

# Study of neutrino interaction with T2K on-axis neutrino detector Proton Module

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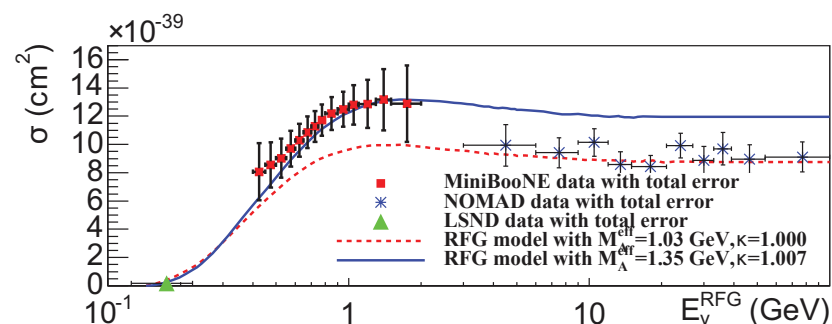
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## Abstract.

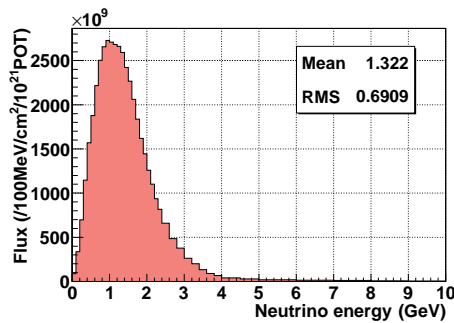
T2K is a long baseline neutrino oscillation experiment. We have constructed a new neutrino detector, "Proton Module" to measure the neutrino cross section precisely using the T2K neutrino beam. We report the status of the data acquisition and the Monte Carlo study.

## 1. Introduction

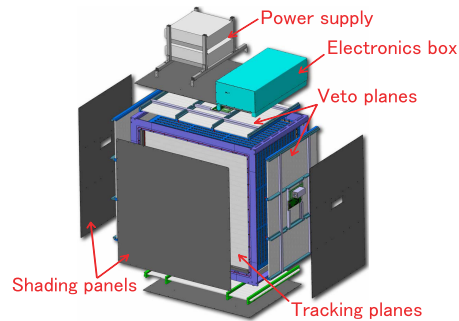
T2K (Tokai-to-Kamioka) [1] is a long baseline neutrino oscillation experiment aiming to search for the electron neutrino appearance and to measure the oscillation parameters associated with the muon neutrino disappearance precisely. A high intensity neutrino beam from J-PARC (Japan Proton Accelerator Research Complex) is measured with the 280 m near detector complex (ND280) and the 295 km far detector (Super-Kamiokande). For the oscillation analysis of T2K, there is a large systematic error attributed to the uncertainty of the neutrino cross section. The charged current quasi-elastic (CCQE) interaction ( $\nu_\ell + n \rightarrow \ell^- + p$ ) events are used as signal in T2K. The  $\nu_\mu$  CCQE cross section on  $^{12}\text{C}$  was measured by MiniBooNE [2], NOMAD [3] and LSND [4]. However, they cannot be consistently described with a current neutrino interaction model (Fig. 1). The T2K on-axis neutrino beam covers the energy region of 1.5~4 GeV, which is not covered with the past experiments (Fig. 2). We have constructed a new neutrino detector, "Proton Module" (Fig. 3) to measure the neutrino cross section precisely with the T2K on-axis neutrino beam. The Proton Module consists of 34 tracking planes surrounded by 6 veto planes



**Figure 1.** Cross section of the  $\nu_\mu$  CCQE interaction as a function of the neutrino energy [2]



**Figure 2.** The T2K on-axis neutrino beam flux

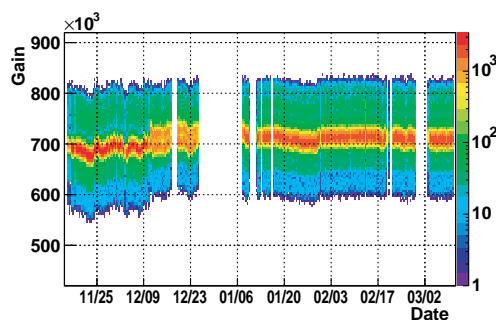


**Figure 3.** Schematic view of the Proton Module

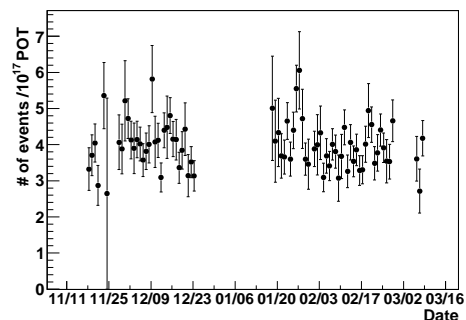
(Fig. 3). Each tracking plane consists of 32 scintillator bars. Scintillation lights are collected and transported with a wavelength shifting fiber which is inserted in a hole at the center of the scintillator bar. Then the lights are read out by a Multi-Pixel Photon Counter (MPPC) attached to one end of the fiber. The dimension of the entire module is  $1.42 \times 1.42 \times 0.96 \text{ m}^3$ , total target mass is 556 kg, and total number of channels is 1204. Since the Proton Module is a fully-active detector, it can reconstruct tracks of various kinds of particles from the interaction point. The Proton Module is placed in the upstream of seven identical detectors called INGRID. INGRID consist of a sandwich structure of iron target plates and tracking scintillator planes. Although their main purpose is to monitor the neutrino beam direction and intensity, they are used as muon counters in this study.

## 2. Data acquisition

The Proton Module started the beam data acquisition on November 16, 2010 and suspended it on March 11, 2011 because of the Tohoku earthquake. The Proton Module suffered no damage from the earthquake. During this time period,  $1.1 \times 10^{20}$  protons on target (POT) of physics data was accumulated. Gains of all MPPCs were monitored and they are stable as shown in Fig. 4. Figure 5 shows the daily neutrino event rate normalized by POT. It is stable within the margin of statistical error.



**Figure 4.** MPPC gain history



**Figure 5.** Daily neutrino event rate

## 3. Monte Carlo study

The analysis method is being studied with Monte Carlo simulations. To simulate the detection of the beam neutrinos by the Proton Module, three Monte Carlo simulation programs are utilized: JNUBEAM [1] for a simulation of neutrino beam line, NEUT [5] for a simulation of neutrino interactions and GEANT4 [6] for a simulation of the detector response.

### 3.1. Neutrino event selection

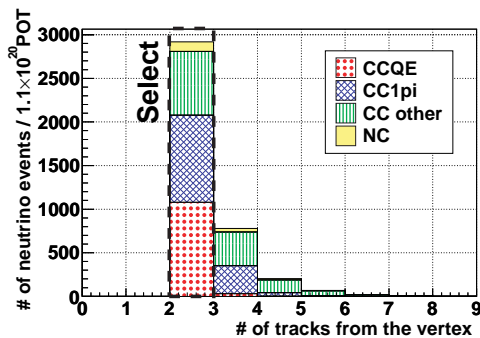
At the beginning, tracks are reconstructed using hit information of each channel. As a result of the simulations, it turned out that most of the tracks reconstructed in the Proton Module are caused by the incoming particles generated by the neutrino interactions in the wall of the detector hall. Four selections are applied to reject these background events. First, events which have a hit at a veto plane in the upstream extrapolated position from reconstructed tracks are rejected. Second, events whose reconstructed vertex is outside of fiducial volume is rejected. The fiducial volume is defined as a volume other than edge scintillator bars. Third, events which have only one track from the vertex are rejected. This is a temporary selection and one track events will be used for the CCQE study in the future. Forth, events which have no tracks in INGRID located just behind the Proton Module are rejected. After these selections, the purity of the neutrino events becomes 99.7 %. Result of the neutrino event selection is summarized in Table 1.

**Table 1.** Summary of the neutrino event selection (Monte Calro simulation per  $1.1 \times 10^{20}$  POT)

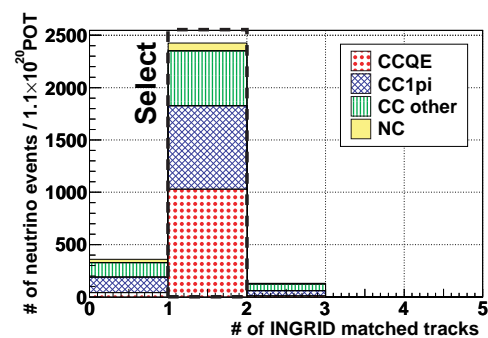
Selection criteria	Neutrino events	Background events	Efficiency	Purity
Tracks in the Proton Module	21337	477585	79%	4.2%
Veto plane cut	18320	61016	67%	23.1%
Fiducial volume cut	14478	23627	53%	38.0%
# of tracks from the vertex $\geq 2$	7897	2464	29%	76.2%
Tracks in INGRID	4109	12	15%	99.7%

### 3.2. CCQE event selection

After the neutrino event selection, additional three selections are applied to enhance the CCQE events. First, events which have two tracks from the vertex are selected (Fig. 6) because final state particles of CCQE are two particles (a muon and a proton). Second, events which have one track matching with tracks in INGRID are selected (Fig. 7) because a muon track is expected to be reconstructed in INGRID but a proton track is not. Third, likelihood selection is applied; the likelihood is defined by the opening angle and the coplanarity angle (Fig. 8, 9). The opening angle is the angle between the two reconstructed tracks and the coplanarity angle is the angle between  $\vec{\nu} \times \vec{\mu}$  and  $\vec{\nu} \times \vec{p}$ . Events whose likelihood is more than 0.6 are selected (Fig. 10). After these selections, the purity of the CCQE events becomes 74%. Result of the CCQE event selection is summarized in Table 2 and an event display of the selected CCQE event is shown in Fig. 11.



**Figure 6.** Number of the tracks from the vertex



**Figure 7.** Number of the INGRID matched tracks

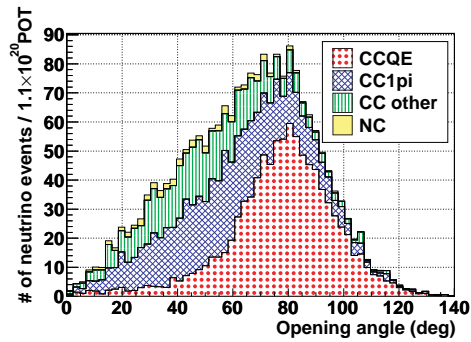


Figure 8. Opening angle between the two tracks

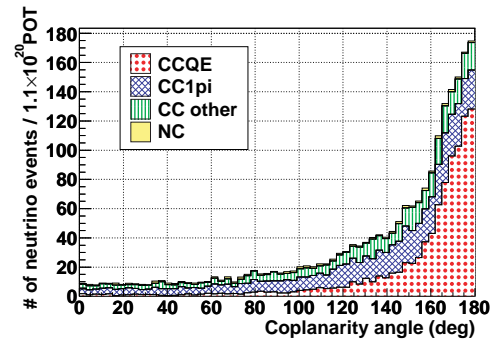


Figure 9. Coplanarity angle

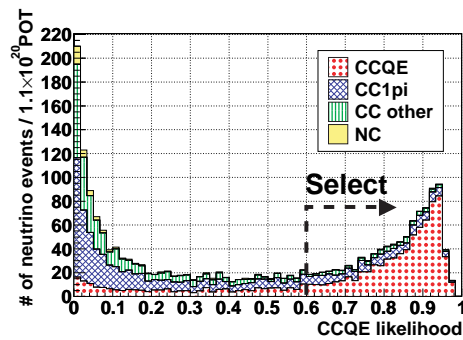


Figure 10. CCQE likelihood

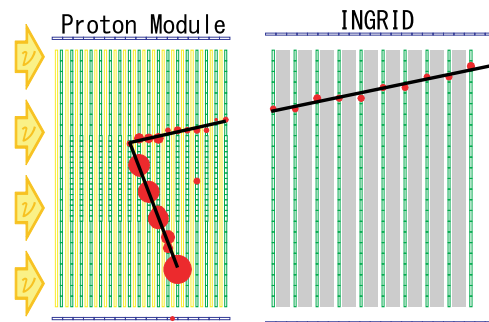


Figure 11. Event display of a selected CCQE event

Table 2. Summary of the CCQE event selection (Monte Carlo simulation per  $1.1 \times 10^{20}$  POT)

Selection criteria	CCQE events	Non-QE events	Efficiency	Purity
Neutrino event selection	1108	3013	12.9%	27%
# of tracks from the vertex = 2	1094	1817	12.7%	38%
# of INGRID matched tracks = 1	1029	1391	12.0%	43%
CCQE likelihood > 0.6	871	313	10.2%	74%

#### 4. Conclusion

The Proton Module acquired the beam data successfully. Based on the Monte Carlo simulation, the method of the CCQE selection is optimized. Our study is going ahead toward the first physics result with the Proton Module.

#### References

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