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Physics sensitivity of a possible extended T2K run – T2K Phase 2

C Bronner¹, S Cao² and M Friend³ for the T2K Collaboration

¹Kavli IPMU (WPI), University of Tokyo, Tokyo, Japan
²High Energy Physics Laboratory, Kyoto University, Kyoto, Japan
³IPNS, High Energy Accelerator Research Organization (KEK), Tsukuba, Japan
E-mail: mfriend@post.kek.jp

Abstract. With recent suggestive physics results, compelling future physics opportunities, and the continued improvement of the J-PARC proton beam power, the T2K collaboration is proposing an extension of the T2K run from the currently approved full statistics of \(7.8 \times 10^{21}\) Protons-on-Target (POT) (expected by 2021) to \(20 \times 10^{21}\) POT (expected by 2027). The T2K collaboration also plans to increase the ‘effective’ T2K Phase 2 statistics by improved analysis techniques and neutrino beamline hardware upgrades. The physics sensitivity of this extended run are shown, including the possibility of excluding \(\sin^2 \delta_{CP} = 0\) to \(3\sigma\) or better in the case of maximal CP violation in the lepton sector. Improvements on the atmospheric neutrino oscillation parameter constraints will also be made by T2K Phase 2, where the final sensitivities depend on the true values of the oscillation parameters.

1. Introduction
The T2K long-baseline neutrino oscillation experiment measures \(\nu_\mu \rightarrow \nu_e\) appearance and \(\nu_\mu \rightarrow \nu_\mu\) disappearance from a primarily \(\nu_\mu\) beam produced at J-PARC in Japan. The polarity of the neutrino beam can be controlled such that a primarily \(\nu\) or \(\bar{\nu}\) beam can be delivered.

A 280-m-baseline Near Detector (ND) is used to constrain the \(\nu\) flux and measure \(\nu\) cross sections, while the far detector is the 295-km-baseline Super-Kamiokande (SK) detector, which has excellent \(\nu_e/\nu_\mu\) particle ID performance for sub-GeV \(\nu\)'s. Four-flavor joint fits to the predicted \(\nu_\mu + \nu_e + \bar{\nu}_\mu + \bar{\nu}_e\) SK reconstructed energy spectra [1, 2] are shown here.

T2K has been approved to take \(7.8 \times 10^{21}\) POT, but an extension to \(20 \times 10^{21}\) POT is now being proposed.

2. T2K Phase 2 target statistics
Upgrades planned for the J-PARC accelerator in order to increase the Main Ring (MR) beam power from 420 kW to \(\sim 1.3\) MW include upgrades to the MR magnet power supplies and RF cavities, as well as a new MR tune point and improved MR beam stability, and will allow T2K Phase 2 to collect \(20 \times 10^{21}\) POT by around 2026, as shown in Fig. 1.

The T2K and T2K Phase 2 effective statistics will also be increased by up to 50%. The current of the electro-magnetic focusing horns will be increased from the current 250 kA to 320 kA, allowing for a \(\sim 10\%\) increase in the right-sign \(\nu\) flux and a \(\sim 5\%\) decrease in the wrong-sign \(\nu\) flux. An increase in the SK fiducial volume, as well as adding new SK samples to the neutrino oscillation fit (i.e. CC\(\pi^+\) and multi-ring events), will also increase the effective statistics.
3. Systematics and importance of systematic error reduction
Current (2016) T2K systematic errors are around 6% on both the number of reconstructed $\nu_e$ appearance and $\nu_\mu$ disappearance events with both $\nu$- and $\bar{\nu}$-mode beam.

Reduced systematic errors assume that the current errors can be reduced to $\sim 4\%$, where systematic errors may be reduced by further constraining the $\nu$ flux by outside hadron production experiments and further constraining $\nu$ cross sections with the T2K near detector. As shown in Fig. 2, studies show that reducing the systematic errors as much as possible would be beneficial at $20 \times 10^{21}$ POT.

4. Resolving $\sin \delta_{CP} \neq 0$
The T2K Phase 2 sensitivities to resolving $\sin \delta_{CP} \neq 0$ plotted as a function of true $\delta_{CP}$ are shown in Fig. 3. The fractions of possible true values of $\delta_{CP}$ where $\delta_{CP} \neq 0$ can be resolved are also given in Table 1. Sensitivities assume $20 \times 10^{21}$ POT with hardware and analysis improvements and a combination of 50% $\nu$- + 50% $\bar{\nu}$-mode beam. For these results, the value of $\sin^2 \theta_{13}$ is constrained by $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ [3].

5. $\nu_\mu$ disappearance sensitivities
The T2K Phase 2 sensitivities to the parameters $\Delta m^2_{32}$ and $\sin^2 \theta_{23}$ are shown in Fig. 4. For these results, the value of $\sin^2 2\theta_{13}$ is constrained by $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ and a combination of 50% $\nu$- + 50% $\bar{\nu}$-mode beam is assumed. Depending on the true value of $\sin^2 \theta_{23}$, an extended T2K run may be able to determine the $\theta_{23}$ octant at the greater than 3$\sigma$ level.

$^0$ All plots assume true normal mass hierarchy (NH), $\sin^2 2\theta_{13} = 0.085$, $\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV$^2$. 
Figure 3. Sensitivity to resolve $\sin \delta_{CP} \neq 0$ if the MH is unknown (left) or known (i.e. measured by an external experiment) (right).

Table 1. The fractions of possible true values of $\delta_{CP}$ (%) where $\delta_{CP} \neq 0$ can be resolved assuming : no systematic error (statistical only), 2016 systematics, and improved systematics are given assuming that the MH is known. The coverages are calculated at three different true values of $\sin^2 \theta_{23}$.

| $\sin^2 \theta_{23}$ (true) | Stat. Only | 2016 Systematics | Improved Systematics |
|-----------------------------|------------|------------------|---------------------|
| $0.43$                      | 57.5       | 45.6             | 51.5                |
| $0.50$                      | 47.9       | 28.3             | 39.7                |
| $0.60$                      | 53.3       | 41.6             | 48.6                |

Figure 4. T2K 2014, full POT, and extended POT 90% C.L. sensitivities for $\Delta m^2_{32}$ and $\sin^2 \theta_{23}$ assuming true $\delta_{CP} = -90^\circ$ and $\sin^2 \theta_{23} = 0.5$ (left) or $\sin^2 \theta_{23} = 0.6$ (right).

6. Conclusion
At $20 \times 10^{21}$ POT, with analysis and hardware improvements and 4% systematic errors, T2K Phase 2 can achieve a $>3\sigma$ measurement of non-zero $\sin \delta_{CP}$ for 36% of possible true values of $\delta_{CP}$, assuming true $\sin^2 \theta_{23} = 0.5$ and that the MH has been determined by an independent experiment. T2K Phase 2 may also be able to determine the $\theta_{23}$ octant at more than $3\sigma$, depending on the true value of $\sin^2 \theta_{23}$.

References
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