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Nuclear Physics B Proceedings Supplement 00 (2014) 1–6
Nuclear Physics B Proceedings Supplement

Initial Probe of δ_{CP} by the T2K Experiment with ν_μ Disappearance and ν_e Appearance

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Abstract

The T2K long-baseline neutrino oscillation experiment has observed the disappearance of ν_μ and the appearance of ν_e from its ν_μ beam and it has accumulated 6.57×10^{20} protons on target, ∼ 8% of its goal POT. Combining its ν_μ disappearance and ν_e appearance measurements with the results from reactor experiments, T2K has obtained the first constraint to date on the CP-violating phase δ_{CP}. Two kind of joint 3-flavour oscillation analyses have been performed, based on either Frequentist or Bayesian methods, and the results from both analyses indicate that δ_{CP} is consistent with $-\pi/2$. Furthermore, the data excluded values for δ_{CP}: the excluded regions found at the 90% CL with the Frequentist analysis are $[0.146,0.825]\pi$ ($[-0.080,1.091]\pi$) for normal (inverted) mass hierarchy; and the Bayesian 90% CI obtained, marginalizing over the mass hierarchy and assuming flat priors, is $[-1.13,0.14]\pi$. Although more T2K neutrino (and possibly anti-neutrino) data is necessary to confirm this result, whose sensitivity could be enhanced in combination with results from a new generation of long-baseline neutrino oscillation experiments and the latest reactor measurements, this first hint on CP violation opens exciting possibilities.

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

1. Introduction

Neutrino oscillations, confirmed by different experimental measurements in the past decades, are a consequence of the existence of flavour neutrino mixing, since the flavour or interaction eigenstates (ν_e,ν_μ,ν_τ) do not correspond to the mass or propagation eigenstates (ν_1,ν_2,ν_3), but to a linear combination of them through a unitary mixing matrix U. In the three active neutrino paradigm, a standard parameterization is given by the PMNS mixing matrix [1, 2] presented in Eq. 1, which is described in terms of three mixing angles (θ_{12}, θ_{13}, θ_{23}) and three phases (δ_{CP},α_1,α_2). These parameters, except the two extra phases (α_1,α_2) that appear only if neutrinos are Majorana particles, are determined by measurements of neutrino oscillations with atmospheric, solar, reactor and accelerator neutrinos. Among them, long-baseline neutrino experiments which have access to 3-flavour neutrino oscillations, like T2K, can search for CP violation in the lepton sector by measuring the δ_{CP} phase, possible after reactor experiments have confirmed that $\theta_{13} \neq 0$ and have provided precise measurements of this angle [3].

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix} \quad (1)$$

The initial probe of δ_{CP} by the T2K experiment indicates that its value is consistent with $-\pi/2$. If this result is confirmed, it would mean that CP violation is observed in the lepton sector, and it could be an indication of *leptogenesis* as the origin of the baryon asymmetry of the Universe [4].

2. The T2K Experiment

The Tokai-to-Kamioka (T2K) experiment [5] 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° away from the direction towards the far detector. The layout of the T2K experiment is presented in Figure 1. The T2K neutrino beam is a highly pure ν_μ 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 ν_μ and ν_e event candidates. With the off-axis configuration, the energy of the neutrino beam is tuned to the maximum of the oscillation probability at $\sim$ 600 MeV, enhancing the charged current quasi-elastic (CCQE) interaction channel and reducing the backgrounds.

The T2K experiment is optimized to perform ν_μ disappearance oscillation analysis to measure the mixing angle θ_{23} and the atmospheric mass-squared splitting Δm^2, and ν_e appearance oscillation analysis to probe the angle θ_{13} and the CP-violating phase δ_{CP}. Since 2010, it has accumulated 6.57 $\times 10^{20}$ protons on target (POT) and observed 120 ν_μ and 28 ν_e event candidates at SK. In addition, T2K has also developed its first joint 3-flavour oscillation analysis, combining the ν_μ disappearance and the ν_e appearance channels.

Figure 1: Layout of the T2K experiment, showing the position of the J-PARC accelerator complex where the muon neutrino is produced, the near detectors located at 280 m from the production target and the far detector Super-Kamiokande, situated 295 km away.

3. Systematic Uncertainties for Oscillation Measurements

The systematic uncertainties considered for the oscillation analyses can be grouped into three different categories. Firstly, independent cross section parameters are those representing the uncertainties on the cross sections used in the interaction models in NEUT [6] which are related to the nuclear model, thus independent between the near and far detector as they contain different nuclei, or those for which the near detector is insensitive. The second category includes the systematic uncertainties related to SK flux simulation and some cross sections which are common to the near and far detector. Fits to external datasets are used to tune the initial models and uncertainties for the flux, whose dominant uncertainty is related to the hadron production, estimated mainly with data from the NA61/SHINE experiment [7]; and for the cross sections, some of them constrained using the MiniBooNE data [8]. A fit to the ND280 data is performed to constrain the uncertainties of the flux and correlated cross sections, which are significantly reduced [8]. Finally, systematic uncertainties related to the far detector efficiencies are estimated using control samples of atmospheric neutrinos, cosmic-ray muons and their decay electrons, applying the ν_μ and ν_e event selections at the same time to take into account correlations. The final state and secondary interaction (FSI+SI) uncertainties are evaluated by varying the pion interaction probabilities in the NEUT cascade model, and the output covariance matrix obtained is combined with the one for the SK efficiencies.

The effect of 1σ systematic parameter variation on the predicted number of ν_μ and ν_e event candidates is summarized in Table 1. Figure 2 shows the total error envelope for the predicted reconstructed energy spectra of the ν_μ and ν_e event candidates, before and after applying the constraint from the fit to the ND280 data.

Table 1: Effect of 1σ systematic parameter variation on the predicted number of ν_μ and ν_e event candidates.

Source of uncertainty	1Rμ $\delta N_{SK}/N_{SK}$	1Re $\delta N_{SK}/N_{SK}$
SK	4.0%	2.7%
FSI+SI (+PN)	3.0%	2.5%
Flux and correlated cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
Total		
(w/o ND280 constraint)	**23.5%**	**26.8%**
(w ND280 constraint)	**7.7%**	**6.8%**

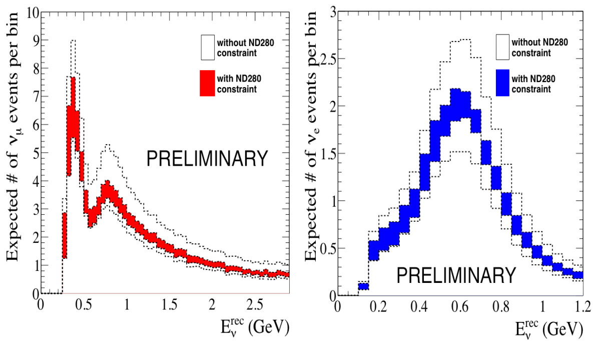

Figure 2: Total error envelope for the predicted reconstructed energy spectra of the ν_μ (left) and ν_e (right) event candidates, for oscillations with typical values before and after applying the constraint from the fit to the ND280 data.

4. T2K Observation of ν_e Appearance

A total of 28 ν_e event candidates, satisfying all the SK cuts required to select a ν_e CCQE enriched sample, were observed in the latest T2K dataset, corresponding to an accumulated exposure of 6.57×10^{20} POT. This number of events is significantly larger than the expected number of events for $\sin^2 2\theta_{13} = 0$ (4.92 events) and even larger than the expected number of events for $\sin^2 2\theta_{13} = 0.1$ (21.56 events).

The ν_e appearance analysis performed with this dataset [9] determined the neutrino oscillation parameters by comparing the expected and the observed number of events using a binned extended maximum-likelihood fit. The likelihood was integrated over the nuisance parameters, including the systematic parameters accounting for the uncertainties from the different sources described in Section 3. Two independent analyses were performed: one using the (p_e,θ_e) distribution of ν_e candidates and an alternative one using the ν_e reconstructed energy spectrum. The best-fit value and 68 CL interval obtained at $\delta_{CP} = 0$ (fixing $\sin^2\theta_{23} = 0.5$ and $|\Delta m^2_{32}| = 2.4\times10^{-3}$ eV^2/c^4) was $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ $\left(\sin^2 2\theta_{13} = 0.170^{+0.045}_{-0.037}\right)$ for the normal (inverted) mass hierarchy assumption.

Two different methods were used to calculate the significance for a non-zero θ_{13}, both giving a significance of 7.3 σ. The first method used the difference of the log likelihood values between the best-fit value obtained for θ_{13} and the value $\theta_{13} = 0$, and the second method computed the significance by generating a large ensemble of MC toy experiments assuming $\theta_{13} = 0$. This result has established the first observation of the explicit appearance of a neutrino flavour from neutrinos of a different flavour through neutrino oscillations.

The confidence regions for $\sin^2 2\theta_{13}$ as a function of δ_{CP} presented in Figure 3 were computed taking into account the uncertainties on $\sin^2\theta_{23}$ and Δm^2_{32} by marginalizing over them following the likelihood surface obtained with the T2K ν_μ disappearance result in [10]. An obvious tension appears between the results from the T2K ν_e appearance analysis shown in Figure 3 and the reactor measurements, since the best-fit values obtained for the T2K data alone are larger than the reactor result, indicating a preference for a value of δ_{CP} toward $-\pi/2$ and the consequent CP violation.

5. T2K Joint 3-flavour Oscillation Analyses

The stand-alone ν_μ disappearance and ν_e appearance analyses performed by the different neutrino oscillation experiments usually fix the oscillation parameters not directly measured. However, it has been proved that a change in their prior values could affect significantly the results for the oscillation parameters measured. Thus, the latest stand-alone analyses performed by the T2K experiment included the effect of the uncertainty on the parameters not directly measured, as explained in Section 4. A further step to properly take into account the interdependencies between the oscillation parameters is to perform a joint 3-flavour oscillation analysis combining the ν_μ disappearance and ν_e appearance channels. It consists in a simultaneous fit, in a 3 flavour framework including matter effects (assuming constant density matter), to the event rate and reconstructed energy spectra of the ν_μ and ν_e event candidates from the T2K beam at SK, in which the four oscillation param-

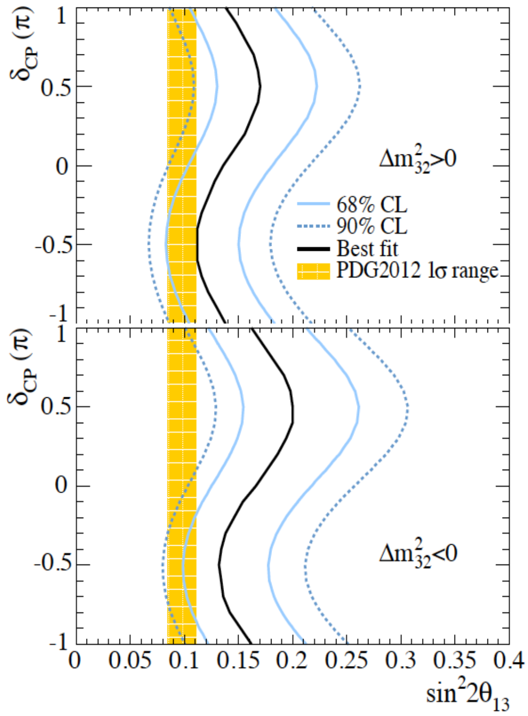

Figure 3: The 68% (solid) and 90% (dashed) CL regions for $\sin^2 2\theta_{13}$ as a function of δ_{CP} assuming normal (top) and inverted (bottom) mass hierarchy, constructed varying the values of the parameters $\sin^2\theta_{23}$ and Δm^2_{32} following the constraint from [10]. The solid lines represent the best-fit values of $\sin^2 2\theta_{13}$ for given δ_{CP} values and the average 1σ range for $\sin^2 2\theta_{13}$ from reactor results [11] is overlaid as a shaded region.

eters $\sin^2\theta_{23}$, Δm^2, $\sin^2\theta_{13}$ and δ_{CP}[1] are jointly determined. Two kind of joint 3-flavour analyses are performed, based on either Frequentist or Bayesian methods, as they will be described in the following Sections.

5.1. T2K Joint ν_μ Disappearance and ν_e Appearance Frequentist Analysis

In this joint 3-flavour oscillation analysis performed combining the ν_μ disappearance and ν_e appearance channels using a Frequentist approach, the oscillation parameters $\sin^2\theta_{23}$, Δm^2, $\sin^2\theta_{13}$ and δ_{CP} are determined by comparing the reconstructed energy spectra of the ν_μ and ν_e event candidates observed at SK with the predicted reconstructed energy spectra. The best-fit values of the oscillation parameters are found by minimizing the negative log-likelihood ratio:

$$\begin{aligned}\chi^2 &= -2\ln\mathcal{L}(\Delta m^2, \sin^2\theta_{23}, \sin^2\theta_{13}, \delta_{CP}; \boldsymbol{f}) = \\ & 2\cdot\sum_{i=0}^{m_\mu-1}\left[(N^p_{SK;\mu,i} - N^d_{SK;\mu,i}) + N^d_{SK;\mu,i}\cdot ln\left(\frac{N^d_{SK;\mu,i}}{N^p_{SK;\mu,i}}\right)\right] \\ & + 2\cdot\sum_{i=0}^{m_e-1}\left[(N^p_{SK;e,i} - N^d_{SK;e,i}) + N^p_{SK;e,i}\cdot ln\left(\frac{N^d_{SK;e,i}}{N^p_{SK;e,i}}\right)\right] \\ & + (\boldsymbol{f}-\boldsymbol{f_0})^T\cdot\mathbf{C}^{-1}\cdot(\boldsymbol{f}-\boldsymbol{f_0}),\end{aligned} \quad (2)$$

where $N^d_{SK;\mu,r}$ ($N^d_{SK;e,r}$) is the observed number of ν_μ (ν_e) event candidates in the r^{th} reconstructed energy bin, with m_μ (m_e) total reconstructed energy bins, and $N^p_{SK;\mu,r}$ ($N^p_{SK;e,r}$) is the corresponding expected number of events, calculated as a function of the oscillation parameters (Δm^2, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, δ_{CP}). The varied (nominal) values of the systematic parameters described in Section 3 are represented by the multidimensional array $\boldsymbol{f}$ ($\boldsymbol{f_0}$), with $\mathbf{C}$ representing the corresponding total covariance matrix.

The profiled $\Delta\chi^2$ as a function of δ_{CP} is calculated by fixing δ_{CP} to different values in the interval [-π, π] and minimizing the negative log-likelihood ratio function in Eq. 2 with respect to the systematic parameters and the other three oscillation parameters using Minuit [12]. Figure 4 shows the result of the profiled $\Delta\chi^2$ as a function of δ_{CP} combining T2K data with the weighted average of the results from the three reactor experiments Daya Bay, RENO and Double Chooz, namely $(\sin^2 2\theta_{13})_{reactor} = 0.095 \pm 0.01$ [3], whose constraint is applied as an additional Gaussian term in Eq. 2. The best-fit value for δ_{CP} obtained combining with the reactor result is approximately -0.49π (-0.50π) for normal (inverted) mass hierarchy. Then, the Feldman-Cousins method of statistical analysis [13] is used to produce confidence intervals, by finding critical values of $\Delta\chi^2$ as a function of δ_{CP}, profiling the other three oscillation parameters following the 3-dimensional $\Delta\chi^2$ surface result of the joint fit with the reactor constraint. The excluded regions found for δ_{CP} at the 90% CL are [0.146,0.825]π ([-0.080,1.091]π) for normal (inverted) mass hierarchy.

5.2. T2K Joint ν_μ Disappearance and ν_e Appearance Bayesian Analysis

A joint 3-flavour oscillation analysis is also performed using a Bayesian approach to extract the most probable values of the oscillation parameters and their uncertainties. Unlike the Frequentist analysis described in Section 5.1, this analysis does not use the fit to the near detector data performed separately to constrain the SK flux and correlated cross sections as explained in

[1] The effect of including the solar parameters Δm^2_{21} and $\sin^2\theta_{12}$ in the fit has been studied and it was found to be negligible; therefore, those parameters are fixed to the values $\sin^2\theta_{12}$=0.306 and Δm^2_{21} = 7.5×10^{-5} eV^2/c^4 from [11] in the analyses.

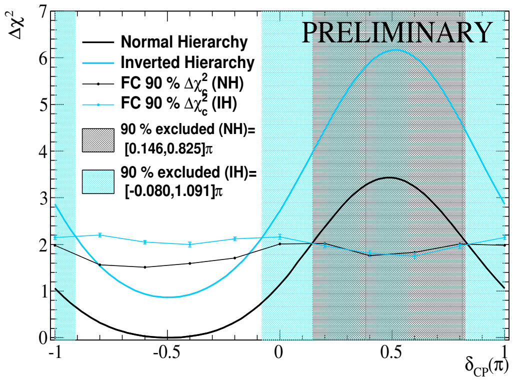

Figure 4: Profiled $\Delta\chi^2$ as a function of δ_{CP}, result of the T2K joint 3-flavour Frequentist analysis combined with the results of the reactor experiments. The critical $\Delta\chi^2$ values and excluded regions obtained at the 90% CL for the normal and inverted hierarchies are overlaid.

Section 3; instead, this analysis fits simultaneously the near and far detector data samples.

To construct Bayesian credible intervals (CI), the posterior probability density function of the oscillation and nuisance parameters is computed as the product:

$$P = P_{SK} \times P_{ND280} \times \pi(o) \times \pi(\boldsymbol{f}) \quad (3)$$

where the likelihood functions for the near and far detector samples, P_{SK} and P_{ND280} respectively, are assumed to be Poissonian, so that the same dependency as in Eq. 2 is obtained for the SK samples, i.e.

$$\ln(P_{SK}) \propto \sum_{i=0}^{m_\mu-1}\left[(N^p_{SK;\mu,i} - N^d_{SK;\mu,i}) + N^d_{SK;\mu,i}\cdot ln\left(\frac{N^d_{SK;\mu,i}}{N^p_{SK;\mu,i}}\right)\right] + \sum_{i=0}^{m_e-1}\left[(N^p_{SK;e,i} - N^d_{SK;e,i}) + N^p_{SK;e,i}\cdot ln\left(\frac{N^d_{SK;e,i}}{N^p_{SK;e,i}}\right)\right] \quad (4)$$

and similarly for the near detector samples, which are binned in two kinematic variables, muon momentum and angle. The prior probability densities used are uniform functions for the oscillation parameters ($\pi(o)$) and multidimensional Gaussians for the systematic parameters ($\pi(\boldsymbol{f})$); the prior probabilities for the two mass hierarchies are assumed to be equal (0.5).

The Markov-Chain Monte Carlo (MCMC) method is used to estimate the posterior density of the oscillation and systematic parameters, by performing a pseudo-random walk through the parameter space and sampling the posterior probability. Then, point estimates for the oscillation parameters are found by maximizing the posterior probability density, and α% credible intervals are constructed by selecting the highest density region containing α% of all the points. The credible intervals are calculated for one or two parameters, marginalizing the posterior probability density function with respect to the rest of parameters by projecting all the steps of the MCMC onto the parameter(s) of interest space.

Figure 5 presents the posterior probability and allowed intervals for δ_{CP} result of the joint 3-flavour Bayesian analysis combined with the reactor measurement (applied in the same way as explained in Section 5.1), marginalized over the mass hierarchy. The preferred value for δ_{CP}, interpreted as the one for which the maximum of the probability density is found, is approximately $-\pi/2$ as for the Frequentist analysis. The 90% CI inclusion region obtained for δ_{CP} is [-1.13,0.14]π.

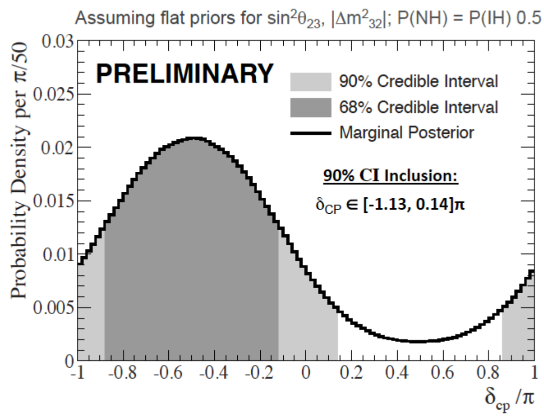

Figure 5: Posterior probability for δ_{CP}, result of the T2K joint 3-flavour Bayesian analysis combined with the reactor measurements, marginalized over the rest of oscillation and systematic parameters and over the mass hierarchy. The 90% and 68% CI obtained are overlaid as shaded regions.

6. Future Sensitivity to δ_{CP}

Sensitivity studies have been performed to study the T2K sensitivity for resolving $\sin\delta_{CP} \neq 0$ at its goal 7.8 $\times 10^{21}$ POT. On the one hand, a sensitivity study was performed using the joint 3-flavour oscillation analysis and assuming 50% neutrino and anti-neutrino running, with a realistic assumption for systematic errors of ~10% for ν_e, ~13% for ν_μ and equivalent errors for anti-neutrino with an additional 10% normalization uncertainty. Figure 6 presents an example of such sensitivity studies for different values of $\sin^2\theta_{23}$ and true values $\Delta m^2_{32} = 2.4\times10^{-3}$ eV^2/c^4, $\sin^2 2\theta_{13} = 0.1$ (being

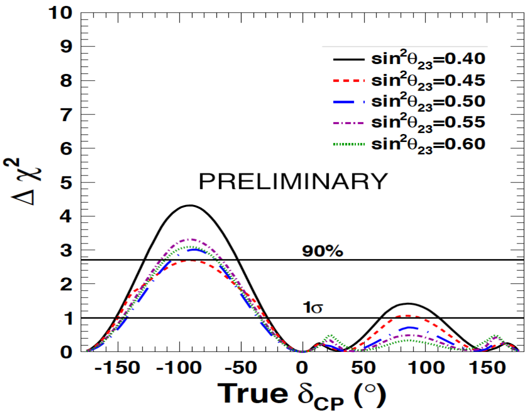

Figure 6: Sensitivity study for resolving $\sin\delta_{CP} \neq 0$, using joint 3-flavour oscillation analysis and assuming 50% of neutrino and anti-neutrino running and realistic systematic errors, for different values of $\sin^2\theta_{23}$ and true values $\Delta m^2_{32} = 2.4\times10^{-3}$ eV^2/c^4, $\sin^2 2\theta_{13} = 0.1$ (constrained with $\sigma(\sin^2 2\theta_{13}) = 0.005$) and normal mass hierarchy.

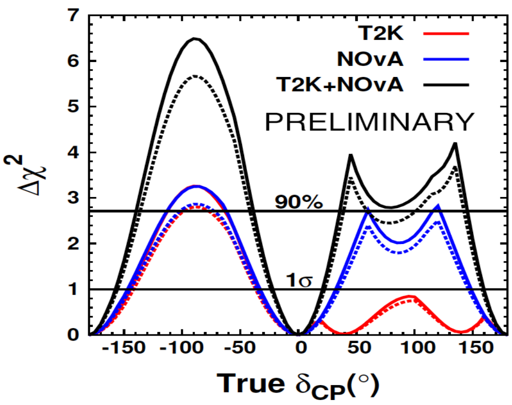

Figure 7: Sensitivity study for resolving $\sin\delta_{CP} \neq 0$, using the joint 3-flavour oscillation analysis assuming 50% of neutrino and anti-neutrino running, for T2K alone (red), NOνA alone (blue) and T2K+NOνA (black) with and without systematics (dashed and solid lines respectively) with true values $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4\times10^{-3}$ eV^2/c^4, $\sin^2 2\theta_{13} = 0.1$ (constrained with $\sigma(\sin^2 2\theta_{13}) = 0.005$) and normal mass hierarchy.

this parameter constrained with $\sigma(\sin^2 2\theta_{13}) = 0.005$ as a realistic projection of the reactor measurements) and normal mass hierarchy. From this sensitivity studies it is clear that T2K has sensitivity to the CP-violating phase δ_{CP} at 90% CL over a significant range.

In addition, sensitivity studies were performed for T2K combined with the NOνA experiment [14], showing an enhancement of the sensitivity for resolving $\sin\delta_{CP} \neq 0$ when results from both experiments are combined. For these studies, a modified version of the GLoBES simulator was used [15], with a joint oscillation analysis assuming 50% neutrino and anti-neutrino running for both T2K and NOνA. The simple systematic errors used were 5% (10%) normalization uncertainty on signal (background). Figure 7 shows an example of this sensitivity study for resolving $\sin\delta_{CP} \neq 0$ for T2K alone, NOνA alone and T2K+NOνA with the same true values used for the previous study and $\sin^2\theta_{23} = 0.5$.

The sensitivity studies performed indicate that T2K will attain its best sensitivity for resolving $\sin\delta_{CP} \neq 0$ with 50% neutrino and anti-neutrino running. In June 2014, T2K has already started collecting data with an anti-neutrino beam.

7. Conclusion

With only ~8% of its goal POT, T2K has observed ν_e appearance in a ν_μ beam with a significance of 7.3σ and has obtained the first hints toward $\delta_{CP} \approx -\pi/2$ by combining the ν_μ disappearance and ν_e appearance measurements with the results from reactor experiments. Furthermore, the excluded regions found for δ_{CP} at the 90% CL with a joint 3-flavour Frequentist analysis are [0.146,0.825]π ([-0.080,1.091]π) for normal (inverted) mass hierarchy; and the Bayesian 90% CI obtained, marginalizing over the mass hierarchy, is [-1.13,0.14]π. T2K sensitivity studies to resolve $\sin\delta_{CP} \neq 0$ show that some δ_{CP} regions can be resolved at the 90% CL depending on the value of $\sin^2\theta_{23}$, and that this sensitivity could be enhanced combining T2K and NOνA results.

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