PROCEEDINGS OF SCIENCE

Recent T2K Neutrino Oscillation Results

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T2K is a long-baseline neutrino oscillation experiment sited in Japan that explores neutrino oscillations via ν_μ disappearance measurements and $\nu_\mu \to \nu_e$ appearance measurements. Neutrino mixing angles and mass differences have been measured under the assumption of both of the possible mass orderings, and constraints have been set on the CP-violating phase δ_{CP}. The best-fit results for the mixing angles $\sin^2\theta_{23}$ for normal mass ordering and for inverted mass ordering, respectively, are $0.532^{+0.030}_{-0.037}$ and $0.532^{+0.029}_{-0.035}$, with corresponding mass differences in each case of $\Delta m^2_{32} = (2.452^{+0.071}_{-0.070}) \times 10^{-3}$ eV^2 and $\Delta m^2_{13} = (2.432^{+0.069}_{-0.071}) \times 10^{-3}$ eV^2. The parameter $\sin^2\theta_{13}$ was measured to be $0.0268^{+0.0055}_{-0.0043}$ (normal ordering) and $0.0300^{+0.0059}_{-0.0050}$ (inverted ordering). The 1σ allowed region for δ_{CP} is $[-2.509, -1.260]$ for normal ordering. No region of inverted ordering is included in the 1σ confidence level. In both cases, the CP-conserving values of $\delta_{CP} = 0, \pi$ have been excluded at the 2σ level. T2K has seen a small preference for normal ordering over inverted ordering with a Bayes factor of 8.0.

European Physical Society Conference on High Energy Physics - EPS-HEP2019 -
10-17 July, 2019
Ghent, Belgium

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PoS(EPS-HEP2019)394

1. Introduction

The mixing of three light neutrino flavours is well-described by the PMNS mixing matrix that describes the relationship between the three non-degenerate neutrino masses and the flavours [1]. In its standard parameterization, this matrix has four free parameters: three mixing angles and a CP-violating phase, δ_{CP}, although two other parameters may exist if neutrinos are Majorana. Of the three mixing angles, θ_{12}, θ_{23} and θ_{13}, the latter two are accessible to accelerator-based neutrino oscillation experiments such as T2K. The PMNS oscillation probabilities depend upon these angles and also upon the differences of the squares of the masses, $\Delta m^2_{ij} = m^2_i - m^2_j$, $i \neq j$, where $i, j = 1, 2$ or 3. The two independent mass differences have been measured, but because oscillations in a vacuum alone cannot determine the sign of Δm^2_{ij}, only the sign of the smaller difference Δm^2_{21} is known and two possibilities still exist for the mass ordering: normal ordering, where the larger difference is $\Delta \mathrm{m}^2_{32}$, or inverted ordering, where the larger difference is $\Delta \mathrm{m}^2_{13}$. T2K has made measurements of θ_{23} θ_{13}, $\Delta \mathrm{m}^2_{32}$ (or for inverted ordering $\Delta \mathrm{m}^2_{13}$) , has provided constraints on δ_{CP}, and shown hints of a preference for normal mass ordering.

2. T2K

The Tokai to Kamioka (T2K) experiment is a long-baseline neutrino oscillation experiment in which a narrow-band ν_μ beam with mean energy around 600 MeV produced by the Japan Proton Accelerator Complex (JPARC) in Tokai, Japan is directed toward the far detector 295 km away, Super-Kamiokande (SK), which measures the oscillated beam. A suite of near detectors are located 280 m from the neutrino production target: the on-axis INGRID and off-axis ND280. INGRID measures the ν_μ and $\bar{\nu}_\mu$ beam flux, direction and stability. ND280 consists of subdetectors including trackers, calorimeters and muon range detectors that provide a range of neutrino interaction targets: water, carbon and lead. ND280 measures the ν_e contamination in the unoscillated beam, and characterizes the flux and the various event topologies at the same 2.5^{o}off-axis angle as SK. Both of the near detectors measure neutrino interaction cross sections. SK is a 50-kton water-Cherenkov detector in which ν_μ and ν_e are detected via the corresponding charged lepton produced in charged-current (CC) interactions. ν_μ and ν_e charged-current quasi-elastic (CCQE) events are selected by characterizing events in which a relativistic charged lepton from the neutrino interaction has produced one ring of Cherenkov light that is imaged onto the photomulitplier tubes. SK has excellent e/μ separation based upon the characteristics of the ring. Recently, a CC sample with one positive pion in the final state has been added to the data samples for T2K, where the pion is identified through a decay electron [2].

T2K measures both the disappearance of ν_μ or conversely its survival probability P($\nu_\mu \rightarrow \nu_\mu$), and the appearance of ν_e i.e. its appearance probability P($\nu_\mu \rightarrow \nu_e$). Via the oscillation probabilities as predicted by the PMNS mixing matrix, T2K has leading-order sensitivity to the oscillation parameters $\sin^2 2\theta_{23}$ and $\Delta \mathrm{m}^2_{32}$ (or $\Delta \mathrm{m}^2_{13}$ for inverted ordering) through ν_μ disappearance, and leading order sensitivity to $\sin^2 \theta_{23}$ and $\sin^2 2\theta_{13}$ via the appearance measurement. Additionally, there is sub-leading sensitivity to the CP-violating parameter $\sin \delta_{CP}$ in the appearance measurements that manifests itself as a 27% difference between the probability of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation, with the former being enhanced and the latter suppressed in the case of $\delta_{CP} = -\pi/2$, as shown in Figure 1, and a 10% sensitivity to matter effects and therefore to the mass ordering. Figure 1 assumes normal mass ordering, $\sin^2\theta_{23} = 0.528$, $|\Delta m^2_{32}| = 2.509\times10^{-}3\ \mathrm{eV}^2$, and values of θ_{13}, θ_{12} and Δm^2_{21} are taken from [1].

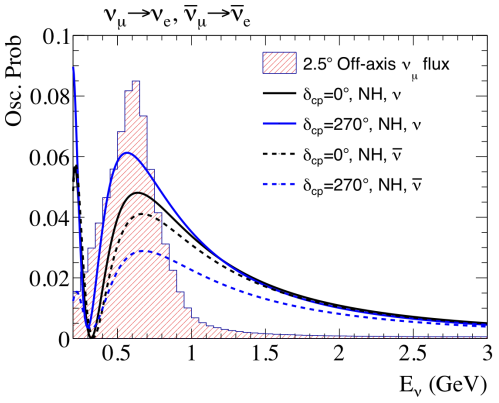

Figure 1: The predicted oscillation probability for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. The shaded histogram shows the position of the T2K neutrino flux spectrum. The lines show the oscillation probability for various values of δ_{CP} .

3. Data

At T2K, the neutrinos are produced by colliding 30 GeV protons onto a carbon target, resulting in the production of hadrons, mainly pions. The pions subsequently enter a decay volume and decay into either ν_μ or $\bar{\nu}_\mu$ and their associated charged lepton. T2K can produce either ν_μ or $\bar{\nu}_\mu$ beam by reversing the current in the focusing horns that select the charge of the pions produced. The data used in this analysis corresponds to approximately 1.51×10^{21} and 1.65×10^{21} protons on target (POT) for neutrino-mode and antineutrino-mode beam, respectively, with a total of 3.16×10^{21} POT at SK. At ND280, a total of approximately 9.66×10^{20} POT were used.

4. Analysis overview

The analysis strategy makes use of the near detector data to significantly reduce systematic uncertainties in the measured oscillation parameters. Both the ND280 and the SK data are modelled by Monte Carlo simulations such that the number of events predicted in each detector depends upon the beam flux at that detector, the neutrino interaction cross sections in the material of each detector, and the detector response. In addition, the number of events in SK depends on the probability of neutrino oscillations.

The beam flux, the cross sections, and the detector responses each have dedicated models. The flux model is honed by external hadron production measurements from the NA61/SHINE experiment [3] as well as INGRID and beam monitor data. The cross-section model is tuned to external cross-section data. The simulations for ND280 are then constrained by a fit to the ND280 data in which approximately 780 parameters are tuned. Figure 2 (right) shows a few of the Final

State Interaction (FSI) cross-section parameters. The parameters shown are used to model CC interactions that produce a final-state pion, and describe, for example, pion absorption, inelastic scattering or charge exchange inside the nucleus. These effects can alter the observable properties of the particles measured in the ND280 data. The data used in the fit are categorized according to 14 observable topologies (Figure 2 left) depending on whether the beam is in neutrino- or antineutrino-mode, and on the number of pions that are visible in addition to the muon from the CC neutrino interaction. Correlations between parameters are assessed via a correlation matrix. The fit therefore tunes the parameters, and reduces the systematic uncertainties that are common to both ND280 and SK by a factor of two to three.

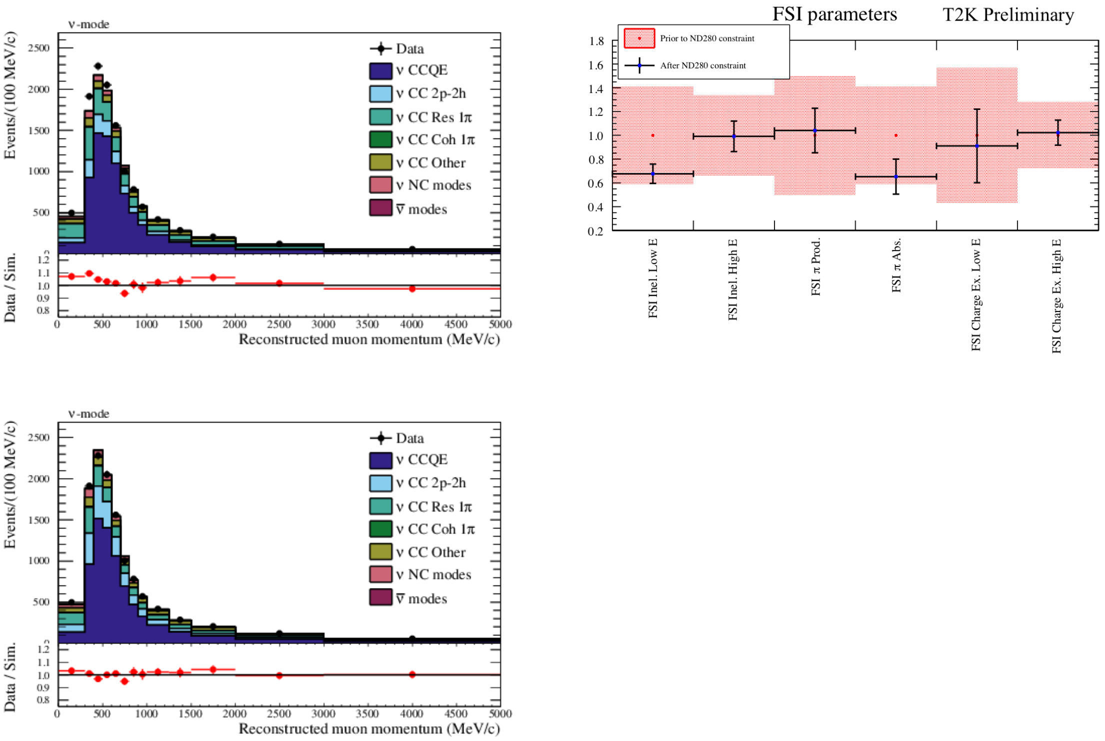

Figure 2: Left: The selected data for one of the 14 topologies of ND280 events that are used to constrain the models: CC events with no detected pions. The points are data and the coloured histogram is the Monte Carlo simulation. The top shows the pre-fit agreement and the bottom shows post-fit. In each case, the lower panel shows the ratio of data to Monte Carlo simulation [2]. Right: A few pre- and post-fit FSI parameters are shown in red and black, respectively. The parameter values are scaled to the pre-fit values.

The subsequent Monte Carlo simulation is used to predict the numbers of events that would be observed in each of the five topologies selected in SK: neutrino-mode and anti-neutrino mode CCQE-like events with either a muon-like or electron-like Cherenkov ring, and the latter with the inclusion of one more ring consistent with that of an electron from charged pion decay via a muon. Table 1 presents predictions and the observed numbers for each of the five SK data sets, where the predictions assume normal mass ordering, the value of θ_{13} from [1], and $\sin^2\theta_{23} = 0.528$. The p-value for the fluctuation in the CC1π^+ sample to be seen in any one of the five samples is 12%.

Sample	Predicted				Observed
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$	
ν-mode μ CCQE	272.34	271.97	272.30	272.74	243
$\bar{\nu}$-mode μ CCQE	139.47	139.12	139.47	139.82	140
ν-mode e CCQE	74.46	62.26	50.59	62.78	75
ν-mode e CC1π	7.02	6.10	4.94	5.87	15
$\bar{\nu}$-mode e CCQE	17.15	19.57	21.75	19.33	15

Table 1: Predictions for events in SK assuming different values of δ_{CP}, versus observations.

5. Recent oscillation results

Three fits are performed to the data to extract the oscillation parameters θ_{23}, θ_{13} and $|\Delta m^2_{32}|$ ($|\Delta m^2_{13}|$ for inverted ordering) and to set limits on δ_{CP}: two frequentist likelihood fits that use SK reconstructed lepton energy for ν_μ events, one of which uses reconstructed lepton energy and angle for ν_e events and the other that uses reconstructed momentum and angle for ν_e events, and one Bayesian analysis with a Markov Chain Monte Carlo that uses reconstructed energy for all samples and performs a simultaneous fit with ND280 and SK data. The two frequentist analyses each perform a fit to the ND280 data and then use it as input to the far detector fit. The three analyses give results that are consistent with each other.

The 68% and 90% confidence levels (CL) for Δm^2 and $\sin^2\theta_{23}$ are shown in Figure 3, where the value of θ_{13} is taken from [1]. The best-fit results for $\sin^2\theta_{23}$ are $0.532^{+0.030}_{-0.037}$ and $0.532^{+0.029}_{-0.035}$ for normal and inverted mass ordering, respectively, both of which are consistent with maximal mixing. The values for $|\Delta m^2_{32}|$ and $|\Delta m^2_{13}|$ are $(2.452^{+0.071}_{-0.070}) \times 10^{-3}$ eV^2 and $(2.432^{+0.069}_{-0.071}) \times 10^{-3}$ eV^2 for normal and inverted mass ordering, respectively.

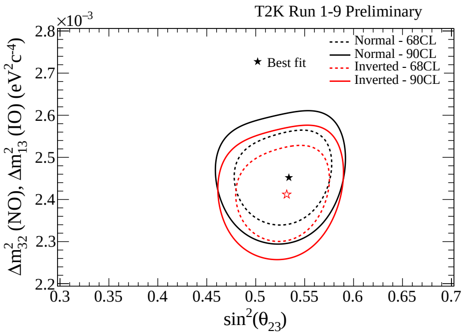

Figure 3: Δm^2 versus $\sin^2\theta_{23}$ for both mass orderings.

At T2K, the difference between the $\bar{\nu}_\mu \to \bar{\nu}_e$ versus $\nu_\mu \to \nu_e$ oscillation rate yields information about the value of δ_{CP}, as shown in Figure 4 (left). The predicted rates are shown for antineutrino-mode electron-like candidates versus neutrino-mode electron-like candidates for several values of θ_{23} and δ_{CP}. The T2K data is shown by the point with error bars, and can be seen to favour $\delta_{CP} = -\pi/2$. Figure 4 (right) shows the Feldman Cousins 2σ critical values for δ_{CP} when the value of θ_{13}

from [1] is taken as a prior in the fit. Note that the CP conserving values of 0 and π are excluded at 2σ. The 1σ allowed region is $\delta_{CP} = [-2,509,-1.260]$ for normal ordering. No region of inverted ordering is included in the 1σ confidence level.

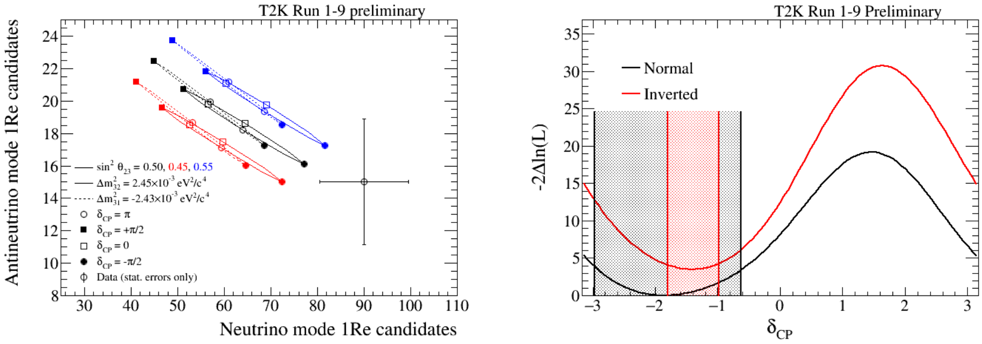

Figure 4: Left: Predicted numbers of antineutrino-mode electron candidates versus neutrino-mode electron candidates, for several parameter values. The point with error bars is T2K data. Right: Feldman Cousins 2σ critical values for δ_{CP} are shown for normal (black) and inverted (red) ordering.

The 68% and 90% CL are shown for θ_{13} in Figure 5 for the T2K data alone (left) and when the fit is constrained by the (reactor experiment) value of θ_{13} from [1] (right). The T2K-only result is compatible with the reactor value shown by the gold band, and has the best-fit values $\sin^2\theta_{13} = 0.0268^{+0.0055}_{-0.0043}$ and $0.0300^{+0.0059}_{-0.0050}$ for normal and inverted ordering, respectively. The left plot shows that the T2K data alone is able to constrain the values of δ_{CP}.

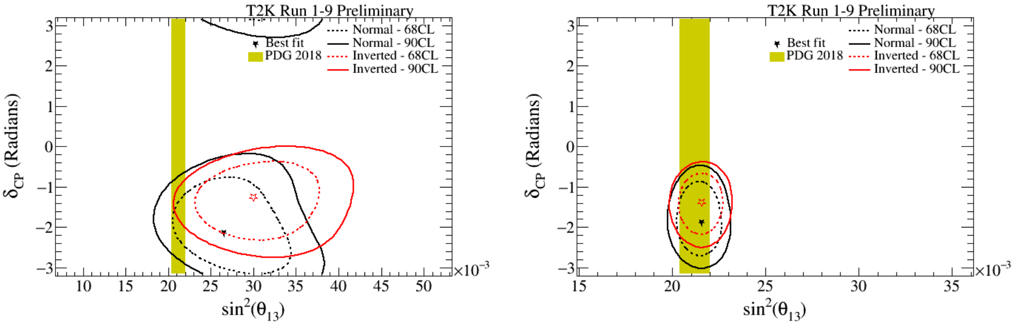

Figure 5: Left: δ_{CP} versus $\sin^2\theta_{13}$ for both normal and inverted mass ordering, from T2K data only. Right: The reactor value (gold band) of θ_{13} is used as a constraint in the fit.

T2K has also conducted a search for $\bar{\nu}_\mu \to \bar{\nu}_e$ events using antineutrino-mode electron-like candidates and a test statistic β that compares the consistency of the data with the PMNS expectation for oscillation ($\beta = 1$), in which case 17.1 events are expected, with no oscillation ($\beta = 0$), in which case 9.4 events are expected. There are 15 events in the data. To improve the power of the analysis, not only the rate but also the shape of the lepton angle versus lepton momentum distribution is taken into account. This leads to an exclusion of $\beta = 0$ (i.e. the hypothesis of no oscillation) at 2σ.

Bayesian posterior probabilities where the reactor value for θ_{13} was used as a prior show a preference for normal ordering over inverted ordering with a Bayes factor of 8.0. There's a slight preference for θ_{23} in the upper octant rather than the lower octant, with a Bayes factor of 3.88.

6. T2K's future plans

T2K will continue with an upgrade of the beam, ND280 and SK, with improvements expected in 2021. The beam intensity will be increased from 485 kW to 750 kW in the near future, with further increases before 2027 and the start of Hyper-Kamiokande [4]. T2K aims to attain 20×10^{21} POT and a 3σ exclusion of $\delta_{CP} = 0$ or π. The ND280 upgrade will reduce the detector systematic uncertainties from 8% to less than 4% by improving the acceptance, timing and efficiency through the addition of new subdetectors [5]. The addition of gadolinium to SK will enhance neutron detection, and improve low-energy $\bar{\nu}_e$ detection and background identification.

7. Conclusions

T2K has measured the oscillation parameters θ_{23}, $|\Delta m^2_{32}|$ (or $|\Delta m^2_{13}|$ for inverted ordering), θ_{13} and set limits on δ_{CP}, excluding CP-conserving values at 2σ. The best-fit results for $\sin^2\theta_{23}$ are $0.532^{+0.030}_{-0.037}$ and $0.532^{+0.029}_{-0.035}$ for normal and inverted mass ordering, respectively, both of which are consistent with maximal mixing. The values for $|\Delta m^2_{32}|$ and $|\Delta m^2_{13}|$ are $(2.452^{+0.071}_{-0.070}) \times 10^{-3}$ eV^2 and $(2.432^{+0.069}_{-0.071}) \times 10^{-3}$ eV^2 for normal and inverted mass ordering, respectively. The best-fit values of $\sin^2\theta_{13}$ are $0.0268^{+0.0055}_{-0.0043}$ and $0.0300^{+0.0059}_{-0.0050}$ for normal and inverted ordering, respectively, compatible with the value from reactor experiments. The 1σ allowed region for δ_{CP} is $[-2,509,-1.260]$ for normal ordering. No region of inverted ordering is included in the 1σ confidence level. A preferred value of δ_{CP} near $-\pi/2$ is seen. Bayesian analysis indicates a preference for normal over inverted mass ordering and a slight preference for $\theta_{23} > 45^{o}$. A search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations is at present inconclusive, but excludes the hypothesis of no oscillations at 2σ. T2K will run at least until the start of Hyper-Kamiokande, with upgraded beam, detectors, and analyses, with the expectation of excluding CP-conserving values of δ_{CP} at the 3σ level.

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