Recent Neutrino Cross Section Results from MicroBooNE

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19 Feb 2021

XIX International Workshop on Neutrino Telescopes
Growing Interest in $\nu$–Ar Cross Sections

- A number of current and future neutrino oscillation experiments are employing Liquid Argon Time Projection Chambers (LArTPCs)
  - Short Baseline Neutrino (SBN) Program
  - Deep Underground Neutrino Experiment (DUNE)

- Measurements of the $\nu$–Ar cross section directly feed into these experiments:
  - Allow us to develop models that are capable of describing neutrino interaction data on argon

• We can test models of neutrino interactions on argon by studying the outgoing particles and their kinematics

• Targeted channels can probe different physics
We can test models of neutrino interactions on argon by studying the outgoing particles and their kinematics.

Targeted channels can probe different physics.

Charged Current (CC) Inclusive

No requirements on the additional particles reconstructed with the outgoing lepton.
• We can test models of neutrino interactions on argon by studying the outgoing particles and their kinematics

• Targeted channels can probe different physics

Testing Models

Charged Current (CC) Inclusive

\[ \nu \rightarrow l \]

Ar

CC Quasi-Elastic (QE)-Like

\[ \nu \rightarrow l \]

\[ n \rightarrow p \]

• No requirements on the additional particles reconstructed with the outgoing lepton

• 1 proton and 1 lepton in the final state
Testing Models

• We can test models of neutrino interactions on argon by studying the outgoing particles and their kinematics.

• Targeted channels can probe different physics.

Charged Current (CC) Inclusive

\[ \nu \rightarrow l \]

CC Quasi-Elastic (QE)-Like

\[ \nu \rightarrow n, p \]

CC 0\(\pi\) Np

\[ \nu \rightarrow l, p, p, X \]

• No requirements on the additional particles reconstructed with the outgoing lepton.

• 1 proton and 1 lepton in the final state.

• N protons and 1 lepton in the final state.
We can test models of neutrino interactions on argon by studying the outgoing particles and their kinematics.

Targeted channels can probe different physics:

- Charged Current (CC) Inclusive
  - No requirements on the additional particles reconstructed with the outgoing lepton
  - 1 proton and 1 lepton in the final state
  - N protons and 1 lepton in the final state

- CC Quasi-Elastic (QE)-Like
  - 1 proton and 1 lepton in the final state

This Talk:

Many More!
Our Physics Probe: LArTPC

- LArTPCs are well equipped to do cross section physics and study the particles from a neutrino interaction
  - Low detection thresholds
  - $4\pi$ acceptance
  - Precise calorimetric information

- Lets see how they work...
Neutrino interacts with the argon inside the TPC volume and produces daughter particles.
Charged daughter particles ionize and excite the argon.
LArTPC Operation

Scintillation

Scintillation light detected by PMTs

→ $t_0$

→ Reconstruction

→ Trigger
LArTPC Operation

Ionisation electrons drift towards the anode with the application of an electric field.

Ionization

Drift

cathode

$E_{\text{drift}}$

19 Feb 2021 K Mistry 12
The signal is recorded on a set of wire planes oriented at different angles.
MicroBooNE

- 85 tonne active volume LArTPC at Fermilab
  - Stable operation since 2015

- 3 planes of wires (vertical, +60°, -60°)
  - 3 mm wire spacing

- 32 PMTs

- Sits in two neutrino beams:
  - BNB (on-axis) \( <E_{\nu_\mu} > = 800 \text{ MeV} \)
  - NuMI (off-axis) \( <E_{\nu_e} > = 650 \text{ MeV} \)
MicroBooNE Event Display

Time (drift direction)

Wire Number (BNB beam direction)

Proton candidate

Proton candidate

Proton candidate

Proton candidate

Bragg Peak

Muon candidate

Colour scale is proportional to the amount of ionization

BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016

19 Feb 2021
$\nu_\mu$ CC Inclusive

Ar

$\nu_\mu$ $\mu$

- First **double differential** cross section measurement on argon
  - 50% purity, 57% efficiency
  - Compared to many interaction generators
    - GENIE v2, GENIE v3, GiBUU, NuWro

- All models overpredict in high-momentum, forward going angular bins
  - Drives the large $\chi^2/N_{\text{d.o.f.}}$
$\nu_\mu$ CC QE-Like and $\nu_\mu$ CC $0\pi$ Np


Phys. Rev. D 102, 112013 (2020)
What physics can we study with low proton thresholds?

- Protons at low momenta give us access to new information about nuclear effects:
  - Nucleon-nucleon correlations e.g. 2 particle 2 hole ($2p2h$)
  - Final State Interactions (FSI)

- LArTPCs are able to push these thresholds down and explore new regions of phase space

- Protons are identified by a Bragg peak in last 30 cm of a track

LArTPCs

**MicroBooNE**: 300 MeV/c

**ArgoNeuT**: 200 MeV/c

**T2K**: 500 MeV/c

**MINERvA**: 450 MeV/c

$dQ/dx = \text{charge deposited per distance}$

*Residual range* = distance from end of track
\( \nu_\mu \) CCQE-Like Cross Section

- First extraction of \( \nu_\mu \)-Ar CCQE-like cross section using a surface LArTPC
  - Proton momentum and angle
  - Muon momentum and angle
  - Calorimetric measured energy and \( Q^2 \)

- \( \approx 84\% \) purity CC 1p 0\( \pi \)
- \( \approx 20\% \) efficiency

- Good agreement with the models except at very forward muon scattering angles

\[ \chi^2/N_{\text{d.o.f.}} \text{ Nom. GENIE: } 33.8/7 \]

\[ \chi^2/N_{\text{d.o.f.}} \text{ Nom. GENIE (cos}\theta < 0.8\text{): } 7.3/6 \]
• Measurement of the cross section as a function of:
  → Proton momentum and angle
  → Muon momentum and angle
  → Muon-proton opening angle

• 71% purity, 29% efficiency

• Generators show reasonable agreement in proton momentum and angle

• Lowest bin in proton momentum has never been seen before
  → Region where FSI and 2p2h are dominant
  → Test modelling of nuclear effects in generators
\( \nu_\mu \text{ CC } 0\pi \text{ Np } (N \geq 1) \)

- Large over-prediction at forward-going angles for the muon
  - Consistent with CC inclusive and CCQE-like measurements

- New models improve the agreement, but not completely

\[ \chi^2/\text{dof} = \begin{cases} 36.9/12 & \text{GENIE v2} \\ 12.8/12 & \text{GENIE v3} \end{cases} \]

\[ \chi^2/\text{dof} = \begin{cases} 19.5/12 & \text{NuWro} \\ 25.6/12 & \text{NEUT} \\ 28.5/12 & \text{GiBUU} \end{cases} \]

\[ \mu\text{BooNE} \]

Phys. Rev. D 102, 112013 (2020)
$\nu_e + \bar{\nu}_e$ CC Inclusive using the NuMI beam

arXiv:2101.04228 [hep-ex]
Electron-Photon Separation

- Able to demonstrate the first fully automated discrimination of electron and photon induced electromagnetic (EM) showers in a LArTPC

- Utilize the energy loss per cm (dE/dx):
  - **Electrons**: dE/dx near the start of a EM-shower is a minimum ionizing particle (MIP) ~ 2 MeV/cm
  - **Photons**: dE/dx near the start of a EM-shower is twice a MIP from the e⁻/e⁺ pair produced ~ 4 MeV/cm
• First $\nu_e + \bar{\nu}_e$ measurement using the NuMI beam from MicroBooNE
  → 214 selected events

• Final selection purity of 39% and efficiency 9%

• Total cross section is in agreement with the GENIE v2, GENIE v3 and NuWro generators

• Next generation of analyses in progress using improvements to simulation
  → Significantly reduced cosmic backgrounds (largest contribution in this analysis)
  → Reduced uncertainties, improved purity and efficiency
  → Coming soon: differential cross section in variables such as the outgoing lepton energy!

For more details Marina’s flash talk on this measurement earlier today! ★

Cross Section Measurement

\[ \times 10^{-39} \]

\[ \nu_e + \bar{\nu}_e \text{ CC Cross Section [cm}^2 / \text{nucleon]} \]

Data (stat. + sys.)
- GENIE v2.12.2
- GENIE v3.0.6
- NuWro v19.02.1

MicroBooNE NuMI Data $2.4 \times 10^{20}$ POT

arXiv:2101.04228 [hep-ex]
Many more measurements coming!

- MicroBooNE is starting to ramp up its cross section program
  
  > Six cross section publications to date and many more in the works!

- New analyses use a tuned version of GENIE v3
  
  > Tuned CCQE and CCMEC models to T2K $\nu_\mu$ CC $0\pi$ data MICROBOONE-NOTE-1074-PUB

- Good progress on measurements include:

  - $\nu_\mu$ CC inclusive MICROBOONE-NOTE-1069-PUB
  - See Wenqiang’s flash talk today 🌟
  - $\nu_\mu$ CC $\pi^0$
  - $\nu_\mu$ CC $1\pi^\pm$
  - $\nu_\mu$ CC coherent $\pi^+$
  - $\nu_\mu$ CC $0\pi$ $2p$
  - $\nu_\mu$ CC $0\pi$ $1p$ Single Transverse Variables (STV)
  - $\nu_\mu$ CC kaon production MICROBOONE-NOTE-1071-PUB
  - $\nu_\mu$ CC $0\pi$ $0,1p$
  - $\nu_\mu$ CC $\eta$ production
  - $\nu_\mu$ NC $\pi^0$ / $\nu_\mu$ CC $\pi^0$ ratio
  - $\nu_\mu$ NC $1p$ MICROBOONE-NOTE-1067-PUB
  - $\nu_\mu$ CC hyperon production (NuMI)
  - $\nu_\mu$ CC inclusive (NuMI)
  - $\nu_e$ CC inclusive (NuMI)
  - $\nu_e$ CC $0\pi$ $Np$ (NuMI)
  - ...

19 Feb 2021
• Cross section measurements of $\nu$-Ar interactions will allow us to develop models that describe $\nu$-Ar interaction data

• Recent results from MicroBooNE
  → Hints of mis-modelling in the prediction of high momentum, forward going muons
  → Able to study protons at low momenta, 300 MeV/c
  → First measurement of the $\nu_e$-Ar cross section using the NuMI beam at MicroBooNE
  → Demonstrate a fully automated electron photon separation using the dE/dx of an EM-shower

• Many new measurements coming soon!
Thank You

Interested in more from MicroBooNE?

- MiniBooNE anomalous excess:
  - Mark Ross-Lonergan
  - Hanyu Wei
  - Andrew Mogan

- LArTPC detector characterization, R&D:
  - Maya Wospakrik

- Astrophysics and BSM Capabilities in MicroBooNE:
  - Pawel Guzowski
Extras
Signal Definitions

$\nu_\mu$ CC QE-Like

- 1 muon
  $\rightarrow p_\mu > 100\ \text{MeV}/c$
- 1 proton
  $\rightarrow p > 300\ \text{MeV}/c$

$\nu_\mu$ CC 0$\pi$ Np (N$\geq$1)

- 1 muon
  $\rightarrow p_\mu > 100\ \text{MeV}/c$
- At least 1 proton
  $\rightarrow 300 < p_p < 1200\ \text{MeV}/c$
- No pions


Phys. Rev. D 102, 112013 (2020)
Across all kinematic variables, agreement is improved if forward muon angles are excluded.
CCQE-Like Cross Section Model Comparisons

- **Nominal**: GENIE v2.12.2. Bodek-Ritchie Fermi Gas, Llewellyn-Smith CCQE model, empirical MEC model, Rein-Sehgal resonant and coherent scattering model, “hA” FSI model

- **hA2015**: GENIE v2.12.2 with a more recent “hA2015” FSI model

- **Alternative**: GENIE v2.12.10. Local Fermi Gas, Nieves CCQE model, Nieves MEC model, KLN-BS resonant and BS coherent scattering models, and hA2015 FSI model

- **v3.0.6**: GENIE v3.0.6. Same model configuration as Alternative model, with hA2018 FSI model
• All three compare to the same GENIE models
  → Cross comparison

\[ \nu_\mu \text{ CC Inclusive} \]

Inclusive

Some deficit

\[ \nu_\mu \text{ CC } 0\pi \text{ Np} \]

More exclusive

Turnover in data

\[ \nu_\mu \text{ CC QE-Like} \]

Even more exclusive

Even more deficit


MICROBOONE-NOTE-1069-PUB

Phys. Rev. D 102, 112013 (2020)
Improvements to Simulation

- Major improvements to the detector simulation in upcoming analyses
  - Includes the simulation of induced charge effects on neighbouring wires
  - Expect drastically reduced detector systematics for future analyses

- Example here shows the improvement for the $\nu_\mu$ CC inclusive

<table>
<thead>
<tr>
<th>Source</th>
<th>Previous Analysis</th>
<th>This Analysis</th>
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<tbody>
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<td>Detector response</td>
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<tr>
<td>Cross section</td>
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<td>Flux</td>
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<td>10.5%</td>
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<tr>
<td>Dirt background</td>
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<td>3.3%</td>
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<td>CRT</td>
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<tr>
<td>Total Sys. Error</td>
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<td>Statistics</td>
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<tr>
<td>Total (Quadratic Sum)</td>
<td>23.8%</td>
<td>12.7%</td>
</tr>
</tbody>
</table>
Nucleon-Nucleon Correlations

• Neutrino can interact with a correlated pair of nucleons inside the nucleus
  → Meson Exchange Current (MEC)
  → Short Range Nucleon-Nucleon Correlations (SRC)

• As a result, we get two proton emission (or more!)
  → “2 particle 2 hole” or 2p2h
  → Final state is different from the traditional QE interaction, 1ℓ 1p, state
Final State Interactions (FSI)

• Nucleons from the $\nu$-Ar interaction can re-scatter while propagating through the nucleus
  → Charge exchange
  → Elastic scattering
  → Absorption
  → Pion Production

• The resulting particles seen in the detector are different to the initial interaction
  → Scales with nucleus size
  → Impacts final particle momenta and particle multiplicities
• NuMI is off axis to MicroBooNE (side and top view)
  → Neutrinos can reach MicroBooNE with angles ranging from 8 – 120 deg
  → Majority of selected neutrinos come from target ~8 deg in the $\nu_e + \bar{\nu}_e$ measurement presented in this talk

arXiv:2101.04228 [hep-ex]

NuMI Flux at MicroBooNE
• BNB Flux at MicroBooNE peaked around 1 GeV (on-axis)
• NuMI flux at MicroBooNE covers a wide range of energies (off-axis)