PROCEEDINGS OF SCIENCE

Neutrino-induced proton knockout in MicroBooNE

Samantha Sword-Fehlberg[a,*]

[a] *Physics Department, New Mexico State University, Las Cruces, NM, 88003 USA*

E-mail: fehlberg@nmsu.edu

The MicroBooNE detector is the world's longest-running liquid argon time projection chamber (LArTPC), currently installed in the Booster Neutrino Beam at Fermilab. One of the primary physics goals of MicroBooNE is to perform detailed studies of neutrino-argon scattering cross sections, which are critical for the success of future neutrino oscillation experiments. At neutrino energies relevant for the Short-Baseline Neutrino Program, the most plentiful event topology involves mesonless final states containing one or more protons. A low reconstruction threshold enabled by LArTPC technology has allowed MicroBooNE to pursue various analyses studying neutrino-induced proton production at accelerator energies. This talk presents several recent results from that effort, including a neutral-current elastic differential cross section as a function of Q^2, as well as charged-current measurements examining exclusive final states containing protons.

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[*] Speaker

1. Introduction

Neutrino cross-sections can probe physics related to neutrino interaction channels, nuclear properties of the target nucleus, and properties of individual nucleons. All of this physics can be probed by looking at mesonless final states with any number of protons. For instance, selecting events with any number of protons allows us to probe Quasi-Elastic (QE), Resonance (RES), Meson Exchange Currents (MEC), and Deep Inelastic Scattering (DIS) interactions. These events are also sensitive to nuclear effects such as Fermi Motion and Final State Interactions (FSI). Events with a single proton are sensitive to the QE interaction channel, but can also provide insight to the single proton structure, and events with 2 protons are sensitive to MEC interactions as well as Short-Range Nucleon-Nucleon Correlations (SRC). By employing the great calorimetric reconstruction of Liquid Argon Time Projection Chamber (LArTPC) technology, MicroBooNE has pushed proton-momentum reconstruction to unprecedentedly low energy thresholds, making it well poised to study neutrino-induced proton knockout events. This talk will summarize MicroBooNE's 4 current proton cross-section analyses: Charged-Current N Proton (CCNP) [1], Charged-Current Quasi-Elastic Like (CCQE-like) [2], Charged-Current 2 Proton (CC2p) [3], and Neutral-Current Elastic (NCE) [4].

2. Charged-Current N Proton Analysis

The CCNP analysis is sensitive to all neutrino interaction processes and nuclear effects. While MicroBooNE does have an existing cross-section measurement of CCNP events [5], significant updates to the Monte-Carlo (MC) simulation, event reconstruction algorithms, and systematic uncertainty calculations have been made since then. Furthermore, there is approximately 4.2x more data available to be analyzed. The goal of the new analysis is to extract the double differential cross-section as a function of leading proton (the proton identified to have the highest momentum) and muon kinematics. The analysis identifies an event as signal if there is exactly 1 muon with P_μ > 0.1 GeV/c , N protons with 0.25 < P_p <1.2 GeV/c, and 0 mesons of any kind. The analysis is able to achieve an efficiency of 36.6% and a purity of 77.4%. From the selected events, a variety of kinematic quantities can be reconstructed such as the leading proton's momentum and angle with respect to the beam (denoted θ_p). Figure 1 displays the cos(θ_p) of the leading proton in a variety of regions of reconstructed leading proton momentum. We note

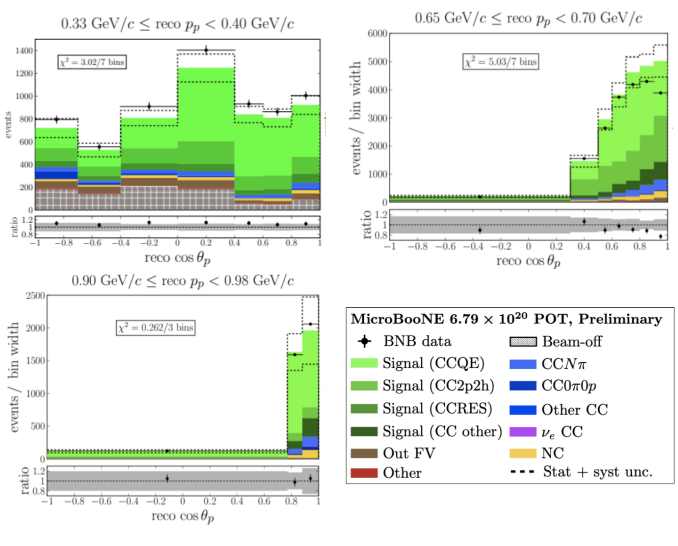

Figure 1: Selected CCNP events as a function of cos(θ_p) in different regions of leading proton reconstructed momentum.

that there is tension between the data (black points) and the MC predictions (colors). Future work will involve the extraction of the double differential cross-sections.

3. Charged-Current Quasi-Elastic-Like Analysis

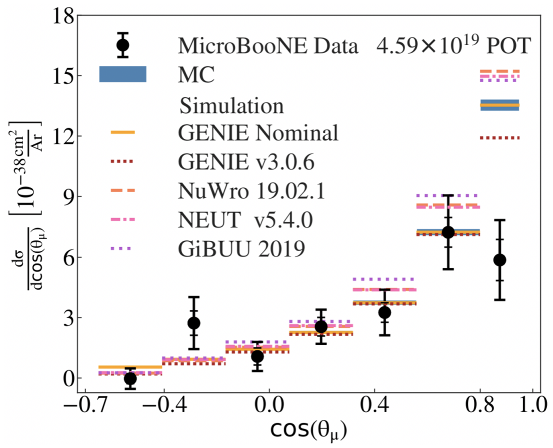

Figure 2: CCQE-like differential cross-section as a function of $\cos(\theta_\mu)$.

QE interactions are the dominant interaction channel in the total CC cross-section at MicroBooNE beam energies. CCQE events are characterized by topologies with a single muon and single proton in the final state. The main goal of the CCQE-like analysis is to extract the differential cross-section as a function of muon and proton kinematics. The analysis requires events to have 1 muon with P_μ > 0.1 GeV/c, 1 proton with P_p > 0.3 GeV/c, 0 charged pions with $P_{\pi^\pm}$ > 70 MeV/c, and 0 neutral pions of any momentum. In addition to these kinematic limits, the analysis has additional requirements in order to enhance the selection of CCQE-like events. This includes a non-colinearity requirement ($|\Delta\theta_{\mu,p} - 90^o| < 55^o$), the muon and proton coplanarity relative to the beam axis ($|\Delta\phi_{\mu,p} - 180^o| < 35^o$), and small missing transverse momentum ($P_T = |P_T^\mu + P_T^P| < 0.35$ GeV/c). The analysis uses 4.59 x 10^{19} protons on target (POT) from MicroBooNE's first year of running and achieves an efficiency and purity of 19.6% and 84.0% respectively. Figure 2 displays the CCQE-like single differential cross-section as a function of $\cos\theta_\mu$. There is notable disagreement in the most forward going bin between the data points (black) and the MC predictions (colors). While the CCQE-like analysis has concluded and been published [2], progress is being made on a CC1p0π analysis that will utilize more statistics, improved MC models, updated event reconstruction tools, and updated systematics procedures. The CC1p0π analysis aims to extract double-differential cross-sections.

4. Charged-Current 2 Proton Analysis

Charged-Current events with 2 protons in the final state are sensitive to 2-particle, 2-hole processes (2p2h) such as MECs and SRCs. While many models exist for MECs, many event generators do not take contributions from SRCs into account. Two measurements of CC2p events on ^{40}Ar exist, but both are statistically limited [6, 7]. MicroBooNE has performed a study of different MEC model sets found within GENIE to identify variables with sensitivity to differences between these models. The goal of the analysis is to extract the single differential cross-section as a function of these variables with higher statistics. Signal events were required to have 1 muon with $0.1 < P_\mu < 1.2$ GeV/c, 2 protons with $0.3 < P_p < 1.0$ GeV/c, 0 charged pions with $P_{\pi^\pm} > 65$ MeV/c, and 0 neutral pions. The selection was able to achieve an efficiency of 13% and a purity of 65.4%.

Figure 3 shows the cosine of the opening angle between the protons in the lab frame ($\cos(\gamma_{\mathrm{Lab}})$) with the MC broken down in terms of different topologies. Data points are not displayed on these plots as the systematic uncertainties have yet to be evaluated. The CC2p contribution (pink band) shows a slight preference of back-to-back protons. The analysis is working to finish the evaluation of systematic uncertainties and the extraction of the differential cross-sections. There is also work being done on the development of an event generator model set in which contributions of SRCs are considered under Generalized Contact Formalism (GCF) [8].

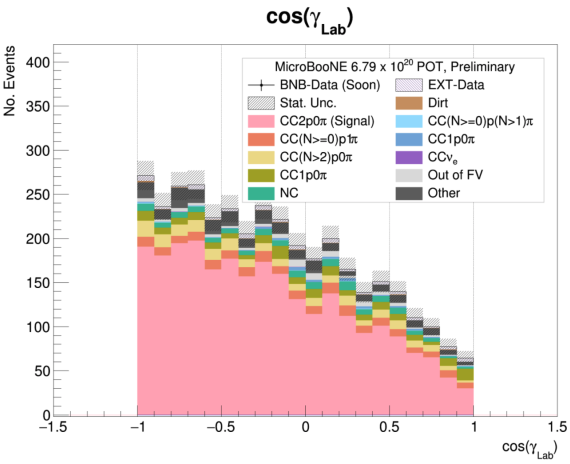

Figure 3: Selected CC2p events as a function of $\cos(\gamma_{\mathrm{Lab}})$.

5. Neutral Current Elastic Analysis

The NC axial form factor of the proton , G_A^{NC} , has yet to be fully measured. When the square of the 4-momentum transfer (Q^2) equals 0, G_A^{NC} depends on g_A and Δs, the strange quark's contribution to the nucleon spin. While measurements of Δs from neutrino experiments exist, they are conflicting [9, 10]. The use of LArTPC technology allows MicroBooNE to reconstruct protons with momentum as low as 300 MeV/c, which is equivalent to a Q^2 of 0.1 GeV^2. This incredible advancement provides an opportunity for MicroBooNE to extract a value for Δs at the lowest Q^2 value to date. The analysis aims to do the extraction by first measuring the Neutral Current Elastic (NCE) differential cross-section as a function of Q^2. Signal events are required to have 1 proton with $P_p > 0.3$ GeV/c, 0 muons with $P_\mu > 0.1$ GeV/c, 0 charged pions with $P_{\pi_\pm} > 65$ MeV/c, any number of neutrons, a true NCE event (as determined by MC-truth), and the struck nucleon is a proton (as determined by MC-truth). The analysis achieves an efficiency of 37.7% and a purity of 22.7%. Figure 4 shows the single differential cross-section as a function of Q^2, where Q^2 is calculated from the reconstructed proton kinetic energy. We see good data-MC agreement across the range of Q^2. We are currently working to improve purity by reducing a variety of backgrounds and to decrease the error caused by bins with low statistics. After this is complete, we will extract the value for Δs.

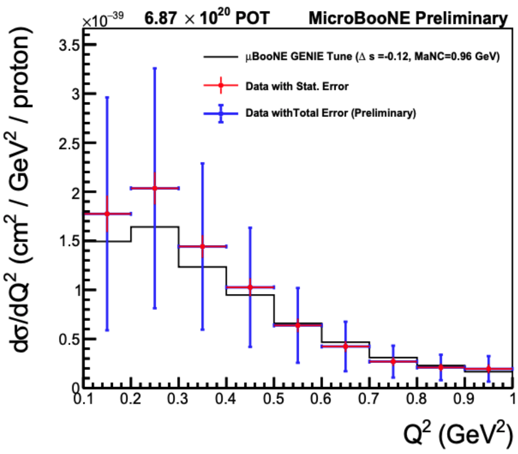

Figure 4: NCE differential cross-section as a function of Q^2.

6. Summary

MicroBooNE's CCNP, CCQE-Like, CC2p, and NCE proton knockout analyses are producing some of the world's first measurements of neutrino differential cross-sections on ^{40}Ar for these specific topologies. Results from the CCQE-Like analysis have been published, but results from the CCNP analysis, the follow-on CC1p0π analysis, the CC2p analysis, and the NCE analysis are expected to be published soon.

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