Toward a differential measurement of the $\nu_e \text{ CC1eNp}$ cross section in MicroBooNE

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New Perspectives 2020

July 21, 2020

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The NuMI Beamline

Neutrinos at the Main Injector (NuMI):

- Neutrinos from NuMI enter MicroBooNE at angles ~ 10-140° from the beamline
- 120 GeV proton beam + Off-axis nature = Greater $\nu_e/\bar{\nu}_e$ flux content (~5%)
- Excellent source for $\nu_e/\bar{\nu}_e$ cross section studies!
$\nu_e$ Cross Sections in LArTPCs

“uncertainty on the $\nu_e$ and $\bar{\nu}_e$ cross-sections… [is] the second-largest single source of systematic uncertainty in the CP asymmetry measurement.”


Charged-current quasi-elastic (CCQE) interactions

- Vital to reach discovery precision in the $\nu_e$ appearance oscillation channel
  - neutrino mass ordering, CP violation, existence of sterile neutrinos
- Limited data available on $\nu_e$ cross sections overall
  - CC inclusive, CCQE-like differential results on carbon (T2K, MINERvA)
  - Only result on argon: Flux-averaged CC inclusive – 13 events (ArgoNeut)
- No exclusive differential $\nu_e$-Ar cross sections currently exist
- CC1eNp: mostly CCQE $\rightarrow$ a dominant interaction in SBN & DUNE

What is needed to measure the cross section?

1. Accurate flux prediction
2. High purity, high statistics sample of CC1eNp events
Updating the NuMI Flux Prediction

- **PPFX**: An experiment-agnostic reweight package developed by MINERvA to correct the NuMI GEANT4 simulation using external hadron production data.

Updating the NuMI Flux Prediction

- **PPFX**: An experiment-agnostic reweight package developed by MINERvA to correct the NuMI GEANT4 simulation using external hadron production data.

- **Dedicated, cross-collaboration effort** to update the NuMI flux prediction at MicroBooNE using the PPFX software.

**Updating the NuMI Flux Prediction**

- PPFX equips us with the most accurate NuMI flux prediction at MicroBooNE to date.

- $\nu_\mu$ flux dominated by pion decays:
  \[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

- $\nu_e$ flux dominated by muon & kaon decays:
  \[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]
  \[ K^+ \rightarrow \pi^0 + e^+ + \nu_e \]
Event Selection: CC$^1\nu$e$^{-}$n$^p$ Topology

**Charged-current interactions**
- neutrino $\rightarrow$ charged lepton partner
- isospin of the nucleon flips

**1eNp event signature**
- 1 electron shower, attached to neutrino interaction vertex
- $N>0$ tracks: short, highly ionizing
Selected 1eNp signal candidate
*Color corresponds to energy deposit!
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**μBooNE**
Event Selection: Background Rejection

Cosmic muons

$\nu_\mu$ CC events

$\pi^0 \rightarrow \gamma\gamma$ events

Event Selection Algorithm

Select well-reconstructed events away from TPC edges with neutrino candidate present

Quality cuts

Signal Topology

Cosmic Rejection

$\nu_\mu$ Rejection

$\pi^0$ Rejection

MicroBooNE “In Progress”

$8.793 \times 10^{19}$ POT, Area-Normalized

CC1eNp signal
Event Selection Algorithm

one shower

Quality cuts

Signal Topology

Cosmic Rejection

$\nu_\mu$ Rejection

$\pi^0$ Rejection
Event Selection Algorithm

Cosmic background misreconstructed as a neutrino interaction

Quality cuts

Signal Topology

Cosmic Rejection

$\nu_\mu$ Rejection

$\pi^0$ Rejection

MicroBooNE Simulation
“In Progress”

- Cosmic Cont.: 134.5
- Out FV: 363.7
- $\nu_\mu / \bar{\nu}_\mu$ $\text{N}\pi^0$: 406.0
- $\nu_\mu / \bar{\nu}_\mu$ other: 527.9
- $\nu_e / \bar{\nu}_e$ other: 98.7
- $\nu_\tau$ CC0πNp: 100.1

EXT: 922.7

Pure cosmic background
Event Selection Algorithm

Quality cuts

Signal Topology

Cosmic Rejection

$\nu_\mu$ Rejection

$\pi^0$ Rejection

$\nu_\mu$ CC background: low shower hits ratio

CC1eNp signal: high shower hits ratio

MicroBooNE Simulation

"In Progress"

$\nu_\mu$ / $\bar{\nu}_\mu$, $\nu_e$ / $\bar{\nu}_e$

Cosmic Cont.: 134.5
Out FV: 363.7
$\nu_\mu$ / $\bar{\nu}_\mu$, $\nu_e$ CC0N: 406.0
$\nu_\mu$ / $\bar{\nu}_\mu$, other: 527.9
$\nu_e$ / $\bar{\nu}_e$, other: 98.7
$\nu_e$ CC0N: 100.1
EXT: 922.7

Shower Hits / Total Hits
Event Selection Algorithm

Quality cuts
Signal Topology
Cosmic Rejection
$\nu_\mu$ Rejection
$\pi^0$ Rejection

Amount of energy deposited at start of photon-like showers: 2x what we expect from electron-like showers

MicroBooNE Simulation “In Progress”

- Cosmic Cont.: 13.9
- Out FV: 24.3
- $\nu_\mu / \bar{\nu}_\mu$ N$\pi^0$: 72.5
- $\nu_\mu / \bar{\nu}_\mu$ other: 9.6
- $\nu_e / \bar{\nu}_e$ other: 28.3
- $\nu_e$ CC0$\pi$Np: 54.7
- EXT: 43.4

$\nu / 8.793E19$ POT

dE/dx on the Collection Plane [MeV/cm]
Selection Performance

- High purity post-selection event sample (67%) with significant reduction of all backgrounds
- Optimization studies ongoing!
- Current dataset – 27.5 signal events – good shape agreement with NuMI data
Projected Event Rate

MicroBooNE has collected $9.23 \times 10^{20}$ POT in Neutrino Mode – 10.5x what is currently available

Neutrino Mode -- Projected $9.23 \times 10^{20}$ POT

289 signal events
67% purity
Projected Event Rate

MicroBooNE has collected $9.23 \times 10^{20}$ POT in Neutrino Mode – **10.5x what is currently available**

**Neutrino Mode -- Projected $9.23 \times 10^{20}$ POT**

- Cosmic Cont.: 6.9
- Out FV: 22.5
- $\nu_\mu / \overline{\nu}_\mu$: 29.3
- $\nu_\mu / \overline{\nu}_\mu$ other: 18.7
- $\nu_e / \overline{\nu}_e$ other: 50.4
- $\nu_e$ CC0nNp: 288.6
- EXT: 12.1

289 signal events
67% purity

**Antineutrino Mode -- Projected $11.95 \times 10^{20}$ POT**

- Cosmic Cont.: 11.0
- Out FV: 27.3
- $\nu_\mu / \overline{\nu}_\mu$: 44.1
- $\nu_\mu / \overline{\nu}_\mu$ other: 24.9
- $\nu_e / \overline{\nu}_e$ other: 70.3
- $\nu_e$ CC0nNp: 243.8
- EXT: 15.8

244 signal events
56% purity

**TOTAL PROJECTED = $2.12 \times 10^{21}$ POT → over 500 signal events!**
Summary

- $\nu_e$ - Ar cross sections crucial to the future success of SBN & DUNE

- MicroBooNE is positioned to perform a world-leading $\nu_e$ exclusive (CC1eNp) cross section measurement using the NuMI dataset:
  - New & improved NuMI flux prediction using PPFX
  - High purity 1eNp event selection
  - Total projected $2.12 \times 10^{21}$ POT $\rightarrow$ over 500 signal events!

- Current progress demonstrates MicroBooNE’s powerful ability to measure & reconstruct electron neutrinos
The NuMI Beamline

[Diagram of NuMI Beamline with labels for Target Hall, Decay Pipe, Absorber, Muon Monitors, Hadron Monitor, and Protons from Main Injector.]
Why does the off-axis nature of NuMI yield a higher $\nu_e/\bar{\nu}_e$ flux?

- At our energy scales, most $\nu_\mu/\bar{\nu}_\mu$'s come from 2-body decays – forward-boosted, constrained by kinematics
- In contrast, most $\nu_e/\bar{\nu}_e$'s come from 3-body decays – more freedom with kinematics, easier for a neutrino to be produced at higher angles
- Probability of seeing $\nu_\mu/\bar{\nu}_\mu$ drops faster than probability of seeing $\nu_e/\bar{\nu}_e$ as we move to higher angles

![Flux plots](https://arxiv.org/pdf/1412.3086.pdf)

### Table

<table>
<thead>
<tr>
<th>Off-axis angle (°)</th>
<th>$\nu_e$ Flux 0.3-0.9 GeV</th>
<th>$\nu_\mu$ Flux 0.3-5.0 GeV</th>
<th>Ratio $\nu_e/\nu_\mu$</th>
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<tbody>
<tr>
<td>2.5</td>
<td>1.24E+15</td>
<td>2.46E+17</td>
<td>0.507%</td>
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<td>3.0</td>
<td>1.14E+15</td>
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<td>0.600%</td>
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<tr>
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<td>1.00E+15</td>
<td>1.47E+17</td>
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<tr>
<td>4.0</td>
<td>8.65E+14</td>
<td>1.14E+17</td>
<td>0.760%</td>
</tr>
</tbody>
</table>


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How to Set a Cross Section

\[ \text{# of events} = \text{flux} \times \text{interaction probability} \]

\[ \sigma = \frac{N - B}{\epsilon \times N_{\text{Target}} \times \Phi_{\nu_e}} \]

- **efficiency**: correction factor to scale up observed # of signal events

  \[ \text{efficiency} = \frac{\text{# of selected signal events}}{\text{# generated signal events}} \]

- **accurate** prediction of the \( \nu_e \) flux passing through the detector \([/\text{cm}^2]\)
Selection Performance

**Neutrino Mode**

**Antineutrino Mode**
How can we have a signal-dominated event sample in Antineutrino Mode?

Flux content switches to a primarily antineutrino beam...

... but the $\nu_e / \bar{\nu}_e$ cross sections stay the same
NuMI POT Collected in MicroBooNE

January 29, 2016 – March 20, 2020