current Inclusive Analysis

<table>
<thead>
<tr>
<th>Model Set</th>
<th>Chi2</th>
<th>N Bins</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENIE v2 (with MEC)</td>
<td>245.9</td>
<td>42</td>
</tr>
<tr>
<td>GENIE v3</td>
<td>108.8</td>
<td>42</td>
</tr>
<tr>
<td>NuWro 19.02.1</td>
<td>126.5</td>
<td>42</td>
</tr>
<tr>
<td>GiBUU (2019)</td>
<td>172.9</td>
<td>42</td>
</tr>
</tbody>
</table>

- Majority of tension in the most forwarding going bins.
- GENIE v3 (incorporating RPA effects) gives the best description.

Data with associated efficiency and correlation matrix [here](#).
### Uncertainty Evaluation

#### Leading Systematic Contributions

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative Err.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Model</td>
<td>16.2%</td>
</tr>
<tr>
<td>Neutrino Flux</td>
<td>12.2%</td>
</tr>
<tr>
<td>Events outside TPC</td>
<td>10.9%</td>
</tr>
<tr>
<td>All Others</td>
<td>&lt; 5%</td>
</tr>
</tbody>
</table>

- Uncertainties largest in regions dominated by background (low momentum, backward going).
- Strongly correlated across bins, detector modeling has a strong impact on efficiency.
Charged Current $\pi^0$ Selection

- Excellent channel for benchmarking EM shower performance.
- First ever measurement in a LArTPC with automated shower reconstruction.
- Low energy showers difficult to tag, require at least one shower in analysis. Two for mass-peak.

![Diagram showing charged current interactions](image)
- Similar selection as Inclusive, only now require at least one photon induced shower in addition to $\mu^-$.

- A Scaling of FSI in GENIE compatible across D, C and Ar.

- Our measurement is consistent with GENIE and NuWro.

### Charged Current $\pi^0$

<table>
<thead>
<tr>
<th>Type</th>
<th>% Error</th>
<th>Affected Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>16%</td>
<td>Flux division, Background Estimation</td>
</tr>
<tr>
<td>Cross-Section</td>
<td>17%</td>
<td>Background Estimation</td>
</tr>
<tr>
<td>Detector Modeling</td>
<td>21%</td>
<td>Background Estimation Efficiency Correction</td>
</tr>
</tbody>
</table>

Follow on analysis will have higher efficiency and smaller errors.
Cross Sections with Proton Final States

- Final states with 1 proton and no mesons arguably most important cross section for MicroBooNE.

Future SB neutrino experiments use 1\(e\) 1\(p\) as a potential sterile signature.

LAr TPCS can detect and reconstruct protons at lower momenta than scintillator detectors (\(~300\text{ MeV/c}\)).
Identifying Protons

- Protons reconstructed by identifying the Bragg peak of particles as they stop.
- Fit track’s dE/dx vs. Residual range to Bethe-Bloch expectation for protons.
- Improved simulation with data measured E field will improve our modeling of this observable.

For Leading Proton:

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>85.2%</td>
<td>92.6%</td>
</tr>
</tbody>
</table>
Proton kinematics show better shape agreement than muon kinematics.
Charged-Current N Protons

- Caveat: Top row requires **exactly** two protons in final state.
Charged-Current 2 Proton

- $e^-$ nuclear experiments show strong evidence for interactions off nucleon pairs.
- Signature is two protons knocked out back to back in CM frame.

- Searching for evidence of this in MicroBooNE.
- Shape better modeled by incorporating QE nuclear effects.

**Science 320, 1476 (2008)**
**ν_e-Argon Cross-Section**

- Identifying $\nu_e$ important for resolving the MiniBooNE LEE.
- Use NuMI (off-axis) beam: $\nu_e$ content order of magnitude higher than BNB.

- First $\nu_e$ measurement on Argon.
- Only using one plane for PID currently. Leads to inability to detect vertical electrons.
- Simulation of full 3 planes underway.

_MICROBOONE-NOTE-1038-PUB_
Conclusions

- MicroBooNE is making rapid progress in measuring cross-sections relevant for oscillation and electroweak nuclear physics:
  - CC $\pi^0$ (Paper Published)
  - Double-differential CCInclusive (Paper Submitted)
  - CC N proton (Paper In-Progress)
  - CC 2 protons (Paper In-Progress)
  - CC Inclusive $\nu_e$ (Paper In-Progress)
- These measurements form a springboard for resolving the MiniBooNE low energy excess.
- Measurements will be considerable help for theorists and model builders.
- Looking forward to measurements of more exotic processes ($K^+$, $\pi^+$, exclusive $\nu_e$) as time progresses!
Thank you For Listening!

References for MicroBooNE Papers and Public notes on next slide
(https://microboone.fnal.gov/public-notes/)
References

• Charged-Current Inclusive double differential:
  • arXiv 1905.09694 (submitted to PRL)

• Charged-Current single production:
  • PRD 99, 091102(R) (2019)

• Charged-Current $\nu_e$:
  • MICROBOONE-NOTE-1038-PUB

• Charged-Current N protons:
  • MICROBOONE-NOTE-1056-PUB

• Pandora reconstruction:

• Multiple Coulomb Scattering:
  • JINST 12, no. 10 P10010 (2017)
Backup Slides
Cosmic Mitigation

- 32 PMTs are used to detect prompt scintillation light, enables us to search for events in a 1.6 us beam window.

- Greyed Regions unlikely to contain neutrino events.

- Still a BG to contend with for overlapping events and beam gates with no neutrino interaction.
Cosmic Mitigation

- Remove and tag “obvious” cosmic rays:
  - Stopping muons with michel tagging.
  - Downward or upwarding going thoroughgoing particles.
  - Particles which enter through the sides; cathode or anode.
- Compare the amount of light observed in PMTs to the predicted amount based on the track’s position within a beam spill.
• Relevant energy range (left) and expected sensitivity (right).

• Modeling of off-axis NuMI flux extremely difficult, power of this measurement comes from being able to positively ID electrons, and cross-check LEE signal analysis.
Neutrino Induced Kaons

- Background for $p^+$ decay.
- Candidate $K^+$ based on similar cuts as proton ID.
- Still evaluating backgrounds and systematics, planning to publish search.

Run 5147 Event 2180
• Reconstruction begins with “hit finding:” locating hits from waveforms along the wires, and deconvolving the signal to an \((x, u, v, t)\) coordinate.
• Hits clustered together to form cluster objects, clusters stitched into 3D tracks and showers.
**Multiple Coulomb Scattering**

\[
\sigma_o^{HL} = \frac{S_2}{p\beta c} z \sqrt{\frac{\ell}{X_0}} \left[ 1 + \epsilon \times \ln \left( \frac{\ell}{X_0} \right) \right]
\]

- Highland formula relates rms of scattering to p.

![Graph](image)

Data driven validation for MCS momentum resolution

Momentum resolution well-modeled at large momentum

[MicroBooNE Preliminary](#)

1.62e20 POT

2 segments removed

- BNB Data
- BNB MC