Latest results from T2K

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Thank to the stable operation at intense beam power, T2K data with neutrino-mode operation almost doubled in one year. A number of critical improvements to the oscillation analysis have been introduced and resulted in an unprecedented level of sensitivity in searching for CP violation in the neutrino sector. T2K firstly reports that the CP-conserving values of parameter δ_{CP} in the PMNS mixing matrix fall out of its 2σ C.L. measured range.

1 Introduction to Neutrino Oscillations

Neutrino oscillation phenomenon, in which neutrinos can transform from one flavour to another, indicates that neutrinos have mass and their flavor definitive eigenstates are different from their mass definitive eigenstates. This phenomenon is now well-established and so far is the only experimental evidence for the incompleteness of the Standard Model of elementary particles. Except for some known anomalies, the up-to-date neutrino data from both natural and artificial sources are well described by the 3×3 leptonic mixing matrix, so-called the PMNS (Pontecorvo, Maki, Nakagawa and Sakata) matrix [1]. This unitary matrix, to connect the flavor definitive eigenstates, $(\nu_e, \nu_\mu, \nu_\tau)$, with mass definitive eigenstates (ν_1, ν_2, ν_3), is parameterized with three mixing angles $(\theta_{12}, \theta_{13}, \theta_{23})$ and one single Dirac phase δ_{CP}[a], which represents the potential source of CP violation in the lepton sector, as shown in Eq. 1,

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{1}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. Along with the above parameters, the probability for a α-flavour neutrino to oscillate into β-flavour, $P_{(\nu_\alpha \to \nu_\beta)}$, are driven by its energy, the distance it has travelled, and the mass-squared differences $\Delta m^2_{ij} = m^2_i - m^2_j$ where i, j are mass eigenstate index. Remarkable efforts from various neutrino oscillation experiments for more than fifty years since its first experimental observation, the oscillation parameters, including three mixing angles and two mass-squared differences, are measured with high precision (within 5% uncertainty). However some crucial pieces are still missing to complete the neutrino oscillation picture described by the PMNS matrix, including the CP-violating phase δ_{CP} value, the mass hierarchy (sign of Δm^2_{32}) and whether or not θ_{23} is exactly 45°. Above all, the unitarity of the neutrino mixing matrix is still questionable.

2 The T2K Experiment

T2K (Tokai-to-Kamioka) is a long-baseline accelerator-based neutrino experiment placed in Japan. Details are described elsewhere [2]. Schematic view of T2K is shown in Fig. 1. The

[a] If neutrino is Majorana particle, two additional phases are included but should not take any impact on neutrino oscillation measurements.

original goal of T2K is to discover the appearance of electron neutrinos from muon neutrinos, which had been completed in 2013 [3]. T2K physic potential has been re-evaluated and the CP violation search in the lepton sector is put at the center of T2K targets since then [4]. In addition, T2K has a rich program of non-standard physics and neutrino interactions which are not covered in these proceedings.

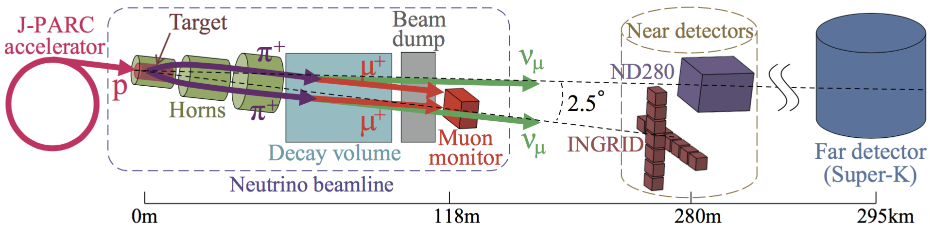

Figure 1 – Schematic view of T2K experiment

To collect data, T2K takes advantages of using one of the most intense and nearly pure ν_μ ($\overline{\nu}_\mu$) beam from J-PARC. The 30 GeV proton beam with intensity of 2.5×10^{14} protons per pulse (repetition cycle of 2.48 s) is extracted and bent 80.7° toward the T2K far detector, Super-K, before striking onto a 90 cm-long graphite-cored target to produce charged pions and kaons. These mesons are focused or defocused by a system of three magnetic horns. The focused charge is defined by the horn current polarity, producing either a nearly pure ν_μ or $\overline{\nu}_\mu$ from the focused secondaries decaying in the 96 m-long decay volume. Almost all hadrons except high energetic (>5 GeV) muons, which are monitored by so-called MUMON detector, are absorbed by a beam dump made of 3.2 m-thick graphite and iron places. Several monitors are placed along the beamline to track the beam, monitor its (in)stability, measure number of protons passed through and to project its center position and direction right at the target. There is a near detector complex placed 280 m from the neutrino production target, consisting of so-called INGRID and ND280 which are placed on-axis and 2.5° off-axis with the neutrino beam respectively. While the former is used to monitor the (in)stability of neutrino production and measure the neutrino profile around the beam center, the latter aims for characterizing the unoscillated neutrino beam and understanding neutrino-nucleon (nucleus) interactions. The central part of ND280 is the tracker which is composed of two fine-grained detectors (FGD1, 2) and three time projection chambers (TPCs). Both FGDs are used as the targets of neutrino interactions with a total target mass of 1.1 tons each. While FGD1 is made solely of scintillator bars, FGD2 is scintillator-water interleaved. The most upstream of tracker places a π_0 detector (P0D) which consists of water bags placed between scintillator planes and brass or lead sheets. The P0D is optimized for tagging π_0, mainly coming from the neutral current process which can mimic the ν_e signal observed in T2K far detector. Both tracker and P0D are surrounded by Electromagnetic calorimeters (ECals), which are designed to obtain high energy resolution and identification of neutral particles and electron/positron showers. Also ECals provide information whether particles are escaping or entering the tracker system. All sub-detectors are placed within a 0.2 T magnetic field produced by the former UA1/NOMAD dipole magnet.

Excellent capability of Super-K detector in distinguishing muon and electron, consequently tagging $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$, allows T2K to carry out two kinds of measurements: disappearance of $\overset{(-)}{\nu}_\mu$ and appearance of $\overset{(-)}{\nu}_e$ from the correspondingly genuine $\overset{(-)}{\nu}_\mu$ beam. Fig. 2 shows these oscillation probabilities with T2K flux overlaid. It shows that the narrow flux peak is right at the dip of the $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$ and the peak of $\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_e$. This indeeds is resulted from the optimal design in which the Super-K is at an angular offset of 2.5° from the average beam direction.

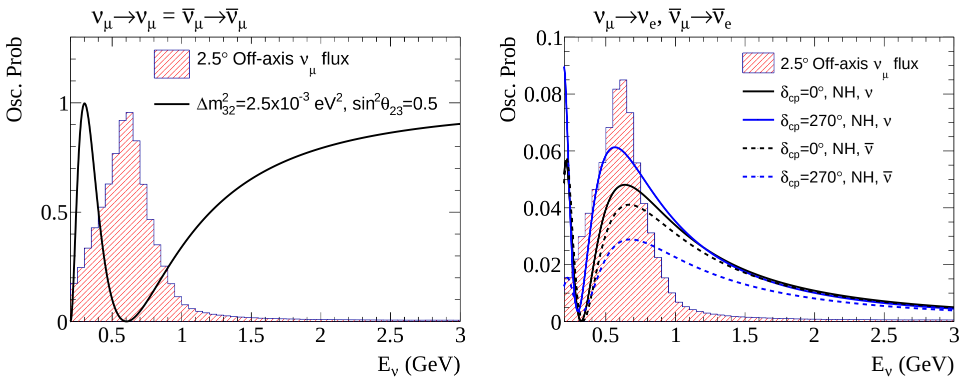

Figure 2 – Oscillation probability of $\nu_\mu \to \nu_\mu$ (left) and $\nu_e \to \nu_e$ (right) with their antineutrino counterparts.

While the disappearance of $\overset{(-)}{\nu}_\mu$ is essential to extract $\Delta m^2_{32}, \theta_{23}$ parameters, the appearance of $\overset{(-)}{\nu}_e$ is sensitive to the θ_{13} and δ_{CP} parameters. The CP violation if happen can manifest itself into the difference between the $\nu_\alpha \to \nu_\beta$ and its CP conjugate $\overline{\nu}_\alpha \to \overline{\nu}_\beta$. In T2K, a complete three-flavor oscillation formulas including the matter effect with the earth density $\rho = 2.6$ g/cm^3 is deployed. In practical, with conventional $\nu_\mu(\overline{\nu}_\mu)$ beam, the CP violation phase can be measured by comparing $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ probabilities. In approximation at the maximum oscillation length of Δm^2_{31}, this CP asymmetry is expressed as:

$$A_{CP}\left(\frac{\Delta m^2_{31}}{4E}L = \frac{\pi}{2}\right) = \frac{P_{\nu_\mu \to \nu_e} - P_{\overline{\nu}_\mu \to \overline{\nu}_e}}{P_{\nu_\mu \to \nu_e} + P_{\overline{\nu}_\mu \to \overline{\nu}_e}} \approx -0.27 \sin\delta_{CP} \pm \frac{L[km]}{2800}$$

where $+$ or $-$ sign depends whether mass hierarchy is normal or inverted respectively. For T2K experiment, with a relatively short baseline of 295 km, the mass hierarchy effect is relatively small, about 10%; while the CP effect can be up to 27% when δ_{CP} is around $\pi/2$.

T2K started taking data from January 2010 and up to December 2017, a total 2.65×10^{21} Protons-on-target (POT), consisting of 1.51×10^{21} POT (57.14%) in neutrino-mode operation and 1.14×10^{21} POT (42.86% in antineutrino-mode operation), have been delivered to T2K detectors. This exposure is equal to 34% of fully approved T2K data set. At the time of writing these proceedings, T2K is running in anti-neutrino mode with a stable beam power of 485 kW and a total exposure excesses 3×10^{21} POT.

3 T2K Oscillation Analysis

As in previous T2K results [4], neutrino oscillation parameters are estimated by comparing model predictions with observations at both T2K near and far detectors. The overall T2K oscillation analysis strategy is briefly described, following by crucial updates implemented for this reported result. The (anti-)neutrino fluxes are initially inferred by the combination of hadron production models, the external thin-target hadron-production data, the actual proton beam conditions, the horn currents, and the neutrino beam-axis direction measurements. At the peak energy ($\sim$ 600 MeV), the flux uncertainty is approximately 9%, dominated by the uncertainty in hadron production data. However, its impact on estimating the neutrino oscillation parameters, given that the T2K near detector and far detector are observing data from nearly the same flux, is largely suppressed when the T2K near detector data are included. In fact, due to the convolution of both flux and neutrino interaction models on the near detector data, the data samples from ND280 are used in the manner that the parameters modeling the flux and interaction models are constrained simultaneously. At last, the Super-K data along with its detector model are added in to the framework of oscillation parameter extraction.

Doubling the neutrino data set is the main driver for improving sensitivities on oscillation parameters reported in these proceedings. In addition to this, a number of critical improvements to the oscillation analysis have been introduced. Charged-current quasi-elastic (CCQE) interactions, dominating interactions at T2K energy range, which are simulated with primary neutrino-nucleon cross section calculated from the Llewellyn-Smith model and the nuclear medium described by the Smith-Moniz Relativistic Fermi Gas model, includes the effect of long-range correlations in nucleus. Furthermore, a model for multi-nucleon scattering which can mimic the CCQE-like signals[b] observed in T2K far detector when the knocked-out protons are below the water Cherenkov's threshold (about 1 GeV), are added in the simulation package. The contribution for this scattering to the CCQE-like sample is about 10-20% depending on the model. Processes of single incoherent pion production in the final state via the resonance excitation, originally described by the Rein-Sehgal model, are revived with the modified form factor and tuned to match with bubble chamber and most recent neutrino-nucleus data. For the single coherent pion production, a tuned model of Rein-Sehgal to match with the recent MINERvA data is deployed.

Another very important improvement in this analysis comes from the new reconstruction algorithm, called fiTQun, with complete charge and time information. This improvement allows to extend detector fiducial volume while keeping the selection performance at the same level to the previous reconstruction. This leads to 20% effective statistic increase in selecting e-like events. T2K also adds a brand-new signal sample for extracting the oscillation parameters, charged-current 1π e-like sample which increases 10% statistics for neutrino e-like sample. In total, there are five far detector data samples used for extracting oscillation parameters, consisting of two samples of single-ring μ-like events in both ν-mode and $\overline{\nu}$-mode; two samples of single-ring e-like events in both ν-mode and $\overline{\nu}$-mode; and the fifth one is single-ring e-like events with presence of one decay electron in ν-mode. Except the fifth which mainly originates from the charged current single pion production, others are dominated by the CCQE interactions.

Table 1: Uncertainties on the number of predicted events in the Super-K samples from different systematic sources.

Uncertainty source	$\delta_{N_{SK}}/N_{SK}$ (%)					
	1-Ring μ		1-Ring e			
	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	ν mode $1\pi^+$	$\nu/\bar{\nu}$
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI & SI & PN	2.20	1.98	3.01	2.31	11.43	1.57
ND280 constrained flux & cross-section	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.00	0.00	2.63	1.46	2.62	3.03
NC 1γ	0.00	0.00	1.08	2.59	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.98	0.18
Total Error	4.40	3.76	6.10	6.51	20.94	4.77

About the usage of ND280 data to constrain the flux and neutrino interaction model, this analysis incorporates the FGD2 data to include interactions on H_2O target. In the previous report in this conference series, only data from FGD1 with carbon target was used. In total, 14 near-detector data samples are used to further constrain the flux and neutrino interaction models, including 6 samples for ν-mode (3 samples per FGD categorized according to number of observed pions (0, 1 and more than 1) in presence of μ^- track) and 8 samples for $\overline{\nu}$-mode (4 samples per FGD divided based on a combination of non-existed pion or existed pion and the presence of μ^+ track or μ^- track). To estimate uncertainties on the far-detector events, summarized in Table 1, the near detector systematic and flux parameters are marginalized. A joint fit based on the likelihood maximum approach to five far detector data samples is performed in order to measure the interested oscillation parameters $\sin^2\theta_{23}$, Δm^2_{32}, $\sin^2\theta_{13}$ and δ_{CP}. T2K

[b]defined as events with lepton but no pion detected.

experiment is not sensitive to the so-called solar neutrino oscillation parameters, Δm^2_{21} and θ_{12}. Priors for for these parameters are taken from PDG, particularly $\sin^2 2\theta_{12} = 0.846 \pm 0.021$ and $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}(\mathrm{eV}^2/\mathrm{c}^4)$. Flat priors are used for $\sin^2\theta_{23}$, $|\Delta m^2_{32}|$ and δ_{CP}. When the reactor measurement is taken into account, a Gaussian prior of $\sin^2\theta_{13} = 0.0857 \pm 0.0046$ [1] is used.

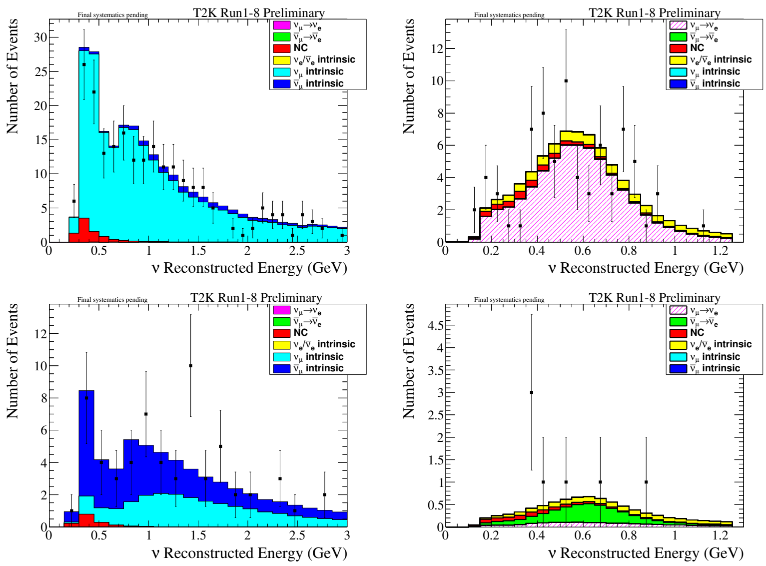

Figure 3 – T2K far-detector data sample distributions for ν-mode at top plots (left to right: CCQE-like ν_μ, CCQE-like ν_e and CC1π^+-like ν_e) and $\overline{\nu}$-mode at bottom plots (left to right: CCQE-like $\overline{\nu}_\mu$ and CCQE-like $\overline{\nu}_e$).

Table 2: Observed and predicted number of events in the T2K far-detector data samples. Normal mass hierarchy is assumed.

Sample	Prediction at true δ_{CP}			Data
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	
1Ring e-like CCQE-enriched, ν-mode	73.5	61.5	49.9	74
1Ring e-like CC1π^+-enriched, ν-mode	6.9	6.0	4.9	15
1Ring e-like CCQE-enriched, $\overline{\nu}$-mode	7.9	9.0	10.0	7
1Ring μ-like CCQE-enriched, ν-mode	267.8	247.4	267.7	240
1Ring μ-like CCQE-enriched, $\overline{\nu}$-mode	63.1	62.9	63.1	68

4 T2K Latest Results and Future Prospects on Neutrino Oscillations

The results presented below are based on a total exposure of 2.23×10^{21} POT, consisting of 1.47×10^{21} POT in ν-mode and 0.76×10^{21} POT in $\overline{\nu}$-mode. Reconstructed energy distributions of five far-detector data samples with oscillation parameters at best fit values are shown in Fig. 3. Number of observed events in T2K far detector in comparison to the MC prediction with various values of δ_{CP} is shown in Table 3. Fig. 4 shows allowed region on Δm^2_{32} vs. $\sin^2\theta_{23}$ and favored region on $\sin^2\theta_{13}$ vs. δ_{CP}. T2K data continue to favor the maximal disappearance. By marginalizing the likelihood over the nuisance parameters and other oscillation parameters, the resulting posterior probabilities show a moderate preference to normal mass hierarchy (86.8%) and $\theta_{23} > 45^\circ$ (78.1%). Parameter $\sin^2\theta_{13} = 0.0277^{+0.0054}_{-0.0047}$, measured by T2K data, is consistent with reactor measurements. Fig. 5 shows 2σ C.L. interval for the measured $\Delta\chi^2$ distribution as a function of δ_{CP} which is obtained by integrating over other parameters and taking the reactor measurement into account. The best fitted values of δ_{CP} are closed to $-\pi/2$ for both cases of mass hierarchy. The resulting intervals at 2σ C.L. are [-2.91,-0.60] for normal mass hierarchy

($\Delta m^2_{32} > 0$) and [-1.54, -1.19] for inverted mass hierarchy ($\Delta m^2_{32} < 0$). The CP conserving values (0 and π) fall outside of these intervals.

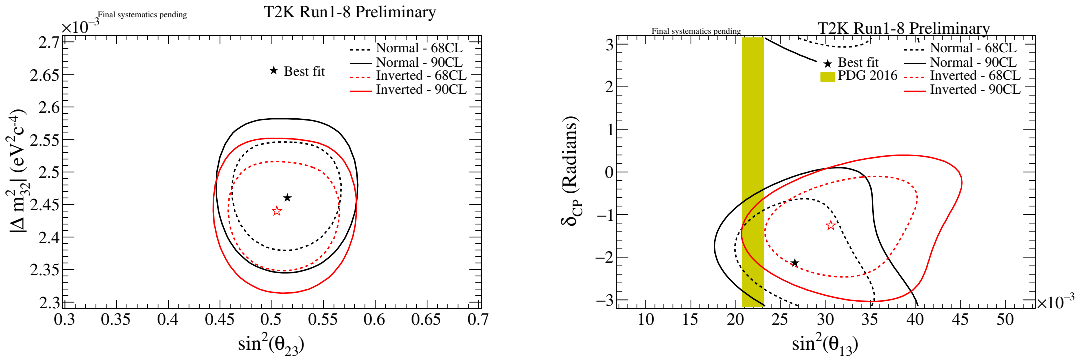

Figure 4 – Left: allowed region for Δm^2_{32} vs. $\sin^2\theta_{23}$. Right: favored region on $\sin^2\theta_{13}$ vs. δ_{CP} overlaid with reactor measurement (yellow band).

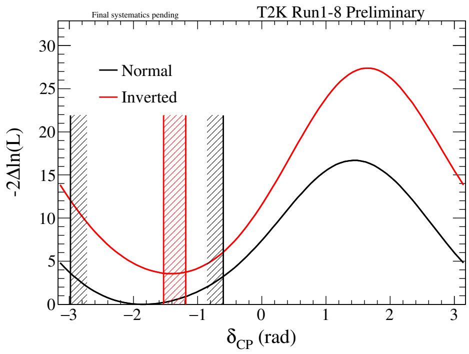

Figure 5 – 2σ confidence interval for the measured $\Delta\chi^2$ distribution. θ_{13} constrained by reactor measurements is used.

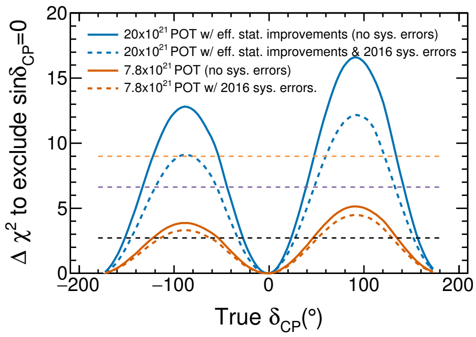

Figure 6 – Sensitivity of T2K-II as a function of true δ_{CP} assuming that the mass hierarchy is known.

Approved T2K statistics, 7.8×10^{21} POT, can be accumulated by 2021. J-PARC aims for upgrade and operations at and higher than 1MW from 2021. Hyper-Kamiokande, the next generation of neutrino experiments in Japan, is expected to start operation around 2026. T2K-II, extended operation until 2026, will collect 20×10^{21} POT. Such amount of data along with neutrino beamline upgrade and analysis improvement make T2K(-II) physics potentials even more interesting. In particular, 3σ or higher significance sensitivity to CP violation can be achieved if δ_{CP} close to $\pi/2$, as shown in Fig. 6. The precision of Δm^2_{32} can be 1% while that on θ_{23} is about 0.5°-1.7° depending on the true value. For more detail, refer to physics potential of T2K-II[5]. Also it is shown in Fig. 6 that the impact on δ_{CP} measurement from systematic error is significant and thus motivates for the ND280 upgrade which is now happening actively.

References

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