Recent Cross-section Measurements from MicroBooNE

Lake Louise Winter Institute
12th Feb 2020

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On behalf of the MicroBooNE collaboration
The Need for Neutrino Scattering Measurements

What we can measure:

\[
R(\mathbf{x}) = \sum_i \sum_j \int_{E_{\text{min}}}^{E_{\text{max}}} \Phi(E_{\nu}) \times \sigma_i(E_{\nu}, \mathbf{x}) \times \epsilon(\mathbf{x}) \times N_j \times P(\nu_A \rightarrow \nu_B)
\]

Neutrino oscillation analysis for three flavours or more:
- Extract oscillation probability
- Constrain systematics
- Develop neutrino interaction generators

Background for beyond standard model physics (BSM):
- Milli-charged particles
- Neutrino trident
- Proton decay
- Direct dark matter search
Not an Easy Task

Mix of interaction modes

Nuclear effect

Plot by Patrick Stowell

MicroBooNE Cross-section
MicroBooNE has the advantage of
High-precision event reconstruction
High-statistics $\nu$-Ar data

* See Sophie’s MicroBooNE overview talk

MicroBooNE’s Cross-section Service

Modern accelerator-based neutrino experiments studying neutrino scattering

| Experiment     | beam $|E_{\nu}$| $|E_{\bar{\nu}}$| neutrino target(s) | run period  |
|----------------|----------|------------|------------------|--------------|
| ArgoNeuT       | $\nu, \bar{\nu}$ | 4.3, 3.6  | Ar               | 2009 – 2010  |
| ICARUS (at CNGS)| $\nu$   | 20.0       | Ar               | 2010 – 2012  |
| K2K            | $\nu$   | 1.3        | CH, H$_2$O       | 2003 – 2004  |
| MicroBooNE     | $\nu$   | 0.8        | Ar               | 2015 – 2017  |
| MINERvA        | $\nu, \bar{\nu}$ | 3.5 (LE), 5.5 (ME) | He, C, CH, H$_2$O, Fe, Pb | 2009 – 2019 |
| MiniBooNE      | $\nu, \bar{\nu}$ | 0.8, 0.7  | CH$_2$           | 2002 – 2019  |
| MINOS          | $\nu, \bar{\nu}$ | 3.5, 6.1  | Fe               | 2004 – 2016  |
| NOMAD          | $\nu, \bar{\nu}$ | 23.4, 19.7 | C–based          | 1995 – 1998  |
| NOvA           | $\nu, \bar{\nu}$ | 2.0, 2.0  | CH$_2$           | 2010 – 2015  |
| SciBooNE       | $\nu, \bar{\nu}$ | 0.8, 0.7  | CH               | 2007 – 2008  |
| T2K            | $\nu, \bar{\nu}$ | 0.6, 0.6  | CH, H$_2$O, Fe  | 2010 – 2015  |

PDG (Neutrino Cross Section Measurements Review)

- **Constrain model systematics for future oscillation studies**
  SBN and DUNE have the same target material: argon

- **Probe for nuclear effects**
  Argon is a big nucleus. Our studies are sensitive to final states.

- **Contribute $\nu$-Ar scattering measurements for the development of various generators**
  Data on neutrino interaction with argon nucleus is rare!
Topology-based Cross-section Analyses

BNB
Booster Neutrino Beam

\( \nu_\mu \) CC inclusive

NC elastic

\( \nu_\mu \) CC \( \pi^0 \)

\( \nu_\mu \) CC \( 0\pi \) 2p

\( \nu_\mu \) CC \( 0\pi \) Np

NuMI
The Neutrinos at the Main Injector beam

\( \nu_e \) CC inclusive

MicroBooNE Cross-section

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νμ Charge Current Inclusive

νμ + Ar → μ⁻ + X

- First double differential cross-section on argon muon kinematics: $p_\mu$ and $\cos \theta_\mu$
- First inclusive measurement on argon at low $O(1\text{GeV})$ neutrino energies
- Full angular coverage
- Full momentum coverage

Multiple Coulomb Scattering (MCS)* is used to reconstruct muon momentum, which allows muon to be either contained or exiting

* JINST 12 P10010 (2017)
ν_μ Charge Current Inclusive: Selection

Selected Events: 27,200
Signal purity: 50.4%

- Cosmic rejection:
  - Through-going tacks
  - Tracks outside of the TPC time window with the trigger t0
  - Stopping muons (by Bragg peak and/or Michel electron tagging)
- Flash Match:
  Check the consistency of reconstructed light signals from the PMTs and the modelled light signal corresponding to a cluster of charge deposition
- Reconstruction quality
- M.I.P consistency (by calorimetry)
- Fiducial volume


MICROBOONE-NOTE-1045-PUB
\( E_{\text{syst}} = E_{\text{flux}} + E_{\text{xsec}} + E_{\text{detector}} + \ldots \)
\[ \left\langle \frac{d^2 \sigma}{dp_\mu^{\text{reco}} \cos \theta_\mu^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{c}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu \cdot \Delta \cos \theta_\mu)_i} \]

\( i \) identifies a bin in the \( p_\mu \cos \theta_\mu \) space

**Forward folding** with detector smearing and efficiency published

<table>
<thead>
<tr>
<th>Model</th>
<th>( \chi^2 ) / Nbins</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENIE v2 + MEC</td>
<td>245.9/42</td>
</tr>
<tr>
<td>GENIE v3</td>
<td>108.8/42</td>
</tr>
<tr>
<td>GiBUU</td>
<td>172.9/42</td>
</tr>
<tr>
<td>NuWro</td>
<td>126.5/42</td>
</tr>
</tbody>
</table>

Test against different models:
High \( \chi^2 \) is mostly driven by high momentum bins in forward direction

MicroBooNE 1.6 \( \times 10^{20} \) POT

-1.00 \( \leq \cos(\theta_\mu^{\text{reco}}) \leq -0.50 \)

**MicroBooNE Cross-section**


MICROBOOONE-NOTE-1045-PUB
**νμ CC π⁰**

**From νμ CC pre-selection**

**Single-shower selection:**
- Able to reconstruct and distinguish photon shower
- Able to identify vertex
- Verified with conversion distance

**Two-shower verification:**
- Test with π⁰ mass

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(σ)Φ = 1.9 ± 0.2(stat) ± 0.6(syst) × 10⁻³⁸ cm²/Ar

First on argon
Flux integrated cross-section measurement of νμ CC π⁰

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C. Adams et al 2020 JINST15 P02007

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Proton identification
Using $\chi^2$ test statistics to compare dE/dx profile to the theoretic profile from Bethe-Bloch
Protons are required to be contained

Proton purity > 92%

Proton threshold
- Kinematic energy: 47 MeV
- Track length: 1.5 cm

Proton interaction probability is high

The lowest energy threshold in current running accelerator-based neutrino experiments.
$\nu_\mu$ CC $0\pi$ 2$p$

Same selection in different models

- Probe nuclear dynamics
- Support the development of generators

MICROBOONE-NOTE-1056-PUB PRL in preparation

MicroBooNE Cross-section 12

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$\nu_\mu$ CC $0\pi$ Np ($N>0$)

Proton multiplicity

<table>
<thead>
<tr>
<th>Ntrue</th>
<th>Nreco=1</th>
<th>Nreco=2</th>
<th>Nreco=3</th>
<th>Nreco=4</th>
<th>Nreco=5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>0</td>
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<tr>
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<td>49</td>
<td>1</td>
<td>1</td>
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<td>4</td>
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<tr>
<td>5</td>
<td>7</td>
<td>17</td>
<td>10</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Proton Multiplicity

[Leading proton] Momentum

[Leading proton] $\cos \theta_n$

 MICROBOONE-NOTE-1056-PUB

PRD in preparation (differential cross-section measurement)
\( \nu_\mu + \text{Ar} \rightarrow \nu_\mu + p + N^* \)

- The topology is a single proton
- Decent efficiency (expect \( \sim 1000 \) NC elastic events in the collected data)
- Goal: cross-section and axial mass measurement

\[ Q_p^2 = 2T_p M_p \]
\( \nu_e \mathrm{CC\ inclusive} \)

\[ \nu_e / \bar{\nu}_e + \text{Ar} \rightarrow e^\pm + X \]

- **Using NuMI** (5% \( \nu_e \) in NuMI flux comparing <1% \( \nu_e \) in BNB flux) to measure \( \nu_e \) inclusive cross-section
- **Automated selection**
  - Identify electron shower
  - \( \sim 100 \) signal events
- **Verified with closure test in measuring cross-section**

\[ \sigma_{\text{MC}} = 4.83 \pm 0.69 \text{ (stat)} \pm 1.20 \text{ (sys)} \times 10^{-39} \text{ cm}^2 \]

**Paper in preparation**
Work in Progress - Near Future Measurements

Mostly topology-based measurement

- $\nu_\mu$ CC inclusive (with updated simulation, detector calibration and cosmic ray tagger)
- $\nu_\mu$ CC $\pi^+$
- $\nu_\mu$ CC $\pi^0$ (differential cross-section measurement)
- $\nu_\mu$ CC 0$\pi$ 0$p$
- $\nu_\mu$ CC 0$\pi$ 1$p$
- Transverse variables in $\nu_\mu$ CC0$\pi$
- $\nu_\mu$ CC kaon production
- NC elastic scattering

**BNB**

- $\nu_e$ CC inclusive
- $\nu_e$ CC Np
- Kaon decay at rest

**NuMI**

MicroBooNE Cross-section 16

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MicroBooNE v-Argon cross-section measurements are important for:
- Constraining model systematics for future oscillation experiments (SBN/DUNE)
- The development of neutrino interaction generators
- Understanding backgrounds for beyond standard model physics

MicroBooNE published cross-section measurements:
- $\nu_\mu$ CC inclusive (first double differential measurement on argon, first inclusive measurement in $O(1$ GeV) neutrino energy on argon)
- $\nu_\mu$ CC $\pi^0$ (first $\pi^0$ cross-section measurement on argon)

Preliminary results (public)
- $\nu_\mu$ CC $0\pi 2p$
- $\nu_\mu$ CC $0\pi Np$
- NC elastic
- $\nu_e$ NC inclusive (NuMI)

More results coming soon!
Back Up
νμ Charge Current Inclusive: Migration Matrix

MicroBooNE Simulation

Generated Bin Number

\( E_{\text{syst}} = E_{\text{flux}} + E_{\text{xsec}} + E_{\text{detector}} \)

\[
E_{ij} = \frac{1}{N_s} \sum_{s=0}^{N_s} (\sigma_i^s - \sigma_i^{cv})(\sigma_j^s - \sigma_j^{cv})
\]

\[
E_{ij}^{\text{det}} = \sum_{m=1}^{u} (\sigma_i^{cv} - \sigma_i^m)(\sigma_j^{cv} - \sigma_j^m)
\]

### Systematic Sample

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Relative uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam flux</td>
<td>12.4</td>
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<tr>
<td>Cross section modeling</td>
<td>3.9</td>
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<tr>
<td><strong>Detector response</strong></td>
<td><strong>16.2</strong></td>
</tr>
<tr>
<td>Dirt background</td>
<td>10.9</td>
</tr>
<tr>
<td>Cosmic ray background</td>
<td>4.2</td>
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<tr>
<td>MC statistics</td>
<td>0.2</td>
</tr>
<tr>
<td>Statistics</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>23.8</strong></td>
</tr>
</tbody>
</table>

**MicroBooNE Cross-section**

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$\nu_\mu$ Charge Current Inclusive: Covariance Matrix

MicroBooNE Cross-section

\( \nu_\mu \) **Charge Current Inclusive**

\[
\left\langle \frac{d^2\sigma}{dp_\mu^{\text{reco}} d \cos \theta_\mu^{\text{reco}}} \right\rangle_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu \cdot \Delta \cos \theta_\mu)_i},
\]

*Forward folding* with detector smearing and efficiency published

\[
\tilde{\epsilon}_i = \frac{\sum_{j=1}^{M} S_{ij} N_{j}^{\text{sel}}}{\sum_{j=1}^{M} S_{ij} N_{j}^{\text{gen}}},
\]

$\nu_\mu$ Charge Current Inclusive: Results

Flux integrated cross-section per nucleon

$$\sigma = 0.693 \pm 0.010 \text{(stat)} \pm 0.165 \text{(syst)} \times 10^{-38} \text{ cm}^2$$
### νμ Charge Current Inclusive: Model Comparison

<table>
<thead>
<tr>
<th>Model Element</th>
<th>GENIE v2 + MEC (v2.12.2)</th>
<th>GENIE v3 (v3.00.04 G1810a0211a)</th>
<th>NuWro (19.02.1)</th>
<th>GiBUU (2019)</th>
</tr>
</thead>
</table>

**MicroBooNE Cross-section**

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$\nu_\mu$ Charge Current Inclusive: Results

MicroBooNE Cross-section

\( \nu_\mu \text{ CC } 0\pi 2p: \text{ Model Comparison} \)

<table>
<thead>
<tr>
<th>Model element</th>
<th>GENIE Default</th>
<th>GENIE Alternative</th>
</tr>
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<tbody>
<tr>
<td>Nuclear Model</td>
<td>Bodek-Ritchie Fermi Gas</td>
<td>Local Fermi Gas</td>
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<tr>
<td>Quasi-elastic</td>
<td>Llewellyn-Smith</td>
<td>Nieves</td>
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<tr>
<td>Meson-Exchange Current</td>
<td>Empirical</td>
<td>Nieves</td>
</tr>
<tr>
<td>Resonant</td>
<td>Rein-Seghal</td>
<td>Berger-Seghal</td>
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<tr>
<td>Coherent</td>
<td>Rein-Seghal</td>
<td>Berger-Seghal</td>
</tr>
<tr>
<td>FSI</td>
<td>hA</td>
<td>hA2014</td>
</tr>
</tbody>
</table>
$\nu_\mu$ CC $0\pi$ $2\rho$

Angle in between the two protons