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, $\Delta m_{21}^2$ and $\Delta m_{32}^2$; three mixing angles, $\theta_{12}$, $\theta_{23}$, and $\theta_{13}$; and a complex CP-violating phase, $\delta_{CP}$. 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 $\delta_{CP}$, the $\theta_{23}$ 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 $\Delta m_{31}^2 > 0$ and inverted mass hierarchy (IH) if $\Delta m_{31}^2 < 0$.

Both the T2K [4] and Hyper-Kamiokande (Hyper-K) [5] experiments aim to measure $\theta_{23}$ and $|\Delta m_{31}^2| \approx |\Delta m_{32}^2|$ precisely via $\nu_\mu$ disappearance. The T2K and Hyper-K experiments can also measure $\nu_\mu$ to $\nu_e$ appearance that is sensitive to $\theta_{13}$ and can explore $\delta_{CP}$, 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 $\nu_\mu$ 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 $\nu_e$ appearance probability at a baseline of $L = 295$ 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 $\mu$-like ($\nu_{\mu}$) and $e$-like ($\nu_{e}$) sub-samples. The ND280 analysis selects charged current (CC) $\nu_{\mu}$ interactions and separates the sample based on the number of reconstructed pions and decay electrons: CC0$\pi$, CC1$\pi$ 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 $\nu_{e}$ and $\nu_{\mu}$ candidate total event rates. The prior uncertainties in () brackets do not include the ND280 data.

| Systematic Error Source | $\nu_{\mu}$ Candidates | $\nu_{e}$ 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 $\Delta m^{2}_{32}$ or $\Delta m^{2}_{23}$ 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 $\rho = 2.6 \text{ g/cm}^{3}$ [6], $\delta_{CP}$ 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 $\Delta m^{2}_{21} = (7.50 \pm 0.20) \times 10^{-5} \text{ eV}^{2}/c^{4}$ [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 $\delta_{CP}$, 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 $\delta_{CP}$ 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 Confidence Intervals. $\delta_{CP} \approx -\pi/2$ is preferred since the T2K data alone prefers a larger $\theta_{13}$ 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 $\nu_\mu$-disappearance and $\nu_e$-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. $\Delta m_{32}^2$ ($\Delta m_{13}^2$) is used for the NH (IH) assumption. The errors are not shown for $\delta_{CP}$ 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 $\delta_{CP}$ is shown in Figure 2.

| MH          | $|\Delta m^2_{32,13}| \times 10^{-3}$ eV$^2$ | $\sin^2 \theta_{23}$ | $\sin^2 \theta_{13}$ | $\delta_{CP}$ (rad) |
|-------------|------------------------------------------|------------------------|------------------------|----------------------|
| T2K-only    |                                         |                        |                        |                      |
| NH          | $2.51^{+0.11}_{-0.12}$                  | $0.524^{+0.031}_{-0.030}$ | $0.0422^{+0.012}_{-0.012}$ | 1.9                  |
| IH          | $2.49 \pm 0.12$                        | $0.523^{+0.073}_{-0.065}$ | $0.0491^{+0.013}_{-0.011}$ | 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 $\delta_{CP}$, showing the 90% CL regions based on the FC $\Delta \chi^2$ for NH and IH. Right: The posterior probability and 68% and 90% Confidence Intervals for $\delta_{CP}$, marginalized over all the other parameters including the MH with priors $\pi$(NH) = $\pi$(IH) = 0.5.
Table 3. The expected number of $\nu_e$ and $\nu_\mu$ candidate events for the appearance and disappearance final states, respectively. NH, $\sin^2\theta_{13} = 0.1$ and $\delta_{CP} = 0$ are assumed. Background is categorized by the flavor before oscillation.

|            | signal |                  | BG |                  | total |
|------------|--------|------------------|----|------------------|-------|
| $\nu$ mode| $\nu_\mu \rightarrow \nu_\mu$ | $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ | $\nu_\mu$ | $\bar{\nu}_\mu$ | $\nu_e$ | $\bar{\nu}_e$ | NC | $\nu_\mu \rightarrow \nu_e$ | $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ | $\nu_e$ | $\bar{\nu}_e$ | NC | $\nu_\mu \rightarrow \nu_e$ |
| $\nu$ mode| 3016   | 28               | 11 | 0                | 503   | 20            | 172 | 3750                          |
| $\nu$ mode| 396    | 2110             | 4  | 5                | 222   | 265           | 265 | 3397                          |

Disappearance

|            | signal |                  | BG |                  | total |
|------------|--------|------------------|----|------------------|-------|
| $\nu$ mode| $\nu_\mu \rightarrow \nu_\mu$ | $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ | $\nu_e$ | $\bar{\nu}_e$ | NC | $\nu_\mu \rightarrow \nu_e$ |
| $\nu$ mode| 17225  | 1088             | 11 | 1                | 999   | 49            | 19372                      |
| $\nu$ 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 value of $\theta_{13}$ (it was not known at that time) and more generally the latest knowledge of the oscillation parameters. It uses a framework for the oscillation analysis developed by T2K and 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 $1.56 \times 10^{22}$ protons on target (POT) 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: $\sin^2\theta_{13}$ (0, 1 fitted), $\delta_{CP}$ (0, fitted), $\sin^2\theta_{23}$ (0.5, fitted), $\Delta m^2_{32}$ (2.4 $\times$ 10$^{-3}$ eV$^2$, fitted), mass hierarchy (normal, fitted), $\sin^2\theta_{12}$ (0.8704, fixed) and $\Delta m^2_{12}$ (7.6 $\times$ 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 $\nu_e$ and $\nu_\mu$ 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 in Table 3. Figure 3 shows the expected significance to exclude $\sin \delta_{CP} = 0$ (the CP conserved case). The significance is calculated as $\sqrt{\chi^2}$, where $\chi^2$ is the difference of the trial value of $\delta_{CP}$ and for $\delta_{CP} = 0^\circ$ or 180$^\circ$ (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 $\delta_{CP}$ 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 $\delta_{CP}$.

Figure 3 (right) shows the 1$\sigma$ uncertainty of $\delta_{CP}$ 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 $\delta_{CP}$ for which $\sin \delta_{CP} = 0$ can be excluded with 3\(\sigma\) (red solid line) and 5\(\sigma\) (blue dashed line) significance as a function of the integrated beam power (NH). Right plot: expected 1\(\sigma\) uncertainty of $\delta_{CP}$ as a function of integrated beam power.

Figure 4. 90\% CL allowed regions in the $\sin^2 \theta_{23}$-$\Delta m_{32}^2$ plane. The true values are $\sin^2 \theta_{23} = 0.45$ and $\Delta m_{32}^2 = 2.4 \times 10^{-3}$ 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$\times$10$^{22}$ POT), the value of $\delta_{CP}$ can be determined to better than 19$^\circ$ for all values of $\delta_{CP}$.

The use of $\nu_\mu$ sample in addition to $\nu_e$ enables us to also measure $\sin^2 \theta_{23}$ and $\Delta m_{32}^2$ and Hyper-K will be able to provide a precise measurement of $\sin^2 \theta_{23}$ and $\Delta m_{32}^2$. Figure 4 shows the 90\% CL allowed regions on the $\sin^2 \theta_{23}$-$\Delta m_{32}^2$ plane, for the true values of $\sin^2 \theta_{23} = 0.45$ and $\Delta m_{32}^2 = 2.4 \times 10^{-3}$ eV$^2$. With a constraint on $\sin^2 2\theta_{13}$ from the reactor experiments, the
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 $\delta_{\text{cp}}$ is given by the thickness of the band.

Octant degeneracy is resolved and $\theta_{23}$ can be precisely measured.

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 $\theta_{23}$ by atmospheric neutrino data are shown in Figure 5. Depending upon the true value of $\theta_{23}$ 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 $\theta_{23}$ 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 $\nu_\mu$ disappearance and $\nu_e$ appearance analysis based on $0.657 \times 10^{21}$ POT is presented. T2K is producing the leading measurement on $\theta_{23}$ and, combined with reactor neutrino data, non-trivial exclusion intervals in $\delta_{\text{CP}}$. Hyper-Kamiokande is the next generation long baseline neutrino experiments. It will be able to measure $\delta_{\text{CP}}$ with 3(5) $\sigma$ significance for 76(58)% of the possible values of $\delta_{\text{CP}}$ to better than 19$^\circ$ for all values of $\delta_{\text{CP}}$.

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