Initial probe of δ_{CP} by T2K with combined electron neutrino appearance and muon neutrino disappearance.

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T2K is a long-baseline neutrino oscillation experiment in which a ν_μ beam is produced at the J-PARC facility and detected 295 km away by the Super-Kamiokande, water Cherenkov detector. Up to May 2013, T2K has accumulated 6.57×10^{20} protons on target, approximately 8% of the experimental goal. T2K has observed 120 ν_μ candidates, which show a clear disappearance oscillation pattern, and 28 ν_e candidates, with which ν_e appearance was established. The measurement of ν_e appearance is particularly important because it enables us to determine $\delta_{\rm CP}$ when θ_{23} and θ_{13} are known. Using values of θ_{23} determined by T2K disappearance measurements and θ_{13} measured by reactor $\bar{\nu}_e$ experiments, T2K has obtained the first constraint on $\delta_{\rm CP}$ from a ν_e appearance measurement.

1 The Tokai to Kamioka experiment

The Tokai to Kaimoka (T2K) experiment is a long-baseline neutrino oscillation experiment located in Japan. An intense, high purity ν_μ beam is produced (at J-PARC) by colliding a 30 GeV proton beam with a stationary graphite target, resulting in a beam of secondary hadrons. Three magnetic horns are used to select π^+, which decay to produce an almost pure beam of ν_μ (approximately 1% ν_e contamination). The neutrino beam is directed 2.5° away from the axis between the target and the far detector 295 km away. This off-axis technique produces a narrow band beam with a peak energy around 0.6 GeV. This corresponds to the energy of the first $\nu_\mu \to \nu_e$ oscillation maximum.

The near detector complex is located 280 m downstream from the neutrino production point and consists of an on-axis Interactive Neutrino GRID (INGRID) detector and an off-axis near detector (ND280). INGRID is used to monitor the beam intensity and direction. ND280 is used to measure the neutrino flux and interaction cross-sections, which reduces systematic uncertainties on the oscillation analyses. The off-axis detector consists of several sub-detectors inside a 0.2 T magnet, namely a π^0 detector, two active fine grain detectors, three gaseous argon time projection chambers, an electromagnetic calorimeter and a side muon range detector.

The far detector, located 295 km from the neutrino production point, is the Super-Kamiokande water Cherenkov detector. Super-Kamiokande is divided into an inner and outer detector. The inner detector has a 22.5 kton water fiducial volume that is surrounded by 11,129 photomultiplier tubes (PMTs). The inner detector and PMTs are surrounded by a 2 m wide outer detector. Neutrino interactions with water produce Cherenkov light which can be used to distinguish between electron and muon-like events. Good separation between ν_e and ν_μ candidates is achieved via a particle identification variable, with a probability of misidentifying a μ as an e of $< 1\%$.

T2K was optimised to perform a high precision measurement of the mixing parameters θ_{23} and Δm^2_{32} via ν_μ disappearance and to search for the mixing angle θ_{13} via ν_e appearance in the far detector. Recent work from the collaboration has provided the first hints that the parameter δ_{CP} may not be zero. Up to May 2013 T2K has collected 6.57×10^{20} protons on target.

2 Joint ν_μ and ν_e analysis

Charged current (CC) ν_μ interactions in the near detector are used to constrain the energy spectrum of the neutrino beam and neutrino interaction cross section parameters. Details of this analysis are given in [1]. CC interactions that pass the selection criteria are divided into three classes: CC-0π, which is dominated by CC quasi elastic scattering (CCQE) interactions; CC$-1\pi^+$, from CC resonant pion production; and finally CC-other which covers all remaining CC topologies that are selected. The three samples are fitted with a total of 25 beam parameters, 21 cross section parameters and 210 parameters that describe ND280 detector systematics. The fit to the ND280 data gives estimates for 22 beam flux parameters at the far detector (Super-Kamiokande), 5 common cross section parameters and their covariance. Inclusion of information from ND280 reduces the uncertainty on the expected number of electron-like events at the far detector from 27.2% to 8.8%.

At Super-Kamiokande, candidate events are selected if they are in time with the T2K neutrino beam, the energy of the Cherenkov ring is above 30 MeV, the ring occurs in the inner detector and there is low activity in the outer detector. A further cut is applied to ensure that the event vertex is at least 2 m from the wall of the inner tank and such events are "fully contained fiducial volume" (FCFV). Full details are given in [1]. Candidate ν_e interactions in the FCFV sample are identified by looking for events with a single electron-like Cherenkov ring with a reconstructed electron momentum above 100 MeV/c and reconstructed neutrino energy below 1250 MeV. The momentum cut is necessary to eliminate decay-electrons from stopping muons generated by CC interactions in the detector. Finally, additional contamination from π^0 events, which can mimic ν_e interactions is reduced by using a new reconstruction algorithm based upon the work in [2]. The application of this cut removes 69% of the π^0 background events relative to previous T2K ν_e appearance selections [3].

A binned extended maximum likelihood fit is used to determine the neutrino oscillation parameters. The likelihood comprises of four components: a normalization term ($\mathcal{L}_{norm}$), a spectral shape term ($\mathcal{L}_{shape}$), a systematics term ($\mathcal{L}_{syst}$) and a constraint term ($\mathcal{L}_{const}$) from other measurements. The likelihood is therefore:

$$\mathcal{L}(N_{obs}, \overrightarrow{x}, \overrightarrow{o}, \overrightarrow{f}) = \mathcal{L}_{norm}(N_{obs}; \overrightarrow{o}, \overrightarrow{f}) \times \mathcal{L}_{shape}(\overrightarrow{x}; \overrightarrow{o}, \overrightarrow{f}) \times \mathcal{L}_{syst}(\overrightarrow{f}) \times \mathcal{L}_{const}(\overrightarrow{o}),$$

where N_{obs} is the number of observed events, $\overrightarrow{x}$ is a set of kinematic variables, $\overrightarrow{o}$ represents the oscillation parameters and $\overrightarrow{f}$ describes the systematic uncertainties. Full details of the likelihood fit used in the T2K analysis is given in [1]. In the fit, values for several oscillation parameters are fixed as follows: $\sin^2\theta_{12} = 0.306, \Delta m^2_{21} = 7.6 \times 10^{-5}\mathrm{eV}^2$ [4], $\sin^2\theta_{23} = 0.5, |\Delta m^2_{32}| = 2.4 \times 10^{-3}\mathrm{eV}^2$ [5] and $\delta_{\mathrm{CP}} = 0$. For the normal (inverted) hierarchy case, the best-fit value (68% confidence level) is $\sin^2 2\theta_{23} = 0.140^{+0.038}_{-0.032}(0.170^{+0.045}_{-0.037})$. In total, 28 candidate ν_e events were observed, which is significantly larger than the predicted background of 4.92 ± 0.55. Figure 1 shows the best fit reconstructed neutrino energy for the 28

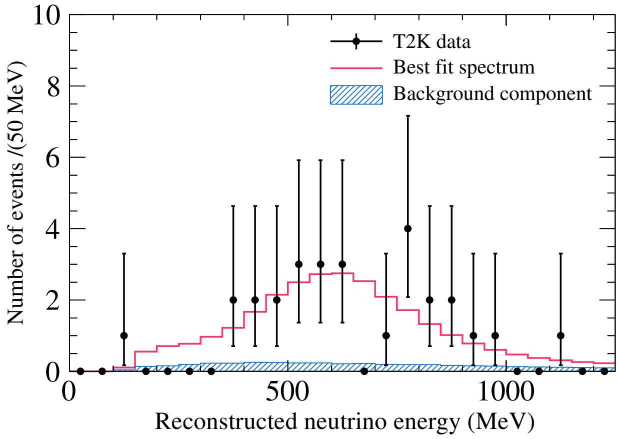

Figure 1: The E_ν^{rec} distribution for ν_e candidates with the MC prediction at the best fit of $\sin^2\theta_{13} = 0.144$ (normal hierarchy).

observed ν_e events. The significance for a non-zero value of θ_{13} is calculated to be 7.3σ using the difference of log likelihood values between the best-fit value of θ_{13} and $\theta_{13} = 0$ and using a test statistic having fixed values of θ_{23} and δ_{CP}.

Using any value of the parameters θ_{23} and δ_{CP} consistent with their present uncertainties returns a significance of greater than 7σ. The uncertainty associated with θ_{23} and Δm^2_{32} are taken into account via the $\mathcal{L}_{const}$ term in the fit and marginalising the likelihood over θ_{23} and Δm^2_{32}. Values of $\sin^2\theta_{23}$ and Δm^2_{32} are taken from the T2K ν_μ disappearance results [5]. Performing the fit for all values of δ_{CP} results in the allowed contours shown in Figure 2

Constraints on the parameter δ_{CP} can be obtained by combining the T2K results with the measured θ_{13} value from reactor anti-neutrino experiments. Details of the constraint are given in [1]. The combined T2K and reactor neutrino measurement indicates a preferred value of $-\pi/2$ for δ_{CP}. The Feldman-Cousins method is used to determine the 90% C.L. limits shown in Figure 3. The data excludes values of δ_{CP} between 0.19π and 0.80π at 90% C.L. for the normal hierarchy. For the inverted hierarchy values between $-\pi$ and -0.97π and -0.04π and π are excluded at 90%C.L.

3 Conclusions

The T2K experiment has made the first observation of ν_e appearance in a ν_μ beam at a baseline of 295 km and peak beam energy of 0.6 GeV. A best fit value for $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ ($0.170^{+0.045}_{-0.037}$) for the normal (inverted) neutrino mass hierarchy and assuming fixed values of $|\Delta m^2_{32}| = 2.4 \times 10^3$ eV^2, $\sin^2\theta_{23} = 0.5$ and $\delta_{\text{CP}} = 0$. This best fit value has a significance of 7.3σ over the hypothesis of $\sin^2 2\theta_{13} = 0$. By combining the T2K result with the world average value of θ_{13} from reactor experiments, δ_{CP} between 0.19π and 0.80π at 90% C.L. for the normal hierarchy. For the inverted hierarchy values between $-\pi$ and -0.97π and -0.04π and π are excluded at 90% C.L. The T2K experiment will continue to take data and investigate

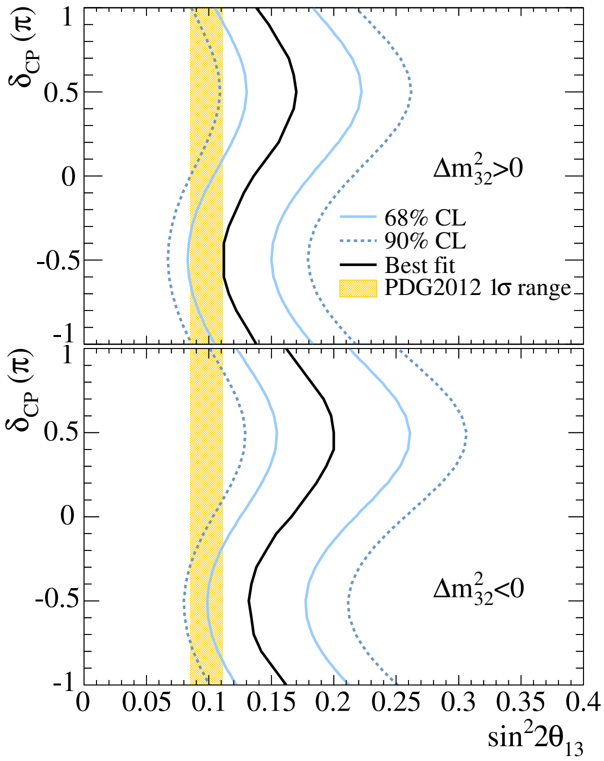

Figure 2: Allowed region of 68% (thin, solid, light blue) and 90% C.L. (dashed, blue) for $\sin^2 2\theta_{13}$ for each value of $\delta_{\rm CP}$. The thick (black) solid line is the best fit value for each value of $\delta_{\rm CP}$. Run1-4 data, marginalized over $\sin^2\theta_{23}$ and Δm^2_{32}. The values of $\sin^2\theta_{23}$ and Δm^2_{32} are varied in the fit with the constraint from [5]. The shaded region shows the average value of θ_{13} from the PDG 2012 [6].

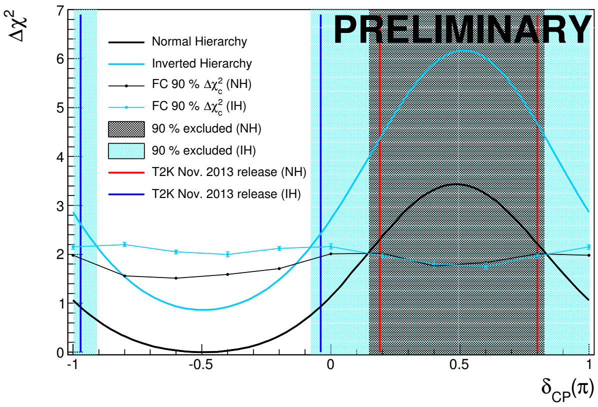

Figure 3: Profiled $\Delta\chi^2$ as a function of δ_{CP} for the combined reactor neutrino results and T2K joint three flavour frequentist analysis. The critical $\Delta\chi^2$ values and excluded regions obtained at the 90% C.L. for the normal and inverted hierarchies are overlaid.

CP violation in the lepton sector more precisely.

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