

Review Article

T2K and Beyond

M. G. Catanesi

INFN Sezione di Bari, Via Orabona 4, 70125 Bari, Italy

Correspondence should be addressed to M. G. Catanesi; gabriella.catanesi@cern.ch

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This paper presents the *state of the art* of the T2K experiment and the measurements prospects for the incoming years. After a brief description of the experiment, the most recent results will be illustrated. The observation of the electron neutrino appearance in a muon neutrino beam and the new high-precision measurements of the mixing angle θ_{13} by the reactor experiments have led to a reevaluation of the expected sensitivity to the oscillation parameters, relative to what was given in the original T2K proposal. For this reason the new physics potential of T2K for 7.8×10^{21} p.o.t. and for data exposure 3 times larger than that expected to be reachable with accelerator and beam line upgrades in 2026 before the start of operation of the next generation of long-baseline neutrino oscillation experiments will also be described in the text. In particular the last challenging scenario opens the door to the possibility of obtaining, under some conditions, a 3σ measurement excluding $\sin(\delta_{CP}) = 0$.

1. Introduction

In the last 15 years several experimental measurements confirmed the neutrino oscillations hypothesis by attacking the problem on different fronts:

- (i) The observation of a zenith-angle-dependent deficit in muon neutrinos produced by high-energy proton interactions in the atmosphere [1] supported the possibility that a particular neutrino flavor can be transmuted into another one.
- (ii) The *anomalous* solar neutrino flux [2] problem was shown to be due to neutrino oscillation by precise measurements [3–6].
- (iii) Taking advantage of nuclear reactors as intense sources, the disappearance of electron antineutrinos has been firmly established [6–9].

- (iv) The development of high intensity proton accelerators that can produce focused neutrino beams with mean energy from a few hundred MeV to tens of GeV has enabled measurements of the disappearance of muon neutrinos (and muon antineutrinos) [10–12] and appearance of electron neutrinos (and electron antineutrinos) [13–16] and tau-neutrinos [17] over distances of hundreds of kilometres.

As a matter of fact the possibility for a neutrino of a particular flavor to be transmuted into another flavor has profound implications demonstrating that neutrinos have mass. Recently this extraordinary achievement in physics was fully recognized in the scientific community by the awarding of the Nobel Prize 2015 to T. Kajita and A. B. McDonald.

To date, all the experimental results cited above are well described within the three neutrino generations oscillation framework. In this case the unitary mixing

matrix, often referred to as the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix [18], can be written as a 3×3 matrix:

$$\begin{aligned}
 U &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\
 &= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\text{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{23}c_{13} \end{pmatrix}, \tag{1}
 \end{aligned}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. In this case four parameters are required to describe the matrix: three angles θ_{12} , θ_{23} , and θ_{13} and the CP-violating phase δ_{CP} .

In this context the T2K experiment, proposed in 2003 [19] and approved in 2006 to collect data corresponding to 7.8×10^{21} protons-on-target (p.o.t) from a 30 GeV proton beam at the J-PARC accelerator facility in Japan, played an important role and will keep playing it in the future.

T2K is a long-baseline neutrino oscillation experiment designed to achieve the following main physics goals:

- (i) search for $\nu_{\mu} \rightarrow \nu_e$ appearance and establish $\theta_{13} \neq 0$ with a sensitivity down to $\sin^2 2\theta_{13} \sim 0.008$ (90% CL);
- (ii) precision measurement of oscillation parameters in ν_{μ} disappearance mode with $\delta(\Delta m_{32}^2) \sim 10^{-4} \text{ eV}^2$ and $\delta(\sin^2 2\theta_{23}) \sim 0.01$;
- (iii) search for exotic physics including Lorenz violation and search for sterile components in ν_{μ} (ν_e) disappearance at the near detector and more.

The T2K experiment began the physics data-taking in 2010 [20]. Despite the devastating March 2011 earthquake in eastern Japan, which caused severe damage to the accelerator complex at J-PARC and abruptly discontinued the data-taking run of the experiment, in July 2011 the T2K collaboration announced a first indication of $\theta_{13} \neq 0$ [13] and in 2013 reached a major physics goal: the discovery of $\nu_{\mu} \rightarrow \nu_e$ appearance at 7.3σ level of significance when a mere 8.4% of the total approved p.o.t. [15] was recorded. This is the first time that explicit flavor appearance has been observed from another neutrino flavor with a significance larger than 5σ . This observation opened the door to the search for CP violation (CPV) in the lepton sector.

Following this discovery, the primary physics goal for T2K and, at large, for the neutrino physic community has become a detailed investigation of the three-flavor paradigm; this requires the determination of the unknown CP-violating phase δ_{CP} , the resolution of the mass hierarchy (MH), and the precise measurement of θ_{23} to determine the octant.

T2K, along with the Nova [21] experiment that started data-taking one year earlier, will play a major role in the determination of these parameters for at least a decade.

In this paper, after a brief description of the experiment in Section 2, we will describe the most recent results obtained by T2K (Section 3). In Section 4 we will provide a reevaluation of the expected sensitivity to the oscillation parameters, relative to what was given in the original T2K proposal [19], by taking into account the actual observation of the electron neutrino appearance in a muon neutrino beam by T2K and the new high-precision measurements of the mixing angle θ_{13} from reactor experiments. In Section 5.1 we will briefly describe the proposed upgrade plan for the J-PARC accelerators and neutrino experimental facility aiming to reach a 1.3 MW beam power [22, 23]. Finally in Section 5.2 we will describe the physics potential of T2K for data exposure 3 times larger than the presently approved one.

2. The T2K Experiment

The T2K (Tokai-to-Kamioka) experiment is a second generation LBL (long-baseline) neutrino oscillation experiment to probe physics beyond the Standard Model. T2K uses an almost pure ν_{μ} beam produced using the new MW-class proton synchrotron at J-PARC (Japan Proton Accelerator Research Complex jointly constructed and operated by KEK and JAEA). The neutrino beam is detected first in the near detector *ND280* and then travels 295 km to the far detector *Super-Kamiokande* (see Figure 1).

T2K adopts the off-axis method to generate a narrow-band neutrino beam using the proton synchrotron at J-PARC. In this method the neutrino beam is purposely directed at an angle with respect to the baseline connecting the proton target to the far detector, Super-Kamiokande. The off-axis angle is set at 2.5° so that the narrow-band ν_{μ} beam generated towards the far detector has a peak energy at $\sim 0.6 \text{ GeV}$ (see Figure 2). Such configuration maximizes the effect of the neutrino oscillation at 295 km and minimizes the background to electron neutrino appearance detection. The angle can be reduced to 2.0° , allowing variation of the peak neutrino energy, if necessary. The J-PARC beamline can also provide to the experiment an antineutrino beam instead of a neutrino beam. As it will be shown in Sections 4 and 5, this aspect is very important to constrain the δ_{CP} phase.



FIGURE 1: The neutrino beam journey in the T2K experiment. The high intensity neutrino beam is produced at J-PARC (Tokai, Mito, Ibaraki Prefecture, Japan) and travels 295 km to the Super-Kamiokande detector (mount Kamioka, close to Hida, Gifu Prefecture, Japan).

2.1. Near Detectors. The near detectors were constructed in an underground hall of 33.5 m depth and 17.5 m diameter at 280 m downstream of the target. They are used to measure the neutrino energy spectrum, flavor content, and interaction rates of the unoscillated beam and to predict the neutrino interactions at Super-Kamiokande. Two detectors were installed: an on-axis detector (aimed in the direction of the neutrino beam center) and an off-axis detector (aimed in the direction of SK).

The on-axis detector, namely, the INGRID detector, consists of 16 $1\text{ m} \times 1\text{ m} \times 1\text{ m}$ cubic modules as shown in Figure 3(a). Each module is a “sandwich” of iron/scintillator detectors: 14 of them are arranged so as to form a cross configuration, and the remaining two diagonal modules are positioned off the cross axes. The center of the cross corresponds to the neutrino beam center, defined as 0° with respect to the direction of the primary proton beamline. INGRID is able to measure the on-axis neutrino beam profile and direction with an accuracy of ± 1 mrad. Note that the monitoring of beam direction with high precision is very important for the *off-axis* configuration. In fact 1 mrad divergence corresponds to a change of 2% in the integral of the neutrino flux expected at SK.

The off-axis detector (named ND280) shown in Figure 3(b) is a magnetized tracking detector. The detector elements are contained inside the refurbished UA1 magnet. Inside the upstream end of magnet sits a π^0 -detector (P0D) consisting of tracking planes of scintillating bars alternating with either water target/brass foil or lead foil. Downstream of the P0D is the tracker, composed of three time projection chambers (TPCs) and two fine grained detectors (FGDs) consisting of layers of finely segmented scintillating bars.

The tracker is designed to study charged current interactions in the FGDs. The P0D, TPCs, and FGDs are all surrounded by an electromagnetic calorimeter (ECal) for detecting electrons and photons to better constrain the ν_e contamination in the beam and the γ background, while the return yoke of the magnet is instrumented with scintillator slabs to measure the range of the muons (Side Muon Range Detectors, SMRD) escaping from the sides of the off-axis detector.

In addition, the near off-axis detector can also perform accurate cross section measurements on different target materials (carbon, water, oxygen, and argon) to minimize

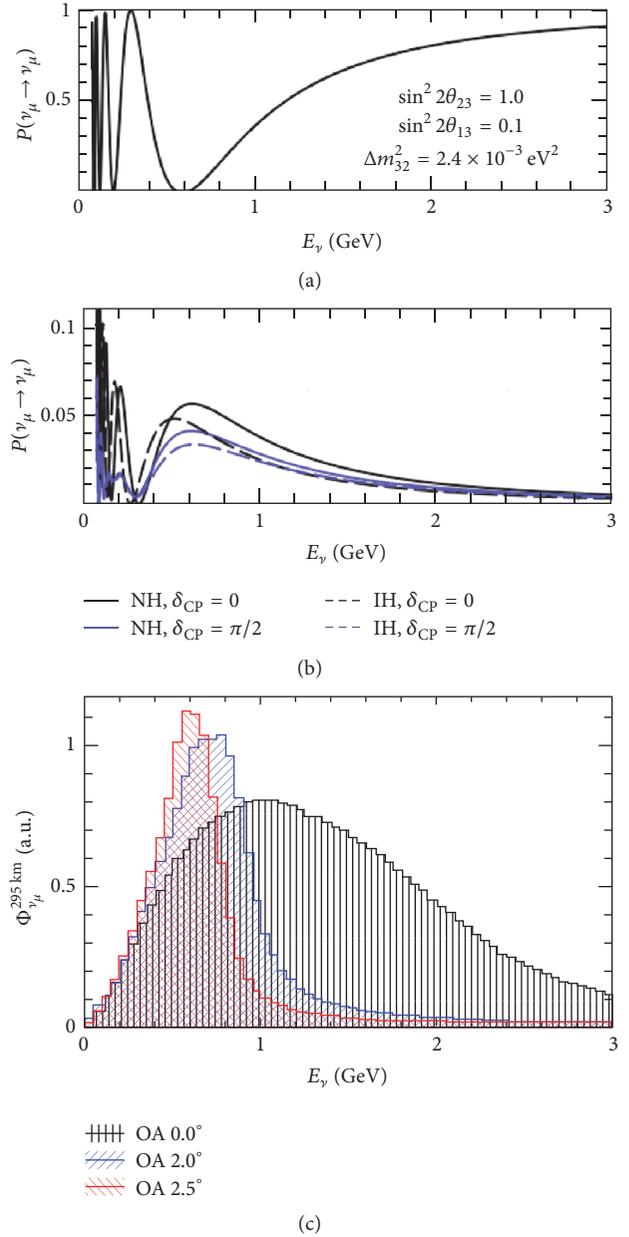


FIGURE 2: The muon neutrino survival probability (a) and electron neutrino appearance probabilities (b) at 295 km and the unoscillated neutrino fluxes for different values of the off-axis angle (OA) (c). The appearance probability is shown for two values of the phase δ_{CP} and for normal (NH) and inverted (IH) mass hierarchies.

the impact of the interaction model uncertainties on the systematic error budget.

2.2. Super-Kamiokande. The far detector, Super-Kamiokande (SK), is a 50 kton water Cherenkov detector [26] located 1000 m underground in the Kamioka mine, Japan. Its distance from J-PARC is 295 km. In the inner detector (ID), 22.5 kton of fiducial volume is viewed by 11,129 20-inch diameter PMTs. The outer detector (OD), which surrounds the ID, is also a water Cherenkov detector: it is used to veto events that enter or exit the ID. SK started its operation in April

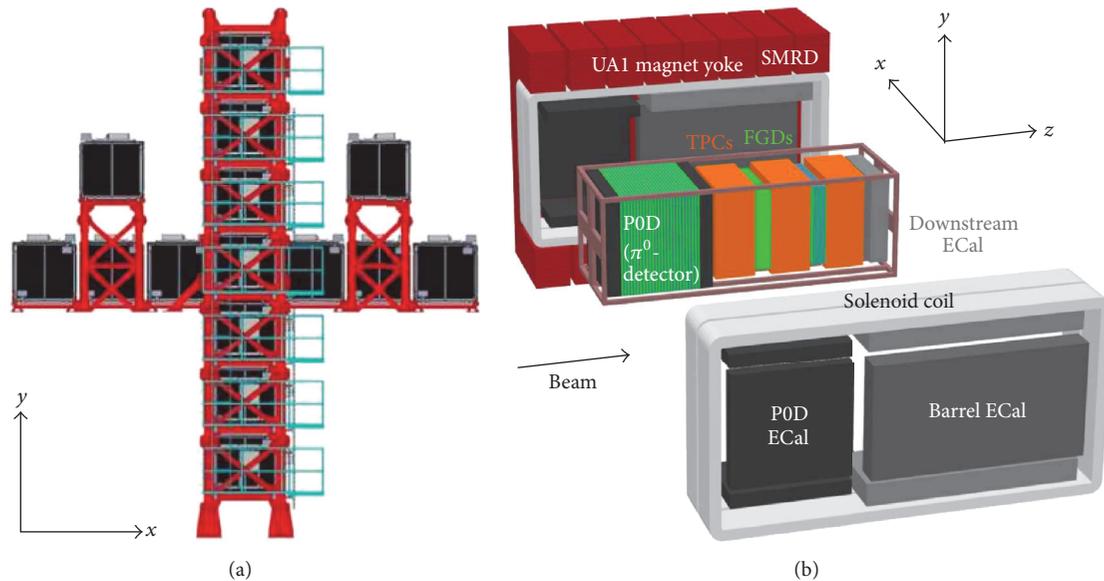


FIGURE 3: Schematic view of the INGRID on-axis detector (a) and the ND280 off-axis detector (b).

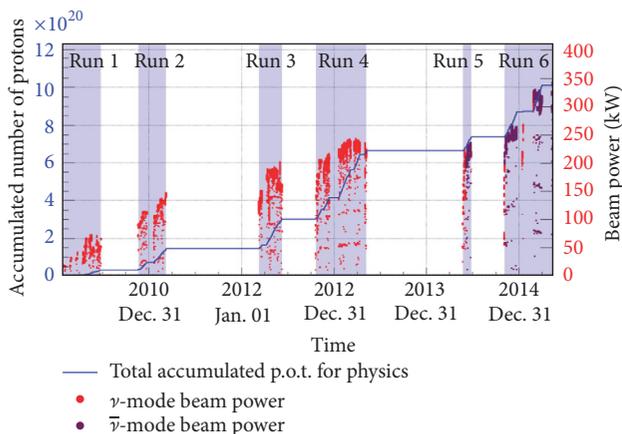


FIGURE 4: The evolution of the primary proton beam intensity and integrated proton delivery in the T2K experiment. Red (violet) dots show averaged beam power per hour in the neutrino (antineutrino) mode beam; the scale is given in the right vertical axis. The blue solid line shows the accumulated number of delivered protons from the beginning of the experiment. The scale is given in the left vertical axis.

1996. After a complete upgrade of its electronics systems in 2008, it was named SK-IV. The most important characteristic of SK, as the far detector of the T2K experiment, is its ability to differentiate between muons and electrons with high efficiency. Considering that the majority of the neutrino interactions in this range of energies are charged current quasielastic (CCQE) interactions, the identification of muons and electrons directly implies the identification of the parent ν_μ ($\bar{\nu}_\mu$) or ν_e ($\bar{\nu}_e$). Details about the SK particle identification performances are reported in [27]. It was verified that the probability of misidentification is less than 1%.

2.3. Data-Taking Status. The evolution of the proton beam delivery is shown in Figure 4. The physics data-taking started

in January 2010. That year one beam pulse had only six bunches in 5 microseconds. The number of protons per pulse (ppp) was limited to $2. \times 10^{13}$, and the beam pulse cycle was at that time 3.52 seconds. Many efforts were made by the J-PARC accelerator group to increase the beam power. To date the number of bunches in each pulse is 8, and the number of protons per pulse is 1.8×10^{14} . In the meantime, the beam cycle time was reduced to 2.48 seconds. The maximum beam power achieved through June 2015 was 371 kW. T2K accumulated 1.1×10^{21} p.o.t. until June 4, 2015. This is about 14% of the final goal of 7.8×10^{21} p.o.t., which can be obtained over five years of beam operation [22, 23, 28].

In June 2014, the direction of the magnetic horn current was reversed and an antineutrino beam run was started. In the next section, results based on 6.57×10^{20} p.o.t. neutrino beam data [12, 15, 29] and 4.04×10^{20} p.o.t. antineutrino beam data recorded until June 2015 will be reported [30].

2.4. Analysis Strategy. T2K employs various analysis methods to estimate oscillation parameters. In general, these methods extract oscillation parameters from the data by comparing the observed and predicted ν_e and ν_μ interaction rates and energy spectra at the far detector. The rate and spectrum depend on the oscillation parameters, the incident neutrino flux, neutrino interaction cross sections, and the detector response. The initial estimate of the neutrino flux is determined by detailed simulations incorporating proton beam measurements, INGRID measurements, and the pion and kaon production rates measured by the NA61/SHINE [31, 32] experiment.

The ND280 detector measurement of ν_μ charged current (CC) events (unoscillated spectra) is used to constrain the initial flux estimates and parameters of the neutrino interaction models that affect the predicted rate and spectrum of neutrino interactions at both ND280 and Super-K.

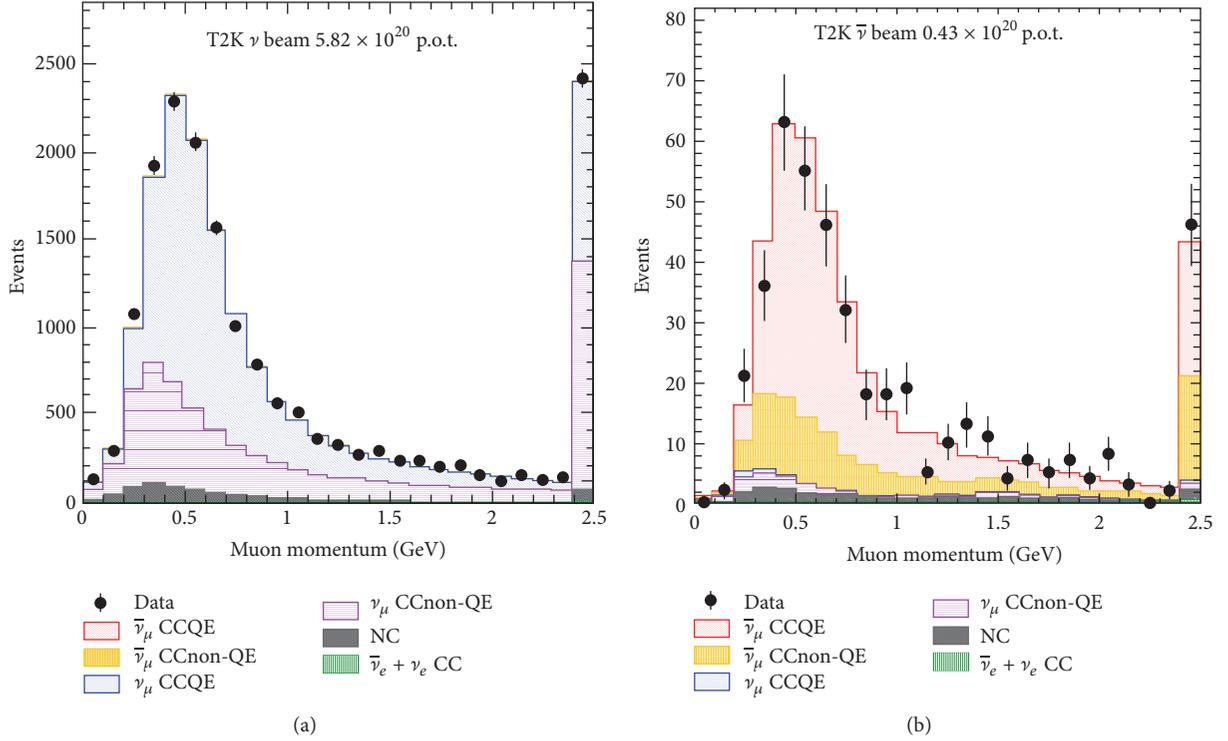


FIGURE 5: Muon momentum distribution of CC ν_μ events (a) and CC $\bar{\nu}_\mu$ events (b) in ND280. Data points include statistical and systematic errors. After the adjustment of systematic uncertainties, there is agreement between the data and Monte Carlo simulation.

ν_μ ($\bar{\nu}_\mu$) CC interactions are selected by requiring that the highest-momentum negative- (positive-) curvature track in an event starts within the upstream FGD (FGD1) fiducial volume (FV) and has an energy deposit in the middle TPC (TPC2) consistent with a muon. The muon PID requirement is based on a truncated mean of measurements of energy loss in the TPC gas [33]. Events with a track in the TPC upstream of FGD1 are rejected and the remaining ν_μ CC candidates are divided into three subsamples according to the number of associated pions: ν_μ CC 0π , dominated by CCQE interactions, ν_μ CC $1\pi^+$, dominated by CC resonant pion production, and the so-called ν_μ CC *other*, dominated by deep inelastic scattering.

Several control samples are used to assess the uncertainty in the modeling of FGD and TPC response. A detailed description of the systematic errors considered in the analysis and the numerical evaluation of each of them can be found in [13]. All the parameters related to cross sections and neutrino fluxes are adjusted based on the comparison between ND280 data and Monte Carlo. As is shown in Figure 5, after the adjustment [12, 13], the agreement is good.

Thanks to the inputs from the ND280 analysis, the systematic errors on the expected neutrino events at SK are strongly reduced. The effect is illustrated in Figure 6: they decrease from 23.5% to 7.7% for ν_μ candidates and from 26.8% to 6.8% for ν_e candidates.

At SK, ν_e and/or ν_μ charged current quasielastic (CCQE) events are selected, with efficiencies and backgrounds determined through detailed simulations tuned to control samples,

accounting for final state interactions (FSI) inside the nucleus and secondary hadronic interactions (SI) in the detector material. These combined results are used in a fit to determine the oscillation parameters.

3. Recent T2K Results

3.1. Neutrino Events Selection in SK. In the years 2010–2013, neutrino events corresponding to 6.57×10^{20} p.o.t. have been recorded in SK. The event selection process comprises two steps. The first is the same for ν_μ and ν_e , and it allows accepting only the beam-related Fully Contained Fiducial Volume (FCFV) events. Note that, with the addition of the request that the event time stamp is within a range of 2 to 10 μs from the beam spill time recorded in Tokai, the applied cuts are the same as those in the well-established atmospheric neutrino analysis [34].

Applying these conditions, 377 events have been selected as FCFV events. The expected number of background events from non-beam-related sources in accidental coincidence was estimated to be 0.0085.

From this point on, separate conditions have been applied to the ν_μ and ν_e samples, allowing the selection of 120 ν_μ and 28 ν_e candidates.

To identify ν_μ CC candidate events the following conditions have been applied:

- (i) There is only one reconstructed Cherenkov ring.
- (ii) The ring is μ -like.

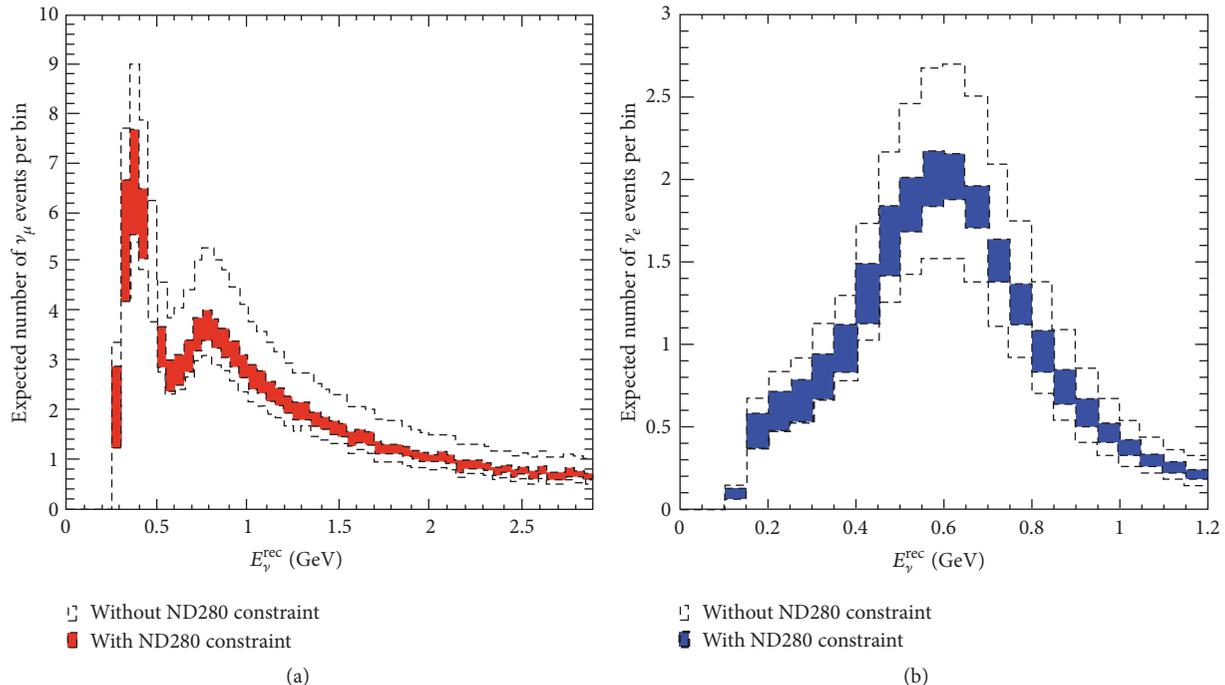


FIGURE 6: Total error envelopes for the reconstructed energy distributions of ν_μ CC (a) and ν_e CC (b) candidate events at SK, using typical oscillation parameter values, with and without the ND280 constraint applied.

- (iii) The reconstructed momentum is higher than 200 MeV.
- (iv) There are less than two reconstructed Michel electrons.

The momentum cut (>200 MeV) is applied to reject charged pions and misidentified electrons from the decay of unobserved muons and pions. The requirement to have fewer than two Michel electrons rejects events with additional unseen muons or pions.

For the selection of the ν_e CC candidate events the criteria listed below have been used:

- (i) There is only one reconstructed Cherenkov ring.
- (ii) The ring is e -like.
- (iii) The visible energy (E_{vis}) is higher than 100 MeV.
- (iv) There is no reconstructed Michel electron.
- (v) The reconstructed energy (E_{rec}) is less than 1.25 GeV.
- (vi) The event is not consistent with π_0 hypothesis.

The E_{vis} requirement removes low energy neutral current (NC) interactions and electrons from the decay of unseen parents that are below Cherenkov threshold or fall outside the beam time window. Since above 1.25 GeV the intrinsic ν_e beam is dominant, a reconstructed energy below this threshold is also requested.

Finally the same selection criteria have been applied to the corresponding Monte Carlo sample, obtaining the numbers of expected neutrino candidates for the no-oscillation hypothesis: they are 446 ± 23 for ν_μ and 4.9 ± 0.6 for ν_e , respectively.

3.2. ν_μ Disappearance. As reported in the previous subsection, 120 muon neutrino candidates have been observed in 6.57×10^{20} p.o.t., to be compared with the 446 ± 23 expected if no oscillation is assumed. The neutrino energy distribution for the selected sample of 120 events is shown in Figures 7(a) and 7(b) together with the ratio of oscillated to unoscillated events as a function of neutrino energy for the data and the best fit spectrum. In Figure 7(a) is also visible the small contribution at low energy from NC as estimated by MC. The disappearance of muon neutrinos events as well as the distortion of the neutrino energy spectrum are evident.

The best fit oscillation parameters measured under those conditions are as follows: $\sin^2(\theta_{23}) = 0.51 \pm 0.056$ and $|\Delta m_{32}^2| = 2.51 \pm 0.10 \times 10^{-3} \text{ eV}^2$, respectively [12].

The constraint in the two-dimensional $\sin^2(\theta_{23})$ - Δm_{32}^2 plane for normal and inverted mass hierarchy is shown in Figure 7(c). The T2K results are consistent with those from SK [35] and MINOS [25] and provide the most stringent constraint for $\sin^2(\theta_{23})$.

3.3. ν_e Appearance. As presented in Section 3.1, by analyzing a data sample at SK corresponding to 6.57×10^{20} p.o.t. 28 electron neutrino candidates have been observed, where 4.9 ± 0.6 where expected from a no-oscillation hypothesis. This result [15] confirmed, with higher statistic, previous T2K claims [13, 14] based on 1.43×10^{20} and 3.01×10^{20} p.o.t., respectively.

From a statistical point of view, the significance of the signal corresponds to 7.3 standard deviations. It can be concluded with certainty that for the first time the electron

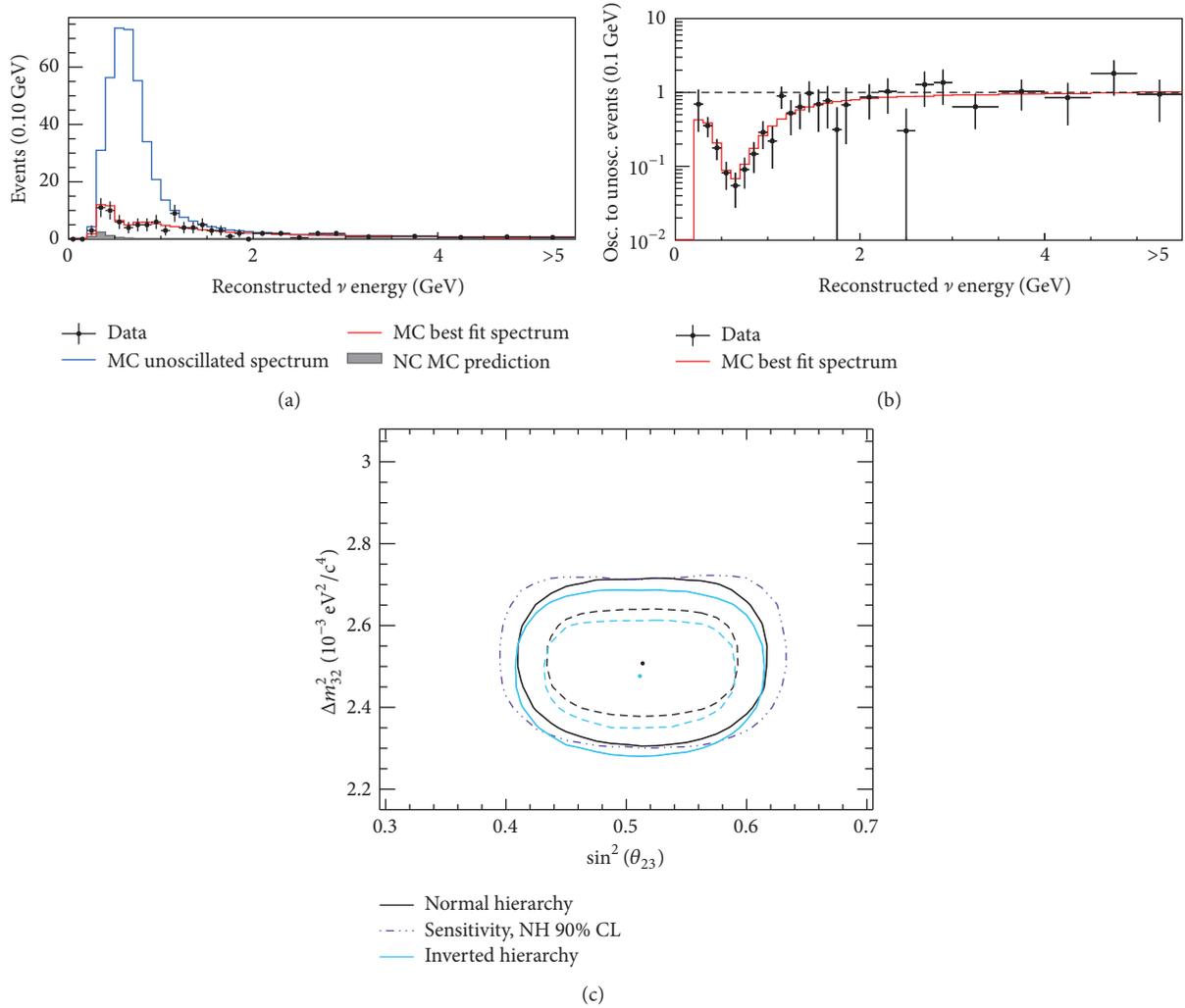


FIGURE 7: (c) The 68% (dashed) and 90% (solid) CL intervals for the ν_μ disappearance analysis assuming normal and inverted mass hierarchies. The 90% CL sensitivity contour for the normal hierarchy is overlaid for comparison. (a) Reconstructed neutrino energy spectrum for data, best fit prediction, and unoscillated prediction. (b) Ratio of oscillated to unoscillated events as a function of neutrino energy for the data and the best fit spectrum.

neutrino appearance has been observed in an almost pure ν_μ beam.

This result is very relevant, in particular because it opens the possibility of new studies in the lepton sector of charge-parity (CP) violation, which provides a distinction in physical processes involving matter and antimatter.

Constraints on oscillation parameters have been carefully calculated by comparing data and expectations. The allowed region in the $\sin^2 2\theta_{13}$ - δ_{CP} plane for normal mass hierarchy and inverted mass hierarchy are shown in Figures 8(a) and 8(b) together with the constraints from reactor experiments [15]. The overlap between T2K and the reactor results indicates that negative δ_{CP} is favoured with a slight preference (67%) for the normal mass hierarchy.

For $\delta_{\text{CP}} = 0$ and normal (inverted) hierarchy, the best fit value with a 68% CL is $\sin^2 2\theta_{13} = 0.136(+0.044/-0.033)$ ($\sin^2 2\theta_{13} = 0.166(+0.051/-0.042)$).

At 90% confidence level and including reactor measurements, T2K excludes the region $\delta_{\text{CP}} = [0.15, 0.83]\pi$ for

normal hierarchy and $\delta_{\text{CP}} = [-0.08, 1.09]\pi$ for inverted hierarchy.

The T2K and reactor data weakly favour the normal hierarchy with a Bayes Factor of 2.2.

The $-2\Delta \ln \mathcal{L}$ value as a function of δ_{CP} for normal hierarchy (solid line) and inverted hierarchy (dotted line) is shown in Figure 8(c) [15]. The likelihood is marginalized over $\sin^2 2\theta_{13}$, $\sin^2 \theta_{23}$, and Δm_{32}^2 . The solid (dotted) line with markers corresponds to the 90% CL limits for normal (inverted) hierarchy, evaluated by using the Feldman-Cousins method. The δ_{CP} regions with values above the lines are excluded at 90% CL.

More recently [36] the T2K collaboration published an analysis that for the first time combines measurements of muon neutrino disappearance and electron neutrino appearance to estimate four oscillation parameters and the mass hierarchy. *Frequentist* and *Bayesian* intervals have been used for combinations of these parameters, with and without the inclusion of recent reactor measurements.

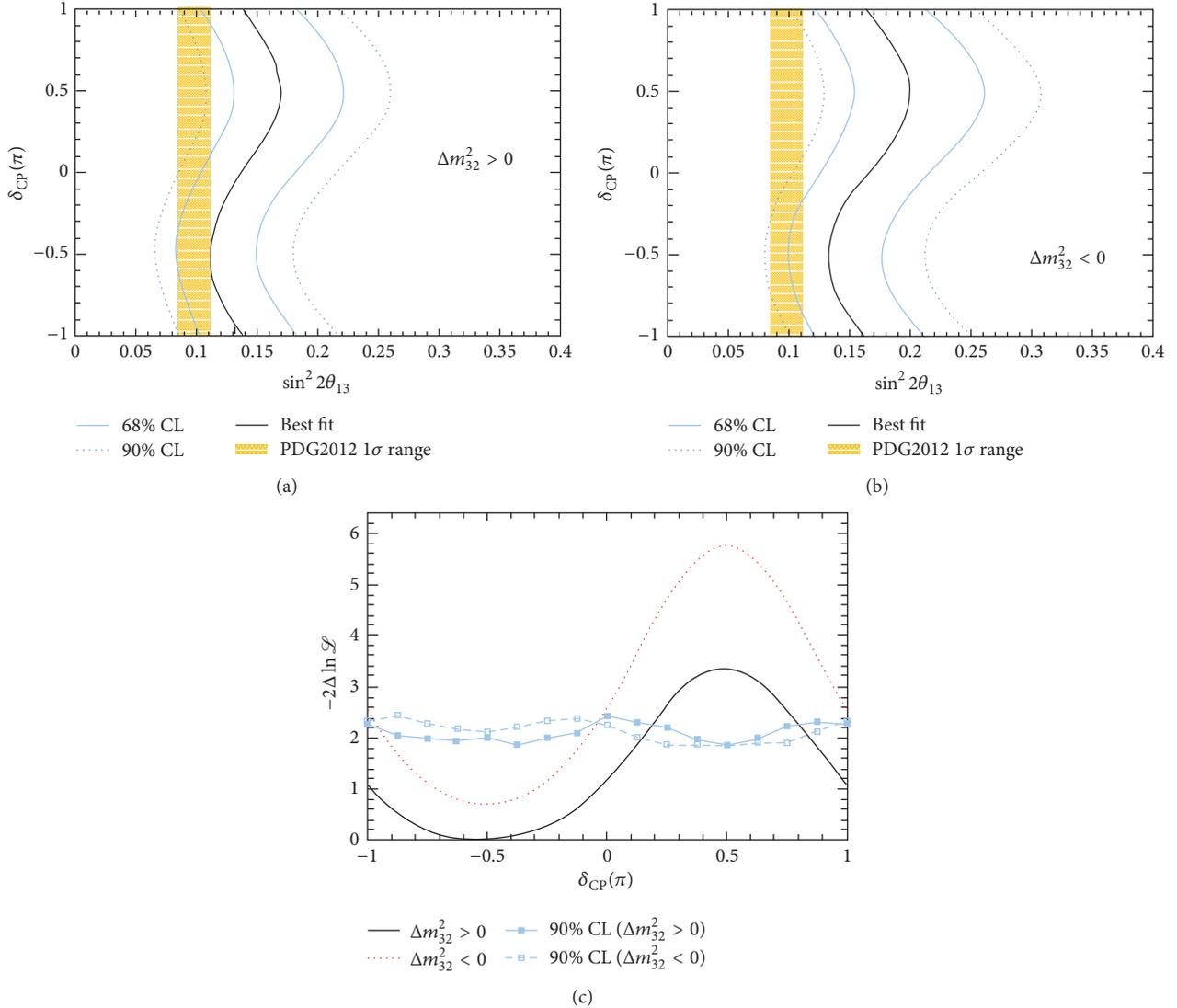


FIGURE 8: (a, b) The 68% and 90% CL allowed regions for $\sin^2 2\theta_{13}$, as a function of δ_{CP} assuming normal hierarchy (a) and inverted hierarchy (b). The solid line represents the best fit $\sin^2 2\theta_{13}$ value for given δ_{CP} values. The values of $\sin^2 2\theta_{23}$ and Δm_{32}^2 are varied in the fit with the constraint from [12]. The shaded region shows the average θ_{13} value from the PDG2012 [24]. (c) The $-2\Delta \ln \mathcal{L}$ value as a function of δ_{CP} for normal hierarchy (solid line) and inverted hierarchy (dotted line). The solid (dotted) line with markers corresponds to the 90% CL limits for normal (inverted) hierarchy, evaluated by using the Feldman-Cousins method. The δ_{CP} regions with values above the lines are excluded at 90% CL.

3.4. $\bar{\nu}_\mu$ Disappearance (Preliminary). Recently T2K reported [30] an initial measurement of muon antineutrino disappearance using the accelerator-produced off-axis neutrino beam at J-PARC.

The event selection applied at SK is unchanged with respect to the neutrino beam mode previously described.

Using a dataset corresponding to 4.04×10^{20} protons-on-target, 34 fully contained μ -like events were observed while 103 events were predicted by Monte Carlo for the unoscillated case.

The best fit oscillation parameters measured under those conditions are $\sin^2(\bar{\theta}_{23}) = 0.45$ and $|\Delta \bar{m}_{32}^2| = 2.51 \times 10^{-3} \text{ eV}^2$ with 68% confidence intervals of 0.38–0.64 and 2.26–2.80 ($\times 10^{-3} \text{ eV}^2$), respectively.

Preliminary results from the $\bar{\nu}_\mu$ disappearance analysis are illustrated in Figure 9.

The distribution of reconstructed neutrino energy for the 34 single ring μ -like events, together with expectations for no-oscillation hypothesis, is shown in Figure 9(a). The deficit is clearly seen.

In Figure 9(b), the constraints on oscillation parameters $|\Delta \bar{m}_{32}^2|$ and $\sin^2(\bar{\theta}_{23})$ obtained from this analysis are compared with previous results. Clearly they are in agreement with antineutrino measurements from both the MINOS and Super-Kamiokande collaborations and also with precise measurements of neutrino disappearance from T2K.

In spite these results representing only 10% of the expected T2K antineutrino dataset, they are already

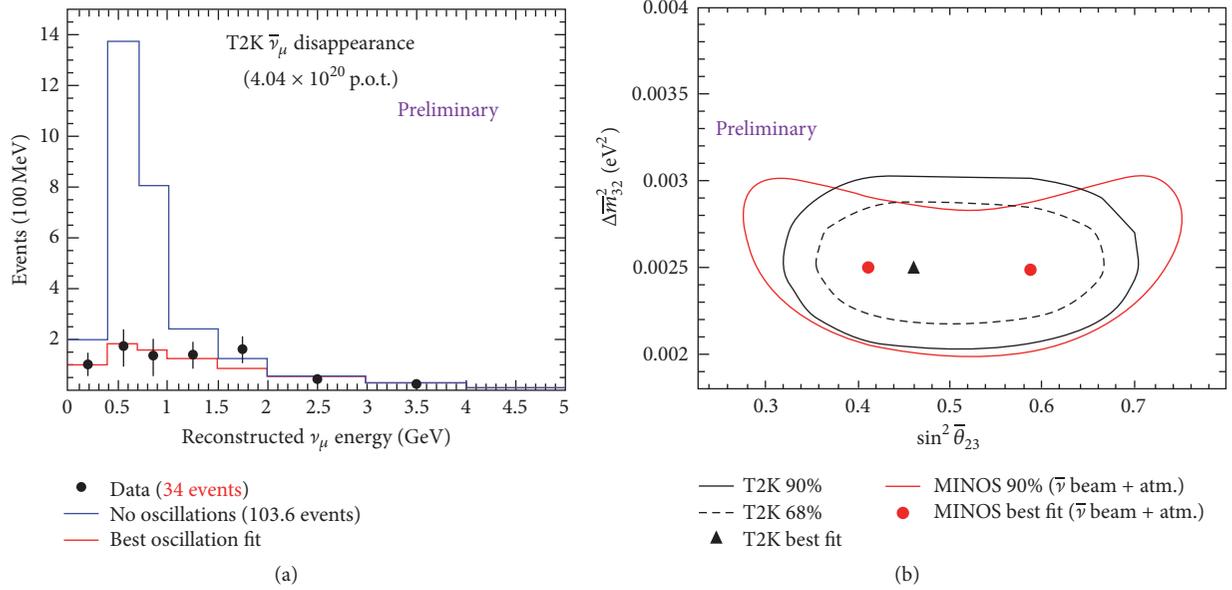


FIGURE 9: (a) Distribution of reconstructed neutrino energy for 34 single ring μ -like events observed in antineutrino beam corresponding to 4.04×10^{20} p.o.t. The expectations for no oscillation and for best fit oscillation parameters are also shown. (b) Constraints on oscillation parameters $|\Delta\bar{m}_{32}^2|$ and $\sin^2(\bar{\theta}_{23})$ obtained from $\bar{\nu}_\mu$ disappearance. Constraints from the MINOS [25] experiment are also shown.

competitive with both MINOS [25] and SK [37], demonstrating the effectiveness of the off-axis beam technique.

3.5. $\bar{\nu}_e$ Appearance (Preliminary). The selection process of $\bar{\nu}_e$ candidates in SK is exactly the same as that for neutrino beam data. After all selections, three events remain as possible candidates of the $\bar{\nu}_e$ appearance signal. The expected number of background events is calculated by Monte Carlo assuming the absence of $\bar{\nu}_\mu$ - $\bar{\nu}_e$ oscillation. Background events include ν_e appearance from ν_μ - ν_e oscillation, misidentified ν_μ (or $\bar{\nu}_\mu$), and original ν_e (or $\bar{\nu}_e$) from the decay of muons in the T2K beam line. The number of background events varies from 1.51 to 1.77, depending on mass hierarchy and δ_{CP} .

Obviously, the observation of three candidates is not significant evidence of $\bar{\nu}_e$ appearance but the collaboration plans to multiply by factor 3 the statistic in the incoming years.

4. T2K Physics Potential for 7.8×10^{21} p.o.t.

The observation of the electron neutrino appearance in a muon neutrino beam by T2K and the high-precision measurement of the mixing angle θ_{13} by reactor experiments have led to reevaluation of the physics potential of T2K for the approved dataset (7.8×10^{21} p.o.t.) that, according to the latest plans of the accelerator group in J-PARC, will be achieved by ~ 2020 .

In particular in [38] the sensitivities for CP violation in neutrinos, nonmaximal $\sin^2 2\theta_{23}$, octant of θ_{23} , and mass hierarchy have been explored for T2K alone and in combination with NO ν A and reactor experiments results.

Special care was also taken in studying the effect coming for various combinations of ν -mode and $\bar{\nu}$ -mode data-taking. In fact the probability of $\nu_\mu \rightarrow \nu_e$ is slightly different from the probability for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation because of the swap in the sign of the δ_{CP} term. This implies that the antineutrino oscillation probability is larger (smaller) than the neutrino oscillation probability for positive (negative) δ_{CP} by up to 25%. Accordingly, comparison of oscillation probabilities between neutrino mode and antineutrinos mode could help in the determination of the δ_{CP} value.

4.1. T2K Alone. A three-flavor analysis combining appearance and disappearance, for both ν -mode and $\bar{\nu}$ -mode, has been performed assuming the expected full statistics of 7.8×10^{21} p.o.t..

The selection of candidate events in SK was done using the same criteria described in Section 3.1.

The study includes either statistical errors only or statistical and systematic errors established for the 2012 oscillation analyses. In addition, signal efficiency and background are taken into account.

It should be emphasized that this evaluation is conservative, considering that the analyses performed on data collected in the years 2013–2015 already showed an improved precision by about 20%, or more, with respect to the numbers quoted in [38].

Reconstructed appearance and disappearance energy spectra generated for the approved full T2K statistics, assuming a data-taking condition of either 100% ν -mode or 100% $\bar{\nu}$ -mode, are shown in Figure 10. All the oscillation parameters have been used in generating the spectra. δ_{CP} , $\sin^2 2\theta_{13}$, $\sin^2 \theta_{23}$, and Δm_{32}^2 were left unknown in the fit, while

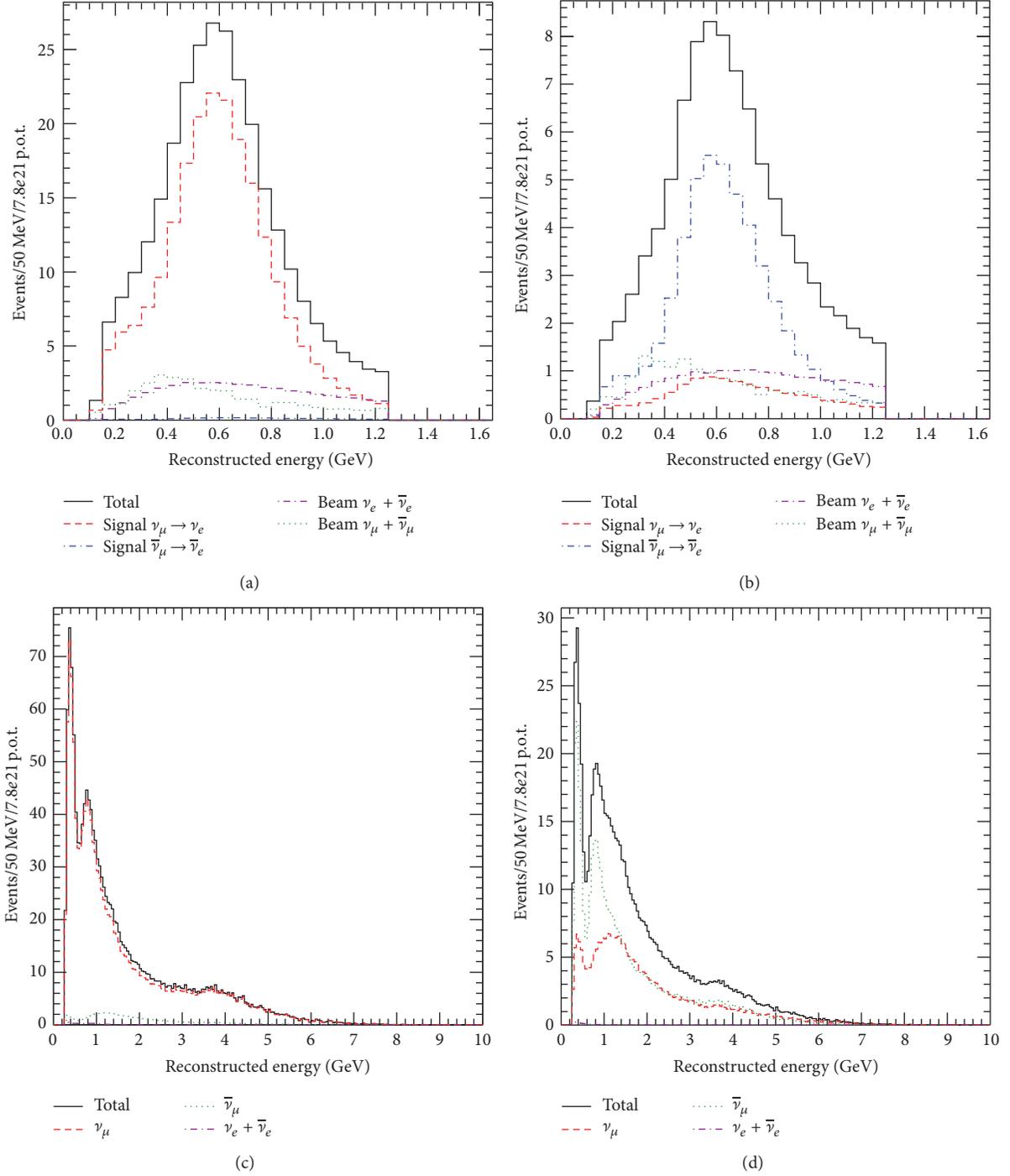


FIGURE 10: (a) ν_e appearance reconstructed energy spectrum, 100% ν -mode running. (b) $\bar{\nu}_e$ appearance reconstructed energy spectrum, 100% $\bar{\nu}$ -mode running. (c) ν_μ disappearance reconstructed energy spectrum, 100% ν -mode running. (d) $\bar{\nu}_\mu$ disappearance reconstructed energy spectrum, 100% $\bar{\nu}$ -mode running. All the oscillation parameters have been used in generating the spectra. δ_{CP} , $\sin^2 2\theta_{13}$, $\sin^2 \theta_{23}$, and Δm_{32}^2 were left unknown in the fit, while $\sin^2 2\theta_{12}$ and Δm_{21}^2 are assumed to be fixed to the values given in Table 1.

$\sin^2 2\theta_{12}$ and Δm_{21}^2 are assumed to be fixed to the values given in Table 1. The expected number of ν_e or $\bar{\nu}_e$ appearance events at 7.8×10^{21} p.o.t. obtained from [38] is shown in Table 2 for two different values of δ_{CP} ($-90^\circ, 0^\circ$). The number of events is broken down into those coming from appearance signal

or intrinsic beam background events that undergo charged current (CC) interactions in SK or beam background events that undergo neutral current (NC) interactions.

The values given in Table 2 indicate that statistics is much more favourable for the ν -mode, where a signal 3 times larger

TABLE I: Nominal values of the oscillation parameters.

Parameter	$\sin^2 2\theta_{13}$	δ_{CP}	$\sin^2 \theta_{23}$	Δm_{32}^2	Hierarchy	$\sin^2 2\theta_{12}$	Δm_{21}^2
Nominal value	0.1	0	0.5	$2.4 \times 10^{-3} \text{ eV}^2$	Normal	0.8704	$7.6 \times 10^{-5} \text{ eV}^2$

TABLE 2: Expected numbers of ν_e or $\bar{\nu}_e$ appearance events at 7.8×10^{21} p.o.t.. The number of events is broken down into those coming from appearance signal or intrinsic beam background events that undergo charged current (CC) interactions in SK or beam background events that undergo neutral current (NC) interactions.

	δ_{CP}	Total	Signal $\nu_\mu \rightarrow \nu_e$	Signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
100% ν -mode	0°	291.5	211.9	2.4			
100% ν -mode	-90°	341.8	262.9	1.7	41.3	1.4	34.5
100% $\bar{\nu}$ -mode	0°	94.9	11.2	48.8			
100% $\bar{\nu}$ -mode	-90°	82.9	13.1	34.9	17.2	0.4	17.3

is expected. However, only combining ν -mode and $\bar{\nu}$ -mode will give an advantage in constraining δ_{CP} .

This effect is clearly illustrated in Figure 11.

In this example, (a) and (b) of Figure 11 show δ_{CP} versus $\sin^2 2\theta_{13}$ 90% CL intervals, each given for 50% of the full T2K p.o.t., of ν - and $\bar{\nu}$ -mode at true $\delta_{\text{CP}} = -90^\circ$ assuming NH and without a reactor constraint (if the fit is assuming the correct mass hierarchy (MH) it is called NH, while if it is assuming the incorrect MH it is called IH).

When the two contours are combined in Figure 11(c), it becomes evident that δ_{CP} can be constrained without any requirement from external data.

However, for other parameters (like θ_{23}) the constraint from the reactor measurements is very important and it is not avoidable if one wishes to discriminate the octant and cancel the degeneracies.

Figure 12 shows, as an example, the 90% CL regions for Δm_{32}^2 versus $\sin^2 \theta_{23}$ at the full T2K statistics for $\sin^2 \theta_{23} = 0.4$. In this case the θ_{23} octant cannot be resolved only by combining both ν -mode and $\bar{\nu}$ -mode data (Figure 12(a)). In fact the reactor constraint on θ_{13} should be included to resolve degeneracies between the oscillation parameters $\sin^2 \theta_{23}$, $\sin^2 2\theta_{13}$, and δ_{CP} as clearly illustrated in Figure 12(b).

4.2. T2K + NO ν A. Since the ability of T2K to measure the value of δ_{CP} is greatly enhanced by the knowledge of the mass hierarchy, the same study [38] has also incorporated the impact of expected data from the NO ν A experiment using the GLOBES tools [39].

The NO ν A experiment [21], which started operating in 2014, has a longer baseline (810 km) and higher peak neutrino energy (~ 2 GeV) than T2K. Accordingly, the impact of the matter effect on the predicted far detector event spectra is larger in NO ν A ($\sim 30\%$) than in T2K ($\sim 10\%$), leading to a better sensitivity to the mass hierarchy.

The study assumes the T2K final statistic (7.8×10^{21} p.o.t.) [19] and 1.8×10^{21} p.o.t. in ν -mode and 1.8×10^{21} p.o.t. $\bar{\nu}$ for NO ν A [21]. The result is illustrated in Figures 13 and 14 for the NH and IH case, respectively. The plots on the left assume a data-taking condition of 100% ν -mode for T2K and 50% ν -

50% $\bar{\nu}$ -mode for NO ν A. The plots on the right assume a data-taking condition of 50% ν - 50% $\bar{\nu}$ -mode for both T2K and NO ν A.

Because of the complementary nature of these two experiments, when T2K data is combined with data from NO ν A, the region of oscillation parameter space where there is sensitivity to observe a nonzero δ_{CP} is substantially increased compared to when each experiment is analyzed alone.

The results of the studies in [38] are actually used to guide the optimization of the future run plan for T2K.

5. T2K Physics Potential for 20×10^{21} p.o.t. or More

In summer of 2015 the T2K collaboration has been considering an extension of the data-taking run beyond the approved total 7.8×10^{21} to 20×10^{21} p.o.t. or more (25×10^{21} p.o.t.). In fact, from studies [40, 41], based on the same considerations described in Section 4.1, an enhancement of the statistics by factor 3 or more could possibly lead to a 3σ measurement excluding $\sin(\delta_{\text{CP}}) = 0$ (depending on the true value of δ_{CP} and on the knowledge of the MH) and showing the first evidence of CP violation in the lepton sector.

In this section we will give a short summary of those recent studies with the *caveat* that all the plots showed below must be considered *work in progress*.

5.1. J-PARC Beam Update. The extended T2K p.o.t. projection, based on the latest J-PARC beam schedule (red dots), is shown in Figure 15 together with a new possible J-PARC beam upgraded schedule as envisaged in [28] (blue dots). The extended T2K p.o.t. projection includes the MR (Main Ring) update (recently approved) that will allow reaching power of 750 kW in 2019 and up to 1.3 MW when the repetition cycle will be reduced from 2.4 s to 1.3 s.

The MR beam power time evolution together with the possible data accumulation is shown in Figure 16 [23], where 5-month neutrino beam operation each year and realistic running time efficiency are assumed.

The new projection shown in Figure 15 (blue dots) assumes an effective p.o.t. calculated by also taking into

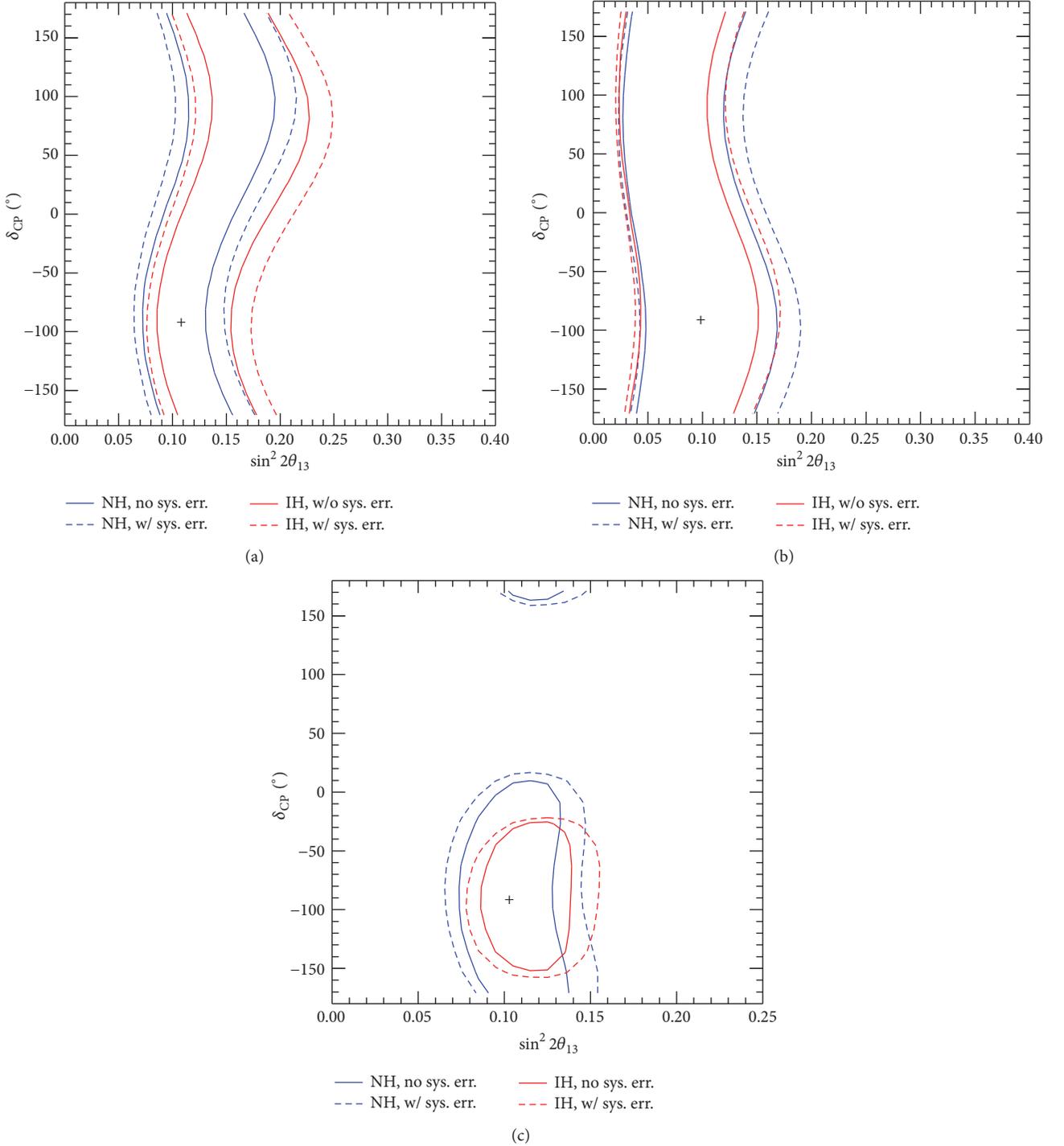


FIGURE 11: Expected δ_{CP} versus $\sin^2 2\theta_{13}$ 90% CL intervals, where (a) and (b) are given for neutrino and antineutrino mode running for 50% of the full T2K p.o.t. each and (c) demonstrated the sensitivity of the total T2K p.o.t. with 50% ν -mode plus 50% $\bar{\nu}$ -mode running. Contours are plotted for the case of true $\delta_{CP} = -90^\circ$ and NH. The blue curves are fits assuming the correct MH(NH), while the red ones are fits assuming the incorrect MH(IH), and contours are plotted from the minimum χ^2 value for both MH assumptions. The solid contours are with statistical error only, while the dashed contours include the systematic errors used in the 2012 oscillation analysis assuming full correlation between ν - and $\bar{\nu}$ -mode running errors.

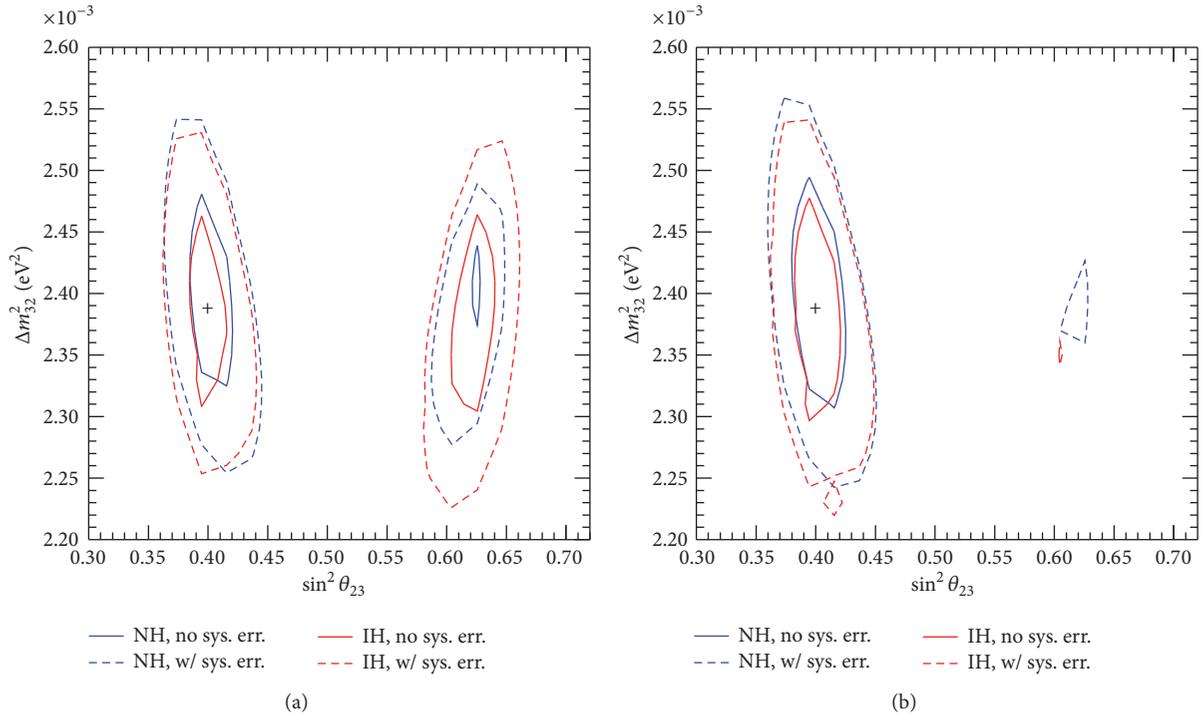


FIGURE 12: Δm_{32}^2 versus $\sin^2 \theta_{23}$ 90% CL intervals for 7.8×10^{21} p.o.t. (50% ν -mode plus 50% $\bar{\nu}$ -mode running). Contours are plotted for the case of true $\delta_{\text{CP}} = 0^\circ$, $\sin^2 \theta_{23} = 0.4$, $\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2$, and NH. The plot on (a) does not include the reactor constraint; the plot on (b) includes it. The blue curves show fits assuming the correct MH(NH), while the red ones show fits assuming the incorrect MH(IH). The solid contours are with statistical error only, while the dashed contours include the 2012 systematic errors fully correlated between ν -mode and $\bar{\nu}$ -mode.

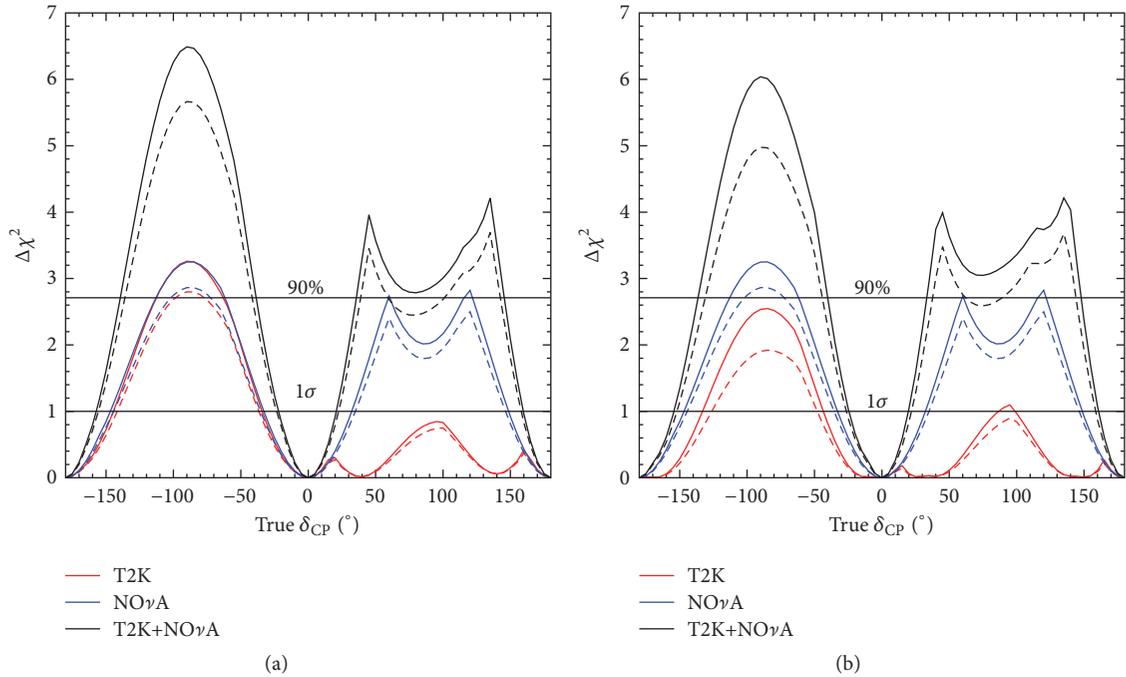


FIGURE 13: The predicted $\Delta \chi^2$ for rejecting the $\sin \delta_{\text{CP}} = 0$ hypothesis, as a function of δ_{CP} for T2K (red), NO ν A (blue), and T2K + NO ν A (black), assuming NH. Dashed (solid) curves indicate studies where normalization systematics are (not) considered. (a) 1:0 T2K, 1:1 NO ν A ν : $\bar{\nu}$. (b) 1:1 T2K, 1:1 NO ν A ν : $\bar{\nu}$.

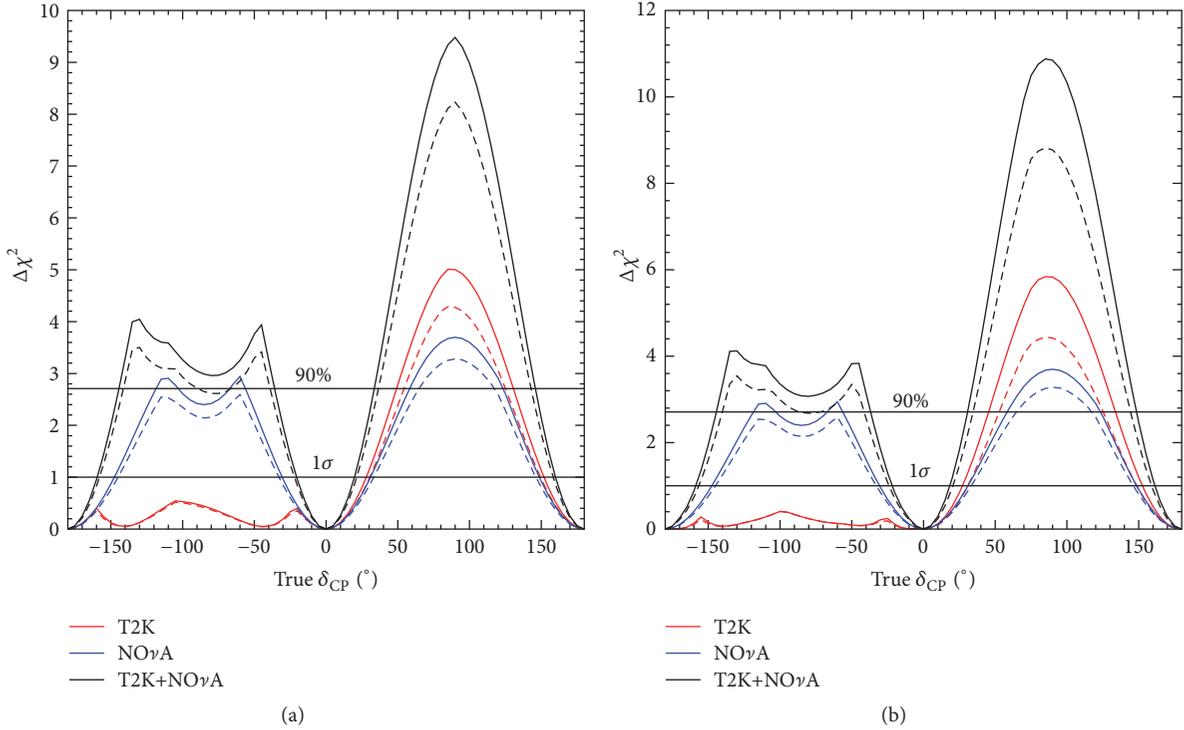


FIGURE 14: The predicted $\Delta\chi^2$ for rejecting the $\sin \delta_{CP} = 0$ hypothesis, as a function of δ_{CP} for T2K (red), NO ν A (blue), and T2K + NO ν A (black), assuming IH. Dashed (solid) curves indicate studies where normalization systematics are (not) considered. (a) 1:0 T2K, 1:1 NO ν A ν : $\bar{\nu}$. (b) 1:1 T2K, 1:1 NO ν A ν : $\bar{\nu}$.

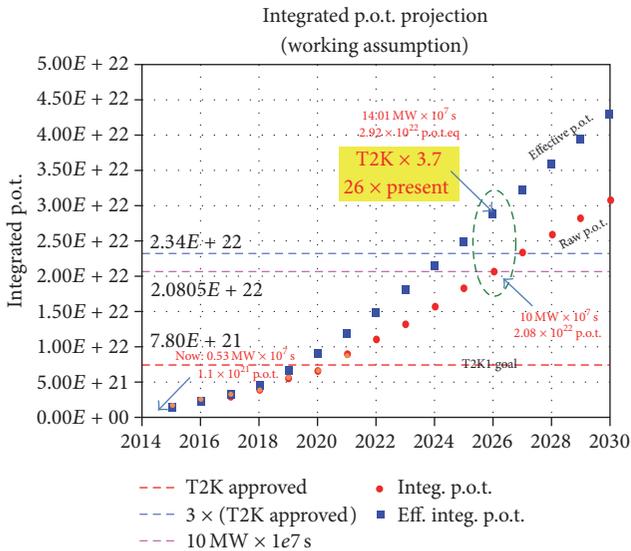


FIGURE 15: The extended T2K p.o.t. projection, based on the last J-PARC beam schedule (red dots) together with a new possible J-PARC beam upgraded schedule as envisaged in [28] (blue dots). The new projection assumes an effective p.o.t., calculated including additional hardware upgrades and analysis improvements in SK.

account additional hardware upgrades and some analysis improvements in SK. The possible hardware improvements include an increase of the horn current from ± 250 kA to ± 320 kA. This will lead up to a 10% more neutrino flux

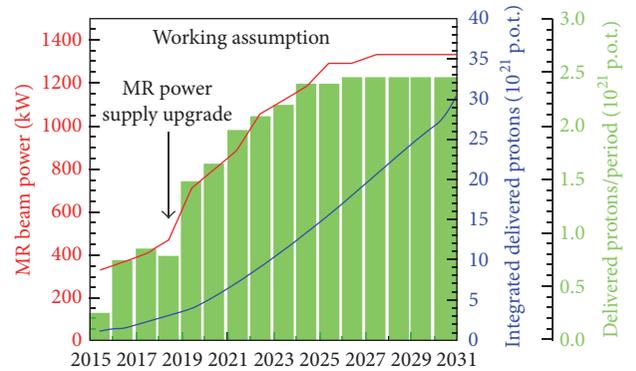


FIGURE 16: Anticipated MR beam power and POT accumulation versus calendar year [23].

at the far detector. The analysis improvements include the expansion of the SK fiducial volume and/or adding new SK event selections. As an example, adding CC 1π events will increase the event sample at the far detector by 14%.

According to the projections showed in Figures 15 and 16, T2K will be able to collect neutrino events corresponding to 20×10^{21} p.o.t. (25×10^{21} p.o.t.) before the year 2026 (2028) (red dots) or 2024 (2025) (blue dots).

Tables 3 and 4 [40, 41] show the expected numbers of ν_e or $\bar{\nu}_e$ appearance events and ν_μ or $\bar{\nu}_\mu$ disappearance events for two different values of δ_{CP} ($-90^\circ, 0^\circ$) at 7.8×10^{21} p.o.t. and 25×10^{21} p.o.t., respectively. A combination of 50% ν - + 50% $\bar{\nu}$ - mode beam running is assumed.

TABLE 3: Expected numbers of ν_e or $\bar{\nu}_e$ appearance events for two different values of δ_{CP} (-90° , 0°) at 7.8×10^{21} p.o.t. and 25×10^{21} p.o.t., respectively. A combination of 50% ν - + 50% $\bar{\nu}$ -mode beam running is assumed.

		ν_e signal	ν_e bkg.	$\bar{\nu}_e$ signal	$\bar{\nu}_e$ bkg.
7.8e21 p.o.t.	0°	98.2	26.8	25.6	16.3
	-90°	121.4	26.4	19.0	17.2
25e21 p.o.t.	0°	314	85.9	82.1	52.2
	-90°	389	84.6	60.9	55.1

TABLE 4: Expected numbers of ν_μ or $\bar{\nu}_\mu$ disappearance events assuming or not the oscillation hypothesis at 7.8×10^{21} p.o.t. and 25×10^{21} p.o.t., respectively. A combination of 50% ν - + 50% $\bar{\nu}$ -mode beam running is assumed.

		ν_μ -model	$\bar{\nu}_\mu$ -mode
7.8e21 p.o.t.	w/o oscillation	2648	1007
	w/ oscillation	741	342
25e21 p.o.t.	w/o oscillation	8519	3228
	w/ oscillation	2375	1096

5.2. *T2K Sensitivities to the Oscillation Parameters with 20×10^{21} p.o.t.* At the beginning of January 2016 the T2K collaboration has submitted an EoI (Expression of Interest) [42] to the Japanese PAC Committee, aiming to extend the T2K run to 20×10^{21} p.o.t (T2K-II). For this study T2K systematic errors are encoded into a covariance matrix with bins in reconstructed neutrino energy. Errors on the shape of the reconstructed energy spectra are taken into account. Two hypotheses have been considered on both reconstructed ν_e appearance and ν_μ disappearance events: the current (2016) T2K systematic error on the far detector prediction (the total systematic error on the far detector prediction is now 6.8% [36]) and a possible reduction to 4% that seems to be reachable in the next years by T2K.

The T2K sensitivity to a nonzero $\sin(\delta_{\text{CP}})$ also depends on the true values of the oscillation parameters. In this case all plots assume $\sin^2 2\theta_{13} = 0.085$ and $\Delta m_{32}^2 = 2.5 \times 10^{-3}$.

The updated horn current of ± 320 kA and a combination of 50% ν - + 50% $\bar{\nu}$ -mode beam running are also assumed.

In Figure 17 the predicted $\Delta\chi^2$ for rejecting the $\sin \delta_{\text{CP}} = 0$ hypothesis is plotted versus p.o.t. (assuming $\delta_{\text{CP}} = -90^\circ$ and true normal mass hierarchy (NH)) for various true values of $\sin^2 \theta_{23}$ with or without systematic errors. It is clear that not only the improvement in statistics but also the reduction of the T2K systematic errors would be more than beneficial in the case of an extension of T2K.

Also the knowledge of the mass hierarchy is an important element, as it can be seen by looking at Figure 18 where $\Delta\chi^2$ for rejecting the $\sin \delta_{\text{CP}} = 0$ is plotted versus true δ_{CP} . In fact, comparing Figure 18(b) (that assumes MH is known) with Figure 18(a) (that assumes MH is unknown), it is clear that the sensitivity to $\sin \delta_{\text{CP}} = 0$ will be enhanced in the first case. However several experiments (JUNO, NO ν A, ORCA, and PINGU) are expected or plan to determine the mass

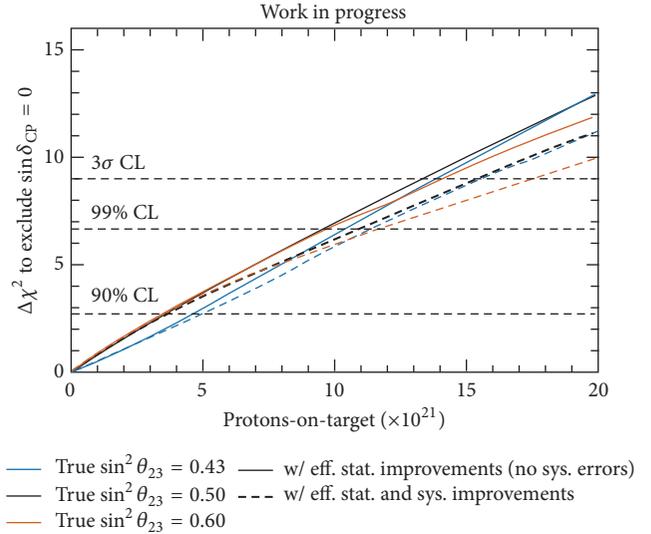


FIGURE 17: Predicted $\Delta\chi^2$ for rejecting the $\sin \delta_{\text{CP}} = 0$ hypothesis versus p.o.t. assuming $\delta_{\text{CP}} = -90^\circ$ and NH for various true values of $\sin^2 \theta_{23}$ with or without systematic errors.

hierarchy before or during the proposed period of T2K-II [21, 43–45]. In this context the sensitivity shown in Figure 18(b) seems to illustrate a realistic scenario.

6. Conclusions

The T2K experiment, proposed in 2003 and approved in 2006 to collect data corresponding to 7.8×10^{21} protons-on-target (p.o.t.) from a 30 GeV proton beam at the J-PARC accelerator facility in Japan, is one of the most important players in the field of neutrino oscillations.

Built to search for $\nu_\mu \rightarrow \nu_e$ appearance and to make precision measurements of oscillation parameters in ν_μ disappearance, it realized its first goal with just 8.4% of the total approved p.o.t. and at the same time provided the most stringent constraints on $\sin^2(\theta_{23})$ obtained until now.

The T2K collaboration is now looking to the determination of the unknown CP-violating phase δ_{CP} and to more precise measurements of θ_{23} to determine the octant.

Reevaluation of the expected sensitivity to the oscillation parameters that takes into account the observation of the electron neutrino appearance was done considering two different scenarios: the approved data-taking and data exposure 3 times larger.

In the latter case, assuming a combination of 50% ν - + 50% $\bar{\nu}$ -mode beam running, it might be possible to obtain a 3σ measurement excluding $\sin(\delta_{\text{CP}}) = 0$ (assuming $\delta_{\text{CP}} = -90^\circ$ and NH) around the year 2025, before the next generation of neutrino experiments will start their operation.

Competing Interests

The author declares that they have no competing interests.

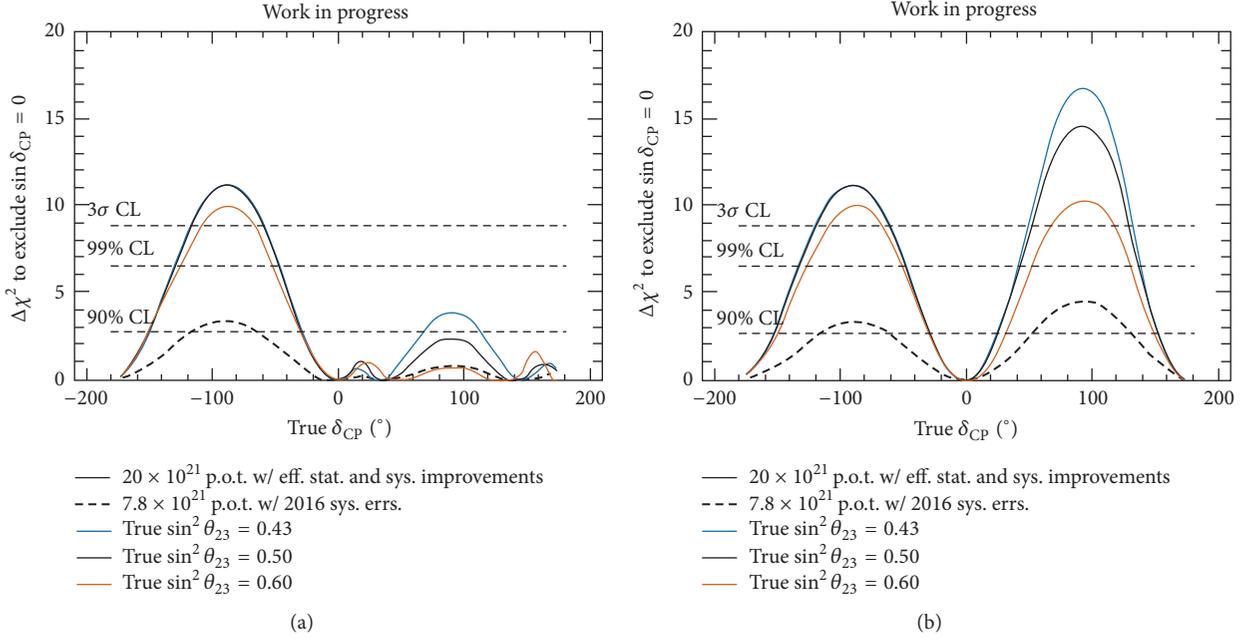
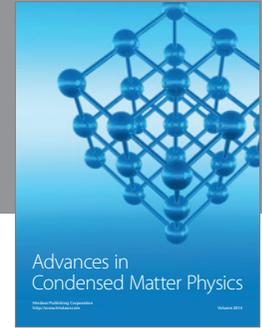
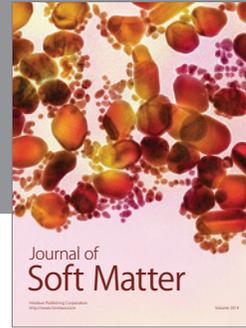
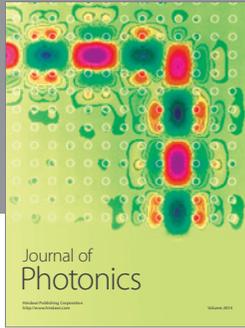
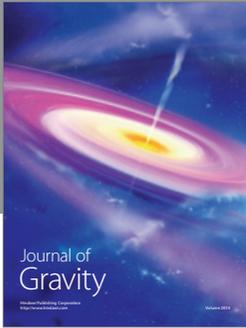


FIGURE 18: Sensitivities to CP violation as a function of true value of δ_{CP} for T2K and extended T2K for various true values of $\sin^2\theta_{23}$ assuming (b) or not (a) that the true MH is the normal MH.

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