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Status of the Hyper-Kamiokande experiment

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Hyper-Kamiokande is a next-generation neutrino experiment currently under construction in Japan. Its massive 186-kiloton fiducial volume far water Cherenkov detector, the new Intermediate Water Cherenkov Detector (IWCD), together with the upgraded J-PARC neutrino beam to the power of 1.3 MW and the upgraded near ND280 detector, will host a rich physics program, including precise studies of neutrino oscillations, nucleon decay searches, and neutrino astrophysics. The Hyper-Kamiokande is aiming to start collecting data in 2028. In this contribution, the status of the Hyper-Kamiokande experiment will be presented. The expected sensitivities of neutrino oscillation parameters, including CP violation (δ_{CP}), θ_{23}, and Δm^2_{23}, will also be discussed.

The 17th International Conference on Heavy Quarks and Leptons (HQL 2025)
15-19 September, 2025
Peking University, Beijing, China

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 ISSN 1824-8039 . Published by SISSA Medialab.

PoS(HQL2025)010

1. Introduction

The properties of neutrinos, despite being the most abundant particles with non-zero mass in the Universe, remain incompletely understood, but they may, among other things, bring us closer to answering the question of why we currently observe a clear matter dominance over antimatter. To further understand the nature of these particles, next-generation neutrino experiments are being built, which will utilize very high-intensity accelerator neutrino beams and detectors with much greater mass than their predecessors. One of these is the Hyper-Kamiokande, whose current state of construction and predicted sensitivities to selected neutrino oscillation parameters are presented in this contribution.

2. The Hyper-Kamiokande project

The Hyper-Kamiokande project consists of four pillars: an upgraded J-PARC neutrino beam and ND280 near neutrino detectors, and two newly built water Cherenkov detectors - intermediate IWCD (Intermediate Water Cherenkov Detector) and far Hyper-K (Hyper-Kamiokande), discussed shortly in this section.

2.1 The J-PARC neutrino beam

Hyper-Kamiokande will use the neutrino beam provided by the J-PARC accelerator complex, currently exploited by the T2K experiment. The muon (anti)neutrino beam is produced in the following way: 30 GeV protons colliding with a graphite target produce mainly pions, which are focused by three magnetic horns and are further directed to a 96 m long, helium-filled decay volume where they decay into muons and muon neutrinos. By changing horns polarity, flux dominated by ν_μ or $\bar{\nu}_\mu$, with a $< 1\%$ background of electron neutrinos, is produced. Hyper-Kamiokande far detector, like Super-Kamiokande for T2K, is located 2.5° of the neutrino beam axis, because thanks to the kinematics of decaying pions, the resulting ν_μ ($\bar{\nu}_\mu$) beam has a narrow energy peak at ~0.6 GeV, what maximizes the probability of neutrino oscillations at a distance of 295 km. The already achieved high intensity of the J-PARC neutrino beam of ~0.9 MW will be increased to 1.3 MW when Hyper-K starts collecting data. This will be achieved by increasing: the number of protons per pulse from 2.6×10^{14} to 3.3×10^{14}, the horn current from 250 kA to 320 kA, and the repetition rate from 1.35 s/cycle to 1.16 s/cycle.

2.2 The near detectors

Two detectors, INGRID and ND280, located 280 m from the production target, form a set of near detectors of the Hyper-K experiment. INGRID is on-axis and monitors the neutrino beam stability and profile. ND280, a multipurpose magnetized tracker located 2.5° off-axis, measures the neutrino interactions (cross sections) and energy spectrum before the oscillations occur. The ND280 detector has been upgraded [1] recently with a Super Fine Grained Detector (SuperFGD), two Time Projection Chambers (TPCs), and a Time of Flight (ToF) detector. They significantly improved the ND280 efficiency in backward angles, 3D track reconstruction, and particle identification. SuperFGD, consisting of 2 million $1cm^3$ optically isolated, plastic scintillator cubes read out in 3 perpendicular directions, is also a 2-ton target for neutrino interactions. Two horizontal gaseous Ar

TPCs with a central cathode, with a 1 m drift distance, are placed top and bottom of SuperFGD. The ToF detector, with 6 scintillator planes with 150 ps timing resolution, is outside. The upgraded detectors are surrounded by an electromagnetic calorimeter and a muon range detector. The entire setup is embedded in a 0.2 T magnet.

2.3 The Intermediate Water Cherenkov Detector

The Intermediate Water Cherenkov Detector (IWCD), based on the nuPRISM detector design [2], is a new detector whose construction, located 850 m downstream of the neutrino beam production target, has just started. Its inner detector of 7 m diameter, height of 8 m, and fiducial mass of 300 tons will be moving in a vertical cylinder pit of a diameter of 10 m and a height of 50 m. This will allow it to cover a range of off-axis angles from 1.5° to 4°, and therefore probe neutrino interactions at different energies with high accuracy. The inner detector will be equipped with 400 multi-PMT photosensors, each consisting of 19 3-inch diameter PMTs and integrated electronics. The mPMTs have several significant advantages over 20" PMTs, which will constitute the vast majority in the far detector, i.e., directionality to various angles of incident light, reduced dark rate, weaker sensitivity to Earth's magnetic field, and better timing properties. The IWCD will measure the cross sections of ν_μ, ν_e, $\bar{\nu}_\mu$, and $\bar{\nu}_e$, including the double ratio $\frac{\sigma(\nu_e)}{\sigma(\nu_\mu)}/\frac{\sigma(\bar{\nu}_e)}{\sigma(\bar{\nu}_\mu)}$ with an accuracy of $\sim$ 3% at 600 MeV to significantly improve δ_{CP} measurement, by reducing systematic uncertainties.

2.4 The far Hyper-Kamiokande detector

The Hyper-K far detector will be located 295 km from the production target. The detector is a cylinder (71 m height, 68 m diameter) filled with ultra-pure water, and consists of two optically separated parts: the inner detector (ID) acting as a target for neutrino interactions, surrounded by the outer detector (OD) acting as a veto for cosmic muons and charged particles produced by neutrino interactions in the outside rocks. The ID will be equipped with 20,000, 50 cm PMTs and 800 multi-PMTs, whereas the OD, with 3,600 8 cm PMTs mounted on wavelength shifting plates. The Hyper-K 50 cm PMTs have twice better performance (photodetection efficiency, charge, and time resolutions) with respect to Super-K 50 cm PMTs. Therefore, although Hyper-K photocathode coverage is only 50% of that of Super-K, the photon detection performance will be comparable.

3. Selected Hyper-Kamiokande sensitivities

In this section, the Hyper-K sensitivities for long-baseline oscillation measurements of δ_{CP}, θ_{23}, and Δm^2_{23} are presented. They were obtained using Super-K Monte Carlo events, scaling them to the larger Hyper-K size, 1 - 10 years data taking time, taking into account the horn current increased to 320 kA, slightly different position of the far detector, and assuming a ratio of 1:3 neutrino to antineutrino beam modes, which corresponds to 2.7×10^{21} protons on target (POT) per year. The following values of oscillation parameters were assumed: $sin^2\theta_{12} = 0.307$, $sin^2\theta_{23} = 0.528$, $\Delta m^2_{32} = 2.509 \times 10^{-3} eV^2$, $\Delta m^2_{12} = 7.53 \times 10^{-5} eV^2$, $sin^2\theta_{13} = 0.0218$, $\delta_{CP} = -1.601$ rad, and normal mass ordering. The extensive description of the Hyper-K physics program can be found in the design report [3]

Three approaches to systematic uncertainties are shown on plots: (1) only statistical uncertainties, (2) improved, profiting from IWCD and upgraded ND280, and (3) the T2K error analysis from

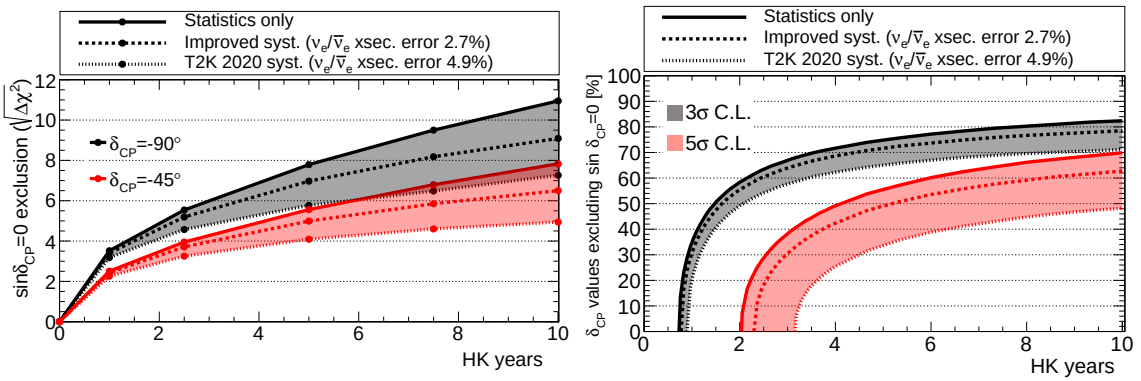

Figure 1: Hyper-Kamiokande sensitivity to CPV as a function of data-taking time for the different systematic error models: $sin\delta_{CP} = 0$ exclusion for $\delta_{CP} = -90°$ or $-45°$ (left), and the percentage of δ_{CP} values for which $sin\delta_{CP} = 0$ can be excluded at 3 or 5σ (right). The shaded regions show the span of possible sensitivities when varying the assumed systematic errors. Figure adopted from [5].

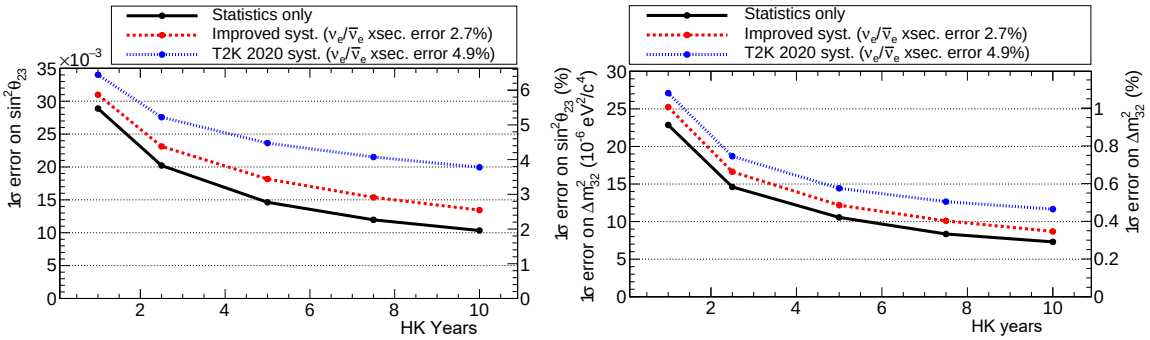

Figure 2: 1σ errors as a function of data-taking time on: $sin^2\theta_{23}$ for $sin^2\theta_{23} = 0.528$ (left), and Δm^2_{32} (right) for the different error models. Figure adopted from [5].

2020 [4]. Oscillation parameters vary in the multi-parameter fit to match far detector event samples to the extrapolated near detector ones. More details can be found in [5].

3.1 δ_{CP} measurement

Hyper-K will use the difference in ν_e and $\bar{\nu}_e$ appearance probabilities to investigate CP violation. A δ_{CP} phase equal to 0° or 180° means CP conservation, whereas equal to $-90°$ (increase of ν_e events in the 1st oscillation maximum in ν_μ beam and decrease of $\bar{\nu}_e$ events in the $\bar{\nu}_\mu$ beam), or 90° (decrease of ν_e events in the 1st oscillation maximum in ν_μ beam and increase of $\bar{\nu}_e$ events in the $\bar{\nu}_\mu$ beam) maximal CP violation. As shown in Fig. 1, Hyper-K can claim the 5σ discovery of CP violation in less than 3 (6) years for the $\delta_{CP} = -90°(-45°)$, and at 5σ for 60% of true δ_{CP} values, with improved systematics. The CP violation sensitivity is mostly degraded by the uncertainty on the $\frac{\sigma(\nu_e)}{\sigma(\bar{\nu}_e)}$ cross-section ratio.

3.2 θ_{23} and Δm^2_{23} measurements

The resolutions on the $sin^2\theta_{23}$ mixing parameter and Δm^2_{32} as a function of years of Hyper-K data taking are shown in Fig. 2. The ultimate resolution of 0.4% on Δm^2_{32}, which does not depend

much on the actual value of the oscillation parameters, can be achieved. On the other hand, the ultimate resolution on the $sin^2\theta_{23}$ varies from 0.4% to 2% close to the maximal mixing as presented in Fig. 3.

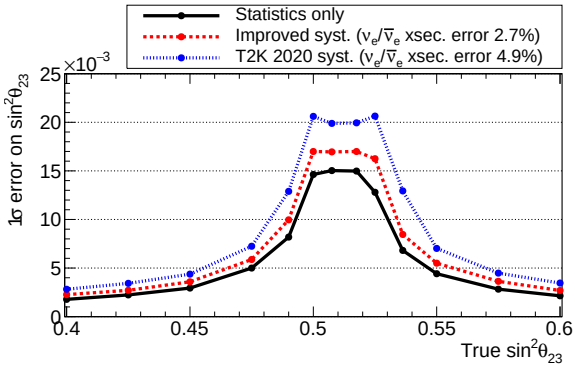

Figure 3: 1σ errors as a function of $sin^2\theta_{23}$ value after Hyper-K 10 years of data-taking.

4. Summary

The construction of the Hyper-Kamiokande experiment is progressing as planned, reaching one of the most important milestones in July 2025, which is the completion of underground works, including the excavation of the main detector chamber with a diameter of 69 m and a height of 94 m, for both cylindrical section and a domed roof. Data collection is scheduled to begin in 2028, including the study of neutrino long-baseline oscillations using an intense beam of J-PARC muon (anti)neutrinos. In this brief contribution, the significance of reducing systematic uncertainties for enhancing the sensitivity of measurements related to the CP-violating phase (δ_{CP}), and neutrino oscillation parameters θ_{23}, and Δm^2_{23} was highlighted.

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