Selected results from T2K

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The T2K ("Tokai to Kamioka") experiment is a long-baseline neutrino oscillation experiment in Japan. A beam of muon neutrinos or muon anti-neutrinos is produced at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai. The unoscillated neutrino flux is measured by the near detector complex 280 m from the proton target, and the oscillated neutrino flux is measured by the far detector, Super-Kamiokande, 295 km away. The major T2K neutrino oscillation results to date (from neutrino beam run periods) are reviewed, and a first look at the recent anti-neutrino beam run periods is provided.

1 Overview of the T2K experiment

T2K is a long-baseline neutrino oscillation experiment, making use of a neutrino beam, a near detector (ND280), and a far detector (Super-Kamiokande) to explore neutrino oscillation and cross section physics. Full detail on the experimental setup is available elsewhere [1].

1.1 Neutrino beam

At the Japan Proton Accelerator Research Complex (J-PARC) in Tokai, Japan, a 30 GeV beam of protons is collided with a graphite target. This produces a beam of mostly pions, which are focussed by three magnetic horns, and which subsequently decay to produce the neutrino beam. The direction of the current through the horns determines whether π^+ (which decay into neutrinos), or π^- (which decay into anti-neutrinos) are focussed, hence determining whether the beam is in neutrino mode or anti-neutrino mode respectively. This process is simulated using a combination of FLUKA [2,3] and GEANT3 [4] (with GCALOR [5]), and is tuned to external data (e.g. NA61/SHINE). This model also provides the correlations between different flavours and bins of neutrino energy in both beam modes at ND280 and Super-Kamiokande, which allows ND280 measurements to reduce flux uncertainties at Super-Kamiokande. The beam model was recently updated, and now simulates both neutrino and anti-neutrino beam modes, and has reduced uncertainties due to improvements in the hadron production modelling.

1.2 Detectors

Both ND280 and Super-Kamiokande are located 2.5° off-axis from the neutrino beam, which results in an energy spectrum that is peaked at 0.6 GeV, and is much narrower than the on-axis spectrum.

ND280 consists of multiple subdetectors in a 0.2 T magnetic field (provided by the former UA1/NOMAD magnet), situated 280 m from the beam target. For the analysis results discussed here, ND280 measurements were done using the Fine-Grained Detectors (FGDs), which are made up of scintillator bars which act as an active neutrino target, and the gas-filled Time Projection Chambers (TPCs), which provide momentum measurements and measurement of dE/dx for particle identification. ND280 measures the neutrino beam flux and some neutrino cross section model parameters that are used in the oscillation analyses, thus reducing uncertainties in the oscillation analyses.

Super-Kamiokande is a water Cherenkov detector located 295 km from the beam target. It has a 22.5 kton fiducial mass, and is instrumented with approximately 11000 PMTs. Event selection begins with events that occur within the fiducial volume and are fully contained within the inner detector, called "Fully Contained Fiducial Volume" events, or FCFV. For these events, good discrimination between ν_μ and ν_e is achieved through the shape of the Cherenkov ring. Electrons scatter, undergo bremsstrahlung, and initiate electromagnetic showers, resulting in fuzzy Cherenkov rings, whereas muons, being much heavier, maintain their initial direction, producing sharp Cherenkov rings.

1.3 Neutrino oscillation in a $\nu_\mu/\bar{\nu}_\mu$ beam

An overview of the theory and status of 3 flavour neutrino mixing is given elsewhere [6] in these proceedings. T2K makes use of a beam of muon neutrinos or muon anti-neutrinos, so for the neutrino energy spectrum of T2K muon neutrino disappearance (Eq. 1) and electron neutrino appearance (Eq. 2) are the two relevant channels, where each equation was derived from the PMNS matrix, makes use of the approximation that $|\Delta m^2_{32}| \approx |\Delta m^2_{31}|$, and employs the short-hand of $x \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{32}}$ and $D \equiv \frac{\Delta m^2_{32} L}{4E}$. In addition, Eq. 2 is approximated to first order in $\Delta m^2_{21}/\Delta m^2_{31}$, and accounts only for CP-odd terms. A paper [7] is available with more details.

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2 D \tag{1}$$

$$\begin{aligned} P\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e\right) \approx \frac{\sin[(1\mp x)D]}{(1\mp x)} \Bigg(& \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin[(1\mp x)D]}{(1\mp x)} \\ & \mp \sin\delta_{CP}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin D\frac{\sin(xD)}{x}\frac{\Delta m^2_{21}}{\Delta m^2_{32}}\Bigg) \end{aligned} \tag{2}$$

In both Eq. 1 and Eq. 2, the D term provides dependence on the distance the neutrinos travel, their energy, and the mass-squared splitting Δm^2_{32}. For T2K, these values are such that the probabilities of muon neutrino disappearance and electron neutrino appearance are maximal at Super-Kamiokande. From Eq. 2 it is evident that measurements of θ_{13} by measuring $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ depend on the CP violating phase δ_{CP}, and in different ways. Therefore, taking data with ν_μ and $\bar{\nu}_\mu$ beams increases the sensitivity T2K has to δ_{CP}.

1.4 Neutrino interactions at T2K

For the neutrino energy spectrum at T2K, the "Charged Current Quasi-Elastic" (CCQE) neutrino interaction process is dominant. For neutrinos, the process is given by Eq. 3, where ℓ denotes a negative lepton.

$$\nu_\ell + n \to \ell + p \tag{3}$$

CCQE is the T2K signal mode, and has the benefit that the energy of the neutrino can be reconstructed from the momentum and angle of the outgoing lepton, using Eq. 4.

$$E_\nu = \frac{m_p^2 - m_n^2 - m_\ell^2 + 2m_n E_\ell}{2(m_n - E_\ell + p_\ell cos\theta_\ell)} \tag{4}$$

In addition to this signal mode, there are also a number of background modes to consider. If they were mis-identified as CCQE, this would affect the shape of the reconstructed neutrino energy spectrum, and thus the oscillation analysis results. One such interaction is the multi-nucleon-neutrino interaction, in which a neutrino interacts with multiple correlated nucleons, producing a signal at Super-Kamiokande that is identical to CCQE (since outgoing protons are typically below Cherenkov threshold, and thus not detected). For upcoming T2K analyses, the Nieves multi-nucleon interaction model [8,9] has been implemented as part of the CCQE model. In addition, this CCQE model has been tuned to neutrino and anti-neutrino data from MINERνA and MiniBooNE.

For the neutrino energy spectrum at T2K, the “Charged Current RESonant pion production” (CCRES) interaction process is the dominant background process, and is shown in Eq. 5.

$$\nu_\ell + N \rightarrow \ell + \Delta \rightarrow \ell + \pi + N^{'} \tag{5}$$

If the pion is not detected, this interaction would be mis-identified as a CCQE interaction. One way this pion could be missed is if it were to be absorbed before exiting the nucleus in a “Final State Interaction” (FSI). In addition, the pion could interact outside the nucleus before it is detected, or be below Cherenkov threshold and not otherwise be detected through a Michel electron signal from its decay. The CCRES model has been retuned for upcoming analyses, with new form factors implemented [10], and a re-analysis of the ANL and BNL bubble chamber datasets performed [11].

2 Neutrino beam mode oscillation analyses

2.1 ν_μ disappearance measurement

As per the experimental design, the deficit of muon neutrinos at Super-Kamiokande due to oscillation is quite large, as is shown in Fig. 1 (left). This corresponds to 120 events selected, when 446.0 ± 22.5 (syst) would be expected without oscillations. The resulting contours for Normal Hierarchy (NH) and Inverted Hierarchy (IH) are shown in Fig. 2. This corresponds to a measurement of $\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$ (0.511 ± 0.055) for NH (IH), which is the most precise measurement of this neutrino mixing parameter. There is a paper [12] that describes this study in more detail.

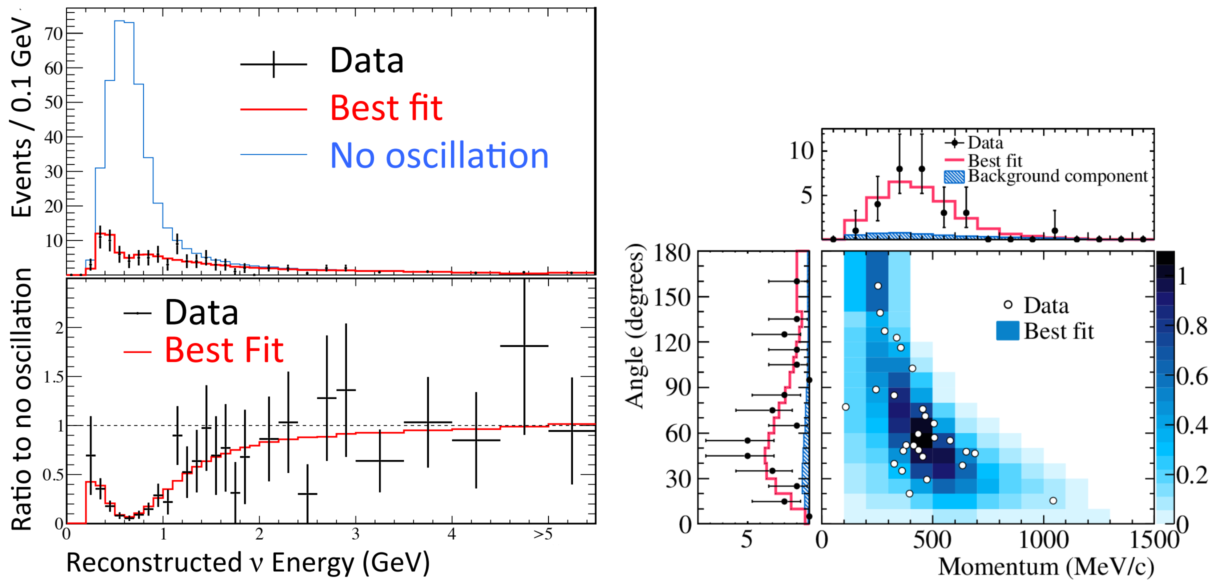

Figure 1 – Reconstructed muon neutrino energy spectrum at Super-Kamiokande, showing data and the best fit Monte Carlo prediction, along with the no oscillation Monte Carlo prediction (left). Momentum and angle of outgoing electron candidate for Super-Kamiokande electron neutrino event selection, showing data and the Monte Carlo best fit and expected background (NH). (right).

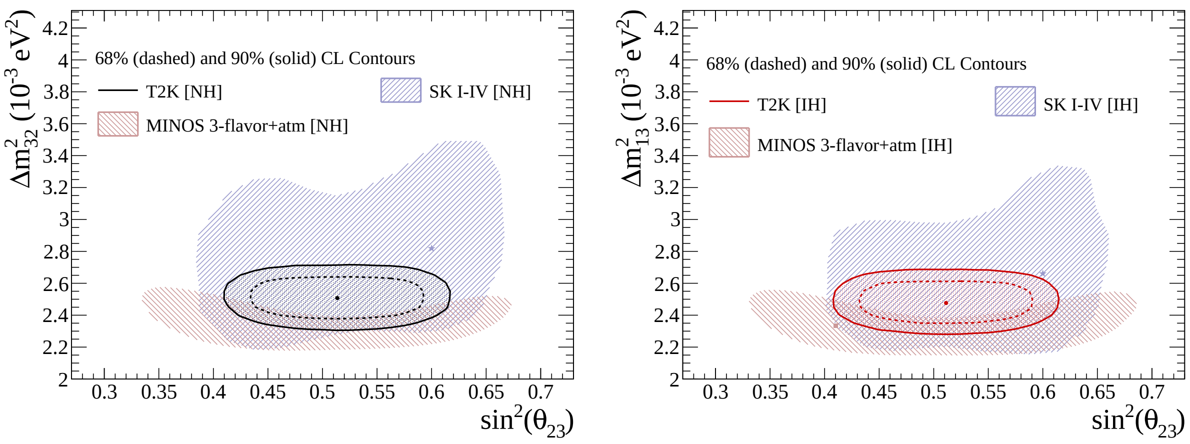

Figure 2 – The 68% and 90% confidence regions for $\sin^2\theta_{23}$ and Δm^2_{32} for NH (left) or Δm^2_{13} for IH (right) from the muon neutrino appearance analysis, with Super-Kamiokande and MINOS 90% confidence regions shown for comparison.

2.2 $\nu_\mu \rightarrow \nu_e$ appearance measurement

T2K observed a total of 28 electron neutrino events with an expected background of 4.92 ± 0.55 events. The observed events, the Monte Carlo best fit, and the expected background are shown in Fig. 1 (right). This corresponds to a significance of 7.3σ for the discovery of $\nu_\mu \rightarrow \nu_e$ oscillation. The resulting contours for NH and IH are shown in Fig. 3 (left), along with the PDG2012 1σ range coming from reactor neutrino oscillation experiments. More information on this study is available in a paper [13].

2.3 Joint $\nu_\mu + \nu_e$ analysis (Bayesian version)

Standalone appearance and disappearance measurements only consider the spectrum of the relevant neutrino flavour at Super-Kamiokande. However, as shown in Eqs. 1 and 2, the relationship between $P(\nu_\mu \rightarrow \nu_\mu)$, $P(\nu_\mu \rightarrow \nu_e)$, θ_{23}, θ_{13}, δ_{CP} and Δm^2_{32} is complicated. So, a joint analysis where the ν_μ and ν_e spectra were considered simultaneously was performed. In addition, the constraint from reactor experiments was included. The Bayesian version of this analysis used a Markov Chain Monte Carlo to produce posterior distributions for the oscillation parameters of interest. When including the reactor constraint and marginalizing over the mass hierarchy, the posterior density distribution for δ_{CP} shown in Fig. 3 (right) is produced, which hints towards $\delta_{CP} \approx -\frac{\pi}{2}$. In addition, the T2K and reactor data are found to weakly favour the Normal Hierarchy with a Bayes factor of 2.2, and to weakly favour the upper θ_{23} octant. This analysis and frequentist joint analyses are described in a recently published paper [14].

3 First look at anti-neutrino beam mode

Since the summer of 2014, T2K has been taking data in anti-neutrino beam mode. As of March 5, 2015, 7.001×10^{20} protons had been delivered to the T2K target in neutrino mode, and 2.057×10^{20} protons had been delivered to the T2K target in anti-neutrino mode.

Up to December 22, 2014, 394 FCFV events had been observed at Super-Kamiokande in neutrino mode, and 40 FCFV events had been observed in anti-neutrino mode. An important part of using these events to study neutrino oscillations is to make use of ND280 measurements to reduce systematic uncertainties from the neutrino beam flux and neutrino cross section models. To assist in this effort, two samples were devised to select muon anti-neutrino events in anti-neutrino beam mode. The CC-1Track sample is sensitive to the T2K signal mode, and requires that only one track was reconstructed, and that it is positive and muon-like. For this sample,

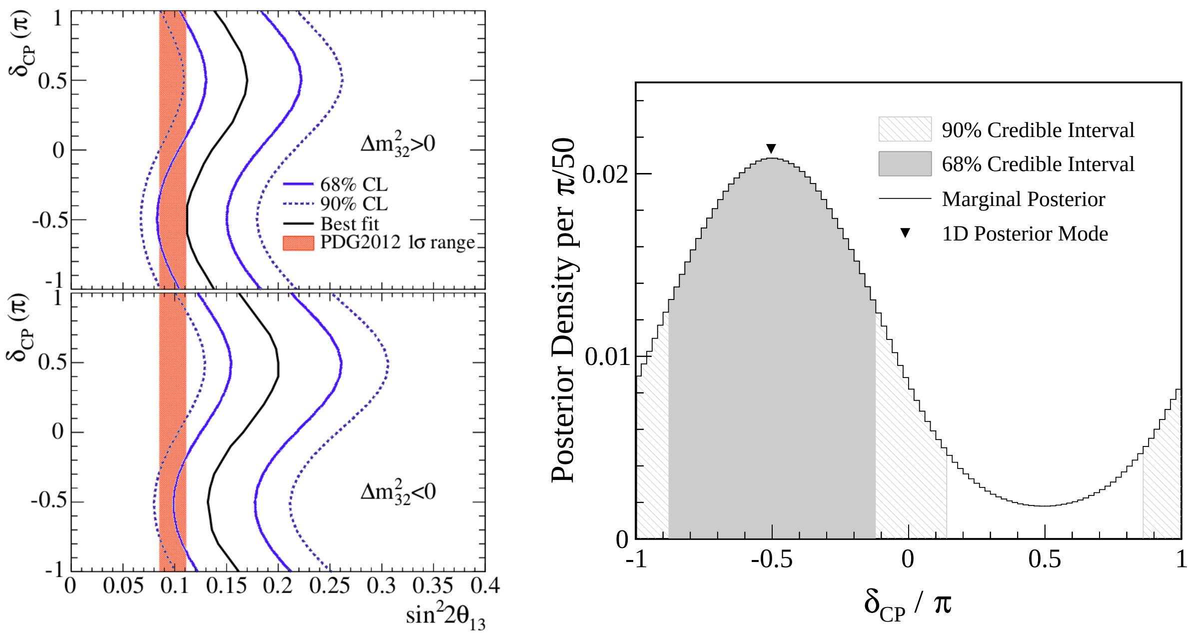

Figure 3 – The 68% and 90% confidence regions for $\sin^2 2\theta_{13}$ and δ_{CP} from the electron neutrino appearance analysis, with the PDG2012 1σ range shown for comparison (left). Posterior density distribution for δ_{CP} from the Bayesian joint analysis with the reactor constraint, where the mass hierarchy has been marginalized over (right).

the momentum of the muon candidate and the cosine of angle it makes with the beam is shown in Fig. 4. The CC-NTracks sample is sensitive to the T2K background modes, and requires that there is more than one track reconstructed, and that the highest momentum positive track is muon-like. For this sample, the momentum of the muon candidate and the cosine of angle it makes with the beam is shown in Fig. 5. Both of these samples will be included as part of the ND280 measurements used in the upcoming T2K anti-neutrino oscillation results.

4 Conclusion and outlook

Using its neutrino beam mode data, T2K has produced some exciting results so far. Through its ν_μ disappearance measurement, T2K has produced the world leading measurement of θ_{23}. By measuring appearance of ν_e, T2K has discovered $\nu_\mu \to \nu_e$ oscillation at 7.3σ. Finally, joint analysis of the ν_μ and ν_e data, combined with the constraint from reactor neutrino experiments,

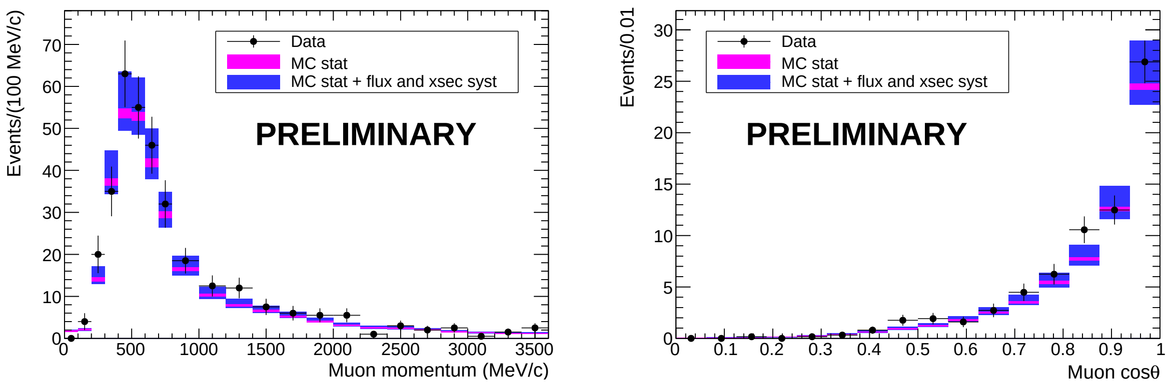

Figure 4 – Momentum (left) and cosine of angle with the neutrino beam (right) of the muon candidate in the ND280 $\bar{\nu}_\mu$ CC-1Track selection. The Monte Carlo prediction includes error bands for the MC statistical error and the prior errors on the flux and interaction models from tuning to external data. ND280 detector systematics are not included, and are expected to be $\approx 4\%$ at the peak.

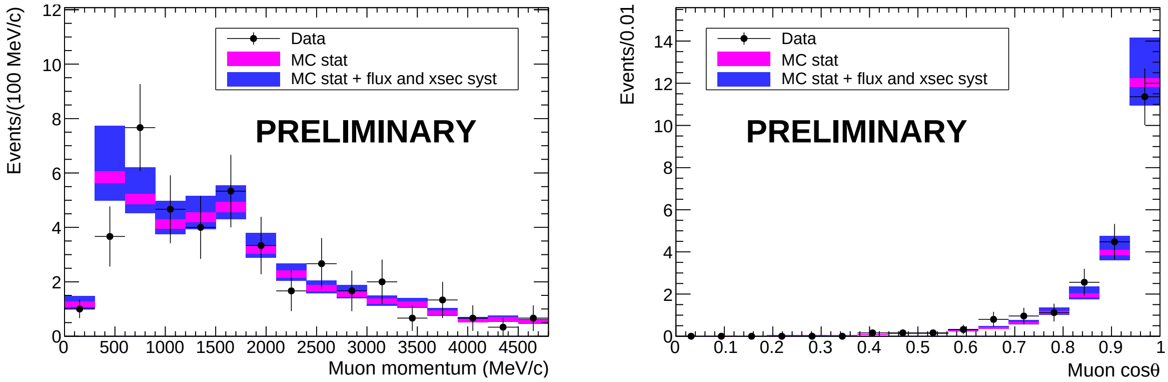

Figure 5 – Momentum (left) and cosine of angle with the neutrino beam (right) of the muon candidate in the ND280 $\bar{\nu}_\mu$ CC-NTracks selection. The Monte Carlo prediction includes error bands for the MC statistical error and the prior errors on the flux and interaction models from tuning to external data. ND280 detector systematics are not included, and are expected to be $\approx 4\%$ at the peak.

hints towards $\delta_{CP} \approx -\frac{\pi}{2}$, and Normal Hierarchy with a Bayes Factor of 2.2. T2K is now taking data in anti-neutrino beam mode, and has recently updated its neutrino beam flux and neutrino cross section models for upcoming analyses. Analysis of this data is well underway, with T2K's first anti-neutrino oscillation results coming in the near future.

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