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T2K results on long-baseline oscillations

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Tokai-to-Kamioka is a long-baseline neutrino oscillation experiment in Japan, studying the oscillations of accelerator-generated muon neutrinos and antineutrinos. The survival probability of muon (anti)neutrinos is sensitive to θ_{23} and Δm^2_{32}, whereas the appearance probability of electron (anti)neutrinos is sensitive to θ_{13}, the θ_{23}-octant, the CP-violating phase δ_{CP} and neutrino mass ordering. The latest constraints on these oscillation parameters are presented, with updates to most parts of the analysis, including improved flux tuning and interaction model, as well as new near and far detector samples. With ongoing upgrades, T2K will continue to challenge key open questions of the three-flavor oscillation picture that have implications for cosmology, searches for neutrinoless double-beta decay, and flavor symmetries.

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1. Introduction

The Tokai-to-Kamioka (T2K) experiment [1] is a long-baseline neutrino experiment in Japan, studying the oscillations of a muon neutrino or antineutrino beam created at the J-PARC accelerator and detected 295 km away at the Super-Kamiokande (SK) detector. The three-flavor formalism of neutrino oscillations has now been established by various experiments over the past few decades. The following questions currently remain:

- The value of the CP-violation phase δ_{CP}: if $\sin\delta_{\mathrm{CP}} \neq 0$, CP is violated in the lepton sector.
- The sign of Δm^2_{32}, referred to as mass ordering: two possibilities exist, the normal ordering (NO) with two light and one heavy neutrino ($m_1 < m_2 \ll m_3$), and inverted ordering (IO) with one light and two heavy neutrinos ($m_3 \ll m_1 < m_2$).
- Whether θ_{23} is maximal or otherwise its octant (i.e. $\theta_{23} < \pi/4$ or $> \pi/4$).

The first two have important implications for cosmology, such as leptogenesis scenarios [2], and neutrino-less double-beta decay searches [3]. These parameters manifest themselves in the T2K experiment as a change in the $\nu/\overline{\nu}$ difference of $\nu_\mu \to \nu_e$ appearance rates, which can be precisely studied thanks to selective ν_μ or $\overline{\nu}_\mu$-enhanced beam operation modes. The third question could shed some light on discrete flavor symmetry models [4].

2. Experiment

The T2K neutrino beam is produced by 30 GeV protons impinging on a 90 cm graphite target. Three magnetic horns selectively focus the positively (or negatively) charged π, K mesons produced in hadronic interactions, which decay in-flight in a 96 m decay volume, and produce a ν_μ (or $\overline{\nu}_\mu$) beam (respectively). These two operation modes are referred to as neutrino- and antineutrino-modes. The beam is intentionally steered 2.5° away from SK to reduce the contribution from forward emission of high-energy neutrinos, thus achieving a narrowband neutrino beam peaking at an energy of about 600 MeV close to the first oscillation maximum.

A suite of near detectors monitors and measures the neutrino beam and interactions before oscillation. An on-axis detector, "INGRID", monitors the beam direction and intensity using iron-scintillator sandwich detectors. The off-axis detector, "ND280", is placed in the same direction as SK and measures the neutrino flux and interaction cross-sections. It mainly consists of active scintillator and passive water targets with precise tracking using time projection chambers (TPCs), all placed inside a 0.2 T magnet for charge and momentum measurement.

SK [5], the far detector, is a 50 kt pure water-Cherenkov detector lined with approximately $11,000$ photo-multiplier tubes for observing Cherenkov-rings from charged particles produced by neutrino interactions inside the detector. It provides good μ/e-particle identification from the ring shape, perfectly suited for studying the ν_e-appearance signal and ν_μ-survival rates. The neutrino energy can be reconstructed from the measured lepton momentum and angle with respect to the neutrino beam by assuming two-body scattering with a target nucleon at rest. While SK is not magnetized, the neutrino/antineutrino-beam modes allow separate study of $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations, with ND280 further constraining the wrong-sign backgrounds in each beam operation mode.

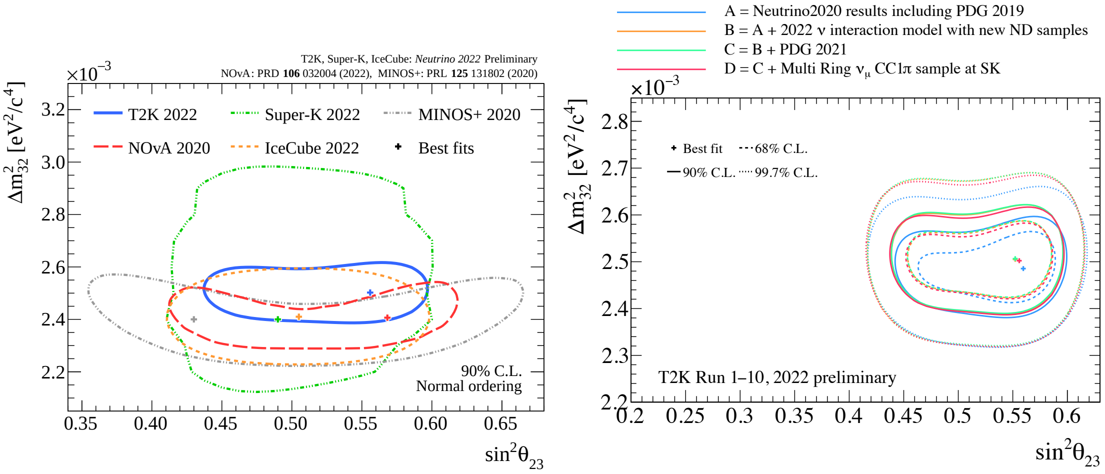

Figure 1: *Left:* T2K's (preliminary) constraints on the atmospheric oscillation parameters assuming normal ordering, compared against constraints from NOvA [14], SuperK atmospheric [15] (preliminary), IceCube [16] (preliminary), and MINOS+ [17]. *Right:* Evolution of the constraint on atmospheric parameters from the previous 2020 analysis.

3. Analysis

In this analysis (first shown at *Neutrino 2022* [7]), we use the data collected from the start of T2K in 2010 until early 2020. This corresponds to a total of 3.6×10^{21} protons on target, with an approximately 6 : 5 ratio for $\nu : \bar{\nu}$-mode. While the data is the same as the analysis shown at *Neutrino 2020* [6], many analysis improvements have been made, as will be described below. The run 11 data collected in early 2021 is the first run with gadolinium loaded into SK [8], and not used for this analysis yet.

The first step in the analysis is to predict the neutrino flux based on the information from proton beam monitors and external hadron production experiments. In this analysis, the tuning of charged kaons and protons emitted from the target has been updated from using thin target measurements (mainly from Ref. [9]) to new high-statistics NA61/SHINE measurements using a replica of the T2K target [10], resulting in a reduction of uncertainties in the high-energy tail around a few GeVs. The beam line modeling was also updated to include a more realistic modeling of cooling water in the focusing horns, resulting in a slightly increased flux uncertainty at the flux peak.

Next, the unoscillated flux and interaction cross-sections are constrained using ND280 measurements. Significant updates have been made to the interaction model: For the charged-current quasi-elastic (CCQE) interaction based on a Benhar Spectral Function model [11] tuned to $e + A$ scattering data, new uncertainties on the nuclear shell structure as well as a $|\mathbf{q}|^2$-dependence of the removal energy have been added. Empirical degrees of freedom were replaced by a physics-motivated low-Q^2 modeling. Uncertainties targeting proton tagging have been introduced, including a separation of uncertainties for CC multi-nucleon knock-out processes (2p2h) by exiting pp and pn pairs, and uncertainties on the final-state interactions for nucleons. The CC resonant interactions based on Rein-Sehgal model [12] with relativistic Fermi-gas nuclear model now feature a new tune to bubble chamber data and new uncertainties including an effective binding energy treatment.

The ND280 data is split into 22 samples separated by the following categories:

- π^+, p, and γ multiplicity as a handle on the neutrino interaction modes. This is a finer separation compared to the previous analysis, which separated only based on the charged pion multiplicity ($3 \to 5$ categories). The antineutrino mode samples still use the older separation by pion multiplicity.
- Lepton charge as a handle on the wrong-sign background in antineutrino mode.
- Interaction vertex in the scintillator-only or scintillator-water target as a handle on the $\nu + \mathrm{O}$ cross-section.

The fit result with correlated flux × cross-section uncertainties is propagated to the far detector analysis via covariance matrix; or by performing a joint ND+SK fit to also capture non-Gaussianities in the likelihood, both methods giving consistent results. The total uncertainty on the predicted event rates in the ν-mode single-ring μ-like events at SK reduces from 17% to 3% thanks to the ND constraint. The p-value for the fit to the ND data is calculated to be $p = 10.9\%$, passing the predefined 5%-threshold.

At SK the samples are separated into μ-like and e-like ring events, where for neutrino-mode each is further separated based on the presence of a charged pion. For μ-like events this ν_μ CC$1\pi^+$-sample was added for the first time in this analysis, featuring, for the first time in T2K, multi-ring events as well. By being dominated by CC resonant interactions this sample is distributed toward higher neutrino energies above the oscillation maximum and hence is not expected to provide strong constraints on oscillation parameters. The 40% increase in statistics however is expected to make the analysis more robust against mis-modeling of the feed-down from higher energies into the oscillation-parameter sensitive CCQE-enhanced sample.

T2K's constraints on oscillation parameters can be roughly divided into contributions from each sample group. The μ-like events (so called "disappearance"-channel) constrain $\sin^2 2\theta_{23}$ and Δm^2_{32} via amplitude and peak energy of the ν_μ-disappearance. The e-like events (so called "appearance"-channel) are sensitive to $\sin^2 2\theta_{13} \sin^2 \theta_{23}$ in the overall appearance probability (thus also the θ_{23}-octant), whereas a difference in ν vs. $\overline{\nu}$ appearance probabilities is sensitive to a combination of $\sin \delta_{\mathrm{CP}}$ and the neutrino mass ordering.

T2K's θ_{13}-constraint via $\nu_\mu \to \nu_e$ appearance is consistent with the much stronger constraint from reactor experiments ($\overline{\nu}_e \to \overline{\nu}_e$ disappearance). In the following the results on other oscillation parameters are computed including this additional reactor-constraint on θ_{13} from Ref. [13], which provides better sensitivity for δ_{CP}, mass ordering, and θ_{23}-octant.

4. Results

For atmospheric mixing parameters, Δm^2_{32} and θ_{23}, T2K's world-leading measurement (Fig. 1 left) is still compatible with both octants, weakly preferring the upper octant (Bayes factor $P_{\mathrm{upper}}/P_{\mathrm{lower}} = 3.0$). The largest change compared to the *Neutrino 2020* results is due to the new interaction model (Fig. 1 right). The new ν_μ CC$1\pi^+$ sample, as its energy is above oscillation maximum, only gives a small contribution.

For the constraints due to e-like samples, the best-fit value of δ_{CP} lies near maximal CP-violation (Fig. 2 left), with CP-conserving values of 0 and π excluded at 90% confidence level (π is within 2σ). A large region of δ_{CP} is excluded at 3σ confidence level. The data shows a weak preference for normal ordering with Bayes factor of $P_{\mathrm{NO}}/P_{\mathrm{IO}} = 2.8$. The constrains are slightly weaker compared

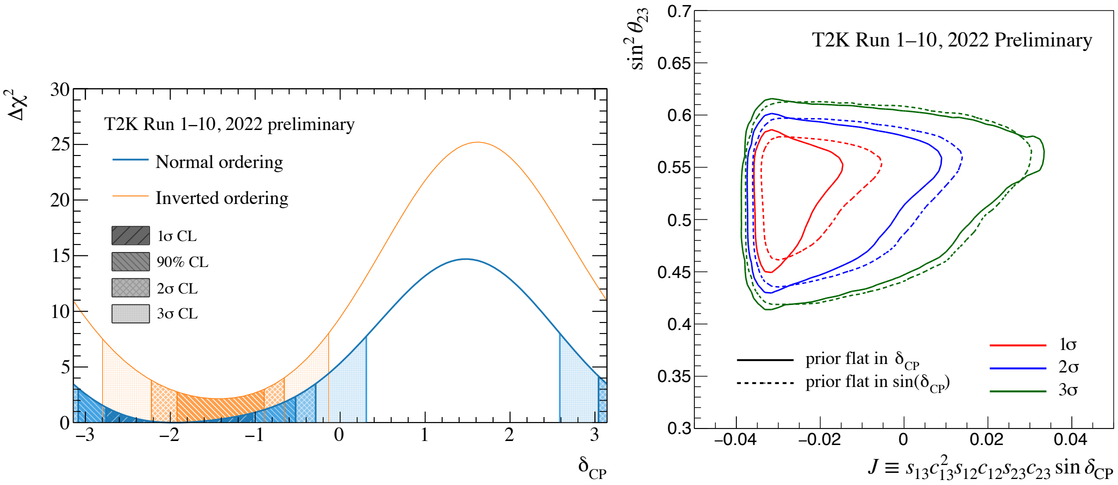

Figure 2: *Left:* $\Delta\chi^2$-distribution and Feldman-Cousins confidence intervals for δ_{CP}. *Right:* Credible region for the Jarlskog invariant J and $\sin^2\theta_{23}$ marginalized over both mass orderings for different δ_{CP}-priors.

to the *Neutrino 2020* results, which is mostly caused by the changes to the predicted event rates from the updated interaction model with new ND samples.

The constraints on CP-violation can also be shown as constraints on the Jarlskog invariant, which is a PMNS parameterization-invariant measure for CP-violation. The Bayesian constraint shown in Fig. 2 (right) depends on the choice of δ_{CP} prior and assumed $\sin^2\theta_{23}$ values and currently contains the CP-conserving value of $J = 0$ inside of the 2σ credible region.

An extensive set of studies is performed to test the robustness of the assumed interaction and uncertainty model for mis-modeling effects by fitting various “simulated data” from theory- or data-driven alternative interaction models. Here, the alternative model is used to create a simulated data set without statistical fluctuations at both the near and far detectors. This is passed through the whole analysis to obtain confidence intervals on oscillation parameters. If the interaction uncertainty model is unable to absorb the changes due to the alternative model at the near detector, the oscillated spectrum at the far detector cannot be accurately predicted, which can result in biased oscillation parameter constraints. Any shift or shrinkage of the computed intervals compared to corresponding intervals for the baseline interaction model is tested. For θ_{23} no significant changes are observed. An additional gaussian uncertainty with $\sigma = 2.7 \times 10^{-5}\,\mathrm{eV}^2$ is applied to account for a small shift observed in Δm^2_{32}. For δ_{CP} the left (right) 90% confidence interval edge moves at most by 0.06 (0.05) radians, with no change of main conclusions.

Joint fits of NOvA + T2K and SK (atmospheric) + T2K experiments with different oscillation baselines, energies, and detector technologies are ongoing. These are expected to yield increased sensitivity in δ_{CP}, mass ordering, and θ_{23} beyond a simple statistics increase by resolving degeneracies and constraining common systematics. The collaborations are working together toward first results including studies on the potentially non-trivial systematic correlations between experiments. First sensitivity studies from the SK+T2K joint fit are discussed in the contribution by J. Xia.

5. Outlook toward the future

The beam line is undergoing a series of upgrades [18]. The beam power will increase from the current 500 kW toward 1.3 MW through upgrades to the main ring power supply and RF cavities. The neutrino beam line is being upgraded to accept this higher power beam. In addition, the horn current will increase from the current 250 kA to the design value of 320 kA for approximately 10% more neutrinos per beam-power and a reduction of the wrong-sign background. The 320 kA operation is being aimed for the next run.

ND280 is also undergoing a major upgrade [19] and will feature a new 3D scintillation detector with high-angle TPCs and a time-of-flight enclosure. This results in an increased target mass, 4π coverage like SK, and a lower proton momentum tracking threshold, for a reduction of interaction model systematics and a better understanding of nuclear effects [20]. This upgrade is covered in more detail in the contribution by J. Chakrani.

6. Summary

We presented the latest T2K neutrino oscillation results using 3.6×10^{21} protons on target, with many improvements at each level of analysis. CP conserving values of δ_{CP} are excluded at 90% confidence level, while excluding a large range at 3σ confidence level. A weak preference for normal ordering and upper octant is seen. With new detectors and stronger beam, T2K is expected to collect more exciting physics results in the upcoming years.

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