



# Joint $\nu_\mu$ Disappearance and $\nu_e$ Appearance Analysis at the T2K Experiment Using a Frequentist Approach

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## Abstract

The T2K long-baseline neutrino oscillation experiment has observed the disappearance of  $\nu_\mu$  and the appearance of  $\nu_e$  from its  $\nu_\mu$  beam. Since 2010, it has accumulated  $6.57 \times 10^{20}$  protons on target and observed 120  $\nu_\mu$  and 28  $\nu_e$  event candidates. With this dataset, corresponding to only  $\sim 8\%$  of its goal POT, T2K has achieved world leading results: the best precision in  $\theta_{23}$ , the strongest evidence of  $\nu_e$  appearance in a  $\nu_\mu$  beam and the first hint on  $\delta_{CP}$ . Its first joint 3-flavour oscillation analysis, combining the  $\nu_\mu$  disappearance and  $\nu_e$  appearance channels, is presented in this paper using a Frequentist approach. The results of this analysis, combined with the measurements from reactor experiments, indicate that  $\delta_{CP}$  is consistent with  $-\pi/2$ . Furthermore, the data excluded values of  $\delta_{CP}$  in the interval  $[0.146, 0.825]\pi$  ( $[-0.080, 1.091]\pi$ ) at the 90% CL for normal (inverted) mass hierarchy.

**Keywords:** Neutrino oscillation, Muon neutrino disappearance, Electron neutrino appearance, T2K, CP violation

## 1. The T2K Experiment

The Tokai-to-Kamioka (T2K) experiment [1] is a long-baseline neutrino oscillation experiment located in Japan, and the first long-baseline neutrino oscillation experiment using an off-axis configuration, with the neutrino beam directed at an angle of  $2.5^\circ$  away from the direction towards the far detector. The T2K neutrino beam is a highly pure  $\nu_\mu$  beam produced via the decay of the secondary particles (essentially pions and kaons) originated in the interactions with a graphite target of a 30 GeV proton beam generated at the Japan Proton Accelerator Research Complex (J-PARC) site in Tokai. Measurements of the unoscillated neutrino event rate are provided by a near detector complex located at 280 m from the production target, which consists of an on-axis detector, INGRID, that monitors the neutrino beam direction and intensity in a daily basis by means of neutrino interactions in iron; and a set of multiple sub-detectors placed off-axis inside a magnetic field, ND280, that measures the event rate, energy spectrum and flavour composition of the neutrino beam. The

far detector Super-Kamiokande (SK), a 50 kton water Čerenkov detector situated in the Kamioka mine, 295 km away, provides the measurements of the neutrino event rate after oscillations, efficiently separating the  $\nu_\mu$  and  $\nu_e$  event candidates.

## 2. Systematic Uncertainties for Oscillation Measurements

The systematic uncertainties considered for the oscillation analyses can be grouped into three different categories: i) independent cross section parameters, representing the uncertainties on the cross sections related to the nuclear model, or those for which the near detector is insensitive; ii) uncertainties related to SK flux simulation and cross sections common to the near and far detector; and iii) systematic uncertainties related to the far detector efficiencies, estimated using control samples, and linearly combined with the final state and secondary interaction (FSI+SI) uncertainties. Fits to external datasets are used to tune the initial values and uncertainties for the flux [3] and cross sections models,

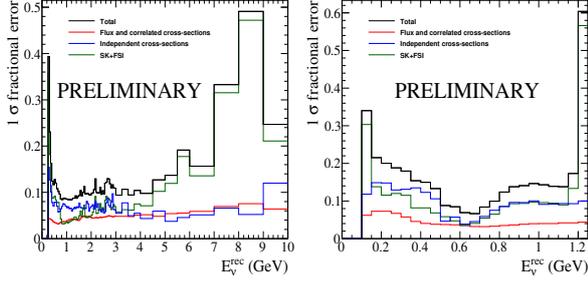


Figure 1: The  $1\sigma$  fractional error for the reconstructed energy spectra of the  $\nu_\mu$  (left) and  $\nu_e$  (right) event candidates due to the effect of the systematic errors, separated into categories and calculated using MC toy experiments with typical values of the oscillation parameters.

simulated using NEUT [2], and a fit to the ND280 data is performed to constrain the flux and correlated cross section uncertainties [4]. Figure 1 shows the fractional error for the reconstructed energy spectra of the  $\nu_\mu$  and  $\nu_e$  events due to the effect of the systematics.

### 3. T2K Joint $\nu_\mu$ Disappearance and $\nu_e$ Appearance Analysis Using a Frequentist Approach

The joint 3-flavour oscillation analysis, combining the  $\nu_\mu$  disappearance and the  $\nu_e$  appearance channels, consists in a simultaneous fit in a 3 flavour framework, including matter effects (assuming constant density matter), to the reconstructed energy spectra of the  $\nu_\mu$  and  $\nu_e$  event candidates from the T2K beam at SK, in which the four oscillation parameters  $\sin^2 \theta_{23}$ ,  $\Delta m^2$ ,  $\sin^2 \theta_{13}$  and  $\delta_{CP}$  (the solar parameters are fixed since their effect is negligible) are jointly determined, taking their interdependencies into account. The analysis presented here is performed using a Frequentist approach, and the best-fit values of the oscillation parameters are found by minimizing the negative log-likelihood ratio:

$$\chi^2 = -2 \ln \mathcal{L}(\Delta m^2, \sin^2 \theta_{23}, \sin^2 \theta_{13}, \delta_{CP}; \mathbf{f}) =$$

$$2 \cdot \sum_{i=0}^{m_\mu-1} \left[ (N_{SK;\mu,i}^p - N_{SK;\mu,i}^d) + N_{SK;\mu,i}^d \cdot \ln \left( \frac{N_{SK;\mu,i}^d}{N_{SK;\mu,i}^p} \right) \right]$$

$$+ 2 \cdot \sum_{i=0}^{m_e-1} \left[ (N_{SK;e,i}^p - N_{SK;e,i}^d) + N_{SK;e,i}^p \cdot \ln \left( \frac{N_{SK;e,i}^d}{N_{SK;e,i}^p} \right) \right]$$

$$+ (\mathbf{f} - \mathbf{f}_0)^T \cdot \mathbf{C}^{-1} \cdot (\mathbf{f} - \mathbf{f}_0), \quad (1)$$

where  $N_{SK;\mu,r}^d$  ( $N_{SK;e,r}^d$ ) is the observed number of  $\nu_\mu$  ( $\nu_e$ ) events in the  $r^{\text{th}}$  reconstructed energy bin, with  $m_\mu$  ( $m_e$ ) total reconstructed energy bins, and  $N_{SK;\mu,r}^p$  ( $N_{SK;e,r}^p$ ) is the corresponding expected number of events, calculated as a function of the oscillation parameters, and  $\mathbf{f}$  ( $\mathbf{f}_0$ ) represents the varied (nominal) values

of the systematic parameters, being  $\mathbf{C}$  the corresponding total covariance matrix.

The best-fit values obtained for the oscillation parameters are summarized in Table 1. When combining with the reactor experiments, the weighted average of the results from the reactor experiments Daya Bay, RENO and Double Chooz, namely  $(\sin^2 2\theta_{13})_{\text{reactor}} = 0.095 \pm 0.01$  [5], is used by adding a Gaussian term in Eq. 1, and the best-fit value for  $\delta_{CP}$  becomes approximately  $-0.495\pi$  for both mass hierarchies.

Table 1: Best-fit values of the oscillation parameters for the joint 3-flavour Frequentist analysis with and without reactor constraint.  $\Delta\chi^2$  is the difference between the best-fit solution and the one for the alternative mass hierarchy assumption.

	MH	$\Delta m^2$ $10^{-3} eV^2/c^4$	$\sin^2 \theta_{23}$	$\sin^2 \theta_{13}$	$\delta_{CP}$	$\Delta\chi^2$
T2K	NH	2.512	0.524	0.0422	1.909	0.01
T2K	IH	2.488	0.523	0.0491	1.005	-
T2K+reactor	NH	2.509	0.527	0.0248	-1.554	-
T2K+reactor	IH	2.481	0.533	0.0252	-1.556	0.86

Confidence regions as presented in Figure 2 are constructed using the constant  $\Delta\chi^2$  method [6] with respect to a 4-dimensional best-fit point obtained by minimizing Eq. 1. The profiled  $\Delta\chi^2$  as a function of  $\delta_{CP}$  shown in Figure 3 is calculated by fixing  $\delta_{CP}$  to different values and minimizing Eq. 1 with respect to the systematics and the other oscillation parameters. Then, the Feldman-Cousins method [7] is used to produce confidence intervals, by finding critical values of  $\Delta\chi^2$  profiling the other oscillation parameters following the 3-dimensional  $\Delta\chi^2$  surface result of the joint fit with reactor constraint. The excluded regions found for  $\delta_{CP}$  at the 90% CL are  $[0.146, 0.825]\pi$  ( $[-0.080, 1.091]\pi$ ) for normal (inverted) mass hierarchy. Figure 4 compares the confidence regions in  $(\sin^2 \theta_{23}, \Delta m^2)$  for the T2K and the SK [8] and MINOS [9] joint oscillation analyses with constraints from reactor measurements, showing that the stringent limits in  $\theta_{23}$  are obtained by T2K.

### 4. Conclusion

With only  $\sim 8\%$  of its goal POT, T2K has achieved world leading results: the best precision in  $\theta_{23}$ , the strongest evidence of  $\nu_e$  appearance in a  $\nu_\mu$  beam and the first hint on  $\delta_{CP}$ . It has also performed its first joint 3-flavour oscillation analysis, in which the high  $\nu_e$  appearance rate observed, combined with the  $\nu_\mu$  disappearance measurement and the results from reactor experiments, indicates that  $\delta_{CP}$  is consistent with  $-\pi/2$ .

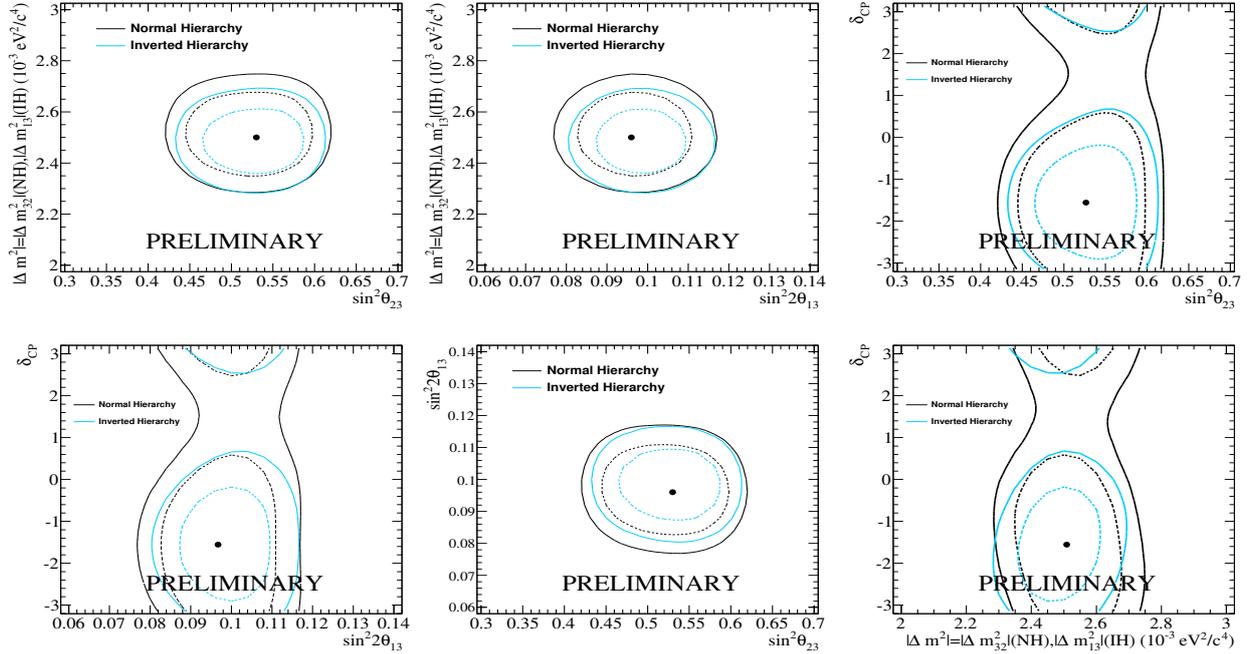


Figure 2: Comparison of 68% (dashed) and 90% (solid) CL regions for the T2K joint 3-flavour Frequentist analysis combined with the reactor measurements, for different mass hierarchy assumptions using a common best-fit point (the one for the normal mass hierarchy).

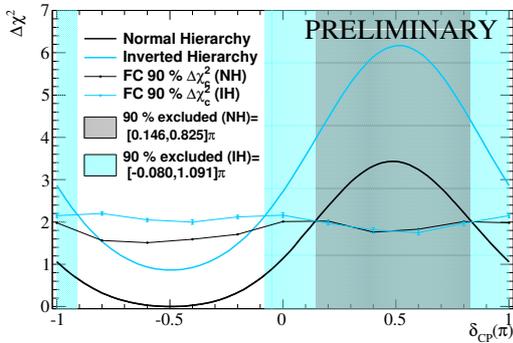


Figure 3: Profiled  $\Delta\chi^2$  as a function of  $\delta_{CP}$ , result of the T2K joint 3-flavour Frequentist analysis with reactor constraint. The critical  $\Delta\chi^2$  values and excluded regions at the 90% CL are overlaid.

Furthermore, the data excluded values of  $\delta_{CP}$  in the interval  $[0.146, 0.825]\pi$   $[-0.080, 1.091]\pi$  at the 90% CL for normal (inverted) mass hierarchy.

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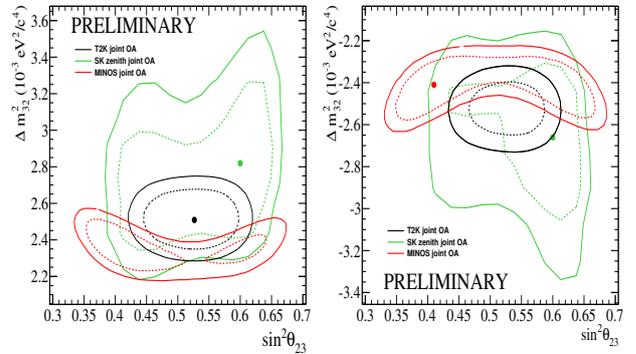


Figure 4: Comparison of 68% (dashed) and 90% (solid) CL regions in  $(\sin^2\theta_{23}, \Delta m^2)$  for the T2K joint 3-flavour Frequentist analysis and the SK [8] and MINOS [9] joint analyses, with reactor constraints.

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