Latest oscillation results from T2K

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Abstract. T2K is a long-baseline neutrino oscillation experiment built to measure \( \nu_\mu \) disappearance and \( \nu_e \) appearance using the J-PARC neutrino beam and the Super-Kamiokande detector. Presented here are the first results in the search for CP violation in neutrino oscillations with a combined analysis of appearance and disappearance channels using data from both neutrino- and antineutrino-mode beams. The data included in this analysis comprises \( 7.48 \times 10^{20} \) protons on target in neutrino mode, giving 37 electron-like and 135 muon-like events at the far detector, and \( 7.47 \times 10^{20} \) protons on target in antineutrino mode, giving 4 electron-like and 66 muon-like events. Including a constraint on \( \sin^2(2\theta_{13}) \) from reactor measurements, the 90% confidence interval for \( \delta_{CP} \) spans the range \([-2.95, -0.44]\) for the normal mass hierarchy.

1. Introduction

The observed baryon asymmetry of the universe cannot easily be explained through the observed sources of CP violation in the Standard Model [1]. Neutrino oscillations raise the possibility of CP-violation in the lepton sector, which could be large enough to produce the requisite baryon asymmetry.

In the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) formalism, neutrino oscillation is parameterised by three mixing angles, \( \theta_{12}, \theta_{23} \) and \( \theta_{13} \), two mass squared splittings, \( \Delta m^2_{21} \) and \( \Delta m^2_{32} \), and one CP violating phase, \( \delta_{CP} \). There are currently three unanswered questions in the PMNS oscillation framework:

- Do the neutrino mass states follow the “normal” \( (\Delta m^2_{32} > 0) \) or the “inverse” \( (\Delta m^2_{32} < 0) \) hierarchy?
- Is \( \theta_{23} \) greater than or less than 45°?
- Is \( \sin \delta_{CP} \neq 0 \)?

2. The T2K experiment

The Tokai-to-Kamiokande (T2K) experiment [2] is working to address all three of the questions above. There are three central components of the T2K experiment - the neutrino beamline and near detectors, both located at J-PARC on the east coast of Japan, and the far detector Super-Kamiokande (SK), 295 km away in Kamioka.

The T2K neutrino beam is produced by impinging a 30 GeV proton beam on to a graphite target to create hadrons. Three magnetic horns are used to focus charged hadrons into a 96 m volume, where they decay in flight to produce neutrinos. The sign of the focussed hadrons is determined by the direction of the horn current, allowing T2K to produce beams largely composed of either neutrinos or antineutrinos. The results presented here use data from
7.48 × 10^{20} \text{ protons-on-target (POT) in neutrino beam mode and } 7.47 × 10^{20} \text{ POT in anti-neutrino beam mode. The T2K off-axis near and far detectors are placed } 2.5^\circ \text{ off the neutrino beam axis, and are therefore exposed to a neutrino flux with a sharply peaked energy spectrum, centred at } 600 \text{ MeV.}

A suite of near detectors, 280 m downstream from the graphite target, samples the neutrino beam before any oscillation has occurred. The on-axis detector, INGRID [2], measures the beam direction. The off-axis detector, ND280 [2], characterises the neutrino beam by identifying and measuring the kinematics of particles produced by neutrino interactions in the detector. ND280 has two fine-grained detectors (FGDs) which are the primary neutrino targets. FGD1 is composed of plastic scintillator, so is fully active, while FGD2 has layers of both plastic scintillator and inactive water. These are sandwiched between three TPCs which provide particle identification, momentum and charge measurements.

SK [3] is a 50 kt water Cherenkov detector situated at a distance that gives the maximal neutrino disappearance probability for the T2K flux. The lepton kinematics of muon-like and electron-like events are then used to infer \( P(\nu_\mu \rightarrow \nu_\mu) \) and \( P(\nu_\mu \rightarrow \nu_e) \) and so measure the parameters governing neutrino oscillation.

3. Near detector analysis

T2K uses parameterised models of the neutrino flux and interaction model to provide the neutrino event rate and associated uncertainty at the near and far detectors. Measuring the flux or cross-section individually is challenging, so a simultaneous fit of both models to the high statistics ND280 data is performed.

Fourteen ND280 samples are included in this analysis [4], seven from each FGD. In neutrino beam mode the highest momentum, negative, muon-like track is chosen as the lepton candidate and the event then sorted according to the number of tagged pions, falling into either the 0π, 1π or “Other” categories. In antineutrino beam mode the charge of the highest momentum, muon-like track is used to determine whether the event came from a neutrino or antineutrino interaction. For both neutrino and antineutrinos the event candidates are sorted into single track and multiple track samples, giving four antineutrino beam mode samples in total.

The neutrino beam mode 0π sample is shown in Fig. 1, both pre- (left) and post-fit (right). This demonstrates the improvement in the data-model agreement from the fit procedure. It also highlights the change in the composition of the sample, with the 2p-2h interaction mode in particular increasing substantially in the post-fit distribution. The near detector analysis

![Figure 1. ND280 neutrino beam mode charged current 0π sample [4]](image-url)
results in a tuned prediction of the unoscillated far detector event rate and introduces anti-
correlation between the flux and cross-section parameters. This reduces the uncertainty on the
SK prediction from $\sim 14\%$ to $\sim 3\%$ for the parameters constrained by the near detector fit.

4. Joint neutrino-antineutrino, disappearance-appearance oscillation analysis

The oscillation analysis [4] uses five SK events samples, all of which start by selecting fully
contained neutrino events reconstructed within the SK fiducial volume. In both the neutrino

![Graph](image1)

(a) Muon-like

![Graph](image2)

(b) Electron-like, no decay electrons

![Graph](image3)

(c) Electron-like, one decay electron

**Figure 2.** SK neutrino beam mode single ring samples

and antineutrino beam mode data these events are split according to whether the most energetic
Cherenkov ring is electron-like or muon-like. The muon-like events are required to have a
reconstructed momentum above 200 MeV/c and at most 1 decay electron, while the electron-like
events are required to have no decay electrons, at least 100 MeV of visible energy, a reconstructed energy below 1250 MeV and not be identified as π⁰-like. There is an additional neutrino beam mode sample of electron-like events with a single decay electron, representing charged current single pion production interactions where the pion is produced below Cherenkov threshold. The neutrino beam mode samples are shown in Fig. 2.

Oscillation parameters are extracted by minimising a likelihood incorporating these samples, the near detector model constraints, the SK detector error constraints and the three-flavour oscillation probabilities, including matter effects. The resulting 68% and 90% allowed regions for the disappearance parameters are presented on the left of Fig. 3, alongside those from other experiments. The right plot in Fig. 3 compares the predicted sample spectrum for the NOνA and T2K best-fit oscillation parameter values, clearly showing that the T2K data prefer more maximal disappearance than allowed by the NOνA oscillation parameters.

(a) 68% and 90% allowed regions for \( \sin^2 \theta_{23} \) and \( |\Delta m^2_{23}| \) (b) The predicted neutrino beam mode, single ring, muon-like SK sample for the NOνA and T2K best-fit oscillation parameter values

Figure 3. Muon neutrino disappearance results

Fig. 4 shows the 68% and 90% allowed regions for \( \delta_{CP} \) and \( \sin^2 \theta_{13} \) from fits both with (right) and without (left) the reactor constraints on \( \sin^2 \theta_{13} \). The antineutrino beam mode data provides a significant constraint on the allowed values of \( \delta_{CP} \) without applying a prior constraint on \( \sin^2 2\theta_{13} \) from reactor measurements, and so provides a test of CP violation without assuming that the PMNS matrix is unitary. Including the reactor constraint in the analysis allows T2K to exclude CP-conserving values of \( \delta_{CP} \) at the 90% confidence limit.

5. Summary

Having collected 1.5 × 10^{21} POT, T2K has produced the first single-experiment constraint on the value of \( \delta_{CP} \). Assuming the normal (inverted) neutrino mass hierarchy, T2K has measured:

- \( \sin^2 \theta_{23} = 0.55^{+0.05}_{-0.09} (0.55^{+0.05}_{-0.08}) \)
- \( |\Delta m^2_{23}| = 2.54 \pm 0.08 (2.51 \pm 0.08) \times 10^{-3} eV^2/c^4 \)
- \( \sin^2 \theta_{13} = 0.027^{+0.007}_{-0.006} (0.030^{+0.008}_{-0.007}) \)
- \( \delta_{CP} = -1.73^{+0.85}_{-0.81} (-1.45^{+0.67}_{-0.72}) \)

The T2K data is consistent with the reactor experiment measurements of \( \sin^2 2\theta_{13} \), prefers maximal muon neutrino disappearance and excludes CP conservation at the 90% confidence limit.
Figure 4. 68% and 90% allowed regions for $\delta_{CP}$ and $\sin^2 \theta_{13}$

limit. T2K has since collected an additional $7.5 \times 10^{20}$ POT of neutrino beam mode data which, combined with improvements to the analysis, will further improve our knowledge of the neutrino oscillation parameters.

References
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