Progress towards the extraction of exclusive $\nu_\mu^{-40}\text{Ar}$ CCQE–like cross–sections using the MicroBooNE LArTPC detector

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On behalf of the MicroBooNE Collaboration
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Motivation

Charged Current Quasi–Elastic (CCQE) Interaction Channel

- Dominant interaction at low energies
- Studies of neutrino energy reconstruction
- Allows high precision oscillation studies
### Existing Data

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target</th>
<th>$\mu$-dependence</th>
<th>$p$-dependence</th>
</tr>
</thead>
</table>
| SciBooNE   | $^{12}\text{C}$ | $d\sigma/dE_{\nu}$  
doi: 10.1063/1.3661556 |                                     |
| MiniBooNE Detector | $^{12}\text{C}$ | $d^2\sigma/dP_{\mu}d\cos\theta_{\mu}$  
| T2K        | $^{12}\text{C}$, $^{16}\text{O}$ | $d\sigma/d\theta_{\mu}$  
$d^2\sigma/dP_{\mu}d\cos\theta_{\mu}$  
Phys Rev D.98.0124004 | $d^2\sigma/dP_{p}d\cos\theta_{p}$  
arXiv:1802.05078 [hep-ex] |
| MINERvA    | $^{12}\text{C}$, $^{56}\text{Fe}$, $^{208}\text{Pb}$ | $d^2\sigma/dP_{||}dP_{T}$  
Phys Rev D97.052002 | $d^2\sigma/dQ^2_{p}$  

- Extracted cross-sections on $^{12}\text{C}$, $^{16}\text{O}$, $^{56}\text{Fe}$, $^{208}\text{Pb}$
- None on $^{40}\text{Ar}$ (heavy asymmetric nucleus, building nucleus of LArTPC detectors)
Objective

First extraction of exclusive $\nu_\mu^{40}\text{Ar}$ CCQE–like differential cross–sections using the MicroBooNE detector.

$\theta$: angle w.r.t. the beam line

$\phi$: angle around the beam line
Signal Definition

Vertex of 2 tracks

- 1 muon ($\geq 100$ MeV/c)
- 1 proton ($\geq 300$ MeV/c)
- No $\pi^0$, no $\pi^\pm$ ($\geq 70$ MeV/c)

*We allow any number of e, $\gamma$, n and charged hadrons below these thresholds, which can be further lowered*
Cosmic Background Rejection

- MicroBooNE is a surface detector dominated by cosmics
  - 1 $\nu$ interaction in $\sim$ 500 events
  - After trigger application, 1 $\nu$ interaction in $\sim$ 10 events

- Development of cosmic rejection machinery using detector and kinematics-based cuts
  - arXiv:1812.05679
Cosmic Background Rejection

Detector–based cuts

- Energy deposition profile
- Track length
- Scintillation light
- Collinearity

Broken Track
Cosmic Background Rejection

Kinematics–based cuts

- Vertex activity
- Coplanarity
- Transverse imbalance $\vec{P}_{miss} = (\vec{P}_\mu + \vec{P}_p)^\perp$
Statistics

- Purity: 78.7 ± 1.1 %
- Efficiency: 15.5 ± 0.2 %

- # events measured: 462.0 ± (stat) 21.5*
- # events expected: 486.4 ± (stat) 5.0

Though low statistics, first indication of consistency between data and simulation

* Using ~ 1 / 20 of the available data–sample
Cross–Section Extraction

- Select events in data sample
- Subtract cosmic related background
- Subtract MC beam related background

\[
\left( \frac{d\sigma}{dp_\mu} \right)_n = \frac{N_n^{on} - N_n^{off} - B_n}{\eta_n^\mu \cdot \Phi_v \cdot N_{targets} \cdot \Delta_n^\mu}
\]

*Same for the proton and other kinematic variables*
(\frac{d\sigma}{dp_\mu})_n = \frac{N_{on} - N_{off}}{\eta_n \cdot \Phi \cdot N_{targets} \cdot \Delta n \cdot B_n}
Cross–Section Extraction

\[
\left( \frac{d\sigma}{dp_\mu} \right)_n = \frac{N_{on}^n - N_{off}^n - B_n}{\eta_n^\mu \cdot \Phi_n \cdot N_{targets} \cdot \Delta_n^\mu}
\]

\( \eta \) – effective detection efficiency (efficiencies & bin migration)

B – background processes

MC
Cross–Section Extraction

\[
\left( \frac{d\sigma}{dp_\mu} \right)_n = \frac{N_n^{on} - N_n^{off} - B_n}{\eta_n \cdot \Phi_\nu \cdot N_{targets} \cdot \Delta^\mu_n}
\]

\[\Phi_\nu \] – neutrino integrated flux

\[N_{targets} \] – number of nuclei

\[\Delta \] – bin width

{\text{Constants}}
Differential Cross–Sections

Work In Progress

Muons

Protons

*d* *d*(*cos(θ*)*)

[10⁻³⁸ cm²]

*Only statistical errors included*

Non–negligible differences
Differential Cross–Sections

Work In Progress

**Muons**

**Protons***

Non–negligible discrepancies

*First attempt to extract proton differential cross–sections at such low momenta
Differential Cross–Sections

Work In Progress

Muons

Protons

Sanity check

Uniform distributions in polar angle
Wrap Up & Future

☑ Progress towards first extraction of exclusive $\nu_\mu - ^{40}\text{Ar}$ CCQE–like differential cross–sections using data from the MicroBooNE LArTPC detector

☑ Finalizing systematical studies

*Paper published in the near future*
Thank you!
Backup Slides
Goals of the Short Baseline Neutrino program:
- low-energy excess observed by MiniBooNE
- sterile neutrinos
- cross section measurements
- R&D for future LArTPC experiments
The MicroBooNE Detector

- 8192 wires (3 mm pitch)
- 170 ton LArTPC (total mass)
- 32 8” Cryogenic PMTs
Pre–Selection

Hardware and Software Triggers

- 1 $\nu$ interaction in $\sim 1000$ triggered events
- PMT trigger enriches this ratio to 1 $\nu$ interaction in $\sim 10$ events

Collection of track pairs at close proximity

- arXiv:1812.05679
Pre–Selection

- Pairs of tracks at close proximity: distance < 11 cm between any two edges (start-start, start-end, end-start, end-end)
## Statistics

<table>
<thead>
<tr>
<th>sample</th>
<th>number of events</th>
<th>beam–on equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam-on</td>
<td>462 ± 21.5</td>
<td>462.0 ± 21.5</td>
</tr>
<tr>
<td>beam-off</td>
<td>15 ± 3.9</td>
<td>10.6 ± 2.7</td>
</tr>
<tr>
<td>overlay</td>
<td>12120.0 ± 110.1</td>
<td>618.3 ± 5.6</td>
</tr>
<tr>
<td>$CC1pO\pi$</td>
<td>9533 ± 97.6</td>
<td>486.4 ± 5.0</td>
</tr>
</tbody>
</table>
Migration Matrices

$p_\mu$

$p_p$

$\cos \theta_\mu$

$\cos \theta_p$
Effective Efficiency

\[ \eta_n = \left( \frac{N_{\text{reconstructed (reco.)}}}{N_{\text{generated (truth)}}} \right)_n \]

\[ = \frac{N_{\text{rec (gen. in bin n)}}}{N_{\text{gen (gen. in bin n)}}} \]

\[ + \frac{N_{\text{rec (migrate into bin n)}} - N_{\text{rec (migrate outside bin n)}}}{N_{\text{gen (gen. in bin n)}}} \]

standard efficiency

efficiency + bin migration
Background
Systematics

- ✔ Event selection cuts
- ✔ Beam flux
- ✔ POT
- ✔ Efficiencies due to correlations

- ☑ Detector modeling
- ☑ Event generator