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## Search for short baseline $\nu_e$ disappearance with the T2K near detector

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The T2K experiment has performed a search for  $\nu_e$  disappearance due to sterile neutrinos using  $5.9 \times 10^{20}$  protons on target for a baseline of 280 m in a neutrino beam peaked at about 500 MeV. A sample of  $\nu_e$  CC interactions in the off-axis near detector has been selected with a purity of 63% and an efficiency of 26%. The p-value for the null hypothesis is 0.085 and the excluded region at 95% C.L. is approximately  $\sin^2 2\theta_{ee} > 0.3$  for  $\Delta m_{\text{eff}}^2 > 7 \text{ eV}^2/c^4$ .

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## I. INTRODUCTION

In the last two decades, several experiments have observed neutrino oscillations compatible with the hypothesis of neutrino mixing in a three active flavors basis, described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [1,2]. Nevertheless, there exist experimental data that cannot be accommodated in this framework: the deficit of  $\nu_e$  originating from intense radioactive sources in the calibration of the solar neutrino gallium detectors SAGE [3,4] and GALLEX [5] and  $\bar{\nu}_e$  rates near nuclear reactors [6]. Those experiments cover  $L/E$  values of order 1 m/MeV, where  $L$  is the neutrino flight path and  $E$  is the neutrino energy, too large to observe any sizeable effect for the standard neutrino mass differences. These anomalies can be interpreted as neutrino oscillations if the PMNS matrix is extended by introducing a new sterile neutrino  $\nu_s$  (3 + 1 model) with a mass of order 1 eV/ $c^2$  [6,7]. The deficit would be due to  $\bar{\nu}_e \rightarrow \nu_s$  oscillations. The  $\nu_e$  beam component is studied at the ND280 near detectors of the T2K experiment [8] to search for  $\nu_e$  disappearance. The analysis presented here considers  $\nu_e \rightarrow \nu_s$  oscillations, given by the  $\nu_e$  survival probability in the approximation of two neutrino mass states:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{ee} \sin^2 \left( 1.267 \frac{\Delta m_{\text{eff}}^2 L}{E} \right) \quad (1)$$

where  $\sin^2 2\theta_{ee}$  is the oscillation amplitude,  $\Delta m_{\text{eff}}^2 [\text{eV}^2/c^4]$  is the mass squared difference between the new sterile mass state and the weighted average of the active standard mass states, with  $L[\text{m}]$  and  $E[\text{MeV}]$ .

While anomalous excesses that might be explained by  $\bar{\nu}_e$  appearance through sterile mixing have been observed by the MiniBooNE [9] and LSND [10] experiments, an explanation of all anomalies as sterile oscillations is disfavored due to tension between appearance and disappearance data [11–14]. In the absence of a consensus candidate model,

new probes using the simple 3 + 1 model may be able to provide some insights into the existing anomalies. This analysis assumes no  $\nu_\mu$  disappearance or  $\nu_e$  appearance.

With the given combination of  $L$  and  $E$ , this analysis is sensitive to  $\nu_e$  disappearance for  $\Delta m_{\text{eff}}^2 \gtrsim 2 \text{ eV}^2/c^4$  in a sample of  $\nu_e$  charged current (CC) interactions [15]. A likelihood ratio fit to the reconstructed neutrino energy spectrum of the  $\nu_e$  CC interactions is used to test the sterile neutrino hypothesis. A high purity sample of photon conversions from  $\pi^0$  decays is included in the fit to control the dominant background in the  $\nu_e$  sample. In addition, a selection of  $\nu_\mu$  CC interactions at ND280 is used to constrain the neutrino flux and cross section uncertainties in order to substantially reduce the uncertainties on the predicted  $\nu_e$  CC interaction rate.

## II. THE T2K EXPERIMENT

The T2K experiment uses a neutrino beam produced at the J-PARC facility in Japan to study neutrino oscillations and neutrino interactions [8]. Electron and muon neutrinos are produced from the decay of pions and kaons generated when a 30 GeV proton beam impinges on a graphite target. The detector ND280 sits 280 m from the proton target  $2.5^\circ$  from the primary proton beam direction (off-axis) and observes interactions of neutrinos from the beam, whose  $\nu_e$  component is peaked at an energy of 500 MeV. The present analysis uses neutrino interactions on a polystyrene scintillator or water inside two fine grained detectors (FGDs) [16] that corresponds to a total fiducial mass of about  $1.6t$ . Three time projection chambers (TPCs) [17] adjacent to the FGDs are used to identify particle type and momentum. Electromagnetic calorimeters (ECal) [18] that surround the FGDs/TPCs (the tracker) along the beam direction (barrel ECal) and downstream (DsECal) additionally separate electron showers from muon tracks. The  $\pi^0$  detector (POD) [19] is located upstream of the Tracker

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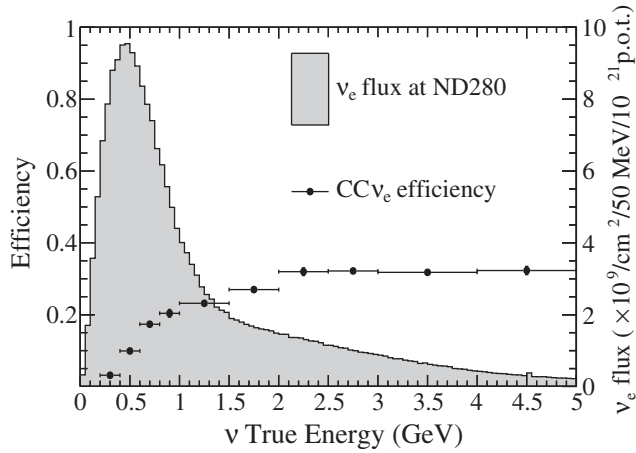


FIG. 1. Expected  $\nu_e$  flux at ND280 and CC  $\nu_e$  selection efficiency as a function of the true neutrino energy are shown.

region and is used to veto interactions outside the FGDs in this analysis.

The results presented in this analysis are based on data taken from January 2010 to May 2013 which corresponds to a total exposure at ND280 of  $5.9 \times 10^{20}$  protons on target (POT) with a horn configuration that enhances neutrinos and suppresses antineutrinos.

### III. $\nu_e$ FLUX AT ND280

The T2K beam is composed mostly of  $\nu_\mu$  with 6.2%  $\bar{\nu}_\mu$ , 1.1%  $\nu_e$  and 0.1%  $\bar{\nu}_e$  [20]. The  $\nu_e$  flux at ND280 as a function of the neutrino energy is shown in Fig. 1. The fluxes of  $\nu_e$  and  $\bar{\nu}_e$  are produced predominantly by  $K^\pm$  and  $K^0$  decays at high energies ( $E > 1$  GeV), and at low energies ( $E < 1$  GeV) mainly by  $\mu$  decay in flight [20].  $K^\pm$  and  $K^0$  tend to decay near the hadron production point due to their short mean lifetime, while  $\mu$ 's decay throughout the 96 m long decay volume, with a nearly flat decay length distribution. The  $\nu_e$  flight path distribution at ND280 is shown in Fig. 2. The average neutrino flight path, for  $\nu_e$  selected in the

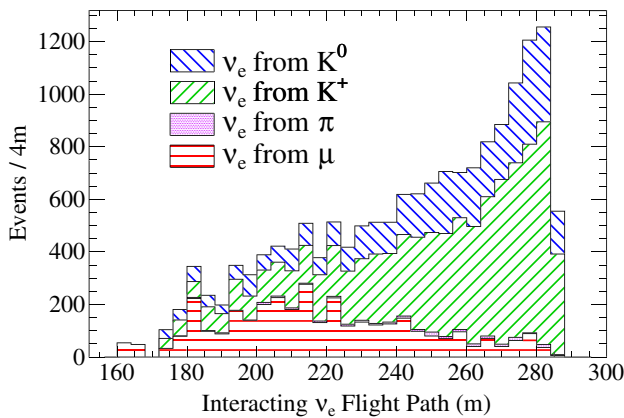


FIG. 2 (color online). Expected neutrino flight path for  $\nu_e$  interacting in the ND280 FV, broken down by the neutrino parent meson.

analysis, is 244 m. The fluxes at the near detectors are predicted using a full Monte Carlo simulation of the beam line and modeling of hadron production cross section based on experimental data from NA61/SHINE [21,22]. The uncertainties on the  $\nu_e$  and  $\bar{\nu}_e$  fluxes range from 10% to 20% as a function of energy, prior to using any additional information from the  $\nu_\mu$  CC interactions at ND280.

### IV. $\nu$ INTERACTIONS AT ND280

The target material of the  $\nu_e$  CC selection in the tracker is either water or a polystyrene scintillator. At T2K energies, the dominant CC interaction is the CC quasielastic (CCQE) scattering off neutrons ( $\nu_l n \rightarrow l^- p$ ), where a negative lepton  $l^-$  of the same flavor as the neutrino is created. At higher energies, neutrino CC interactions with pion production can take place. Those are CC resonant single  $\pi$  production (CCRES), coherent  $\pi$  production (CCCoh) and multi- $\pi$  production due to deep inelastic scattering (CCDIS). As the  $\nu_\mu$  flux is much larger than the  $\nu_e$  flux, the relative rate of  $\nu_\mu$  CC interactions is expected to be  $\sim 100$  times larger than the analysis signal,  $\nu_e$  CC interactions. Event selections in the tracker are designed to enhance the selection of  $\nu$ -carbon or  $\nu$ -oxygen interactions inside the FGD fiducial volume (FV).

The most important background for  $\nu_e$  interactions is  $\bar{\nu}_\mu$  CCDIS or neutral current (NC) interactions which produce a  $\pi^0$  ( $\nu_\mu N \rightarrow \pi^0 X$ ). The  $\pi^0$  predominantly decays to two photons and any electrons produced within the FV by  $\gamma \rightarrow e^+ e^-$  may be misidentified as originating from  $\nu_e$  CC interactions. Electrons in the FV may come from photons produced in  $\nu$  interactions outside of the FV (OOFV) or inside it.

The neutrino event generator NEUT [23] simulates the neutrino interactions at ND280. Uncertainties in the neutrino-nucleus cross section models and reinteractions of pions within the nucleus (*final state interaction*, or FSI) are estimated by comparing the NEUT prediction with external neutrino, pion and electron scattering data [24]. Each cross section is characterized using a minimal set of parameters with large prior uncertainties between 20% and 40%.

### V. FLUX AND CROSS SECTION CONSTRAINTS AT ND280

Assuming no  $\nu_\mu$  disappearance, a measurement of  $\nu_\mu$  CC interactions at ND280 is used to reduce the flux and the cross section uncertainties in the  $\nu_e$  signal prediction. This is possible due to the significant correlation between the  $\nu_\mu$  and  $\nu_e$  fluxes, originated from decays of the same hadron types. A similar technique is used in other T2K measurements [15,25]. Possible differences between  $\nu_e$  and  $\nu_\mu$  cross sections of up to 3%, due to radiative corrections or differences in the nucleon form factors [26], are included as a systematic error.

A predominantly  $\nu_\mu$  CC interaction event sample is selected by identifying the highest momentum negative track originating within the FV which is compatible with a muon. This is done by exploiting the tracking and particle identification capabilities of the TPCs. Based on the presence of charged pions, the  $\nu_\mu$ CC sample is further separated into three categories: events without pions (CC-0 $\pi$ ), events with one  $\pi^+$  (CC- $\pi^+$ ) and other interactions which produce a  $\pi^-$ ,  $\pi^0$  or more than one pion (CC-Oth). This provides sensitivity to the rate of  $\nu_\mu$  CCQE, CCRES and CCDIS interactions. The three samples are binned in muon momentum and angle and they are fitted to evaluate the neutrino flux and cross section uncertainties that are used as prior uncertainties in the  $\nu_e$  disappearance analysis.

## VI. ELECTRON NEUTRINO SELECTION AT ND280 AND SYSTEMATIC UNCERTAINTIES

A sample of  $\nu_e$  CC events is obtained by selecting electronlike events with the most energetic negatively charged track starting either in the FGD1 or FGD2 FV. Electron candidates are selected by combining the particle identification (PID) capabilities of the TPCs and ECal to reject 99.8% of muons.  $\pi^0$  backgrounds are reduced by rejecting events where a positive electronlike track is identified within 100 mm of the electron candidate and the  $e^+e^-$  invariant mass is smaller than 100 MeV/ $c^2$ . Additionally we require that there be no tracks in the detectors upstream of the interaction vertex to reject  $\nu_\mu N \rightarrow \pi^0 X$  interactions outside the FV.  $\nu_e$  CC interactions are selected with an overall efficiency of 26% (see Fig. 1) and a purity of 63%. The majority of the background (72%) is electrons from conversion of  $\pi^0$  decay photons ( $\nu_\mu N \rightarrow \pi^0 X$ ). The remaining background is from neutrino interactions where muons (14%) or protons and pions (14%) are misidentified as electrons. A significant component of the background (35%) is due to particles produced outside the FV, as in the magnet, dead materials of the FGDs and TPCs, ECal, P0D or surrounding material. Those neutrino interactions occur on heavier nuclei (e.g. iron, aluminium, lead) with larger cross section uncertainties (30%). This background is large at low energy.

A control sample is used to measure the  $\nu_\mu N \rightarrow \pi^0 X$  background. It is selected by requiring two electronlike tracks in the TPC with a common vertex in the FGD (distance between the starting points of the two tracks less than 10 mm) and invariant mass less than 50 MeV/ $c^2$ . The control sample has an overall selection efficiency with respect to the total number of photons converting in the FGDs of about 12% and is a highly pure background sample predominantly consisting of photon conversion (92%) from  $\nu_\mu N \rightarrow \pi^0 X$  in NC and CCDIS interactions. The kinematics of the photons in the control and signal samples are similar. Furthermore, 62% of the control

sample  $\nu_\mu$  events are OOFV  $\nu_\mu N \rightarrow \pi^0 X$ , which provides a direct constraint for the  $\nu_e$  sample background. A more detailed description of the selection of both the  $\nu_e$  and the control samples is reported in [15].

The reconstructed  $\nu_e$  energy spectrum ( $E_{\text{reco}}$ ), assuming a CCQE interaction, is inferred from the outgoing electron candidate momentum and angle, as in [27].  $\nu_e$  disappearance would affect the rate and energy spectrum of  $\nu_e$  CC interactions. Figure 3 shows the  $E_{\text{reco}}$  distributions of the  $\nu_e$  and the control samples. A total of 614  $\nu_e$  CC candidates are selected in the  $\nu_e$  sample and  $665 \pm 51$  (syst) events are expected, assuming no oscillation and with the systematic uncertainties described below. The number of selected events in the control sample is 989 in data, with

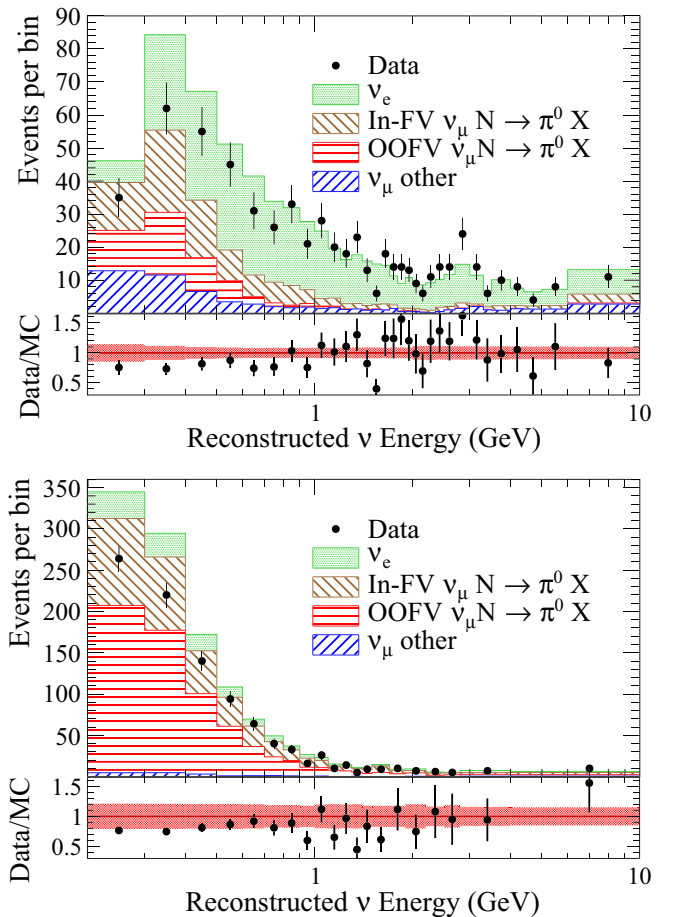


FIG. 3 (color online). Reconstructed energy distributions of the  $\nu_e$  (top) and control (bottom) samples. The distributions are broken down by  $\nu_e$  interactions (signal), background inside the fiducial volume due to  $\nu_\mu N \rightarrow \pi^0 X$  (In-FV  $\nu_\mu N \rightarrow \pi^0 X$ ), background outside the fiducial volume due to  $\nu_\mu N \rightarrow \pi^0 X$  (OOFV  $\nu_\mu N \rightarrow \pi^0 X$ ) and all other sources of background ( $\nu_\mu$  other). Both  $\nu$  and  $\bar{\nu}$  are included in the samples. The ratio of the data to the MC expectation in the null oscillation hypothesis is shown for both samples. The red error band corresponds to the fractional systematic uncertainty. Black dots represent the data with the statistical uncertainty.

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TABLE I. Fractional variation (rms/mean in %) of the expected total number of events for  $\nu_e$  (all events and signal only) and control sample in the null oscillation hypothesis due to the effect of the systematic uncertainties. Existing correlations between systematics are taken into account.

Error source (# parameters)	$\nu_e$ sample (sig + bkg)	$\nu_e$ sample (sig only)	Control sample
$\nu_\mu$ - $\nu_e$ common (40)	4.4	5.2	6.7
Unconstrained (5)	3.7	3.0	17.9
Detector+FSI (10)	5.1	5.5	5.5
Total (55)	7.6	8.1	19.9

an expectation of  $1236 \pm 246$  (syst). Systematic uncertainties on the flux, cross section and detector response are taken into account using the approach adopted in [15]. The systematic uncertainties on the flux and  $\nu_e$ - $\nu_\mu$  common cross sections are constrained by fitting the  $\nu_\mu$  CC sample as described earlier. The unconstrained cross-section systematic uncertainties include several contributions: the difference between the interaction cross section of  $\nu_\mu$  and  $\nu_e$ , between  $\nu$  and  $\bar{\nu}$  and the uncertainty on OOFV interactions. FSI uncertainties contribute 1.5% (2.7%) to the  $\nu_e$  ( $\nu_\mu N \rightarrow \pi^0 X$ ) sample systematic uncertainty. The detector systematic uncertainties have been evaluated independently for the TPCs, FGDs and ECal. The largest sources of uncertainties are given by the TPC momentum resolution and the PID. In Table I, the effect of each group of systematic uncertainties on the total expected number of signal and signal plus background events is shown. In Fig. 3 the effect of the systematic uncertainties on the  $E_{\text{reco}}$  distributions is shown. The simulation overestimates the data in both the  $\nu_e$  and control sample distributions at low energy. However this overestimation in the control sample is within 1 standard deviation of expectation.

## VII. OSCILLATION FIT

The sterile oscillation parameters  $\sin^2 2\theta_{ee}$  and  $\Delta m_{\text{eff}}^2$  are estimated with a Poisson binned likelihood ratio method. The expected reconstructed neutrino energy distributions are compared to data with a simultaneous fit to the selected  $\nu_e$  and control samples. The range of  $E_{\text{reco}}$  is from 0.2 GeV to 10 GeV. The oscillation amplitude  $\sin^2 2\theta_{ee}$  is restricted to the physical region. The effect of systematic uncertainties is included in the fit with nuisance parameters (55 in total) constrained by a Gaussian penalty term. The oscillation probability Eq. (1) affects  $\nu_e$  signal events based on the true neutrino energy and flight path.

The best-fit oscillation parameters are  $\sin^2 2\theta_{ee} = 1$  and  $\Delta m_{\text{eff}}^2 = 2.05 \text{ eV}^2/c^4$ . The  $\chi^2/ndf$  is 42.16/49. Most of the best-fit systematic parameters are within a  $0.5\sigma$  deviation and always within  $1\sigma$  from the prior values. The systematic parameter corresponding to the normalization

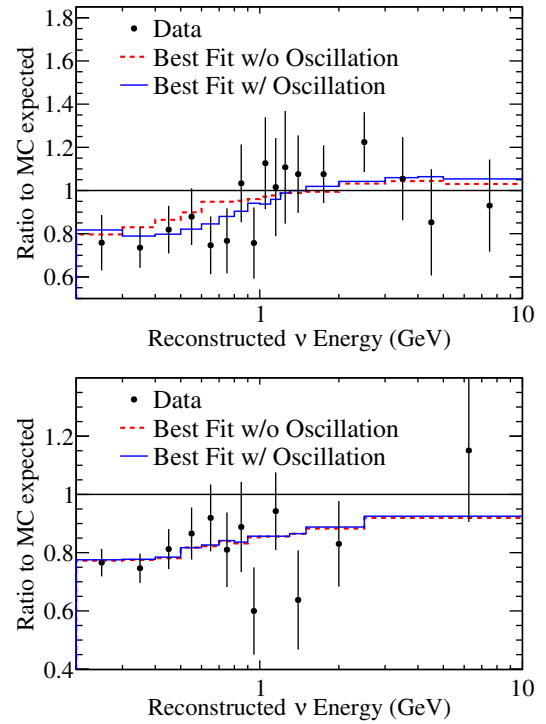
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FIG. 4 (color online). The ratio of the best-fit spectrum to the expected MC distribution, where the fit includes nuisance and oscillation parameters (blue) and nuisance parameters only (red dashed), is shown. The plots show the  $\nu_e$  sample (top) and the control sample (bottom). The black line corresponds to the expected nonoscillated MC before the fit. The black dots show the data. Statistical uncertainties are shown.

of the  $\nu_\mu N \rightarrow \pi^0 X$  OOFV component is reduced by 31% ( $\sim 1\sigma$ ) due to the deficit at low energy in the control sample. If neutrino oscillations are not considered, the parameter is reduced by approximately the same amount, since the

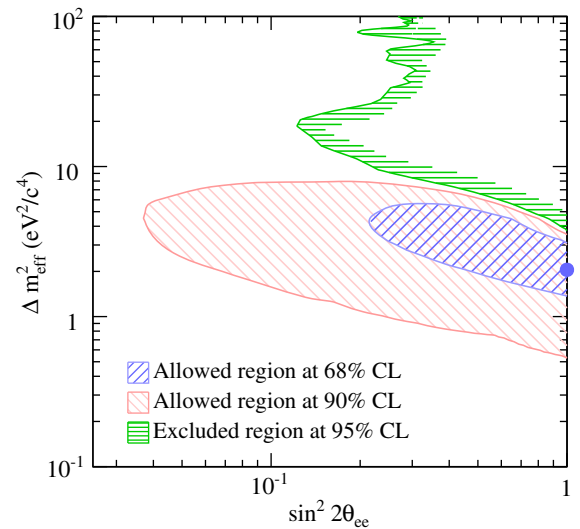


FIG. 5 (color online). 68% and 90% C.L. allowed regions and 95% C.L. exclusion region for the  $\sin^2 2\theta_{ee}$ - $\Delta m_{\text{eff}}^2$  parameters measured with the T2K near detector.

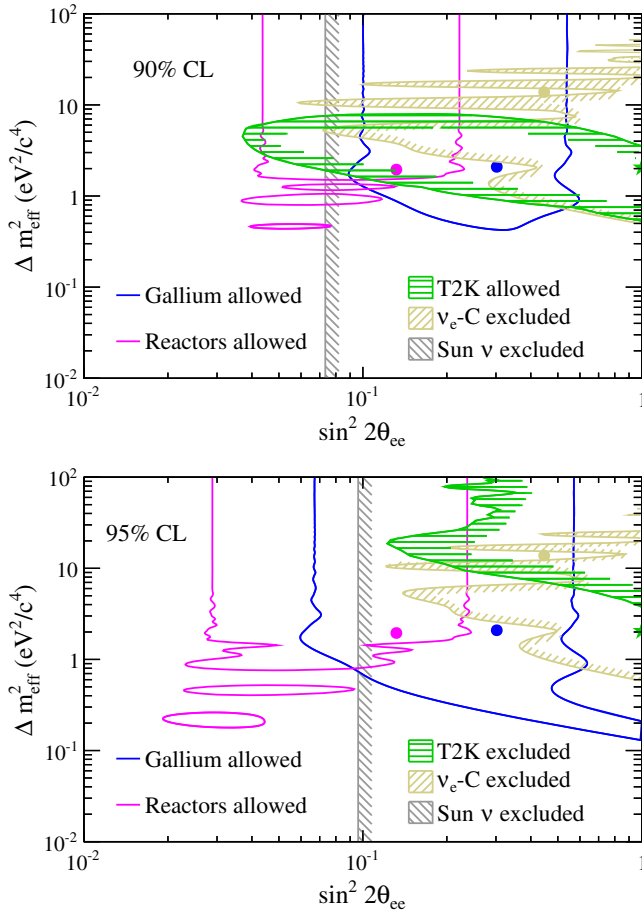


FIG. 6 (color online). The T2K confidence interval in the  $\sin^2 2\theta_{ee}$ - $\Delta m_{\text{eff}}^2$  parameter space at 90% C.L. (top) and 95% C.L. (bottom) is compared with the other experimental results available in literature: allowed regions of gallium and reactor anomalies and excluded regions by  $\nu_e$ -carbon interaction data and solar neutrino data [14]. The T2K best fit is marked by a green star; the best fit of other experimental results corresponds to circles of the same coloring as the limits. In the region  $\Delta m_{\text{eff}}^2 < 0.2 \text{ eV}^2/\text{c}^4$  limits on the mixing angle  $\sin^2 2\theta_{ee}$  have also been set by the Daya Bay experiment [48].

control sample contains a small fraction of electron neutrinos and is therefore independent of oscillations. The ratio between the best-fit and the expected nonoscillated MC distributions is shown as a function of  $E_{\text{reco}}$  for both the  $\nu_e$  and the control samples in Fig. 4. The best fit, where the nuisance parameters are allowed to float while the oscillation parameters are fixed to null, is also shown. The corresponding  $\chi^2/\text{ndf}$  is 45.86/51.

The two-dimensional confidence intervals in the  $\sin^2 2\theta_{ee}$ - $\Delta m_{\text{eff}}^2$  parameter space are computed using the Feldman-Cousins method [28]. The systematic uncertainties are incorporated using the method described in [29]. The 68%, 90% and 95% confidence regions are shown in Fig. 5. The exclusion region at 95% C.L. is approximately given by  $\sin^2 2\theta_{ee} > 0.3$  and  $\Delta m_{\text{eff}}^2 > 7 \text{ eV}^2/\text{c}^4$ .

The p-value of the null oscillation hypothesis, computed using a profile likelihood ratio as a test statistic, is 0.085.

The impact of  $\nu_\mu$  disappearance and  $\nu_e$  appearance on the present result is estimated by considering a non-null  $\sin^2 2\theta_{\mu\mu}$  in the  $3+1$  model. For  $\sin^2 2\theta_{\mu\mu}$  between 0 and 0.05, approximately the region not excluded by other experiments [11,30], the 95% C.L. exclusion on  $\sin^2 2\theta_{ee}$  moves by less than 0.1.

In Fig. 6 the T2K confidence region at 90% and 95% C.L. is compared with  $\nu_e$  disappearance and reactor anomaly regions from the gallium anomaly and reactor anomaly. The excluded regions from  $\nu_e + {}^{12}\text{C} \rightarrow {}^{12}\text{N} + e^-$  scattering data of KARMEN [31,32] and LSND [33] experiments and solar neutrino and KamLAND data [34–46] are also shown. The T2K result excludes part of the gallium anomaly and a small part of the reactor anomaly allowed regions. The current T2K limit at 95% C.L. is contained within the region excluded by the combined fit of the solar and KamLAND data. Another analysis which combines the solar neutrino data with the reactor neutrino data shows weaker limits on  $\sin^2 2\theta_{ee}$  [47].

## VIII. CONCLUSIONS

T2K has performed a search for  $\nu_e$  disappearance with the near detector. The excluded region at 95% C.L. is approximately  $\sin^2 2\theta_{ee} > 0.3$  and  $\Delta m_{\text{eff}}^2 > 7 \text{ eV}^2/\text{c}^4$ . The p-value of the null oscillation hypothesis is 0.085. Further data from T2K will reduce the statistical uncertainty, which is still an important limitation for the analysis.

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