Measurement of Muon Antineutrino Oscillations with an Accelerator-Produced Off-Axis Beam

K. Abe,47 C. Andreopoulos,45,26 M. Antonova,21 S. Aoki,23 A. Ariga,1 S. Assylibekov,7 D. Autiero,28 M. Barbi,39 G. J. Barker,55 G. Barr,35 P. Bartet-Fribourg,36 M. Batkiewicz,12 F. Bay,10 V. Berardi,7 S. Berkman,5 S. Bhadra,59 A. Blondel,11 S. Bolognesi,9 S. Bordoni,14 S. B. Boyd,55 D. Brailsford,23,16 A. Bravar,11 C. Bronner,22 M. Buizza Avanzini,9 R. G. Calland,22 S. Cao,24 J. Caravaca Rodriguez,14 S. L. Cartwright,43 R. Castillo,14 M. G. Catanese,17 A. Cervera,15 D. Cherdack,7 N. Chikuma,46 G. Christodoulou,26 A. Clifton,5 J. Coleman,26 G. Collazuol,19 L. Comrennesi,38 A. Dabrowska,12 G. De Rosa,18 T. Dea...
University of British Columbia, Department of Physics and Astronomy, Vancouver, British Columbia, Canada
4University of California, Irvine, Department of Physics and Astronomy, Irvine, California, USA
5IRFU, CEA Saclay, Gif-sur-Yvette, France
6University of Colorado at Boulder, Department of Physics, Boulder, Colorado, USA
7Colorado State University, Department of Physics, Fort Collins, Colorado, USA
8Duke University, Department of Physics, Durham, North Carolina, USA
9Ecole Polytechnique, IN2P3-CNRS, Laboratoire Leprince-Ringuet, Palaiseau, France
10ETH Zurich, Institute for Particle Physics, Zurich, Switzerland
11University of Geneva, Section de Physique, DPNC, Geneva, Switzerland
12H. Niewodniczanski Institute of Nuclear Physics PAN, Cracow, Poland
13High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan
14Institut de Fisica d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, Campus UAB, Bellaterra (Barcelona), Spain
15IFIC (CSIC and University of Valencia), Valencia, Spain
16Imperial College London, Department of Physics, London, United Kingdom
17INFN Sezione di Bari and Università e Politecnico di Bari, Dipartimento Interuniversitario di Fisica, Bari, Italy
18INFN Sezione di Napoli and Università di Napoli, Dipartimento di Fisica, Napoli, Italy
19INFN Sezione di Padova and Università di Padova, Dipartimento di Fisica, Padova, Italy
20INFN Sezione di Roma and Università di Roma “La Sapienza,” Roma, Italy
21Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
22Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo Institutes for Advanced Study, University of Tokyo, Kashiwa, Chiba, Japan
23Kobe University, Kobe, Japan
24Kyoto University, Department of Physics, Kyoto, Japan
25Lancaster University, Physics Department, Lancaster, United Kingdom
26University of Liverpool, Department of Physics, Liverpool, United Kingdom
27Louisiana State University, Department of Physics and Astronomy, Baton Rouge, Louisiana, USA
28Université de Lyon, Université Claude Bernard Lyon 1, IPN Lyon (IN2P3), Villeurbanne, France
29Michigan State University, Department of Physics and Astronomy, East Lansing, Michigan, USA
30Miyagi University of Education, Department of Physics, Sendai, Japan
31National Centre for Nuclear Research, Warsaw, Poland
32State University of New York at Stony Brook, Department of Physics and Astronomy, Stony Brook, New York, USA
33Okayama University, Department of Physics, Okayama, Japan
34Osaka City University, Department of Physics, Osaka, Japan
35Oxford University, Department of Physics, Oxford, United Kingdom
36UPMC, Université Paris Diderot, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Paris, France
37University of Pittsburgh, Department of Physics and Astronomy, Pittsburgh, Pennsylvania, USA
38Queen Mary University of London, School of Physics and Astronomy, London, United Kingdom
39University of Regina, Department of Physics, Regina, Saskatchewan, Canada
40University of Rochester, Department of Physics and Astronomy, Rochester, New York, USA
41Royal Holloway University of London, Department of Physics, Egham, Surrey, United Kingdom
42RWTH Aachen University, III. Physikalisches Institut, Aachen, Germany
43University of Sheffield, Department of Physics and Astronomy, Sheffield, United Kingdom
44University of Silesia, Institute of Physics, Katowice, Poland
45STFC, Rutherford Appleton Laboratory, Harwell Oxford, and Daresbury Laboratory, Warrington, United Kingdom
46University of Tokyo, Department of Physics, Tokyo, Japan
47University of Tokyo, Institute for Cosmic Ray Research, Kamioka Observatory, Kamioka, Japan
48University of Tokyo, Institute for Cosmic Ray Research, Research Center for Cosmic Neutrinos, Kashiwa, Japan
49Tokyo Metropolitan University, Department of Physics, Tokyo, Japan
50University of Toronto, Department of Physics, Toronto, Ontario, Canada
51TRIUMF, Vancouver, British Columbia, Canada
52University of Victoria, Department of Physics and Astronomy, Victoria, British Columbia, Canada
53University of Warsaw, Faculty of Physics, Warsaw, Poland
54Warsaw University of Technology, Institute of Radioelectronics, Warsaw, Poland
55University of Warwick, Department of Physics, Coventry, United Kingdom

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T2K reports its first measurements of the parameters governing the disappearance of $\bar{\nu}_\mu$ in an off-axis beam due to flavor change induced by neutrino oscillations. The quasimonochromatic $\bar{\nu}_\mu$ beam, produced with a peak energy of 0.6 GeV at J-PARC, is observed at the far detector Super-Kamiokande, 295 km away, where the $\bar{\nu}_\mu$ survival probability is expected to be minimal. Using a data set corresponding to $4.01 \times 10^{20}$ protons on target, 34 fully contained $\mu$-like events were observed. The best-fit oscillation parameters are $\sin^2(\theta_{23}) = 0.45$ and $|\Delta m^2_{32}| = 2.51 \times 10^{-3}$ eV$^2$ with 68% confidence intervals of 0.38–0.64 and 2.26–2.80 $\times 10^{-3}$ eV$^2$, respectively. These results are in agreement with existing antineutrino parameter measurements and also with the $\nu_\mu$ disappearance parameters measured by T2K.

**Introduction.**—In the three-flavor framework, neutrino oscillation can be described by the unitary Pontecorvo-Maki-Nakagawa-Sakata matrix, which is parameterized by three angles $\theta_{12}, \theta_{23}, \theta_{13}$ and a $CP$-violating phase $\delta_{CP}$ [1–3]. Given a neutrino propagation distance, $L$ (km), and energy, $E_\nu$ (GeV), such that $L/E_\nu \sim O(1000)$, the survival probability for a muon neutrino propagating through vacuum can be approximated by

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4 \cos^2(\theta_{13}) \sin^2(\theta_{23})$$

$$\times [1 - \cos^2(\theta_{13}) \sin^2(\theta_{23})] \sin^2\left(\frac{1.267 \Delta m_{32}^2 L}{E_\nu}\right),$$

(1)

where $\Delta m_{32}^2$ (eV$^2$) is the neutrino mass squared splitting, defined as $m_3^2 - m_2^2$. Equation (1) shows that measuring the disappearance probability as a function of $L/E_\nu$ leads to a measurement of the oscillation parameters. In this model of neutrino oscillation, the disappearance probability in vacuum is identical for neutrinos and antineutrinos. The disappearance probabilities in matter can differ by as much as 0.1% for the T2K baseline and neutrino flux, but our data set is not sensitive to this small effect. Observing a significant difference between the disappearance probabilities of neutrinos and antineutrinos would, therefore, be evidence for new physics [3]. Results from the MINOS [4] and Super-Kamiokande (SK) Collaborations [5] indicate no significant difference between muon antineutrino oscillations and muon neutrino oscillations.

In this Letter, we present the first measurement of $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ by the T2K Collaboration. This analysis allows the dominant 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 $\Delta m_{32}^2 \neq \Delta \bar{m}_{32}^2$, where the barred parameters refer to antineutrino oscillations. $\theta_{13}, \theta_{12}$, and $\Delta \bar{m}_{31}^2$ are assumed to be identical to their matter counterparts since our data set cannot constrain them. This ensures that the expected background at the far detector is consistent with the current knowledge of neutrino oscillations, while allowing us to use the T2K antineutrino-mode data to measure $\bar{\theta}_{23}$ and $\Delta \bar{m}_{32}^2$.

**T2K experiment.**—The T2K experiment [6] is composed of a neutrino beam line, a suite of near detectors, and the far detector, Super-Kamiokande. Both the far detector and one of the near detectors are placed 2.5° off the neutrino beam axis and so observe a narrow-band beam [7]. This “off-axis” method reduces backgrounds from higher-energy neutrinos, producing a neutrino flux that peaks around 0.6 GeV, the energy at which the first minimum in the $\bar{\nu}_\mu$ survival probability is expected to occur at the T2K baseline.

The J-PARC main ring provides a 30-GeV proton beam which impinges upon a graphite target, producing pions and kaons. The target is held inside the first of three magnetic horns which focus charged particles into a 96-m-long decay volume, where they decay and produce neutrinos. The polarity of the horn current determines whether positive or negative mesons are focused, which in turn determines whether the neutrino beam is largely composed of muon neutrinos or muon antineutrinos. The decay volume ends in a beam dump followed by the muon monitor, which measures the neutrino beam direction on a bunch-by-bunch basis using muons from the meson decays.

The near-detector complex [6] consists of the on-axis Interactive Neutrino GRID detector (INGRID) [8] and the off-axis detector (ND280), both 280 m downstream of the proton-beam target. INGRID is a $7 \times 7$ array of iron-scintillator detectors, arranged in a “cross” configuration at the beam center. INGRID provides high-statistics monitoring of the neutrino beam intensity, direction, profile, and...
stability and has shown that the neutrino beam direction is controlled to 0.4 mrad. ND280 consists of a number of subdetectors installed inside the refurbished UA1/NOMAD magnet, which provides a 0.2 T field. The near-detector analysis described here uses the tracker region of ND280, which consists of three time projection chambers (TPC1, 2, 3) [9] interleaved with two fine-grained detectors (FGD1, 2) [10]. The FGDs are the neutrino target and track charged particles coming from the interaction vertex, while the TPCs perform 3D tracking and determine the charge, momentum, and energy loss of each charged particle traversing them. The observed energy loss is used for particle identification which, when combined with particle charge information, allows a precise separation and measurement of the $\bar{\nu}_\mu$ (right-sign) and $\nu_\mu$ (wrong-sign) interactions in the antineutrino-mode beam.

The far detector is a 50-kt (22.5-kt fiducial mass) water Cherenkov detector [11,12], where the volume is divided into an outer detector (OD) with 1885 outward-facing 20-cm-diameter photomultiplier tubes and an inner detector (ID) with 11 129 inward-facing 50-cm-diameter photomultiplier tubes. The events arriving at SK from the J-PARC beam spill are synchronized with a global positioning system with <150 ns precision.

The results presented here are based on data taken in three periods: two where the beam operated in antineutrino mode, (1) June 2014 and (2) November 2014–June 2015, and one in neutrino mode, (3) November 2010–May 2013. The oscillation analysis uses periods (1) and (2), while the near-detector analysis uses data from periods (1) and (3). This corresponds to an exposure of $4.01 \times 10^{20}$ protons on target (POT) in antineutrino mode for the oscillation analysis, and an exposure of $0.43 \times 10^{20}$ POT in antineutrino mode plus $5.82 \times 10^{20}$ POT in neutrino mode for the near-detector analysis.

Analysis strategy.—This analysis resembles that of Ref. [13], fitting samples of charged-current (CC) interactions at ND280 to produce a tuned prediction of the unoscillated antineutrino spectrum at the far detector, including its associated uncertainty. This analysis differs from Ref. [13] in that both $\nu_\mu$ and $\bar{\nu}_\mu$ samples at ND280 are fitted. This ensures that the neutrino interaction model is consistent between both neutrino- and antineutrino-beam-mode data sets and provides a constraint on both the right-sign signal and the wrong-sign background in the antineutrino-mode beam.

Flux simulation.—The nominal neutrino flux at ND280 and SK (without oscillation) is predicted by simulating the secondary beam line [14] using FLUKA2011 [15,16] and GEANT3 with GCALOR [17,18]. The simulated hadronic interactions are tuned to external hadron-production data. The unoscillated neutrino flux prediction at SK is shown in Fig. 1 for each neutrino type and for both neutrino- and antineutrino-mode beams. At the peak energy of the T2K beam, the $\nu_\mu$ flux in the neutrino-mode beam is 20% higher than the $\bar{\nu}_\mu$ flux in the antineutrino-mode beam, due to the larger production cross section for $\pi^+$ compared to $\pi^-$ in proton-carbon interactions. The ratio of the wrong-sign component ($\nu_\mu$ in the $\bar{\nu}_\mu$ beam), mainly coming from forward-going high-energy pions, to the right-sign component ($\bar{\nu}_\mu$) at the peak energy is 3%. The largest sources of neutrino flux uncertainty are from beam-line and hadron-production modeling uncertainties, which are common to ND280 and SK. The new NA61/SHINE 2009 thin-target data [19] are included in the hadron-production tuning for this analysis, reducing the total flux uncertainty from between 12%–15% to 10% around 0.6 GeV.

Neutrino interaction simulation.—Neutrino interactions are modeled with the NEUT Monte Carlo event generator [20–24]. The generator uses the same model with common parameters to describe both $\nu$ and $\bar{\nu}$ interactions. In the case of CC quasielastic (CCQE) reactions ($\nu_\mu + n \rightarrow \mu^- + p$ or $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$) neutrino and antineutrino cross sections differ by the sign of the vector-axial interference term [25,26]. At a neutrino energy of 0.6 GeV, this makes the neutrino-oxygen CCQE cross section a factor of ~4 larger than that of antineutrinos.

To set the initial values and uncertainties of some parameters, such as the CCQE axial mass and the normalization of the multinucleon contribution, results from the MiniBooNE and MINERvA experiments [27–30] on CH2 and CH targets are used. These parameters are then tuned by the near-detector fit.

Near-detector fit.—The seven samples used in the near-detector fit are summarized in Table I. Muon-neutrino-induced CC interactions in the neutrino beam mode are found by requiring that the highest-momentum, negative-curvature track in an event starts within the upstream FGD (FGD1) fiducial volume (FV) and has an energy deposit in TPC2 consistent with a muon. Events with a TPC track that starts upstream of the start point of the muon candidate are rejected, and the remaining $\nu_\mu$ CC candidates are divided into three subsamples according to

![FIG. 1. The nominal unoscillated neutrino flux prediction at SK for each neutrino type in the neutrino-mode beam (left) and antineutrino-mode beam (right). The shaded boxes indicate the total systematic uncertainty on each energy bin.](image-url)
the number of associated pions: $\nu_\mu$ CC $0\pi$, $\nu_\mu$ CC $1\pi^+$, and $\nu_\mu$ CC other, which are dominated by CCQE, CC resonant pion production, and deep inelastic scattering interactions, respectively [13]. For the antineutrino-beam-mode samples, the selection of $\bar{\nu}_\mu$ ($\nu_\mu$) CC interactions is similar to that used in the neutrino beam mode, except the positive (negative) track must be the highest-momentum track in the event. The selected $\bar{\nu}_\mu$ ($\nu_\mu$) CC candidate events are divided into two subsamples rather than three, due to the small amount of antineutrino-mode data used in this analysis. These are defined by the number of reconstructed tracks crossing TPC2: $\bar{\nu}_\mu$ ($\nu_\mu$) CC 1 track, dominated by CCQE interactions; and $\bar{\nu}_\mu$ ($\nu_\mu$) CC $N$ tracks ($N > 1$), a mixture of resonant production and deep inelastic scattering.

The fit uses a binned likelihood, with the samples binned according to the muon momentum and angle ($\theta$) relative to the central axis of the detector, roughly 1.7° away from the incident (anti)neutrino direction. The TPCs calculate the muon momentum from the curvature of the lepton in the ND280 magnetic field, with a resolution of 6% at the muon momentum from the curvature of the lepton in incident (anti)neutrino direction. The TPCs calculate the central axis of the detector, roughly 1.7° away from the interactions; and events at SK. For the parameters that ND280 can constrain, the fit reduces their effect on the uncertainty on the expected number of events at SK from 9.2% to 3.4%.

Far-detector selection.—At the far detector, fully contained fiducial volume (FCFV) events are selected by requiring no hit clusters in the OD, that the reconstructed energy spectrum of the 34 selected events is similar to that of oxygen events, giving a 9.5% uncertainty on the number of events at SK. For the parameters that ND280 can constrain, the fit reduces their effect on the uncertainty on the expected number of events at SK from 9.2% to 3.4%.

To decouple the properties of the carbon target at ND280 from those of the oxygen target at SK, separate Fermi momentum, binding energy, multinucleon event normalization, and CC coherent pion-production normalization parameters are introduced for interactions on oxygen. Since oxygen comprises only 3.6% by mass of the FGD1 target, this near-detector analysis is insensitive to these parameters. A conservative (100% uncertainty) ansatz is adopted for the normalization of multinucleon ejection oxygen events, giving a 9.5% uncertainty on the number of events at SK. For the parameters that ND280 can constrain, the fit reduces their effect on the uncertainty on the expected number of events at SK from 9.2% to 3.4%.

Far-detector selection.—At the far detector, fully contained fiducial volume (FCFV) events are selected by requiring no hit clusters in the OD, that the reconstructed interaction vertex is more than 2 m away from the ID wall, and that the visible energy in the event is larger than 30 MeV. The last criterion requires that the amount of Cherenkov light is more than that of a 30-MeV electromagnetic shower.

To enhance the $\bar{\nu}_\mu$ CCQE purity of the sample, selected events must have a single, $\mu$-like Cherenkov ring, no more than one decay electron, and a muon momentum greater than 0.2 GeV [13]. The number of data and MC events passing each selection criterion are shown in Table II and the reconstructed energy spectrum of the 34 selected events is plotted in Fig. 3. The reconstructed neutrino energy is calculated using the muon momentum and production angle, under the assumption that a CCQE interaction occurred on a nucleon at rest. The selection efficiency for $\bar{\nu}_\mu$ CCQE is estimated to be 77% while backgrounds...
TABLE II. The number of events observed at the far detector in the antineutrino-beam-mode data after applying each selection cut. MC expectation is calculated assuming oscillations with $\sin^2(\theta_{23}) = 0.5$, $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV$^2$, and $\sin^2(\theta_{13}) = 0.0257$. The "$\bar{\nu}_e + \nu_e + \text{NC}" column includes the NC interactions of all the (anti)neutrino flavors. Efficiency numbers are calculated with respect to the number of MC events generated in the fiducial volume (FV interaction).

| Selection | Total | CCQE | CCnonQE | $\bar{\nu}_e + \nu_e + \text{NC}$ |
|-----------|-------|------|---------|------------------------------------|
| FV interaction | 186.7 | 17.8 | 11.4 | 20.0 | 36.5 | 101 |
| FCFV | 90 | 99.7 | 14.4 | 8.6 | 15.1 | 26.6 | 35.1 |
| Single ring | 50 | 52.2 | 14.0 | 7.7 | 8.1 | 13.8 |
| $\mu$-like | 40 | 39.4 | 13.8 | 7.6 | 7.8 | 8.0 | 2.2 |
| $P_\mu > 0.2$ GeV | 40 | 39.3 | 13.8 | 7.6 | 7.8 | 8.0 | 2.2 |
| $N_{\text{decay-}e} < 2$ | 34 | 36.1 | 13.7 | 7.5 | 7.3 | 5.6 | 2.1 |
| Efficiency (%) | 77.1 | 65.7 | 36.6 | 15.3 | 2.0 |

from neutral-current (NC), $\nu_e$, and $\bar{\nu}_e$ interactions are reduced by a factor of 50. The systematic uncertainties in the detector response are evaluated using atmospheric neutrinos, cosmic-ray muons, and their decay electrons [13].

Oscillation fit.—The oscillation parameters $\sin^2(\theta_{12})$, $\sin^2(\theta_{23})$, and $\Delta m^2_{32}$ are estimated using a maximum-likelihood fit to the measured reconstructed energy spectrum in the far detector. All oscillation parameters are fixed as shown in Table III. Oscillation probabilities are calculated using the full three-flavor oscillation framework [31], assuming the normal mass hierarchy ($\Delta m^2_{32} > 0$). Matter effects are included with an Earth density of $\rho = 2.6$ g/cm$^3$ [32].

Confidence regions are constructed for the oscillation parameters using the constant $\Delta\chi^2$ method [33]. A marginal likelihood is used for this, integrating over the nuisance parameters $f$ with prior probability functions $\pi(f)$ to find the likelihood as a function of only the relevant oscillation parameters $o$,

$$L(o) = \int \prod_i E_{\text{bins}} L_i(o, f) \times \pi(f) df,$$

where $E_{\text{bins}}$ denotes the number of reconstructed neutrino energy bins.

We define $\Delta\chi^2 = -2 \ln[L(o)/\max(L)]$ as the ratio of the marginal likelihood at a point $o$ 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. The Feldman-Cousins critical chi-square value was calculated for a coarse set of points in the oscillation parameter space. The difference in the confidence region calculated from these points and that from the standard chi-square values was found to be negligible.

Table IV summarizes the fractional error on the expected number of SK events from a $1\sigma$ variation of the flux, cross-section, and far-detector systematic parameters. Although the fractional error on the expected number of events due to

| Source of uncertainty (number of parameters) | $\delta n_{\text{SK}}^{\exp} / n_{\text{SK}}^{\exp}$ (%) |
|---------------------------------------------|----------------------------------|
| ND280-unconstrained cross section (6)       | 10.0                             |
| Flux and ND280-constrained cross section (31)| 3.4                              |
| Super-Kamiokande detector systematics (6)   | 3.8                              |
| Fion FSI and interactions (6)               | 2.1                              |
| Total (49)                                  | 11.6                             |
90% confidence regions in the $\sin^2(\theta_{23})$ of the T2K $\nu\bar{\nu}$ 90% confidence regions. One-dimensional $\Delta \chi^2$ profiles for the two parameters are shown at the top and right, overlaid with lines representing the 1D $\Delta \chi^2$ values for the 68% and 90% confidence intervals.

systematic errors is large, the effect of systematic parameters on the confidence regions found in this fit is negligible due to the limited data statistics. The impact of fixing the values of $\sin^2(\theta_{23})$ and $\Delta m^2_{32}$ in the fit is also negligible.

The observed $\bar{\nu}_\mu$ reconstructed energy spectrum from the antineutrino-beam-mode data is shown in the upper plot of Fig. 3, overlaid with the best-fit spectrum assuming normal hierarchy, separated by interaction mode. The lower plot in Fig. 3 is the ratio of data to the expected, unoscillated hierarchy, separated by interaction mode. The lower plot in Fig. 3 is the ratio of data to the expected, unoscillated hierarchy, separated by interaction mode.

The best-fit values obtained are $\sin^2(\theta_{23}) = 0.45$ and $|\Delta m^2_{32}| = 2.51 \times 10^{-3}$ eV$^2$, with 68% confidence intervals of 0.38–0.64 and 2.26–2.80 $\times 10^{-3}$ eV$^2$, respectively. A goodness-of-fit test was performed by comparing this fit to an ensemble of toy experiments, giving a $p$-value of 0.38.

The fit results are shown in Fig. 4 as 68% and 90% confidence regions in the $\sin^2(\theta_{23}) - \Delta m^2_{32}$ plane. The 90% confidence regions from the T2K neutrino-beam-mode joint disappearance and appearance fit [13], the SK fit to $\bar{\nu}_\mu$ in atmospheric neutrino data [5], and the MINOS fit to $\bar{\nu}_\mu$ beam and atmospheric data [4] are also shown for comparison. A second, fully Bayesian, analysis was also performed, producing a credible region matching the confidence regions presented above.

Conclusions.—We report the first study of $\bar{\nu}_\mu$ disappearance using an off-axis beam and present measurements of $\sin^2(\theta_{23}) = 0.45$ and $\Delta m^2_{32} = 2.51 \times 10^{-3}$ eV$^2$. These results are consistent with the values of $\sin^2(\theta_{23})$ and $\Delta m^2_{32}$ observed previously by T2K [13], providing no indication of new physics, and are also in good agreement with similar measurements from MINOS [4] and the SK Collaboration [5]. The results presented here, with the first T2K antineutrino data set, are competitive with those from both the MINOS and SK Collaborations, demonstrating the effectiveness of the off-axis beam technique.

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