PROCEEDINGS OF SCIENCE

Neutrino Physics Results from T2K with 2.62×10^{21} protons on target

E. D. Zimmerman[*][†]
University of Colorado
UCB 390, Boulder, Colo. 80309 USA
E-mail: edz@colorado.edu

T2K is an accelerator-based long-baseline neutrino oscillation experiment at the J-PARC 30 GeV proton synchrotron; T2K's far detector is Super-Kamiokande. Operating since 2010, T2K has made the first observation of $\nu_\mu \to \nu_e$ oscillations and made precise measurements of the oscillation parameters in the Δm^2_{32} oscillation sector. T2K's current (2018) results and plans for the future are presented.

Neutrino Oscillation Workshop (NOW2018)
9 - 16 September, 2018
Rosa Marina (Ostuni, Brindisi, Italy)

[*]Speaker.
[†]for the T2K Collaboration

PoS(NOW2018)001

1. T2K

The Tokai-to-Kamioka (T2K) [1] project is a long-baseline neutrino oscillation experiment based in Japan. T2K uses the J-PARC Main Ring proton synchrotron's 30 GeV (kinetic energy) proton beam to create an intense horn-focused neutrino source directed 2.5° off-axis from the Super-Kamiokande (SK) [2] large underground water Cherenkov detector. The experiment also includes a set of near detectors 280 m from the primary interaction target (ND280 and INGRID) for constraining the predicted event rates, beam monitoring, and cross-section physics. T2K, commissioned in 2010, had as its original goal the search for $\nu_\mu \to \nu_e$ oscillations. Since discovering this oscillation mode in 2013 [3], T2K has gone on to make precise measurements of Δm^2_{32} and θ_{23} via ν_μ disappearance [4, 5] and has more recently produced combined oscillation parameter fits from all observed neutrino flavors and the first δ_{CP} exclusions [6].

2. Data collection runs

T2K's first physics data collection was in 2010. Since then, 3.16×10^{21} protons on target have been delivered, with more than half accumulated since summer 2016 (Fig. 1). Approximately half the operation has been in antineutrino (reverse horn current) mode, with antineutrino statistics doubled since fall 2017. (The oscillation results here, however, include only 1.12×10^{21} protons on target in antineutrino mode.) T2K's beam power has steadily increased, and in recent years operation at 485 kW has been typical.

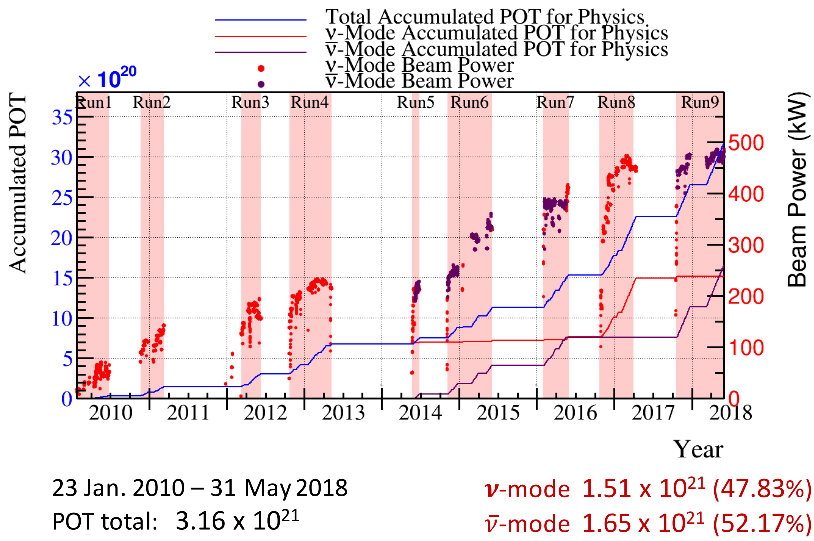

Figure 1: Beam delivery for T2K, 2010-2018.

3. Modeling flux and cross-sections

Oscillation measurements require precise knowledge of both the neutrino flux and the neutrino interaction. T2K's near detector constraints reduce but do not eliminate flux and cross-section uncertainties. Models are used to implement the ND280 constraints on the parameters and extrapolate the constraints to the far-detector event rate predictions. T2K fits parameters for the flux and cross-section models to the reconstructed ND280 data, and then extrapolates to predict event rates in SK. The ND280 ν_μ charged-current data consist of fourteen separate samples: in neutrino mode, samples are segregated by number of pions (zero, one, or more than one) and vertex location in either carbon- or oxygen-rich targets. In antineutrino mode, events are separated by vertex target, muon charge, and number of tracks (one or more than one).

3.1 Flux model

The T2K neutrino flux model [7, 8] is based on input from Monte Carlo generators modified by the results of external hadron production measurements. The most significant constraints come from the NA61/SHINE experiment at CERN, which has measured hadron production yields for thin targets [9] as well as a replica of the T2K target [10] in a 30 GeV proton beam.

3.2 Neutrino interaction model

Neutrino interactions are modeled using a relativistic Fermi gas (RFG) model with a dipole form factor. For 1p1h (scattering off a single nucleon), we use Random Phase Approximation parameters [11] applied to our RFG model. For 2p2h (scattering off correlated nucleon pairs) we use the model of Nieves *et al.* [11]. Single-pion production is modeled using the model of Rein and Sehgal [12] normalized to deuterium-target bubble-chamber data [13, 14] and recent data on coherent pion production from the MINERvA experiment [15]. Deeply inelastic scattering is a minor source of events in T2K, and is modeled through PYTHIA 5.9 [16]. Final state interactions are modeled using two models [17, 18] tuned to external pion-nuclear scattering data.

4. Far-detector event selection

The oscillation event selections in the far detector identify ν_μ and ν_e events with a single reconstructed Cherenkov ring. These require an event during the neutrino beam pulse, fully contained in SK's inner detector and passing fiducial cuts, an identified muon or electron, a visible energy greater than 30 MeV, and a reconstructed energy less than 1.25 GeV/c^2 under a quasielastic hypothesis. For electron candidates, the events must have zero stopped-muon-decay electrons; for muon neutrinos they may have zero or one. These requirements are the same for neutrino and antineutrino samples. An additional sample in neutrino mode only consists of ν_e candidates with one decay electron. These are reconstructed under a $\nu_e + N \to e^- + \pi^+ + N'$ hypothesis where the π^+ is assumed to be below Cherenkov threshold. (No equivalent selection exists for antineutrinos, since the π^- that would result is captured by a nucleus before decaying.)

In the past two years, the SK event reconstruction and event selection has been upgraded with a new maximum-likelihood-based algorithm [19]. This algorithm has improved particle identification performance and has allowed an increase in the effective fiducial volume of the detector, increasing the acceptance by 22% for electron neutrino appearance events. In the future, this new algorithm will allow the incorporation of event samples with multiple reconstructed rings.

5. Oscillation results

T2K's oscillation results with 2.2×10^{21} protons on target were published [20] in July 2018. The current update, to 2.62×10^{21}, primarily represents additional antineutrino data. These results are based on 243 (1211.4) ν_μ and 90 (20.3) ν_e candidates (of which 15 (4.8) are $e^- + \pi^+$ candidates with a decay electron) in neutrino mode, and 102 (314.3) $\bar{\nu}_\mu$ and 9 (4.820) $\bar{\nu}_e$ candidates in antineutrino mode. The numbers in parentheses are the no-oscillation predictions for these numbers. The oscillation fit procedures are essentially unchanged from the 2018 publication.

5.1 The 2-3 sector

Fits to the 2-3 sector parameters, driven primarily by ν_μ disappearance, continue to favor maximal mixing ($\theta_{23} = 45°$). The best fit parameters in the normal mass ordering case are $\sin^2\theta_{23} = 0.536$ and $\Delta m^2_{32} = 2.434 \times 10^{-3}$ eV^2. In the inverted ordering, the best fit parameters are $\sin^2\theta_{23} = 0.536$ and $\Delta m^2_{13} = 2.410 \times 10^{-3}$ eV^2. The 90% and 68% confidence contours for these parameters are shown in Fig. 2.

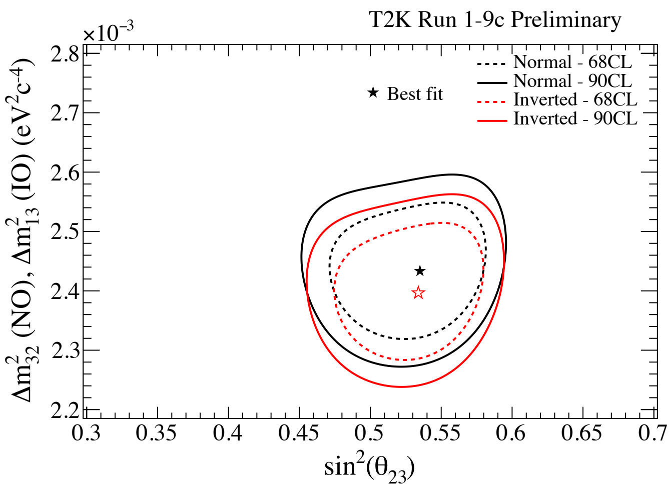

Figure 2: T2K best fit, 68%, and 90% confidence level contours for 2-3 sector oscillation parameters.Each contour is plotted with respect to the minimum under that mass ordering assumption.

5.2 The 1-3 sector and *CP* violation

The $\nu_e/\bar{\nu}_e$ appearance mode allows T2K to measure $\sin^2(\theta_{13})$. The best fit value from T2K in the normal ordering assumption is $\sin^2\theta_{13} = 0.0268$ with a 1σ range of $(0.0222, 0.0319)$. For the inverted ordering assumption, the best fit $\sin^2\theta_{13} = 0.0305$ with a 1σ range of $(0.0253, 0.0369)$.

When fitting for δ_{CP}, T2K achieves significantly higher precision by using an external constraint on θ_{13} from reactor measurements [21, 22, 23]. Taking this constraint to be $\sin^2(2\theta_{13}) = 0.0857 \pm 0.0046$ [24], T2K finds a best fit to be $\delta_{CP} = -1.822$ radians in the normal ordering hypothesis, with a 1σ range of $(-2.412, -1.169)$. In the inverted ordering hypothesis, the best fit is

$\delta_{CP} = -1.382$ radians with a 1σ range of $(-1.925, -0.898)$. The likelihood curves are shown in Fig. 3. As can be seen in the figure, the data are most consistent with maximal *CP* violation, and *CP*-conserving values of $\delta_{CP} = 0$ or π are disfavored at more than 2σ.

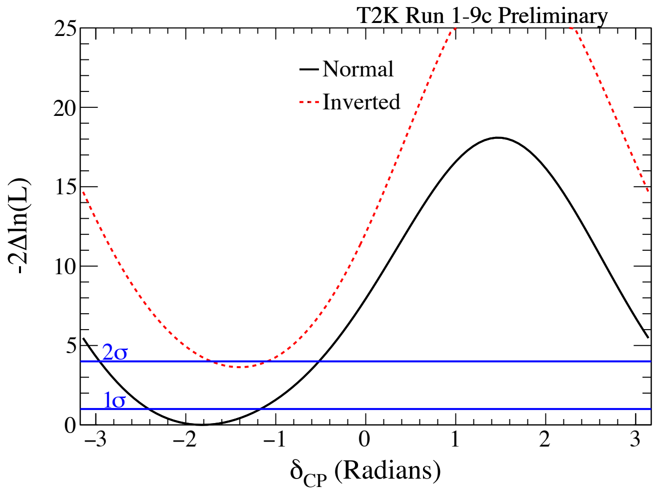

Figure 3: Likelihood $(-2\Delta \ln L)$ vs. δ_{CP} for T2K neutrino data with reactor constraint for θ_{13}. Both curves are plotted with respect to the global minimum from both normal and inverted orderings.

6. T2K's future plans

T2K has submitted a proposal for "T2K-II," [25] a program of extended running before the DUNE/Hyper-K era that would enable 3σ sensitivity to *CP* violation for the case where *CP* violation is maximal (which is also the best-fit point for T2K's data set so far). Successful implementation of this program will require successful upgrades of the accelerator complex and the secondary beam that are underway or in planning stages now. A separate project of near-detector upgrades is planned for installation in 2021, including a new scintillator-based "super fine-grained detector" (SFGD) with 1 cm scintillator pitch and three-dimensional readout, two new horizontal TPCs based on resistive micromegas technology, and surrounding time-of-flight detectors.

References

[1] K. Abe *et al.* [T2K Collaboration], Nucl. Instrum. Meth. A **659** (2011) 106

[2] `http://www-sk.icrr.u-tokyo.ac.jp`

[3] K. Abe *et al.* [T2K Collaboration], Phys. Rev. Lett. **112** (2014) 061802

[4] K. Abe *et al.* [T2K Collaboration], Phys. Rev. Lett. **112** (2014) 181801

[5] K. Abe *et al.* [T2K Collaboration], Phys. Rev. D **96** (2017) 011102

[6] K. Abe *et al.* [T2K Collaboration], Phys. Rev. D **96** (2017) 092006; Erratum: Phys. Rev. D **98** (2018), 019902

[7] K. Abe *et al.* [T2K Collaboration], Phys. Rev. D **87** (2013) 012001; Addendum: [Phys. Rev. D **87** (2013) 019902]

[8] M. Posiadała-Zezula [T2K and NA61/SHINE Collaborations], J. Phys. Conf. Ser. **888** (2017) no.1, 012064.

[9] N. Abgrall *et al.* [NA61/SHINE Collaboration], Phys. Rev. C **84** (2011) 034604

[10] N. Abgrall *et al.* [NA61/SHINE Collaboration], Eur. Phys. J. C **76** (2016) 617

[11] J. Nieves, I. Ruiz Simo and M. J. Vicente Vacas, Phys. Rev. C **83** (2011) 045501

[12] D. Rein and L. M. Sehgal, Annals Phys. **133** (1981) 79.

[13] G. M. Radecky *et al.*, Phys. Rev. D **25** (1982) 1161; Erratum: Phys. Rev. D **26** (1982) 3297

[14] T. Kitagaki *et al.*, Phys. Rev. D **34** (1986) 2554

[15] A. Mislivec *et al.* [MINERvA Collaboration], Phys. Rev. D **97** (2018) 032014

[16] T. Sjostrand, Comput. Phys. Commun. **82** (1994) 74.

[17] L. L. Salcedo, E. Oset, M. J. Vicente-Vacas and C. Garcia-Recio, Nucl. Phys. A **484** (1988) 557

[18] P. de Perio, AIP Conf. Proc. **1405** (2011) 223

[19] A. D. Missert [T2K Collaboration], J. Phys. Conf. Ser. **888** (2017) no.1, 012066

[20] K. Abe *et al.* [T2K Collaboration], Phys. Rev. Lett. **121** (2018) 171802

[21] F. P. An *et al.,* [Daya Bay Collab.], Phys. Rev. Lett. **112** (2014) 061801

[22] J. K. Ahn *et al.* [RENO Collaboration], Phys. Rev. Lett. **108** (2012) 191802

[23] Y. Abe *et al.,* [Double Chooz Collab.], Phys. Rev. **D86** (2012) 052008

[24] K. A. Olive *et al.* [Particle Data Group], Chin. Phys. C **38** (2015) 090001

[25] K. Abe *et al.*, arXiv:1609.04111 [hep-ex]