PROCEEDINGS OF SCIENCE

Measuring the electron anti-neutrino beam component in the ND280

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The main irreducible background in the T2K electron-neutrino appearance analysis is the electron-neutrino contamination in the muon-neutrino beam. In order to quantify this background, a selection for charged-current electron-neutrino interactions in the near detector (ND280) Tracker region was developed by combining the particle identification abilities of the time projection chambers and electromagnetic calorimeters. We measured a data/MC ratio of 1.01 ± 0.10 for the electron-neutrino component of the beam which is an important confirmation of our predictions of the expected backgrounds. In 2014 the T2K experiment reversed the polarity of the magnetic horns and began running with an anti-neutrino beam for the first time. Differences in the oscillation probabilities between neutrinos and anti-neutrinos may provide insight into CP violation in the leptonic sector. The current ND280 Tracker electron-neutrino charged-current selection has been used as a starting point for the electron anti-neutrino charged-current selection. The additional challenges and selection criteria of the electron anti-neutrino selection will be presented.

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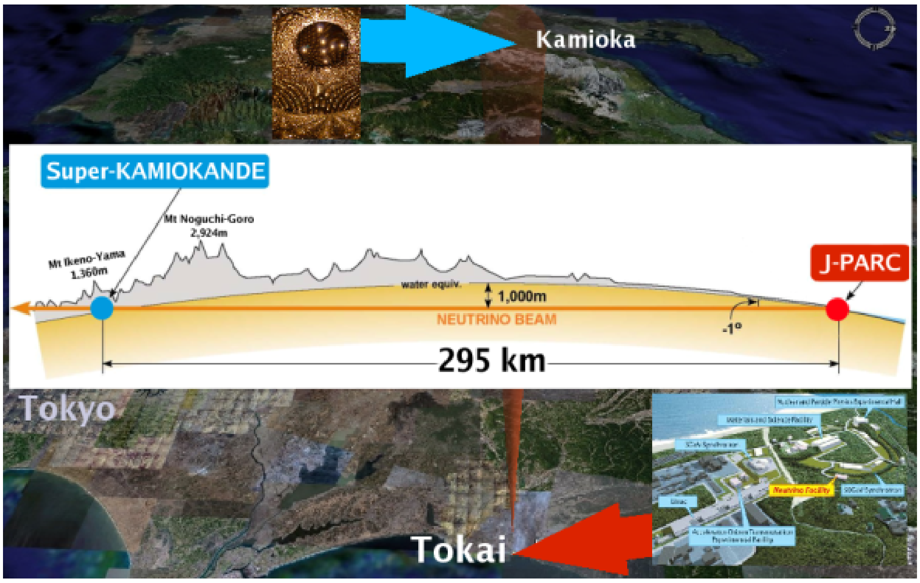

Figure 1: The T2K experiment showing J-PARC (bottom) and Super-Kamiokande (top).

1. The T2K Experiment

The Tokai to Kamioka (T2K) experiment is a long-baseline neutrino oscillation experiment which uses a ν_μ beam, produced at the Japanese Proton Accelerator Complex (J-PARC) in Tokai on the east coast of Japan. The main objective of the experiment is the precise measurement of the oscillation parameter θ_{13} via ν_e appearance and the parameters Δ m^2_{23} and θ_{23} via ν_μ disappearance[1]. Neutrinos are produced by firing protons from the J-PARC accelerator into a carbon target to produce a shower of hadronic particles. A series of three magnetic horns then focuses π^+ to travel down a decay volume, while simultaneously dispersing any other particles. The π^+ then decay into μ^+ and ν_μ. While the μ^+ are then absorbed by the beam dump and the rock at the end of the decay volume, the ν_μ pass through due to their low interaction cross-section. Neutrino interactions are observed in the T2K far detector Super-Kamiokande (SK) which is 295 km away from the beam source (Figure 1) and 2.5 degrees away from the axis of the neutrino beam[1]. The 2.5 degrees off axis results in a narrow energy peak centered at 600 MeV which gives T2K the most efficient L/E for a long-baseline oscillation experiment looking at ν_e appearance. Unfortunately, the method used to generate the ν_μ beam is not perfect and the beam also contains traces of ν_e, $\bar{\nu_\mu}$ and $\bar{\nu_e}$ mostly from the decays of μ^+ in the decay volume ($\mu^+ \rightarrow e^+ + \nu_e$) and from the decays of K^+, some of which make it through the magnetic horns ($K^+ \rightarrow e^+ + \nu_e + \pi^0$). The measured ν_e contamination in the T2K neutrino beam is $(1.2 \pm 0.1)\%$ [2].

Neutrinos are also observed with two near detectors in the ND280 complex 280 m from the beam source. The Interactive Neutrino Grid (INGRID) is an on-axis detector that measures beam flux and profile, and an off-axis detector which, like SK is 2.5 degrees from the beam axis, the ND280 (Figure 2), is used to measure neutrino interaction properties and measure the contamination in the beam from other varieties of neutrinos. The ND280 detector is made up of a set of sub-detectors. Firstly there is the upstream π^0 detector (P0D) followed by a tracker region com-

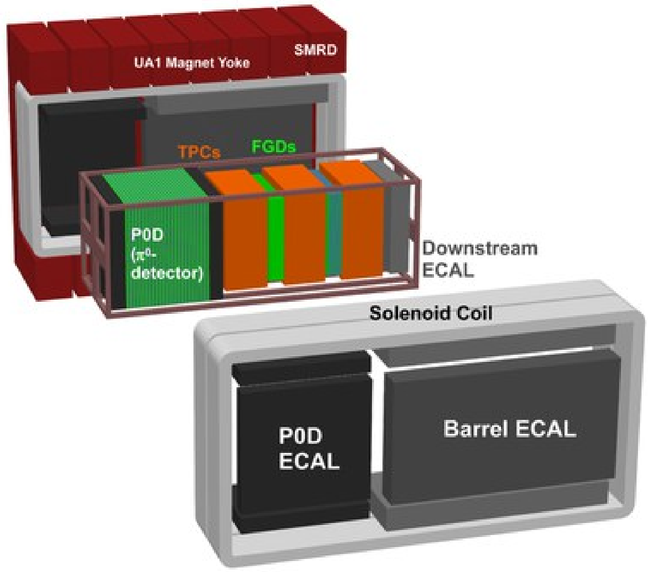

Figure 2: An exploded view of the ND280 showing the tracking region inside the basket (the TPCs and FGDs), with the P0D and Barrel ECALs surrounding it. The former UA1 Magnet is on the outside providing a 0.2T magnetic field. In this image the beam is coming from the left.

prised of three gaseous argon time projection chambers (TPCs) interspersed with two scintillator-based fine grain detectors (FGDs) as shown in Figure 2. Of the two FGDs, the most upstream of the pair (FGD1) is constructed entirely out of plastic scintillator, making charged-current neutrino interactions within its volume effectively interactions on carbon; whereas, the most downstream (FGD2) has alternating layers of water between the scintillator making it a joint oxygen carbon target. The P0D and tracker region are surrounded by a set of electromagnetic sampling calorimeters (ECals) consisting of alternating layers of lead and scintillator. The barrel ECals (BrECal) consist of 31 lead-scintillator layers and the downstream ECal (DsECal) consists of 34 lead-scintillator layers[3]. The yoke of the magnet is also instrumented with plastic scintillator to form side muon range detectors (SMRDs) however the SMRD is not used in the selections discussed below.

2. Selecting ν_e Charged Current Events in the ND280 Tracker

To select ν_e CC inclusive interactions in the tracker region, FGD1 and FGD2 are used as the target mass. Events in which there are electron-like tracks are selected using TPC particle identification (PID) criteria that is based on the rate of energy loss as the particle traverses the detector (dE/dx). Following the application of PID criteria, the sample is 92% pure in electrons but only 27% of these electrons originate from a ν_e interaction, with the majority of the non-ν_e events originating from photons converting to an e^+e^- pair in the FGDs fiducial volume. To reduce the contamination from photon events an upstream veto is applied which rejects events with reconstructed tracks in the P0D, TPC, or ECals that start more than 10 cm upstream from the initial position of the reconstructed electron candidate. If an electron-like positive track is reconstructed within 10 cm of the electron candidate and the pair of tracks have a reconstructed mass of less than

100 MeV/c^2, the event is rejected. Following these cuts the photon contamination is reduced to 30% from 65%. A more detailed description of the ν_e selection to this stage can be seen in Table 1 and in reference [2].

Further criteria are then applied to separate the ν_e CC inclusive sample into a CC quasi-elastic sample (CCQE) (shown in figure 3) and a CC non-quasi-elastic sample (CCnonQE) (shown in figure 4). The large errors on the data points are due to low sample size. The CCQE sample is 48% pure and the CCnonQE sample is 52% pure.

For the CC inclusive sample the ratio of data over Monte Carlo is 1.01 ± 0.10. A further measurement was performed by independently fitting ν_e originating from μ^+ and kaon parents using the CC inclusive sample. The data over Monte Carlo ratios were found to be 0.68 ± 0.30 for ν_e originating from μ^+ and 1.10 ± 0.14 for ν_e originating from kaons [2].

3. Selecting $\bar{\nu}_e$

The $\bar{\nu}_e$ contamination in the T2K anti-neutrino beam has not yet been measured, but this contamination results in an irreducible background in the $\bar{\nu}_e$ appearance oscillation measurement. In order to create a $\bar{\nu}_e$ selection, the existing T2K ν_e selection was modified by reversing the charge requirement to look for positive particles instead of negative ones. The other criteria were retained because they do not have any charge dependence and so simply reversing the charge requirement should result in $\bar{\nu}_e$ being selected. However, this immediately presented new challenges. Protons, which were previously removed by the negative charge requirement, now pass the selection cuts. This background can be seen in figure 5.

As mentioned above the TPC PID depends on dE/dx. As can be seen in figure 6, the positron and proton dE/dx is similar around momentum of 1000 MeV/c; therefore, the TPC PID cannot be used to discriminate between protons and positrons in this region. In order to remove the proton background, the ratio of electromagnetic energy deposited in the ECal to the momentum measured by the TPCs (E/P) was used, in the region where the proton background dominates. For a given momentum, the proton has far less kinetic energy to deposit in the ECals than a positron, so E/P is higher for positrons. Additional ECal PID variables, combining the number of ECal hits in the ECal and the patterns of energy deposition in the ECal into log-likelihood variables, are also used for distinguishing between particles to further improve the selection. The requirement based on E/P and likelihood variables are shown in Table 1. All criteria in Table 1 except the proton cut are shared between the ν_e and $\bar{\nu}_e$ CC inclusive selections. This results in a 96% reduction of the proton background as seen in figure 7.

4. $\bar{\nu}_e$ results

The criteria described in section 3 result in a selection with a purity of $(42.4 \pm 3.6)\%$ and an efficiency of $(32.7 \pm 2.8)\%$ for $\bar{\nu}_e$ CC interactions in the FGD fiducial volume. This selection will be applied to the T2K anti-neutrino beam data. The uncertainties are statistical only.

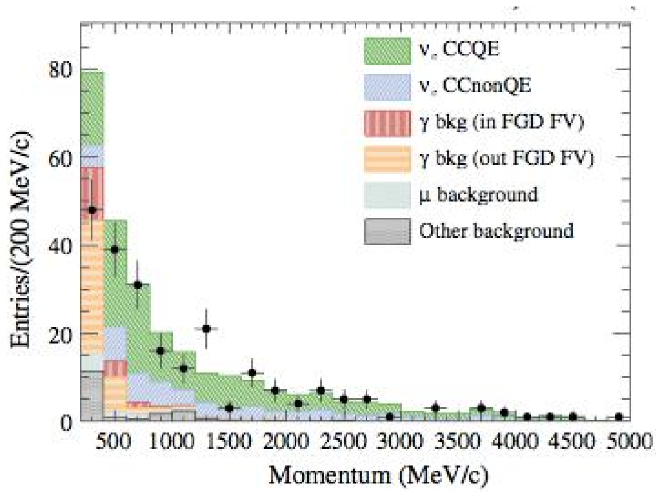

Figure 3: Reconstructed electron momentum of events in the CCQE-like sample. The error on the data points is statistical. The coloured histogram is Monte Carlo. The CCQE events are displayed in green, with the dominant background from gamma conversions being shown in red or orange, differentiating if the neutrino which produced the photon interacted inside the FGD fiducial volume or outside it. The other background is mainly misidentified pions [2].

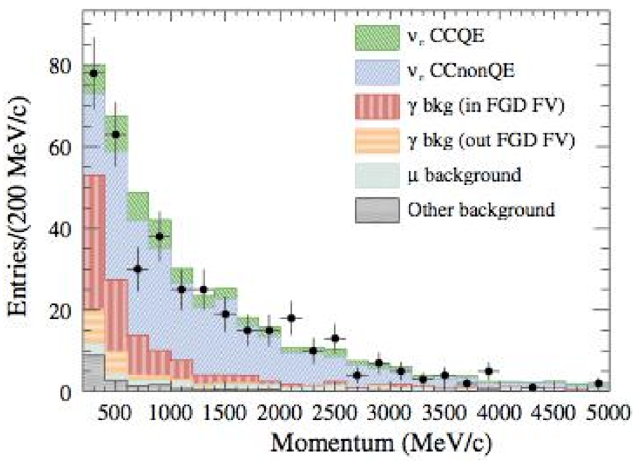

Figure 4: Reconstructed electron momentum of events in the CCnonQE-like sample. The error on the data points is statistical. The coloured histogram is Monte Carlo. The CCnonQE events are displayed in grey, with the dominant background from gamma conversions being shown in red or orange, differentiating if the neutrino which produced the photon interacted inside the FGD fiducial volume or outside it. The other background is mainly misidentified pions [2].

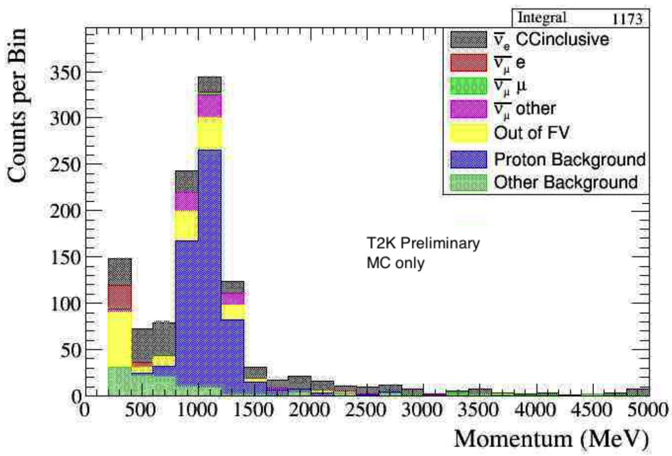

Figure 5: The $\bar{\nu}_e$ selection after only changing the charge requirement. The large proton background (blue) can be seen in the area around 1000 MeV/c dominating over the $\bar{\nu}_e$ signal (black) .

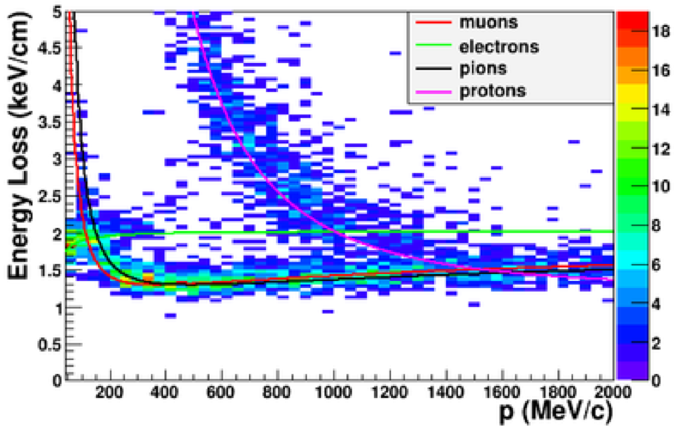

Figure 6: The energy loss curves for several particles. It can be seen that the proton and electron (positron) curves have similar values around 1000 MeV / c momentum.

5. Conclusion

The $\bar{\nu}_e$ selection is now complete with a purity of $(42.4 \pm 3.6)\%$ and an efficiency of $(32.7 \pm 2.8)\%$. Systematic studies are ongoing. Preliminary results indicate that systematic uncertainties will be slightly larger than those presented in [2] due to the uncertainty associated with the proton background. Once the systematics have been fully analysed we will be ready to use the selection on antineutrino data taken by the T2K experiment to measure the $\bar{\nu}_e$ contamination in the T2K anti-neutrino beam, which is expected to be of order 1.0%. This contamination feeds into the T2K $\bar{\nu}_e$ appearance oscillation measurement as it will be the main irreducible background.

References

[1] K. Abe et al, The T2K experiment ,Nucl.Instrum. Methods Phys. Res., Sect A659, 106 (2011)

Cut name	Requirements
event quality	-
Positive Track	A positive track
Momentum	Momentum > 200 MeV
FGD FV	Track start inside FGD fiducial volume
TPC Quality	TPC hits > 35
PID	Apply PID as detailed on page 9 of [2]
TPC2 PID	If 2nd TPC segment is present require not muon-like
TPC Veto	Veto events with upstream TPC activity
Pair Veto	Veto events which look like pair produced tracks
P0D Veto	Veto events with P0D activity
ECal Veto	Veto events with upstream ECal activity
Proton Cut*	If in momentum 600 MeV to 2000 MeV require: E/P > 0.7 and ecalNhits > 20 and Likelihood_ECal_emhip < -3 and Likelihood_ECal_mipem > 28 and Likelihood_ECal_mippion > 22

Table 1: The paramaters of the $\bar{\nu}_e$ and ν_e CC inclusive selections. *The proton cut is unique to the $\bar{\nu}_e$ selection.

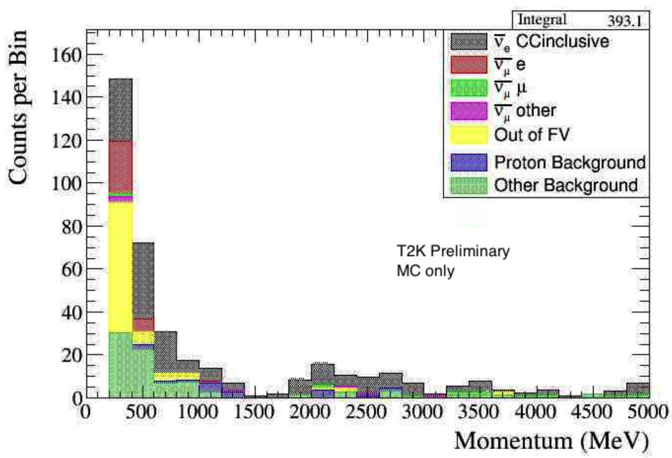

Figure 7: The $\bar{\nu}_e$ selection after the full selection has been applied. The $\bar{\nu}_e$ signal can be seen in black and the rest of the events are predominantly gamma background as in the ν_e selection. The other background is also predominantly gamma

[2] K. Abe et al, Measurement of the intrinsic electron neutrino component in the T2K neutrino beam with the ND280 detector, Phys. Rev. D 89, 092003, 2014.

[3] D.Allan et al,The Electromagnetic Calorimeter for the T2K Near Detector ND280, JINST 8 P10019 (2013)