First oscillation analysis using neutrino and antineutrino data at T2K

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Abstract. We present details of the first T2K neutrino and antineutrino oscillation results, in which data collected using both a muon neutrino-enhanced neutrino beam and a muon antineutrino-enhanced neutrino beam are analysed, equating to $7.002 \times 10^{20}$ protons on target (POT) and $7.471 \times 10^{20}$ POT respectively. Both $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance data are analysed using a Bayesian Markov Chain Monte Carlo method, providing the first ever sensitivity to the CP-violating phase $\delta_{CP}$ from T2K data alone. The T2K data favour near-maximal mixing, with $\sin^2 \theta_{23}$ and $\Delta m_{32}^2$ consistent with previous T2K measurements, a value of $\sin^2 \theta_{13}$ consistent with measurements by reactor experiments, and $\delta_{CP}$ close to $-\pi/2$. When fitting with T2K data alone, the 90% credible interval for $\delta_{CP}$ disfavours values around $\pi/2$: $\delta_{CP} \in [0.38, 2.60]$ rad. When using a prior on $\sin^2 \theta_{13}$ from reactor measurements, the 90% credible interval contains $\delta_{CP} \in [-3.10, -0.17]$ rad, disfavouring the CP-conserving values 0 and $\pm \pi$. The effect on this result of the $\delta_{CP}$ prior is also investigated and presented.

1. Introduction
The T2K experiment [1] uses a 30 GeV proton beam from the J-PARC accelerator facility to produce a muon neutrino beam, which is measured by two detectors located 280 m from the neutrino production point, and a far detector, Super-Kamiokande. The far detector and one of the near detectors are placed 2.5$^\circ$ off-axis with respect to the beam, resulting in a quasi-monochromatic neutrino energy spectrum that is sharply peaked around 0.6 GeV. The T2K beam can be run in either neutrino or antineutrino configuration, for a beam which is predominantly composed of $\nu_\mu$ or $\bar{\nu}_\mu$ respectively, and the 295 km baseline between neutrino production and the far detector is carefully chosen to correspond to the first minimum in the $\nu_\mu/\bar{\nu}_\mu$ survival probability at the peak energy.

The results presented here are produced using a Bayesian oscillation analysis based on a Markov Chain Monte Carlo method. The analysis method itself is similar to that used in previous T2K results [2]: data samples of charged-current interactions in the far detector and the off-axis near detector are fit simultaneously to determine the oscillation and systematic parameters.

Candidate $\nu_\mu$ and $\bar{\nu}_\mu$ interactions are selected in the off-axis near detector, and used to constrain the flux and cross-section systematic parameters for the far detector prediction. The most notable update from previous analyses [3] is the inclusion of a sample of neutrino and antineutrino interactions on water at the near detector, which considerably reduces the systematic uncertainty at the far detector.
Both $\mu$-like and $e$-like events are selected at the far detector from the neutrino and antineutrino-mode beam, giving four data samples in total. The data analysed at the far detector corresponds to $7.002 \times 10^{20}$ POT in neutrino mode and $7.471 \times 10^{20}$ POT in antineutrino mode. The number of data events observed, along with the prediction, in each of these four samples is shown in table 1.

| Data sample | $\nu$-mode $\mu$-like | $\nu$-mode $e$-like | $\bar{\nu}$-mode $\mu$-like | $\bar{\nu}$-mode $e$-like |
|-------------|----------------------|---------------------|-----------------------------|-----------------------------|
| Predicted events (unosc.) | 491.2 | 5.8 | 185.4 | 2.3 |
| Predicted events (osc.) | 127.9 | 27.0 | 64.4 | 6.0 |
| Observed events | 125 | 32 | 66 | 4 |

2. Oscillation Analysis Results

The results of two fits are presented here. The first, referred to as ‘T2K-only’, uses a flat prior on the parameter $\sin^2 \theta_{13}$, and the second uses a Gaussian prior according to the measurements by reactor experiments reported in [4]: $\sin^2 2\theta_{13} = 0.085 \pm 0.005$. In both fits, Gaussian priors are also applied to the solar parameters, to which T2K is not sensitive: $\sin^2 \theta_{12} = 0.304 \pm 0.014$ and $\Delta m^2_{21} = 7.52 \pm 0.18 \times 10^{-5} \text{eV}^2$.

Figure 1 shows the 2D credible interval contours in $\sin^2 \theta_{23} - \Delta m^2_{32}$ (top) and $\sin^2 \theta_{13} - \Delta m^2_{32}$ (bottom left), along with the 1D posterior probability distribution and credible intervals as a function of $\delta_{CP}$ (bottom right). Good agreement is seen between both fits, and the results are consistent with previous T2K measurements [2] and the reactor constraint. The data show a weak preference for the upper octant ($\sin^2 \theta_{32} > 0.5$) and normal hierarchy ($\Delta m^2_{32} > 0$), with $71\%$ and $75\%$ posterior probability respectively from the fit with reactor constraint. The $90\%$ credible interval for $\delta_{CP}$ gives $\delta_{CP} \notin [0.38, 2.60] \text{rad}$ for the ‘T2K-only’ fit, and $\delta_{CP} \in [-3.10, -0.17]$ when using the reactor constraint on $\sin^2 2\theta_{13}$.

2.1. Effect of Priors

This is the first T2K analysis to disfavour the CP-conserving values $\delta_{CP} = 0, \pm \pi$ at $90\%$ probability, and it is important to consider the effect that the chosen prior may have on this result. Bayesian analyses combine measurements from the data with prior assumptions and information, and the strength of the information from the data can be determined by investigating how the result changes under different priors. Two priors on $\delta_{CP}$ were investigated: flat in $\delta_{CP}$ (used for the results presented above, and motivated by the desire to measure $\delta_{CP}$), and flat in $\sin(\delta_{CP})$ (motivated by the desire to measure CP violation, as the CP-violating terms in the oscillation probability contain $\sin(\delta_{CP})$). The effect of changing between these two priors is presented in figure 2. The CP-conserving values of $\delta_{CP}$ are no longer disfavoured at $90\%$ probability when using a prior flat in $\sin(\delta_{CP})$. However, the change in credible intervals is not large, indicating that the information from the data is not significantly weaker than the choice of prior.

Alternate priors for the oscillation parameters $\sin^2 \theta_{23}$, $\Delta m^2_{32}$, and $\sin^2 \theta_{13}$ were also considered (flat priors are currently used for these parameters, except where the reactor constraint is used on $\sin^2 \theta_{13}$) and found to have little effect on the result.
Figure 1. Highest posterior density credible intervals and best-fit points. Two best-fit points are defined in the 2D figures (top: $\sin^2\theta_{23}-\Delta m^2_{32}$, bottom left: $\sin^2\theta_{13}-\delta_{CP}$): the mode of the 2D posterior probability distribution (in which all parameters other than those shown in the figure are marginalised), and the mode of the 4D $\sin^2\theta_{23}-\sin^2\theta_{13}-\Delta m^2_{32}-\delta_{CP}$ posterior probability distribution. The 1D posterior probability distribution as a function of $\delta_{CP}$ is also shown (bottom right).

Figure 2. Posterior probability density and credible intervals as a function of $\delta_{CP}$ from the fit with reactor constraint, using a flat prior in $\delta_{CP}$. The credible intervals obtained using a prior flat in $\sin(\delta_{CP})$ are overlaid.

3. Conclusions
The first analysis of neutrino and antineutrino oscillation at T2K is complete, providing the first ever T2K-only measurement of $\delta_{CP}$ and the most precise T2K measurement of the other oscillation parameters $\sin^2\theta_{23}$, $\Delta m^2_{32}$, and $\sin^2\theta_{13}$. The results are consistent with previous measurements from T2K and reactor neutrino experiments, and favour $\delta_{CP}\simeq-\pi/2$. When using a prior on $\sin^22\theta_{13}$ from reactor measurements, $\delta_{CP}=(0,\pi)$ is disfavoured at 90%, with some dependence on the chosen prior.

References
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