T2K experiment: results and prospects

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Abstract

The long-baseline accelerator experiment T2K has for first time observed ν_e appearance in a ν_μ beam: 28 electron neutrino events were detected from a pure muon neutrino beam corresponding to a significance of 7.3σ when compared to 4.92 ± 0.55 expected background events. The most precise measurement of the mixing angle θ_{23} is consistent with maximal mixing. A combined joint analysis of the appearance and disappearance T2K data, which included the value of θ_{13} from reactor experiments, obtained the first constraint on CP-violating phase δ_{CP} with a best fit point around $-\pi/2$. Future T2K perspectives are also discussed.

1 Introduction

The study of the neutrino properties has provided convincing evidence of neutrino oscillations and therefore has proved that neutrinos have non–zero masses. This phenomenon is the first clear example of new physics beyond the Standard Model (SM). Three generation neutrino oscillations are described by an extension of the SM in which three flavor eigenstates ν_e, ν_μ, and ν_τ are connected to the neutrino mass eigenstates ν_1, ν_2, and ν_3, respectively, by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [1, 2], which is parametrized in terms of three mixing angles θ_{12}, θ_{23}, θ_{13} and CP violating phase δ_{CP}.

The probability for ν_μ to oscillate into ν_e is given by:

$$\begin{aligned} P(\nu_\mu \to \nu_e) &\simeq \sin^2\theta_{13}\sin^2\theta_{23}\sin^2\Big(\frac{\Delta m^2_{32}L}{4E_\nu}\Big) \\ &- \frac{\sin2\theta_{12}\sin2\theta_{23}}{2\sin\theta_{13}}\sin\Big(\frac{\Delta m^2_{21}L}{4E_\nu}\Big)\sin^2 2\theta_{13}\sin\Big(\frac{\Delta m^2_{31}L}{4E_\nu}\Big)\sin\delta_{CP} \\ &+ \text{solar term} + \text{matter term}, \qquad (1) \end{aligned}$$

where E_ν is the muon neutrino energy, L is the baseline length, m^2_{ij} are the neutrino squared mass differences $m^2_i - m^2_j$. In this scheme, oscillation probabilities between the three active neutrinos depend on the values of 3 mixing angles, $m^2_i - m^2_j$, and possibly δ_{CP}. These parameters (except for δ_{CP}) are determined in oscillation experiments with atmospheric, solar, reactor and accelerator neutrinos. It should be also noted that the sign of m^2_{32} is unknown. Both the normal mass hierarchy ($m_3 \gg m_2 > m_1$) and inverted hierarchy ($m_2 > m_1 \gg m_3$) are possible.

The leading order probability for a muon neutrino to oscillate into another flavor state is given by:

$$\begin{aligned} P(\nu_\mu \to \nu_\mu) &\simeq 1 - (\cos^4\theta_{13}\sin^2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\Big(\frac{\Delta m^2_{31}L}{4E_\nu}\Big) \\ &+ \text{matter term}. \qquad (2) \end{aligned}$$

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Expressions (1) and (2) are exploited in the T2K experiment which measures both the ν_e appearance probability and the ν_μ disappearance probability to obtain the oscillation parameters.

The main goals of the T2K (Tokai-to-Kamioka) experiment are to search and to measure $\nu_\mu \to \nu_e$ oscillation and the mixing angle θ_{13}, to precisely measure the oscillation parameters θ_{23} and Δm^2_{32}, and to probe CP violation in neutrino oscillations. T2K began data taking in 2010 and obtained the first indication of $\nu_\mu \to \nu_e$ oscillation at 2.5σ significance [3] in 2011.

2 T2K facility

The T2K experiment [4] uses a high-intensity off–axis neutrino beam produced by a 30 GeV proton beam at J-PARC (Japan Proton Accelerator Research Complex), Super-Kamiokande (SK) as a far neutrino detector, and a set of dedicated neutrino detectors located at a distance of 280 m from the pion production target to measure the properties of the unoscillated neutrino beam. A schematic view of the T2K setup is shown in Fig. 1.

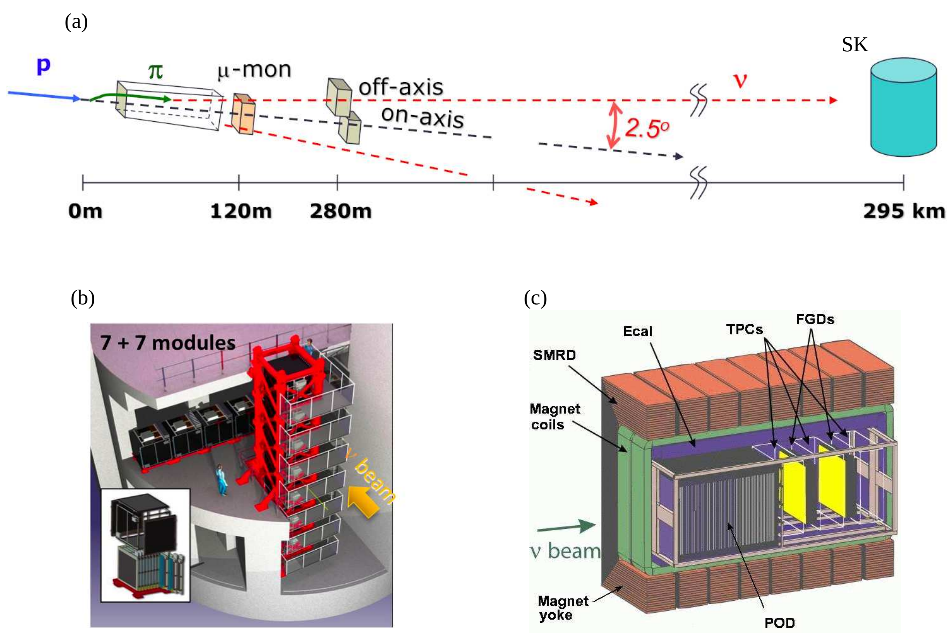

Figure 1: General layout of the T2K experiment. (a) The main elements of the set-up: the neutrino beam line, muon monitor, near neutrino detector at 280 meters from the pion production target, and the far neutrino detector Super-Kamiokande (SK). (b) The on-axis neutrino beam monitor INGRID. (c) The off-axis near neutrino detector ND280 comprised of a detector of neutral pions (POD), an electromagnetic calorimeter (ECAL), a side muon range detector (SMRD), two highly segmented scintillator detectors (FGD) and three time-projection chambers (TPC).

Pions and kaons generated by 30 GeV protons hitting a graphite target are focused by three magnetic horns and enter the decay tunnel where they decay to produce the neutrino beam. The horns are operated in neutrino mode to focus π^+'s for a high purity muon neutrino beam. To maximize the sensitivity for muon neutrino oscillations for a baseline of 295 km, T2K adopted an off–axis beam configuration at an angle of 2.5° away from the direction of the proton beam. The neutrino energy is almost independent on the pion energy at this angle and a quasi–monochromatic neutrino spectrum could be obtained in the direction of SK. This approach allows the experiment to use the beam tuned to the first oscillation maximum with a significantly reduced high energy tail, as shown in Fig. 2. The beam intensity and direction are

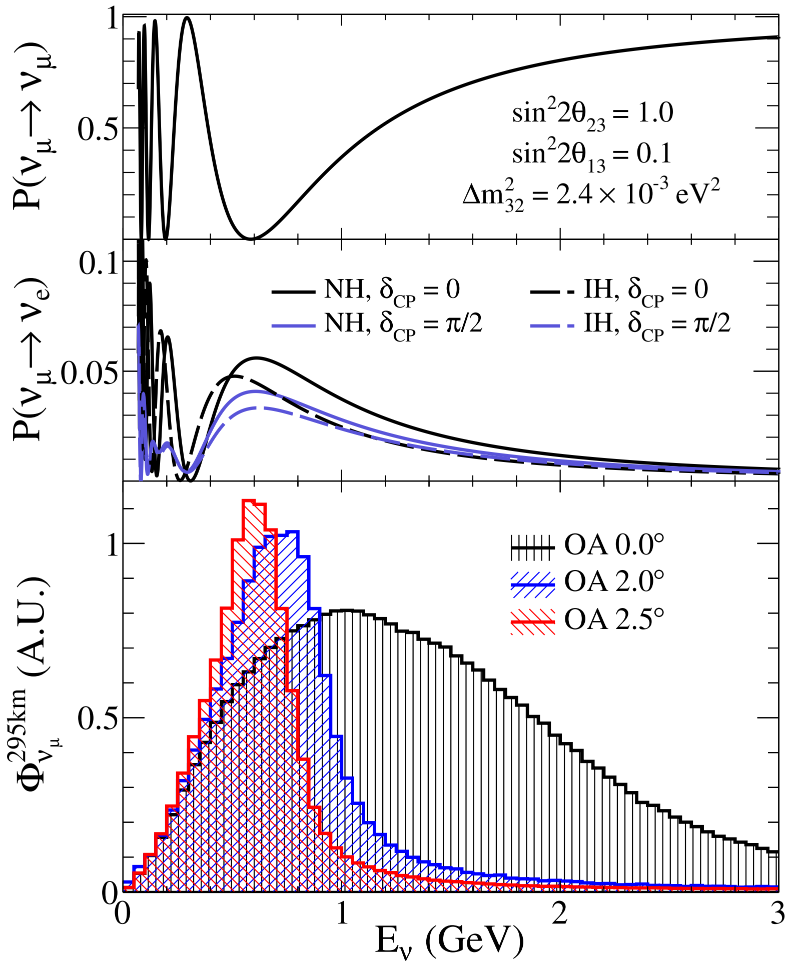

Figure 2: Probabilities of $\nu_\mu \rightarrow \nu_\mu$ (top) and $\nu_\mu \rightarrow \nu_e$ (middle) oscillations as a function of neutrino energy for a baseline of 295 km. The probabilities are calculated for the normal mass hierarchy (NH) and inverted mass hierarchy (IH). Neutrino spectra at SK at angles 0°, 2.0°, and 2.5° (bottom).

measured by muon monitors located beyond the beam dump. The near detectors (see Fig. 1), designed to characterize the neutrino beam, are located in an underground hall, 280 m from the target. The on–axis near detector, INGRID, consists of an array of 7×7 iron–scintillator stacks formed in a cross–configuration (neutrino monitor) to provide a measurement of the neutrino beam intensity and direction. A set of multiple sub-detectors placed inside a magnetic field at an angle of 2.5° relative to the proton beam direction, ND280, measures the event rate, energy spectrum, flavor composition of the neutrino beam, and neutrino cross sections. The off–axis detector consists of the UA1 magnet operated with a magnetic field of 0.2 T, a π^0-detector (POD), a tracking detector which includes three time projection chambers and two fine-grained scintillator detectors (FGD's), an electromagnetic calorimeter (ECAL), and a side muon range detector (SMRD). The far detector, Super-Kamiokande, a 50 kt Cherenkov detector located at a distance of 295 km from the pion production target, measures the spectra of muon and electron neutrinos after possible oscillations. The results presented below are based on 6.7×10^{20} (about 8% of the final goal) protons on target accumulated since 2010.

2.1 Super-Kamiokande event selection

The following criteria were applied in the SK to select electron and muon neutrinos for oscillation analysis: an event is correlated in time with the J-PARC beam, fully contained within the fiducial volume and contains only one Cherenkov ring. The Cherenkov cone shape is used to make a selection between electrons and muons, and the reconstructed momentum of the detected lepton should be more than 100 (200) MeV/c for electrons (muons). Events are required to have the reconstructed neutrino energy of less than 1250 MeV. The reconstructed vertex must be in the fiducial volume of the SK. To suppress a large source of background from neutral pions produced in neutral current interactions, a sophisticated π^0 rejection procedure was applied to the sample of ν_e candidates. As a result, the π^0 background events were suppressed by about 300 times with a ν_e signal efficiency of more than 50%.

3 Oscillation analysis

The oscillation analysis includes the following steps:

- Simulation of the neutrino flux: the dominating uncertainties from the hadron production cross section are effectively constrained using the NA61/SHINE data [5].

- Simulation of neutrino interactions and cross section parameters: the NEUT Monte Carlo generator [6] is used to simulate neutrino interactions in T2K's detectors. Data from external experiments, pion–nucleus scattering experiments and especially from the MiniBooNE experiment [7], are used to constraint the model uncertainties.

- The neutrino flux, spectrum, and cross section parameters are constrained using the neutrino data measured by the ND280.

- The ν_e and ν_μ events are measured at the SK. The neutrino energy for each event passed the selection cuts is calculated under the quasi-elastic assumption.

- The systematic uncertainty due to the SK selection cuts is evaluated with atmospheric neutrino data, cosmic-ray muons, their decay electrons, and a MC hybrid π^0 sample. Additional systematic uncertainties due to pion interactions in the target nucleus (FSI) and SK detector (SI) are evaluated by varying pion interaction probabilities in the NEUT model.

- The neutrino oscillation parameters are obtained using 3-flavor oscillation scheme by comparing the measured event rate and energy distribution of ν_e (appearance) and ν_μ (disappearance) events detected at SK with the predictions at the far detector. The predictions depend on the oscillation parameters, the initial neutrino flux, neutrino cross sections, and the far detector response. The ND280 data is used to tune the initial neutrino flux estimates and parameters of neutrino interaction models.

The main systematic uncertainties considered for oscillation analysis have the following sources: neutrino flux uncertainties; uncertainties of neutrino cross section parameters, both common and uncommon to the near and far detector; uncertainties related to the SK efficiencies; the final state and secondary interaction uncertainties at SK. The effect of 1σ systematic parameter variation on the predicted number of ν_μ and ν_e event candidates at SK summarized in Table 1, demonstrating the great power of the ND280 in reducing systematic uncertainties.

Table 1: Relative uncertainties in the predicted number of ν_μ and ν_e event candidates at SK.

Systematic error source	ν_μ sample	ν_e sample
Neutrino flux and cross sections		
w/o ND280	21.8%	26.0%
with ND280	2.7%	3.1%
Independent neutrino cross sections	5.0%	4.7%
Final state hadronic interactions	3.0%	2.4%
SK efficiency	4.0%	2.7%
Total		
Without ND280	23.5%	26.8%
With ND280	7.7%	6.8%

Fig. 3 shows the total error envelopes combining all systematic uncertainties for the ν_e and ν_μ energy spectra with and without constraint from the fit to the ND280 data. A clear reduction of systematic errors is seen after applying the ND280 constraints.

3.1 Observation of ν_e appearance

The measurement of ν_e appearance is performed by looking for single ring electron-like events in the SK detector due to the charged current quasi-elastic scattering, $\nu_e + n \rightarrow p + e^-$. After all cuts, the total number of candidate ν_e events selected in data was 28. The number of expected events for $\theta_{13} = 0$ is estimated to be 4.92 ± 0.55. Fig. 4 shows the reconstructed neutrino energy distribution for the 28 ν_e observed events. The best fit result corresponds to a 7.3σ significance for a non-zero value of θ_{13}. This result was the first direct observation of the neutrino oscillation in the appearance mode: ν_e appearance in a muon neutrino beam [8]. The confidence regions for $\sin^2 2\theta_{13}$ as a function of δ_{CP} in the range $[-\pi, \pi]$ for the normal and inverted mass hierarchy are shown in Fig. 5. For $\delta_{CP} = 0$, the best-fit values $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ (normal hierarchy) and $\sin^2 2\theta_{13} = 0.170^{+0.045}_{-0.037}$ (inverted hierarchy) are obtained.

3.2 ν_μ disappearance

T2K observed 120 ν_μ events at SK [10]. The simulations predicted 446 events, if no oscillations occurred. Oscillation parameters $\sin^2\theta_{23}$, Δm^2_{23} for the normal mass hierarchy (NH), and Δm^2_{13} for the inverted mass hierarchy (IH) were obtained using a maximum likelihood fit to the SK ν_μ spectrum for a three–flavor oscillation framework. Fig. 6 shows the 68% and 90% CL confidence regions for oscillation parameters for both normal and inverted mass hierarchies with results from other recent experiments. The world-best result for θ_{23} obtained in T2K is consistent with maximal mixing: $\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$ for NH and $\sin^2\theta_{23} = 0.511 \pm 0.055$ for IH.

3.3 Joint 3-flavor oscillation analysis and δ_{CP}

The highest sensitivity of the T2K experiment to δ_{CP} and θ_{23} can be reached in a joint 3-flavor oscillation analysis exploiting a combination of the ν_μ disappearance and ν_e appearance data. Such an analysis consists of a simultaneous fit to the event rate and reconstructed energy spectra of the both ν_μ and ν_e event samples. To obtain the oscillation parameters and their errors, two 3-flavor analyses were performed: a frequentist-based approach and a Bayesian

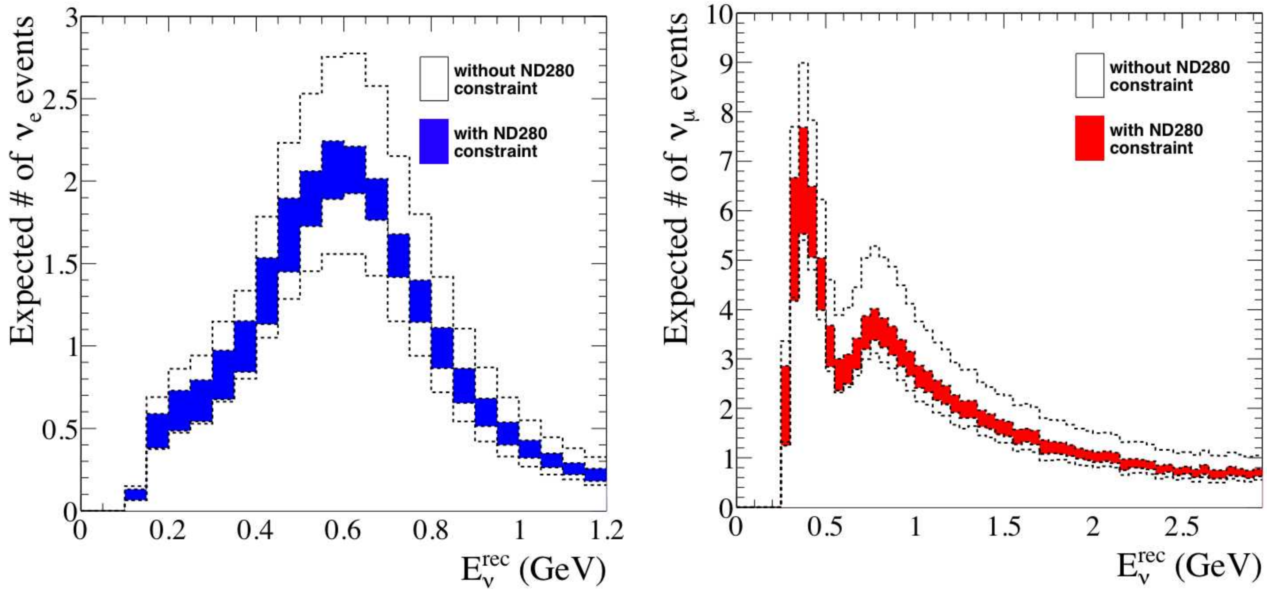

Figure 3: Total error envelopes for the predicted ν_e (left) and ν_μ (right) energy spectra with and without ND280 constraints using the typical values of the oscillation parameters: $\sin^2\theta_{12} = 0.306$, $\Delta m^2_{21} = 7.5\times10^{-5}$ eV^2, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4\times10^{-3}$ eV^2, $\sin^2\theta_{13} = 0.0243$, $\delta_{CP} = 0$, normal mass hierarchy.

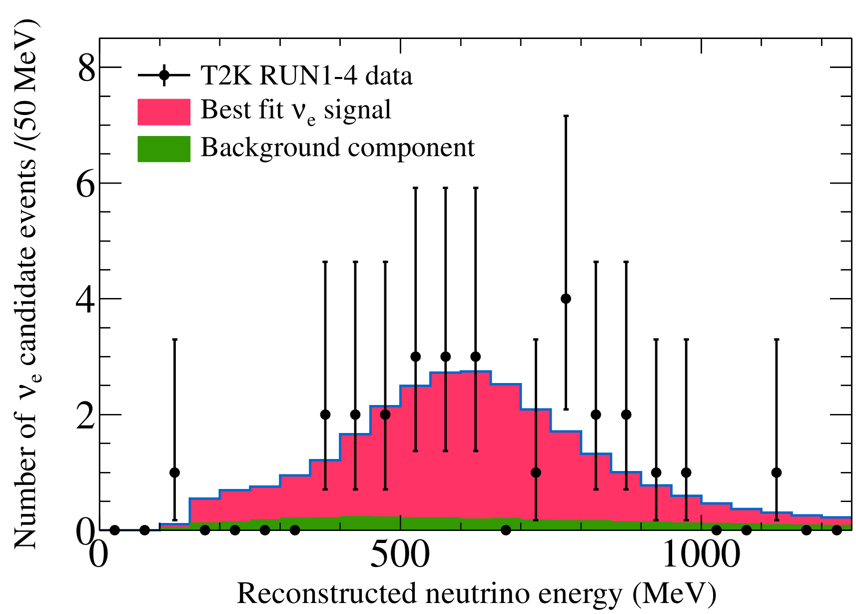

Figure 4: The reconstructed neutrino energy distribution for the 28 ν_e observed events with the Monte Carlo prediction (red) at the best fit for the case of normal hierarchy, $\sin^2 2\theta_{13} = 0.144$, and $\delta_{CP} = 0$. The background component is shown in green.

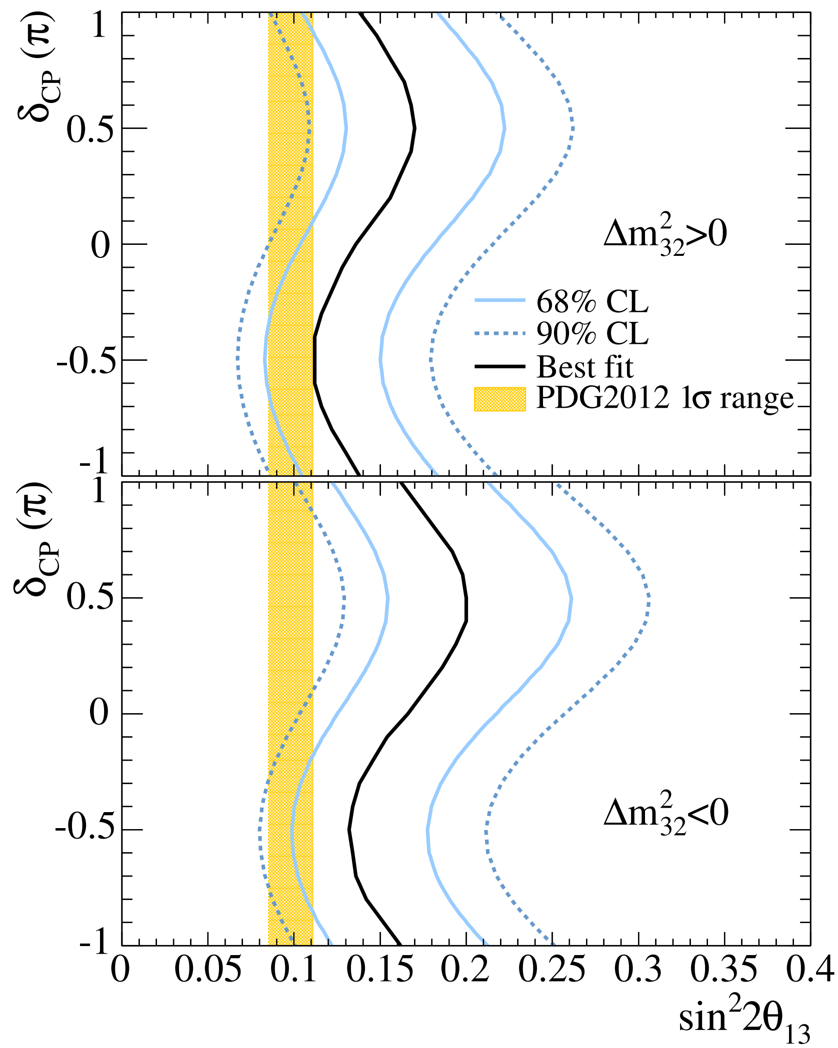

Figure 5: Allowed regions for $\sin^2 2\theta_{13}$ (68% and 90% CL) as a function of δ_{CP} for the normal (top) and inverted (bottom) neutrino mass hierarchy. The values of $\sin^2 2\theta_{23}$ and Δm^2_{32} are varied in the fit with the constraint from the T2K ν_μ disappearance measurements. The solid line represents the best fit $\sin^2 2\theta_{13}$ value for the given δ_{CP} values. The shaded region shows the average 1σ $\sin^2 2\theta_{13}$ range from reactor experiments [9].

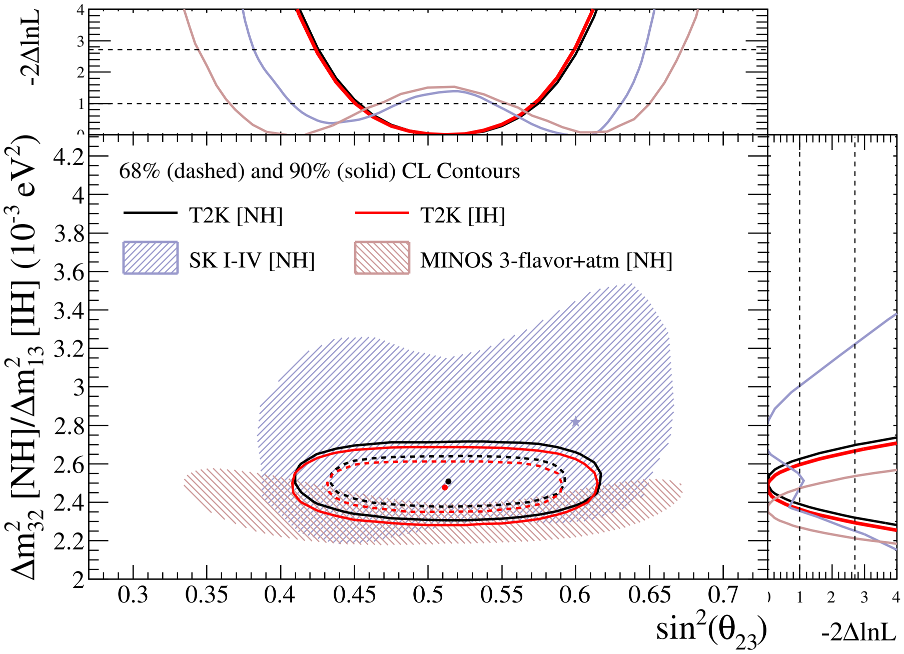

Figure 6: The 68% and 90% CL confidence regions for $\sin^2\theta_{23}$ and Δm^2_{23} (NH) or Δm^2_{13} (IH). The SK [11] and MINOS [12] 90% CL regions for NH are also shown.

analysis using a Markov chain Monte Carlo. Details of the analyses can be found in Ref. [13]. To evaluate the allowed intervals for δ_{CP} both analyses were combined with the average value of $\sin^2 2\theta_{13} = 0.095 \pm 0.01$ [9] from the reactor experiments Daya Bay, RENO and Double Chooz. Fig. 7 shows the result of joint fit as a function of δ_{CP} in the case of the frequentist approach. The preferred value of δ_{CP} is approximately $-\pi/2$ for both the normal and inverted mass hierarchy. The excluded regions found for δ_{CP} at the 90% confidence level approximately $(0.2 - 0.8)\pi$ for the normal hierarchy and from $\sim -0.1\pi$ to 1.1π for the inverted hierarchy. Consistent results were obtained in the Bayesian analysis.

4 Future prospects

These world-leading results were obtained with only about 8% of total POT approved for T2K. The observation of the ν_e appearance and large value of θ_{13} gives real chances to study CP violation in neutrino oscillations by current long-baseline experiments. To demonstrate the T2K physics potential, the sensitivity to δ_{CP} was studied using 3-flavor analysis combining appearance and disappearance for both neutrino (50%) and anti-neutrino (50%) data assuming the full exposure 7.8×10^{21} POT from a 30 GeV proton beam [14]. With realistic systematic errors of 10% (13%) for ν_e (ν_μ) and $\bar{\nu}_e$ ($\bar{\nu}_\mu$) plus a normalization error of 10%, for oscillation parameters $\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2, the sensitivity to δ_{CP} at the 90% CL can be reached around the T2K-preferred value of $-\pi/2$. Significant improvement can be obtained in case of the combination of the data from the T2K and NOνA [15] experiments. The combined T2K + NOνA analysis used a simplified treatment of systematic errors: a 5% (10%) of normalization uncertainty on signal (background) events for both appearance and disappearance spectra. Details of the analysis can be found in Ref. [14]. A modified version of the GLoBES package [16] was used in this study. Fig. 8 shows the sensitivity to δ_{CP} of each experiment, as well as the significant enhancement of the sensitivity in case of the combined analysis of the two data sets. For example, for $\delta_{CP} \sim -\pi/2$ the predicted $\Delta\chi^2$ to reject the $\delta_{CP} = 0$ hypothesis increases from about 3 for T2K and NOνA alone to more ~ 6 for the

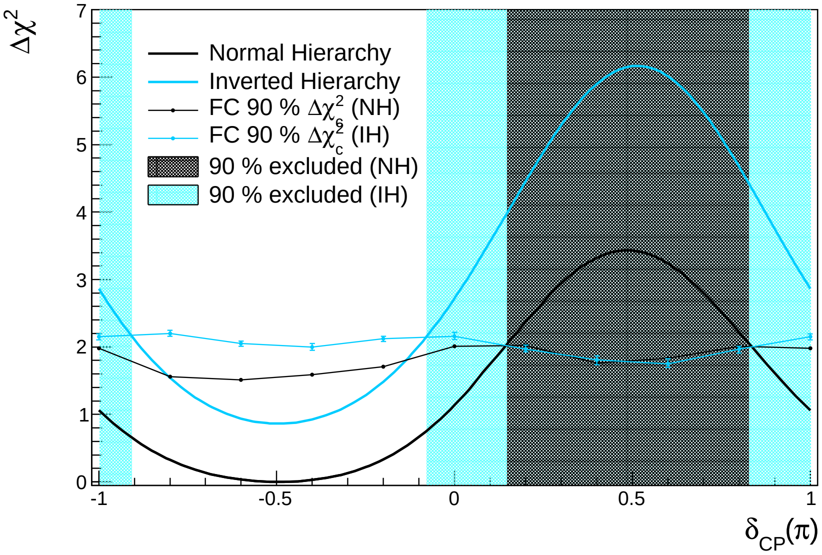

Figure 7: The $\Delta\chi^2$ as a function of δ_{CP} from the joint 3-flavor frequentist analysis combined with the θ_{13} constrained by reactor experiments. Excluded regions of δ_{CP} for normal and inverted hierarchies are shown.

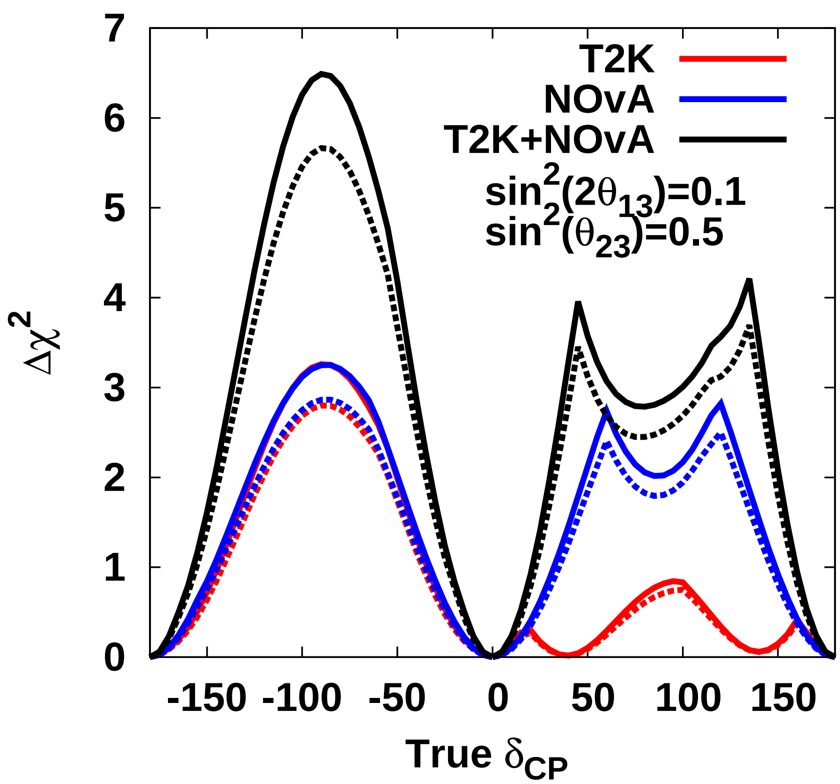

Figure 8: Estimated sensitivity to δ_{CP} for normal mass hierarchy assuming 50% of neutrino and 50% of anti-neutrino run for T2K (red), NOνA (blue), and T2K + NOνA (black) with (solid) and without (dashed) systematics. The values of oscillation parameters: $\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2. The $\Delta\chi^2$ was minimized relative to $\delta_{CP} = 0, \pi$.

combined fit.

5 Conclusion

T2K has for the first time directly observed ν_e appearance in a pure ν_μ beam with a significance of 7.3σ and also achieved the world leading precision on the mixing angle θ_{23} from the measurement of the ν_μ disappearance. The combination of the T2K joint 3-flavor analysis with the average θ_{13} value from reactor experiments allowed us to exclude some values of δ_{CP} at the 90% CL. T2K continues to take data with neutrinos and anti-neutrinos to measure the neutrino oscillation parameters more precisely and to further explore CP violation in the lepton sector.

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