Latest Neutrino Oscillation Results from T2K

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Neutrinos are Standard Model particles that lead us to many open questions. Very abundant but yet challenging to detect, they are a key towards physics beyond the Standard Model and they play a role in major questions about our Universe. In particular, the Dirac phase of CP symmetry violation (δ_{CP}) that parameterizes the asymmetry in flavor oscillation probabilities between neutrino and anti-neutrinos is one of the most studied parameters. If $\sin(\delta_{CP})$ is non-zero, this would mean that neutrinos, and the leptonic sector in general, may participate in the unexplained matter/anti-matter asymmetry of the Universe via yet-to-be-discovered leptogenesis mechanisms. The neutrino oscillation long baseline program in Japan is currently leading the sensitivity to CP violation in neutrino oscillations. More specifically, the Tokai to Kamioka (T2K) experiment measures muon neutrino disappearance and electron neutrino appearance in a 600 MeV accelerator beam of (anti-) neutrinos with a baseline of 295 km. Its sensitivity is based on a complex set of near detectors, both on- and off-axis, as well as an off-axis water Cherenkov far detector. We will present here the analysis principle, with a focus on the far detector fit, and the latest accelerator neutrino oscillation results.

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1. The Tokai to Kamioka (T2K) experiment

The Tokai to Kamioka (T2K) experiment is a long baseline neutrino oscillation experiment located in Japan and taking data since 2010 [1]. A focused muon neutrino beam of average energy 600 MeV is produced by the J-PARC accelerator in Tokai [2]. The horn current sign can be selected so that the experiment can take data with either a neutrino or an anti-neutrino beam depending on the data taking runs. A dedicated set of complementary near detectors monitors and characterizes the product of flux and cross-section in the beam before propagation along the baseline. After 295 km, the neutrinos from the beam reach the far detector: Super-Kamiokande [3] in the Kamioka mine. Super-Kamiokande (SK) is a 50 kTon water Cherenkov detector which allows to detect the charged lepton outgoing the neutrino-nucleus interaction in the detector (mainly charged current quasi-elastic CCQE). Analysis of the Cherenkov rings and the collected charge allows to reconstruct the flavor and the kinematics of the interaction. This reconstruction , as it will be explained, is at the core of the oscillation analysis since it allows to study spectra of neutrinos of different flavor after propagation.
The far detector is off-axis by 2.5° in order to select a narrower range of neutrino energies, facilitating the reconstruction. Moreover, the energy selected, together with the near-to-far detector distance, correspond to an optimization of the oscillation parameters measurement as we expect a maximum probability of oscillation for beam neutrinos at SK. Some of the near detectors are located at the same off-axis angle and at a distance of 280 m from the accelerator target: ND280. It is made of an inner tracker (vertical time projection chambers (TPC) and Fined grained detectors (FGD)), a π^0 detector and a calorimeter. This is ideal to constrain the flux and cross-section in the same conditions as at the far detector. Another main near detector is, on the contrary, located on axis so as to monitor more directly the beam parameters. It is called INGRID [4]. There are also additional near detectors at different off-axis angles such as the detectors called WAGASCI [5] (WAter Grid SCIntillator Detector) that are scintillators with a grid structure filled with water and a spectrometer called BabyMIND [6] at 1.5°.

2. The oscillation analysis in T2K

With the T2K data, it is possible to study simultaneously muon (anti-)neutrino disappearance, electron (anti-)neutrino appearance and the asymmetry of this oscillation probability between neutrinos and anti-neutrinos. This way, T2K is sensitive to the so-called atmospheric parameters $\sin^2\theta_{23}$ and Δm^2_{32} (NO)/Δm^2_{31} (IO) as well as to the CP violation phase δ_{CP}.
One T2K fitter, called MaCh3 fits simultaneously the near and far detector data in order to obtain Bayesian constrains on oscillation parameters, using a Markov-Chain Monte Carlo (MCMC) algorithm. However, here we will focus on the other analysis workflow used in T2K. In this analysis method, the fit of the flux [7] and cross-section models [8, 9] to the near detector data is first performed through a likelihood maximization. The models are built both from theory and data such as the hadron production data from the NA61/SHINE experiment [10]. The near detector data is split into 22 samples according to beam mode, target detector and reconstruction topology. From this near detector fit, constraints on the product of flux and cross-section are extracted in the form of a covariance matrix including all related systematic parameters. This information is passed on

to the far detector fitters.

At the level of the far detector fit, predicted spectra of neutrinos are built from the information of the near detector, the detector model, and external prior constraints on oscillation parameters to which T2K is not the most sensitive experiment. Those parameters are: $\sin^2 2\theta_{13}$ constrained by reactor experiments, $\sin^2\theta_{12}$ and Δm^2_{12} measured in solar neutrino experiments. Gaussian prior around values from the PDG [11] are used. The analysis method uses a negative log-likelihood minimization with marginalization over the nuisance parameters to fit the predicted spectra to the reconstructed far detector data. Six samples are used, 4 of them are 1-ring samples broken down by beam mode and flavor. The two others are events with the presence of a pion in the final state. The results presented here used a 2D binning (neutrino energy or lepton momentum and lepton angle with the beam axis) for 5 of the 6 samples. The sixth sample is analyzed in neutrino reconstructed energy only. This analysis workflow is said to be semi-frequentist as it uses priors on a number of parameters but then proceeds to a frequentist analysis producing confidence intervals.

The results presented here are an update of the analysis strategy with respect to the last published analysis with the same data [12]. There are a few key new features. The main one is the inclusion of the sixth sample at the far detector for the first time. It selects muon-flavored events in neutrino mode with a pion in the final states and at least one decay electron also detected. It corresponds to a 40% increase in muon neutrino statistics. Most of the events in this sample are above the oscillation maximum in terms of energy hence a small impact on the oscillation analysis sensitivity. However, this sample is of great importance to validate the background modeling and to constrain systematic parameters. Another new feature is a globally more sophisticated cross-section model, with 21 new systematic parameters and a new implementation of the uncertainty parameter on the removal energy of the nucleon that interacts with the neutrino. The energy scale implementation at SK has also been updated to apply more directly to the lepton momentum and take into account bin migration event by event.

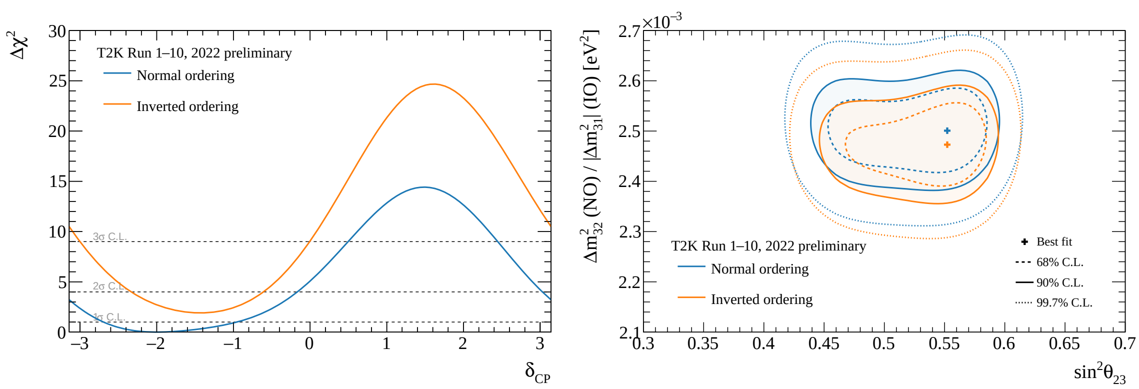

Figure 1: T2K Data fit results: likelihood curve for δ_{CP}(left) and confidence contours in the atmospheric 2D space $\sin^2\theta_{23}$ and Δm^2_{32} (NO)/Δm^2_{31} (IO) (right).

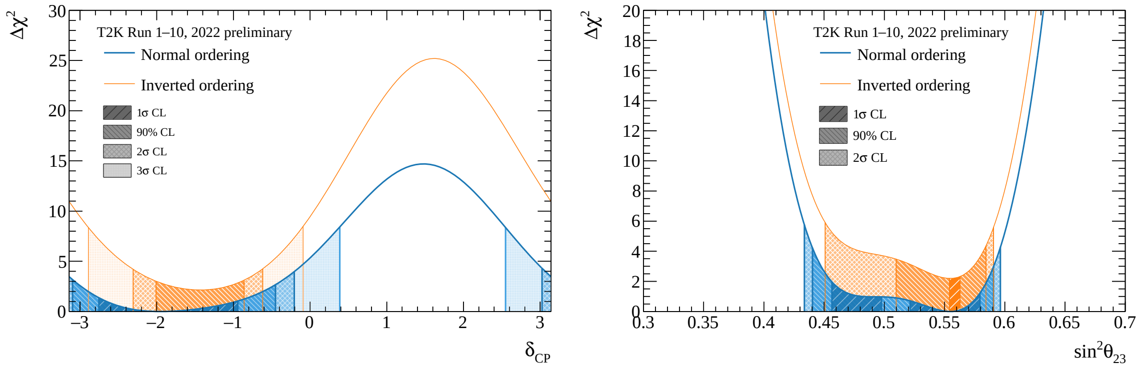

Figure 2: Feldman-Cousins studies results: likelihood curve with FC computed confidence intervals for δ_{CP}(left) and for $\sin^2\theta_{23}$ (right).

3. Latest results

Using the method described above, new T2K constraints on oscillation parameters were obtained for both mass orderings: normal ordering (NO) and inverted ordering (IO). In particular, figure 1 shows the obtained likelihood curve for δ_{CP} on the right-hand side and the obtained confidence contours in the 2D atmospheric plane: $\sin^2\theta_{23}$ and Δm^2_{32} (NO)/Δm^2_{31} (IO). The results are presented in both the normal and inverted neutrino mass ordering hypotheses. It can be deduced from these results that the preferred scenario by T2K data is the normal ordering with $\sin^2\theta_{23}$ in the upper octant (>0.5) but other scenarios are not fully rejected. It is important to note here that additional studies have been performed to validate these results. Specifically, studies with simulated data have been conducted to check the impact of the choice of model for flux and cross-section since there is not any model that fully reproduces all known data from different experiments (other neutrino experiments and electron scattering data). Data was simulated from each alternative model and analyzed as real data, with a fit of the nominal T2K model. The impact on oscillation parameters was computed and compared to predefined criteria. It was found that some of these alternative studies had a significant impact on the atmospheric Δm^2 parameter so an additional uncertainty computed to be of 3.1×10^{-5} eV^2/c^4 is taken into account in this result. In the end, the quoted result is Δm^2_{32} (NO) = $2.506^{+0.047}_{-0.059} \times 10^{-3}$ eV^2/c^4 and Δm^2_{31} (IO) $2.473^{+0.051}_{-0.054} \times 10^{-3}$ eV^2/c^4 which is clearly reaching a precision era for this measurement.

Because δ_{CP} and $\sin^2\theta_{23}$ have inherently non-gaussian likelihood curves, classic critical χ^2 values under the Gaussian assumption can not be used to build confidence intervals for these two parameters. Instead, Feldman-Cousins [13] studies are conducted separately for each of these two parameters with a large number of simulated data sets (50 000 for δ_{CP} and 20 000 for $\sin^2\theta_{23}$) for each parameter value to test, throwing systematic parameters by taking into account constraints from the near detectors. Oscillation parameters constrained externally are thrown from their usual external Gaussian prior as explained before. Other oscillation parameters in T2K, are thrown from a post fit distribution close to the data fit result. This way, specific critical χ^2 values can be computed in order to build confidence intervals with the proper coverage. The resulting computed confidence intervals are reported in figure 2 on the likelihood curves for δ_{CP} (left-hand plot) and

$\sin^2\theta_{23}$ (right-hand plot). The main conclusion here is the exclusion of the conservation of the CP symmetry at better than 90%C.L. and close to a 2σ level.

4. Conclusions and perspectives

As a conclusion, T2K is now on its way to a precision measurement of the disappearance parameters and is still pursuing the discovery of the leptonic CP symmetry violation. Looking into the future, T2K is getting ready for a new phase of the experiment with a number of ongoing upgrades. The beam is being upgraded to be able to collect more data as most of T2K uncertainties are currently statistically dominated. As we accumulate more data, the importance of systematic will grow. To that end, the near detector ND280 is going through a major upgrade [14] with prospects for more precise cross-section measurements. On the analysis side, more and more effort is invested in studying the impact of models and systematic parameters to prepare for the future as well. All these efforts will carry on continuously and become a legacy for the next generation experiments such as Hyper-Kamiokande [15] which will use the same accelerator and near detectors. In the same idea, combined analyses with atmospheric neutrinos or other experiments are also ongoing in order to break the degeneracy between oscillation parameters and therefore improve the precision measurements.
Finally, new data is taken in T2K and improvements to the analysis are continuously done to provide even better measurements in the very near future.

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