

# Measurement of Neutrino Oscillation Parameters from Muon Neutrino Disappearance with an Off-axis Beam

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The T2K collaboration reports a precision measurement of muon neutrino disappearance with an off-axis neutrino beam with a peak energy of 0.6 GeV. Near detector measurements are used to constrain the neutrino flux and cross section parameters. The Super-Kamiokande far detector,

which is 295 km downstream of the neutrino production target, collected data corresponding to  $3.01 \times 10^{20}$  protons on target. In the absence of neutrino oscillations,  $205 \pm 17$  (syst.) events are expected to be detected and only 58 muon neutrino event candidates are observed. A fit to the neutrino rate and energy spectrum assuming three neutrino flavors, normal mass hierarchy and  $\theta_{23} \leq \pi/4$  yields a best-fit mixing angle  $\sin^2(2\theta_{23}) = 1.000$  and mass splitting  $|\Delta m_{32}^2| = 2.44 \times 10^{-3} \text{ eV}^2/c^4$ . If  $\theta_{23} \geq \pi/4$  is assumed, the best-fit mixing angle changes to  $\sin^2(2\theta_{23}) = 0.999$  and the mass splitting remains unchanged.

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*Introduction.*—Oscillations between different neutrino flavor states are a physics process well described by the  $3 \times 3$  Pontecorvo-Maki-Nakagawa-Sakata mixing matrix [1], which is parametrized by three mixing angles  $\theta_{12}$ ,  $\theta_{23}$ ,  $\theta_{13}$ , and a CP violating phase  $\delta_{CP}$ . In this mixing scheme, the angle  $\theta_{23}$  and mass splitting  $\Delta m_{32}^2$  are the main parameters that govern atmospheric and long-baseline  $\nu_\mu$  disappearance oscillations. The oscillation probability in natural units and in the limit  $|\Delta m_{32}^2| \gg |\Delta m_{21}^2|$  is

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - [\cos^4(\theta_{13}) \sin^2(2\theta_{23}) + \sin^2(\theta_{23}) \times \sin^2(2\theta_{13})] \sin^2(\Delta m_{32}^2 L / 4E_\nu), \quad (1)$$

where  $L$  is the neutrino propagation distance and  $E_\nu$  is the neutrino energy. Recent measurements [2–5] are near  $\theta_{23} = \pi/4$  where  $\sin^2(2\theta_{23})$  becomes maximal. In light of recent  $\theta_{13} > 0$  measurements [6], there is considerable interest to determine if  $\theta_{23}$  is non-maximal. This can have an important impact on neutrino mass models and the interpretation of  $\nu_e$  appearance results. In this paper, we report on new measurements on the value of  $\sin^2(2\theta_{23})$ .

*T2K Experiment.*—The T2K experiment [7] uses a 30 GeV proton beam accelerated by the J-PARC accelerator facility. This combines (1) a muon neutrino beam line, (2) the near detector complex, which is located 280 m downstream of the neutrino production target, monitors the beam, and constrains the neutrino flux parametrization and cross sections, and (3) the far detector, Super-Kamiokande (SK), which detects neutrinos at a baseline distance of  $L = 295$  km from the target. The neutrino beam is directed  $2.5^\circ$  away from SK producing a narrow-band  $\nu_\mu$  beam [8] at the far detector. The off-axis angle is chosen such that the energy peaks at  $E_\nu = \Delta m_{32}^2 L / 2\pi \approx 0.6$  GeV which corresponds to the first oscillation minimum of the  $\nu_\mu$  survival probability at SK. This enhances the sensitivity to determine  $\theta_{23}$  from the oscillation measurements and reduces backgrounds from higher-energy neutrino interactions at SK.

The J-PARC main ring accelerator provides a fast-extracted high-intensity proton beam. The primary beam line has 21 electrostatic beam position monitors, 19 secondary emission monitors, an optical transition radiation monitor, and five current transformers to measure the proton current before a graphite target. Pions and kaons produced in the target decay in the helium-filled secondary beam line, which contains three focusing horns and a 96-m-long decay tunnel. This is followed by a beam dump and a set of muon monitors.

The near detector complex contains an on-axis Interactive Neutrino Grid detector (INGRID) [9] and an off-axis magnetic detector, ND280. The INGRID detector has 14 seven-ton iron-scintillator tracker modules arranged in a 10-m horizontal by 10-m vertical crossed array. This detector provides high-statistics monitoring of the beam intensity, direction, profile, and stability. The off-axis detector is enclosed in a 0.2-T magnet that contains a sub-detector optimized to measure  $\pi^0$ s (PØD) [10], three time projection chambers (TPC1,2,3) [11] alternating with two one-ton fine grained detectors (FGD1,2) [12], and an electromagnetic calorimeter (ECal) that surrounds the TPC, FGD, and PØD detectors. A side muon range detector (SMRD) [13], built into slots in the magnet flux return steel, detects muons that exit or stop in the magnet steel when the path length exceeds the energy loss range. A schematic diagram of the detector layout has been published elsewhere [7].

The SK water Cherenkov far detector [14] has a fiducial volume of 22.5 kt contained within a cylindrical inner detector (ID) instrumented with 11129 inward facing 20-inch phototubes. Surrounding the ID is a 2-meter wide outer detector (OD) with 1885 outward-facing 8-inch phototubes. A Global Positioning System with  $<150$  ns precision synchronizes the timing between reconstructed SK events and the J-PARC beam spill.

These results are based on three running periods: Run 1 (January-June 2010), Run 2 (November 2010-March 2011), and Run 3 (January-June 2012). The proton beam power on the target steadily increased from Run 1, reaching 200 kW with about  $10^{14}$  protons per pulse on the target by the end of Run 3. The total neutrino beam exposure on the SK detector corresponds to a total integrated  $3.01 \times 10^{20}$  protons on target (POT).

*Analysis Strategy.*—The analysis method estimates oscillation parameters by comparing the observed and predicted  $\nu_\mu$  interaction rate and energy spectrum at the far detector. The rate and spectrum depend on the os-

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cillation parameters, the incident neutrino flux, neutrino interaction cross sections, and the detector response. The initial estimate of the neutrino flux is determined by detailed simulations incorporating proton beam measurements, INGRID measurements, and the pion and kaon production measured by the NA61/SHINE [15] experiment. The ND280 detector measurement of  $\nu_\mu$  charged current (CC) events is used to constrain the initial flux estimates and parameters of the neutrino interaction models that affect the predicted rate and spectrum of neutrino interactions at both ND280 and SK. At SK,  $\nu_\mu$  charged current quasi-elastic (CCQE) events are selected and efficiencies are determined, along with their dependence on final state interactions (FSI) inside the nucleus and secondary pion interactions (SI) in the detector material. These combined results are used in a binned likelihood ratio fit to determine the oscillation parameters.

*Initial Neutrino Flux Model.*—To predict the neutrino flux at the near and far detectors, the interactions of the primary beam protons and subsequent secondary particles in a graphite target are modeled with a FLUKA2008 [16] simulation. GEANT3 [17] simulations model the secondary particles in the magnetic horns and the decay region, and their decays into neutrinos. The hadron interactions are modeled with GCALOR [18]. The simulation is tuned using measurements of the primary proton beam profile and the T2K horn magnetic fields and the NA61/SHINE hadron production results [15]. In addition, the contribution to the flux uncertainty from the secondary beam line component alignment and the neutrino beam direction are evaluated. The stability of the beam direction and neutrino rate per proton on target are monitored continuously with INGRID, and the variations are measured to be less than the assigned systematic uncertainties [19]. The total uncertainties in the flux are 10-20% in the relevant energy range, dominated by the hadron production uncertainties. More details of the flux calculation are described elsewhere [8].

*Neutrino Interaction Simulations and Cross Section Parameters*—Neutrino interactions in the ND280 and SK detectors are simulated with the NEUT Monte Carlo generator [20]. External data, primarily from the Mini-BooNE experiment [21], are used to tune some NEUT neutrino interaction parameters. These determine the input parameter uncertainties used in the fit to the ND280 data [19]. Neutrino interaction parameters fall into two categories: parameters that are common between ND280 and SK, and independent parameters affecting interactions at only one of the detectors. The common parameters include the axial masses for CCQE and resonant pion production, as well as 5 energy dependent normalizations; these are included in the fit to the ND280 data, which is discussed in the next section. Since the ND280 target is mainly carbon and differs from the SK target which is mainly oxygen, additional independent parameters are required. These affect the nuclear model for CCQE (Fermi momentum, binding energy and spectral function modeling) and include five cross section param-

eters related to pion production, the neutral current (NC) cross section, the  $\nu_e/\nu_\mu$  CC cross section ratio, and the  $\nu/\bar{\nu}$  CC cross section ratio. These independent cross section uncertainties (11 parameters) produce a 6.3% fractional error in the expected number of SK events as listed in Table I. Not simulated by NEUT are multi-nucleon knock-out processes [22] that may affect strongly [23] the determination of the oscillation parameters by causing an additional bias between reconstructed and true neutrino energy. An estimation of the bias on the oscillation parameters from these processes [22] appears to be smaller than the current statistical precision when the overall rate of CC interactions with ND280 data is constrained and the uncertainties in pion-less  $\Delta$  particle decay are included.

*ND280 Measurements, Flux and Common Cross Section fits.*—The ND280 detector measures a sample of inclusive CC events with a vertex in FGD1 located upstream of FGD2 and with the muon passing through TPC2. The event selection uses the highest-momentum negatively charged track entering TPC2 that matches a vertex inside the upstream FGD1 fiducial volume. In addition, the measured track energy loss in TPC2 must be compatible with a muon. Events originating from interactions in upstream detectors are vetoed by excluding events with a track in the TPC1 upstream of FGD1. This suppresses events with interactions occurring upstream of FGD1 or with a charged particle going backwards from FGD1 into TPC1. Using an inclusive CC selection, the efficiency is 47.6% with a purity of 88.1%. The main backgrounds are events where the neutrino interactions occur outside FGD1 and migrate into the fiducial volume due to mis-reconstruction, or from neutral particles interacting within the FGD1.

This CC inclusive sample is further subdivided into two mutually exclusive samples: a CCQE-enhanced sample and the remaining events which are called the CC-non-QE-enhanced sample (CCnQE). This separation is made to improve constraints on the neutrino flux and cross section parameters. The CCQE selection vetoes events with additional tracks that cross FGD1 and TPC2 or have electrons from muon decay found inside FGD1. After beam and data quality cuts, there are 5841 CCQE and 5214 CCnQE events that correspond to an integrated dataset of  $2.66 \times 10^{20}$  POT. These two data selections are each subdivided into 5(momentum)  $\times$  4(angular) bins which produces a 40-bin histogram used in a fit to the ND280 data.

The 40-bin histogram and cosmic ray control samples are fit to estimate the neutrino flux crossing ND280 in 11 bins of  $E_{\nu_\mu}$ , 7 common and 4 ND280 neutrino interaction parameters, detector response parameters, and their covariance. This ND280 fit also estimates the SK flux parameters, which are constrained through their prior covariance with the ND280 flux parameters as calculated by the beam simulation described earlier. The largest detector systematics are from the absolute track momentum scale, pion secondary interactions, and background



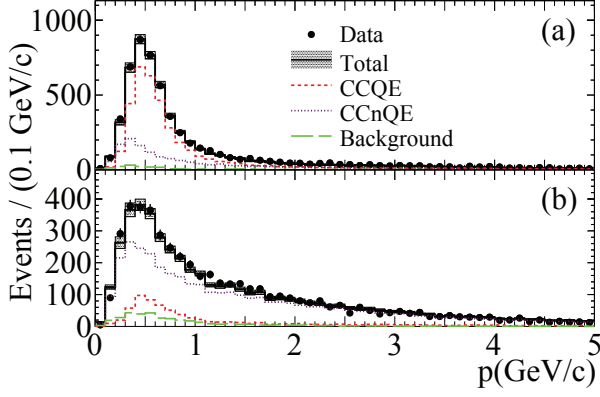


FIG. 1. The ND280 momentum data distributions of (a) the CCQE and (b) CCnQE-enhanced selections. The predicted total, CCQE, CCnQE and background event distributions from the ND280 fit are overlaid on both figures.

uncertainties. The reconstructed ND280  $\mu^-$  momentum distribution for CCQE and CCnQE selections and predicted event distributions from the ND280 fit to data is shown in Fig. 1. For the oscillation fits, the ND280 fit provides a systematic parameter error matrix which consists of 11  $E_{\nu_\mu}$  SK flux normalizations, 5  $E_{\bar{\nu}_\mu}$  SK flux normalizations and the 7 common neutrino interaction parameters. The fractional error on the predicted number of SK candidate events from the uncertainties in these 23 parameters, as shown in Table I, is 4.2%. Without the constraint from the ND280 measurements this fractional error would be 21.8%.

*SK Measurements.*—The SK far detector  $\nu_\mu$  candidate events are selected from fully-contained beam events. The SK phototube hits must be within  $\pm 500 \mu\text{s}$  of the expected neutrino arrival time, and there must be low outer detector activity to reject entering background. The events must also satisfy: visible energy  $> 30 \text{ MeV}$ , exactly one reconstructed Cherenkov ring,  $\mu$ -like particle ID, reconstructed muon momentum  $> 200 \text{ MeV}$ , and  $\leq 1$  reconstructed decay electron. The reconstructed vertex must also be in the fiducial volume (at least 2 m away from the ID walls). Criteria to remove “flasher” (intermittent light-emitting phototube) backgrounds are also applied. More details about the event selection and reconstruction in SK are found elsewhere [14].

Assuming a quasi-elastic interaction with a bound neutron and neglecting the Fermi motion, the neutrino energy is deduced from the detected muon and given by

$$E_{\text{reco}} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos \theta_\mu)}, \quad (2)$$

where  $p_\mu$ ,  $E_\mu$ , and  $\theta_\mu$  are the reconstructed muon momentum, energy, and the angle with respect to the beam direction, respectively;  $m_p$ ,  $m_n$ , and  $m_\mu$  are masses of the proton, neutron, and muon, respectively, and  $E_b = 27 \text{ MeV}$  is the average binding energy of a nucleon in

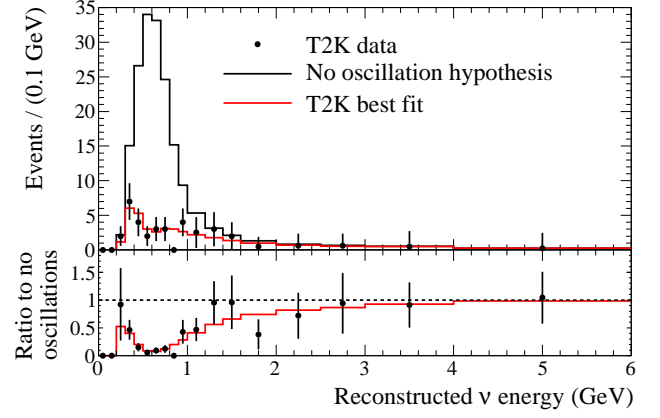


FIG. 2. The 58 event 1-ring  $\mu$ -like SK reconstructed energy spectrum. Top: The expected spectrum assuming no oscillations, and the best fit from the primary analysis for octant 1. The octant 2 best-fit spectrum is almost identical. Bottom: The ratio of the observed spectrum and best fit to no oscillations. The fit uses finer binning than is shown here.

$^{16}\text{O}$ . The  $E_{\text{reco}}$  distribution of the 58 events satisfying the selection criteria is shown in Fig. 2. The no-oscillation hypothesis prediction is the solid line in Fig. 2 and the MC expectation is  $205 \pm 17$  (syst.) events, of which 77.7% are  $\nu_\mu + \bar{\nu}_\mu$  CCQE, 20.7% are  $\nu_\mu + \bar{\nu}_\mu$  CCnQE, 1.6% are NC and 0.02% are  $\nu_e + \bar{\nu}_e$  CC. The expected resolution on reconstructed energy for  $\nu_\mu + \bar{\nu}_\mu$  CCQE events around the oscillation maximum is  $\sim 0.1 \text{ GeV}$ .

Eight SK detector systematic uncertainties are associated with event selection and reconstruction. The SK energy scale uncertainty is evaluated by comparing energy loss in data and MC for samples of cosmic-ray stopping muons and associated decay-electrons, as well as by comparing reconstructed invariant mass for data and MC for  $\pi^0$ s produced by atmospheric neutrinos. The other seven SK event-selection-related uncertainties are also evaluated by comparing MC and data results for atmospheric neutrino samples. The  $\nu_\mu + \bar{\nu}_\mu$  CCQE ring-counting-based selection uncertainty is evaluated in three energy bins, including correlations between energy bins. Other uncertainties result from additional  $\nu_\mu + \bar{\nu}_\mu$  CCQE selection criteria, as well as selection criteria (including ring-counting) for  $\nu_\mu + \bar{\nu}_\mu$  CCnQE,  $\nu_e + \bar{\nu}_e$  CC, and NC events. These uncertainties (8 parameters) produce a 10.1% fractional error on the expected number of SK events, as listed in Table I.

Systematic uncertainties on pion interactions in the target nucleus (FSI) and SK detector (SI) are evaluated by varying underlying pion scattering cross sections in the NEUT and SK detector simulations. These uncertainties are evaluated separately for  $\nu_\mu + \bar{\nu}_\mu$  CCQE in three energy bins,  $\nu_\mu + \bar{\nu}_\mu$  CCnQE,  $\nu_e + \bar{\nu}_e$  CC, and NC events. The total FSI+SI uncertainty (6 parameters) on the predicted SK event rate is 3.5% as listed in Table I.

*Oscillation Fits.*—The oscillation parameters are esti-

Source of uncertainty (no. of parameters)	$\delta n_{\text{SK}}^{\text{exp}} / n_{\text{SK}}^{\text{exp}}$
ND280-independent cross section (11)	6.3%
Flux & ND280-common cross section (23)	4.2%
Super-Kamiokande detector systematics (8)	10.1%
Final-state and secondary interactions (6)	3.5%
Total (48)	13.1%

TABLE I. Effect of  $1\sigma$  systematic parameter variation on the number of 1-ring  $\mu$ -like events, computed for oscillations with  $\sin^2(2\theta_{23}) = 1.0$  and  $|\Delta m_{32}^2| = 2.4 \times 10^{-3} \text{ eV}^2/\text{c}^4$ .

mated using a binned likelihood ratio to fit the SK spectrum in the parameter space of  $\sin^2(2\theta_{23})$ ,  $|\Delta m_{32}^2|$ , and all 48 systematic parameters,  $\mathbf{f}$ , by minimizing

$$\chi^2(\sin^2(2\theta_{23}), |\Delta m_{32}^2|; \mathbf{f}) = (\mathbf{f} - \mathbf{f}_0)^T \cdot \mathbf{C}^{-1} \cdot (\mathbf{f} - \mathbf{f}_0) + 2 \sum_{i=1}^{73} n_i^{\text{obs}} \ln(n_i^{\text{obs}}/n_i^{\text{exp}}) + (n_i^{\text{exp}} - n_i^{\text{obs}}). \quad (3)$$

$\mathbf{f}_0$  is a 48-dimensional vector with the prior values of the systematics parameters,  $\mathbf{C}$  is the  $48 \times 48$  systematic parameter covariance matrix,  $n_i^{\text{obs}}$  is the observed number of events in the  $i^{\text{th}}$  bin and  $n_i^{\text{exp}} = n_i^{\text{exp}}(\sin^2(2\theta_{23}), |\Delta m_{32}^2|; \mathbf{f})$  is the corresponding expected number of events. The sum is over 73 variable-width energy bins, with finer binning in the oscillation peak region. Oscillation probabilities are calculated using the full three neutrino oscillation framework. Normal mass hierarchy is assumed, octants 1 ( $\theta_{23} \leq \pi/4$ ) and 2 ( $\theta_{23} \geq \pi/4$ ) are separately fit, matter effects are included with an Earth density of  $\rho = 2.6 \text{ g/cm}^3$  [24], and other oscillation parameters are fixed at the 2012 PDG recommended values [25] ( $\sin^2(2\theta_{13}) = 0.098$ ,  $\Delta m_{21}^2 = 7.5 \times 10^{-5} \text{ eV}^2/\text{c}^4$ ,  $\sin^2(2\theta_{12}) = 0.857$ ), and with  $\delta_{CP} = 0$ .

The fit to the 58 events using Eq. 3 yields the best-fit point for octant 1(2) at  $\sin^2(2\theta_{23}) = 1.000(0.999)$  and  $|\Delta m_{32}^2| = 2.44(2.44) \times 10^{-3} \text{ eV}^2/\text{c}^4$ , with  $\chi^2/\text{ndf} = 56.04(56.03)/71$ . The best-fit neutrino energy spectrum is shown in Fig. 2. for octant 1; the best-fit spectrum for octant 2 is essentially identical. The point estimates of the 48 nuisance parameters are all within 0.35 standard deviations of their prior values.

The 2D confidence regions for the oscillation parameters  $\sin^2(2\theta_{23})$  and  $|\Delta m_{32}^2|$  are constructed using the constant  $\Delta\chi^2$  method [25]. The 68% and 90% contour regions are shown in Fig. 3 for both octant 1 and 2 separately. Since  $\theta_{13}$  is non-zero, the oscillation probability (Eq. 1) as a function of  $\sin^2(2\theta_{23})$  is different for octant 1 and 2 and this results in a contour that is wider in the  $\sin^2(2\theta_{23})$  direction for octant 2 than octant 1. Also shown in this figure are the 1D profile likelihoods for each oscillation parameter separately.

An alternative analysis employing a maximum likelihood fit was performed with the following likelihood func-

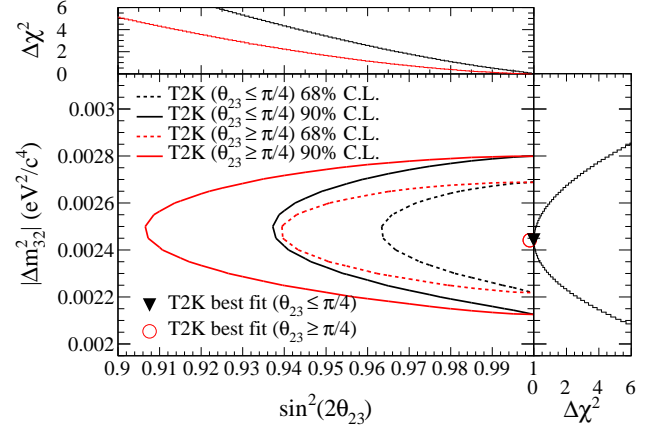


FIG. 3. The 68% and 90% C.L. contour regions for  $\sin^2(2\theta_{23})$  and  $|\Delta m_{32}^2|$  are shown for the primary analysis for octant 1 (black) and octant 2 (red). The 1D profile likelihoods for each oscillation parameter separately are also shown. The  $|\Delta m_{32}^2|$  1D profiles for both octants are identical.

tion:

$$\mathcal{L} = \mathcal{L}_{\text{norm}}(\sin^2(2\theta_{23}), |\Delta m_{32}^2|, \mathbf{f}) \times \mathcal{L}_{\text{shape}}(\sin^2(2\theta_{23}), |\Delta m_{32}^2|, \mathbf{f}) \mathcal{L}_{\text{syst}}(\mathbf{f}), \quad (4)$$

where  $\mathcal{L}_{\text{norm}}$  is the Poisson probability for the observed number of events,  $\mathcal{L}_{\text{shape}}$  is the likelihood for the reconstructed energy spectrum, and  $\mathcal{L}_{\text{syst}}$  is analogous to the first term in Eq. 3. The best-fit point for octant 1(2) is at  $\sin^2(2\theta_{23}) = 1.000(0.999)$  and  $|\Delta m_{32}^2| = 2.44(2.44) \times 10^{-3} \text{ eV}^2/\text{c}^4$ .

The primary and alternative analyses are consistent; the binned maximum fractional difference between best-fit spectra is 1.7%, and the confidence regions are almost identical.

A complementary analysis was performed, using Markov Chain Monte Carlo [25] methods to produce a sample of points in the full parameter space distributed according to the posterior probability density. This analysis uses both ND280 and SK data simultaneously, rather than separately fitting the ND280 and SK measurements; the likelihood is the product of the ND280 and SK likelihoods, with the shared systematics treated jointly. The maximum probability density is found to be  $\sin^2(2\theta_{23}) = 0.999$  and  $|\Delta m_{32}^2| = 2.45 \times 10^{-3} \text{ eV}^2/\text{c}^4$  for both octants, using a uniform prior probability distribution for the oscillation parameters. The contours from this analysis, evaluated separately for the two octants, are similar in shape and size to the two previously described analyses, but are not expected to be identical due to the difference between Bayesian and classical intervals. This analysis also has similar results to the ND280 data fit described previously and provides a cross check.

*Conclusions.*—Other recent experimental results are compared in Figure 4 to the T2K primary result (90% C.L. region) which is consistent with maximal mixing. In this paper the  $\nu_\mu$  disappearance analysis, based

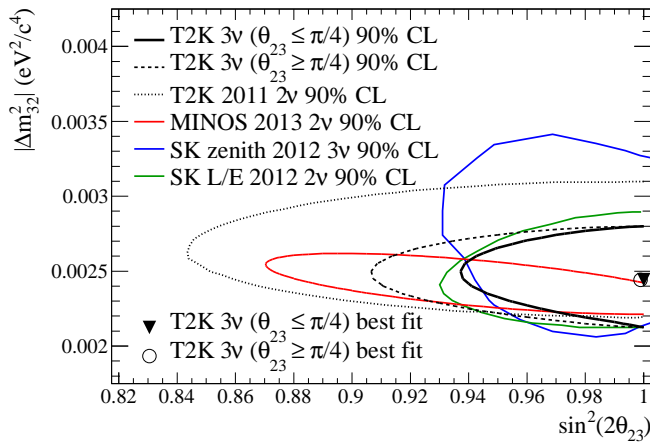


FIG. 4. The 90% C.L. contour regions for  $\sin^2(2\theta_{23})$  and  $|\Delta m^2_{32}|$  for the primary T2K analysis, are shown for octant 1 (solid) and octant 2 (dashed). The T2K 2011[2], SK[26], and MINOS[5] 90% C.L. contours with different flavor assumptions are shown for comparison.

on the  $3.01 \times 10^{20}$  POT off-axis beam exposure, has determined, assuming octant 1(2), a best-fit mass splitting of  $|\Delta m^2_{32}| = 2.44(2.44) \times 10^{-3} \text{ eV}^2/\text{c}^4$  and mixing angle,  $\sin^2(2\theta_{23}) = 1.000(0.999)$ . The results from either octant assumption favor maximal mixing. We anticipate future T2K data will improve our neutrino disappearance measurements, and our own measurements combined with

other accelerator and reactor measurements will lead to important constraints and more precise determinations of the fundamental neutrino mixing parameters.

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