T2K LATEST RESULTS*

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T2K is a long baseline neutrino experiment producing a beam of neutrinos at the Japan Particle Accelerator Research Centre (J-PARC) and measuring their oscillation by comparing the measured neutrino spectrum at a near detector complex and at the water Cherenkov detector Super Kamiokande (Super-K), located 295 km away. In recent years, significant updates were applied to the T2K oscillation analysis, including: improved flux predictions, updated neutrino interaction modelling, and new selection samples in both near detector and Super-K. Current oscillation analysis results are presented with CP conservation excluded at the 90% confidence level. Additionally, an overview of T2K cross-section studies is discussed.

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1. Introduction: neutrino oscillations

Neutrino flavour-mass mixing is described by the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

$$|\nu_l\rangle = \sum_{i=1}^{3} U^*_{li}\,|\nu_i\rangle\ , \tag{1}$$

where index l labels flavour states and i labels mass states. The usual parametrisation includes three mixing angles (θ_{12}, θ_{13}, θ_{23}) and CP-violation phase δ_{CP}

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\mathrm{e}^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}\mathrm{e}^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} ,$$

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where s_{ij} is $\sin(\theta_{ij})$ and c_{ij} is $\cos(\theta_{ij})$. Two Majorana phases could also be included, but they do not play a role in neutrino oscillations. Oscillation probabilities are however sensitive to differences in squared neutrino masses $\Delta m_{ij}^2 = m_i^2 - m_j^2$. One of the unanswered questions in neutrino physics is the problem of mass hierarchy — whether the third mass state is the heaviest ($m_3 > m_2 > m_1$, Normal Hierarchy) or the lightest of all three ($m_2 > m_1 > m_3$, Inverted Hierarchy). Different experiments are sensitive to different oscillation parameters as they probe different energy scales and oscillation modes. T2K is sensitive to $\Delta m_{32}^2, \theta_{23}, \theta_{13}$ and $\delta_{\rm CP}$.

The probability that a neutrino produced in ν_α flavour state and propagating in vacuum will interact as a neutrino in ν_β state is expressed as [1]

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) \; = \; & \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right) \sin^2\left(\Delta m_{ij}^2 \frac{L}{4E}\right) \\ & \pm 2\sum_{i>j} \mathrm{Im}\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right) \sin\left(\Delta m_{ij}^2 \frac{L}{4E}\right) , \end{aligned} \tag{2}$$

where L is neutrino propagation distance and E is neutrino energy. The $\pm$ sign distinguishes neutrinos and antineutrinos.

The $\delta_{\rm CP}$ value may be studied by comparing the electron neutrino and antineutrino appearance probabilities. The difference of the probabilities $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$ is proportional to $\sin(\delta_{\rm CP})$. CP symmetry is conserved in the case of $\delta_{\rm CP} = 0$ or π, while maximal CP violation corresponds to $\delta_{\rm CP} = \pm\frac{\pi}{2}$. Matter effects are included in T2K oscillation analyses, however, their impact is small compared to maximal CP violation.

2. Design of T2K experiment

T2K [2] is a long baseline neutrino experiment in Japan with a neutrino beam produced in the J-PARC facility. Two near detectors are used to study neutrino interactions 280 meters from the beam source, where the oscillation probability is negligible. Super-Kamiokande is used as the far detector 295 km away, where the distance-to-energy ratio corresponds to maximal electron neutrino appearance probability.

2.1. The neutrino beam

The schematic drawing of neutrino beam production is presented in Fig. 1. This procedure starts with a 30 GeV proton beam, which is directed onto a graphite target. In the proton interactions with a target, secondary particles are produced, mostly pions and kaons. Those secondary particles propagate in the magnetic field produced by 3 magnetic horns. The magnetic field is optimized to focus pions of a chosen charge in the decay volume. Then, in the decay volume, pions decay into muons and neutrinos. The direction of the current powering the magnets may be reversed and thus setup may work in two modes: neutrino mode when mostly positive pions are focused and antineutrino mode when mostly negative pions are focused.

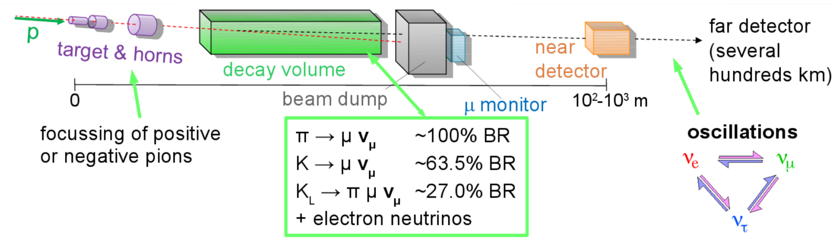

Fig. 1. Neutrino beam production. By focussing positive or negative pions, one can obtain a beam in neutrino or antineutrino mode.

T2K is historically the first off-axis neutrino experiment. The far detector and one of the near detectors are measuring neutrinos emitted at an angle of 2.5° from the proton beam axis. The energy spectrum of such neutrinos is much narrower than for neutrinos emitted parallel to the proton beam. The

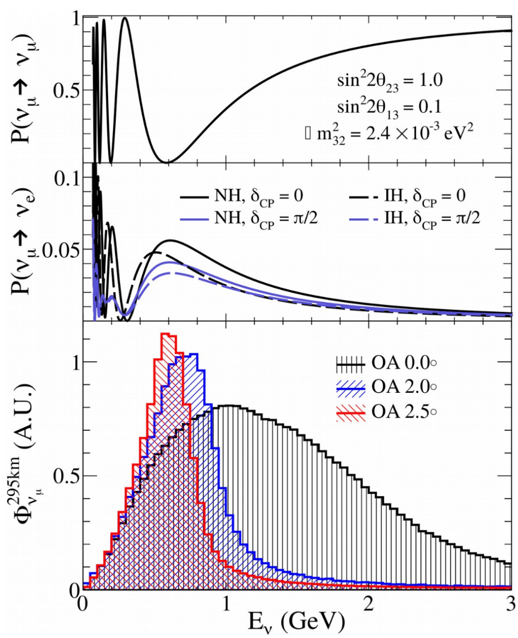

Fig. 2. Top plot: ν_μ disappearance probability. Middle plot: ν_e appearance probability (different mass hierarchy and δ_{CP} scenarios). Bottom plot: neutrino energy spectrum at the T2K far detector.

narrow energy spectrum enhances sensitivity to the oscillation effect at the far detector as presented in Fig. 2. Additionally, this strategy decreases the contribution of non-quasielastic neutrino interactions. A change of the off-axis angle by one milliradian corresponds to relative neutrino energy peak change $\Delta E/E$ by about 2%.

2.2. On-axis near detector INGRID

The on-axis near detector INGRID is a cross-shaped detector composed of 14 iron/scintillator modules (see Fig. 3). The nominal neutrino beam axis goes through the central part of INGRID. The detector monitors precisely the direction, profile, and intensity of the neutrino beam. Additionally, in the past, the fully scintillator Proton Module was installed upstream of the central INGRID module for the cross-section measurements.

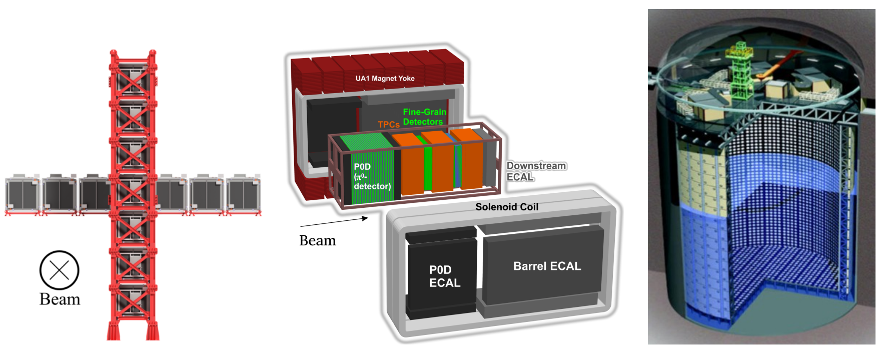

Fig. 3. Detectors relevant for T2K oscillation analysis (not to scale). Left: on-axis near detector INGRID. The nominal neutrino beam axis goes through the central part of INGRID, in the inward direction in this graphic. Middle: off-axis near detector ND280 (exploded view). Right: far detector Super-Kamiokande.

2.3. Off-axis near detector ND280

The magnetized off-axis near detector ND280 is used to constrain the off-axis flux and neutrino interaction models. Charged current interactions are studied in the tracker, which is the central part of the detector (Fig. 3) and is made of two scintillator fine-grained detectors (FGDs) and three gaseous time projection chambers (TPCs). FGDs serve as targets for neutrino interactions and provide good vertex and track reconstruction resolution. TPCs provide even better tracking resolution, which is vital for momentum measurement that uses track curvature information. In addition, TPCs allow for particle identification based on energy loss $\mathrm{d}E/\mathrm{d}x$ measurement.

2.4. ND280 analysis samples

For the oscillation analysis, multiple ND280 samples are used. The classification is based on three different signatures: CC0π, with reconstructed muon track and no pion tracks, CC1π with reconstructed muon track, single reconstructed pion of the opposite charge, and no other pions (such a signature is usually related to resonant interaction); and CC-other sample with reconstructed muon track and any other combination of particles multiplicity. There are separate samples for neutrino and antineutrino beam modes as well as for interaction vertices reconstructed in FGD1 or FGD2.

Starting from the 2022 oscillation analysis, the selection for the neutrino beam mode takes into account additional information on the multiplicity of reconstructed proton tracks and photon signatures. Events with reconstructed μ^- can be thus assigned to one of five samples: CC0π-0p-0γ, CC0π-Np-0γ, CC1π-0γ, CC-other-0γ, or CC-photon.

2.5. Far detector Super-Kamiokande

The T2K far detector Super-Kamiokande is a 50 kt water Cherenkov detector, equipped with about eleven thousand photomultiplier tubes measuring Cherenkov light inside the tank (Fig. 3). Cherenkov light is used to detect charged particles produced in neutrino-charged current interactions. Cherenkov light appears only when the particle propagates faster than the speed of light in medium, and thus for the T2K energy scale, it is usually visible for electrons, muons, and pions, but not for protons. Emitted light forms a cone-like wavefront which is measured on the Super-K wall as a ring signature. The features of such rings are quite different for muons and electrons, which makes it possible to distinguish ν_μ and ν_e interactions.

2.6. Far detector analysis samples

The oscillation analysis in the far detector is based on data samples with a single ring, which are summarised in Table 1. Events with a single ring are usually associated with the CC quasielastic interaction. They are

Table 1. Summary of single-ring Super-K samples used in the oscillation analysis. ME — Michel electron.

Beam mode	e-like ring	μ-like ring
Neutrino	1 Ring + 0 ME	1 Ring + 0 or 1 ME
	1 Ring + 1 ME	
Antineutrino	1 Ring + 0 ME	1 Ring + 0 or 1 ME

particularly useful, because under the assumption of 2 body-like interaction it is possible to reconstruct neutrino energy only from lepton momentum and angle. One of the e-like ring samples is designed to look for single-pion production events by using the Michel electron signature.

Additionally, the new data sample in the far detector was introduced in the 2022 oscillation analysis, where multi-ring events were used to select muon neutrino interactions with single π^+ production (one of the observed rings associated with π^+). This allowed to increase by about 30% the statistics of μ-like events in the neutrino beam mode.

3. Oscillation analysis strategy

T2K oscillation analysis embraces two possible approaches. The first one, hybrid frequentist analysis, is done in two stages: the ND280 fit and then the oscillation fit. The ND280 fit constrains neutrino flux and interaction models by fitting parametrised Monte Carlo predictions to near-detector data. After the systematic parameters are constrained in the ND280 fit, the ND280 post-fit Monte Carlo predictions are fitted to Super-Kamiokande data. At the latter stage, oscillation parameters are extracted. In the second, Bayesian approach, the fit is done simultaneously to near-detector and far-detector data. The Markov Chain Monte Carlo method with the Metropolis Hastings algorithm is applied. The oscillation fit results are reported for both the frequentist and Bayesian analysis. A detailed description and comparison of these approaches can be found in [3].

3.1. Recent updates in the oscillation analysis

As already described in Section 2, the recent T2K oscillation analysis uses newly introduced near- and far-detector samples. Another important update is the improved flux prediction based on T2K replica target data with bigger statistics from the NA61/SHINE experiment [4]. New measurements allowed to decrease the flux systematic uncertainty in a broad neutrino energy range.

Additionally, several updates were implemented in the neutrino interaction modelling. That includes in particular new uncertainties on Δ resonance decay and effective binding energy in the case of CC resonant interaction, and improved uncertainties for a spectral function model describing the initial nucleon state in the case of CC quasielastic interaction [5].

4. Results of 2022 oscillation analysis

This section summarises the crucial results of the 2022 oscillation analysis. Figure 4 presents the T2K frequentist result on Δm^2_{32} *versus* $\sin^2\theta_{23}$ compared to other experiments (for normal mass hierarchy). T2K's contour was computed with the constant $\Delta\chi^2$ method. All experiments seem to give rather a consistent picture. When the 90% confidence level lines are drawn for each experiment, there is a phase-space region where all contours overlap. The T2K best fit point indicates a slight preference for the upper octant of θ_{23}.

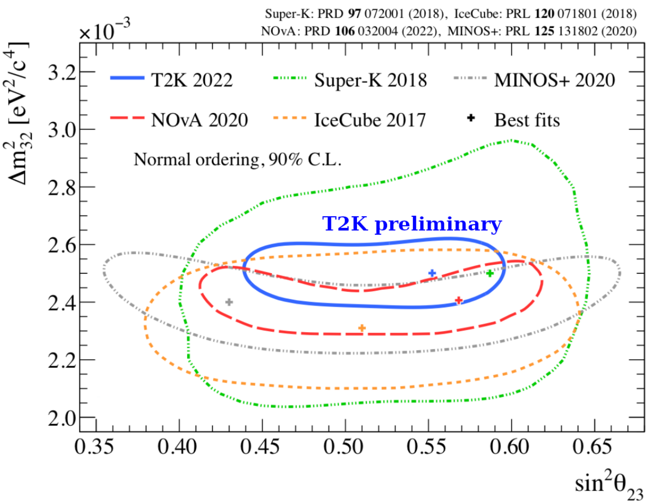

Fig. 4. T2K oscillation analysis results compared with other experiments. Best fit points for NOvA, Super-K, IceCube, and MINOS+ taken from [3]. Note that for Super-K and IceCube, these are not the most up-to-date results.

T2K excludes CP-conserving values at the 90% confidence level and favors the normal mass hierarchy at 73% (77.6%) posterior probability for the Bayesian (frequentist) approach. The best fit δ_{CP} value is near maximal CP violation with 68% credible intervals corresponding to $[-2.58, -1.01]$ ($[-2.45, -0.96]$) rad range for the Bayesian (frequentist) approach. CP violation can be expressed also in another way, by using the Jarlskog invariant J_{CP}, which is equal to

$$J_{\mathrm{CP}} = \frac{1}{8}\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\cos\theta_{13}\sin\delta_{\mathrm{CP}} \,.$$

The value of this quantity is independent of the parametrisation of the PMNS matrix and is proportional to the difference of oscillation probabilities for the $(\nu_\mu \to \nu_e)$ appearance and $(\bar{\nu}_\mu \to \bar{\nu}_e)$ appearance. Figure 5 presents the results of the T2K oscillation fit for the Jarlskog invariant. This quantity is fitted only in the Bayesian analysis and thus the prior probability density function is needed. It can be chosen as uniform in δ_{CP} or uniform in $\sin\delta_{\mathrm{CP}}$. This leads to a bit different results, but in both cases, the CP-conserving value is excluded at the 90% confidence level.

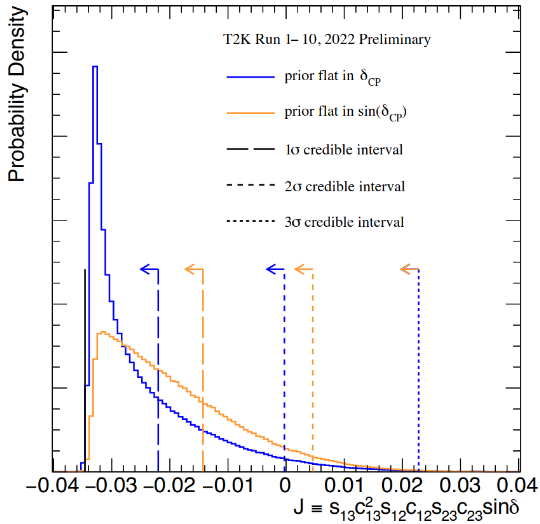

Fig. 5. T2K CP violation search summarised in terms of the Jarlskog invariant (Bayesian analysis approach, marginalised over both hierarchies).

5. Cross-section measurements in T2K

T2K has a rich program of cross section measurements in the near-detectors site. Neutrino interactions can be measured on multiple targets and at different angles with respect to the neutrino beam axis. It is also possible to have joint measurements and extract cross section for different targets or angles simultaneously. Apart from the benefit of the oscillation analysis, cross-section measurements serve to explore the nuclear effects or the rare processes.

5.1. Joint on/off-axis ν_μ CC0π measurement

One of the recent measurements relevant for the oscillation analysis is the measurement of the neutrino CC0π process in the joint on-axis and off-axis analysis. That is the first on-axis/off-axis measurement at T2K. Due to different on/off axis energy spectra, this study allows to better understand the energy dependence of the cross section. This measurement also provides constraints on flux modelling. Off-axis sample is based on neutrino interactions in the upstream FGD of ND280. For the on-axis interactions, data were collected with the INGRID detector. Reconstructed muon tracks had to start in the scintillator material of the upstream Proton Module with a possible segment in the downstream INGRID module. The cross section is reported as a double differential in muon momentum and cosine of the polar angle for on-axis neutrino flux and off-axis neutrino flux [6].

5.2. ν_μ and $\bar{\nu}_\mu$ CC coherent pion production on carbon

Measurement of the neutrino and antineutrino CC coherent pion production on carbon is based on data collected in the upstream FGD of ND280. Signal samples consist of events with exactly two tracks (μ-like and π-like), low energy deposit around the interaction vertex, and low transferred momentum. Due to the statistical limitations, the results are reported as single-energy bin cross sections [7].

6. Summary and outlook

The T2K Collaboration made some important improvements in the 2022 oscillation analysis: new flux prediction, new near- and far-detector samples, corrections and new uncertainties in modelling the neutrino interactions. The results of the T2K oscillation analysis favours CP violation, normal mass hierarchy, and the upper octant of θ_{23}. Apart from the oscillation analysis, T2K has a broad program of cross section measurements, with some new results published in 2023. The T2K experiment is scheduled to operate for a few more years with the upgraded near detector ND280. The upgrade is expected to be finished in 2024 and will allow us to obtain more precise measurements for the oscillation analysis and cross sections.

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