PROCEEDINGS OF SCIENCE

Neutrino Oscillation Physics Potential of a Possible Extension of the T2K Experiment

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T2K (Tokai to Kamioka), the world's first off-axis long-baseline neutrino beam experiment, was built for the precision measurement of neutrino oscillations. T2K makes use of a highly intense and almost pure $\nu_\mu/\bar{\nu}_\mu$ beam produced at the J-PARC accelerator complex and sent 295 km across Japan to the far detector, Super-Kamiokande. After the $\nu_\mu \to \nu_e$ appearance was observed at T2K in 2013, confirming the non-zero mixing angle θ_{13}, T2K started to search for the first time for experimental evidence of CP violation in neutrino oscillations. To enhance this search substantially, the T2K collaboration is proposing an extension of data taking until 2026 for an overall accumulation of 20×10^{21} protons-on-target (POT). This amount of data, along with T2K hardware upgrades and analysis improvements, allows us to intensively explore CP violation in the lepton sector, to precisely measure neutrino oscillation parameters, and to positively search for unknown physics.

38th International Conference on High Energy Physics
3-10 August 2016
Chicago, USA

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PoS(ICHEP2016)1093

1. The T2K Experiment and Proposal of Running Extension

The T2K experiment is described in detail elsewhere [1]. To make use of the $\nu_\mu/\overline{\nu}_\mu$ beam produced at J-PARC, T2K employs a near detector complex, 280 m downstream of the proton beam target, to monitor and characterize the $\nu/\overline{\nu}$ beam before the neutrinos oscillate, and a far detector, Super-Kamiokande, 295 km away from the target, to observe the $\nu/\overline{\nu}$ oscillation patterns. That Super-Kamiokande is located at an offset of 2.5° from the average beam direction is to yield a narrow band beam with peak neutrino energy of 0.6 GeV, at the maximum of ν oscillation probability.

In 2013, $\nu_\mu \to \nu_e$ appearance was discovered by T2K [2]. Along with the $\overline{\nu}_e$ disappearance at reactor experiments, this observation confirmed the non-zero θ_{13} and thus opened the door to exploring CP violation effect, which arises from an irreducible phase $\delta_{\rm CP}$ in the standard mixing matrix. T2K also provided the first hint at maximum CP violation with $\delta_{CP} \sim -\frac{\pi}{2}$ and normal mass hierarchy [3]. If this scenario is assumed, T2K with the fully approved 7.8×10^{21} POT exposure, which is predicted to finish data taking by 2020, would observe the CP violation with 90% C. L. [4]. By that time, the Main Ring (MR) beam power is predicted to have been increased to about 750 MW by reducing the repetition cycle from 2.48 s to 1.3 s. To prepare for the next generation of the long baseline ν experiments at J-PARC, T2HK (Tokai to Hyper-Kamiokande) [5], the MR beam power is planned to be upgraded to 1.3 MW by further reducing the repetition cycle and increasing the intensity. T2K-II, which is proposed to extend the data-taking until 2026, would benefit from this upgrade and accumulate 20×10^{21} POT in total.

2. T2K-II Target Statistics and Systematic Improvements

Along with the MR beam power upgrade, increasing the T2K horn current from 250 kA to 320 kA would would increase the ν flux by 10%, and reduce the wrong-sign background ($\overline{\nu}$ (ν) components in ν ($\overline{\nu}$)-mode flux respectively) by $5-10\%$. Also analysis improvements, such as enlarging the fiducial volume of the T2K far detector, and including the charged-current 1π events into the signal sample potentially increase event numbers by up to 40%.

Table 1: Number of events expected to be observed at the T2K far detector for 10×10^{21} POT ν-mode + 10×10^{21} POT $\bar{\nu}$-mode with an effective improvement in event statistics of 50%. Assumed relevant parameters are: $\sin^2 2\theta_{13} = 0.085$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.509 \times 10^{-3}$ eV^2, and normal mass hierarchy.

	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode	0	454.6	346.3	3.8	72.2	1.8	30.5
ν_e sample	$-\pi/2$	545.6	438.5	2.7	72.2	1.8	30.5
$\bar{\nu}$-mode	0	129.2	16.1	71.0	28.4	0.4	13.3
$\bar{\nu}_e$ sample	$-\pi/2$	111.8	19.2	50.5	28.4	0.4	13.3

	Total	Beam CC ν_μ	Beam CC $\bar{\nu}_\mu$	Beam CC $\nu_e + \bar{\nu}_e$	$\nu_\mu \to \nu_e +$ $\bar{\nu}_\mu \to \bar{\nu}_e$	NC
ν-mode ν_μ sample	2612.2	2290.5	150.0	1.6	7.0	163.1
$\bar{\nu}$-mode $\bar{\nu}_\mu$ sample	1217.5	482.1	672.5	0.6	1.0	61.3

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The combination of these effects would effectively increase the data sample by up to 50%. Table 1 shows event numbers predictions for T2K-II at the far detector.

Systematics, categorized into three sources: the ν flux, the interaction model, and the detector response, need to be improved for enhancing the CP violation search. The total errors on T2K far detector event samples currently vary from 5.5% to 6.8%. The ν flux error, which is currently dominated by the hadron interaction modeling can be improved with the T2K replica target data from NA61/SHINE. Knowledge of ν and $\overline{\nu}$ interactions would be improved significantly thanks to additional data at T2K itself and measurements from other ν experiments. Detector systematic improvements are foreseen from including ν interaction modeling from the T2K data, and utilizing other data sources such as calibrations, entering muons, and decay electrons. Considering these expected improvements, a 4% systematic error is predicted to be achievable by the time of T2K-II.

3. Sensitivity of T2K-II to CP Violation

The physics potential of T2K-II is explored with a joint analysis of $\nu/\overline{\nu}$ oscillations with the $\nu_\mu/\overline{\nu}_\mu$ disappearance and $\nu_\mu/\overline{\nu}_\mu \to \nu_e/\overline{\nu}_e$ channels. Sensitivity of T2K-II to CP violation plotted as a function of true δ_{CP} and POT exposure is shown in Figure 1.

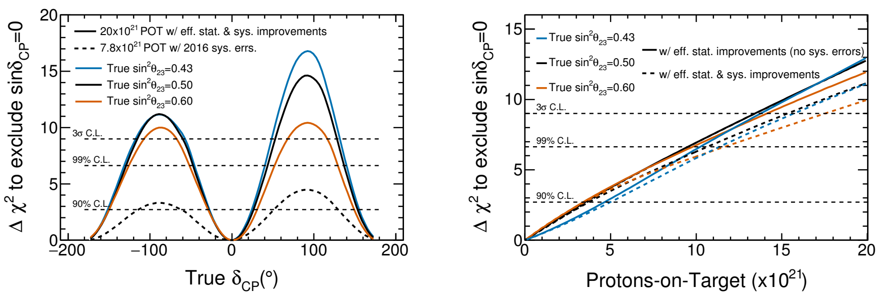

Figure 1: Sensitivity of T2K-II to CP violation plotted as function of true δ_{CP} (left) and of POT (right). The normal mass hierarchy is assumed as known. The improved systematic error is applied. The right-hand plot assumes $\delta_{CP} = -\frac{\pi}{2}$. 0.43 and 0.6 are the 90% C. L. bounds of currently measured $\sin^2\theta_{23}$ by T2K.

With the current level of systematic uncertainties, the fraction of the range in which CP conservation, $\sin\delta_{CP} = 0$, can be excluded at the 99% (3σ) C. L. is $34.7-46.6\%$ ($5.2-28.3\%$) respectively, depending on the true value of θ_{23}. If systematic improvements are taken into account, the corresponding fractional region is $41.8-51.5\%$ ($23.9-39.7\%$). If systematics are removed completely, $49.1-57.5\%$ ($36.7-47.9\%$) of δ_{CP} can be explored at the 99% (3σ) C. L. significance respectively. This study assumes that the data exposure in the ν-mode and the $\bar{\nu}$-mode are the same. Additional studies show that taking data equally in ν-mode and $\bar{\nu}$-mode is not the most optimal configuration for every true value of θ_{23} but gives high sensitivity to the CP violation across the overall range of θ_{23}.

4. Sensitivity of T2K-II to Atmospheric Neutrino Oscillation Parameters

Figure 2 shows the expected 90% C.L. significance contours for Δm^2_{32} vs $\sin^2\theta_{23}$ for the full T2K-II statistic for two cases ($\sin^2\theta_{23}$=0.5, 0.6). If θ_{23} is not maximal, the octant degeneracy can be solved by more or less 3σ if the $\theta_{23} \geq 0.6$ or $\theta_{23} \leq 0.43$. If θ_{23} is maximum, the expected 1σ precision of $\sin^2\theta_{23}$ is 1.7°. For the case of $\sin^2\theta_{23} = 0.43, 0.6$, the uncertainty is 0.5°, 0.7° respectively. For the proposed T2K-II, precision of Δm^2_{32} of around 1% can be achieved.

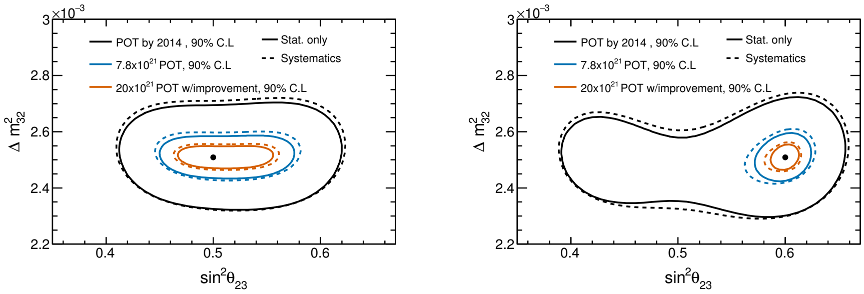

Figure 2: Expected 90% C.L. significance sensitivity to Δm^2_{32} and $\sin^2\theta_{23}$ at true $\sin^2\theta_{23}$=0.5 (left) and $\sin^2\theta_{23}$=0.6 (right) with with current values for the systematic errors.

5. Summary and Outlook

The T2K collaboration is considering extending data-taking to 2026, which will be called T2K-II. The increased statistics and potential systematics improvements allow T2K-II to explore the CP violation at 3σ or higher significance for maximum CP violation. The fractional region where the CP violation can be explored with 99% (3σ) C.L significance is 41.8% – 51.5% (23.9% – 39.7%) respectively, depending on the true value of θ_{23}. Δm^2_{32} would be measured with precision up to 1%. If θ_{23} is not maximal, T2K-II will be able to resolve the octant degeneracy up to 3σ in some cases.

Besides, T2K-II would allow us to perform world-leading searches for non-standard neutrino interaction physics. The search for Lorentz violation, which has been explored at T2K through sidereal time analyses, would improve its sensitivity significantly with statistics of T2K-II. Such high event numbers are also extremely important for searching for sterile neutrinos at intermediate baselines [6]. Other potential physics are non-standard neutrino production and/or interactions, heavy sterile neutrino decay and neutrino magnetic moments. These reasons make the proposed T2K-II experiment a highly interesting prospect to be pursued before the next generation of long-baseline neutrino experiments expectedly start.

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