

Expression of Interest for an Extended Run at T2K to 20×10^{21} POT

T2K collaboration

January 6, 2016

Abstract

Recent measurements at T2K indicate that CP violation in neutrino mixing may be observed in the future by long-baseline neutrino oscillation experiments. We explore the physics program of an extension to the currently approved T2K running of 7.8×10^{21} protons-on-target to 20×10^{21} protons-on-target, aiming at initial observation of CP violation with 3σ or higher significance for the case of maximum CP violation. With accelerator and beam line upgrades, as well as analysis improvements, this program would occur before the next generation of long-baseline neutrino oscillation experiments that are expected to start operation in 2026.

1 Introduction

The discovery of $\nu_\mu \rightarrow \nu_e$ oscillations by T2K[1] has opened the possibility of observing CP-violation (CPV) in the lepton sector, which would be a crucial hint towards understanding the matter-antimatter asymmetry of the universe. In neutrino oscillations, CPV can arise from δ_{CP} , an irreducible CP-odd phase in the lepton mixing matrix, which can be measured at T2K by comparing the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities or by comparing these oscillations with $\bar{\nu}_e$ disappearance measured by reactors. While the current significance is marginal, T2K measurements with 6.6×10^{20} protons-on-target (POT) hint at maximum CP violation with $\delta_{CP} \sim -\frac{\pi}{2}$ and normal mass hierarchy[2], in which case T2K could observe CPV with 90% C.L. sensitivity with the currently approved exposure of 7.8×10^{21} POT[3] expected around 2020. Future proposed projects such as Hyper-Kamiokande[4] and DUNE[5] aim to achieve $> 3\sigma$ sensitivity to CPV across a wide range of δ_{CP} on the time scale of 2026 and beyond.

By the time T2K finishes its currently approved running, the J-PARC Main Ring (MR) beam power is expected to exceed 750 kW. If data-taking is extended till 2026, when Hyper-Kamiokande and DUNE are expected to start, sensitivity to CPV would significantly improve with the additional statistics. This would also have the benefit of establishing higher beam power for the next generation of measurements at Hyper-Kamiokande from the start.

The T2K collaboration has initiated the study of “T2K-II”, a second phase of the experiment in which more than 3σ sensitivity to CPV can be achieved if $\delta_{CP} \sim -\frac{\pi}{2}$ and the mass hierarchy is normal in a five or six year period after the currently approved running. This would require not only a beam time extension, but additional improvements explored in this document, including further improvements to the MR beam power, neutrino beam line upgrades, and analysis developments to improve statistical and systematic uncertainties. We then discuss the physics potential resulting from these combined developments.

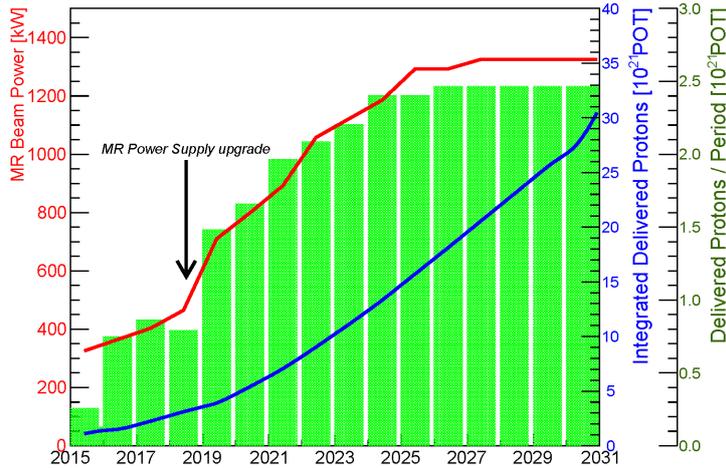


Figure 1: Anticipated MR beam power and POT accumulation vs. calendar year.

2 Data accumulation Plan and Improvement of effective Statistics

Projected MR beam power and POT accumulation The MR beam power has steadily increased since the start of the operation. In June 2015, 360 kW beam with 1.68×10^{14} protons-per-pulse (ppp) every 2.48 seconds was successfully provided to the neutrino beamline. Discussions with the J-PARC Accelerator Group have resulted in a plan to achieve the design intensity of 750 kW by reducing the repetition cycle to 1.3 seconds. This requires an upgrade to the power supplies for the MR main magnets, RF cavities, and some injection and extraction devices by January 2019. Studies to increase the ppp are also in progress, with 2.73×10^{14} ppp equivalent beam with acceptable beam loss already demonstrated in a test operation with two bunches.

Based on these developments, MR beam power prospects were updated and presented in the accelerator report at the last PAC in July 2015[6] and anticipated beam power of 1.3 MW with 3.2×10^{14} ppp and a repetition cycle of 1.16 seconds are presented at international workshops[7, 8]. A possible data accumulation scenario is shown in Fig. 1, where 5 months neutrino beam operation each year and realistic running time efficiency are assumed. We expect to accumulate 20×10^{21} POT by JFY2026 with 5 months operation each year and by JFY2025 with 6 months operation each year as requested by T2K.

Beamline upgrade The beam intensity in the current neutrino beam facility is limited to 3.3×10^{14} ppp by the thermal shock induced by the beam on the target and beam window. The MR power upgrade plan allows 1.3 MW beam operation without increasing the ppp. However, the beamline cooling capacity for components like the target and helium vessel is sufficient for up to 750 kW; these would need to be upgraded to accept 1.3 MW beam operation.

The T2K horns were originally designed to be operated at 320 kA current, but so far have been operated at 250 kA because of a problem with the power supplies. The upgrades required for 320 kA operation will be implemented in stages and will be completed by 2019. Horn operation at 320 kA gives a 10% higher neutrino flux and also reduces contamination of the wrong-sign component of neutrinos (*i.e.*, anti-neutrinos in the neutrino beam mode or neutrinos in the anti-neutrino beam mode) by 5-10%.

Table 1: Number of events expected to be observed at the far detector for 10×10^{21} POT ν - + 10×10^{21} POT $\bar{\nu}$ -mode with a 50% statistical improvement. Assumed relevant oscillation parameters are: $\sin^2 2\theta_{13} = 0.085$, $\sin^2 \theta_{23} = 0.5$, $\Delta m_{32}^2 = 2.5 \times 10^{-3} \text{ eV}^2$, and normal mass hierarchy (MH).

	True δ_{CP}	Total	Signal $\nu_\mu \rightarrow \nu_e$	Signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	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 $\nu_e + \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e +$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	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

Improved Super-K Sample Selection The current efficiency to select oscillated ν_e CC events in the 22.5 kt fiducial volume at Super-K is 66%. The inefficiency results from targeting events with a single Cherenkov ring from the outgoing lepton without additional rings or decay electrons arising from pions that may be produced in the interaction. Recent developments in multi-ring event reconstruction will enable us to identify and reconstruct ν_e CC $\pi^{\pm/0}$ interactions, leading to higher effective efficiency for the ν_e CC selection. Reoptimization of other selection criteria are also being investigated.

Improvements to the single-ring μ -like selection used to identify ν_μ CC events will enhance T2K's sensitivity to θ_{23} and Δm_{32}^2 and subsequently CP violation through the improved constraint on these parameters. We expect to reduce the NC π^+ contamination in this sample by more than 50% in the region where the oscillation effect is maximal. As with the ν_e , a dedicated multi-ring ν_μ CC π^+ reconstruction is under development, potentially allowing up to 40% more ν_μ CC events to be used in the oscillation analyses.

Finally, the fiducial volume definition for both selections will be improved to accept well-reconstructed events near the edge of the detector that are currently rejected. This is expected to add 10-15% more events while maintaining sufficient control of external backgrounds entering the tank.

Taken together, these improvements can potentially increase the ν_e and ν_μ CC event samples identified at Super-K by up to 40%.

Short Summary We expect to accumulate an integrated 20×10^{21} POT when T2K running is extended by five to six years. Effective statistics per POT for CP violation studies will be improved by up to 50% by analysis improvements and beamline upgrades.

The number of events expected at the Super-K far detector for an exposure of 20×10^{21} POT with a 50% statistical improvement is given in Table 1 assuming either true $\delta_{CP} = 0$ or $-\pi/2$.

Table 2: Errors on the number of predicted events in the Super-K samples from individual systematic error sources in neutrino (ν mode) and antineutrino beam mode ($\bar{\nu}$ mode). Also shown is the error on the ratio 1Re events in ν mode/ $\bar{\nu}$ mode. The uncertainties represent work-in-progress for T2K neutrino oscillation results in 2016.

Error Type	$\delta_{N_{SK}}/N_{SK}$ (%)				
	1-Ring μ		1-Ring e		
	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	$\nu/\bar{\nu}$
SK Detector	4.6	3.9	2.8	4.0	1.9
SK Final State & Secondary Interactions	1.8	2.4	2.6	2.7	3.7
ND280 Constrained Flux & Cross-section	2.6	3.0	3.0	3.5	2.4
$\sigma_{\nu_e}/\sigma_{\nu_\mu}, \sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.0	0.0	2.6	1.5	3.1
NC 1γ Cross-section	0.0	0.0	1.4	2.7	1.5
NC Other Cross-section	0.7	0.7	0.2	0.3	0.2
Total Systematic Error	5.6	5.5	5.7	6.8	5.6
External Constraint on $\theta_{12}, \theta_{13}, \Delta m_{21}^2$	0.0	0.0	4.2	4.0	0.1

3 Improvement of Systematics

Systematic errors are categorized based on their source into neutrino flux, neutrino interaction model, and detector model uncertainties. The uncertainties in the neutrino flux and interaction model are first constrained by external measurements and then further constrained by a fit to data from the ND280 near detector.

The uncertainty on the total predicted number of events in the Super-K samples encapsulate the first order impact of systematic errors on the oscillation parameter measurements and the current sizes are summarized in Table 2. The CP phase δ_{CP} is measured through the difference in the oscillation probabilities for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. Hence, we also show the uncertainty on the ratio of expected $\nu_e/\bar{\nu}_e$ candidates at Super-K with neutrino (ν) and antineutrino ($\bar{\nu}$) beam mode.

The uncertainty from oscillation parameters not measured by T2K-II is negligible for $\nu_\mu/\bar{\nu}_\mu$ events at SK in the $\nu_\mu/\bar{\nu}_\mu$ disappearance measurements. The 4% uncertainties on the $\nu_e/\bar{\nu}_e$ samples arise from the precision of the θ_{13} measurement by reactor experiments ($\sin^2(2\theta_{13}) = 0.085 \pm 0.005$) [9]. However, this uncertainty is correlated between ν and $\bar{\nu}$ beam mode samples and its impact on the observation of a CP asymmetry in T2K data is small.

As will be described in Sec. 4, the current systematic errors, if they are not improved, will significantly reduce the sensitivity to CP violation with the T2K-II statistics. Any improvement on the systematics would enhance physics potential. Here, we describe projected improvements.

Neutrino Flux The neutrino flux prediction uncertainty is currently dominated by uncertainties on the hadron interaction modelling in the target and surrounding materials in the neutrino beamline and by the proton beam orbit measurement. These errors can be represented as an absolute flux uncertainty relevant for neutrino cross section measurements, and an extrapolation uncertainty which impacts oscillation measurements. At the peak energy (~ 600 MeV), these are currently $\sim 9\%$ and $\sim 0.3\%$, respectively. Fur-

ther improvement is expected with the incorporation of the T2K replica target data from NA61/SHINE, improvements in the beam direction measurement, and improved usage of the near detector measurements, to achieve $\sim 6\%$ uncertainty on the absolute flux.

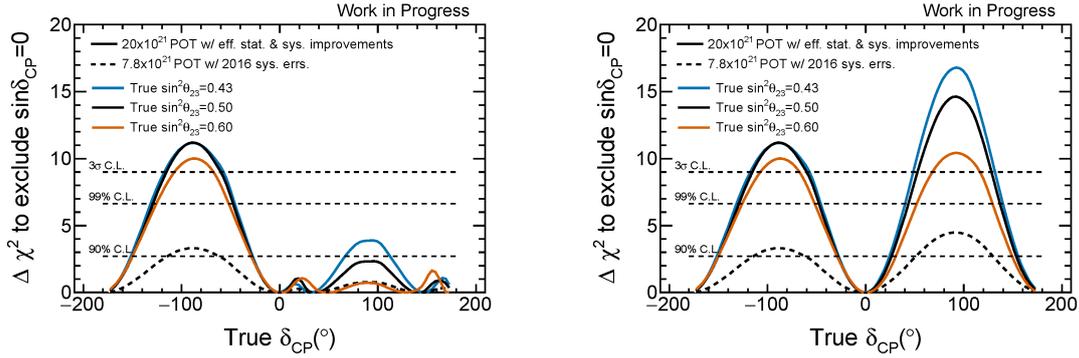
Near Detector measurement Currently, detector-related systematic uncertainties of $\sim 2\%$ have been achieved in $\nu_\mu/\bar{\nu}_\mu$ charged-current samples selected in ND280. Some uncertainties, such as those related to reconstruction efficiencies and backgrounds, may be reduced by further effort and development. By far the largest uncertainty, however, arises from pion secondary interaction uncertainties, which may be reduced by external measurements or by studying pion interactions within ND280 itself. With additional data, we expect to reduce this uncertainty and achieve $\sim 1\%$ overall systematic error in the ND280 samples.

Neutrino Interaction T2K has engaged in continuous development and improvement of neutrino-nucleus interaction modelling, including effects arising from nucleon correlations and final state interaction of hadrons within the target nucleus. These models are further constrained by the near detector, but the constraints are limited by differences in the neutrino energy spectrum and acceptances between the near detector and Super-K.

We will continue to engage in model developments and comparisons with ND280 and externally published measurements. Combined with the recent incorporation of neutrino interactions on the water targets and future improvements to the phase space coverage of the ND280 measurements, systematic errors, and flux prediction uncertainties, we expect to reduce the flux and cross section systematics. The large sample of $\nu_e/\bar{\nu}_e$ events in ND280 with the additional running will also allow us to improve the uncertainties arising from uncertainties in the ratios $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ and $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$. In addition, a task force was formed by the collaboration in 2015 to investigate the prospect and need of ND280 upgrade.

Super-K Systematics Improvement The current Super-K detector systematic errors are determined mainly by a fit to the Super-K atmospheric neutrino data and constraints on the energy scale uncertainty from cosmic muon control samples. The atmospheric neutrino fit will be updated to include the cross section modelling from the T2K data. Longer-term improvements would utilize calibration, entering muon, and decay electron data to constrain fundamental detector parameters, rather than fitting neutrino data, which is susceptible to atmospheric flux and neutrino cross section uncertainties. The expected improvement to the Super-K detector uncertainties is under study. The secondary interaction and final state interaction systematic errors uncertainties will also benefit from the ND280 and external pion interaction measurements and neutrino interaction model development.

Short Summary The current systematic error on the far detector prediction is 5.5 to 6.8%. Considering the present situation and projected improvements, we consider that 4% systematic error is a reachable and reasonable target for T2K-II. In what follows, this improvement in systematic error is modelled by scaling the covariance matrix that reflects the current systematic error to obtain an uncertainty in the far detector prediction that is 2/3 its current size. Whether a near detector upgrade is needed to achieve this goal will be investigated in one year time scale.



(a) Assuming the MH is unknown.

(b) Assuming the MH is known – measured by an outside experiment.

Figure 2: Sensitivity to CP violation as a function of true δ_{CP} for the full T2K-II exposure of 20×10^{21} POT with a 50% improvement in the effective statistics, a reduction of the systematic uncertainties to 2/3 of their current size, and assuming that the true MH is the normal MH.

4 Expected Physics Outcomes

CP violation and precise determination of Δm_{32}^2 and $\sin^2\theta_{23}$

We assume that the full T2K-II exposure is 20×10^{21} POT taken equally in ν -mode and $\bar{\nu}$ -mode. Further optimization of the running ratio between ν -mode and $\bar{\nu}$ -mode will be pursued in the future. Sensitivities were initially calculated with the current T2K (2016 oscillation analysis) event rates and systematics, and the effect of the enhancements from beam line and analysis improvements was implemented by a simple scaling. Assumed relevant oscillation parameters are: $\sin^2 2\theta_{13} = 0.085$, $\sin^2\theta_{23} = 0.5$, $\Delta m_{32}^2 = 2.5 \times 10^{-3}$ eV², and normal mass hierarchy (MH). Cases for the current 90% C.L. edges of $\sin^2\theta_{23}$ *i.e.* 0.43 and 0.6 are also studied.

The sensitivity to CP violation ($\Delta\chi^2$ for resolving $\sin\delta_{CP} \neq 0$) plotted as a function of true δ_{CP} is given in Fig. 2 for the full T2K-II exposure with a 50% statistical improvement and a reduction of the systematic uncertainties to 2/3 of its current magnitude. When calculating sensitivities, the values of $\sin^2\theta_{23}$, Δm_{32}^2 , and δ_{CP} are assumed to be constrained by the T2K-II data only, while $\sin^2 2\theta_{13}$ is constrained by $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ [9]. Several experiments (JUNO, NOvA, ORCA, PINGU) are expected or plan to determine the mass hierarchy before or during the proposed period of T2K-II[10, 11, 12, 13]. Hence both MH-unknown and -known cases are shown in Fig. 2. The fractional region for which $\sin\delta_{CP} = 0$ can be excluded at the 99% (3 σ) C.L. is 70% (36%) of possible true values of δ_{CP} assuming the improved systematic errors and that the MH has been determined by an outside experiment. If systematic errors are eliminated completely, the fractional region where CPV can be resolved by 99% (3 σ) becomes 73% (43%).

The expected evolution of the sensitivity to CP violation ($\Delta\chi^2$ for resolving $\sin\delta_{CP} \neq 0$) as a function of POT assuming that the T2K-II data is taken in roughly equal alternating periods of ν -mode and $\bar{\nu}$ -mode (with true normal MH and $\delta_{CP} = -\pi/2$) is given in Fig. 3.

The expected 90% C.L. contour for Δm_{32}^2 vs $\sin^2\theta_{23}$ for the full T2K-II exposure is shown in Fig. 4. The expected 1 σ precision on $\sin^2\theta_{23}$ is $\sim 1.7^\circ$ ($\sim 0.7^\circ$) assuming $\sin^2\theta_{23} = 0.5$ ($\sin^2\theta_{23} = 0.43, 0.6$), and the expected precision on Δm_{32}^2 is $\sim 1\%$ assuming the true oscillation parameters given above and true $\delta_{CP} = -\pi/2$.

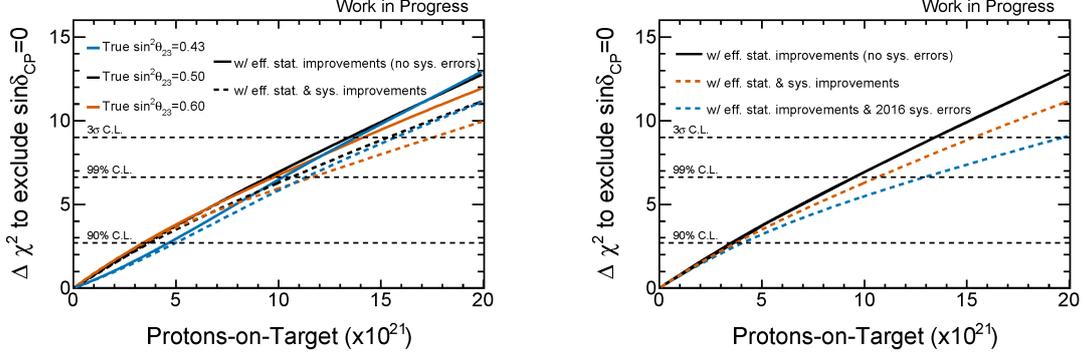
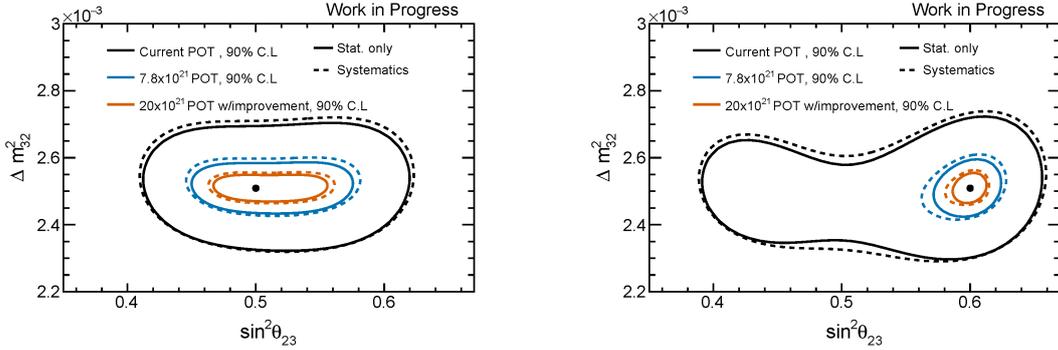


Figure 3: Sensitivity to CP violation as a function of POT with a 50% improvement in the effective statistics, assuming the true MH is the normal MH and the true value of $\delta_{CP} = -\pi/2$. The plot on the left compares different true values of $\sin^2 \theta_{23}$, while that on the right compares different assumptions for the T2K-II systematic errors with $\sin^2 \theta_{23} = 0.50$.



(a) Assuming true $\sin^2 \theta_{23} = 0.50$.

(b) Assuming true $\sin^2 \theta_{23} = 0.60$.

Figure 4: Expected 90% C.L. sensitivity to Δm_{32}^2 and $\sin^2 \theta_{23}$ with the 2016 systematic error. The current POT corresponds to 6.9×10^{20} POT ν - + 4.0×10^{20} POT $\bar{\nu}$ -mode. For the ultimate T2K-II exposure of 20×10^{21} POT, a 50% increase in effective $\bar{\nu}$ statistics is assumed.

Neutrino Interaction Studies

The additional run time of T2K-II will provide improved measurements of neutrino and antineutrino scattering, which probe nuclear structure through the axial vector current; these data sets may be used to solve long-standing experimental disagreements seen in previous measurements. The reduced uncertainties of the neutrino/antineutrino flux, increased statistical samples, and improvements to the acceptance of the T2K detectors will enable more detailed kinematic measurements to be made for interaction channels already measured by T2K, including studies of nuclear effects relevant for quasi-elastic and single pion resonance channels and measurements on water. T2K also has near detectors placed in two different locations; combined measurements of these detectors provide unique information about the energy dependence of neutrino interactions.

With T2K-II, there are two opportunities for neutrino interaction studies which are otherwise limited by statistical uncertainty. First, are measurements of neutrino interactions in the argon gas of the TPCs, where a very low threshold for tracking (below what can be achieved with liquid argon detectors) can provide unique information about proton multiplicity in neutrino-nucleus interactions. Approximately 10,600 ν -Ar and 1,900 $\bar{\nu}$ -Ar interactions are expected. Second, with expected datasets of 8,000 ν_e CC and 2,000 $\bar{\nu}_e$ CC candidates, the differences between electron and muon neutrino interactions can be studied; these differences are an important source of systematic uncertainty for CP violation measurements.

Non-standard Physics Studies

The high statistics at T2K-II would enable world-leading searches for various physics beyond the standard model. The combination of accelerator-based long baseline measurements with $\nu_\mu/\bar{\nu}_\mu$ beams and reactor measurements with $\bar{\nu}_e$ flux may give redundant constraints on $(\Delta m_{32}^2, \sin^2 \theta_{23}, \delta_{CP})$. Any inconsistency among these measurements would indicate new physics such as unitarity violation in the three-flavor mixing, sterile neutrinos, non-standard interactions, or CPT violation. With measurements at the near detectors, one could search for, for example, sterile neutrinos introduced to account for the LSND or reactor anomalies, non-standard interactions in neutrino production or interaction, heavy sterile neutrino decay, and neutrino magnetic moments larger than the standard model prediction. Sidereal time dependence of the event rate either at the near detector or Super-K can be used to search for Lorentz violation.

Since neutrino mass likely originates from physics at very high energy scales ($\gtrsim 10^{14}$ GeV), new physics at these energy scales could produce effects of comparable size to neutrino oscillation. Redundant and precise measurements of neutrino oscillation are equally compelling and complementary to precision searches at colliders for new physics at the TeV scale.

5 Prospects

The T2K collaboration has a strong interest to further pursue the long baseline experiment beyond the current data taking goal to explore CP violation in a wide range of δ_{CP} with 99%C.L., to reach 3σ or higher sensitivity for the case of maximum CP violation, to precisely determine oscillation parameters, and to search for possible new physics. We will quantify the impact of hardware upgrades and analysis improvements to the physics potential of such an extension in a letter-of-intent in 2016. The collaboration will also welcome new members to participate in a formal proposal.

References

- [1] K. Abe *et al.* [T2K Collaboration], Phys. Rev. Lett. **112**, 061802 (2014) doi:10.1103/PhysRevLett.112.061802 [arXiv:1311.4750 [hep-ex]].
- [2] K. Abe *et al.* [T2K Collaboration], Phys. Rev. D **91**, no. 7, 072010 (2015) doi:10.1103/PhysRevD.91.072010 [arXiv:1502.01550 [hep-ex]].
- [3] K. Abe *et al.* [T2K Collaboration], PTEP **2015**, no. 4, 043C01 (2015) doi:10.1093/ptep/ptv031 [arXiv:1409.7469 [hep-ex]].
- [4] K. Abe *et al.* [Hyper-Kamiokande Proto-Collaboration], PTEP **2015**, 053C02 (2015) doi:10.1093/ptep/ptv061 [arXiv:1502.05199 [hep-ex]].
- [5] *Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report*, <http://lbne2-docdb.fnal.gov/cgi-bin/ShowDocument?docid=10687&asof=2015-7-14>
- [6] F. Naito, *PAC for Nuclear and Particle Physics experiments at the J-PARC 50 GeV Proton Synchrotron*, <https://kds.kek.jp/indico/event/19054/>
- [7] T. Kobayashi, *Workshop for Neutrino Program with Facilities in Japan*, <https://kds.kek.jp/indico/event/19079/>
- [8] N. Saito, *International Workshop for the Next Generation Nucleon Decay and Neutrino Detector (NNN15)*, <https://www.bnl.gov/nnn2015/>
- [9] K. A. Olive *et al.* [Particle Data Group Collaboration], Chin. Phys. C **38**, 090001 (2014). doi:10.1088/1674-1137/38/9/090001
- [10] F. An *et al.* [JUNO Collaboration], arXiv:1507.05613 [physics.ins-det].
- [11] R. B. Patterson [NOvA Collaboration], Nucl. Phys. Proc. Suppl. **235-236**, 151 (2013) doi:10.1016/j.nuclphysbps.2013.04.005 [arXiv:1209.0716 [hep-ex]].
- [12] M. G. Aartsen *et al.* [IceCube PINGU Collaboration], arXiv:1401.2046 [physics.ins-det].
- [13] U. F. Katz [KM3NeT Collaboration], [arXiv:1402.1022 [astro-ph.IM]].