Measurement of the $\nu_\mu$ CCQE Cross Section with the ND280 Detector at T2K

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The first measurement of the $\nu_\mu$ Charged Current Quasi-Elastic (CCQE) cross section on Carbon by the T2K experiment is presented. The cross section is extracted in bins in $E_\nu$ from a binned template fit of the NEUT MC model to the observed $p_\mu - \cos(\theta_\mu)$ distribution in the off-axis near detector. A fit for the effective quasi-elastic axial mass is also shown.
T2K is an accelerator based long baseline neutrino oscillation experiment [1]. The Charged-Current Quasi-Elastic (CCQE) interaction, $\nu + n \rightarrow l^- + p$, is the main signal in the neutrino oscillation measurement. Oscillation probability depends on the neutrino energy. This two-body interaction is important because the initial neutrino energy can be inferred from the final state lepton kinematics. Recent CCQE measurements [2] have shown disagreement between low/high energy experiments and nuclear/deuterium targets. Understanding the CCQE interaction in the few GeV energy range is essential for current and future long baseline neutrino oscillation experiments.

The T2K off-axis near detector, shown in fig. 1, is divided into a tracker and $\pi^0$ detector region. This analysis used events reconstructed in the tracker region. The Fine Grained Detector (FGD1) consists of layers of plastic scintillator bars, $10 \times 10$ mm in cross section, readout with wavelength shifting fibers into Multi-Pixel Photon Counters (MPPCs). It provided target mass and track reconstruction near the interaction vertex. The Time Projection Chambers (TPCs) provided PID based on $dE/dx$ in the Argon based gas and momentum measurement from track curvature in the magnetic field. The analysis shown here is based on $2.7 \times 10^{20}$ POT. The predicted flux at the ND280 is shown in fig. 2.

CCQE-like interactions containing a muon with no pions in the final state were selected. A good-quality track starting within the FGD fiducial volume with a muon-like TPC PID was required. Events with additional tracks in the TPC were vetoed as most protons from CCQE interactions stop in the FGD. To further reduce the $\pi$ background, events with Michel electrons reconstructed within the FGD were vetoed. This event selection achieved an efficiency of 40% and purity 72% for true CCQE events. The reconstructed muon kinematics are shown in fig. 3.

The CCQE cross section was extracted by fitting the NEUT MC model [3] to the reconstructed $p_\mu - \cos(\theta_\mu)$ distribution. The NEUT CCQE model uses the Smith-Moniz implementation of the Fermi Gas Model and a cascade model for FSI. No additional contribution from multi-nucleon effects were included.

Simulated template histograms were fit to the observed $p_\mu - \cos(\theta_\mu)$ distribution. The

![Figure 1: The ND280 off axis near detector.](image1)

![Figure 2: Predicted neutrino flux at the ND280.](image2)
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CCQE cross section was extracted by weighting 5 template histograms in bins of $E_\nu$. Systematic uncertainties were accounted for by varying bin contents with nuisance parameters. A maximum likelihood fit was used to find the best fit parameters.

Figure 4 shows the best fit CCQE cross section. A $\chi^2$ test comparing the fitted result with the nominal NEUT model gives $p$-value of 17% indicating agreement between the data and the cross section model. The best-fit to the ND280 data preferred a lower overall cross section than the NEUT prediction. However, the fit results were still consistent with the NEUT prediction within error.

An alternative approach to fitting the cross-section normalisation, is to directly fit the CCQE model parameters. The axial mass parameter $M_A^{QE}$ was varied to obtain the best fit to the observed data. The best-fit using shape and normalisation information was $M_A^{QE}$-norm = $1.14^{+0.27}_{-0.20}$ GeV. The best-fit using only shape information was $M_A^{QE}$-shape = $1.38^{+0.30}_{-0.27}$ GeV. Large effective $M_A^{QE}$ is believed to be due to unaccounted for nuclear effects. Note that the meaning of this effective parameter depends on the details of the QE model; comparison with results from other experiments should be done with care.

References