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Sensitivity of the T2K accelerator-based neutrino experiment with an Extended run to 20×10^{21} POT

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Recent measurements at the T2K experiment 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 $3\,\sigma$ 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.

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I. INTRODUCTION

The discovery of $\nu_\mu \rightarrow \nu_e$ oscillations by the T2K accelerator-based long-baseline experiment[1, 2] 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[3]. 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[4–6]. 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[7]. Recent results from the NOvA experiment[8], another accelerator-based long-baseline experiment, are consistent with this picture, though the statistical uncertainties are still large. In this maximal case, T2K could observe CPV with 90% C.L. sensitivity with the 7.8×10^{21} POT currently approved by J-PARC and expected by around 2020[9]. Future proposed projects such as Hyper-Kamiokande[10] and DUNE[11] 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 until 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 $3\,\sigma$ 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 discuss the physics potential resulting from these combined developments.

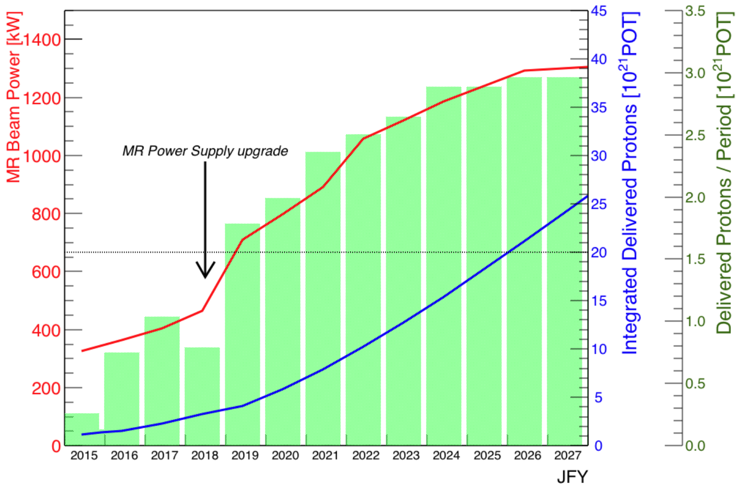


FIG. 1: Anticipated MR beam power and POT accumulation vs. calendar year.

II. DATA ACCUMULATION PLAN AND IMPROVEMENT OF EFFECTIVE STATISTICS

a. Projected MR beam power and POT accumulation The MR beam power has steadily increased since the start of the operation. In May 2016, 420 kW beam with 2.2×10^{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 a 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[12] and anticipated beam power of 1.3 MW with 3.2×10^{14} ppp and a repetition cycle of 1.16 seconds were presented[13, 14]. A possible data accumulation scenario is shown in Fig. 1, where 5 months of 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 of operation each year and by JFY2025 with 6 months of operation each year.

b. 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%.

c. 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^2_{32} and subsequently CP violation through the improved constraint on these parameters. We expect to reduce the NCπ^+ 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 CCπ^+ 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%.

d. 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 I assuming either true $\delta_{CP} = 0$

TABLE I: 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: $\sin^2 2\theta_{13} = 0.085$, $\sin^2 \theta_{23} = 0.5$, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, and normal mass hierarchy (MH).

	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	467.6	356.3	4.0	73.3	1.8	32.3
ν_e sample	$-\pi/2$	558.7	448.6	2.8	73.3	1.8	32.3
$\bar{\nu}$-mode	0	133.9	16.7	73.6	29.2	0.4	14.1
$\bar{\nu}_e$ sample	$-\pi/2$	115.8	19.8	52.3	29.2	0.4	14.1

	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	2735.0	2393.0	158.2	1.6	7.2	175.0
$\bar{\nu}$-mode $\bar{\nu}_\mu$ sample	1283.5	507.8	707.9	0.6	1.0	66.2

or $-\pi/2$.

III. 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 encapsulates the first order impact of systematic errors on the oscillation parameter measurements and the current sizes are summarized in Table II. The CP phase δ_{CP} is measured through the difference in the oscillation probabilities for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$. 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 mainly from the precision of the θ_{13} measurement by reactor

TABLE II: 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.

	$\delta_{N_{SK}}/N_{SK}$ (%)				
	1-Ring μ		1-Ring e		
Error Type	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	1.2
NC Other Cross-section	0.7	0.7	0.2	0.3	0.1
Total Systematic Error	5.6	5.5	5.7	6.8	5.9
External Constraint on θ_{12}, θ_{13}, Δm^2_{21}	0.0	0.0	4.2	4.0	0.1

experiments($\sin^2(2\theta_{13}) = 0.085 \pm 0.005$)[15]. 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. IV, 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.

e. Neutrino Flux The neutrino flux prediction[16] 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 ($\sim$ 600 MeV), these are currently $\sim$ 9% and $\sim$ 0.3% , respectively. Further 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.

f. 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.

g. Neutrino Interaction T2K has engaged in continuous development and improvement of neutrino-nucleus interaction modelling[17, 18], including effects arising from nucleon correlations[19, 20] 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 $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$[21]. In addition, a task force was formed by the collaboration in 2015 to investigate the prospect and need of ND280 upgrade.

h. 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.

i. 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.

IV. EXPECTED PHYSICS OUTCOMES

j. CP violation and precise determination of Δm^2_{32} and $\sin^2\theta_{23}$

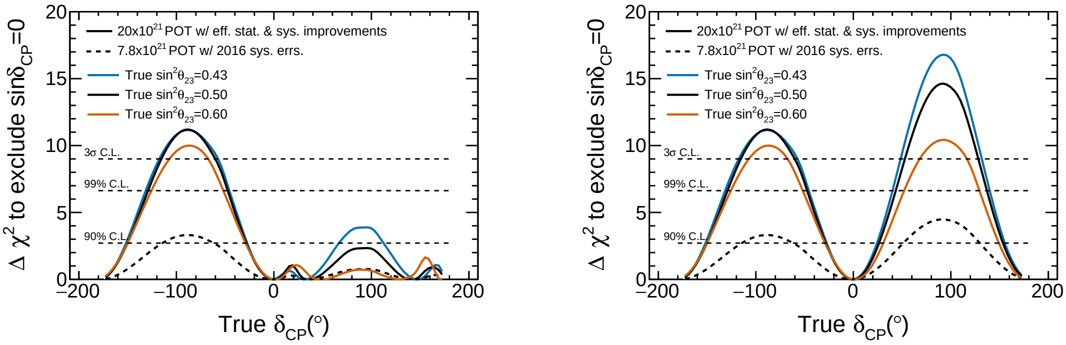
We assume that the full T2K-II exposure is 20×10^{21} POT taken equally in ν-mode and $\bar{\nu}$-mode. Further optimization of the running ratio between ν-mode and $\bar{\nu}$-mode will be pursued in the future. Sensitivities were initially calculated with the current T2K (2016 oscillation analysis) 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: $\sin^2 2\theta_{13} = 0.085$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.5\times10^{-3}$ eV^2, 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^2_{32}, and δ_{CP} are assumed to be constrained by the T2K-II data only, while $\sin^2 2\theta_{13}$ is constrained by $\sin^2 2\theta_{13} = 0.085\pm0.005$[15].

Several experiments (JUNO[22], NOvA[23], ORCA[24], PINGU[25]) are expected or plan to determine the mass hierarchy before or during the proposed period of T2K-II. 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% (3σ) C.L. is 49% (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% (3σ) becomes 51% (43%). More details of coverage at different values of $\sin^2\theta_{23}$ can be found in Table III.

TABLE III: Table of δ_{CP} fractional coverages (%) with three options of systematic treatment: no systematic error (statistical only), 2016 systematics and improved systematics. The coverages are calculated at three different values of $\sin^2\theta_{23}$ (0.43, 0.5, and 0.60) and it is assumed that the MH has been determined by an outside experiment.

	$\sin^2\theta_{23} = 0.43$		$\sin^2\theta_{23} = 0.50$		$\sin^2\theta_{23} = 0.60$	
—	99% C. L.	3σ	99% C. L.	3σ	99% C. L.	3σ
Stat. Only	57.5	47.9	53.3	43.1	49.1	36.7
2016 systematics	45.6	28.3	41.6	20.5	34.7	5.2
Improved systematics	51.5	39.7	48.6	36.1	41.8	23.9



(a) Assuming the MH is unknown.

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

FIG. 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.

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

k. Neutrino Interaction Studies

The additional run time of T2K-II will provide improved measurements of neutrino and

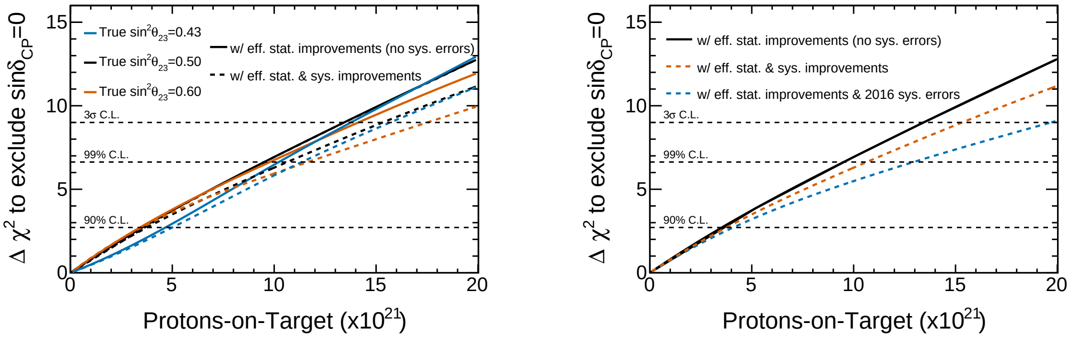
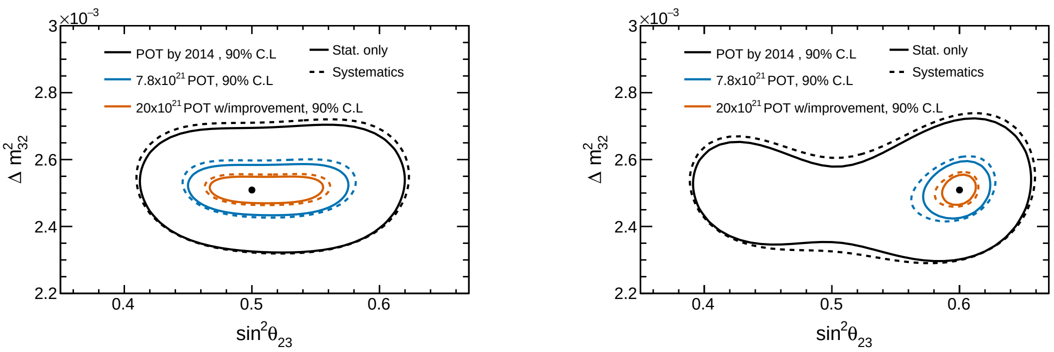


FIG. 3: Sensitivity to CP violation as a function of POT with a 50% improvement in the effective statistics, assuming the true MH is the normal MH and the true value of $\delta_{CP} = -\pi/2$. The plot on the left compares different true values of $\sin^2\theta_{23}$, while that on the right compares 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 $\sin^2\theta_{23} = 0.60$.

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

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.

l. 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 $(\Delta m^2_{32}, \sin^2\theta_{23}, \delta_{CP})$. 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[26] or reactor anomalies[27], 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[28].

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.

V. SUMMARY

The prospect of the accelerator intensity and beamline upgrades togehter with analysis improvements are discussed based on the running experience. The extended running of the T2K experiment from 7.8×10^{21} protons-on-target to 20×10^{21} protons-on-target enables exploration of CP violation in a wide range of δ_{CP} with 99%C.L., to reach $3\,\sigma$ or higher sensitivity for the case of maximum CP violation, to precisely determine oscillation parameters, and to search for possible new physics. This program would occur before the next generation of long-baseline neutrino oscillation experiments that are expected to start operation in 2026.

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CNRS/IN2P3: Centre National de la Recherche ScientifiqueInstitut National de Physique Nucleaire et de Physique des Particules RSF: Russian Science Foundation MES: Ministry of Education and Science, Russia ERDF: European Regional Development Fund SNSF: Swiss National Science Foundation SER (should be SERI): State Secretariat for Education, Research and Innovation

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