PROCEEDINGS OF SCIENCE

Neutrino Oscillation Measurements at T2K

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T2K is a long-baseline neutrino oscillation experiment, which studies the oscillations of neutrinos from a beam produced using the J-PARC accelerator chain. The neutrino beam propagates over 295 km before reaching the Super-Kamiokande detector, where they can be detected after having oscillated. The ability of the experiment to run with either neutrino beams or anti-neutrino beam makes it well suited to study the differences between the oscillations of neutrinos, in particular to look for a possible violation of CP symmetry in the lepton sector. T2K has produced a new analysis of its first 10 years of data, with improved models to describe neutrino interactions and fluxes as well as additional samples of near and far detector events. We will present the results of the measurement of the parameters describing neutrino oscillations obtained with the new analysis. In parallel, T2K has been working on joint analyses with other experiments, and we will give an update on the perspective of two joint analyses in preparation, with the Super-Kamiokande and the NOvA collaborations respectively.

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1. T2K Experiment

T2K is an international long-baseline experiment located in Japan [1]. A beam of muon neutrinos is produced on the eastern shore of Japan and sent towards the west where, under the Japanese Alps, at a distance of 295 km, the oscillations are studied in the Far Detector (FD).

The beam is created in the Japan Proton Accelerator Research Center (J-PARC). Protons are accelerated to the energy of 30 GeV and then hit the target made of graphite. In these collisions, new particles are produced, mostly pions and kaons, which are focused by 3 magnetic horns and directed towards the decay volume where decay, producing neutrinos. By switching the direction of the current in the horns, positively (Forward Horn Current, FHC) or negatively (Reverse Horn Current, RHC) charged mesons can be focused, while of opposite charge defocused, thus obtaining a neutrino or antineutrino beam, respectively.

At a distance of 280 m from the target, the near detector complex (ND) is located. It consists of INGRID, an on-axis detector. One of them, called ND280, is a multi-purpose detector equipped with a magnetic field. Part of it, used in the oscillation analysis, is the tracker surrounded by an electromagnetic calorimeter. The tracker consists of two Fine Grained Detectors (FGDs) and three Time Projection Chambers (TPCs). One of the FGDs is made of scintillators, and the other one contains also layers of water. FGDs are sandwiched between TPCs, which allows for particle momentum reconstruction, charge measurement and identification using energy loss. ND280 data is crucial to tune cross-section and flux models and shrinking the related uncertainties in the oscillation measurement. This ND analysis will be referred to as ND280 fit.

The Far Detector of the T2K experiment is Super-Kamiokande [2], containing 50 kilotons of ultra-pure water. It is equipped with over 11,000 photo-multipliers which detect the Cherenkov light produced by charged particles travelling through water. The detector can distinguish muons and electrons based on Cherenkov ring properties. The reconstruction of neutrino energy is also possible with good accuracy.

2. The Flux and Cross Section Modelling

The simulation of the neutrino flux [3] starts with the interactions of the primary protons in the target done with FLUKA simulator [4]. Then, (simulated) particles exiting the target are propagated through the horns' magnetic field and through decay volume by GEANT3 [5]. The results are reweighted to match the hadron-production measurements from the NA61/SHINE experiment.

In the current analysis, the NA61/SHINE [6] T2K replica target data described in Ref. [7] has been used. This allowed decreasing flux prediction uncertainties with respect to a previous analysis [8] as can be seen in Fig. 1.

In the energy range of interest to T2K, the dominant reaction is the charged current (CC) quasi-elastic (QE)interaction, both for neutrinos and antineutrinos. T2K uses Spectral Function formalism to describe the interaction with a nucleus for CC QE. Hence significant emphasis is placed on improving parametrisation of uncertainties of the model, which includes normalization of each nuclear shell. Pauli Blocking is also included to give more freedom in the region of low four-momentum transfer [9].

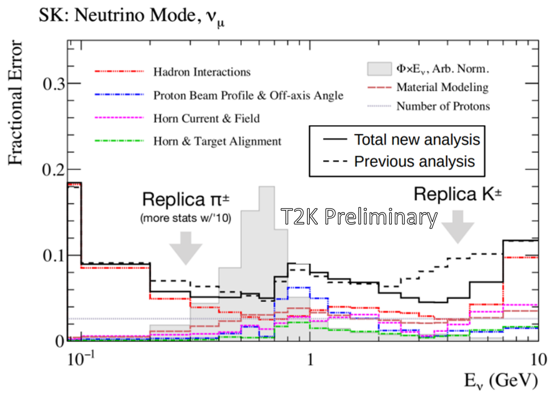

Figure 1: Fractional flux error as a function of neutrino energy with old and new NA61/SHINE tuning.

Another important reaction is 2p2h where emphasis is put on better describing uncertainty coming from proton-neutron (pn) and neutron-neutron (nn) pairs contributions. For resonant scattering, the Δ resonance decay and effective binding energy uncertainties are added. In addition, nucleon Final State Interaction uncertainty is included.

Summarizing, the treatment of the neutrino interactions is now more sophisticated but also introduces many more parameters to the fit (75 cross-section parameters) which is almost twice as many as in the previous analysis [10].

3. ND and FD event samples

Previously the ND280 fit was using samples for FHC and RHC based on the multiplicity of pions in the final state: no π in a final state ($CC0\pi$), one π in a final state ($CC1\pi$) and other combination of π the final state (CC-Other). Since the cross-section model is getting more complex and demanding, ND280 samples have been updated. In the new analyses both proton and photon tagging has been introduced for FHC selections. For the "photon sample" a photon is tagged in electromagnetic calorimeter. Such photons come mostly from π^0 decays and the sample is dominated by DIS and multiπ events. Thanks to that tag the purity of $CC0\pi$ and $CC1\pi$ samples is about 10% higher.

The $CC0\pi$ sample is now split into two, depending on the presence of a detected proton in the final state. Muons in two such samples occupy different regions of the kinematic phase space. The CC0π-0p-0γ sample contains also a much higher fraction of true CC QE events. Also, the two samples probe different regions of the energy and momentum transfer plane.

As for the FD, five samples of so-called one-ring events are used in the analysis. A single ring means that only one Cherenkov ring, produced by a charged lepton, is observed in the detector and such samples are dominated by QE events. There are two samples of muon-like events, for FHC and RHC, and 3 samples for electron-like events, one for RHC and two for FHC. The additional FHC one is 1π sample when a delayed Michel electron from $\pi \rightarrow \mu \rightarrow e$ decay chain is observed in the event. In addition, a new sample of multi-ring events is introduced, which consist of events with one of the following topologies:

- Two rings 1 μ^- and a 1 π^+ and Michel electron from 1 μ^-

- One ring and 2 Michel electrons (from 1 π^+)

The new sample increased ν mode μ-like statistics by ~30%. In addition, it has higher energy than one-ring sample so it helps to crosscheck the cross-section model.

4. Results

T2K uses different analysis methods, the first analysis uses sequential ND+FD fit and a frequentist approach while the second one uses Bayesian Markov Chain Monte Carlo and simultaneous ND+FD fit.

Fig. 2 left shows nominal (prior) and fitted (postfit) values values for selected CC QE-related parameters. One can observe that some parameters have been pulled from prior values (within 2σ) and the errors are significantly reduced. After propagating parameters to SK (Fig. 2 right) the impact of ND280 fit is clear. The predicted spectra have been tuned, as well as error dropped substantially.

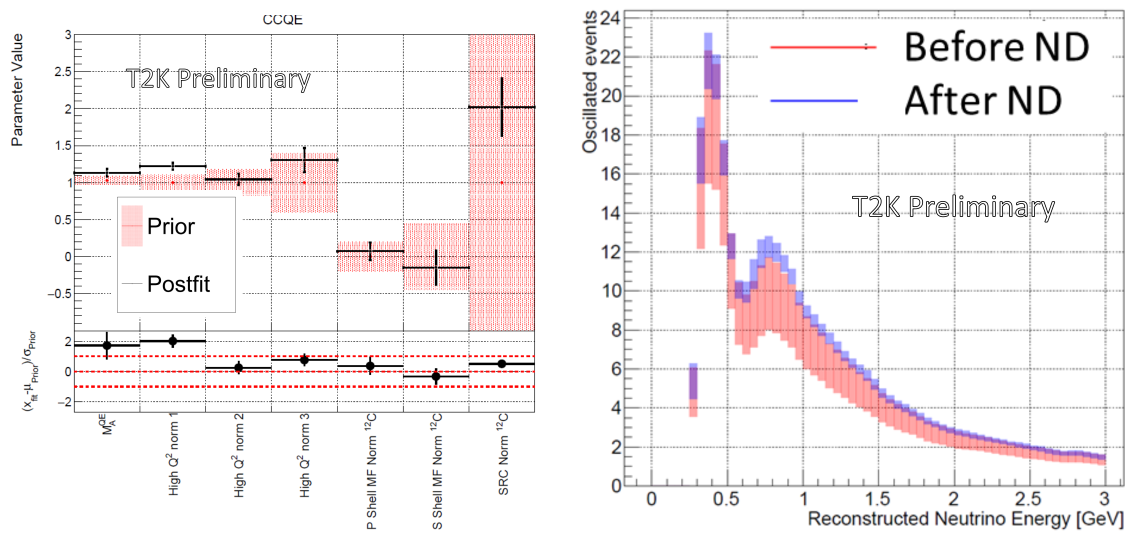

Figure 2: Prefit and postfit values for selected cross-section parameters (left) and FD spectrum before and after applying the constraints from the fit to ND data (right).

Results of oscillation parameters are shown in Fig. 3. Both CP-conserving values of $\delta_{CP} = 0$ and $\delta_{CP} = \pi$ are outside of 90% CL intervals. New results are in very good agreement with the results of the previous analysis [10].

An alternative measurement of CP violation using the Jarlskog invariant:

$$J = s_{13}c_{13}^2 s_{12}c_{12}s_{23}c_{23}\sin\delta_{CP}, \tag{1}$$

is performed and the results are presented in Fig. 4. The choice whether to set flat prior in δ_{CP} or in $\sin\delta_{CP}$ is relevant, however, it does not change the physical conclusion which is that T2K has a preference for maximal CP violation.

In addition, T2K is working on two joint-fits. One is with SK, with particular sensitivity to mass ordering from high-energy neutrinos (since the atmospheric sample covers a wider range

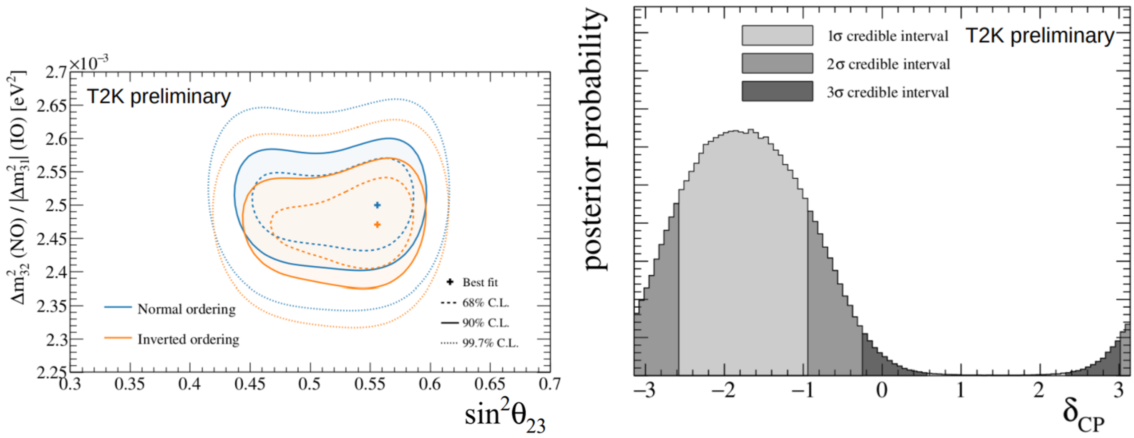

Figure 3: Atmospheric oscillation parameters form Frequentist analysis (left) and δ_{CP} from Bayesian analysis (right).

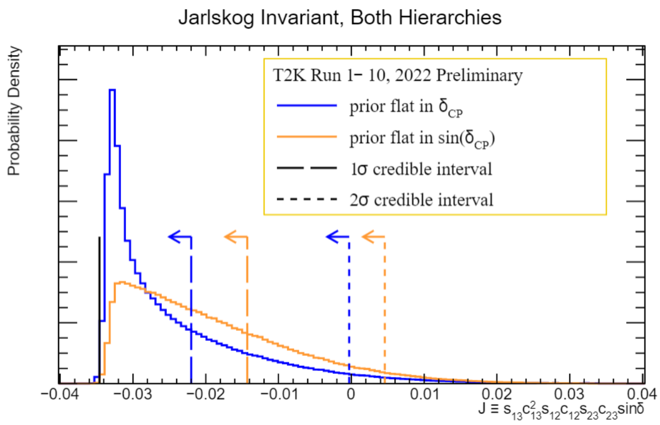

Figure 4: Distribution of Jarlskog invariant from Bayesian analysis with flat prior set either in δ_{CP} or $\sin\delta_{CP}$. Both shows T2K has a preference for maximal CP violation.

of energies and baseline than T2K). The second one is with NOvA. Both experiments are long-baseline, however, baselines, peak neutrino energy, detector technology, etc., are different, making them complementary.

Acknowledgments

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