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We report measurements by the T2K experiment of the parameters $\theta_{23}$ and $\Delta m^2_{32}$ governing the disappearance of muon neutrinos and antineutrinos in the three-flavor neutrino oscillation model. Utilizing the ability of the experiment to run with either a mainly neutrino or a mainly antineutrino beam, the parameters are measured separately for neutrinos and antineutrinos. Using $7.482 \times 10^{20}$ POT in neutrino running mode and $7.471 \times 10^{20}$ POT in antineutrino mode, T2K obtained $\sin^2(\theta_{23}) = 0.51^{+0.08}_{-0.07}$ and $\Delta m^2_{32} = 2.53^{+0.15}_{-0.13} \times 10^{-3} \text{eV}^2/\text{c}^4$ for neutrinos, and $\sin^2(\theta_{23}) = 0.42^{+0.25}_{-0.07}$ and $\Delta m^2_{32} = 2.55^{+0.33}_{-0.27} \times 10^{-3} \text{eV}^2/\text{c}^4$ for antineutrinos (assuming normal mass ordering). No significant differences between the values of the parameters describing the disappearance of muon neutrinos and antineutrinos were observed.

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I. INTRODUCTION

An update to T2K’s results on the $\bar{\nu}_\mu$ disappearance oscillation analysis [1] using larger statistics and a substantial improvement to the analysis procedure is presented. The results presented here include data taken in periods where the beam was operated in neutrino mode, mainly November 2010–May 2013 and in antineutrino mode, June 2014, November 2014–June 2015, and January 2016–May 2016. This corresponds to an exposure of $7.48 \times 10^{20}$ and $7.47 \times 10^{20}$ protons on target (POT) for neutrinos and antineutrinos, respectively, reflecting an increase of 86.3% of the antineutrino mode statistics compared to the result reported in [1]. Data taken during the same periods were used for the result reported in [2], with the difference that only the muon neutrino and antineutrino candidate events are used for the result presented here. Additional degrees of freedom are also allowed in the present analysis to search for potential differences between the oscillations of neutrinos and antineutrinos.

The standard picture of neutrino oscillations invokes three species of neutrinos and a unitary mixing matrix parameterized by three angles $\theta_{12}$, $\theta_{23}$, $\theta_{13}$ and a $CP$-violating phase $\delta_{CP}$, plus two mass-squared splittings $\Delta m^2_{32}$ and $\Delta m^2_{41}$. In this model, the survival probability in vacuum is identical for muon neutrinos and antineutrinos. For the neutrino energies used by T2K, matter effects do not significantly affect this symmetry. Any difference in the oscillations could be interpreted as possible $CPT$ violation and/or evidence of nonstandard interactions [3,4]. Nonstandard interactions include phenomena not described by the Standard Model (SM). The analysis presented allows the antineutrino oscillation parameters for $\bar{\nu}_\mu$ disappearance to vary independently from those describing neutrino oscillations, i.e., $\theta_{23} \neq \bar{\theta}_{23}$ and $\Delta m^2_{32} \neq \Delta m^2_{41}$, where the barred parameters govern antineutrino oscillations. All other parameters are assumed to be the same for neutrinos and antineutrinos since this data set cannot constrain them. A direct comparison, within the same experiment, of the neutrino and antineutrino oscillation parameters is an important check of this model.

II. EXPERIMENTAL APPARATUS

T2K utilizes the J-PARC facility operating in Tokai, Japan. The neutrino beam illuminates detectors located both off axis (at an angle of $2.5^\circ$ to the beam axis) and on axis. The off-axis configuration produces a narrow width (in energy) neutrino beam that peaks around 0.6 GeV which reduces backgrounds from higher-energy neutrino interactions. This is the energy at which the first minimum in the $\nu_\mu$ and $\bar{\nu}_\mu$ survival probability is expected to occur at the T2K baseline. The Super-Kamiokande (SK) 50-kilotone water Cherenkov detector [5,6], situated 295 km away on the off-axis direction, is used to detect the oscillated neutrinos. The detector is divided by a stainless steel structure into an inner detector (ID), which has 11,129 inward-facing 20-inch-diameter photomultiplier tubes, and an outer detector (OD), instrumented with 1,885 outward-facing 8-inch-diameter photomultiplier tubes that is mainly used as a veto. The events at SK are timed using a clock synchronized with the beam line using a GPS system with $<150$ ns timing resolution.
Located 280 m from the target are a suite of detectors used to constrain the beam flux and backgrounds. These include the on-axis detector (INGRID [7]) and a suite of off-axis detectors (ND280: P0D – π0 Detector [8], FGD-Fine Grained Detector [9], TPC [10], ECAL [11] and SMRD-Side Muon Range Detector [12]). The INGRID is composed of seven vertical and seven horizontal modules arranged in a cross pattern. Its primary purpose is to measure and monitor the beam profile and stability using neutrino interactions. The ND280 off-axis detector is a magnetized composite detector designed to provide information on the \( \nu_\mu \) and \( \bar{\nu}_\mu \) unoscillated spectra directed at SK and constrain the dominant backgrounds. In addition, it constrains the combination of flux and interaction cross sections. Details of the experiment can be found in [13].

III. ANALYSIS DESCRIPTION

The data observed at the far detector are compared to the predictions of the three-flavor oscillation model to make statistical inferences. To be able to make those predictions, a model of the experiment is constructed using a simulation of the flux of neutrinos reaching the detectors and a model describing the interactions of neutrinos. The predictions from this model are compared to the data observed in the near detectors to tune the predictions for the far detector by constraining the model parameters. This section describes the different parts of the analysis, focusing on the improvements since the result reported in [1].

A. Beam flux prediction

The fluxes of the different flavors of neutrinos reaching the detectors are predicted by a series of simulations [14]. The flux and properties of the proton beam reaching the target are measured by the proton beam line monitors, and used as inputs for the simulations. Interactions of the target are measured by the proton beam line monitors, and the flux and properties of the proton beam reaching the SMRD-Side Muon Range Detector [12]). The INGRID is off-axis detectors (ND280: \( \bar{\nu}_\mu \) and \( \bar{\nu}_e \) unoscillated spectra directed at SK and constrain the dominant backgrounds. In addition, it constrains the combination of flux and interaction cross sections. Details of the experiment can be found in [13].

B. Neutrino interaction models

A significant difference between neutrinos and antineutrinos which needs to be taken into account for a direct comparison of their oscillations is the difference in their interactions with matter. In T2K the signal interaction is the charged current quasielastic (CCQE) one, \( \nu_\mu + n \rightarrow p + \mu^- \) for neutrinos and \( \bar{\nu}_\mu + p \rightarrow n + \mu^+ \) for antineutrinos. For this interaction mode and (anti)neutrinos of 0.6 GeV, the cross section of \( \nu_\mu \) on \( ^{16}O \) is larger than that of \( \bar{\nu}_\mu \) by approximately a factor of 4. The main difference is a result of the difference of the sign of the vector-axial-interference term in the cross section [19,20], with additional differences coming from nuclear effects.

Interactions of \( \nu \) and \( \bar{\nu} \) are modeled using the NEUT Monte Carlo event generator [21–23]. CCQE events have been generated according to the Smith-Moniz relativistic Fermi gas (RFG) model [24] with corrections of long-range nuclear correlations computed in random phase approximation (RPA) [22]. Multinucleon interaction (2p-2h) processes have been modeled following [22,25]. Single and multipion processes are also included with the same assumptions used in our previous publications [1,26].

The initial values and uncertainties of the interaction model parameters are tuned by a fit of the near-detector data. The fitted values are used to provide constraints for the fit to extract oscillation parameters of the far detector data. Data from MiniBooNE [27,28] and MINERvA [29,30] on CCQE-like events are no longer exploited in the near detector fit for setting priors for the CCQE axial mass and the normalization of the multinucleon (2p-2h) contribution, but are used in the choice of the default model; RFG + RPA + 2p-2h was chosen because it is most consistently able to describe current measurements from MiniBooNE and MINERvA (see [31] for details).

With respect to our previous disappearance result [1] an additional uncertainty in the description of the ground state of the nucleus has been introduced. The difference between the local Fermi gas model implemented in [22] and the global RFG in NEUT has been parameterized as a function of lepton momentum and angle and used as an uncertainty.

The treatment of 2p-2h interactions has also been refined: two separate, uncorrelated parameters have been
introduced for interactions on C and O in place of an uncertainty on the $A$-scaling law. This choice is motivated and made possible by the addition of the water-enriched sample in the near detector fit. Since part of the uncertainties on those processes are different for neutrinos and antineutrinos, an additional 2p-2h normalization factor for $\bar{\nu}$ was included to supplement these two parameters.

Finally further improvements involve the treatment of coherent $\pi$ production: a reweighting as a function of $E_p$ from the Rein-Sehgal model [32] to the Berger-Sehgal one [33] was applied to the Monte Carlo. In addition the normalization of this process has been reduced to better match dedicated measurements from MINERvA [34] and T2K [35].

C. Near detector analysis

A binned likelihood fit of the events selected as charged current (CC) interactions in the near detectors is used to constrain the flux and neutrino interaction uncertainties, producing a tuned prediction of the event rates at the far detector. The analysis uses events observed in the tracker (the 2 FGDs and 3 TPCs), with a reconstructed vertex in one of the two FGDs, and identified as a muon neutrino (the 2 FGDs and 3 TPCs), with a reconstructed vertex in detector. The analysis uses events observed in the tracker producing a tuned prediction of the event rates at the far detector by constraining the flux and neutrino interaction uncertainties, as the near detector measurement is mainly sensitive to the product of the two. The error on the number of expected events in the far detector samples due to these uncertainties is reduced from 10.8% to 2.8% for the $\nu_\mu$ sample, from 11.9% to 3.3% for the $\bar{\nu}_\mu$ sample, and on the ratio of the expected numbers of $\bar{\nu}_\mu$ and $\nu_\mu$ events from 6.1% to 1.8%.

D. Far detector

The far detector employed by T2K is the Super-Kamiokande (SK) water Čerenkov detector [5,6]. Events at the far detector (SK) are reconstructed using photomultiplier tube hits chosen based on the arrival time of the hits relative to the leading edge of the neutrino spill. To construct the analysis samples, events that are fully contained and inside the fiducial volume (FCFV) are selected. Events are defined as fully contained when there is little activity in the outer detector and as inside the fiducial volume when the distance from the reconstructed interaction vertex to the nearest inner detector wall is larger than 2 m. The fiducial mass determined by these criteria is 22.5 kiloton.

In order to enhance the purity of the samples in $\bar{\nu}_\mu$ or $\nu_\mu$ CCQE events, a single muonlike Čerenkov ring is required, corresponding to a muon momentum greater than 200 MeV/c, and with no more than one delayed electron.

The number of data and MC events passing each selection criterion are shown in Tables I and II. Expected numbers of events for MC are calculated assuming oscillations in the normal hierarchy scenario with values of the atmospheric parameters corresponding to the result reported in

### TABLE I. The number of expected and observed events at SK in neutrino mode after each selection is applied. Efficiency numbers are calculated with respect to the number of MC events generated in the fiducial volume (FV interaction).

|                  | Data | MC  | $\bar{\nu}_\mu$ | $\nu_\mu$ | $\nu_\mu$ | $\bar{\nu}_\mu$ | $\bar{\nu}_\mu$ + NC |
|------------------|------|-----|-----------------|------------|-----------|-----------------|----------------------|
| FV interaction   | 744.9| 6.4 | 100.2           | 11.6       | 246.1     | 380.6           |                      |
| FCFV             | 438  | 431.9| 4.9            | 78.8       | 8.4       | 187.9           | 152.0                |
| Single ring      | 220  | 223.5| 4.7            | 73.5       | 4.6       | 70.7            | 70.1                 |
| $\mu$-like       | 150  | 156.6| 4.7            | 72.2       | 4.4       | 65.6            | 9.6                  |
| $P_\mu > 0.2$ GeV| 150  | 156.2| 4.7            | 72.0       | 4.4       | 65.6            | 9.6                  |
| $N_{\text{decay}} < 2$ | 135  | 137.8| 4.6            | 71.3       | 4.1       | 48.5            | 9.2                  |
| Efficiency (%)   | 71.9 | 71.2 | 35.3           | 19.7       | 2.4       |                  |                      |
TABLE III. Percentage change in the number of 1-ring single CCQE or NC events in SK in antineutrino mode after each selection is applied. Efficiency numbers are calculated with respect to the number of MC events generated in the fiducial volume (FV interaction).

| Source of uncertainty (number of parameters) | Neutrino mode | Antineutrino mode |
|-----------------------------------------------|---------------|-------------------|
| Flux + ND280 constrained cross section (without ND280 fit result) (61) | 10.81% | 11.92% |
| Flux + ND280 constrained cross section (using ND280 fit result) (61) | 2.79% | 3.26% |
| Flux + all cross section (65) | 2.90% | 3.35% |
| Super-Kamiokande detector systematics (12) | 3.86% | 3.31% |
| Pion FSI and reinteractions (12) | 1.48% | 2.06% |
| Total (using ND280 fit result) (77) | 5.06% | 5.19% |

[26], \( \sin^2(\theta_{23}) = \sin^2(\bar{\theta}_{23}) = 0.528 \), \( \Delta m^2_{32} = \Delta m^2_{32} = 2.509 \times 10^{-3} \text{ eV}^2/\text{c}^4 \), and \( \sin^2(\theta_{13}) = 0.0217 \) from [37].

The fraction of events corresponding to \( \bar{\nu}_\mu \) interactions in neutrino beam mode is 6% while the fraction of \( \nu_\mu \) interactions in antineutrino beam mode is 38%. The efficiency and purity for \( \nu_\mu \) CCQE event selection in the neutrino mode are estimated to be 71% and 52%, respectively. For the antineutrino mode the efficiency and purity are estimated to be 77% and 35% for \( \bar{\nu}_\mu \) CCQE. In both modes, the rejection efficiency for NC event is 98%.

Table III summarizes the fractional error on the expected number of SK events using a 1σ variation of the flux, cross section, and far detector uncertainties.

The analysis method here follows from what was presented in [1]. As described in Sec. I, the three-flavor neutrino oscillation formalism is extended to include independent parameters \( \sin^2(\theta_{23}) \) and \( \Delta m^2_{32} \) which only affect antineutrino oscillations. Any difference between \( \sin^2(\bar{\theta}_{23}) \) and \( \sin^2(\theta_{23}) \) or \( \Delta m^2_{32} \) and \( \Delta m^2_{32} \) could be interpreted as new physics.

With the number of events predicted in the antineutrino sample, the uncertainties on the background models have a non-negligible impact on the measurement of \( \sin^2(\bar{\theta}_{23}) \) and \( \Delta m^2_{32} \). The largest is the contribution from the uncertainty on \( \sin^2(\theta_{23}) \) and \( \Delta m^2_{32} \) due to the significant neutrino background in the antineutrino sample. This provides the motivation for a simultaneous fit of the neutrino and antineutrino data sets.

The oscillation parameters of interest, \( \sin^2(\theta_{23}) \), \( \Delta m^2_{32} \), \( \sin^2(\bar{\theta}_{23}) \), and \( \Delta m^2_{32} \), are estimated using a maximum likelihood fit to the measured reconstructed energy spectra in the far detector, for neutrino mode and antineutrino mode \( \mu \)-like samples. In each case, fits are performed by maximizing the marginal likelihood in the two dimensional parameter space for each pair of parameters. The marginal likelihood is obtained by integrating over the nuisance parameters \( f \) with prior probability densities \( \pi(f) \), giving a likelihood as a function of only the relevant oscillation parameters \( o \):

\[
\mathcal{L}(o) = \int \prod_i \mathcal{L}_i(o, f) \times \pi(f) df.
\]

where bins denotes the number of analysis bins. All other oscillation parameters, except \( \delta_{CP} \), are treated as nuisance parameters along with systematic parameters and are marginalized in the construction of the likelihood in accordance with the priors detailed in Table IV. \( \delta_{CP} \) is fixed to 0 in each fit as it has a negligible impact on the disappearance spectra at T2K. Oscillation probabilities are calculated using the full three-flavor oscillation framework [38], with \( \sin^2(\bar{\theta}_{23}) \) and \( \Delta m^2_{32} \) for \( \bar{\nu} \), and \( \sin^2(\theta_{23}) \) and \( \Delta m^2_{32} \) for \( \nu \).

TABLE IV. Prior constraints of the nuisance oscillation parameters in the fit. All the Gaussian priors are from [37].

| Parameter | Prior | Range |
|-----------|-------|-------|
| \( \sin^2(\theta_{23}) \) | Uniform | [0;1] |
| \( \sin^2(\theta_{13}) \) | Gauss | 0.085 ± 0.005 |
| \( \sin^2(\theta_{12}) \) | Gauss | 0.846 ± 0.021 |
| \( \Delta m^2_{32} \) (NH) | Uniform | [0; +∞[ |
| \( \Delta m^2_{32} \) (IH) | Uniform | [−∞; 0[ |
| \( \Delta m^2_{31} \) | Gauss | \( (7.53 ± 0.18) \times 10^{-5} \text{ eV}^2/\text{c}^4 \) |
| \( \delta_{CP} \) | Fixed | 0 |
$\Delta m^2$ for $\nu$. Matter effects, almost negligible in this analysis, are included with a matter density of $\rho = 2.6$ g/cm$^3$ [39].

Confidence regions are constructed for the oscillation parameters using the constant $\Delta \chi^2$ method [37]. We define $\Delta \chi^2 = -2 \ln(\mathcal{L}(\mathbf{o})/\max(\mathcal{L}))$ as the logarithm of the ratio of the marginal likelihood at a point $\mathbf{o}$ in the $\sin^2(\theta_{23}) - \Delta m^2_{32}$ oscillation parameter space and the maximum marginal likelihood. The confidence region is then defined as the area of the oscillation parameter space for which $\Delta \chi^2$ is less than a standard critical value. This method was used as the difference between the confidence regions produced by it and those obtained using the Feldman-Cousins [40] method was found to be small. For the Feldman-Cousins method, the critical chi-square values were calculated for a coarse set of points in the oscillation parameter space.

IV. RESULTS AND DISCUSSION

The reconstructed energy spectra of the events observed during neutrino and antineutrino running modes are shown in Fig. 1. These are overlaid with the predictions for the best-fit values of the oscillation parameters assuming normal hierarchy, and in the case of no oscillations. The lower plots in Fig. 1 show the ratio of data to the unoscillated spectrum.

Assuming normal hierarchy, the best-fit values obtained for the parameters describing neutrino oscillations are $\sin^2(\theta_{23}) = 0.51$ and $\Delta m^2_{32} = 2.53 \times 10^{-3}$ eV$^2$/c$^4$ with 68% confidence intervals of 0.44–0.59 and 2.40–2.68 (10$^{-3}$ eV$^2$/c$^4$), respectively. For the antineutrino parameters, the best-fit values are $\sin^2(\bar{\theta}_{23}) = 0.42$ and $\Delta m^2_{32} = 2.55 \times 10^{-3}$ eV$^2$/c$^4$ with 68% confidence intervals of 0.35–0.67 and 2.28–2.88 (10$^{-3}$ eV$^2$/c$^4$), respectively. For comparison, the best-fit values (68% confidence intervals) obtained when using the same oscillation parameters for neutrinos and antineutrinos are 0.52 (0.43–0.595) for $\sin^2(\theta_{23})$ and 2.55 (2.47–2.63) $\times$ 10$^{-3}$ eV$^2$/c$^4$ for $\Delta m^2_{32}$. The values for the inverted hierarchy can be obtained by replacing $\Delta m^2_{32}$ by $\Delta m^2_{21}$, effectively changing the sign of $\Delta m^2_{32}$ and shifting its absolute value by $\pm \Delta m^2_{31}$.

![Graph](image)

FIG. 1. Top: Reconstructed energy distribution of the 135 far detector $\nu_{\mu}$,CCQE candidate events (left) and 66 $\bar{\nu}_{\mu}$,CCQE candidate events (right), with predicted spectra for best-fit and no oscillation cases. Bottom: Ratio to unoscillated predictions.

![Graph](image)

FIG. 2. 90% confidence regions for $\sin^2(\theta_{23})$ and $\Delta m^2_{32}$ in $\nu$ mode (corresponding to 7.482 $\times$ 10$^{20}$POT) and $\bar{\nu}$-mode (corresponding to 7.471 $\times$ 10$^{20}$POT). Normal hierarchy is assumed. 90% confidence regions obtained by SK [41] and MINOS [42] for $\bar{\nu}$ are also shown. The best-fit in the case $\sin^2(\bar{\theta}_{23}) > 0.5$ is also displayed for comparison with the MINOS result.
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