Precision measurement of ν_μ disappearance by T2K

Erez Reinherz-Aronis

Colorado State University, Fort Collins, Colorado, USA

DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-04/165

T2K is a long-baseline neutrino oscillation experiment, where a muon neutrino beam is produced at the J-PARC facility and after traveling 295 km it is detected by Super-Kamiokande, a water Cherenkov detector with a 22.5 kton fiducial mass. One aim of the experiment is to precisely determine the mixing angle θ_{23} and the mass squared difference Δm^2_{23} using a measurement of muon neutrino disappearance. The T2K accumulated dataset is 6.57×10^{20} protons on target, which is 8% of the experimental goal. Here we present an analysis of the T2K muon neutrino disappearance data and the worlds best constraint on the value of the mixing angle θ_{23} obtained by this analysis.

1 Introduction

Neutrinos can be characterized by two different eigenstates states: Flavor eigenstates and Mass eigenstates. On one hand neutrinos production and detection is described by their flavor eigenstates, on the other hand neutrinos propagation through space is determined by their mass eigenstates. The relation between the flavor and mass states is given by the PMNS matrix [1, 2, 3, 4], which is a 3×3 unitary matrix, parametrized by 3 mixing angles and one phase. Moreover, it can be written as a multiplication of three 2D rotation matrixes. This commonly representation have been driven by the challenge to detect neutrinos.

The PMNS matrix has been tested by various experiments, different techniques, with different neutrino sources (such as solar, atmospheric, accelerator/reactor) and has been found to describe the relation between Flavor and Mass states to a good accuracy.

The probability of a muon neutrino with energy E_ν to remain a muon neutrino after traveling a distance L is given by

$$P(\nu_\mu \rightarrow \nu\mu) \;\simeq\; 1 - 4\,\cos^2\theta_{13}\,\sin^2\theta_{23} \cdot \left[1 - \;\cos^2\theta_{13} \cdot \sin^2\theta_{23}\right] \cdot \sin^2(1.267\Delta m^2 L/E_\nu) \qquad (1)$$

where θ_{13} and θ_{23} are the PMNS mixing angles and $\Delta m^2(eV^2/c^4)$ is the neutrino mass-squared splitting. We note that the PMNS matrix depends on the difference between the neutrino masses (Δm^2) not on their absolute masses. Hence the absolute neutrino mass ordering is unknown. This is called the mass hierarch problem in neutrinos. In the case of three neutrinos there are two ways to order the masses, i.e the Normal Hierarchy (NH) and the Inverted Hierarchy (IH). In Eq. (1) the mass-squared split depends on the mass order and is $\Delta m^2_{32} = m^2_3 - m^2_2$

for the NH and $\Delta m^2_{13} = m^2_1 - m^2_3$ for the IH.

In these proceedings we present the recent T2K muon neutrino disappearance oscillation measurement with an accumulated data of 6.57×10^{20} protons on target (POT). This data has doubled since our previous measurement [5] and utilized the new near-detector selections samples which better constrain the measured neutrino charged current (CC) interactions.

2 T2K

Tokai-to-Kamioka (T2K) [6] is a neutrino oscillation experiment, located in Japan, with a baseline of 295 km. The experiment consists of a neutrino beam produced by the J-PARC lab, a near detector complex 280 m downstream of the target (ND280), and the well known Super-Kamiokande (SK) as its far detector (Figure (1) shows a profile of the T2K experiment setup) The neutrino beam is produced by colliding 30 GeV protons with a thick graphite target,

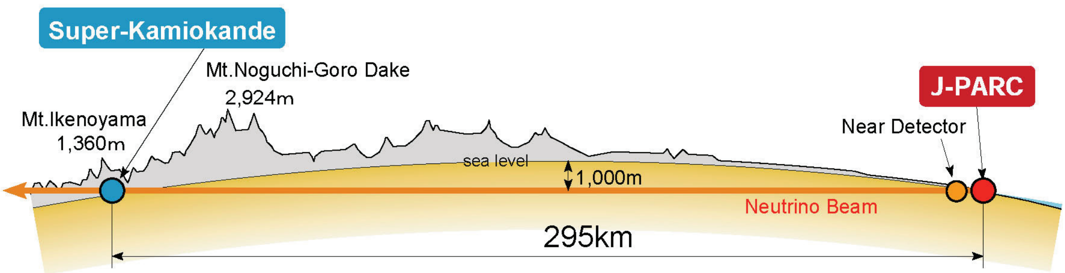

Figure 1: A schematic of a neutrinos traveling from the neutrino beamline at J-PARC, through the near detectors (green dot) which are used to determine the properties of the neutrino beam, and then 295 km underneath the main island of Japan to Super-Kamiokande.

creating charged mesons. The charged pions and kaons are then focused towards the axis of the proton beam by three magnetic horns and are directed into a decay volume, where they decay in-flight to muon neutrinos.

T2K is an off-axis experiment, where its beam is directed 2.5˙ away from the target-SK line, this results and with neutrino energies that are peaked around the oscillation maximum (∼650 MeV) [7] and a smaller high energy tail, which are one of the main sources of backgrounds.

In the near detector complex the direction and stability of the beam is monitored by the on-axis INGRID detector [8]. The ND280 off-axis detectors [6], which have a similar opening angle as SK from the beam, are design to measure the unoscillated beam flux and energy spectrum for the SK (far detector) oscillation measurements.

3 Oscillation Analysis

The T2K analysis extracts the oscillation parameters using the near and far detector measurements. The near detector primarily measures and constrains the produced neutrino flux in order to predict the unoscillated neutrino rate at the far detector. Then the neutrino disappearance is determined by comparing the observed far detector neutrino rates to the predicted unoscillated neutrino rates. Fig. 2 shows the unoscillated expected numbers of events (blue) and the measured number of events (black) as a function of the neutrino energy. The far detector

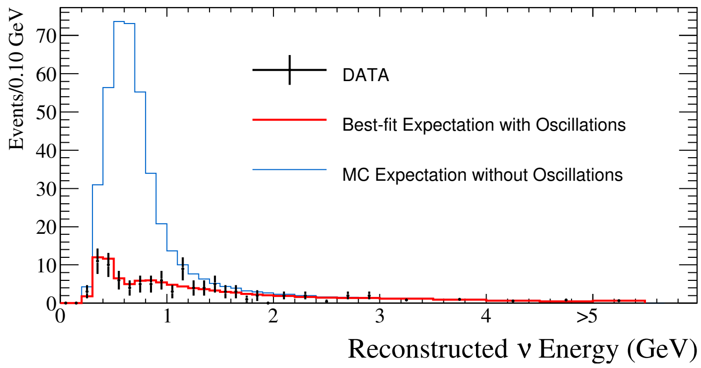

Figure 2: Reconstructed ν energy spectrum at the far detector for data (black), best-fit MC spectrum (red), and spectrum without oscillations (blue).

predictions depend on the input oscillation parameters, the unoscillated incident neutrino flux, the neutrino interaction cross sections and the detector response. A measurement of ν_μ CC events in ND280 is used to tune both the initial flux estimates and parameters of the neutrino interaction models. The measurement also estimates the uncertainties in the predicted neutrino spectrum at the far detector.

In this analysis, the ND280 measurement provides better constraints on the flux and interaction model parameters by using improved event selections, reconstruction, and higher ND280 statistics. This enhanced was achieved by dividing CC events into three categories based on the number of pions in the final state (for more detailed please see J. Perkin in these proceedings).

Source of uncertainty (number of parameters)	$\delta n_{SK}^{exp}/n_{SK}^{exp}$
ND280-independent cross section (11)	4.9%
Flux and ND280-common cross section (23)	2.7%
SK detector and FSI+SI systematics (7)	5.6%
$\sin^2\theta_{13}, \sin^2\theta_{12}, \Delta m^2_{21}, \delta_{CP}$	0.2%
Total (45)	8.1%

Table 1: The effect of 1 σ systematic parameter variation on the number of μ-like events, computed for oscillations with $\sin^2\theta_{23} = 0.5$ and $|\Delta m^2_{32}| = 2.40 \times 10^{-3}$ eV^2/v^4.

We estimated oscillation parameters using an unbinned maximum likelihood fit to the SK spectrum for the parameters $\sin^2\theta_{23}$ and either Δm^2_{32} or Δm^2_{13} for the NH and IH respectively. Oscillation probabilities are calculated using the full three-flavor oscillation framework with the other oscillation parameters are fit with constraints $\sin^2\theta_{13} = 0.0251 \pm 0.0035$, $\sin^2\theta_{12} = 0.312 \pm 0.016$, and $\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5} \mathrm{eV}^2/\mathrm{c}^4$ [9]. In addition, we have fitted 45 nuisance parameters (systematic uncertainties related to flux, cross section, final state nuclear effects and detector performance) which are summarized in Table 1 for the different uncertainties categories. Fig. 3 presents the ratio of the observed spectrum (points) to the unoscillation hypothesis, and our best fit (solid red line) to the data.

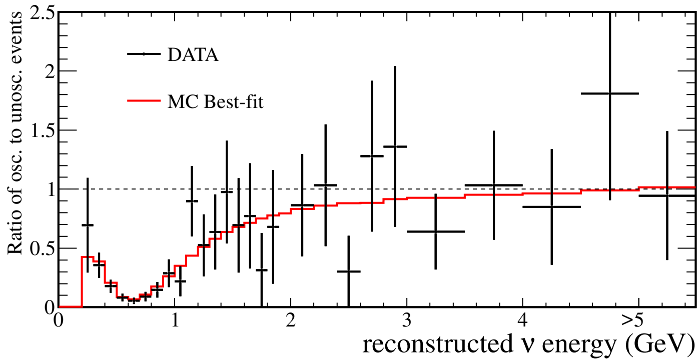

Figure 3: Ratio of far detector neutrino rates over the unoscillated neutrino rates as a function of neutrino energy for data (points) and MC expectations (red line) using the best-fitted neutrino parameters.

In Fig. 4 we present both the 68% and 90% C.L. confidence regions which were achieved using a Feldman-Cousins [12] and Cousins-Highland [13] alike methods which marginalizes over the second oscillation parameter. These limits are overlaid and compared to both MINOS [11] (hatch brown) and SK-atmospheric [10] (hatch blue) disappearance results.

4 Conclusion

T2K has made the most precise measurement of $\sin^2\theta_{23}$ using a data set based on 6.57×10^{20} POT. This measurement of $\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$ ($\sin^2\theta_{23} = 0.511 \pm 0.055$) for the NH (IH) is consistent with maximal mixing. The best-fit mass-squared splitting is $\Delta m^2_{32} = 2.51 \pm 0.10$ ($\Delta m^2_{32} = 2.48 \pm 0.10$) $\times 10^{-3} \mathrm{eV}^2/\mathrm{c}^4$ for the case of the NH (IH).

References

[1] B. Pontecorvo, Sov. Phys. JETP **6**, 429 (1957) [Zh. Eksp. Teor. Fiz. **33**, 549 (1957)].

[2] B. Pontecorvo, Sov. Phys. JETP **7**, 172 (1958) [Zh. Eksp. Teor. Fiz. **34**, 247 (1957)].

[3] B. Pontecorvo, Sov. Phys. JETP **26**, 984 (1968) [Zh. Eksp. Teor. Fiz. **53**, 1717 (1967)].

[4] Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. **28**, 870 (1962).

[5] K. Abe *et al.* [T2K Collaboration], Phys. Rev. Lett. **111**, no. 21, 211803 (2013) [arXiv:1308.0465 [hep-ex]].

[6] K. Abe *et al.* [T2K Collaboration], Nucl. Instrum. Meth. A **659**, 106 (2011) [arXiv:1106.1238 [physics.ins-det]].

[7] K. Abe *et al.* [T2K Collaboration], Phys. Rev. D **87**, 012001 (2013) [arXiv:1211.0469 [hep-ex]].

[8] K. Abe, N. Abgrall, Y. Ajima, H. Aihara, J. B. Albert, C. Andreopoulos, B. Andrieu and M. D. Anerella *et al.*, Nucl. Instrum. Meth. A **694**, 211 (2012) [arXiv:1111.3119 [physics.ins-det]].

[9] J. Beringer *et al.* [Particle Data Group Collaboration], Phys. Rev. D **86**, 010001 (2012).

[10] A. Himmel [Super-Kamiokande Collaboration], AIP Conf. Proc. **1604**, 345 (2014) [arXiv:1310.6677 [hep-ex]].

[11] P. Adamson *et al.* [MINOS Collaboration], Phys. Rev. Lett. **112**, 191801 (2014) [arXiv:1403.0867 [hep-ex]].

[12] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998) [physics/9711021 [physics.data-an]].

[13] R. D. Cousins and V. L. Highland, Nucl. Instrum. Meth. A **320**, 331 (1992).

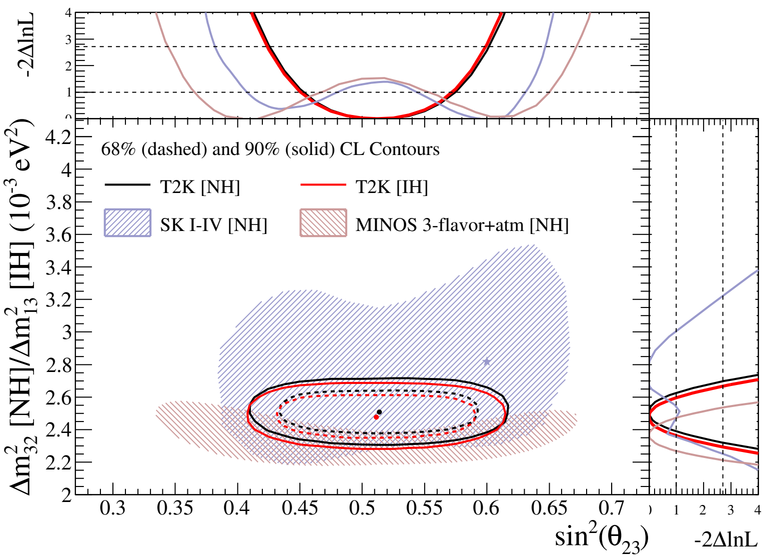

Figure 4: The 68% and 90% C.L. confidence regions for $\sin^2\theta_{23}$ and Δm^2_{32} (NH) or Δ^2_{13} (IH). The SK [10] and MINOS [11] 90% C.L. regions for NH are shown for comparison.