Neutrino Oscillation Physics Potential of the T2K Experiment

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The observation of the recent electron neutrino appearance in a muon neutrino beam and the high-precision measurement of the mixing angle θ_{13} have led to a re-evaluation of the physics potential of the T2K long-baseline neutrino oscillation experiment. Sensitivities are explored for CP violation in neutrinos, non-maximal $\sin^2 2\theta_{23}$, the octant of θ_{23} , and the mass hierarchy, in addition to the measurements of δ_{CP} , $\sin^2 \theta_{23}$, and Δm_{32}^2 , for various combinations of ν -mode and $\bar{\nu}$ -mode data-taking.

With an exposure of 7.8×10^{21} protons-on-target, T2K can achieve 1- σ resolution of 0.050(0.054) on sin² θ_{23} and 0.040(0.045) $\times 10^{-3}$ eV² on Δm_{32}^2 for 100%(50%) neutrino beam mode running assuming sin² $\theta_{23} = 0.5$ and $\Delta m_{32}^2 = 2.4 \times 10^{-3}$ eV². T2K will have sensitivity to the CP-violating phase δ_{CP} at 90% C.L. or better over a significant range.

For example, if $\sin^2 2\theta_{23}$ is maximal (i.e $\theta_{23}=45^\circ$) the range is $-115^\circ < \delta_{\rm CP} < -60^\circ$ for normal hierarchy and $+50^\circ < \delta_{\rm CP} < +130^\circ$ for inverted hierarchy. When T2K data is combined with data from the NO ν A experiment, the region of oscillation parameter space where there is sensitivity to observe a non-zero δ_{CP} is substantially increased compared to if each experiment is analyzed alone.

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1 1. Introduction

The experimental confirmation of neutrino oscillations, where neutrinos of a particular fla-2 vor (ν_e,ν_μ,ν_τ) can transmute to another flavor, has profound implications for physics. The 3 observation of a zenith-angle-dependent deficit in muon neutrinos produced by high-energy 4 proton interactions in the atmosphere [1] confirmed the neutrino flavor oscillation hypoth-5 esis. The "anomalous" solar neutrino flux [2] problem was shown to be due to neutrino 6 oscillation by more precise measurements [3, 4, 5, 6]. Atmospheric neutrino measurements 7 have provided further precision on the disappearance of muon neutrinos [7, 8] and the 8 appearance of tau neutrinos [9]. Taking advantage of nuclear reactors as intense sources. 9 the disappearance of electron antineutrinos has been firmly established using both widely 10 distributed multiple sources at an average distance of 180 km [6] and from specialized 11 detectors placed within $\sim 2 \text{ km}$ [10, 11, 12]. The development of high-intensity proton accel-12 erators that can produce focused neutrino beams with mean energy from a few hundred 13 MeV to tens of GeV have enabled measurements of the disappearance of muon-neutrinos 14 (and muon antineutrinos) [8, 13, 14] and appearance of electron-neutrinos (and electron 15 antineutrinos) [15, 16, 17, 18] and tau-neutrinos [19] over distances of hundreds of kilometers. 16 While the early solar and atmospheric oscillation experiments could be described in a two-17 neutrino framework, recent experiments with diverse neutrino sources support a three-flavor 18 oscillation framework. In this scenario, the three neutrino flavor eigenstates mix with three 19 mass eigenstates (ν_1, ν_2, ν_3) through the Pontecorvo-Maki-Nakagawa-Sakata [20] (PMNS) 20 matrix in terms of three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$ and one complex phase (δ_{CP}) . The prob-21 ability of neutrino oscillation depends on these parameters, as well as the difference of the 22 squared masses of the mass states $(\Delta m_{21}^2, \Delta m_{31}^2, \Delta m_{32}^2)$. Furthermore, there is an explicit 23 dependence on the energy of the neutrino (E_{ν}) and the distance traveled (L) before detec-24 tion. To date, all the experimental results are well-described within the neutrino oscillation 25 framework as described in Sec. 2. 26

T2K is a long-baseline neutrino oscillation experiment proposed in 2003 [21] with three main physics goals that were to be achieved with data corresponding to 7.8×10^{21} protonson-target (POT) from a 30 GeV proton beam:

³⁰ • search for $\nu_{\mu} \rightarrow \nu_{e}$ appearance and establish that $\theta_{13} \neq 0$ with a sensitivity down to ³¹ $\sin^{2} 2\theta_{13} \sim 0.008(90\% \text{ C.L.});$

³² • precision measurement of oscillation parameters in ν_{μ} disappearance with $\delta(\Delta m^2_{32}) \sim 10^{-4} \text{ eV}^2$ and $\delta(\sin^2 2\theta_{23}) \sim 0.01$; and

 \circ search for sterile components in ν_{μ} disappearance.

The T2K experiment began data taking in 2009 [22] and a major physics goal, the discovery 35 of $\nu_{\mu} \rightarrow \nu_{e}$ appearance, has been realized at 7.3 σ level of significance with just 8.4% of 36 the total approved POT [17]. This is the first time an explicit flavor appearance has been 37 observed from another neutrino flavor with significance larger than 5σ . This observation 38 opens the door to study CP violation (CPV) in neutrinos as described in Sec. 2. Following 39 this discovery, the primary physics goal for the neutrino physics community has become 40 a detailed investigation of the three-flavor paradigm which requires determination of the 41 CP-violating phase δ_{CP} , resolution of the mass hierarchy (MH), precise measurement of θ_{23} 42 to determine how close θ_{23} is to 45°, and determination of the θ_{23} octant, *i.e.*, whether the 43 mixing angle θ_{23} is less than or greater than 45°. T2K, along with the NO ν A [23] experiment 44

that recently began operation, will lead in the determination of these parameters for at leasta decade.

This paper provides a comprehensive update of the anticipated sensitivity of the T2K 47 experiment to the oscillation parameters as given in the original T2K proposal [21], and 48 includes an investigation of the enhancements from performing combined fits including the 49 projected NO ν A sensitivity. It starts with a brief overview of the neutrino oscillation frame-50 work in Sec. 2, and a description of the T2K experiment in Sec. 3. Updated T2K sensitivities 51 are given in Sec. 4, while sensitivities when results from T2K are combined with those from 52 the NO ν A experiment are given in Sec. 5. Finally, results of a study of the optimization of 53 the ν and $\bar{\nu}$ running time for both T2K and NO ν A are given in Sec. 6. 54

55 2. Neutrino Mixing and Oscillation Framework

Three-generation neutrino mixing can be described by a unitary matrix, often referred to as the PMNS matrix. The weak flavor eigenstates, ν_e , ν_μ , and ν_τ are related to the mass eigenstates, ν_1 , ν_2 , and ν_3 , by the unitary mixing matrix U:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$
(1)

⁵⁹ where the matrix is commonly parameterized as

$$U_{PMNS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{bmatrix} \begin{bmatrix} C_{13} & 0 & S_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -S_{13}e^{+i\delta_{CP}} & 0 & C_{13} \end{bmatrix} \begin{bmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
(2)

with $C_{ij}(S_{ij})$ representing $\cos \theta_{ij}(\sin \theta_{ij})$, where θ_{ij} is the mixing angle between the genera-60 tions i and j. There is one irreducible phase, δ_{CP} , allowed in a unitary 3×3 mixing matrix.¹ 61 After neutrinos propagate through vacuum, the probability that they will interact via one 62 of the three flavors will depend on the values of these mixing angles. As neutrinos propagate 63 through matter, coherent forward scattering of electron-neutrinos causes a change in the 64 effective neutrino mass that leads to a modification of the oscillation probability. This is the 65 so-called *matter effect*. Interference between multiple terms in the transition probability can 66 lead to CP violation in neutrino mixing if the phase δ_{CP} is non-zero. 67

For T2K, the neutrino oscillation modes of interest are the $\nu_{\mu} \rightarrow \nu_{e}$ appearance mode and the ν_{μ} disappearance mode. The $\nu_{\mu} \rightarrow \nu_{e}$ appearance oscillation probability (to first order approximation in the matter effect[24]) is given by

$$P(\nu_{\mu} \rightarrow \nu_{e}) = 4C_{13}^{2}S_{13}^{2}S_{23}^{2}\sin^{2}\Phi_{31}(1 + \frac{2a}{\Delta m_{31}^{2}}(1 - 2S_{13}^{2})) +8C_{13}^{2}S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta_{CP} - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21} -8C_{13}^{2}C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta_{CP}\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21} +4S_{12}^{2}C_{13}^{2}(C_{12}^{2}C_{23}^{2} + S_{12}^{2}S_{23}^{2}S_{13}^{2} - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta_{CP})\sin^{2}\Phi_{21} -8C_{13}^{2}S_{13}^{2}S_{23}^{2}(1 - 2S_{13}^{2})\frac{aL}{4E_{\nu}}\cos\Phi_{32}\sin\Phi_{31},$$

$$(3)$$

¹ If the neutrino is a Majorana particle, two additional phases are allowed that have no consequences for neutrino oscillations.

where $\Phi_{ji} = \Delta m_{ji}^2 L/4E_{\nu}$. The terms that include $a \equiv 2\sqrt{2}G_F n_e E_{\nu} = 7.56 \times 10^{-5} [\text{eV}^2] (\frac{\rho}{[g/cm^3]}) (\frac{E_{\nu}}{[GeV]})$ 71 are a consequence of the matter effect, where n_e and ρ are the electron and matter densities, 72 respectively. The equivalent expression for antineutrino appearance, $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$, is obtained by 73 reversing the signs of terms proportional to $\sin \delta_{CP}$ and a. The first and fourth terms of 74 Eq.3 come from oscillations induced by θ_{13} and θ_{12} , respectively, in the presence of non-zero 75 θ_{23} . The second and third terms come from interference caused by these oscillations. At the 76 T2K peak energy of ~ 0.6 GeV and baseline length of L = 295 km, $\cos \Phi_{32}$ is nearly zero and 77 the second and fifth terms vanish. The fourth term, to which solar neutrino disappearance 78 is attributed, is negligibly small. Hence, the dominant contribution for ν_e appearance in the 79 T2K experiment comes from the first and third terms. The contribution from the matter 80 effect is about 10% of the first term without the matter effect. Since the third term contains 81 $\sin \delta_{CP}$, it is called the 'CP-violating' term. It is as large as 27% of the first term without the 82 matter effect when $\sin \delta_{CP} = 1$ and $\sin^2 2\theta_{23} = 1$, meaning that the CP-violating term makes 83 a non-negligible contribution to the total ν_e appearance probability. The measurement of 84 θ_{13} from the reactor experiments is independent of the CP phase, and future measurements 85 from Daya Bay [10], Double Chooz [11] and RENO [12] will reduce the θ_{13} uncertainty such 86 that the significance of the CP-violating term will be enhanced for T2K. It is also impor-87 tant to recognize that since the sign of the CP-violating term is opposite for neutrino and 88 antineutrino oscillations, data taken by T2K with an antineutrino beam for comparison to 89 neutrino data may allow us to study CP violation effects directly. 90

⁹¹ The ν_{μ} disappearance oscillation probability is given by

$$1 - P(\nu_{\mu} \to \nu_{\mu}) = (C_{13}^4 \sin^2 2\theta_{23} + S_{23}^2 \sin^2 2\theta_{13}) \sin^2 \Phi_{32}$$
(4)

(where other matter effect and Δm_{21}^2 terms can be neglected). The ν_{μ} disappearance measurement is sensitive to $\sin^2 2\theta_{23}$ and Δm_{32}^2 . Currently, the measured value of $\sin^2 2\theta_{23}$ is consistent with full mixing, but more data are required to know if that is the case. If the mixing is not maximal, the ν_e appearance data, together with the ν_{μ} disappearance data, have the potential to resolve the θ_{23} octant degeneracy because the first term of Eq.3 is proportional to $\sin^2 \theta_{23}$.

The NO ν A experiment is similar to T2K in the basic goals to measure ν_{μ} disappearance and 98 ν_e appearance in an off-axis muon neutrino beam. The most important difference between 99 the two experiments is the distance from the neutrino source to the far detector, 810 km for 100 $NO\nu A$ and 295 km for T2K, with a correspondingly higher peak neutrino beam energy for 101 $NO\nu A$ to maximize the appearance probability. $NO\nu A$ is projected to have similar sensitivity 102 compared to T2K for θ_{23} , θ_{13} , and δ_{CP} , but better sensitivity to the sign of Δm_{32}^2 since, as 103 can be seen in a in Eq. 3, the size of the matter effect is proportional to the distance L. The 104 combination of results from the two experiments at different baselines will further improve 105 the sensitivity to the sign of Δm_{32}^2 and to $\delta_{\rm CP}$. 106

¹⁰⁷ In this paper we present the updated T2K sensitivity to neutrino oscillation parameters ¹⁰⁸ using a large value of $\sin^2 2\theta_{13}$ similar to that measured by the reactor experiments, together ¹⁰⁹ with the sensitivity when projected T2K and NO ν A results are combined.

The latest measured values of the neutrino mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, |\Delta m_{32}^2|, \Delta m_{21}^2)$, δ_{CP} are listed in Table 1 [25]. The CP-violating phase, δ_{CP} , is not yet well constrained, nor is the sign of $\Delta m_{32}^2 \equiv m_3^2 - m_2^2$ known. The sign of Δm_{32}^2 is related to the ordering of the three mass eigenstates; the positive sign is referred to as the normal MH (NH) and the ¹¹⁴ negative sign as the inverted MH (IH). Of the mixing angles, the angle θ_{23} is measured with ¹¹⁵ the least precision; the value of $\sin^2 2\theta_{23}$ in Table 1 corresponds to $0.4 < \sin^2(\theta_{23}) < 0.6$. ¹¹⁶ Many theoretical models, e.g. some based on flavor symmetries and some on random draws ¹¹⁷ on parameter spaces, sometimes try to explain the origin of the PMNS matrix together ¹¹⁸ with the Cabibbo-Kobayashi-Maskawa matrix, which describes mixing in the quark sector. ¹¹⁹ Precise determination of how close this mixing angle is to 45° would be an important piece ¹¹⁹ of understanding the origin of flavor mixing of both quarks and leptons.

Value
0.857 ± 0.024
> 0.95
0.095 ± 0.010
$(7.5 \pm 0.20) \times 10^{-5} \text{ eV}^2$
$(2.32^{+0.12}_{-0.08}) \times 10^{-3} \text{ eV}^2$
unknown

Table 1: Neutrino oscillation parameters from [25].

-

120

121 3. T2K Experiment

The T2K experiment [22] uses a 30-GeV proton beam accelerated by the J-PARC accelerator 122 facility. This is composed of (1) the muon neutrino beamline, (2) the near detector complex, 123 which is located 280 m downstream of the neutrino production target, monitors the beam, 124 and constrains the neutrino flux parameterization and cross sections, and (3) the far detector, 125 Super-Kamiokande (Super-K), which detects neutrinos at a baseline distance of 295 km from 126 the target. The neutrino beam is directed 2.5° away from Super-K, producing a narrow-band 127 ν_{μ} beam [26] at the far detector. The off-axis angle is chosen such that the energy peaks 128 at $E_{\nu} = \Delta m_{32}^2 L/2\pi \approx 0.6$ GeV, which corresponds to the first oscillation minimum of the ν_{μ} 129 survival probability at Super-K. This enhances the sensitivity to θ_{13} and θ_{23} and reduces 130 backgrounds from higher-energy neutrino interactions at Super-K. 131

The J-PARC main ring accelerator provides a fast-extracted high-intensity proton beam to a graphite target located in the first of three consecutive electro-magnetic horns. Pions and kaons produced in the target are focused by the horns and decay in flight to muons and ν_{μ} 's in the helium-filled 96-m-long decay tunnel. This is followed by a beam dump and a set of muon monitors, which are used to monitor the direction and stability of the neutrino beam.

The near detector complex contains an on-axis Interactive Neutrino Grid detector 138 (INGRID) [27] and an off-axis magnetized detector, ND280. INGRID measures the neu-139 trino interaction event rate at various positions from 0° to $\sim 1^{\circ}$ around the beam axis, and 140 provides monitoring of the intensity, direction, profile, and stability of the neutrino beam. 141 The ND280 off-axis detector measures neutrino beam properties and neutrino interactions 142 at approximately the same off-axis angle as Super-K. It is enclosed in a 0.2-T magnet that 143 contains a subdetector optimized to measure π^0 s (PØD) [28], three time projection cham-144 bers (TPC1,2,3) [29] alternating with two one-ton fine-grained detectors (FGD1,2) [30], and 145

an electromagnetic calorimeter (ECal) that surrounds the TPC, FGD, and PØD detectors.
A side muon range detector (SMRD) [31] built into slots in the magnet return-yoke steel
detects muons that exit or stop in the magnet steel. A schematic diagram of the detector
layout has been published elsewhere [22].

The Super-K water Cherenkov far detector [32] has a fiducial mass of 22.5 kt contained 150 within a cylindrical inner detector (ID) instrumented with 11,129 inward facing 20-inch 151 phototubes. Surrounding the ID is a 2-meter wide outer detector (OD) with 1,885 outward-152 facing 8-inch phototubes. A Global Positioning System receiver with <150 ns precision 153 synchronizes the timing between reconstructed Super-K events and the J-PARC beam spill. 154 T2K employs various analysis methods to estimate oscillation parameters from the data, 155 but in general it is done by comparing the observed and predicted ν_e and ν_{μ} interaction 156 rates and energy spectra at the far detector. The rate and spectrum depend on the oscil-157 lation parameters, the incident neutrino flux, neutrino interaction cross sections, and the 158 detector response. The initial estimate of the neutrino flux is determined from detailed sim-159 ulations incorporating proton beam measurements, INGRID measurements, and pion and 160 kaon production measurements from the NA61/SHINE [33, 34] experiment. The ND280 161 detector measurement of ν_{μ} charged current (CC) events is used to constrain the initial flux 162 estimates and parameters of the neutrino interaction models that affect the predicted rate 163 and spectrum of neutrino interactions at both ND280 and Super-K. At Super-K, ν_e and ν_{μ} 164 charged current quasi-elastic (CCQE) events, for which the neutrino energy can be recon-165 structed using simple kinematics, are selected. Efficiencies and backgrounds are determined 166 through detailed simulations tuned to control samples which account for final state inter-167 actions (FSI) inside the nucleus and secondary hadronic interactions (SI) in the detector 168 material. These combined results are used in a fit to determine the oscillation parameters. 169 As of May 2013, T2K has accumulated 6.57×10^{20} POT, which corresponds to about 8.4% 170

of the total approved data. Results from this dataset on the measurement of θ_{23} and $|\Delta m_{32}^2|$ by ν_{μ} disappearance [14], and of θ_{13} and δ_{CP} by ν_e appearance have been published [17]. It is reported in [17] that combining the T2K result with the world average value of θ_{13} from reactor experiments leads to some values of δ_{CP} being disfavored at 90% CL.

4. T2K Projected Sensitivities to Neutrino Oscillation Parameters

To demonstrate the T2K physics potential, we have performed sensitivity studies using combined fits to the reconstructed energy spectra of $\nu_e(\bar{\nu_e})$ and $\nu_\mu(\bar{\nu_\mu})$ events observed at Super-K with both ν -mode beam, and $\bar{\nu}$ -mode beam in the three-flavor mixing model. Results shown here generally use the systematic errors established for the 2012 oscillation analyses [35, 16] as described below, although, in addition, we have studied cases with projected systematic errors as described in Sec. 4.5.

Since the sensitivity depends on the true values of the oscillation parameters, a set of oscillation parameters (θ) is chosen as a test point for each study and is used to generate simulated 'observed' reconstructed energy spectra. Then, a hypothesis test for the set of parameters of interest (H_0) is applied using

$$\Delta \chi^2 = \chi^2(H_0) - \chi^2_{min}.$$
(5)

The value of $\chi^2(H_0)$ is calculated as $-2 \ln \mathcal{L}(\theta|H_0)$, where $\mathcal{L}(\theta|H_0)$ is the likelihood to observe the spectrum generated at θ when the 'true' oscillation parameters are given by H_0 . The minimum value of χ^2 in the oscillation parameter space is given by χ^2_{min} . The oscillation parameter set which gives χ^2_{min} is equivalent to θ , since spectra are generated without statistical fluctuations in this analysis. When we test only one or two of the five varied oscillation parameters ($\sin^2 2\theta_{13}$, δ_{CP} , $\sin^2 \theta_{23}$, Δm^2_{32} , and the MH), the tested parameters are fixed at a set of test points, and the remaining oscillation parameters are fit to give a minimized $\chi^2(H_0)$.

In most cases, this $\Delta \chi^2$ closely resembles a χ^2 distribution for n degrees of freedom, 194 where n corresponds to the number of tested oscillation parameters. Then, critical χ^2 values 195 for Gaussian distributed variables $(\Delta \chi^2_{critical})$ can be used for determining confidence level 196 (C.L.) regions [36]. Each simulated spectrum is generated at the MC sample statistical mean, 197 and therefore the results of this test represent the median sensitivity. Thus the results of 198 these studies indicate that half of experiments are expected to be able to reject H_0 at the 199 reported C.L. This is accurate if two conditions are met: (1) the probability density function 200 (pdf) for $\Delta \chi^2$ follows a true χ^2 distribution, and (2) the $\Delta \chi^2$ value calculated with the MC 201 sample statistical mean spectra $(\Delta \chi^2)$ is equivalent to the median of the $\Delta \chi^2$ pdf. Then, 202 $\Delta \chi^2$ can be used to construct median sensitivity C.L. contours. Studies using ensembles of 203 toy MC experiments where statistical fluctuations expected at a given POT and systematic 204 fluctuations are included have shown that calculating C.L.s by applying a $\Delta \chi^2_{critical}$ value 205 to $\Delta \chi^2$ gives fairly consistent C.L.s, and that $\Delta \chi^2$ is in good agreement with the median 206 $\Delta \chi^2$ value of each ensemble of toy MC experiments, except in the case of a mass hierarchy 207 determination. Therefore, in this paper we show C.L.s constructed by applying the $\Delta \chi^2_{critical}$ 208 value to $\Delta \chi^2$ as our median sensitivity. The exception of the MH case will be discussed in 209 detail in Sec. 5. 210

211 4.1. Expected observables and summary of current systematic errors

Our sensitivity studies are based on the signal efficiency, background, and systematic errors established for the T2K 2012 oscillation analyses[35, 16]; however, we note that errors are lower in more recent published analyses. Since official T2K systematic errors are used, these errors have been reliably estimated based on data analysis, unlike previous sensitivity studies which use errors based only on simulation and estimations [21]. Systematic errors therefore include both normalization and shape errors, and are implemented as a covariance matrix for these studies, where full correlation between ν - and $\bar{\nu}$ -modes is generally assumed.

For the ν_e sample, interaction candidate events fully contained in the fiducial volume with 219 a single electron-like Cherenkov ring are selected. The visible energy is required to exceed 220 100 MeV/c, events with a delayed electron signal are rejected, and events with an invariant 221 mass near that of the π^0 are rejected, where the invariant mass is reconstructed assuming 222 the existence of a second ring. Finally, events are required to have a reconstructed neutrino 223 energy below 1250 MeV. The efficiency of the event selection for the CC ν_e signal is 62% 224 and the fraction of CCQE events in the signal is 80%. For the ν_{μ} sample, again events 225 must be fully contained in the fiducial volume, but they must now have a single muon-like 226 Cherenkov ring with a momentum exceeding 200 MeV/c. There must be either zero or one 227 delayed electron. The efficiency and purity of ν_{μ} CCQE events are estimated to be 72% and 228 61%, respectively. 229

Fits are performed by calculating $\Delta \chi^2$ using a binned likelihood method for the appearance and disappearance reconstructed energy spectra in Super-K. Reconstructed appearance and disappearance energy spectra generated for the approved full T2K statistics, 7.8×10^{21} POT, assuming a data-taking condition of either 100% ν -mode or 100% $\bar{\nu}$ -mode are given in Fig. 1. These spectra are generated assuming the nominal oscillation parameters given in Table 3.

Although errors on the shape of the reconstructed energy spectra are used for the analysis described in Sec. 4, the total error on the number of events at Super-K is given in Table 2. This includes uncertainties on the flux prediction, uncertainties on ν interactions both constrained by the near detector and measured by external experiments, Super-K detector errors, and final state interaction uncertainties, all of which can cause fluctuations in the shape of the final reconstructed energy spectra.

Table 2: The systematic errors in percentage on the predicted number of events at Super-K (assuming the oscillation parameters given in Table 3 are the true values of the oscillation parameters) as used in the 2012 oscillation analyses.

	Appearance	Disappearance
Flux and cross section constrained by the near detector	5.0~%	$4.2 \ \%$
Cross section not constrained by the near detector	7.4~%	6.2~%
Super-K detector and FSI	3.9~%	11.0~%
Total	9.7~%	13.3~%

²⁴² When performing fits, the oscillation parameters δ_{CP} , $\sin^2 2\theta_{13}$, $\sin^2 \theta_{23}$, and Δm_{32}^2 are ²⁴³ considered unknown unless otherwise stated, while $\sin^2 2\theta_{12}$ and Δm_{21}^2 are assumed fixed ²⁴⁴ to the values given in this table. Tables 4 and 5 give the number of events expected with ²⁴⁵ the T2K full statistics. Fig. 2 shows the dependence of the ν_e appearance reconstructed ²⁴⁶ energy spectrum on δ_{CP} . Some of the sensitivities are enhanced by constraining the error ²⁴⁷ on $\sin^2 2\theta_{13}$ based on the projected precision of reactor measurements. For this study, the ²⁴⁸ uncertainty (referred to as the ultimate reactor error) on $\sin^2 2\theta_{13}$ is chosen to be 0.005, ²⁴⁸ which corresponds to the 2012 systematic error only of the Daya Bay experiment[37]².

Table 3: Nominal values of the oscillation parameters. When the reactor constraint is used, we assume 0.005 as the expected uncertainty of the reactor measurement.

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	0.1	0	0.5	2.4×10^{-3}	normal	0.8704	7.6×10^{-5}
Value				eV^2			eV^2

249

² The statistical error is 0.010 for [37]





(a) ν_e appearance reconstructed energy spectrum, 100% $\nu\text{-mode running.}$

(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.

Fig. 1: Appearance and disappearance reconstructed energy spectra in Super-K for ν_e , ν_{μ} , $\bar{\nu}_e$, and $\bar{\nu}_{\mu}$ at 7.8×10^{21} POT for the nominal oscillation parameters as given in Table 3

250 4.2. Expected 90% C.L. regions

In this section we show expected 90% C.L. intervals for the T2K full statistics of $7.8 \times$ 251 10^{21} POT. Contours showing both the T2K sensitivity for δ_{CP} vs. $\sin^2 2\theta_{13}$ and for Δm_{32}^2 252 vs. $\sin^2 \theta_{23}$ are provided, where the assumed true value of the oscillation parameters is 253 indicated by a black cross. The oscillation parameters δ_{CP} , $\sin^2 2\theta_{13}$, $\sin^2 \theta_{23}$, and Δm_{32}^2 are 254 considered unknown, as stated above. Both the NH and IH are considered, and $\Delta \chi^2$ values 255 are calculated from the minimum χ^2 value for both MH assumptions. The blue curves are 256 generated assuming the correct MH and the red curves are generated assuming the incorrect 257 MH, such that if an experiment or combination of experiments from the global neutrino 258 community were to determine the MH the red contour would be eliminated. A contour 259

Table 4: Expected numbers of ν_e or $\bar{\nu}_e$ appearance events at 7.8×10^{21} POT. 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 Super-K, or beam background events that undergo neutral current (NC) interactions.

			Signal	Signal	Beam CC	Beam CC	
	δ_{CP}	Total	$\nu_{\mu} \rightarrow \nu_{e}$	$\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$	$\nu_e + \bar{\nu}_e$	$ u_{\mu} + \bar{\nu}_{\mu} $	NC
100% $\nu\text{-mode}$	0°	291.5	211.9	2.4	41.9	1 /	245
100% $\nu\text{-mode}$	-90°	341.8	262.9	1.7	41.0	1.4	04.0
100% $\bar{\nu}$ -mode	0°	94.9	11.2	48.8	17.9	0.4	17.2
100% $\bar{\nu}\text{-mode}$	-90°	82.9	13.1	34.9	11.2	0.4	17.5

Table 5: Expected numbers of ν_{μ} or $\bar{\nu}_{\mu}$ disappearance events for 7.8×10^{21} POT. The first two columns show the number of ν_{μ} and $\bar{\nu}_{\mu}$ events, broken down into those that undergo charged-current quasi-elastic (CCQE) scattering at Super-K, and those that undergo other types of CC scattering (CC non-QE). The third column shows CC ν_e and $\bar{\nu}$ events, both from intrinsic beam backgrounds and oscillations, while the fourth column shows NC events.

		CCQE	CC non-QE	$CC \nu_e + \bar{\nu}_e$	
	Total	$ u_\mu(ar u_\mu)$	$ u_\mu(ar u_\mu)$	$\operatorname{CC} \nu_{\mu}(\bar{\nu}_{\mu}) \to \nu_{e}(\bar{\nu}_{e})$	NC
100% running in ν -mode	1,493	782(48)	544 (40)	4	75
100% running in $\bar{\nu}$ -mode	715	130(263)	151(138)	0.5	33

consisting of the outermost edge of all contours in each plot can be considered as the T2K
sensitivity assuming an unknown MH. For the sake of brevity, only results assuming true
NH are shown; similar conclusions can be drawn from plots assuming true IH.

Figure 3 gives an example of the difference in the shape of the T2K sensitive region for ν vs. $\bar{\nu}$ -mode at true $\delta_{CP} = -90^{\circ}$ (and the other oscillation parameters as given in Table 3) by comparing the ν -mode – Fig. 3 (a) – and $\bar{\nu}$ -mode – Fig. 3 (b) – C.L. contours without a reactor constraint at 50% of the full T2K POT. These two contours are then combined in Fig. 3 (c), which shows the 90% C.L. region for 50% ν - plus 50% $\bar{\nu}$ -mode running to achieve the full T2K POT. This demonstrates that δ_{CP} can be constrained by combining ν -mode and $\bar{\nu}$ -mode data.

Figures 4 and 5 show example 90% C.L. regions for δ_{CP} vs. $\sin^2 2\theta_{13}$ at the full T2K statistics, both for T2K alone and including an extra constraint on the T2K predicted data fit based on the ultimate reactor error $\delta(\sin^2 2\theta_{13}) = 0.005$ as discussed above, for true δ_{CP} of 0° and -90°, respectively. In the case of $\delta_{CP} = -90^\circ$, we start to have sensitivity to resolve δ_{CP} without degeneracies.

Figure 6 shows example 90% C.L. regions for Δm_{32}^2 vs. $\sin^2 \theta_{23}$ at the full T2K statistics for $\sin^2 \theta_{23} = 0.4$. The θ_{23} octant can be resolved in this case by combining both ν -mode and $\bar{\nu}$ -mode data and also including a reactor constraint on θ_{13} , where this combination of inputs is required to resolve degeneracies between the oscillation parameters $\sin^2 \theta_{23}$, $\sin^2 2\theta_{13}$, and δ_{CP} , demonstrating the importance of the reactor constraint in this case.



Fig. 2: ν_e appearance reconstructed energy spectra in Super-K for 7.8×10^{21} POT in either ν -mode or $\bar{\nu}$ -mode at various values of assumed true δ_{CP} with $\sin^2 \theta_{23} = 0.5$.

280 4.3. Sensitivities for CP-violating term, non-maximal θ_{23} , and θ_{23} octant

The sensitivities for CP violation, non-maximal θ_{23} , and the octant of θ_{23} (i.e., whether the mixing angle θ_{23} is less than or greater than 45°) depend on the true oscillation parameter values. Fig. 7 shows the expected $\Delta \chi^2$ for the sin $\delta_{CP} = 0$ hypothesis, for various true values of δ_{CP} and sin² θ_{23} . To see the dependence more clearly, $\Delta \chi^2$ is plotted as a function of δ_{CP} for various values of sin² θ_{23} in Fig. 8 (normal MH case) and Fig. 9 (inverted MH case). For favorable sets of the oscillation parameters and mass hierarchy, T2K will have greater than 90% C.L. sensitivity to non-zero sin δ_{CP} .



Fig. 3: Expected δ_{CP} vs. $\sin^2 2\theta_{13}$ 90% C.L. intervals, where (a) and (b) are each given for 50% of the full T2K POT, and (c) demonstrates the sensitivity of the total T2K POT 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 fit assuming the correct MH(NH)

, while the red are fit 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.



(c) 100% $\nu\text{-mode},$ with ultimate reactor con- (d) 50% $\nu\text{-},$ 50% $\bar{\nu}\text{-mode},$ with ultimate reactor straint.

Fig. 4: δ_{CP} vs. $\sin^2 2\theta_{13}$ 90% C.L. intervals for 7.8×10^{21} POT. Contours are plotted for the case of true $\delta_{CP} = 0^{\circ}$ and NH. The blue curves are fit assuming the correct MH(NH), while the red are fit 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 2012 systematic errors fully correlated between ν - and $\bar{\nu}$ -mode.

Figures 10 and 11 show the $\sin^2 \theta_{23}$ vs. δ_{CP} regions where T2K has more than a 90% C.L. sensitivity to reject maximal mixing or reject one octant of θ_{23} . In each of these figures, the oscillation parameters δ_{CP} , $\sin^2 2\theta_{13}$, $\sin^2 \theta_{23}$, Δm_{32}^2 , and the MH are considered unknown and a constraint based on the ultimate reactor error is used. Note that the T2K sensitivity to reject maximal mixing is roughly independent of $\nu - \bar{\nu}$ running ratio, while the sensitivity to reject one octant is better when ν - and $\bar{\nu}$ -modes are combined. Again, the combination of ν - and $\bar{\nu}$ -modes, as well as the tight constraint on θ_{13} from the reactor measurement,



(c) 100% $\nu\text{-mode},$ with ultimate reactor con- (d) 50% $\nu\text{-},$ 50% $\bar{\nu}\text{-mode},$ with ultimate reactor straint.

Fig. 5: δ_{CP} vs. $\sin^2 2\theta_{13}$ 90% C.L. intervals for 7.8×10^{21} POT. Contours are plotted for the case of true $\delta_{CP} = -90^{\circ}$ and NH. The blue curves are fit assuming the correct MH(NH), while the red are fit 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 2012 systematic errors fully correlated between ν - and $\bar{\nu}$ -mode.

²⁹⁵ are all required to resolve the correct values for the parameters $\sin^2 \theta_{23}$, $\sin^2 2\theta_{13}$, and δ_{CP} ²⁹⁶ from many possible solutions. Resolving the values of these three oscillation parameters is ²⁹⁷ required in order to also resolve the θ_{23} octant.

²⁹⁸ These figures show that by running with a significant amount of $\bar{\nu}$ -mode, T2K has sensi-

299 tivity to the CP-violating term and octant of θ_{23} for a wider region of oscillation parameters

 $(\delta_{CP}, \theta_{23})$ and for both mass hierarchies, particularly when systematic errors are taken into

³⁰¹ account. The optimal running ratio is discussed in more detail in Sec. 6.



(c) 100% ν -mode, with ultimate reactor error.

(d) 50% $\nu\text{-},$ 50% $\bar{\nu}\text{-mode},$ with ultimate reactor error.

Fig. 6: Δm_{32}^2 vs. $\sin^2 \theta_{23}$ 90% C.L. intervals for 7.8×10^{21} POT. Contours are plotted for the case of true $\delta_{CP} = 0^{\circ}$, $\sin^2 \theta_{23} = 0.4$, $\Delta m_{32}^2 = 2.4 \times 10^{-3} \text{ eV}^2$ and NH. The blue curves are fit assuming the correct MH(NH), while the red are fit 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 2012 systematic errors fully correlated between ν - and $\bar{\nu}$ -mode.

302 4.4. Precision or sensitivity vs. POT

The T2K uncertainty (i.e. precision) vs. POT for $\sin^2 \theta_{23}$ and Δm_{32}^2 is given in Fig. 12 for the 100% ν -mode running case and the 50% plus 50% $\nu - \bar{\nu}$ -mode running case. The precision includes either statistical errors only, statistical errors combined with the 2012 systematic errors, or statistical errors combined with conservatively-projected systematic errors for the full POT. See Sec. 4.5 for details about the projected systematic errors used.



Fig. 7: The expected $\Delta \chi^2$ for the $\sin \delta_{CP} = 0$ hypothesis, in the $\delta_{CP} - \sin^2 \theta_{23}$ plane. The $\Delta \chi^2$ map shown in color is calculated assuming no systematic errors. The solid contours show the 90% C.L. sensitivity with statistical error only, while the dashed contours include the 2012 T2K systematic error. The dashed contour does not appear in (a) because T2K does not have 90% C.L. sensitivity in this case.

Generally, the effect of the systematic errors is reduced by running with combined ν -mode 308 and $\bar{\nu}$ -mode. When running 50% in ν -mode and 50% in $\bar{\nu}$ -mode, the statistical 1 σ uncertainty 309 of $\sin^2 \theta_{23}$ and Δm^2_{32} is 0.045 and $0.04 \times 10^{-3} \text{ eV}^2$, respectively, at the T2K full statistics. 310 It should be noted that the sensitivity to $\sin^2 \theta_{23}$ shown here for the current exposure 311 $(6.57 \times 10^{20} \text{ POT})$ is significantly worse than the most recent T2K result [14], and in fact the 312 recent result is quite close to the final sensitivity (at 7.8×10^{21} POT) shown. This apparent 313 discrepancy comes from three factors. About half of the difference between the expected 314 sensitivity and observed result is due to an apparent statistical fluctuation, where fewer T2K 315



Fig. 8: The expected $\Delta \chi^2$ for the $\sin \delta_{CP} = 0$ hypothesis, plotted as a function of δ_{CP} for various values of $\sin^2 \theta_{23}$ (given in the legend) in the case of normal mass hierarchy.

 ν_{μ} events have been observed than expected. Of the remaining difference, half comes from 316 the use of a Feldman-Cousins statistical analysis for the T2K official oscillation result which 317 this sensitivity study does not use. The rest comes from the location of the best fit point: the 318 expected error depends on the true value of $\sin^2 \theta_{23}$ because a local minimum in each octant 319 on each side of the point of maximal disappearance, $\sin^2 \theta_{23} \simeq 0.503$ for $\sin^2 2\theta_{13} = 0.1$, 320 increases the full width of the $\Delta \chi^2$ curve such that the farther the true point is from maximal 321 disappearance, the larger the error on $\sin^2 \theta_{23}$ becomes (where the studies here assume a true 322 value of $\sin^2 \theta_{23}$ slightly lower than the point of maximal disappearance $-\sin^2 \theta_{23} = 0.5$). 323 Therefore, if results from future running continue to favor maximal disappearance we expect 324



Fig. 9: The expected $\Delta \chi^2$ for the $\sin \delta_{CP} = 0$ hypothesis, plotted as a function of δ_{CP} for various values of $\sin^2 \theta_{23}$ (given in the legend) in the case of inverted mass hierarchy.

modest improvements in our current constraints, eventually approaching a value close to, and possibly slightly better than, the predicted final sensitivity shown here.

Figure 13 shows the $\sin^2 \theta_{23}$ region where maximal mixing or one of the θ_{23} octants can be 327 rejected, as a function of POT in the case of $50\% \nu$ - plus $50\% \bar{\nu}$ -mode running. Although these 328 plots are made under the condition that the true mass hierarchy is normal and $\delta_{CP} = 0^{\circ}$, 329 dependence on these conditions is moderate in the case of 50% ν - plus 50% $\bar{\nu}$ -mode running. 330 The sensitivity to reject the null hypothesis $\sin \delta_{CP} = 0$ depends on the true oscilla-331 tion parameters and is expected to be greatest for the case $\delta_{CP} = +90^{\circ}$ and inverted MH. 332 Figure 14 shows how the expected $\Delta \chi^2$ evolves as a function of POT in this case, as well as 333 for $\delta_{CP} = -90^{\circ}$ and normal MH, another case in which the sensitivity is high. These plots 334



Fig. 10: The region, shown as a shaded area, where T2K has more than a 90 % C.L. sensitivity to reject maximal mixing. The shaded region is calculated assuming no systematic errors (the solid contours show the 90% C.L. sensitivity with statistical error only), and the dashed contours show the sensitivity including the 2012 systematic errors.

indicate the earliest case for T2K to observe CP violation. If the systematic error size is negligibly small, T2K may reach a higher sensitivity at an earlier stage by running in 100% ν -mode, since higher statistics are expected in this case. However, with projected systematic errors, 100% ν -mode and 50% ν -mode + 50% $\bar{\nu}$ -mode running give essentially equivalent sensitivities.



Fig. 11: The region, shown as a shaded area, where T2K has more than a 90% C.L. sensitivity to reject one of the octants of θ_{23} . The shaded region is calculated assuming no systematic errors (the solid contours show the 90% C.L. sensitivity with statistical error only), and the dashed contours show the sensitivity including the 2012 T2K systematic errors.

340 4.5. Effect of reduction of the systematic error size

An extensive study of the effect of the systematic error size was performed. Although the actual effect depends on the details of the errors, here we summarize the results of the study. As given in Table 2, the systematic error on the predicted number of events in Super-K in the 2012 oscillation analysis is 9.7% for the ν_e appearance sample and 13% for the ν_{μ} disappearance sample.

In Sec. 4.4 we showed the T2K sensitivity with projected systematic errors which are estimated based on a conservative expectation of T2K systematic error reduction. In this



Fig. 12: The uncertainty on $\sin^2 \theta_{23}$ and Δm_{32}^2 plotted as a function of T2K POT. Plots assume the true oscillation parameters given in Table 3. The solid curves include statistical errors only, while the dashed curves assume the 2012 systematic errors (black) or the projected systematic errors (red). A constraint based on the ultimate reactor precision is included.

case the systematic error on the predicted number of events in Super-K is about 7% for the 348 ν_{μ} and ν_{e} samples and about 14% for the $\bar{\nu}_{\mu}$ and $\bar{\nu}_{e}$ samples. These errors were calculated 349 by reducing the 2012 oscillation analysis errors by removing certain interaction model and 350 cross section uncertainties from both the ν_e - and ν_{μ} -mode errors, and by additionally scaling 351 all ν_{μ} -mode errors down by a factor of two. Errors for the $\bar{\nu}_{\mu}$ - and $\bar{\nu}_{e}$ -modes were estimated 352 to be twice those of the ν_{μ} and ν_e -modes, respectively. These reduced ν -mode errors are 353 in fact very close to the errors used for the oscillation results reported by T2K in 2014, 354 where the T2K oscillation analysis errors have similarly been reduced by improvements in 355 understanding the relevant interactions and cross sections. 356



Fig. 13: The region where maximal mixing or one θ_{23} octant can be rejected at the stated confidence levels (given by the shaded region), as a function of POT in the case of 50% ν -, 50% $\bar{\nu}$ -mode. These plots are made under the condition that the true mass hierarchy is normal and $\delta_{CP} = 0$. The dashed contours include the 2012 systematic errors fully correlated between ν and $\bar{\nu}$. A constraint based on the ultimate reactor precision is included.

For the measurement of δ_{CP} , studies have shown that it is desirable to reduce this to $5\sim 8\%$ for the ν_e sample and $\sim 10\%$ for the $\bar{\nu}_e$ sample to maximize the T2K sensitivity with full statistics. The measurement of δ_{CP} is nearly independent of the size of the error on the ν_{μ} and $\bar{\nu}_{\mu}$ samples as long as we can achieve uncertainty on $\bar{\nu}_{\mu}$ similar to the current uncertainty on ν_{μ} . For the measurement of θ_{23} and Δm_{32}^2 , the systematic error sizes are significant compared to the statistical error, and the result would benefit from systematic error reduction even for uncertainties as small as 5%.

These error reductions may also be achievable with the implementation of further T2K and external cross section and hadron production measurements, which continue to be made with improved precision.

$_{367}$ 5. T2K and NO ν A Combined Sensitivities

The ability of T2K to measure the value of δ_{CP} (or determine if CPV exists in the lepton 368 sector) is greatly enhanced by the determination of the MH. This enhancement results 369 from the nearly degenerate ν_e appearance event rate predictions at Super-K in the normal 370 hierarchy with positive values of δ_{CP} compared to the inverted hierarchy with negative 371 values of δ_{CP} . Determination of the MH thus breaks the degeneracy, enhancing the δ_{CP} 372 resolution for $\sim 50\%$ of δ_{CP} values. T2K does not have sufficient sensitivity to determine the 373 mass hierarchy by itself. The NO ν A experiment [23], which started operating in 2014, has a 374 longer baseline (810 km) and higher peak neutrino energy ($\sim 2 \text{ GeV}$) than T2K. Accordingly, 375 the impact of the matter effect on the predicted far detector event spectra is larger in $NO\nu A$ 376 $\sim 30\%$) than in T2K ($\sim 10\%$), leading to a greater sensitivity to the mass hierarchy. Because 377 of the complementary nature of these two experiments, better constraints on the oscillation 378



Fig. 14: The expected $\Delta \chi^2$ for the sin $\delta_{CP} = 0$ hypothesis, plotted as a function of POT. Plots assume true sin² $2\theta_{13} = 0.1$, various true values of sin² θ_{23} (as given in the plot legends), and δ_{CP} and the MH as given in the figure captions. The solid curves include statistical errors only, while the dash-dotted (dashed) curves assume the 2012 systematic errors (the projected systematic errors). Note that the sensitivity heavily depends on the assumed conditions, and that the conditions applied for these figures correspond to the cases where the sensitivity for sin $\delta_{CP} \neq 0$ is maximal.

parameters, δ_{CP} , $\sin^2 \theta_{23}$ and the MH can be obtained by comparing the $\nu_{\mu} \rightarrow \nu_e$ oscillation probability of the two experiments. To evaluate the benefit of combining the two experiments, we have developed a code based on GLoBES [38, 39]. The studies using projected T2K and NO ν A data samples show the full physics reach for the two experiments, individually and combined, along with studies aimed at optimization of the ν -mode to $\bar{\nu}$ -mode running ratios of the two experiments. Figure 15 shows the relation between the expected number of events of T2K and NO ν A for various values of δ_{CP} , $\sin^2 \theta_{23}$ and mass hierarchies. The NH and IH predictions occupy distinct regions in the plot suggesting how a combined analysis T2K-NO ν A fit leads to increased sensitivity. However, this plot does not include the (statistical + systematic) uncertainties on measurements of these event rates. This would result in regions of overlap where the MH can not be determined, and the sensitivity to δ_{CP} is degraded. In order to evaluate the effect of



Fig. 15: Relation between the expected number of $\nu_e + \bar{\nu}_e$ signal events produced by neutrinomode running and antineutrino mode running in T2K and NO ν A, for various values of δ_{CP} , $\sin^2 \theta_{23}$ and mass hierarchy. In the plot of predicted T2K rate versus the predicted NO ν A rate (left) the blue (IH) and red (NH) upper bands are for neutrino-mode running while the red (NH) and blue (IH) bottom bands are for the antineutrino mode running. The predicted number of $\nu_e + \bar{\nu}_e$ events produced in neutrino-mode running versus events produced in antineutrino mode running (right) are shown for T2K in red (NH) and blue (IH), and for NO ν A in green (NH) and magenta (IH). Representative points at the edges of the δ_{CP} and $\sin^2 \theta_{23}$ ranges are highlighted. Systematic and statistical uncertainties are not included.

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combining the results from T2K and NO ν A quantitatively, we have conducted a T2K-NO ν A 391 combined sensitivity study. The GLoBES [38, 39] software package was used to fit oscillation 392 parameters based on the reconstructed neutrino energy spectra of the two experiments. The 393 fits were conducted by minimizing $\Delta \chi^2$ which is calculated from spectra generated with dif-394 ferent sets of oscillation parameters, and includes penalty terms for deviations of the signal 395 and background normalizations from nominal. The best-fit $\Delta \chi^2$ calculated by GLoBES, was 396 the metric chosen to characterize sensitivity, as it is related to the probability that a given 397 data set can result from two different hypotheses. 398

GLoBES combines flux, cross section, energy resolution/bias and efficiency information for an experiment to estimate energy spectra of neutrino interaction samples used for analyses. Then GLoBES uses a full three-flavor oscillation probability formulation to fit analysis spectra generated assuming different oscillation parameters to each other (varying oscillation parameter values and parameters accounting for systematic uncertainties within their uncertainties). The oscillation parameters, unless otherwise stated, are those shown in Table 3.
The GLoBES three-flavor analysis package works very similarly to fitter used for the studies
presented in Section 4. Several validation studies were done to ensure that the two methods
produced the same results when given the same inputs.

The T2K, NO ν A, and combined sensitivities were generated using a modified version of GLoBES that allowed for use of inputs generated from Monte Carlo simulations of T2K neutrino interactions in the Super-Kamiokande detector. The inputs describing the NO ν A experiment were developed in conjunction with NO ν A collaborators, and validated against official NO ν A sensitivity plots [40, 41, 42]. We assume the same run plan as presented in NO ν A's TDR: 1.8×10^{21} POT for ν and 1.8×10^{21} POT for $\bar{\nu}$ modes, corresponding to 3 years of running in each mode.

The GLoBES inputs defining the analysis sample acceptances for the signal, the NC background, the ν_{μ} CC background, and the ν_{e} CC background were tuned to match this official event rate prediction from NO ν A. For example, Table 6 summarizes the expected number of ν_{e} appearance events for NO ν A [42] when $\sin^{2} 2\theta_{13} = 0.95$ is assumed and the solar oscillation terms or matter effects in the oscillation probability are neglected.

Table 6: Expected number of ν_e appearance signal and background events for NO ν A at 1.8 × 10²¹ POT for each of ν and $\bar{\nu}$ modes[42]. The oscillation probabilities used to calculate the predicted number of events assumed sin² $2\theta_{13} = 0.095$ and do not include the solar oscillation terms or matter effects.

Beam	Signal	NC Bkg	$\nu_{\mu} CC$	$\nu_e \ {\rm CC}$	Total Bkg
ν -mode	72.6	20.8	5.2	8.4	34.5
$\bar{\nu} ext{-mode}$	33.8	10.6	0.7	5.0	16.3

Since NO ν A has only recently began taking data, detailed evaluation of systematic uncer-420 tainties is not yet published. Therefore, the combined sensitivity studies used a simplified 421 systematics treatment for both T2K and NO ν A: a 5% normalization uncertainty on sig-422 nal events and a 10% normalization uncertainty on background events for both appearance 423 and disappearance spectra. Uncertainties that impact the spectral shape are not consid-424 ered. This is a reasonable choice since both experiments use a narrow band beam and much 425 of the oscillation sensitivity comes from the measured event rates. The uncertainties are 426 assumed to be uncorrelated for ν_e appearance, $\bar{\nu}_e$ appearance, ν_{μ} disappearance, and $\bar{\nu}_{\mu}$ dis-427 appearance. This simple systematics implementation, referred to in the rest of the paper as 428 "normalization systematics", is the same as the one adopted in the NO ν A TDR and is also 429 a reasonable representation of the projected uncertainties at T2K. The sensitivities shown 430 here are obtained assuming $\sin^2 2\theta_{13} = 0.1$ with the projected reactor constraint of 5%. 431

When determining the MH, $\Delta \chi^2$ is not distributed according to a χ^2 distribution because the MH is a discrete, rather than a continuous, variable. Toy MC studies, where many pseudo-experiments are generated with statistical and systematic fluctuations, were used to evaluate the validity of applying a $\Delta \chi^2$ test statistic, as given in Eq. 5, for the MH determination. Table 7: Values of T_{MC} and T_{Median} and their associated p-values. The *T* values correspond to the vertical lines shown in Fig.16. The p-values are computed either with a χ^2 distribution for one degree of freedom from the spectra at the toy MC statistical mean or using an ensemble of toy MC experiments.

	by MC	mean spectra	by toy MC experiments		
	T_{MC}	$\operatorname{p-value}(\chi^2)$	T_{Median}	p-value(toy MC)	
NH, $\delta_{CP} = -90^{\circ}$	11.4	0.00073	11.8	0.000065	
NH, $\delta_{CP} = 0^{\circ}$	3.22	0.073	3.57	0.019	
NH, $\delta_{CP} = +90^{\circ}$	3.47	0.063	2.34	0.040	
IH, $\delta_{CP} = -90^{\circ}$	3.33	0.068	2.30	0.042	
IH, $\delta_{CP} = 0^{\circ}$	3.19	0.074	3.79	0.015	
IH, $\delta_{CP} = +90^{\circ}$	11.6	0.00067	12.5	0.000031	

437 The left column of Fig. 16 shows distributions for a test static for $H_0 = IH$:

$$T = \chi_{IH}^2 - \chi_{NH}^2, (6)$$

where χ^2_{IH} and χ^2_{NH} are the minimum χ^2 values obtained by fitting the oscillation parameters 438 while fixing the MH to the inverted or normal mass hierarchy, respectively. This T is plotted 439 here instead of $\Delta \chi^2$ for easier interpretation. In the figure, the blue (red) distributions are 440 for the case where test or 'observed' spectra were generated for the inverted (normal) mass 441 hierarchy with statistical and systematic fluctuations. Except for δ_{CP} , the test oscillation 442 parameters were fixed to the nominal values given in Table 3. The value of δ_{CP} was fixed to 443 that given in each caption for the NH, while it was thrown over all values of δ_{CP} for the IH. 444 This is done in order to calculate the p-value for $H_0 = IH$ with unknown δ_{CP} when the test 445 point is in the NH [43]. The right column of Figure 16 is the same, but with the opposite 446 MH hypothesis test $(H_0 = NH)$: 447

$$T = \chi_{NH}^2 - \chi_{IH}^2 \tag{7}$$

with a test point in the IH. The *T*-value calculated using the spectrum generated from the MC sample statistical mean (T_{MC}) , which is generally used in this paper, is compared with the median *T*-value for the ensemble of toy MC experiments (T_{median}) in Table 7 for different oscillation parameter sets. The p-values calculated for T_{MC} , assuming that $\Delta \chi^2$ follows a true χ^2 distribution, compared with the p-values calculated as the fraction of the *T* distribution for $H_0 = (\text{correct MH})$ above T_{median} are also given.

Figures 17 through 19 show plots of expected C.L. contours for T2K, NO ν A and a T2K-NO ν A combined fits as functions of $\sin^2 \theta_{23}$ vs. δ_{CP} . Regions where $\sin \delta_{CP} = 0$, one MH and one θ_{23} octant are expected to be ruled out at the 90% C.L are shown. Significantly wider regions are covered by combining the results from T2K and NO ν A.

In Figures 20 and 21 the $\Delta \chi^2$ for $\sin \delta_{CP} = 0$ and for each MH is plotted as a function of 'true' δ_{CP} in case of $\sin^2(\theta_{23}) = 0.5$. The 'true' value of $\sin^2(\theta_{23}) = 0.5$ was chosen to present a simplified view of the sensitivities for maximal mixing. The T2K's $\Delta \chi^2$ is smaller at $\delta_{CP} = +90^{\circ}(-90^{\circ})$ compared to that at the opposite sign of $\delta_{CP} = -90^{\circ}(+90^{\circ})$ for NH(IH) case while those are similar for NO ν A. This comes from the large degeneracy between the CP-violating term and the matter effect for T2K. In case of NO ν A, the matter effect is large



Fig. 16: Distributions of the test statistic, T for toy MC experiments with the null hypothesis $H_0 = I(N)H$ are shown in the left (right) column. Toy MC experiments are generated with the nominal oscillation parameters except for the MH and δ_{CP} ; those generated with NH are indicated in red and those with IH in blue. The value of δ_{CP} is fixed to the value indicated in the sub-captions when $H_0 = (\text{correct MH})$, but thrown when $H_0 = (\text{incorrect MH})$, where the correct MH is also given in the sub-captions. Solid lines indicate the value of the MH determination sensitivity metric used in this paper (calculated using the spectra at the MC sample statistical mean), and dashed lines indicate the *T*-value for the median of the toy MC distribution.



Fig. 17: Regions where T2K (red), NO ν A (blue), and T2K+NO ν A (black) is predicted to rule out sin $\delta_{CP} = 0$ at 90% C.L. Points within the gray regions are where sin $\delta_{CP} = 0$ is predicted to be rejected at 90% C.L. for T2K+NO ν A, assuming simple normalization systematics as described in the text.

enough that the degenerate parameters space is much smaller as can be seen in Fig. 15. The complex structure for positive (negative) values of δ_{CP} with a true NH (IH) is also due to the fact that $\Delta \chi^2$ calculation profiles over MH, and the expected number of ν_e appearance events is nearly degenerate in these regions. T2K would perform better than or comparable to NO ν A, if the MH was assumed to be known. However, there is no experiment, besides NO ν A, that expects to determine the MH on the relevant time scale, thus the case of a known MH is not presented. These figures demonstrate the sensitivity of the two experiments, as



Fig. 18: Regions for T2K (red), NO ν A (blue), and T2K+NO ν A (black) where the incorrect Mass Hierarchy is predicted to be rejected at 90% C.L. Points within the gray regions are where the incorrect mass hierarchy is predicted to be rejected at 90% C.L. for T2K+NO ν A, assuming simple normalization systematics as described in the text.

well as the benefit of combined analysis of the two data sets on the ability to determine MHand CPV.

473 6. Neutrino Mode and Antineutrino Mode Running Time Optimization

As previously shown in Sec. 4, a significant fraction of $\bar{\nu}$ -mode running improves the sensitivity to CP violation, especially when systematic uncertainties are taken into account. In this section studies of the $\nu:\bar{\nu}$ running ratios are shown for T2K, NO ν A, and combined fits of



Fig. 19: Regions for T2K (red), NO ν A (blue), and T2K+NO ν A (black) where the incorrect octant is predicted to be rejected at 90% C.L. Points inside the gray regions are where the incorrect octant is predicted to be rejected at 90% C.L. for T2K+NO ν A assuming simple normalization systematics as described in the text.

⁴⁷⁷ T2K+NO ν A simulated data using the tools developed in Sec. 5. A set of metrics are defined ⁴⁷⁸ that characterize the ability of each experiment or a combined fit of both experiments to ⁴⁷⁹ constrain δ_{CP} , reject $\delta_{CP} = 0$, or determine the MH. The following metrics are used in these ⁴⁸⁰ studies:

⁴⁸¹ • δ_{CP} half-width: The 1σ half-width is defined as half of the 1σ Confidence Interval (C.I.) ⁴⁸² about the true value of δ_{CP} . In some cases there are degenerate 1σ C.I. regions in ⁴⁸³ δ_{CP} that are disconnected from the central value. In this case half of the width of the



Fig. 20: The predicted $\Delta \chi^2$ for rejecting $\sin \delta_{CP} = 0$ hypothesis, as a function of δ_{CP} for T2K (red), NO ν A (blue), and T2K+NO ν A (black). Dashed (solid) curves indicate studies where normalization systematics are (not) considered. The 'true' value of $\sin^2(\theta_{23})$ is assumed to be 0.5, and the 'true' MH is assumed to be the NH (top) or the IH (bottom). The 'test' MH is unconstrained.

degenerate region is added to this metric. This is a measure of the precision that can be acheived in measurment of δ_{CP} .

• Median $\Delta \chi^2$ for $\delta_{CP} = 0$: This metric defines the $\Delta \chi^2$ value for which 50% of true δ_{CP} values can be distinguished from $\delta_{CP} = [0, \pi]$. This is a measure of sensitivity to CPV. • Lowest $\Delta \chi^2$ for mass hierarchy determination: This metric defines the $\Delta \chi^2$ value at

489 which the mass hierarchies can be distinguished for 100% of true δ_{CP} values.



Fig. 21: The predicted $\Delta \chi^2$ for rejecting the incorrect MH hypothesis, as a function of δ_{CP} for T2K (red), NO ν A (blue), and T2K+NO ν A (black). Dashed (solid) curves indicate studies where normalization systematics are (not) considered. The 'true' value of $\sin^2(\theta_{23})$ is assumed to be 0.5, and the 'true' MH is assumed to be the NH (top) or the IH (bottom). The 'test' MH is unconstrained.

Each metric is calculated for a T2K+NO ν A combined analysis for various $\nu:\bar{\nu}$ run ratios. Figure 22 gives the lowest $\Delta \chi^2$ values for mass hierarchy determination for $\nu:\bar{\nu}$ variations in a combined T2K+NO ν A fit. They are computed from the results of studies like the one shown in Fig. 21 and conservatively summarize the content of the plot in one data point. For example, the lowest $\Delta \chi^2$ value for mass hierarchy determination at 1:0 (100% ν ⁴⁹⁵ running) T2K, 5:5 (50% ν / 50% $\bar{\nu}$ running) NO ν A running is the lowest $\Delta \chi^2$ from Fig. 21(a) ($\Delta \chi^2 = 2.19$).



Fig. 22: Lowest $\Delta \chi^2$ for a combined T2K+NO ν A fit to determine the mass hierarchy for various $\nu:\bar{\nu}$ running ratios. True values are assumed to be: MH=NH, $\sin^2(\theta_{23}) = 0.5$. Normalization systematics are assumed.

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Similarly, Fig. 23 gives the median $\Delta \chi^2$ values for $\sin \delta_{CP} = 0$ for $\nu:\bar{\nu}$ variations in a combined T2K+N0 ν A fit. These values are computed from studies like the ones presented in Fig. 20. The $\sin \delta_{CP} = 0$ median $\Delta \chi^2$ value at 1:0 T2K, 5:5 NO ν A running is the median $\Delta \chi^2$ from Fig. 20(a) ($\Delta \chi^2 = 2.6$).



Fig. 23: Median $\Delta \chi^2$ for sin $\delta_{CP} = 0$ for a combined T2K+NO ν A fit. True values are assumed to be: MH=NH, sin²(θ_{23}) = 0.5. Normalization systematics are assumed.

Figure 24 summarizes the data in Fig. 22 and compares it with the metric calculated 501 for T2K only running. The black curve gives the lowest $\Delta \chi^2$ for MH determination in a 502 combined, T2K+NO ν A, fit as a function of T2K $\nu:\bar{\nu}$ running ratio with the NO ν A running 503 fixed at 1:1. As shown previously, the T2K data set alone has almost no sensitivity to the 504 MH determination. The curves for 5:5 NO ν A running with systematics (black dashed) shows 505 an optimal T2K running ratio of around 6:4 for a combined fit. However, the metric is very 506 flat with respect to the T2K $\nu:\bar{\nu}$ run ratio for ν running greater than 50%. Figure 25 shows 507 the summary for median $\Delta \chi^2$ for $\sin \delta_{CP} = 0$. T2K run ratios between 1:0 and 5:5 produce 508 relatively similar values of median $\Delta \chi^2$ for the combined fit. This is also true for combined 509 $T2K+NO\nu A$ running independent of the NO νA run plan optimization. There is a slight 510 preference for all neutrino running in T2K in the combined fit. 511

Figure 26 and 27 summarize the δ_{CP} 1 σ width at various values of δ_{CP} . Again, relatively similar values of δ_{CP} 1 σ width are expected for the T2K run ratios between 1:0 and 1:9.

Fig. 24: Lowest $\Delta \chi^2$ for mass hierarchy determination in a combined, T2K+NO ν A, fit as a function of T2K $\nu:\bar{\nu}$ running ratio for true MH=NH (left) and IH (right). Curves are given for the $\Delta \chi^2$ value at nominal 5:5 NO ν A running (black), best case T2K+NO ν A running (blue), and T2K only running (red). Dashed (solid) curves indicate studies performed (without) assuming normalization systematics.

All of the metrics demonstrate a relatively flat response between approximately 7:3 and 514 3:7 for T2K and for T2K+NO ν A (5:5) with systematics, with a worse response outside that 515 range. These results are consistent with several other studies not shown in this paper (e.g. 516 the measures of the precision on $\sin^2 \theta_{13}$ in ν -mode and in $\bar{\nu}$ -mode). The results are also 517 robust with respect to reasonable variations in $\sin^2 \theta_{23}$, δ_{CP} and the MH. Thus, the results 518 suggest that T2K run with a ν -mode to $\bar{\nu}$ -mode at ratio of 1:1 with an allowed variation 519 of $\pm 20\%$ of the total exposure. The variation can be used to optimize the experiment to 520 any one analysis without significant degradation of the sensitivity to any other analysis. A 521 more detailed optimization of the $\nu:\bar{\nu}$ run ratio will require tighter constraints on oscillation 522

Fig. 25: Median $\Delta \chi^2$ for sin $\delta_{CP} = 0$ in a combined, T2K+NO ν A, fit as a function of T2K $\nu:\bar{\nu}$ running ratio for true MH=NH (left) and IH (right). Curves are given for the $\Delta \chi^2$ value at nominal 5:5 NO ν A running (black), best case T2K+NO ν A running (blue), and T2K only running (red). Dashed (solid) curves indicate studies performed (without) assuming normalization systematics.

⁵²³ parameters from future analyses, a more detailed treatment of systematic uncertainties from ⁵²⁴ both T2K and NO ν A, and a clear prioritization of analysis goals from the T2K and NO ν A ⁵²⁵ collaborations.

526 7. Summary

In this paper we have presented studies of the T2K experiment sensitivity to oscillation 527 parameters by performing a three-flavor analysis combining appearance and disappearance. 528 for both ν -mode, and $\bar{\nu}$ -mode assuming the expected full statistics of 7.8×10^{21} POT. The 529 T2K precision study includes either statistical errors only, systematic errors established 530 for the 2012 oscillation analyses, or conservatively projected systematic errors, and takes 531 into consideration signal efficiency and background. We have derived the sensitivity to the 532 oscillation parameters $\sin^2 2\theta_{13}$, δ_{CP} , $\sin^2 2\theta_{23}$, and Δm_{32}^2 for a range of the true parameter 533 values and using constraints from other experiments. For example, with equal exposure of 534 ν -mode and $\bar{\nu}$ -mode and using signal efficiency from the 2012 analysis we project a dataset 535 of approximately 100 ν_e and 25 $\bar{\nu_e}$ appearance events and 390 (270) ν_{μ} and 130 (70) $\bar{\nu_{\mu}}$ 536 CCQE (CC non-QE) events. From these data, with the projected systematic uncertainties 537 we would achieve a 1- σ resolution of 0.050(0.054) on $\sin^2 \theta_{23}$ and 0.040(0.045) × 10⁻³ eV² 538 on Δm_{32}^2 for 100%(50%) neutrino beam mode running. T2K will also have sensitivity to 539 the CP-violating phase $\delta_{\rm CP}$ at 90% C.L. or higher over a significant range. For example, if 540 $\sin^2 \theta_{23}$ is maximal (i.e $\theta_{23}=45^\circ$) the range is $-115^\circ < \delta_{\rm CP} < -60^\circ$ for normal hierarchy and 541 $+50^{\circ} < \delta_{\rm CP} < +130^{\circ}$ for inverted hierarchy. 542

Since the ability of T2K to measure the value of δ_{CP} is greatly enhanced by the knowledge of the mass hierarchy we have also incorporated the expected data from the NO ν A experiment

Fig. 26: δ_{CP} resolution in a combined, T2K+NO ν A, fit as a function of T2K $\nu:\bar{\nu}$ running ratio. Curves are given for the resolution value, in degress, at nominal 5:5 NO ν A running (black), best case T2K+NO ν A running (blue), and T2K only running (red). Dashed (solid) curves indicate studies performed (without) assuming normalization systematics.

into our projections using the GLoBES tools. With the same normalization uncertainties of 545 5% on the signal and 10% on the background for both experiments we find, for example, that 546 the predicted $\Delta \chi^2$ for rejecting the $\delta_{\rm CP} = 0$ hypothesis for $\delta_{\rm CP} = +90^{\circ}$, IH and $\sin^2 \theta_{23} = 0.5$ 547 from the combined experiment fit is 8.2 compared to 4.3 and 3.2 for T2K and NO ν A alone, 548 respectively. The region of oscillation parameter space where there is sensitivity to observe 549 a non-zero δ_{CP} is substantially increased compared to if each experiment is analyzed alone. 550 From the investigation of dividing the running time between ν - and $\bar{\nu}$ -modes we found 551 that an even split gives the best sensitivity for a wider region of the oscillation parameter 552

Fig. 27: Same as Fig. 26, but for different δ_{CP} values.

space for both T2K data alone, and for T2K data in combination with NO ν A, though the dependence on the ratio is not strong.

It is anticipated that the results of these studies will help to guide the optimization of the future run plan for T2K.

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