Neutrino interaction measurements using the T2K near detectors

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Abstract. The T2K near detectors provide a rich facility for measuring neutrino interactions in a high-flux environment. This talk will discuss the near detector CC-inclusive normalization analysis for the T2K oscillation result in detail, along with the present result, and describe the plan for its extension to more sophisticated measurements. Selection criteria for CCQE interactions will be presented, as will a strategy for calculating cross-section difference between plastic scintillator and water. The unique capacities of the near detectors to measure other exclusive CC and NC channels in a narrow-band off-axis beam will also be explored.

1. Introduction

The T2K (Tokai to Kamioka) long-baseline neutrino oscillation experiment[1] aims to make high-precision measurements of oscillation parameters using a beam of muon neutrinos. In particular, the appearance of electron neutrinos in the beam is studied in an effort to measure a non-zero value of the mixing parameter θ_{13}. Electron neutrino appearance provides a particular challenge for the near detector, as the electron neutrino fraction in the muon neutrino beam is the most significant background to this measurement.

The T2K experiment has had two experimental runs; one at beam power up to 50 kW from January to June 2010, and one at beam power up to 150 kW from November 2010 to March 2011, when it was cut short by the Tohoku earthquake. 1.43×10^{20} protons on target were accumulated by T2K prior to the earthquake.

Recently, T2K has published an electron appearance result with suggestion of large θ_{13} ($\sin^2 2\theta_{13} \approx 0.1$)[2]. The significance of this result has driven further interest in improving background estimates using the near detector.

2. The T2K Experiment

The T2K experiment has three main components: the beam source, the near detector complex, and the far detector, Super-Kamiokande. The ND280 near detector is the focus of this paper.

2.1. Beamline

The T2K beam is produced from the 30 GeV proton beam of the J-PARC Main Ring. These protons are extracted in eight bunches every 3 seconds and collided with a long graphite target. The positively charged secondary particles are focussed down a 96 m decay volume using three magnetic horns. The predominant contribution is from pions, which decay $\pi^+ \rightarrow \mu^+ \nu_\mu$ to produce muon neutrinos. All charged decay products are stopped in a beam dump while the
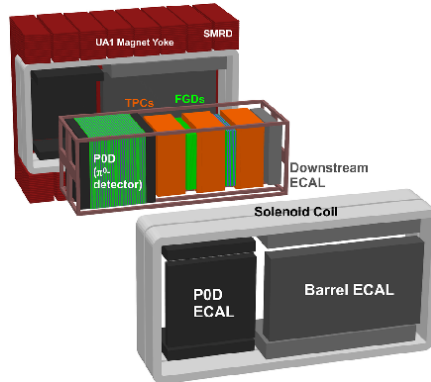
Figure 1. An exploded view of the ND280 detector.

neutrinos pass through freely. The electron neutrino component is produced by other particles decaying in the beam pipe, such as muons and kaons.

The T2K beamline is angled 2.5° away from Super-Kamiokande; this off-axis beam technique provides a narrower energy spectrum peaking near the oscillation maximum, and dramatically reduces the high-energy tail. T2K is the first oscillation experiment to use the off-axis configuration.

2.2. Far Detector (Super-Kamiokande)

The 50 kt water Čerenkov detector Super-Kamiokande (Super-K) is the far detector for T2K, sitting 295 km from the production target at J-PARC. Super-K images the Čerenkov rings produced by charged particles from neutrino charge-current interactions to detect incident neutrinos. The ring imaging allows a high-purity separation of electrons and muons, as the two particles produce Čerenkov rings with much differently defined edges.

Many of the Super-K backgrounds are intended to be well constrained by ND280. In addition to the intrinsic electron neutrino fraction of the T2K beam, we have substantial background from neutral pions. A neutral pion decays to two photons, which are indistinguishable in Super-K from electrons. If one of the decay photons escapes or is otherwise missed, the remaining photon will mimic a CCQE electron neutrino interaction, i.e. our appearance signal.

2.3. Near Detectors

Two near detectors are located in a pit 280 m from the production target at J-PARC. The INGRID detector is a cross-shaped arrangement of 14 iron/scintillator neutrino detector modules, centred on the beam axis. The event rates in these modules are used to measure the stability of the beam flux and direction. At the T2K design intensity, the interaction rate should be sufficient to monitor these on a day-to-day basis.

At the off-axis angle to the neutrino beam is the ND280 spectrometer. The ND280 detector consists of two central detectors, the P0D (Pi-Zero Detector) and the Tracker, surrounded by an electromagnetic calorimeter (ECal) and placed within the 0.2 T magnetic field of the UA1 magnet. Interleaved in the magnet yokes is an additional detector, the Side Muon Range Detector (SMRD). A full diagram of ND280 can be found in Figure 1.

The Tracker consists of three large-volume Time Projection Chambers (TPCs) and two Fine Grained Detectors (FGDs). The TPC gas detectors allow high precision 3D tracking of charged particles and measurements of the energy loss, while the plastic scintillator FGDs provide an active target mass ($\approx$ 1.1 tons per FGD) allowing tracking back to the neutrino interaction vertex. The TPC can measure the momentum and charge of particles from their curvature in
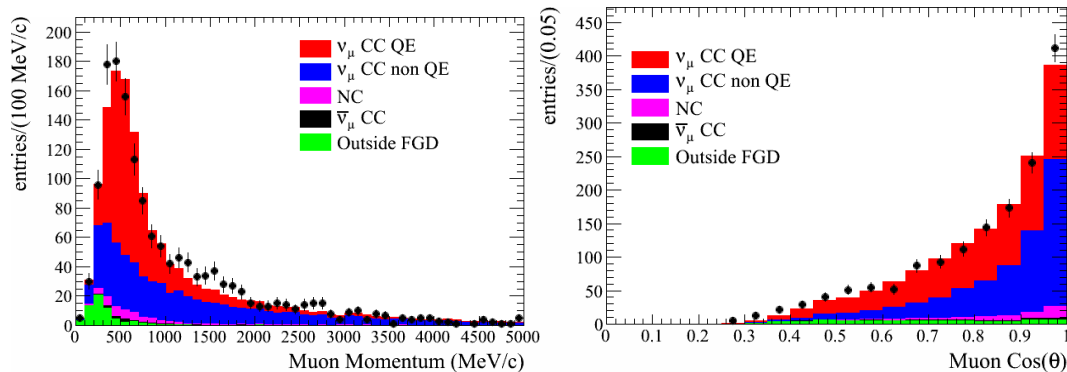
Figure 2. Distribution of muon momentum and angle in data from January-June 2010 and in Monte Carlo.

the magnetic field, and provides a measure of dE/dx for particle identification. Tracks from the TPC can then be traced back into the FGD and associated with FGD activity, allowing the vertex to be localized and the fiducial volume established. FGD-only tracking can then be used to find short-range particles such as protons and pions.

The P0D aims to measure neutral current π^0 production and takes the form of a hybrid calorimeter/tracking detector. The central region of the P0D alternates scintillator planes, water targets, and brass sheets for observation of tracks and showers, while the ends use a scintillator/lead combination to contain the full showers within the P0D.

The lead-scintillator ECal aims to identify particles escaping from the central detector and to detect photons produced in the inner detector. For the first T2K run in early 2010, only the ECal module at the downstream end of the Tracker was operational. The remainder of the ECal was installed and ready for the second run starting November 2010.

3. Current Results

Two neutrino interaction results are available from ND280, both from a Tracker-based analysis: a measurement of the ν_μ charge-current interaction rate and a measurement of the ν_e fraction. These analyses attempt to use the Tracker to find neutrino interactions in the FGD. Presently only inclusive charge-current measurements are complete; work is ongoing to measure specific channels.

3.1. Tracker ν_μ Rate Measurement

The current ν_μ-based analysis is a comparison of the Tracker muon neutrino interaction rate with a NEUT Monte Carlo prediction. The data/Monte Carlo ratio is used to scale the flux prediction at Super-K and provides a useful contribution to the oscillation measurement. We select CC ν_μ events by selecting tracks that begin in the FGD fiducial volume and make it into a downstream TPC. Incoming events are removed by requiring no tracks in upstream TPCs, and the TPC PID is used on the highest-momentum negative track to isolate muons. This selection has a 91% purity for selecting ν_μ charge-current interactions.

The resulting data/Monte Carlo ratio, using the 2.88×10^{19} POT from the first T2K run, is

$$R = 1.036 \pm 0.028(\text{stat})^{+0.044}_{-0.037}(\text{det syst}) \pm 0.038(\text{phys model syst})$$

This normalization reduces the flux uncertainty in the ν_e appearance measurement by 50%.

Figure 2 shows the measured momentum and angular distributions of the selected muons. In each plot, the points are the data with statistical error bars, and the coloured histogram is the Monte Carlo broken down by interaction type.
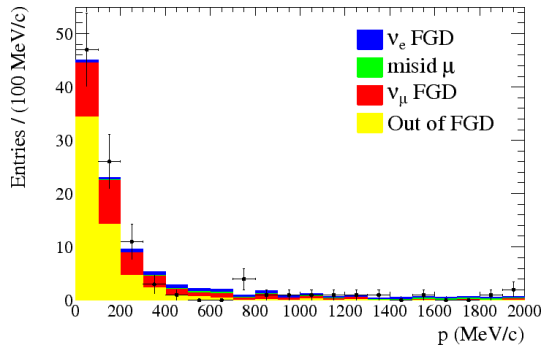
Figure 3. Momentum distribution of electron neutrino candidate events.

3.2. Electron Neutrino Fraction Measurement

The second measurement is of the electron neutrino fraction present in the beam at its origin. This is a more difficult measurement; charge-current muon neutrino interactions are a large fraction of the beam events in ND280, while electron neutrinos have the large muon contribution as background.

While the selection for the electron neutrino candidates is quite similar to that for the muon neutrinos, the extraction of the ν_e fraction must account for the large backgrounds. A likelihood fit with empirical PDFs as a function of momentum for the signal and three categories of background was used to extract the number of electron neutrino interactions.

Figure 3 shows the result of this fit. The resulting ν_e/ν_μ ratio is $(1.0\pm0.7(\text{stat})\pm0.3(\text{syst}))\%$. To check the validity of the beam simulation, a double ratio can be formed between data and Monte Carlo:

$$\frac{(\nu_e/\nu_\mu)_{data}}{(\nu_e/\nu_\mu)_{MC}} = 0.6 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$$

While this measurement is dominated by statistical uncertainties, it does show a rough correspondence between the data and Monte Carlo. The uncertainties are too large to constrain the background at Super-K, but this provides a useful cross-check of our Monte Carlo simulation.

4. Future Prospects

Work is ongoing to extend the ND280 ν_μ analysis to include a selection of muon neutrino CCQE interactions. This, in turn, permits a measurement of the neutrino spectrum, rather than just an overall normalization. In addition, the additional data from Run 2 is being incorporated into the analyses, pending consideration of the differences in detector systematics.

The π^0 analysis is proceeding well. Reconstruction of decay photons in the P0D is now possible to the precision necessary for selection of π^0 decays. Incorporation of the Run 2 data and its full complement of ECal modules will improve the π^0 analysis.

5. Conclusion

The T2K ND280 near detector is operational and is making significant contributions to the oscillation measurements. Completed analyses normalize the ν_μ flux and measure the ν_e fraction of the beam at its source. Improvements to these measurements are ongoing, and work is underway to add a NCπ^0 analysis to constrain that important background.

References
[1] K Abe *et al.* 2011 *Nucl. Instr. Meth.* A 10.1016/j.nima.2011.06.067
[2] K Abe *et al.* 2011 *Phys. Rev. Lett.* **107** 041801