RECENT OSCILLATION RESULTS AT T2K

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The T2K long baseline neutrino oscillation experiment is composed of a near detector at 280m and a far detector at Super-Kamiokande, located 295 km from the neutrino beam source. The 30GeV proton beam at JPARC is used to produce ~ 1 GeV muon neutrinos which are detected using the Cherenkov detector at Super-Kamiokande for oscillation measurements, such as electron neutrino appearance and θ_{23} measurements from muon neutrino disappearance. By reversing the beam polarity antineutrino oscillations may also be studied. Muon antineutrino disappearance and electron antineutrino appearance have been studied with 4×10^{20} protons on target in antineutrino beam mode. The most recent oscillation results from T2K for neutrinos and antineutrinos are presented here.

1 The T2K Experiment

The T2K experiment is a long baseline neutrino experiment with a near detector at 280 m and a far detector at 295 km from the beam source; it is designed to measure ν_μ disappearance and ν_e appearance in a ν_μ beam, as well as the antineutrino equivalents. This enables T2K to have sensitivity to measure the mixing angles θ_{13} and θ_{23}, as well as the CP violating phase δ_{CP}. The last mixing angle θ_{13} can be measured through ν_e appearance. Muon neutrino disappearance can be used to measure the value of θ_{23} and determine the octant ($\theta_{23} > 45°$ or $\theta_{23} < 45°$). The value of δ_{CP} is also unknown; if $\delta_{CP} \neq 0$, this would indicate CP violation in the neutrino sector. The angle δ_{CP} effects the difference between $\nu_\mu \to \nu_e$ oscillations and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. Finally, the sign of Δm^2_{32} is still unknown as well. Positive Δm^2_{32} gives the normal mass hierarchy ($m_1 < m_2 < m_3$) while negative Δm^2_{32} gives the inverted mass hierarchy ($m_3 < m_1 < m_2$). In conjunction with other experiments, T2K could potentially contribute to the determination of the mass hierarchy through matter effects on oscillation.

The T2K neutrino beam is created using the 30 GeV proton beam produced at the Japan-Proton Accelerator Research Center (J-PARC), located in Tokai, Japan [2]. The protons collide with a graphite target, producing pions and a smaller fraction of other mesons; this is then focussed using three magnetic horns. These pions then travel through a 96 m decay volume and decay to produce the T2K neutrino beam. The current polarity in the magnetic horns controls the sign of the magnetic field and changes whether π^+ or π^- are focussed into the decay volume. The π^+ beam decays into neutrinos, and the π^- beam decays to antineutrinos, allowing the T2K neutrino beam to be run in either neutrino mode or antineutrino mode.

1.1 The T2K Detectors

T2K consists of a near detector 280 m from the beam source in Tokai (ND280), and the far detector 295 km from the beam source at Super-Kamiokande [1]. Both ND280 and the Super-Kamiokande (SK) detector are 2.5° off-axis from the neutrino beam, giving a narrow band muon-neutrino beam with a peak energy of 600 MeV. The off-axis detector position produces a narrower energy range for the neutrinos as well as tuning the neutrino energy to peak at the oscillation maximum at Super-Kamiokande. The oscillation probability for neutrinos [3], shown in Eq. 1, depends on the neutrino mixing matrix elements, U_{ij}, the neutrino mass splittings Δm^2_{ij} and the energy and distance travelled by the neutrino in the absence of matter effects – a good approximation as matter effects are small at T2K.

$$P_{\nu_a \to \nu_b}(L, E) = |\sum_{j,k} U^*_{aj} U_{bj} U_{ak} U^*_{bk} e^{-i\frac{\Delta m^2_{jk} L}{2E}}| \tag{1}$$

ND280 is comprised of several different detectors, all sitting in a 0.2 T magnetic field, 280 m from the beam source and off-axis by 2.5°. The main tracker volume consists of three time projection chambers (TPCs), with two Fine-Grained detectors (FGDs) in between. The FGDs are composed of layers of scintillator bars which function as the active target material for ND280, with the second FGD downstream from the beam also containing uninstrumented water volumes, as well as providing tracking and vertexing. The TPCs provide the primary particle identification, momentum measurements and charge identification. This allows the near detector to differentiate between neutrino and antineutrino interactions on an event-by-event basis, which is important for constraining the neutrino contamination in the antineutrino beam flux. The near detectors provide improved constraints on the flux and cross section models for the oscillation fits, reducing the overall uncertainty on the oscillation results.

SK is a 50 kton water Cherenkov detector located underground 295 km from the beam source, with a 22.5 kton fiducial volume [4]. The detector is instrumented with approximately 13000 photomultiplier tubes and provides the primary event selection for the T2K neutrino oscillation analyses. The SK event selection gives strong ν_μ and ν_e separation on the order of 97.7% purity for the muon neutrino selection, but cannot distinguish between neutrinos and antineutrinos on an event-by-event basis, as there is no charge identification and no magnetic field.

2 The T2K Oscillation Analysis Structure

The T2K event selections look for final-state leptons from charged-current neutrino interactions, which are identified using event topology at both near and far detectors. The primary charged-current neutrino interaction mode at the peak T2K beam energy is the Charged-Current Quasi-Elastic (CCQE) interaction, given by Eq. 2 for both the neutrino and antineutrino beams. CCQE interactions are considered the T2K signal mode, because the neutrino energy can be calculated solely from the momentum of the outgoing lepton.

$$\nu_l + n \to l + p \tag{2}$$

Additional charged-current interactions that make up the background are resonant pion production, where π^+ are produced from Δ resonance, coherent interactions which produce pions, and deep inelastic scattering. The neutrino energies in these interactions are significantly more difficult to reconstruct. These can be potentially misidentified as CCQE interactions, which will give incorrect reconstructed neutrino energies.

The selection for $\bar{\nu}_\mu$ events at SK is identical to the selection used for the ν_μ analyses, though unlike the neutrino beam, there is significant wrong-sign contamination for the antineutrino beam from neutrinos. First, the event is required to have a single reconstructed ring that is considered muon-like, with the reconstructed interaction vertex being fully contained in the SK fiducial volume. Second, the reconstructed momentum of the muon must be greater than 200 MeV/c, to remove the low energy background. The selection also requires that there is no more than one decay electron reconstructed, to reduce events produced by non-CCQE interactions.

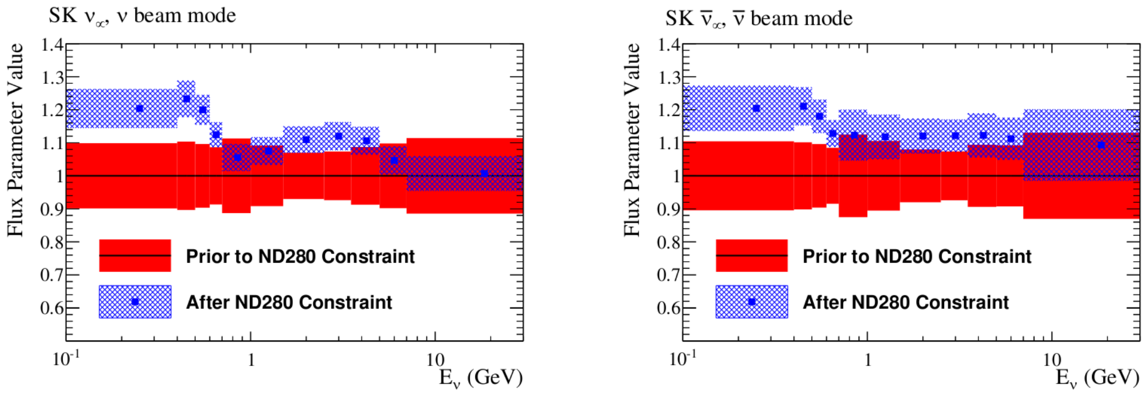

Figure 1 – Neutrino flux predictions at SK with and without the ND280 constraint on the flux and cross section for the ν_μ – ν_e joint analysis. The plot on the left shows the predicted ν_μ event rates at SK in neutrino mode, and the plot on the right shows the predicted $\bar{\nu}_\mu$ flux at SK for antineutrino mode.

As with the $\bar{\nu}_\mu$ selection, the $\bar{\nu}_e$ selection at Super-Kamiokande is the same as for its neutrino counterpart and is constructed to select CCQE interactions. For e-like events, the single reconstructed ring must be electron-like with the visible energy greater than 100 MeV, and the overall event must not be considered to be π^0-like. This is to remove low energy backgrounds from other electron-producing processes, particularly the π^0 background which can appear similar to the electron signal. Additionally, the reconstructed neutrino energy must be less than 1250 MeV to remove intrinsic ν_e background from the beam.

The initial inputs to the oscillation analysis come from external inputs for cross-section and flux parameters. Cross-section data comes from other experiments such as MiniBooNe [5] and Minerνa [6,7], and the flux input constraints from thin-target experiments such as NA-61 [8], which are then used as inputs to the near detector fit. The near detector fit simultaneously constrains the flux and cross section parameters using the near detector data including correlations between the flux and cross section parameters. This also constrains any wrong-sign background components in the flux (neutrinos in the antineutrino beam) as the near detector can separate events by charge identification. The near detector fit output is then used to create the event rate predictions at SK, where the flux and cross section parameters will be marginalized over in the oscillation fit. However, because the near detector target is composed primarily of carbon, while the SK target is water, not all cross section parameters can be constrained with the near detector fit. For those parameters, only external priors are used. This allows the reduction of common systematics in the antineutrino oscillation fit from 9% to 3%, with an additional 10% uncertainty from the cross section parameters that are not fit at ND280. The neutrino mode oscillation fits see a similar reduction in common systematic uncertainties.

In addition to reducing the uncertainties on common systematics between SK and ND280, the near detector fit also provides updated parameter values for generating the SK prediction. In particular, the flux parameters are moved significantly relative to their initial values and prior uncertainties, shown for the ν_μ and $\bar{\nu}_\mu$ fluxes for neutrino and antineutrino mode respectively in Fig. 1. The flux for both neutrinos and antineutrinos is increased for all energies, with the lower energy flux seeing the larger increases, of up to around 20%. This holds true for the neutrino contamination in antineutrino beam mode as well, though to a lesser extent. However, this does not necessarily correspond to an increase the predicted event rate at SK once the ND280 constraint is included, as the near detector fit also changes the values for relevant cross section parameters.

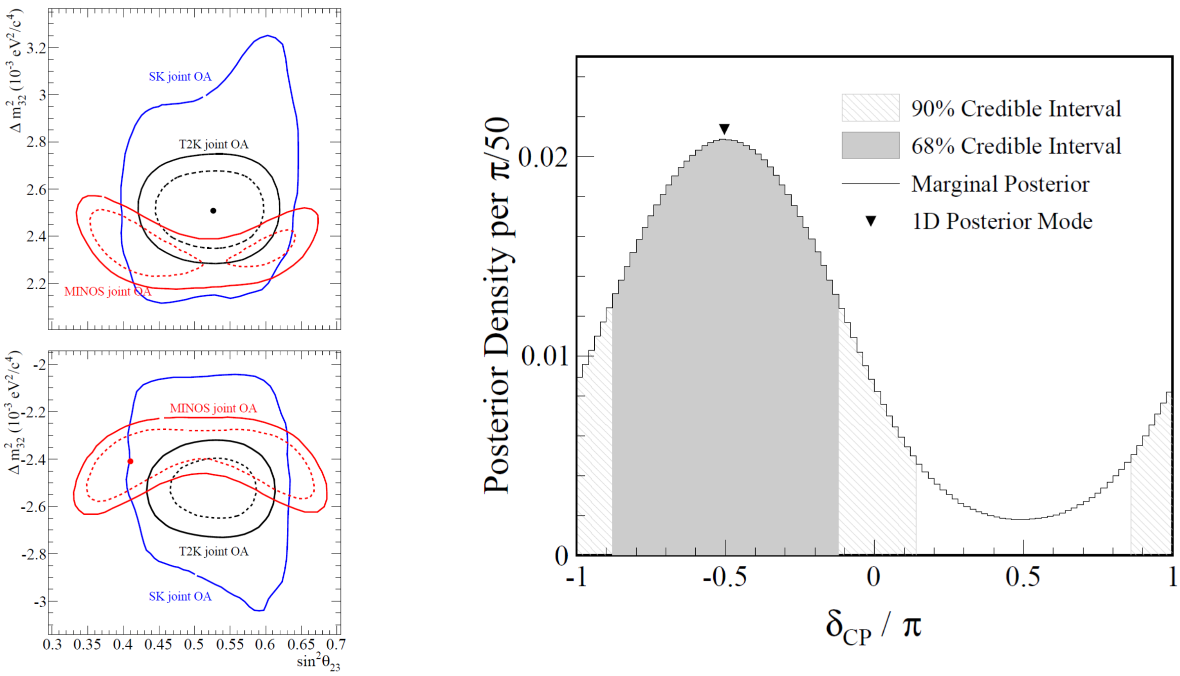

Figure 2 – Left plot shows the Δm^2_{32} and $\sin^2\theta_{23}$ T2K joint 68 % and 90% CL contours for NH (top) and IH (bottom) along with the joint contours from MINOS [11]. Right plot shows the posterior density distribution for δ_{CP} marginalized over the mass hierarchy.

3 Neutrino Oscillation Results

T2K has been running in antineutrino beam mode since summer 2014, and has had 4.01×10^{20} protons on target as of spring 2015, with a previous 7×10^{20} protons on target delivered in neutrino beam mode. The most recent neutrino mode result [9] is the joint ν_μ disappearance and ν_e appearance result, where the T2K ν_μ and ν_e results are fit simultaneously along with constraints from reactor experiments. When the reactor constraint is included, δ_{CP} is excluded at the 90% confidence level in the regions of $[0.15, 0.83]\pi$ for normal hierarchy, and $[-0.08, 1.09]\pi$ for inverted hierarchy. The posterior density distribution for δ_{CP} marginalized over mass hierarchy is shown in the right plot of Fig. 2. Additionally, the joint neutrino oscillation fit finds $\sin^2\theta_{23} = 0.528^{+0.055}_{-0.038}$ and $|\Delta m^2_{32}| = (2.51 \pm 0.11) \times 10^{-3}\mathrm{eV}^2/\mathrm{c}^4$ when the reactor data is included.

3.1 The $\bar{\nu}_\mu$ Disappearance Analysis

T2K has observed 34 muon-like events at Super-Kamiokande, with 103.6 expected ν_μ and $\bar{\nu}_\mu$ events in the case of no neutrino oscillations (78.7 $\bar{\nu}_\mu$ events and 24.8 ν_μ events expected) [10]. The selected events include both neutrinos and antineutrinos as there is no charge identification at SK, and the error is dominated by statistical uncertainties. The observed spectrum, shown in Fig. 3, shows clear evidence of $\bar{\nu}_\mu$ oscillations. Contours for Normal Hierarchy are shown in Fig. 4 along with the contours from the joint ν_μ disappearance result from T2K [9], MINOS [12] and the Super-Kamiokande atmospheric $\bar{\nu}$ fits [13]. T2K measures a value of $\sin^2\bar{\theta}_{23} = 0.45^{+0.38}_{-0.64}$ and $|\Delta\bar{m}^2_{32}| = 2.51^{+0.29}_{-0.26} \times 10^{-3}\mathrm{eV}^2/\mathrm{c}^4$; this is in agreement with the previous measurements from the T2K ν_μ disappearance results and indicates maximal mixing for θ_{23}.

3.2 The $\bar{\nu}_e$ Appearance Analysis

The T2K $\bar{\nu}_e$ appearance analysis uses a discrete parameter β, where $\beta = 0$ represents no $\bar{\nu}_e$ appearance, and $\beta = 1$ represents nominal $\bar{\nu}_e$ appearance – identical to the neutrino case. With

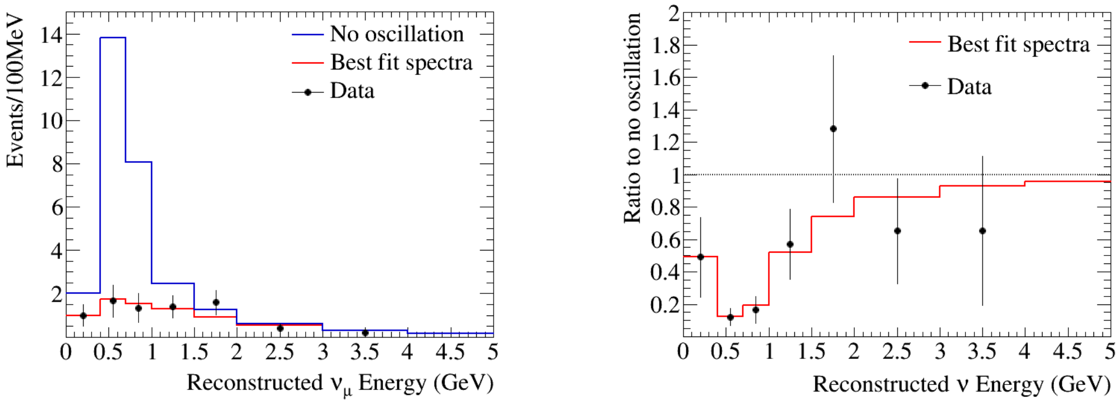

Figure 3 – Predicted and observed event rates for the $\bar{\nu}_\mu$ analysis. The plot on the left shows the observed neutrino event rates at T2K, along with the best fit spectra and the predicted spectra with no oscillations. The plot on the right shows the ratio of observed neutrino events at T2K with the predicted number of events given no oscillations.

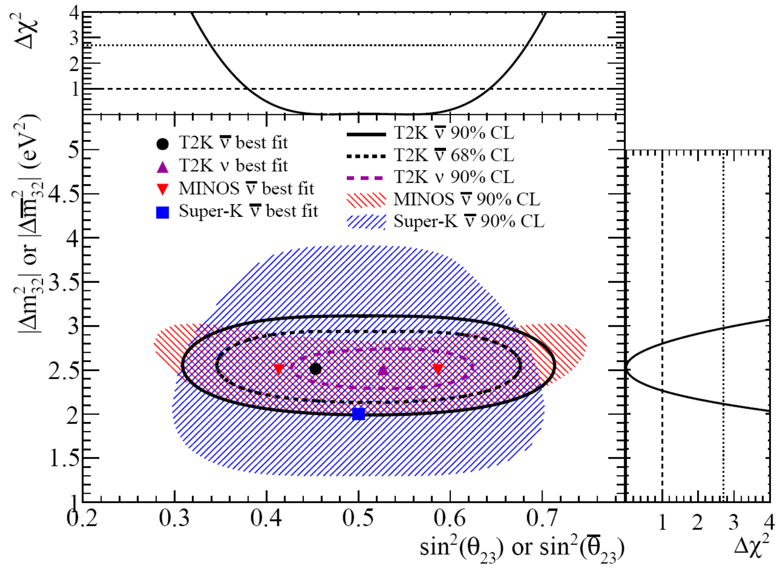

Figure 4 – Plot of the 68% and 90% C.L. regions [9,12,13] for $\sin^2\theta_{23}$ and Δm^2_{32} (NH) or $\sin^2\bar{\theta}_{23}$ and $\Delta\bar{m}^2_{32}$ (IH) for the antineutrino results [10].

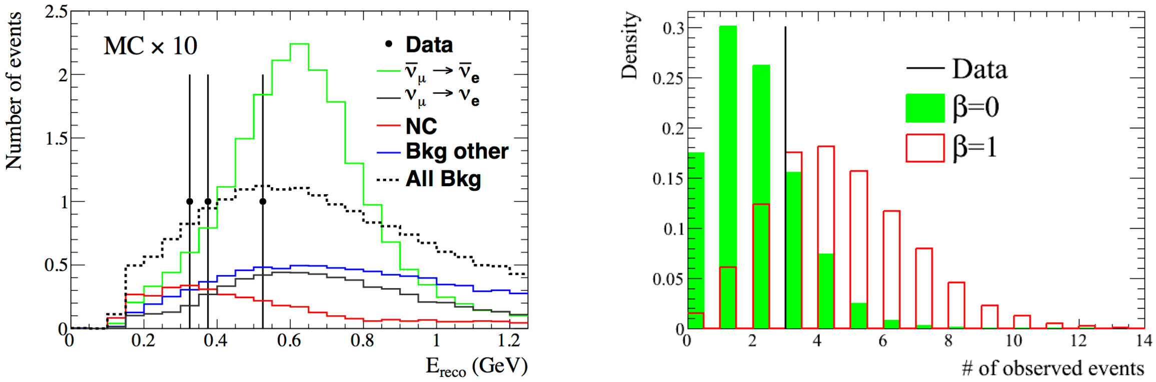

Figure 5 – The left figure shows the predicted spectra for number of events seen at SK for $\bar{\nu}_e$ appearance as a function of likelihood ratio. Right figure shows the probability densities for the predicted number of events for both hypotheses and the number of events observed.

the current limited data statistics, 3 $\bar{\nu}_e$ candidate events were seen. As shown in Fig. 5, T2K cannot distinguish between the two hypotheses at these statistics; evidence is equally strong for either case and would need at least twice the current protons on target to acheive a statistically significant measurement.

4 Conclusions and Outlook

The T2K experiment has produced new and exciting results using antineutrino mode data, as well as producing the world leading measurements of the mixing angle θ_{23} with a joint appearance and disappearance analysis for neutrinos. The T2K $\bar{\nu}_\mu$ measurement of $\bar{\theta}_{23}$ is consistent with the previous neutrino results and with CPT conservation. T2K has taken antineutrino data corresponding to 4×10^{20} protons on target so far and is currently taking more data in the antineutrino mode. Future plans are to improve the near detector fit to further constrain systematics at SK, and to do a full joint neutrino-antineutrino appearance and disappearance analysis with improved antineutrino statistics.

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