Results from T2K:
A joint analysis of neutrino and antineutrino data

H. A. Tanaka, on behalf of the T2K Collaboration
Dept. of Physics, University of Toronto, 60 St. George Street, Toronto, ON M5S 1A7, Canada
Institute of Particle Physics, TRIUMF
E-mail: htanaka@physics.utoronto.ca

Abstract. We report the results of a joint analysis of neutrino and antineutrino oscillations at T2K with the $\nu_\mu(\bar{\nu}_\mu)$ disappearance and $\nu_\mu(\bar{\nu}_\mu)\to\nu_e(\bar{\nu}_e)$ appearance channels. The disappearance channel is primarily sensitive to $\sin^2 2\theta_{23}$ and the mass splitting $\Delta m^2_{32}$, while $\nu_\mu\to\nu_e$ is sensitive to $\sin^2 \theta_{23}$ and $\sin^2 2\theta_{13}$, with the CP violating phase $\delta_{CP}$ and matter effects inducing asymmetries in the oscillation probabilities between the CP conjugate channels.

Since the Neutrino 2016 conference, a small increment of data has been added to the analysis, so that the accumulated protons-on-target are $7 \times 10^{20}$ in $\nu$-mode and $7.47 \times 10^{20}$ in $\bar{\nu}$ mode.

We comment briefly on the future prospects for T2K, including a proposal for extended running to accumulate $20 \times 10^{21}$ protons-on-target, nearly three times the currently approved amount by 2026, to gain substantial sensitivity to CP violating effects in $\delta_{CP}$.

1. Introduction
The observation of $\nu_\mu\to\nu_e$ oscillations at T2K[1] and the disappearance of $\bar{\nu}_e$ by reactor experiments[2, 3, 4] arising from non-zero $\theta_{13}$ have set the stage for CP violating effects in neutrino oscillation arising from an irreducible phase $\delta_{CP}$ in the three-flavor mixing of neutrino and flavor and mass states. This will result in asymmetries in the probabilities for the CP-conjugate channels $\nu_\mu\to\nu_e$ and $\bar{\nu}_\mu\to\bar{\nu}_e$ if $\sin\delta_{CP}\neq0$, with negative (positive) values of $\sin\delta_{CP}$ enhancing (suppressing) $\nu_\mu\to\nu_e$ oscillations and suppressing (enhancing) $\bar{\nu}_\mu\to\bar{\nu}_e$ oscillations. While CP violation is not expected in disappearance channels, $\nu_\mu$ and $\bar{\nu}_e$ disappearance measurements$^1$ provide critical constraints on the mixing angles which enter into the $\nu_\mu(\bar{\nu}_\mu)\to\nu_e(\bar{\nu}_e)$ oscillation probabilities. Since accelerator-based long-baseline experiments like T2K measure both $\nu_\mu$ disappearance and $\nu_e$ appearance and their CP conjugates, it is logical to jointly analyze these four channels to consistently extract the oscillation parameters, and apply measurements of $\theta_{13}$ and $\theta_{12}$ from other experiments as constraints.

We report the first joint analysis of these four modes at T2K following the accumulation of data with the T2K beam operating in both neutrino ($\nu$-) and antineutrino ($\bar{\nu}$-) mode. Previous results have conclusively established the observation of $\nu_\mu\to\nu_e$ oscillations[1], the most precise

$^1$ Where appropriate, CP-conjugate channels are assumed throughout the discussion.
Figure 1. Predicted flux of neutrinos and antineutrinos by species at the SK detector in the absence of oscillation effects for $\nu$-mode (left) and $\bar{\nu}$-mode (right).

measurement of $\theta_{23}$[5], and a joint analysis of these two measurements in $\nu$-mode with $6.57 \times 10^{20}$ protons-on-target (pot)[6]. An analysis of $\bar{\nu}_\mu$ disappearance in $\bar{\nu}$-mode has also been recently published with $4.01 \times 10^{20}$ pot[7]. In this paper, new results using $7.48 \times 10^{20}$ of $\nu$-mode and $7.47 \times 10^{20}$ of $\bar{\nu}$-mode data accumulated before June 2016 are reported.

2. T2K
In the T2K experiment, a $\nu_\mu/\bar{\nu}_\mu$ beam produced by the J-PARC accelerator complex is sent 295 km across Japan to the Super-Kamiokande (SK) detector [8]. The neutrinos are produced by extracting 30 GeV protons from the J-PARC Main Ring and impinging them upon a 91-cm-long graphite target, where pions and other secondary particles are produced. A set of three pulsed electromagnets (“horns”) focusses either positive pions into a helium-filled decay region to produce a beam primarily composed of $\nu_\mu$, or negative pions to produce $\bar{\nu}_\mu$. The beam axis is oriented 2.5° away from SK; this “off-axis” configuration maximizes the neutrino flux at 600 MeV, where the oscillation probability at 295 km is maximal. A suite of detectors 280 meters from the production target positioned both on-axis (INGRID) and off-axis in the direction of SK (ND280) monitors and measures neutrino interactions prior to the onset of neutrino oscillation effects.

3. Predicted Neutrino Flux
The neutrino flux from the T2K beam line is predicted by a detailed Geant3-based Monte Carlo simulation incorporating data from the NA61/SHINE experiment[9], which has provided critical measurements of the hadron production from the proton-carbon interactions[10, 11]. Other particle production measurements are used where there are no NA61/SHINE measurements. Beam monitor data and the beam direction measured by INGRID, a suite of neutrino detectors spanning the beam axis to measure its transverse profile, are incorporated into the flux prediction and its systematic errors. More details can be found in Reference [12]. Figure 1 shows the predicted flux at the SK detector in the $\nu$- and $\bar{\nu}$-modes. Continuous improvements in the tuning of the flux prediction, including new measurements from NA61/SHINE[13, 14], have reduced the typical uncertainty in the flux prediction to $\sim 10\%$.

4. Near Detector Data
The off-axis near detector (ND280) is used to select $\nu_\mu/\bar{\nu}_\mu$ charged current (CC) interactions to constrain systematic uncertainties in the neutrino flux and interaction[15] models. The
 neutrino interactions are identified in the fine-grained detectors (FGDs)[16] which are comprised of an array of scintillator bars with $1 \times 1 \text{cm}^2$ cross section arranged perpendicularly to the incident beam and alternating in $x$ and $y$ layer-by-layer to allow three-dimensional reconstruction of tracks by combining two 2-dimensional views. The upstream FGD1 detector consists of 15 modules, each with a pair of orthogonally oriented layers, while the downstream FGD2 contains seven scintillator modules alternating with six water modules. The two FGDs alternate with three time projection chambers (TPCs)[17] that provide precise tracking of charged particles to measure their sign and momentum by the curvature induced by the 0.2 T magnetic field provided by the UA1 magnet. Ionization measurements also provide valuable particle identification information. The tracking system composed of the FGDs and TPCs lies downstream of a dedicated $\pi^0$ detector (P0D), with both systems surrounded by a lead/scintillator electromagnetic calorimeter (ECAL)[18], which in turn lies within the UA1 magnet. Large scintillator planes placed within slots of the magnet yolk detect and measure the range of muons emerging from the detector and penetrating into the iron[19].

Based on the sign of the identified muon and the pions identified in the interaction with tracking and decay electrons, the observed $\nu_\mu$ CC interactions in $\nu$-mode are categorized into 3 channels: “CC0$\pi$” (no reconstructed pions), “CC1$\pi$” (1 reconstructed charged pion), and “CC other” (all other $\nu_\mu$ charged current events). In $\overline{\nu}$-mode, $\overline{\nu}_\mu$ CC interactions are categorized into “1-track” ($\mu^+$ only) and “N-track”, as are the “wrong-sign” $\nu_\mu$ CC interactions, resulting in four categories. This selection aims to constrain especially the uncertainties of the “quasi-elastic” scattering channel with no final state pions which are identified in the SK detector for the oscillation analysis, while constraining backgrounds arising from pion production channels.

A major advance in this analysis is the use of interactions in FGD2. By including both FGD1 and FGD2 samples, resulting in a total of six channels in $\nu$-mode and eight channels in $\overline{\nu}$-mode, the interaction properties on water can be effectively isolated, reducing the uncertainties related to extrapolating across differing nuclear targets in the near and far detectors.

The muon momentum and polar angle distributions from the fourteen samples are fit to constrain parameters representing the systematic uncertainties in the neutrino flux and interaction models. The muon momentum distribution from the FGD1 $\nu_\mu$ CC0$\pi$ sample in $\nu$-mode and the $\overline{\nu}_\mu$ CC 1-track in $\overline{\nu}$-mode are shown in Figure 2. The predicted distribution and interaction channel composition following the fit are shown. Generally, good agreement in these distributions is obtained by the fit. Table 1 shows the systematic error in the predicted number of events in the muon and electron neutrino samples at SK (described in the next section) tabulated by source prior to the ND280 fit, and the total uncertainty before and after the fit.
### Table 1. Systematic error in predicting the number of observed candidate events before and after the constraints from the near detector measurements.

| Uncertainty Source          | $\nu$-mode | $\bar{\nu}$-mode |
|-----------------------------|------------|------------------|
| $\nu$ flux                  | 7.6 8.9    | 7.1 8.0          |
| $\nu$ interactions          | 7.7 7.2    | 9.3 10.1         |
| final state/secondary int.  | 1.5 2.5    | 2.1 2.5          |
| SK detector                 | 3.9 2.4    | 3.3 3.1          |
| Total before ND constraint  | 12.0 11.9  | 12.5 13.7        |
| Total after ND constraint   | 5.0 5.4    | 5.2 6.2          |

The ND280 data thus significantly reduces the uncertainty in the predicted number of events from 12-14% to 5-6%.

### 5. Far Detector Data

The SK detector\cite{ref20} is a large water Cherenkov detector with 50 kton total mass. The detector is optically separated into two concentric cylindrical volumes which define an inner region where neutrino interactions are identified and an outer volume that serves as a veto. The inner volume is viewed by 11,129 20” photomultiplier tubes to detect and image Cherenkov radiation emitted by particles produced by neutrino interaction occurring in this volume. Typically, events reconstructed at least 2 meters from the boundary of this region are used, defining a 22.5 kton fiducial mass. The outer volume is viewed by 1885 8” PMTs with wavelength shifter plates to tag particles entering the inner volume from outside or those exiting from the inner volume.

The delivery of beam from J-PARC triggers the data acquisition at SK using a GPS-synchronized timing system; data corresponding to each and every instance of beam delivery at J-PARC is recorded. Candidate neutrino interactions are required to be fully contained with minimum veto activity, a vertex reconstructed at least two meters from the edge of the inner volume, and have a single identified Cherenkov ring in order to select “quasi-elastic” scattering channels where the outgoing lepton is the only particle producing a Cherenkov ring. For the “1R$\mu$” events that define the $\nu_\mu/\bar{\nu}_\mu$ sample, the ring pattern is required to be consistent with a muon with momentum greater than 200 MeV/c, and up to one decay electron arising ($\pi \rightarrow \mu \rightarrow e$) decay chain is allowed. With this selection, 135 1R$\mu$ events are identified in the $\nu$-mode data and 66 in $\bar{\nu}$-mode data. For the “1Re” candidates that define the $\nu_e/\bar{\nu}_e$ sample, the ring pattern is required to be consistent with an electron with energy greater than 100 MeV with no decay electrons that may signal the presence of pions in the event. The neutrino energy reconstructed with the lepton kinematics assuming a two-body interaction ($E_\nu$) is required to be less than 1250 MeV. Using a dedicated two-ring reconstruction algorithm, requirements on the likelihoods returned by a single and two-ring fit and the invariant mass of the rings in the two-ring fit further suppress background from $\pi^0$ production. With this selection, 32 and 4 1Re events are identified in $\nu$-mode and $\bar{\nu}$-mode, respectively. The reconstructed energy distributions of the observed candidates is shown in Figure 3.

### 6. Oscillation Results

The extraction of oscillation results follows from predicting the number and kinematic distribution of events in the four samples at SK (1Re/1R$\mu$ in $\nu/\bar{\nu}$-mode) as a function of the oscillation parameters, and forming a likelihood function including nuisance terms. Several methods are used; some use the output covariance from the near detector fit to describe the
Figure 3. Left: reconstructed energy distributions for $\nu_\mu$ (top) and $\nu_e$ (bottom) candidates observed in $\nu$-mode. Right: corresponding distributions for $\bar{\nu}$-mode.

Table 2. Number of expected electron candidates in SK for the $\nu$- and $\bar{\nu}$-mode data for various values of $\delta_{CP}$ and the mass ordering, compared to the observation. The assumed value of other parameters are: $\sin^2 \theta_{13} = 0.0217$, $\sin^2 \theta_{23} = 0.528$, $|\Delta m^2_{32}| = 2.509 \times 10^{-3} \text{eV}^2/c^4$, $\sin^2 \theta_{12} = 0.846$, and $\Delta m^2_{21} = 7.53 \times 10^{-5} \text{eV}^2/c^4$. constraints of uncertainties, while others fit the near and far detector simultaneously. Both fitting and Markov Chain Monte Carlo (MCMC) techniques are used to produce results presented in frequentist and Bayesian formalisms. In analyzing the 1Re samples, some use the reconstructed neutrino energy ($E_\nu$) while others use $E_\nu$ or the outgoing electron momentum in combination with its polar angle $\theta_e$; all analyses use $E_\nu$ in the 1R$\mu$ samples.

The results shown here are produced from a frequentist analysis employing the covariance from the near detector fit and fitting the $E_\nu$ distribution in the 1R$\mu$ samples and $E_\nu/\theta_e$ in the 1Re samples, and a Bayesian analysis simultaneously analyzing the near and far detector data in a MCMC using $E_\nu$ for both 1R$\mu$ and 1Re samples.

The observed 1Re candidates in each running mode are compared to the expected number for several combinations of mass hierarchy and values of $\delta_{CP}$ in Table 2. The left plot on
Figure 4. Left: 90% confidence regions in $\delta_{CP}$ vs. $\sin^2 \theta_{13}$ from the joint analysis without $\theta_{13}$ constrained by reactor measurements (yellow band). Right: Allowed regions in $\Delta m^2_{32}$ vs. $\sin^2 \theta_{23}$ from the joint analysis (black) compared to other recent measurements.

Figure 5. Left: 90% confidence level intervals in $\delta_{CP}$. Right: Posterior probability density from the Bayesian analysis with prior densities uniform in $\delta_{CP}$ (blue) and $\sin \delta_{CP}$ (red).

Figure 4 shows the favored regions in $\sin^2 \theta_{13}$ and $\delta_{CP}$ from the frequentist analysis, where the relatively large $\nu_{\mu} \rightarrow \nu_e$ and small $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$ lead to a preference for $\delta_{CP} \sim -\pi/2$ while $\sin^2 \theta_{13}$ is consistent with values obtained from reactor experiments. The right plot in Figure 4 show the allowed regions in $\Delta m^2_{32}$ and $\sin^2 \theta_{23}$ assuming normal hierarchy, where the T2K data (black) is compared with other recent results[21, 22, 23]. The large $\nu_{\mu}/\bar{\nu}_{\mu}$ disappearance observed in the T2K data continues to favor maximal mixing/disappearance with $\sin^2 \theta_{23} = [0.464, 0.578]$ at 68% confidence level in the normal hierarchy.

In left plot of Figure 5, the $-2\Delta \log L$ as a function of $\delta_{CP}$ with the constraint $\sin^2 2\theta_{13} = 0.085 \pm 0.005[24]$ from the frequentist analysis is shown. The plot shows the 90% confidence level Feldman-Cousins critical values, resulting in interval of $[-3.13, -0.39]$ in normal hierarchy and $[-2.09, -0.74]$ in inverted hierarchy. The right plot in Figure 5 shows the posterior probability density in $\sin \delta_{CP}$ from the Bayesian MCMC analysis, motivated by the linear dependence of the CP asymmetry on this parameter. Two assumptions of the prior probability density (uniform in $\delta_{CP}$ and flat in $\sin \delta_{CP}$) are used. Conclusions such as whether $\sin \delta_{CP} = 0$ lies within the 90% credible interval dependent on this choice; additional data is needed for more definitive conclusions that do not depend on the prior choice. Other measured parameters are not appreciably impacted by the assumed prior probability distributions. By marginalizing over other parameters, a 71.9% posterior probability for normal hierarchy and 68.1% probability
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7. Prospects
The beam power delivered to T2K has been steadily increasing, with nearly a twofold increase to 420 kW between the end of 2014 and June 2016. The first stage of a major upgrade to the J-PARC Main Ring power supplies to double the repetition rate of the accelerator has been approved and is expected to be completed in the 2018 summer maintenance period. With further tuning and mitigation of beam losses, beam power up to 1.3 MW is projected. While irreplaceable components are already designed for multi-MW operation, some components will need to be upgraded in order to handle the higher heat load and radioactivity from the higher power operation.

With the prospects for a large increase in beam power, an extension of the T2K running from the currently approved $7.48 \times 10^{21}$ pot (expected to be achieved around 2021) to $20 \times 10^{21}$ pot by 2026 is under consideration[25]. The primary goal of this extension (“T2K-II”) is to achieve $> 3\sigma$ evidence for CP violation in $\nu_{\mu}/\bar{\nu}_{\mu}$ disappearance and $\nu_{\mu}(\bar{\nu}_{\mu}) \rightarrow \nu_{e}(\bar{\nu}_{e})$ if the parameters are favorable (e.g. $\delta_{CP} \sim \pm \pi/2$). Figure 6 shows the expected significance of excluding CP conservation as a function of delivered pot for three different values of $\sin^{2}\theta_{23}$ and $\delta_{CP} = -\pi/2$. The analysis assumes that a 50% increase in effective statistics/POT can be achieved by increasing the horn current to increase the flux by $\sim 10\%$ and using more events detected in SK by expanding the fiducial volume and including single pion production channels currently not used in the analysis ($\sim 40\%$). The impact of the current systematic errors on the sensitivity is also shown; improved flux modelling and a near detector upgrade are under consideration to this end. The right plot demonstrates the precision on $\theta_{23}$, where the octant of $\theta_{23}$ can be resolved if it lies at the edge of the currently allowed values ($\sin^{2}\theta_{23} = 0.43$ in this example).

8. Conclusion
Results from the first fully joint analysis across all four neutrino oscillation modes observed at T2K ($\nu_{\mu}/\bar{\nu}_{\mu}$ disappearance and $\nu_{\mu}(\bar{\nu}_{\mu}) \rightarrow \nu_{e}(\bar{\nu}_{e})$ appearance) with $7.48(7.47) \times 10^{20}$ pot in $\nu(\bar{\nu})$-mode are presented. The data prefer maximal mixing in $\theta_{23}$, while the relatively large $\nu_{\mu} \rightarrow \nu_{e}$ signal and small $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ signal favor $\delta_{CP} \sim -\pi/2$ with normal hierarchy, which maximizes the former and minimizes the latter. Thanks to rapid increases in beam power and projected
upgrades, beam power should continue to rise in the near future. An extension of the T2K program to $20 \times 10^{20}$ pot has been proposed with the primary goal of observing CP violating effects with $\sim 3\sigma$ significance by 2026 if parameter values are favourable. This will require a program of beamline component upgrades to handle 1.3 MW beam and analysis improvements to improve the effective statistics/pot and reduce systematic uncertainties.

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References
[1] K. Abe et al. Phys. Rev. Lett., vol. 112, p. 061802, 2014.
[2] F. P. An et al. Phys. Rev. Lett., vol. 108, p. 171803, 2012.
[3] J. K. Ahn et al. Phys. Rev. Lett., vol. 108, p. 191802, 2012.
[4] Y. Abe et al. Phys. Rev. Lett., vol. 108, p. 131801, 2012.
[5] K. Abe et al. Phys. Rev. Lett., vol. 112, no. 18, p. 181801, 2014.
[6] K. Abe et al. Phys. Rev., vol. D91, no. 7, p. 072010, 2015.
[7] K. Abe et al. Phys. Rev. Lett., vol. 116, no. 18, p. 181801, 2016.
[8] K. Abe et al. Nucl. Instrum. Meth., vol. A659, pp. 106–135, 2011.
[9] N. Abgrall et al.
[10] N. Abgrall et al.
[11] N. Abgrall et al.
[12] K. Abe et al. Phys. Rev., vol. D88, no. 3, p. 032002, 2013.
[13] N. Abgrall et al.
[14] L. Zambelli in these proceedings.
[15] Y. Hayato Acta Phys. Polon., vol. B40, pp. 2477–2489, 2009.
[16] P. A. Amaudruz et al. Nucl. Instrum. Meth., vol. A696, pp. 1–31, 2012.
[17] N. Abgrall et al. Nucl. Instrum. Meth., vol. A637, pp. 25–46, 2011.
[18] D. Allan et al. JINST, vol. 8, p. P10019, 2013.
[19] T. Yano Nucl. Phys. Proc. Suppl., vol. 229-232, p. 454, 2012.
[20] Y. Fukuda et al. Nucl. Instrum. Meth., vol. A501, pp. 418–462, 2003.
[21] S. Moriyama et al. in these proceedings.
[22] C. Backhouse et al. in these proceedings.
[23] P. Vahle et al. in these proceedings.
[24] K. A. Olive et al., “Review of Particle Physics,” Chin. Phys., vol. C38, p. 090001, 2014.
[25] K. Abe et al. hep-ex:1607.08004, 2016.