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Latest oscillation results from T2K

R. Phillip Litchfield[*†]
Imperial College London
E-mail: p.litchfield@imperial.ac.uk

The T2K long-baseline neutrino oscillation experiment has been running since January 2010, and has roughly doubled the data set in both neutrino and anti-neutrino beam mode since the most recent published results. We present a joint analysis of neutrino and anti-neutrino data, using both disappearance and appearance channels.

This analysis uses a new event reconstruction algorithm, an enlarged fiducial volume, and a new sample of electron-like events with tagged pion decays. The cross-section models used to analyse the data have also been updated to better treat multi-nucleon effects. We present newly-updated measurements of θ_{23} , Δm^2_{23}, θ_{13} and δ_{CP}, using an exposure of $1.49(1.12)\times 10^{21}$ POT in Forward(Reverse) Horn Current mode. By requiring that the value of θ_{13} should be consistent with reactor neutrino measurements, CP-conserving hypotheses ($\delta_{\mathrm{CP}} = \{0,\pi\}$) are excluded at over 2σ.

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*Speaker.
†On behalf of the T2K collaboration

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T2K is a long-baseline neutrino oscillation experiment: it uses a beam of (mostly) muon neutrinos, and the signal appears as distortions of the naïvely-predicted event rate. The distortions are oscillating functions of L/E_ν, the propagation distance divided by the neutrino energy, and are probed using two detectors at 'near' and 'far' baselines. T2K's far baseline is 295 km, the distance between J-PARC and Super-Kamiokande (SK). At this L, the highest energy where the oscillation effect is large is around 600 MeV. The neutrino beam is designed so that the flux at SK is peaked in a narrow range around this energy.

One measurement channel is the observed depletion in the rate of muon-neutrino interations, with the energy of maximum disappearance being sensitive to the mass-squared difference $\left|\Delta m^2_{32}\right|$, and the amplitude of this mode being approximately proportional to $\sin^2 2\theta_{23}$. In this regime most of the muon neutrinos that have disappeared have oscillated to tau neutrinos, but a fraction are observable as electron neutrinos. The probability of this happening depends primarily on $\sin^2 2\theta_{13}$, but also on the value of $\sin^2\theta_{23}$—this lifts a degeneracy of the disappearance measurement.

In addition, the electron neutrino appearance channel is modulated by effects that differ between $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations. This is a violation of CP symmetry, and is parameterised by the complex phase δ_{CP}. The difference also includes a contribution of *induced* CP violation because the neutrinos are propagating through a medium (the Earth's crust) that contains many electrons. This induced CP effect depends on the mass ordering, which corresponds to the sign of Δm^2_{32}. By observing the spectrum of all four neutrino types (ν_μ, $\overline{\nu}_\mu$, ν_e, $\overline{\nu}_e$) and analysing them simultaneously, the different effects of these parameters can be disentangled.

In practice neither the exact flux, nor the interaction cross-section and resulting kinematic distributions of detectable particles are known with enough precision to perform the measurement by dead reckoning. A near detector (ND280) at J-PARC is used to characterise the interactions of the neutrino beam at a short distance from its production. The T2K analysis starts with models of the flux and interactions tuned to the most relevant external data, and then allows a large number of flux and interaction parameters to vary, within the constraint that the resulting model should closely reproduce the ND280 data. This produces an appropriately-weighted ensemble of predictions for what would be seen at SK, in the absence of neutrino oscillations. Measurements of oscillation parameters (Δm^2_{32}, θ_{23}, θ_{13}, and δ_{CP}) can be made by using the full oscillation formula to reweight the predictions and compare them to the SK data, marginalising over the ensemble.

Latest data and changes to the analysis

As shown in Fig. 1, the data is divided into two modes, based on the current of the focusing horns. In *Forward* Horn Current (FHC) data, positive secondary hadrons are focused and produce a beam of mostly ν_μ via the decay $\pi^+ \to \mu^+ + \nu_\mu$. In *Reverse* Horn Current (RHC) mode, negative secondaries are focused to produce more $\overline{\nu}_\mu$. The analysis presented uses an exposure of $1.49\ (1.12) \times 10^{21}$ protons on target in FHC (RHC) mode respectively, nearly double that of the previous analysis [1].

The constraint from the magnetised ND280 uses several samples of neutrino interactions. In FHC mode a negative-curvature muon-like track is always required, and samples are further differentiated depending on whether they have 0, 1, or >1 pion-like tracks in addition to the muon candidate. In RHC mode, the contamination from 'wrong-sign' μ^- is larger, so samples are di-

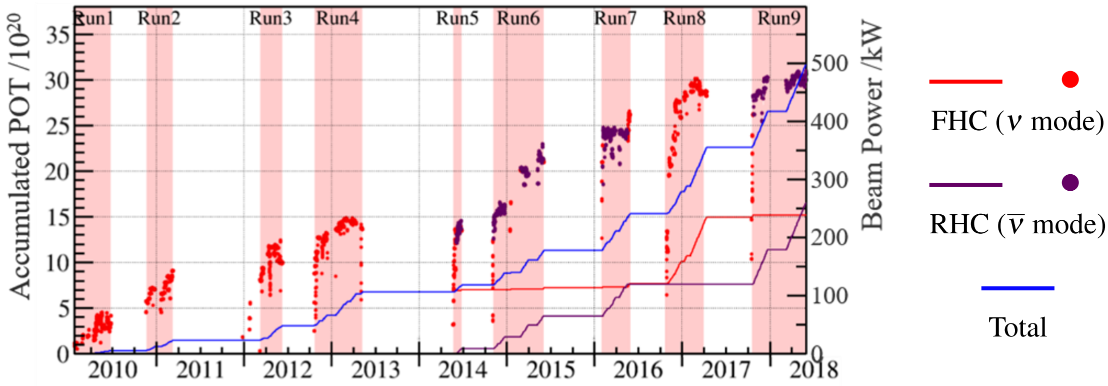

Figure 1: Integrated exposure (left axis, lines) and operating beam power (right axis, dots) of the J-PARC neutrino beam. The analysis presented is based on data taken up until the end of 2017.

vided by the charge of the leading track and whether or not there are *any* extra tracks. The ND280 analysis uses two target regions: one containing only plastic scintillator (carbon & hydrogen) and one that also contains oxygen in the form of water. Events are subdivided according to which target they originated from, providing a statistical constraint on differences between interactions on carbon and oxygen. All 14 samples analysed as a function of the reconstructed muon momentum.

At SK, there is no magnetic field and particles below the Cherenkov threshold can not be observed. On the other hand there is a significant fraction of electron neutrinos from oscillation, and the analysis can make use of high-Q^2 events where the outgoing lepton is at a large angle from the initial neutrino direction. The analysis samples therefore all use events with only one ring in the primary event, and they are classified as muon-like or electron-like based on how sharp the ring is; electrons generally produce more blurry rings because they scatter more as they pass through matter. In addition to these four samples (muon- or electon-like, and FHC or RHC), an additional sample of electron-like events is used in FHC mode, where unseen π^+ can frequently be tagged by the presence of a delayed Michel electron. These additional events tend to slightly higher energies (due to the pion emission requirement) and are not yet expected to be a large sample.

Although the basic principle by which events are classified is the same as all previous analyses, the classifier has recently been updated to use a hit-based likelihood that more efficiently uses the pattern of light in the detector. This allows better μ/e discrimination, but also enables the use of a larger fiducial volume, based on the distance to both the nearest wall and in the direction of the outgoing lepton. This change is roughly equivalent to a 20% increase in the fiducial mass.

In parallel, the interaction model has seen significant updates, primarily related to nuclear effects. A polynomial-based parameterisation of weak charge screening ("RPA") is implemented, and tuned to the ND280 data. Modelling of scattering on correlated pairs ("2p2h") is also improved and can be adjusted to match the data. To support the new Michel-electron sample, the models for pion-producing processes have been re-tuned based on available external data.

Results

The number of electron-like events observed in FHC mode is rather high (and the number in

RHC rather low) compared to predictions using data from reactor experiments [2], so T2K data favours values of $\delta_{\mathrm{CP}} \sim -\pi/2$, which enhances the ν_e appearance rate. After incorporating the reactor constraint, T2K data excludes CP conservation in the neutrino sector at 2σ level. In toy simulations at the best fit point, this occurs in 19% of cases, so while the results are a tighter-than-expected constraint, there is no evidence of inconsistency. The overall best fit for δ_{CP} is found for Normal Ordering (NO) at -1.82. The best fit for Inverted Ordering is less favoured, and occurs at -1.38. The 2σ interval contains the NO region $[-2.91, -0.64]$ and IO region $[-1.57, -1.16]$. These results are presented graphically in Figure 2.

The inclusion of more data, particularly in RHC, has also significantly improved both T2K-only and T2K+reactor constraints on other parameters, compared to the previous result [1]. A summary of 1D intervals calculated from marginalised likelihoods is provided in Table 1.

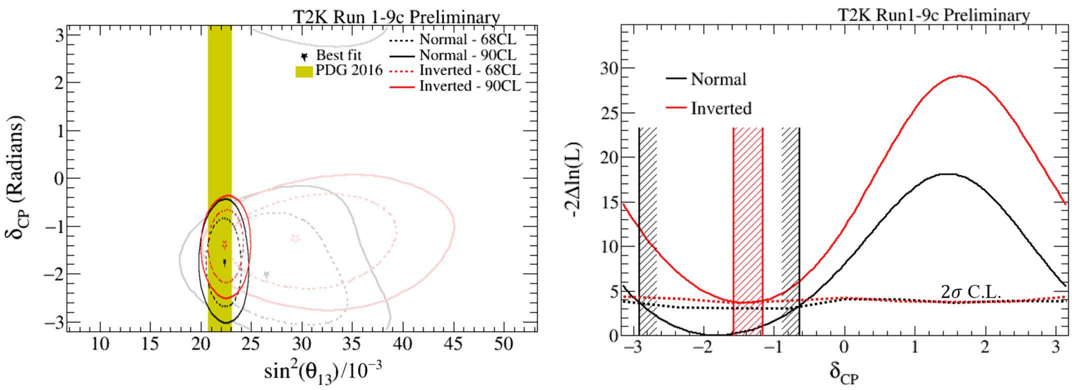

Figure 2: Measurements of δ_{CP}. The left figure shows joint intervals in the θ_{13}–δ_{CP} plane, for each mass ordering and using the marginalised likelihood. The pale lines show T2K alone, the darker lines incorporate the constraint from reactor experiments [2]. The right figure shows the negative log-likelihood in δ_{CP} after also marginalising for θ_{13}, and the resulting frequentist 2σ interval, which includes both orderings.

Parameter	Best fit (NO)	1σ interval (NO)	Best fit (IO)	1σ interval (IO)
$\sin^2\theta_{23}$	0.536	[0.490, 0.567]	0.536	[0.495, 0.567]
^{a} Δm^2_{32} $/10^{-3}\mathrm{eV}^2$	$+2.43$	$[+2.37, +2.51]$	-2.49	$[-2.56, -2.41]$
^{b} $\sin^2\theta_{13}$ $/10^{-3}$	2.68	[2.22, 3.19]	3.05	[2.53, 3.69]

^{a}The interval width increased by $\sim 0.01 \times 10^{-3}\mathrm{eV}^2$ since presentation, due to improved numerical calculation.
^{b}Using T2K data only.

Table 1: Best fit points and likelihood-derived errors on the other oscillation parameters, where all other parameters except the mass ordering have been marginalised over.

References

[1] K. Abe *et al.* [T2K Collaboration], Phys. Rev. D **96** (2017) no.9, 092006 [Erratum: Phys. Rev. D **98** (2018) no.1, 019902] `arXiv:1707.01048 [hep-ex]`.

[2] C. Patrignani *et al.* [Particle Data Group], Chin. Phys. C, 40, 100001 (2016)