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Long-baseline neutrino oscillation sensitivities with Hyper-Kamiokande and impact of Intermediate Water Cherenkov Detector

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Hyper-Kamiokande is a next-generation, long-baseline neutrino experiment under construction in Japan. It will measure neutrino oscillations using the J-PARC neutrino beam which is now serving the T2K experiment. The Hyper-Kamiokande far detector has a fiducial volume 8 times the size of the currently-running Super-Kamiokande detector, and will be instrumented with new photo-sensors. Combined with an upgraded J-PARC neutrino beam, Hyper-Kamiokande will be able to measure neutrino oscillations with unprecedented statistical precision, enabling the potential discovery of CP-violation and precise measurements of the atmospheric oscillation parameters. The Hyper-K sensitivity for a 10-year exposure shows 5-σ significance for the discovery of CP violation for > 55% of true δ_{CP} values and determination of the $\sin^2\theta_{23}$ octant for values outside (0.44, 0.58). This proceeding describes the Hyper-K analysis strategy including upgraded near detectors and the newly proposed Intermediate Water Cherenkov Detector (IWCD). The ability of these upgrades to minimize systematic uncertainties will be described, with emphasis on their effect on the neutrino oscillation sensitivity of Hyper-K.

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1. Introduction

The Hyper-Kamiokande (Hyper-K) experiment will use (anti-)ν_μ produced from the 1.3MW proton beam at J-PARC to measure the disappearance of (anti-)ν_μ and the appearance of (anti-) ν_e. The experiment consists of a suite of upgraded T2K near detectors at a baseline of 280 m, a new Intermediate Water Cherenkov Detector (IWCD) [1] at a 1 km baseline and the Hyper-K far detector situated 295 km away. A general overview of Hyper-K sensitivities is given in ref. [2].

The goal of the long-baseline part of the experiment is to measure neutrino CP violation, the $|\Delta m^2_{32}|$ mass ordering and the θ_{23} octant. This will lead to precise measurements of the neutrino oscillation parameters in the PMNS matrix. The estimated sensitivity from Hyper-K shows that these neutrino oscillation measurements are systematically limited. One of the dominant systematic uncertainties comes from the interaction cross sections of neutrinos with oxygen nuclei, which the IWCD aims to constrain. General analysis methods are summarised in sec. 2 with IWCD strategies in sec. 3 and Hyper-K sensitivities in sec. 4, as an update of previous studies [3, 4].

2. Analysis Methods

The simulation of the neutrino beam is performed using a Monte-Carlo generator as for T2K. In this analysis an exposure of 0.675×10^{21} (2.025×10^{21}) POT per year for the (anti-)neutrino beam is assumed. The Hyper-K analysis uses five event samples, four of which are optimised to preferentially select charged-current quasi-elastic (CCQE)-like events: 1-ring μ-like and 1-ring e-like in the neutrino and anti-neutrino beam modes. The fifth sample is a CC1$\pi^\pm$-like sample with 1 e-like ring and a Michel electron reconstructed in the detector, and is only available for the neutrino beam mode. For a nominal exposure of 10 years, a total of approx. 9300 (12300) events can be accumulated for the (anti-)ν_μ samples, assumed the normal neutrino mass ordering and with true $\sin^2(\theta_{13}) = 0.0218$, $\sin^2(\theta_{23}) = 0.528$, $\delta_{CP} = 0$ and $\Delta m^2_{32} = 2.509 \times 10^{-3} eV^2$. The ν_μ disappearance spectrum is sensitive to $\sin^2\theta_{23}$ and Δm^2_{32} from shifts in the energy and depth of the dip, respectively. For the (anti-)ν_e samples, a total of approx. 2700 (1600) events can be accumulated, providing sensitivity to δ_{CP} by comparing the number of events in the ν_e and $\bar{\nu}_e$ appearance spectra. The analysis uses a binned Poisson likelihood to fit these predicted spectra to various Monte Carlo datasets generated from different assumptions of oscillation parameter values.

The parameterisation of systematic uncertainties at Hyper-K is based on the T2K 2018 model [5] with slight modifications. The flux and cross section are parameterised over true neutrino energies using the results from ND280 postfit dataset as the nominal values. The far detector systematics are parameterised over reconstructed neutrino energies to constrain uncertainties on detector efficiencies, final state interactions (FSI), secondary interactions (SI) and the detector energy scale. The target performance of Hyper-K is described as "improved systematics", with uncertainties scaling down the T2K 2018 errors constrained from the ND280, based on the increased beam exposure and the assumed sensitivities of the ND280 upgrade detector and the IWCD.

3. IWCD Strategy

The IWCD contains an inner detector with a height of 6 m and diameter of 8 m to provide a 300 t fiducial volume. It's equipped with 500 "multi-PMT" (mPMT) photon detector modules.

PoS(NOW2022)028

Respect to the standard photosensor the mPMT, thanks to a better timing, can improve the neutrino-nucleus interaction vertex resolution. It is vertically movable between 1° - 4 ° off the neutrino beam axis to provide neutrino fluxes peaked from 0.4 GeV to 1 GeV.

The ν_μ spectra measured at different positions of IWCD can be combined linearly to produce arbitrary spectrum shapes to extract information on the ν_μ interaction cross section. Relatively large ν_e samples can be obtained at further off-axis angles (θ_{OA}) due to the 1% intrinsic ν_e contamination produced by hadron decays, helping constrain the relative ν_e and ν_μ interaction cross sections. The uncertainty on the ratio of the ν_e interaction cross section to the $\bar{\nu}_e$ cross section is the dominant systematic uncertainty on the Hyper-K CP violation sensitivity,

$$\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}. \tag{1}$$

The current T2K theory-driven errors [6] contribute a 3% error to the event rate for the *e*-like samples. Cross-section measurements can be affected by so-called "feed-down" events, where CC non-QE events with higher true neutrino energy are reconstructed with lower energies, which can change the shape of the reconstructed ν_e spectra. Neutrino interaction events with a large fraction of energies above 1 GeV are required to constrain such feed-down events, which can be achieved with larger θ_{OA} coverage of IWCD.

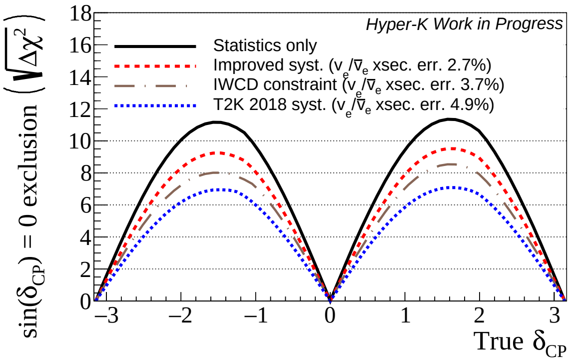
Sample selection at IWCD is performed based on reconstructed kinematic variables and θ_{OA} of the events, with 6 samples selected in total. The (anti-)ν_μ samples contain over a million events in each beam mode and constrain the neutrino flux and overall neutrino cross-section model. High-purity ν_e (approx. 18,000 events) and $\bar{\nu}_e$ (approx. 24,000 events) samples are provided to constrain parameters describing the difference in the (anti-)ν_e and (anti-)ν_μ cross-sections [7]. Major backgrounds in the (anti-)ν_e samples come from neutral current (NC) π^0 events and a small fraction of other NC events. These backgrounds are constrained by the large IWCD 2-ring π^0-like sample.

In reality, the true neutrino energy (E_ν) is unknown. In Hyper-K the true neutrino energy can be reconstructed from the measured lepton momenta and scattering angles assuming the neutrino underwent a CCQE interaction. Including the detector resolution effects on the lepton kinematics, this is referred to as “reco-E_ν^{CCQE}”. The relationship between E_ν and reco-E_ν^{CCQE} can be constrained from E_ν and true-E_ν^{CCQE}, where true-E_ν^{CCQE} is calculated using the Monte-Carlo truth charged lepton momenta and scattering angles but still assuming a CCQE interaction. Thus, cross-section systematics can be parameterised in E_ν (1-D), and also in E_ν vs $E_\nu-$true E_ν^{CCQE} (2-D) to provide extra degrees of freedom in the cross-section model. However, adding this extra freedom will increase the uncertainties on ν_e and ν_μ interaction cross sections, and motivates explicit studies to limit these uncertainties. The ongoing IWCD analysis has additional neutrino interaction cross-section constraints using both the 1-D and 2-D energy dependence, with the 2-D analysis having been performed without any input from the ND280 detector.

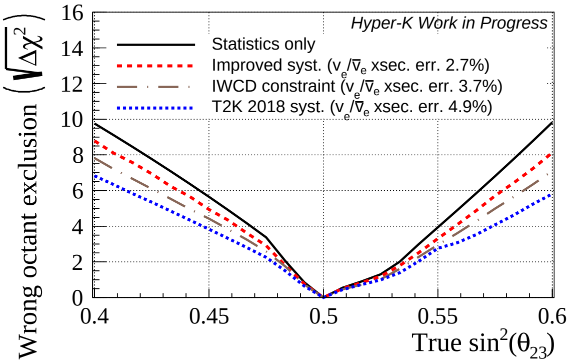
4. Hyper-K Sensitivities

Precise measurements of the oscillation parameters will be achievable with Hyper-K. With a 10-year beam run time assuming Hyper-K "improved" systematics, the 1-σ error on δ_{CP} will be 19° (6.5°) at −90° (0°). In addition, Hyper-K will reach an error of 0.32% on Δm^2_{32}, which is 3.6 times smaller than the current T2K results. For the sensitivity to CP violation and $\sin^2\theta_{23}$, Fig. 1 shows that the Hyper-K "improved" assumption can exclude CP−conservation at the 5-σ level for 61% of true δ_{CP} values, and can exclude the wrong octant at the 5-σ level for true $\sin^2\theta_{23} < 0.45$ and > 0.57, in both cases assuming that the neutrino mass ordering is known. In contrast, continuing with the T2K 2018 systematic uncertainties will exclude CP−conservation for 49% of true δ_{CP} values and provide wrong octant exclusion for true $\sin^2\theta_{23} < 0.43$ and > 0.59. These sensitivities can be improved further by combination with Hyper-K atmospheric neutrino data, which increases the significance with which Hyper-K can reject the incorrect neutrino mass ordering from 3.8-σ to 6.2-σ, with this significance increasing with the true value of $\sin^2\theta_{23}$.

The relative uncertainty on the 1-ring e-like event rates from ν_e in the neutrino beam and $\bar{\nu}_e$ in the anti-neutrino beam, labelled as $\nu_e/\bar{\nu}_e$ cross-section error, is shown in Fig. 1. The flux and cross-section are the dominant sources of the 1-ring e-like event rate uncertainties. Adding the IWCD cross-section constraints reduces the $\nu_e/\bar{\nu}_e$ error from 4.9% (the value in the T2K 2018 model) to 3.7%. This results in an increase in the fraction of true values of δ_{CP} for which Hyper-K can exclude CP−conservation at the 5-σ level from 49% to 58%. With the IWCD constraints, the wrong octant of true $\sin^2\theta_{23}$ can be excluded at 5-σ for true $\sin^2\theta_{23}$ values < 0.44 and > 0.58. The same sensitivity for CP violation is obtained with the IWCD 2-D constraint case.



(a) Significance level to exclude CP conservation



(b) Significance level to exclude the wrong $\sin^2\theta_{23}$ octant

Figure 1: Sensitivities after 10-year run time broken down into uncertainty types of statistical only, Hyper-K "improved", T2K 2018 model, and Hyper-K with the IWCD analysis with the additional neutrino interaction cross-section systematics parametrised in 1−D true neutrino energies. The fits have assumed normal ordering for $|\Delta m^2_{32}|$, true $\sin^2\theta_{23} = 0.528$ for (a), $\delta_{CP} = -1.601$ for (b), $\sin^2\theta_{13} = 0.0218$, $\Delta m^2_{32} = 2.509 \times 10^{-3} eV^2$.

5. Summary

The sensitivities for neutrino oscillation parameter measurements using Hyper-K have been demonstrated, together with the current strategy to reduce the neutrino cross-section uncertainties for the neutrino event rate using the IWCD. In general, the IWCD has demonstrated good potential to increase the sensitivity of Hyper-K for neutrino oscillation measurements. Comparisons of the oscillation sensitivities between T2K 2018 and Hyper-K with IWCD were made, showing a 3.7% $\nu_e/\bar{\nu}_e$ cross-section experimental error which improves upon the 4.9% theory-driven error currently used by T2K. In the future, more fit outcomes with different θ_{OA} are expected, with potential improvements through new uncertainty parameterisation schemes and sample selections.

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