Recent T2K Neutrino Oscillation Results

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Abstract. T2K is a long baseline neutrino experiment producing a beam of muon neutrinos at the Japan Particle Accelerator Research Centre on the East coast of Japan and measuring their oscillated state 295 km away at the Super Kamiokande detector. Since, 2017 T2K has doubled its data in both neutrino and anti-neutrino beam modes. Coupled with improvements in analysis techniques, this has enabled the experiment to make world-leading measurements of the PMNS oscillation parameters $\Delta m^2_{32}$, $\sin^2(\theta_{23})$ and the CP violating phase $\delta_{CP}$. In particular, the CP conserving values of $\delta_{CP}$ now appear to be disfavoured at the 95% CL and there are regions of parameter space excluded at the 99.7% CL. This talk will describe these results and the analysis improvements that have enabled them.

1. T2K experiment

T2K is a long baseline neutrino experiment that measures neutrino oscillations via disappearance of muon neutrinos and appearance of electron neutrinos in a muon neutrino beam [1]. A neutrino beam with energy narrowly peaked at 0.6 GeV is produced at J-PARC facility in Tokai, Japan. Protons from the main ring synchrotron are projected onto a graphite target, producing predominantly charged kaons and pions that decay into muon neutrinos and anti-neutrinos. A magnetic horn selects positively or negatively charged particles to project either $\nu_\mu$ or $\bar{\nu}_\mu$ beam to the far detector. T2K is the first long baseline experiment to target their neutrino beam off-axis (2.5$^\circ$) from the far detector, which selects a narrow neutrino energy range at the maximal disappearance probability and reducing backgrounds [2]. The effect of the off-axis beam is shown in figure 1. ND280 (figure 2) and INGRID (figure 3) are two out of the few near detectors that measure the unoscillated neutrino beam [3]. ND280 is an off-axis detector located 280 m from the graphite target, measuring the neutrino cross-sections, the beam energy profile and composition. It consists of two fine grid detectors (FGDs) that act as a massive target for neutrino interactions. INGRID is an on-axis detector that measures the beam position, direction, intensity and also contributes to the cross-section measurements. Due to its on-axis angle, it measures wider neutrino energies than ND280, as seen in figure 1 Super-Kamiokande (Super-K) is a large water Cherenkov detector located around 295 km from the graphite target. It consists of around 11000 20” PMTs facing inwards and around 1900 8” PMTs facing outwards to veto interactions originating outside of the detector. Super-K measures the oscillated neutrino beam by detecting electron-like and muon-like Cherenkov rings from neutrino interactions resulting in a charged lepton above the Cherenkov threshold [4].
2. Oscillation Analysis

The combined neutrino data from ND280 and Super-Kamiokande are used to study the neutrino oscillations. The detector models, flux and the neutrino interaction uncertainties are sampled simultaneously with the oscillation parameters to extract their highest posterior values. There are separate sets of ND280 data samples for each of the two FGDs, which consist of two different massive target materials; FGD1 contains CH material, whereas FGD2 contains water that helps to constrain water interactions at Super-K. Each FGD has data samples for when the beam is run in the $\nu_\mu$ mode (primary interaction being charged-current interaction with no outgoing pion), and for the $\bar{\nu}_\mu$ beam mode. The higher number of samples in the $\bar{\nu}_\mu$ mode is to constrain wrong-sign interaction background due to a higher $\nu_\mu$ contamination in the $\bar{\nu}_\mu$ beam. The data are binned in the outgoing muon momentum and angle. The effect of the fit to the ND280 data on the systematic errors of the Super-K event rates can be seen in table 1.

Table 1. The effect of the ND280 fit on the event rate systematic errors for the Super-K data samples.

| Super-K sample | Without ND280 | With ND280 |
|---------------|---------------|------------|
| $\nu$-beam 1-Ring-$\mu$ | 14.6% | 5.1% |
| $\nu$-beam 1-Ring-$e$ | 16.9% | 8.8% |
| $\bar{\nu}$-beam 1-Ring-$\mu$ | 12.5% | 4.5% |
| $\bar{\nu}$-beam 1-Ring-$e$ | 14.4% | 7.1% |

The T2K collaboration has doubled the amount of data at Super-K taken with the $\bar{\nu}_\mu$ beam since the 2017 analysis, although only data up to 2017 is used for the ND280 detector fit. Figure 4 shows the data point for the number of $\nu_e$ and $\bar{\nu}_e$ events, with the errors being statistical-only (without the systematic treatment). From that plot alone, it is clear that the appearance data should prefer normal mass hierarchy of $\Delta m^2_{32}$, the upper octant of $\sin^2 \theta_{23}$ and the maximally CP-violating values of $\delta_{CP}$. Three independent oscillation analyses are run by the T2K collaboration; this document describes results from the fully Bayesian neutrino oscillation analysis. The Bayesian framework uses a MCMC sampler that performs a fit to both ND280
3. Results

Figure 5 shows the binned posterior probability for $\delta_{CP}$ marginalized over both mass hierarchies of $\Delta m_{32}^2$. The CP-conserving values of $\delta_{CP}$ (between 0 and $\pi$) are comfortably rejected with at least $2\sigma$ credible interval, with the maximal CP conservation ($\delta_{CP} = \pi/2$) having exceptionally low posterior probability. The higher posterior density area is still very compatible with the maximal CP violation ($\delta_{CP} = -\pi/2$).

Figure 6 shows the credible interval contours for $\Delta m_{32}^2$ against $\sin^2 \theta_{23}$ marginalized over both mass hierarchies. It is easy to see that more posterior probability is contained in the normal hierarchy (positive values of $\Delta m_{32}^2$). The Bayes Factor for the normal over the inverted hierarchy is 8.0, i.e. the normal mass hierarchy is 8 times more probable than the inverted. This classifies as “substantial” according to the Jeffreys scale [5] and “positive” with the Kass and Raftery scale [6]. Figure 7 shows the same credible interval contours as figure 6, but this time with only the normal hierarchy selected. The best fit point and most of the posterior probability lie within the higher octant of $\sin^2 \theta_{23}$ ($\sin^2 \theta_{23} > 0.5$). The Bayes Factor for the higher over the lower octant of $\sin^2 \theta_{23}$ is 3.9, which has the same classification as the Bayes Factor for sign of $\Delta m_{32}^2$. 

Figure 4. The figure shows a data point for the number of $\nu_e$ and $\bar{\nu}_e$ events observed at Super-K, with the statistical errors on top. The prediction ovals are drawn by varying $\delta_{CP}$ for different values of $\sin^2 \theta_{23}$ and for normal and inverted mass hierarchy separately.
Table 2 shows the best-fit points for all the oscillation parameters of interest, together with their 1σ and 2σ credible intervals. All the values are marginalized over both mass hierarchies.

**Figure 6.** Plot showing the 2D Credible Intervals for $\Delta m_{32}^2$ against $\sin^2 \theta_{23}$ marginalized over the mass hierarchy.

**Figure 7.** Plot showing the 2D credible intervals for $\Delta m_{32}^2$ against $\sin^2 \theta_{23}$ for the normal mass hierarchy.

| $\sin^2 \theta_{23}$ | $\Delta m_{32}^2 (\times 10^{-3} \text{eV}^2)$ | $\sin^2 \theta_{13}$ | $\delta_{CP}$ |
|----------------------|-----------------------------------------------|----------------------|---------------|
| Best fit             | 0.537                                         | 2.46                 | 0.0214        | -1.74         |
| 1σ C.I. range        | 0.501 – 0.564                                 | 2.37 – 2.54          | 0.0206 – 0.0222 | -2.39 – -1.13 |
| 2σ C.I. range        | 0.466 – 0.587                                 | -2.58 – -2.41 & 2.28 – 2.63 | 0.0199 – 0.023 | -2.95 – -0.50 |

4. Summary

In summary, we report the results from the joint fit to the ND280 and Super-K data using Bayesian framework, corresponding to $14.94 \times 10^{20}$ Proton on Target (POT) for $\nu_\mu$-beam mode and $16.35 \times 10^{20}$ POT for $\bar{\nu}_\mu$-beam mode. The CP-conserving values of $\delta_{CP}$ are rejected with at least 2σ credible interval and there is a preference for normal mass hierarchy and higher octant of $\sin^2 \theta_{23}$. Future analyses will include smaller systematics thanks to improvement in their treatment and to the upgrade of ND280. Together with the increasing statistics, T2K expects to exclude CP conservation with 3σ by 2026.

References

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