Recent neutrino cross-section results from MicroBooNE

Wenqiang Gu
On behalf of MicroBooNE collaboration

Interested in more about MicroBooNE?
Investigation on LEE by Nicholas Kamp (Tue 11/1)
Astroparticle and BSM by Anyssa Navrer-Agasson (Wed 12/1)
Neutrino-nucleus interactions in LArTPC

• Liquid Argon Time Projection Chamber (LArTPC) is one key technology in the current and future neutrino oscillation experiments

• Understanding $\nu$-Ar cross sections is critical in reducing systematic uncertainties to reach desired precision of these experiments

LArTPC: fully active tracking calorimeter

Made by Bo Yu (BNL)

A candidate of neutral-current interaction

Drift velocity 1.1 mm/μs → several ms drift time
• Both $\nu_\mu$ and $\nu_e$ cross sections are important for oscillation measurements

• At MicroBooNE, two beamlines are available:
  • Booster Neutrino Beamline (BNB): on-axis, >99% $\nu_\mu + \bar{\nu}_\mu$
  • Main injector neutrino beam (NuMI): off-axis, 4% $\nu_e + \bar{\nu}_e$
Studying $\nu$-Ar cross sections at MicroBooNE

- Understanding of charged-current (CC) **inclusive** cross section on argon is desired for oscillation measurements
- **Exclusive** cross sections could further guide event generators to pin down underlying reaction mechanisms
- Leveraging LArTPC’s excellent capability of tracking calorimetry

[Diagram of reaction processes]
Previous results from MicroBooNE

**PRL 123, 131801 (2019)**

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

**PRL 125, 201803 (2020)**

- $4.59 \times 10^{19}$ POT

**PRD 102, 112013 (2020)**

- $\nu_\mu$ CC inclusive
- $\nu_e (\bar{\nu}_e)$ CC inclusive
- CC $1\pi^0X$
- CC Quasi-Elastic (QE)-Like
- CC $0\pi Np$
Previous results from MicroBooNE

- First **double differential** cross section measurement on argon
- Model overpredictions observed in high-momentum, most **forward-going** muon angle
  ➔ nucleon-nucleon correlation (e.g., RPA effect) is a possible explanation
Previous results from MicroBooNE

- First $\nu_e + \bar{\nu}_e$ measurement using the NuMI off-axis beam at MicroBooNE
  - Successful demonstration of $e/\gamma$ separation and electron-neutrino reconstruction

- Consistent with model predictions within uncertainties
Previous results from MicroBooNE

- First measurement of the flux-integrated cross section of $\nu_\mu$ CC single $\pi^0$ production on argon
Previous results from MicroBooNE

- First measurement of $\nu$-Ar CCQE-like single differential cross section
- Model overprediction observed at most forward-going muon angular bin
  ➜ More significant than inclusive measurement

GENIE Nominal’s goodness-of-fit

$\chi^2$/dof = 33.8/7

$\chi^2$/dof = 7.3/6  ($\cos\theta<0.8$)
Previous results from MicroBooNE

- Model overpredictions at most forward-going muon angle
  ➡️ Consistent with CCQE-like results
- Low proton momentum region is sensitive to Final State Interaction (FSI) and $2p2h$ effect
New results from MicroBooNE

$\nu_{\mu}$ CC inclusive

$\nu_{\mu}$ $\rightarrow\mu^{-}$

Ar

$\nu_{e}(\bar{\nu}_{e})$ CC inclusive

$\nu_{e}$ $(\bar{\nu}_{e})$ $\rightarrow e^{-}$ $(e^{+})$

Ar
Evolved detector simulation & signal processing

- Improved evaluation of detector systematic uncertainties with changes to detector modeling

- Advanced 2D deconvolution with consideration of long-range induction effect
Evolved neutrino interaction model

• MicroBooNE’s interaction model evolved from GENIE v2 to GENIE v3
• New model is tuned through fitting to T2K’s $\nu_\mu$ CC0$\pi$ data (CH) at similar beam energy
  ➔ Tune 4 key parameters related to CCQE and 2p2h models

   ➔ No additional fit to MicroBooNE data (Ar)
Evolved cross section extraction method

• Forward-folding

\[
\left( \frac{d\sigma}{dp_\mu} \right)_i = \frac{N_i - B_i}{\tilde{\epsilon}_i \cdot N_{\text{target}} \cdot \Phi_{\nu_\mu} \cdot (\Delta p_\mu)_i}
\]

- \(N_i (B_i)\): # of candidate (bkgd) in reco bin \(i\)
- \(N_{\text{target}}\): # of argon nuclei
- \(\Phi_{\nu_\mu}\): integrated neutrino flux
- \((\Delta p_\mu)_i\): width for reco bin \(i\)
- \(\tilde{\epsilon}_i\): effective efficiency for reco bin \(i\)

• (Wiener-SVD) unfolding

\[
N_i = \sum_j R_{ij} \cdot S_j + B_i
\]

- \(N_i (B_i)\): # of candidate (bkgd) in reco bin \(i\)
- \(R_{ij}\): response (smearing) matrix
- \(S_j\): cross section to be extracted in true bin \(j\)

\(\Rightarrow\) Flux shape uncertainty properly treated \(\dagger\)

\(\dagger\): Phys. Rev. D 102 (2020) 113012

Wiener-SVD: JINST 12 (2017) 10, P10002

15
Evolved inclusive $\nu_\mu$ CC measurement

• Enhanced event selection efficiency (57%→68%) and purity (50%→92%)
• Extracted neutrino energy-dependent inclusive $\nu_\mu$ CC cross section
• Challenge: how to verify the modeling of the undetected missing hadronic energy?
  ➔ Mapping of $E_\nu \rightarrow E_\nu^{\text{rec}}$

True energy components:

$$E_\nu = E_\mu + E_{\text{had,vis}} + E_{\text{had,missing}}$$

Calorimetric energy reconstruction:

$$E_\nu^{\text{rec}} = E_\mu^{\text{rec}} + E_{\text{had,vis}}^{\text{rec}}$$
Conditional constraining procedure

- Overcome the challenge by leveraging LArTPC’s simultaneous measurements of **lepton energy** and **visible hadronic energy**

**Conditional expectation & covariance**

\[ \mu_{X,Y} = \begin{pmatrix} \mu_X \\ \mu_Y \end{pmatrix}, \quad \Sigma_{X,Y} = \begin{pmatrix} \Sigma_{XX} & \Sigma_{XY} \\ \Sigma_{YX} & \Sigma_{YY} \end{pmatrix} \]

\[ \mu_{Y|X} = \mu_Y + \Sigma_{YX} \Sigma_{XX}^{-1} (X - \mu_X) \]

\[ \Sigma_{Y|X} = \Sigma_{YY} - \Sigma_{YX} \Sigma_{XX}^{-1} \Sigma_{XY} \]

* A variant of Gaussian Process regression

\[ \mu(E_{\text{had}}^{\text{rec}}) \quad \Sigma(E_{\text{had}}^{\text{rec}}) = \mu(E_{\text{had}}^{\text{rec}} | E_\mu^{\text{rec}}, E_\nu^{\text{rec}}) \quad \Sigma(E_{\text{had}}^{\text{rec}} | E_\mu^{\text{rec}}, E_\nu^{\text{rec}}) \]

Prior model

Sideband

Posterior model

\[ E_\nu = E_\mu + E_{\text{had,vis}} + E_{\text{had,missing}} \]
Energy model validation: $M(E_{\text{had}}^{\text{rec}})$ vs. $\mu(E_{\mu}^{\text{rec}} | E_{\text{had}}^{\text{rec}}, \cos\theta_{\mu}^{\text{rec}}, E_{v})$

- Measured muon kinematics are used to constrain the overall model (flux, cross section, etc.) for hadronic energy

$$E_{v} = E_{\mu} + E_{\text{had,vis}} + E_{\text{had,missing}}$$

- Significant reduction in overall systematic uncertainties (20% → 5%)

- No sign of mis-modeling of the hadronic missing energy
  - $E_{v} \rightarrow E_{v}^{\text{rec}}$ mapping is good!
Inclusive $\nu_\mu$ CC: energy-dependence

- Improved cosmic-$\mu$ rejection
  - JINST 16 (2021) 06, P06043 (Wire-Cell reconstruction)

- New model validation procedure for $E_\nu$ reconstruction enables unfolding of $\sigma(E_\nu)$

arXiv: 2110.14023
Differential inclusive $\nu_\mu$ CC: hadronic energy transfer

- New model validation procedure for $E_\nu$ reconstruction also enables **differential cross section** as a function of hadronic energy transfer on argon

- Good separation power of model predictions from different generators

- GiBUU’s central prediction gives best agreement at low energy transfer
  $\Rightarrow$ more contribution of $2p2h$

**MicroBooNE 5.3 \times 10^{19}$ POT**

- GENIE v3.00.06
- NuWro 19.02.1
- NEUT 5.4.0.1
- GiBUU 2019.08
- MicroBooNE MC

$\chi^2$/ndf:
- GENIE v3.00.06: $30.9/8$
- NuWro 19.02.1: $24.5/8$
- NEUT 5.4.0.1: $18.4/8$
- GiBUU 2019.08: $17.0/8$
- MicroBooNE MC: $33.8/8$

**Data**

arXiv: 2110.14023
Differential inclusive $\nu_e + \bar{\nu}_e$ CC cross section

- Enhanced event selection efficiency (9%→21%) and purity (39%→72%)
- **Differential** cross sections as a function of electron/positron’s energy and angle are extracted using unfolding techniques
- Consistent results with model predictions within uncertainties

\[
\frac{d\sigma}{dE_e} = 10^{-38} \text{ cm}^2/\text{GeV}/\text{nucleon}
\]

\[
\frac{d\sigma}{d\cos\beta_e} = 10^{-39} \text{ cm}^2/\text{nucleon}
\]

arXiv:2109.06832
More cross-sections in progress

CC0πNp 2D differential

CC 0π2p

Λ⁰ production

NC Elastic

- 2p2h effect
- driven by anti-neutrinos
- \( Q^2 \rightarrow 0.1\text{GeV}^2 \)
- sensitive to strange quark contribution to proton spin
Summary

• Understanding of $\nu$-Ar cross section is vital for LArTPC-based precision neutrino oscillation experiments

• MicroBooNE has produced numerous $\nu$-Ar cross section measurements
  ➢ $\nu_e$ vs. $\nu_\mu$, inclusive vs. exclusive (CCQE-like, CC0$\pi$Np, ...)
  ➢ The only high-stat $\nu$-Ar observatory before SBND is online

• New validation method of neutrino energy modeling enables the energy-dependent inclusive $\nu_\mu$ CC cross section
  ➢ Good separation power of model predictions from different generators
Backup Slides
Protons in LArTPC

• Low-momenta protons give access to exclusive channels of $\nu$-Ar interaction, as well as probes of nuclear effects (2p2h, FSI, etc.)

• LArTPC has excellent proton detection by identifying a Bragg peak in dE/dx at end of particle trajectories