PROCEEDINGS OF SCIENCE

Latest neutrino oscillation results from T2K

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The T2K experiment based in Japan studies neutrino oscillations and interactions using a beam of accelerator-generated (anti) neutrinos. The neutrino oscillation parameters are studied using a suite of near detectors (ND) located 280m from the beam production target and a far detector (FD) (Super-Kamiokande) located 295 km away. T2K's latest neutrino oscillation analysis results use data collected during the first ten years of its running along with improvements in various analysis aspects since the last result. The status of T2K's combined analyses with Super-Kamiokande and NOνA experiments and T2K's upcoming experimental upgrades are also briefly discussed.

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1. The T2K experiment

The Tokai-to-Kamioka (T2K) experiment [1] is a long-baseline neutrino experiment based in Japan. T2K's main physics goals include searching for CP violation in the neutrino sector, precise measurement of neutrino mixing angle θ_{23}, and measurement of Δm^2_{32} (for the normal ordering). T2K also performs cross-section measurements and covers some non-standard model physics analyses too.

A neutrino beam produced upon impinging 30 GeV protons on a graphite target is used to study neutrino oscillations and interactions at T2K. The accelerated protons are produced at the Japan Proton Accelerator Research Center (J-PARC) which is located on the east coast of Japan, in Tokai, Ibaraki prefecture. The beam is then directed toward the west coast to Super-Kamiokande (SK) [2] in Hida, Gifu prefecture, 295 kilometres away from the beam production target.

A set of near detectors, mainly ND280 and INGRID, are located 280 meters down the beamline. INGRID, centred on-axis to the beam, is a sandwich of iron and liquid scintillators that constrain neutrino flux and monitor beam direction and profile. ND280 is a magnetized multi-component detector, consisting of three time projection chambers (TPCs) and two fine grain detectors (FGDs) along with a π^0 detector (P0D). ND280 (hereafter referred to as ND) performs world-leading cross-section studies and constraints interaction uncertainties at the FD. Both ND280 and SK are located 2.5° off-axis to the beam. This is done to receive a ν_μ beam that peaks strongly around 0.6 GeV, corresponding to the neutrino energy for oscillation maxima at 295 km baseline.

T2K can study both ν_μ and $\overline{\nu}_\mu$ disappearance at the FD. The disappearance channel provides sensitivity to $\sin^2 2\theta_{23}$ and Δm^2_{31}. T2K can also study $\nu_e/\overline{\nu}_e$ appearance, which is sensitive to $\sin^2\theta_{13}$ and $\sin\delta_{\mathrm{CP}}$, along with the octant of θ_{23}. To measure the CP-violating parameter δ_{CP}, the differences in ν_e and $\overline{\nu}_e$ appearance rates and spectras are studied at the FD.

2. Oscillation Analysis

T2K performs two independent analyses that make use of two different statistical approaches. The first one uses a hybrid-frequentist approach with Feldman-Cousins, while the second follows a Bayesian approach using Markov Chain Monte Carlo (MCMC) techniques. Both approaches use a Poisson likelihood function that incorporates systematic parameters with either Gaussian or flat priors. In addition, the ND MC statistical uncertainty is implemented using the Barlow-Beeston [3, 4] approach.

In the hybrid-frequentist method, a sequential ND followed by FD fit is performed via a gradient descent/grid search algorithm, where the ND fit constrains the flux and cross-section uncertainties, and tunes the nominal event rate prediction. This is then propagated to the FD fit, which gives the oscillation parameters. In the Bayesian approach, both ND and FD inputs undergo a simultaneous fit, using an MCMC procedure which is based on the Metropolis-Hastings algorithm that produces posterior distributions of the parameters.

For the 2022 summer analysis [5], T2K uses constraints on its flux predictions from NA61/SHINE's [6] 2010 T2K replica data analysis [7]. Their new analysis adds more statistics to the $\pi^\pm$ production and also adds $K^\pm$ and proton data, reducing the overall flux error at T2K by $\sim 6\%$ (Fig. 1) compared to the 2009 replica data [8].

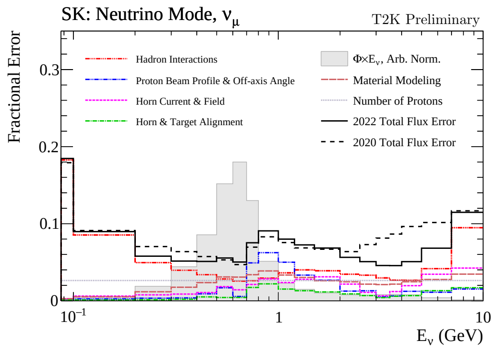

Figure 1: Fractional flux error as a function of neutrino energy with old and new NA61/SHINE tuning.

At the T2K beam's energy, (anti) neutrinos interact most dominantly via the charged-current (CC) quasi-elastic (QE) channel. The CCQE interaction of neutrinos with the nucleus is modelled using the Spectral Function formalism. Improvements with respect to the previous analysis [9] were made in the parametrization of uncertainties for the spectral function model, for example, adding normalization of each nuclear shell. Treatment of nuclear binding energy was also improved. Ad-hoc Q^2 normalization were replaced with Pauli blocking to provide better freedom in low Q^2 regions [10].

The Rein-Sehgal model used to describe the CC resonant pion production (CC1π) was tuned with bubble-chamber data. An effective inclusion of binding energy was also implemented, and new uncertainties were introduced in Δ resonance production and $\pi^{\pm}$ vs π^0 production. There were also improvements made in $2p2h$ and FSI model treatments.

At the ND, existing samples in the neutrino mode were updated by adding proton and photon tagging information. For instance, the older $CC0\pi$ sample is now split into $CC0\pi 0p0\gamma$ and $CC0\pi Np0\gamma$. At the FD, a new neutrino mode ν_μ sample was added which targets the ν_μ CC1π^+ interactions. This sample increases the total ν_μ statistics by $\sim$ 30%. While this sample is less sensitive to oscillation, it helps to test the robustness of the model.

3. Results

In all the results shown below, reactor neutrino experiment constraint [11] on θ_{13} ($\sin^2 2\theta_{13} = 0.0861 \pm 0.0027$) is applied. Both analyses show a preference for θ_{23} to be in the upper octant, although the lower octant is still allowed at 68% CL (Fig: 2,3).

In the case of $\delta_{\rm CP}$, CP-conserving values of 0 and π are outside the 90% CL with the best-fit value near maximal CP violation ($-\pi/2$) (Fig: 2,3). The impact of alternate interaction models was also studied, with no biases found that alter this result. The Bayesian analysis also introduced the Jarlskog invariant $J_{\rm CP}$ [12] as a measurable parameter to search for CP violation.

This parameter, defined as:

$$J_{\rm CP} \equiv \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{\rm CP} \quad (1)$$

provides a PMNS parametrization independent search for CP violation. The posterior probability distribution of $J_{\rm CP}$ depends on the choice whether the prior is flat in $\delta_{\rm CP}$ or in $\sin\delta_{\rm CP}$. Regardless

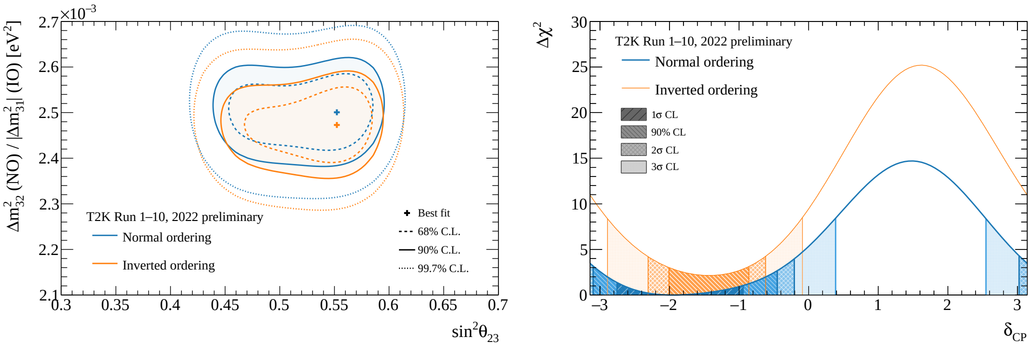

Figure 2: Oscillation parameters $\sin^2\theta_{23}$ vs $\Delta m^2_{3\ell}$ (left) and δ_{CP} (right) from the hybrid-frequentist analysis for both normal and inverted orderings

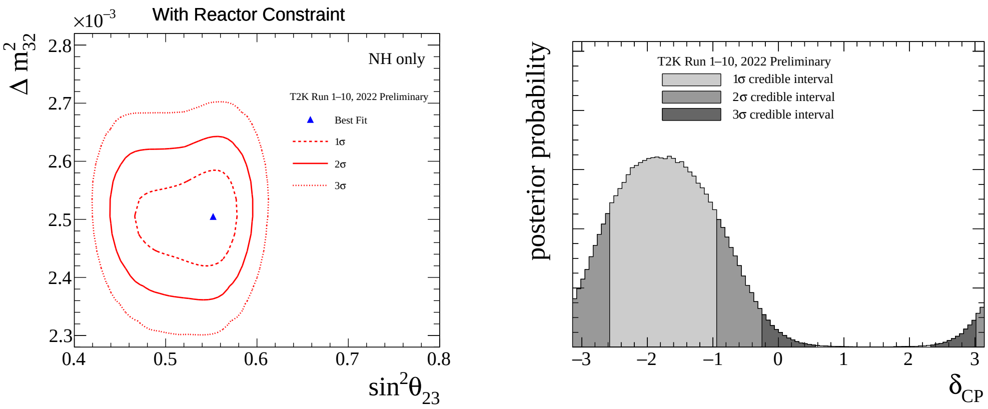

Figure 3: Oscillation parameters $\sin^2\theta_{23}$ vs Δm^2_{32} (left, normal ordering only) and δ_{CP} (right, marginalized over both orderings) from the Bayesian analysis. Note: NH stands for normal hierarchy/ordering.

of the choice, $J_{CP} = 0$ which implies CP conservation, is excluded at 90% credible interval, and preference for maximal CP violation is still valid (Fig: 4).

4. T2K's plans for the future

T2K is currently performing a combined analysis with NOνA and SK collaborations, aiming at further improving the constraints on oscillation parameters. The analysis with NOνA presents great complementarity in studying oscillations due to the differences in both experiments, ranging from detector technology to baseline and neutrino energies. On top of increased sensitivities, this study can also potentially lift degeneracies between δ_{CP} and mass ordering.

The combined studies with SK atmospheric analysis is also interesting since SK is a common detector for both experiments. Thus there can be strong correlations in detector systematics, and it is also possible to choose a common neutrino interaction model. While the δ_{CP} sensitivity is mainly driven by T2K, SK has better mass ordering sensitivity due to its access to a large range of neutrino energy and baselines (Fig: 5).

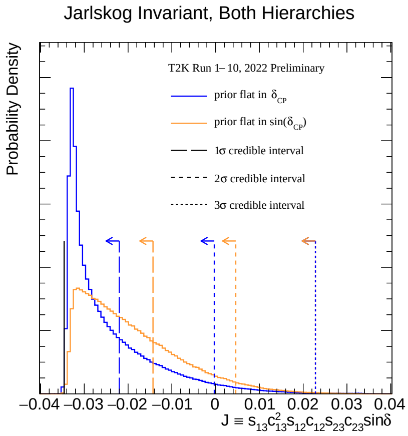

Figure 4: Jarlskog invariant marginalized over orderings, showing posterior probability densities for priors flat in $\delta_{\rm CP}/\sin\delta_{\rm CP}$ from the Bayesian analysis.

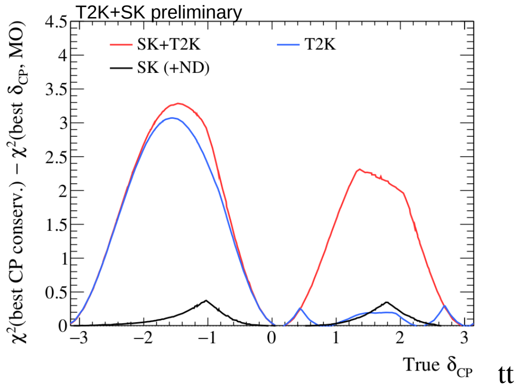

Figure 5: Sensitivity studies from the T2K+SK combined analysis showing the ability to exclude CP conservation (left) and ability to reject wrong mass ordering (right) as a function of true $\delta_{\rm CP}$.

T2K's experimental components are also undergoing upgrades. J-PARC accelerator upgrade will provide a higher intensity proton beam, and the magnetic horn current will operate at a higher current of 320 kA. ND280 will also be upgraded [13] by replacing the P0D detector with a complex of new detectors which will improve cross-section measurements and help reduce interaction uncertainties. SK is being increasingly loaded with gadolinium sulphate since summer 2020. The Gd loaded SK will have neutron tagging ability, helping identify anti-neutrino events better. At FD, new multi-ring ν_e and neutral current (NC) π^0 samples are also being developed, which will converge on time for the next oscillation analysis.

5. Summary

This analysis presents T2K's 2022 oscillation analysis results performed using both a hybrid-frequentist and a Bayesian analysis. Multiple changes were introduced in the analysis components: changes in the flux and neutrino interaction models, inclusion of proton and photon tagging in the ND samples, and introduction of multi-ring ν_μ sample at the FD.

Both the independent analyses exclude conservation of CP symmetry ($\delta_{\rm CP} = 0$ or π) at 90% confidence limit with the best-fit value pointing towards maximal CP violation. The Bayesian analysis also measured the Jarlskog invariant excluding the CP conservation value of $J_{\rm CP} = 0$ at 90% credible interval. The results also show mild preferences for normal mass ordering and an upper octant value for θ_{23}.

T2K is currently performing a combined analysis with the NOνA and SK collaborations, both of which show the potential to constrain various neutrino oscillation parameters better. T2K is also preparing for the next phase of its run, with updates in the J-PARC accelerator, an upgraded ND, and SK-Gd. In addition, the next oscillation analysis will also include two new multi-ring samples at FD.

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