T2K: New physics results

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Abstract. The T2K experiment is designed to probe the $\theta_{13}$ neutrino mixing parameter by looking for the appearance of $\nu_e$ in a pure $\nu_\mu$ beam and to precisely measure atmospheric $\Delta m^2$ and $\theta_{23}$ parameters. A neutrino beam produced at J-PARC, Japan, is aimed at $2.5^\circ$ off-axis angle to the Super-Kamiokande far neutrino detector, 295 km away. The narrow energy neutrino beam peaked at about 600 MeV is optimized to maximize the probability of oscillation at the atmospheric $\Delta m^2$ scale. The neutrino beam is monitored by a complex of neutrino near detectors at 280 m from the production target. T2K has successfully operated since January 2010. Data-taking has been presently paused due to the recent earthquake in Japan. Results on measurements of $\nu_e$ appearance and $\nu_\mu$ disappearance are reported.

1. Introduction

The T2K experiment is a long baseline neutrino oscillation experiment in which a high intensity $\nu_\mu$ beam is produced at J-PARC and detected by Super-Kamiokande (SK) at 295 km. The main purpose of the experiment is to measure the last unknown mixing angle $\theta_{13}$ by discovering $\nu_\mu \rightarrow \nu_e$ oscillation. The expected sensitivity of $\sin^2 2\theta_{13}$ with the approved exposure (3.75 MW$\cdot$10$^7$ sec) is 0.006 at 90% C.L.. Another important goal is precision measurement of the oscillation parameters in $\nu_\mu$ disappearance. We aim to measure $\theta_{23}$ and $\Delta m^2_{23}$ with an accuracy of $\delta (\sin^2 2\theta_{23}) = 0.01$ and $\delta (\Delta m^2_{23}) = 10^{-4}$ eV$^2$, respectively.

The oscillation analyses presented here are based on the first two physics runs: run 1 (Jan-Jun 2010) and run 2 (Nov 2010-Mar 2011). During this time period, the Main Ring proton beam power was continuously increased and reached 145 kW with $9 \times 10^{13}$ protons per pulse. A total of 2,474,419 spills were retained for analysis after beam and far detector quality cuts, yielding $1.43 \times 10^{20}$ protons on target (p.o.t.).

2. Experimental setup

Details of the T2K experimental setup are described elsewhere [1]. The neutrino beam for T2K is produced by 30 GeV protons from the J-PARC Main Ring which are single-turn extracted in 8 bunches (6 bunches during run 1) separated about 580 ns apart and impinge upon a 90 cm-long ($1.9 \lambda_{int}$) graphite target, resulting in the production of secondary particles. Charged particles exiting the target are sign selected and focused into the 96 m long decay tunnel by three magnetic horns pulsed at 250 kA. Neutrinos are primarily produced in the decays of charged pions and kaons. A beam dump is located at the end of the tunnel and is followed by a set of muon monitors, which measures the beam direction and rate stability on a spill-by-spill basis.

The T2K beam is directed $2.5^\circ$ off-axis to SK. This configuration produces a narrow-band $\nu_\mu$ beam [2], tuned at the first oscillation maximum $E_\nu = |\Delta m^2_{23}| L/(2\pi) \simeq 600$ MeV, reducing backgrounds from higher energy neutrino interactions.
The near detector complex located 280 m downstream from the target hosts two detectors, the on-axis Interactive Neutrino GRID (INGRID) and the off-axis detector (ND280). INGRID consists of 14 identical iron-scintillator sandwich modules arranged in crossed horizontal and vertical arrays centered on the beam. By measuring the yield of neutrino interaction in each module, it monitors the beam intensity, direction and profile on a daily basis.

ND280 reconstructs exclusive final states to study neutrino interactions and beam properties corresponding to those expected at the far detector. It consists of several sub-detectors embedded in a 0.2 T magnetic field provided by the refurbished UA1 magnet: three large volume time projection chambers (TPCs) [3] interleaved with two fine-grained tracking detectors (FGDs), a \(\pi^0\)-optimized detector and a surrounding electromagnetic colorimeter. Gaps in the magnet yoke are instrumented with a side muon range detector.

The SK water Cherenkov detector [4] has a fiducial volume (FV) of 22.5 kton within its cylindrical inner detector (ID). The front-end readout electronics allow for a zero-deadtime software trigger. Spill timing information, synchronized by the GPS, is transferred online to SK and triggers the recording of photomultiplier hits within ±500µs of the expected arrival time of the neutrinos.

3. Analysis overview

At T2K, the manifestation of \(\nu_\mu \rightarrow \nu_e\) oscillations is an excess of \(\nu_e\) interactions at SK over the expected background from misidentified interactions of other neutrino flavors and the intrinsic \(\nu_e\) contamination in the beam. The selection criteria for the \(\nu_e\) appearance analysis were fixed from Monte Carlo studies before the data are collected. The observed number of events is compared to expectations based on neutrino flux and cross-section predictions for signal and all sources of backgrounds. In the \(\nu_\mu\) disappearance analysis, the oscillation parameters are determined by the energy-dependent deficit of \(\nu_\mu\) interactions relative to the expectation without oscillation.

The neutrino flux simulation is based on models tuned to experimental data. Pion production in \((p, \theta)\) bins is based on the NA61 measurements [5]. Kaons, as well as pions outside the experimentally measured phase space, are modeled using FLUKA [6]. The NEUT MC event generator [7], which has been tuned with recent neutrino interaction data in an energy region compatible with T2K, is used to simulate neutrino interactions in the near and far detectors.

Due to the large a priori uncertainty in the flux and neutrino interaction predictions, ND280 is used to provide an overall rate normalization factor based on an inclusive \(\nu_\mu\) charged-current (CC) measurement. Tracks starting in the FGD fiducial volume and entering the downstream TPC are selected. The highest momentum negative track is required to be consistent with a muon using the \(dE/dx\) measurement in the TPC. The measured data/MC ratio is:

\[
R_{\text{Data}/\text{MC}} = 1.036 \pm 0.028(\text{stat})^{+0.044}_{-0.037}(\text{det.syst}) \pm 0.038(\text{phys.syst}).
\]

(1)

ND280 data are also used for checking the \(\nu_e\) contamination in the beam. In this case, the most energetic track in the TPCs is identified and required to be negative and consistent with an electron by the measured \(dE/dx\). The measured \(\nu_e/\nu_\mu\) ratio at ND280 is:

\[
N(\nu_e)/N(\nu_\mu) = (1.0 \pm 0.7(\text{stat}) \pm 0.3(\text{syst})) \%,
\]

(2)

which is consistent with the MC expectation.

4. \(\nu_e\) appearance analysis

The \(\nu_e\) appearance analysis produces a sample enhanced in \(\nu_e\) charged-current quasi-elastic interactions (CCQE) arising from \(\nu_\mu \rightarrow \nu_e\) oscillations. Among 88 fully-contained fiducial volume (FCFV) events observed at SK, forty-one events are reconstructed with a single Cherenkov...
ring, and eight of those are $e$-like. Six of these events have $E_{vis} > 100$ MeV and no delayed-electron signal. To suppress misidentified $\pi^0$ mesons, the reconstruction of two rings is forced by comparison of the observed and expected light patterns calculated under the assumption of two showers, and a cut on the two-ring invariant mass $M_{inv} < 105$ MeV$/c^2$ is imposed. No events are rejected by this cut. Finally, the neutrino energy $E_{\nu}^{rec}$ is computed using the reconstructed momentum and direction of the ring, by assuming quasi-elastic kinematics and neglecting Fermi motion. No events are rejected by requiring $E_{\nu}^{rec} < 1250$ MeV, aimed at suppressing events from the intrinsic $\nu_e$ component arising primarily from kaon decays (Figure 1). The $\nu_e$ appearance signal efficiency is estimated from MC to be 66%, while rejection for $\nu_\mu$CC, intrinsic $\nu_e$CC, and NC are > 99%, 77%, and 99%, respectively.

The event vertices in cylindrical coordinates $(R, \phi, z)$ show that the six data events are clustered at large $R$, near the edge of the FV in the upstream beam direction. A KS test on the $R^2$ distribution of our final events yields a $p$–value of 0.03. If this was related to contamination from penetrating particles produced in upstream neutrino interactions, then the ID region outside the FV should show evidence for such events, however this is not observed. In addition, an analysis of the neutrino interactions occurring in the outer detector volume, as well as a $R^2$ distribution of the SK atmospheric neutrino events which pass the same criteria, is consistent with expectations.

The expected number of events for $\theta_{13} = 0$ is $1.5 \pm 0.3$ (syst), which are mainly composed of 0.8 intrinsic beam $\nu_e$ events and 0.6 NC events. The systematic uncertainty on this expected number of events includes contributions from the flux ($\pm 8.5\%$), neutrino interaction modeling ($\pm 14\%$), near detector normalization ($\pm 5.2\%$), and the SK detector response ($\pm 14.7\%$). The flux uncertainty is significantly reduced by the near detector normalization.

Thus, the observation of the six data events exceeds the expectation of a three-flavor neutrino oscillation scenario with $\theta_{13} = 0$. Under this hypothesis, the probability to observe six or more candidate events is $7 \times 10^{-3}$. The allowed region for $\sin^2 2\theta_{13}$ for each value of $\delta_{CP}$ is shown in Figure 2 for normal hierarchy case.

![Figure 1](image1.png)  
**Figure 1.** The reconstructed neutrino energy spectrum of the events which pass all $\nu_e$ appearance signal selection criteria with the exception of the energy cut.

![Figure 2](image2.png)  
**Figure 2.** The 68% and 90% C.L. regions for $\sin^2 2\theta_{13}$ for each value of $\delta_{CP}$, consistent with the observed number of events in the three-flavor oscillation case for normal mass hierarchy.

5. $\nu_\mu$ disappearance analysis  
For the $\nu_\mu$ disappearance analysis, we make a $\nu_\mu$CCQE-enriched sample by applying two additional cuts to the FCFV single-ring $\mu$-like events: the reconstructed muon momentum
< 200 MeV and the number of delayed-electron signals ≤ 1. Thirty-one events passed these
criteria, while we expect 104 events without oscillations. The reconstructed neutrino energy of
the observed 31 events, together with the expected spectra for the no oscillation and the best-fit
oscillation cases, is shown in Figure 3.

To extract the oscillation parameters, we performed two analysis: one using a maximum
likelihood fit in which parameters governing the systematics uncertainties are marginalized, and
another using a binned likelihood-ratio method without fitting the systematics. The allowed
regions obtained by these two analyses are shown in Figure 4. They are consistent with the
results by MINOS [8] and SK atmospheric neutrino data analyses [9].

![Figure 3](image-url1)

**Figure 3.** The reconstructed neutrino energy of the $\nu_\mu$ candidate events.

![Figure 4](image-url2)

**Figure 4.** The 90% C.L. allowed regions for $\sin^2 2\theta_{23}$ and $\Delta m^2_{23}$.

### 6. Conclusions

T2K has performed analyses of $\nu_\mu \rightarrow \nu_e$ appearance [10] and $\nu_\mu$ disappearance with data taken in 2010 and 2011, corresponding to $1.43 \times 10^{20}$ p.o.t. (2% of the approved exposure). Six $\nu_e$ candidate events are observed, while the expected number of events for $\theta_{13} = 0$ is $1.5 \pm 0.3$. Under this hypothesis, the probability to observe six or more candidate events is $7 \times 10^{-3}$, equivalent to 2.5σ significance. The parameters $\sin^2 2\theta_{23}$ and $\Delta m^2_{23}$ are extracted from the $\nu_\mu$ disappearance analysis and are approaching the precision of the current beat measurements from SK and MINOS. The experiment has recovered from the March 11 earthquake and will recommence operations at the beginning of 2012.

### References

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