The T2K CCQE selection and prospects for CCQE, NCE cross-section measurements

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Abstract.
A better understanding of the charge current quasi-elastic (CCQE) interaction channel will lead to a more precise ν_e appearance and ν_μ disappearance measurement at T2K. Measurements looking at the CCQE interaction using the near detector complex (ND280) help constrain cross-section uncertainties as well as the flux prediction at the far detector, Super-Kamiokande. The presented CCQE analysis is derived from a CC-inclusive selection using the tracking portion of ND280. The inclusive sample is broken into a CCQE-enhanced and CC non-QE like sample and each sample is used to constrain various parameters used for the far detector prediction. Future CCQE analyses using the tracker will either use the current selection or investigate newer selections for 2 track topologies. The neutral current equivalent to CCQE, neutral current elastic scattering (NCE), is being investigated using the pi-zero detector (POD). The NCE analysis selects a contained single track sample using muon/proton particle identification.

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INTODUCTION

The T2K experiment[1] is a second generation long-baseline accelerator based neutrino oscillation experiment located in Japan. An intense ν_μ beam is produced by impinging 30 GeV protons on a graphite target. The resulting hardronic shower is focused using three electromagnetic horns. A narrowband beam with a peak energy of 600 MeV is achieved by placing the near and far detector 2.5 degrees off-axis. The T2K peak energy is the optimal energy for the first minimum of the ν_μ disappearance given the 295 km baseline to the far detector Super-Kamiokande (SK). T2K uses a near detector complex (ND280) to measure the initial beam conditions as well as cross-section uncertainties to constrain uncertainties in the far detector prediction. The dominant interaction channel at this neutrino energy is CCQE. This interaction channel is of great interest because SK uses the CCQE interaction channel to measure ν_μ disappearance and ν_e appearance. The understanding of the beam flux as well as various neutrino cross-sections is critical for these neutrino oscillation measurements.

The ND280 complex, Figure 1, is located within the UA1/NOMAD magnet composed of the π^0-detector (POD), two fine-grained-detectors (FGD) interweaved between three time projection chambers (TPC) surrounded by electromagnetic calorimeters (ECal), and a side-muon-range detector (SMRD). A more complete description of the TPC, FGD and P0D detectors used in the analyses presented can be found at [2], [3], and [4], respectively. The TPC plus FGD region of the detector is referred to as the tracker region and is used for the CCQE analysis.

The presented tracker analyses use the upstream FGD and TPC just downstream. The upstream FGD is constructed of alternating X and Y layers of 1 cm^2 extruded polystyrene scintillator bars which have wavelength shifting fibers coupled to MPPCs for readout. The TPC is filled with an argon, CF_4, and isobutane gas mixture. It utilizes MicroMegas detectors for charge amplification from the ion trail left by ionizing particles which enter the gas volume. The FGD provides a carbon-rich target with vertex information while the TPC provides particle identification and momentum measurements. The P0D NCE analysis only uses information from the P0D as the protons resulting from elastic scattering are mostly contained within the detector.

The P0D is a sampling calorimeter, as seen in Figure 2, composed of two ECal sections placed around a water target volume. The ECal sections are constructed of a lead radiator plus X and Y extruded polystyrene scintillator bars. These bars contain wavelength shifting fibers coupled to MPPCs for readout. The water target section uses an alternating XY scintillation readout plus a water target and brass radiator layer. The primary purpose of the P0D is to detect π^0s resulting from neutral current resonant pion production on water. To facilitate this measurement the water in the target region can be removed for a subtraction measurement.

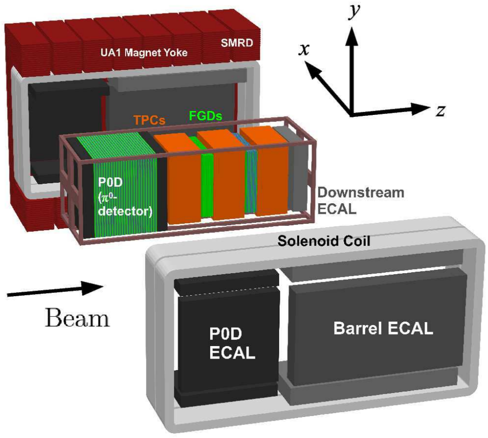


FIGURE 1. ND280 detector complex

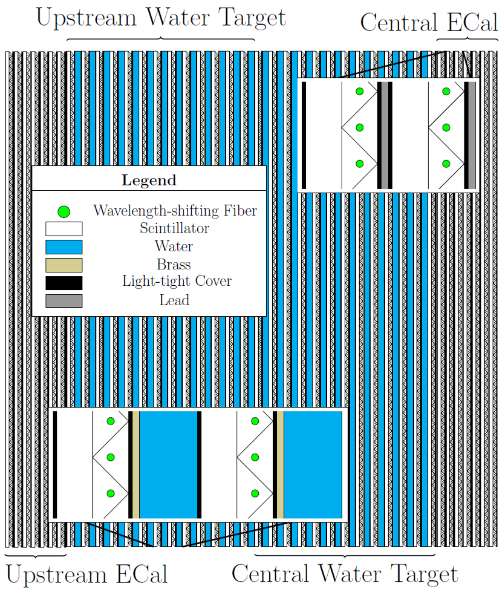


FIGURE 2. P0D construction with a removable water target region

CURRENT CCQE SELECTION AND USE

The tracker CCQE selection is derived from the CC-inclusive selection using the upstream FGD as a target. This selection selects events where a muon-like particle originates in the fiducial volume of the FGD and is detected in the TPC just downstream of the FGD. The TPC provides particle identification as well as an accurate measure of the muon's momentum. The CC-inclusive sample is further broken down into a CCQE-like and CC non-QE-like (CCnQE) sample with the introduction of two additional criteria: a second track condition and a Michel electron cut. It was determined the proton from the CCQE interaction is less likely to propagate into the TPC when compared to the π^+ from resonant pion production. As a result, if a second track is present in the TPC the event is classified as a CCnQE event. The analysis also searches for a Michel electron in the FGD. If a Michel electron is detected the event likely came from a non-QE event and is rejected as a CCQE candidate. The CCQE-like momentum and angle distributions can be seen in Figure 3. The sample is mostly forward going CCQE events with a peak muon momentum at $\sim$500 $\frac{MeV}{c}$.

The CCQE and CCnQE samples are each broken down into 20 momentum-angle bins. The bin boundaries are

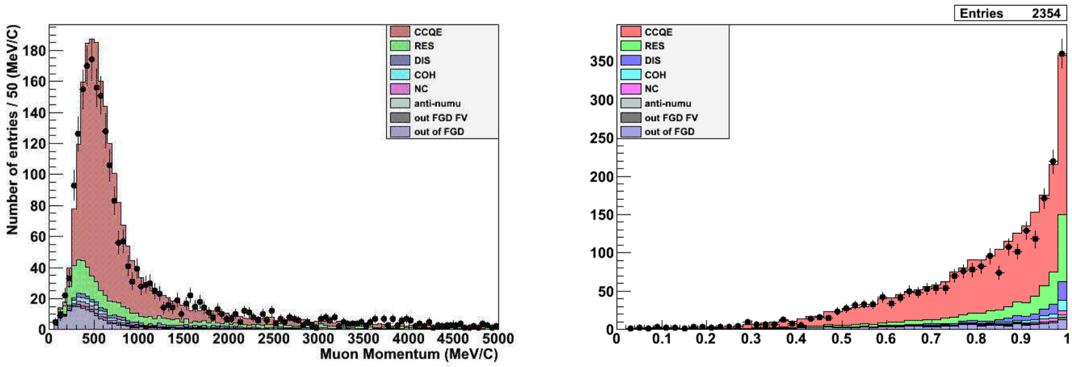
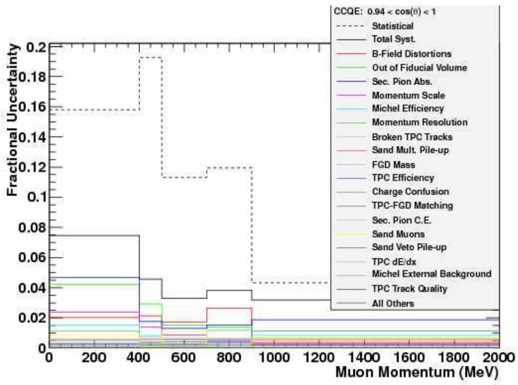


FIGURE 3. CCQE Selection: Muon momentum (l) and angle (r)



CCQE sub-sample (Data / MC)					
$\cos\theta_\mu$ \ P_μ (MeV)	0-400	400-500	500-700	700-900	>900
0-0.84	332 (333.76)	247 (266.88)	309 (338.31)	90 (106.84)	95 (96.47)
0.84-0.90	43 (44.40)	41 (46.73)	95 (104.22)	39 (62.71)	66 (84.63)
0.90-0.94	28 (27.55)	29 (30.32)	59 (73.18)	38 (50.89)	93 (107.21)
0.94-1.00	40 (32.01)	27 (33.33)	78 (91.17)	70 (73.63)	535 (538.40)

FIGURE 4. Example fractional errors for the forward going angle bin (l) and event selection in p-θ bins (r)

determined by the following criteria: keep bin content to at least 20 events, equalize bin content across the momentum angle bins and have bin widths larger than the detector resolution to keep bin to bin migrations from detector effects to a minimum. The result is smaller bins in the forward angles with muon momenta in the peak region. One important systematic uncertainty to highlight investigates the migration of events between the CCQE and CCnQE sample via final state interactions. A certain fraction of the resonant pion interactions will end up with no pions exiting the target nucleus due to various pion re-interactions in the nucleus, one of many types of final state interactions. The pion interactions are reweighted with 5 parameters. A set of 16 parameter sets ,varying these 5 parameters, were selected to represent a "1-σ contour". The parameter sets include values for pion absorption fractions, quasi-elastic scattering as well as inelastic scattering for low and high energy interactions. All systematics are evaluated and passed on in the form of a 40x40 covariance matrix: a 20x20 matrix for each selection along the diagonal along with crossterms off diagonal. An example angle bin, $0.94<\cos(\theta)<1$, as a function of muon momentum can be seen in Figure 4 along with the selection breakdown as a function of angle and momentum. The selection is currently statistically limited using this binning scheme.

The CCQE/CCnQE selections are then used as an input into a fit to provide constraints on parameters used for the prediction at the far detector for the oscillation analysis. The fit takes external constraints on the beam flux from NA61/Shine and beam monitors and cross-section constraints from MinBooNE data fits to NEUT, the Monte Carlo generator used by T2K, which were cross checked with data from the K2K, SciBooNE, and NOMAD experiments. The initial CCQE related parameter values and the respective errors before and after the fit are shown in Figure 5. The central value of M_A^{QE} is largely unaffected but the error was reduced from 0.45 to 0.19 GeV. In addition, the central values for the 0-1.5 GeV and 1.5-3.5 GeV CCQE normalization parameters decreased by $\sim 6\%$ and $\sim 8\%$ respectively with a $\sim 15\%$ decrease in the error.

	Prior Value and Uncertainty	Fitted Value and Uncertainty
M_A^{QE} (GeV)	1.21 ± 0.45	1.19 ± 0.19
CCQE Norm. 0-1.5 GeV	1.000 ± 0.110	0.941 ± 0.087
CCQE Norm. 1.5-3.5 GeV	1.00 ± 0.30	0.92 ± 0.23
CCQE Norm. >3.5 GeV	1.00 ± 0.30	1.18 ± 0.25

FIGURE 5. Prior and post fit values for CCQE parameters

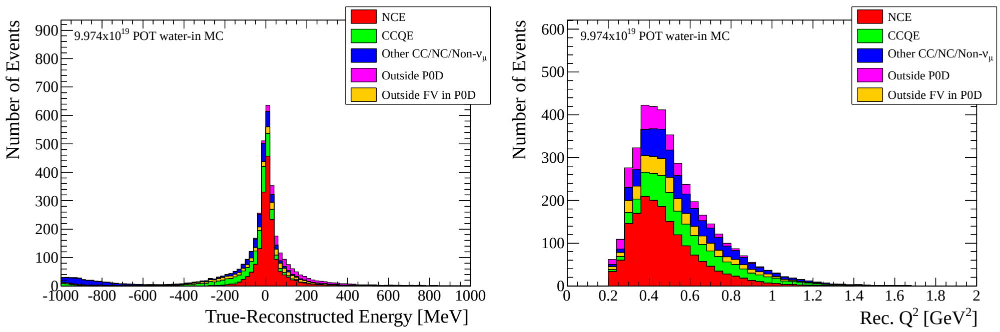


FIGURE 6. Proton kinetic energy residuals (l) and reconstructed Q^2 (r)

FUTURE CCQE ANALYSES

Current analyses in the ND280 tracker are beginning to study the CCQE cross-section. One analysis uses the presented CCQE-like selection to determine an effective M_A^{QE} fitting over bins of neutrino energy. Another analysis looks specifically at a 2 track topology with the interaction vertex originating in the FGD and some combination of the 2 tracks contained in the FGD or exiting into the TPC just downstream of the target FGD.

NCE

There is currently an analysis in the P0D looking at NCE interactions. The event selection consists of a single contained proton-like track originating in the water target by utilizing particle identification, developed for this analysis, to remove the dominant CCQE background. Once a suitable proton-like track is identified the proton kinetic energy is estimated using the integration of the $< \frac{dE}{dx} >$ over the various materials in the detector. The current energy reconstruction residuals can be seen in Figure 6. Once the kinetic energy of the proton is determined an estimation of the interaction Q^2 can be made using a stationary target assumption, eq 1, as seen in Figure 6.

$$Q^2_{rec.} = 2m_pT_p \tag{1}$$

Current studies are centered around reducing backgrounds, although indications are the remaining backgrounds are largely irreducible. A data driven method for measuring the external neutron background is underway as this background is difficult to simulate with minimal information about the surrounding detector hall.

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