Latest Results from T2K and Hyper-Kamiokande Perspectives

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Abstract. We present a review of the latest results on the oscillation mixing parameters obtained by the T2K collaboration and foreseen for the Hyper-Kamiokande experiment by the Hyper-Kamiokande Working Group.

1. Introduction

Neutrino oscillations are governed by the 3×3 Pontecorvo-Maki-Nakagawa-Sakata [1, 2] mixing matrix and parameterized by two mass-squared differences, Δm^2_{21} and Δm^2_{32}; three mixing angles, θ_{12}, θ_{23}, and θ_{13}; and a complex CP-violating phase, δ_{CP}. In recent years, the mass-squared differences and the mixing angles have all been measured to be non-zero [3]. All the parameters except for δ_{CP}, the θ_{23} octant (maximal or non-maximal) and the mass hierarchy have been previously measured as summarized in Reference [3]. The mass hierarchy, MH, is defined normal mass hierarchy (NH) if $\Delta m^2_{31} > 0$ and inverted mass hierarchy (IH) if $\Delta m^2_{31} < 0$.

Both the T2K [4] and Hyper-Kamiokande (Hyper-K) [5] experiments aim to measure θ_{23} and $|\Delta m^2_{31}| \approx |\Delta m^2_{32}|$ precisely via ν_μ disappearance. The T2K and Hyper-K experiments can also measure ν_μ to ν_e appearance that is sensitive to θ_{13} and can explore δ_{CP}, especially through the CP-odd term, in the oscillation probability equation. Hyper-K is specifically designed to measure the CP violation in the neutrino sector, thanks to the increased beam power with respect to T2K and a much larger far detector.

In proceeding, the latest results from T2K and the foreseen sensitivity of Hyper-K for the measurement of the oscillation parameters is presented.

2. The T2K Experiment

An intense and high purity ν_μ beam is produced at J-PARC by colliding a 30 GeV proton beam with a graphite target, then focusing the resulting charged hadrons by magnetic horns prior to decay into neutrinos. The far detector, Super-Kamiokande (SK), is situated 2.5° off-axis from the neutrino beam resulting in a narrow-band energy spectrum peaked at 0.6 GeV, which maximizes the ν_e appearance probability at a baseline of $L = 295\,\mathrm{km}$ and minimizes high energy backgrounds. This baseline corresponds to a matter effect correction of $|x| \approx 5\%$ [6]. The near detector complex, 280 m from the average neutrino production point, consists of an on-axis (INGRID) detector to constrain the beam direction and an off-axis (ND280) detector to constrain the neutrino flux and cross sections.

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The flux prediction is based on simulations tuned and constrained by hadron production data from the NA61/SHINE experiment and in-situ proton beam monitoring. The NEUT simulation package is used for the neutrino interaction model, with prior constraints based on external neutrino, pion and nucleon scattering cross section measurements.

The SK analysis uses a single-ring sample, which enhances charged current (CC) quasi-elastic (QE) events, separated into μ-like (ν_μ) and e-like (ν_e) sub-samples. The ND280 analysis selects charged current (CC) ν_μ interactions and separates the sample based on the number of reconstructed pions and decay electrons: CC0π, CC1π and CC Other. These topologies provide a strong constraint on the flux and interaction model governing CCQE scattering and resonant pion production, the signal and main background to the SK analysis, respectively. The reduction in the uncertainty on the SK predicted event rates due to the ND280 data is shown in Table 1. The SK and ND280 detector errors are constrained by calibration data and control samples such as cosmic rays and atmospheric neutrinos. More details of the SK and ND280 analyses can be found in previous T2K publications e.g. [7, 8] and the references therein.

Table 1. Summary of the effect of the systematic errors on the SK ν_e and ν_μ candidate total event rates. The prior uncertainties in () brackets do not include the ND280 data.

Systematic Error Source	Relative Uncertainty (%)	
	ν_μ Candidates	ν_e Candidates
Flux & Xsec. ND280 Constrained (Prior)	2.7 (21.7)	3.1 (26.0)
Xsec. ND280 Independent	5.0	4.7
Pion Hadronic Interactions	3.5	2.3
SK Detector	3.6	2.9
Total ND280 Constrained (Prior)	7.6 (23.4)	6.8 (26.8)

We estimate oscillation parameters using an unbinned maximum likelihood fit to the SK spectrum for the parameters $\sin^2(\theta_{23})$ and either Δm^2_{32} or Δm^2_{13} for the normal and inverted mass hierarchies respectively, and all 45 systematic parameters. The fit uses 73 unequal-width energy bins, and interpolates the spectrum between bins. Oscillation probabilities are calculated using the full three-flavor oscillation framework. Matter effects are included with an Earth density of $\rho = 2.6\,g/cm^3$ [6], δ_{CP} is unconstrained in the range $[-\pi, \pi]$, and other oscillation parameters are fit with constraints $\sin^2(\theta_{13}) = 0.0251 \pm 0.0035$, $\sin^2(\theta_{12}) = 0.312 \pm 0.016$, and $\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}$ eV$^2/c^4$ [3]. Two-dimensional confidence regions in the oscillation parameters are constructed using the Feldman-Cousins method [9], with systematics incorporated using the Cousins-Highland method [10]. Figure 1 shows 68% and 90% confidence regions for the oscillation parameters for both normal and inverted hierarchies.

We calculate one-dimensional (1D) limits using a new method inspired by Feldman-Cousins [9] and Cousins-Highland [10] that marginalizes over the second oscillation parameter. The 1D 68% confidence intervals are $\sin^2(\theta_{23}) = 0.514^{+0.055}_{-0.056}$ (0.511 ± 0.055) and $\Delta m^2_{32} = 2.51 \pm 0.10$ ($\Delta m^2_{13} = 2.48 \pm 0.10$) $\times 10^{-3}$eV$^2/c^4$ for the NH (IH). The best fit corresponds to the maximal possible disappearance probability for the three-flavor formula.

To measure δ_{CP}, we use a frequentist-based analysis. The best fits for the oscillation parameters after minimizing over all parameters are shown in Table 2 for the NH and IH assumptions. The errors are based on the 1D constant-$\Delta\chi^2$ profile for each parameter. Allowed intervals for δ_{CP} with the reactor constraint are shown in Figure 2 for the frequentist-based analysis including a Feldman-Cousins (FC) critical $\Delta\chi^2$ correction ($\Delta\chi^2_c$) and the Bayesian analysis using the posterior probability and CIs. $\delta_{CP} \approx -\pi/2$ is preferred since the T2K data alone prefers a larger θ_{13} compared to the reactor data.

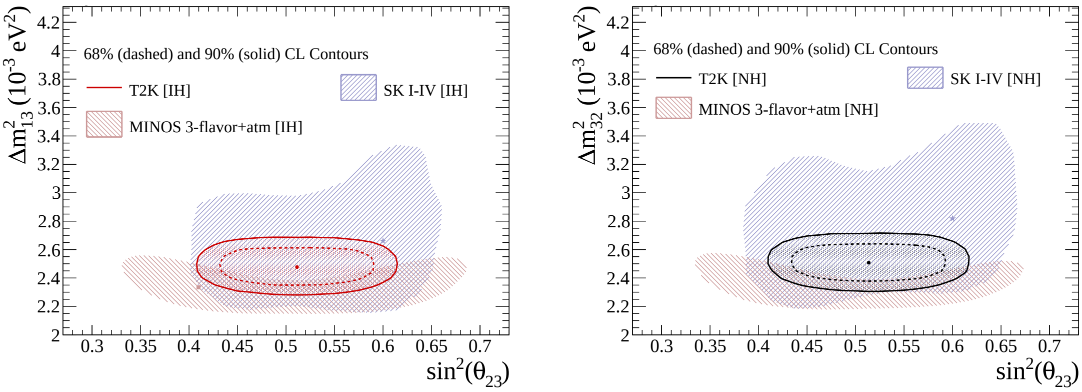

Figure 1. Contours comparing T2K Run 1-4 result with Super-K [11] and MINOS [12] for the Normal (Inverted) Hierarchy in the left (right) plot. The Super-K is a 3-flavor analysis of the atmospheric neutrino data using SK Runs I-IV. The MINOS result is a 3-flavor analysis using both of their ν_μ-disappearance and ν_e-appearance beam neutrino samples along with their atmospheric neutrino sample. For the MINOS contour, both the normal and inverted hierarchy contours are made with respect to a common minimum that is located in the inverted hierarchy parameter space.

Table 2. Best-fits and 1D constant-$\Delta\chi^2$ 68% confidence intervals (errors) for the oscillation parameters assuming each MH with and without the reactor constraint. Δm^2_{32} (Δm^2_{13}) is used for the NH (IH) assumption. The errors are not shown for δ_{CP} in the T2K-only case since there is no strong constraint. The errors for the other parameters in the reactor-constrained case are not yet calculated and will be shown in a future publication, while the exclusion region for δ_{CP} is shown in Figure 2.

	MH	$\lvert\Delta m^2_{32,13}\rvert$ [$\times 10^{-3}$ eV^2]	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP} (rad)
T2K-only	NH	$2.51^{+0.11}_{-0.12}$	$0.524^{+0.057}_{-0.059}$	$0.0422^{+0.0128}_{-0.0212}$	1.9
	IH	2.49 ± 0.12	$0.523^{+0.073}_{-0.065}$	$0.0491^{+0.0149}_{-0.0211}$	1.0
Reactor-constrained	NH	2.51	0.527	0.0248	-1.55
	IH	2.48	0.533	0.0252	-1.56

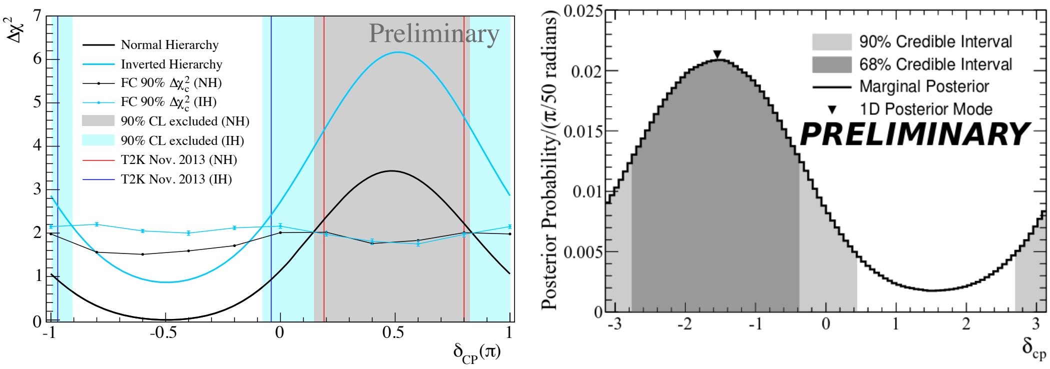

Figure 2. Left: The $\Delta\chi^2$ profile for δ_{cp}, showing the 90% CL regions based on the FC $\Delta\chi^2_c$ for NH and IH. Right: The posterior probability and 68% and 90% CIs for δ_{CP}, marginalized over all the other parameters including the MH with priors $\pi(\text{NH}) = \pi(\text{IH}) = 0.5$.

Table 3. The expected number of ν_e and ν_μ candidate events for the appearance and disappearance final states, respectively. NH, $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$ are assumed. Background is categorized by the flavor before oscillation.

Appearance

	signal		BG					total
	$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ	$\overline{\nu}_\mu$	ν_e	$\overline{\nu}_e$	NC	
ν mode	3016	28	11	0	503	20	172	3750
$\bar{\nu}$ mode	396	2110	4	5	222	265	265	3397

Disappearance

	signal		BG				total
	$\nu_\mu \to \nu_\mu$	$\overline{\nu}_\mu \to \overline{\nu}_\mu$	ν_e	$\overline{\nu}_e$	NC	$\nu_\mu \to \nu_e$	
ν mode	17225	1088	11	1	999	49	19372
$\bar{\nu}$ mode	10066	15597	7	7	1281	6	26964

3. The Hyper-Kamiokande Experiment

The Hyper-Kamiokande experiment [5] is the next generation flagship experiment for the study of neutrino oscillations, nucleon decays, and astrophysical neutrinos. The detector is a third generation underground water Cherenkov (WC) detector situated in Kamioka, Japan. It consists of a 1 million tonne water target which is about 20 times larger than that of the existing Super-Kamiokande detector. It will serve as the far detector for a long baseline neutrino oscillation experiment planned for the upgraded J-PARC beam. It will also serve as a detector capable of observing proton decays, atmospheric neutrinos, and neutrinos from astronomical origins enabling measurements that far exceed the current world best measurements. Hyper-K has a sensitivity to the mass hierarchy through the atmospheric neutrino measurements and will be able to make a definitive measurement. A recent update of the previous sensitivity studies presented in 2011 [5] is based on the latest values of θ_{13} (it was not known at that time) or more generally the latest knowledge of the oscillation parameters, a framework for sensitivity studies developed for the sensitivity study by T2K reported in [13] and the latest systematic errors based on the experience and prospects of the T2K experiment. The document, that contains an update on the R&D of the experiment as well, was submitted in April 2014 to the J-PARC PAC. An integrated beam power of 7.5 MW$\times 10^7$ sec is assumed in this study. It corresponds to 1.56×10^{22} protons on target with 30 GeV J-PARC beam. The ratio of neutrino and anti-neutrino running time is assumed to be 1:3. The oscillation parameters used for the sensitivity analysis are: $\sin^2 2\theta_{13}$ (0.1, fitted), δ_{CP} (0, fitted), $\sin^2\theta_{23}$ (0.5, fitted), Δm^2_{32} (2.4×10^{-3} eV^2, fitted), mass hierarchy (normal, fitted), $\sin^2 2\theta_{12}$ (0.8704, fixed) and Δm^2_{12} (7.6×10^{-5} eV^2, fixed), where in parenthesis the nominal values used in the fits and the treatment used in the fits are indicated. The criteria to select ν_e and ν_μ candidate events are based on those developed for and established with the SK and T2K experiments, and the corresponding number of expected events is shown is Table 3. Figure 3 shows the expected significance to exclude $\sin\delta_{CP} = 0$ (the CP conserved case). The significance is calculated as $\sqrt{\Delta\chi^2}$, where $\Delta\chi^2$ is the difference of χ^2 for the *trial* value of δ_{CP} and for $\delta_{CP} = 0°$ or $180°$ (the smaller value of difference is taken). We have also studied the case with a reactor constraint but the result changes only slightly. Figure 3 (left) shows the fraction of δ_{CP} for which $\sin\delta_{CP} = 0$ is excluded with $3\,\sigma$ and $5\,\sigma$ of significance as a function of the integrated beam power. The normal mass hierarchy is assumed. The results for the inverted hierarchy is almost the same. *CP* violation in the lepton sector can be observed with $3(5)\,\sigma$ significance for 76(58)% of the possible values of δ_{CP}.

Figure 3 (right) shows the $1\,\sigma$ uncertainty of δ_{CP} as a function of the integrated beam power.

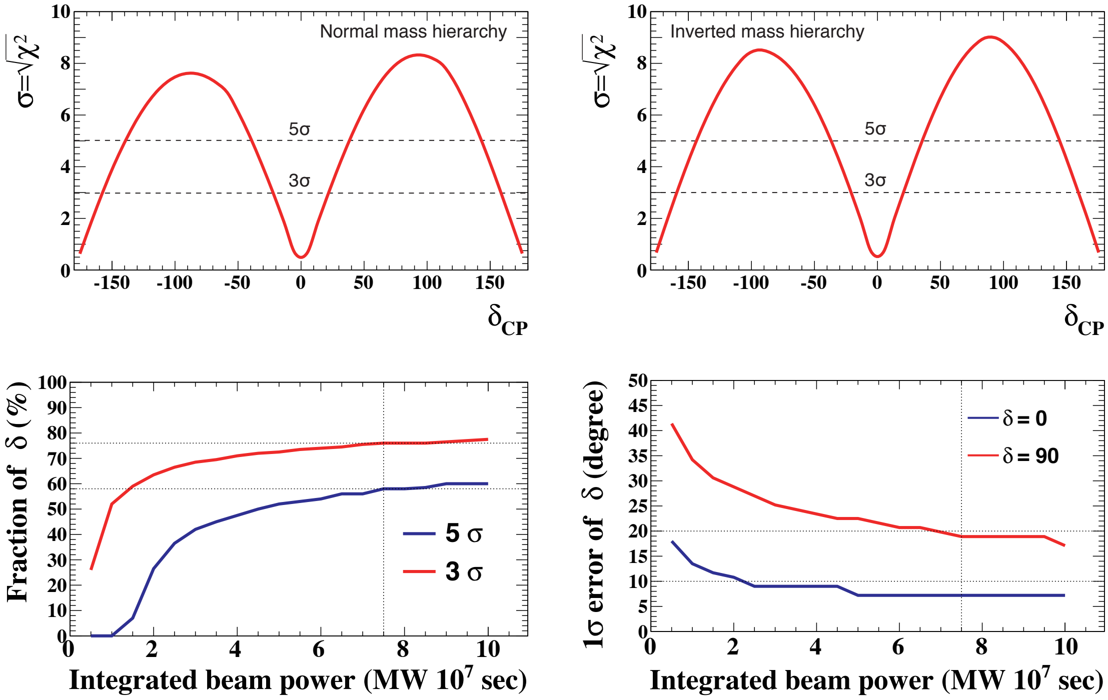

Figure 3. Upper row: expected significance to exclude $\sin\delta_{CP} = 0$. Left: normal hierarchy case. Right: inverted hierarchy case. Bottom row: fraction of δ_{CP} for which $\sin\delta_{CP} = 0$ can be excluded with $3\,\sigma$ (red) and $5\,\sigma$ (blue) significance as a function of the integrated beam power (NH). Right plot: expected $1\,\sigma$ uncertainty of δ_{CP} as a function of integrated beam power.

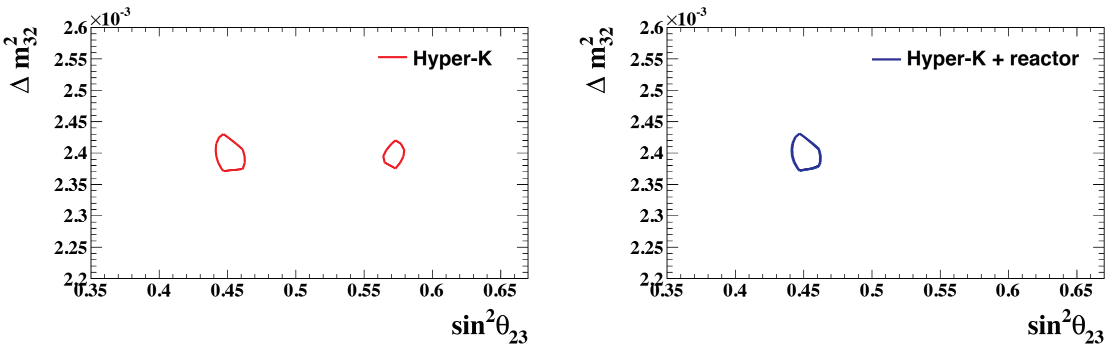

Figure 4. 90% CL allowed regions in the $\sin^2\theta_{23}$–Δm^2_{32} plane. The true values are $\sin^2\theta_{23} = 0.45$ and $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2. Effect of systematic uncertainties is included. Left plot: Hyper-K only. Right plot: With reactor constraint.

With 7.5 MW$\times 10^7$sec of exposure (1.56×10^{22} protons on target), the value of δ_{CP} can be determined to better than 19° for all values of δ_{CP}.

The use of ν_μ sample in addition to ν_e enables us to also measure $\sin^2\theta_{23}$ and Δm^2_{32} and Hyper-K will be able to provide a precise measurement of $\sin^2\theta_{23}$ and Δm^2_{32}. Figure 4 shows the 90% CL allowed regions on the $\sin^2\theta_{23}$-Δm^2_{32} plane, for the true values of $\sin^2\theta_{23} = 0.45$ and $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2. With a constraint on $\sin^2 2\theta_{13}$ from the reactor experiments, the octant degeneracy is resolved and θ_{23} can be precisely measured.

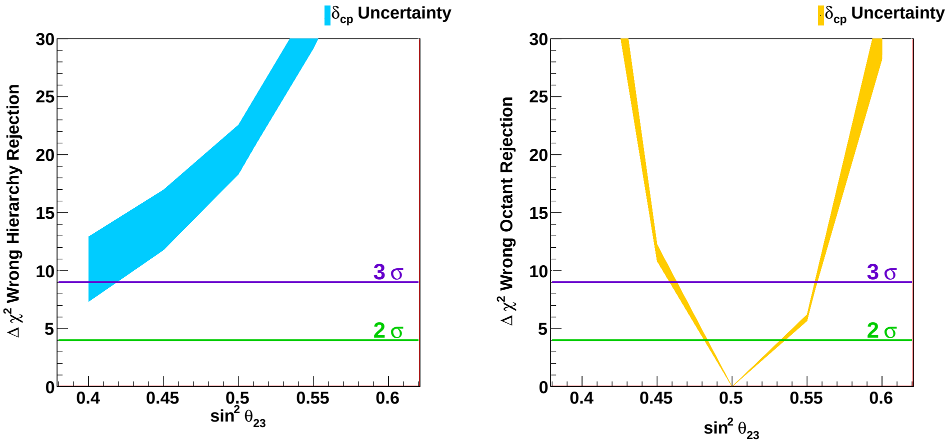

Figure 5. Atmospheric neutrino sensitivities for a ten year exposure of Hyper-K assuming the mass hierarchy is normal. Left: the $\Delta\chi^2$ discrimination of the wrong hierarchy hypothesis as a function of the assumed true value of $\sin^2\theta_{23}$. Right: the discrimination between the wrong octant for each value of $\sin^2\theta_{23}$. The uncertainty from δ_{cp} is given by the thickness of the band.

Atmospheric neutrinos can provide an independent and complementary information to the accelerator beam program on the study of neutrino oscillation. Assuming a 10 year exposure, Hyper-K's sensitivity to the mass hierarchy and the octant of θ_{23} by atmospheric neutrino data are shown in Fig. 5. Depending upon the true value of θ_{23} the sensitivity changes considerably, but for all currently allowed values of this parameter the mass hierarchy sensitivity exceeds $3\,\sigma$ independent of the assumed hierarchy. If θ_{23} is non-maximal, the atmospheric neutrino data can be used to discriminate the octant at $3\,\sigma$ if $\sin^2 2\theta_{23} < 0.99$.

4. Conclusion and Outlook

The first T2K combined ν_μ disappearance and ν_e appearance analysis based on 0.657×10^{21} POT is presented. T2K is producing the leading measurement on θ_{23} and, combined with reactor neutrino data, non-trivial exclusion intervals in δ_{CP}. T2K will continue to lead the search for CP violation in the lepton sector. Hyper-Kamiokande is the next generation long baseline neutrino experiment, which will benefit from an upgraded J-PARC neutrino beam and able to measure δ_{CP} with $3(5)\,\sigma$ significance for 76(58)% of the possible values of δ_{CP} to better than 19° for all values of δ_{CP}.

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