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Oscillation Physics at Hyper-Kamiokande

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Hyper-Kamiokande is a next generation long baseline neutrino oscillation experiment currently under construction in Japan. The project consists of the Hyper-K detector, which is equipped with newly developed high-sensitivity photo-sensors and has a fiducial mass that is 8.4 times larger than its predecessor, Super-Kamiokande, and a high-intensity neutrino beam produced by an upgraded J-PARC accelerator facility. The Hyper-K detector is both a "microscope," used to observe elementary particles, and also a "telescope" for observing the Sun and supernovas using neutrinos. In these proceedings we focus on the oscillation measurements including CP violation (δ_{CP}) and precision measurement of the θ_{23}, θ_{13} and Δm_{23} mixing parameters. We also present the current status of Hyper-Kamiokande construction.

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1. The Hyper-Kamiokande Project

The Hyper-Kamiokande (HK) project consists of three components: A new 260 kton water Cherenkov far detector, an upgraded 1.3 MW neutrino/anti-neutrino beam and an upgraded suite of near detectors. There are two hosts: the University of Tokyo who lead on the far detector, and KEK/JPARC who lead on the beam and near detectors. The collaboration currently consists of around 600 scientists from 104 institutes across 22 countries and is still welcoming new members.

One of the main goals, as discussed in section 2 is the precise measurement of oscillations over the 295 km baseline from J-PARC on the east coast of Japan, to the far detector near Kamioka on the west coast. The JPARC neutrino beam, which currently serves the T2K experiment produces either muon neutrinos or muon anti-neutrinos, depending on the polarity of the three focusing horns. An off-axis technique is employed, resulting in a beam with an energy spectrum peaked at 0.6 GeV at 2.5° off-axis. The peak energy aligns with the 1st oscillation maximum over the 295 km baseline and results in predominantly charged current quasi-elastic (CCQE) interactions, which allows for reconstruction of the incoming neutrino energy from the charged lepton Cherenkov rings seen in the far detector.

A suite of near detectors on the J-PARC site includes the INGRID on-axis detector, and the ND280 off-axis detector, both currently used by the T2K experiment. Measurements at near detectors are essential to constrain uncertainties on the neutrino flux and neutrino interaction models, with samples from ND280 used in oscillation fits to near and far detector data. The ND280 detector has recently been upgraded to improve the angular acceptance and tracking resolution, as discussed in a separate talk at this conference.

For HK, an additional 'Intermediate Water Cherenkov Detector' (IWCD) will be added. This ~300 tonne water Cherenkov detector will be situated ~850 m downstream. The detector will move within a vertical shaft to make measurements at a range of off-axis angles. This 'nu-prism' technique enables the creation of 'mono-chromatic' spectra to constrain the feed-down of non-quasi-elastic events into the peak energy region with 5% precision. Furthermore, the CC$\nu_e/\bar{\nu}_e$ cross-section ratio can be measured to better than 4% precision on this new water target using the intrinsic ν_e and $\bar{\nu}_e$ contamination in the beam.

2. Experimental Sensitivity

2.1 Methodology

To evaluate the sensitivity for long-baseline oscillation measurements, we use monte carlo event samples produced for the Super-Kamiokande (SK) detector but scaled to account for the increased detector mass of HK, and the changes to the neutrino flux (accounting for the increased horn current and change in detector location). The monte carlo is scaled to the appropriate run time (1–10 years) with a 1:3 neutrino to anti-neutrino ratio, corresponding to 0.675×10^{21} protons on target (POT) of ν-mode (Forward Horn Current - FHC) and 2.025×10^{21} POT of $\bar{\nu}$-mode (Reverse Horn Current - RHC) running, which gives a total of 2.7×10^{21} POT per year. A multi-parameter fit is performed to match the far detector event samples to the prediction obtained by extrapolation from near detector data, allowing the oscillation parameters to vary. Other fit inputs include models for the near and far detectors, flux and cross-section modelling, all with associated systematic uncertainties that are

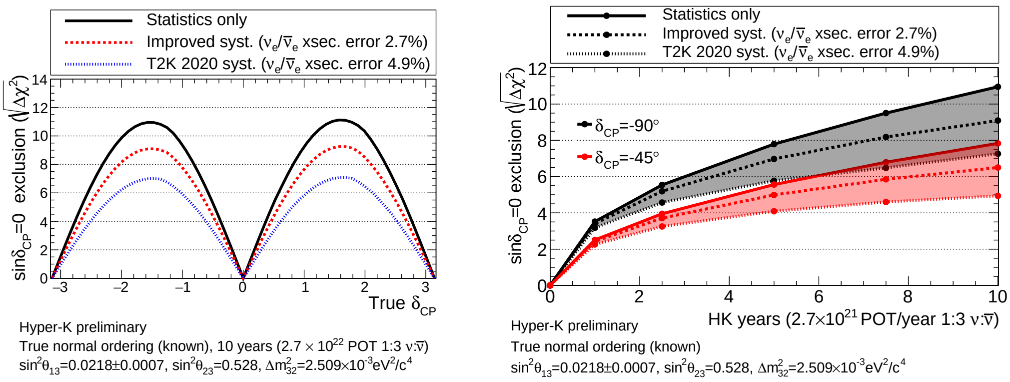

Figure 1: HK sensitivity to δ_{CP} for the different systematic error models. The left plot shows the range of phase space that can be excluded after 10 years of HK running and the right plot shows the time taken to exclude values of $\delta_{CP} = \pi/2$ and $\delta_{CP} = \pi/4$.

treated as nuisance parameters in the fit, some of which can also be constrained by external data such as global cross-section data.

Three systematic error models are used: firstly the T2K 2020 error model after the near detector fit (see ref [1]), which is the unlikely worst case scenario. Secondly, an improved systematics scenario has been calculated by scaling the T2K error model based on an increased run time, and including projected improvements from the ND280-upgrade and IWCD. Thirdly, the scenario with only statistical uncertainties is included as an ideal scenario. The improved systematics model should be considered as the most realistic scenario, which includes reduction in flux, cross-section and far detector systematics by a factor $\frac{1}{\sqrt{N}}$ where $N = 7.5$ is the relative increase in neutrino beam exposure from T2K to HK. Using the upgraded ND280 and IWCD information, we also project the following reductions in cross-section model uncertainties: a factor of 3 reduction in non-quasi-elastic model uncertainties, a factor if 2.5 reduction in all quasi-elastic uncertainties, a factor 2 reduction in all anti-neutrino uncertainties and a reduction in neutral current uncertainties to the 10% level. The $\nu_e/\bar{\nu}_e$ cross-section ratio is particularly important and has been fixed to 2.7% (except in explicit studies where it is set to the T2K 2020 model value of 4.9%).

2.2 Long Baseline Measurements

HK will probe CP-violation through comparison of the ν_e (in FHC mode) and $\bar{\nu}_e$ (in RHC mode) appearance probabilities. Over 10 years of running, we expect more than a thousand electron (anti-) neutrino events, which are characterised by a single electron-like ring in the far detector. A positive CP phase ($0 < \delta_{CP} < \pi$) will increase the number of ν_e observed in the 1st oscillation peak at 0.6 GeV in FHC mode and decrease the number of $\bar{\nu}_e$ observed in the peak in RHC mode, whilst a negative CP phase will have the opposite effect. Assuming that the neutrino mass ordering is already known and is normal, figure 1 shows that for 10 years of HK running 63% of true δ_{CP} values can be excluded at 5σ (left plot), and HK can exclude values of $\delta_{CP} = 90°$ at 5σ with less than 3 years of data (right plot).

Figure 2 shows the 1σ resolution of δ_{CP} as a function of true δ_{CP} value for 10 years of HK running. In this plot, the impact of improving the uncertainty on the $\nu_e/\bar{\nu}_e$ cross-section ratio from

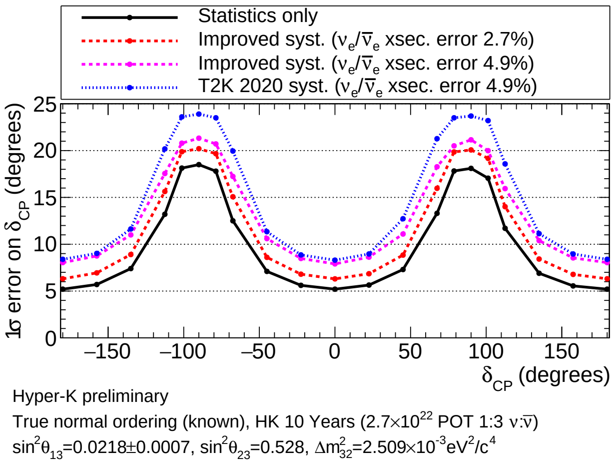

Figure 2: 1σ resolution of δ_{CP} as a function of true δ_{CP}value for 10 HK years. Two improved error models are considered, one where the $\nu_e/\bar{\nu}_e$ cross-section ratio error was fixed to 2.7% and the another where it is fixed to 4.9% (T2K level).

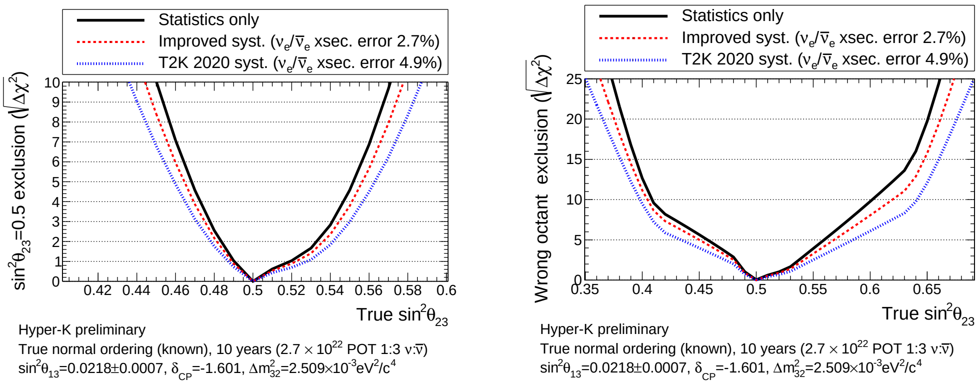

Figure 3: $\sin^2\theta_{23} = 0.5$ (left) and wrong octant (right) exclusion as a function of true $\sin^2\theta_{23}$ for different systematics model for 10 years of HK running.

4.9% to 2.7% is shown explicitly. It is interesting to note that this systematic becomes dominant close to CP conservation but has less impact where the δ_{CP} effect is larger.

HK can probe 2-3 mixing through dip in the ν_μ ($\bar{\nu}_\mu$) appearance spectrum with the sample of single ring muon-like events in the far detector. Figure 3 shows that HK can exclude maximal mixing at 3σ for true $\sin^2\theta_{23} < 0.475$ and $\sin^2\theta_{23} > 0.545$, and reject the wrong octant at 3σ for true $\sin^2\theta_{23} < 0.47$ and $\sin^2\theta_{23} > 0.55$.

Figure 4 shows the constraints that can be placed on both $\sin^2\theta_{13}$ and $\sin^2\theta_{23}$ simultaneously, and the impact of including a constraint from external reactor oscillation experiments which helps to break the degeneracy between these two parameters.

2.3 Including Atmospheric Neutrino Measurements

In addition to long-baseline measurements, HK can also probe oscillations through atmospheric neutrinos. Since atmospheric neutrinos span a wide range of energies and path-lengths, they provide

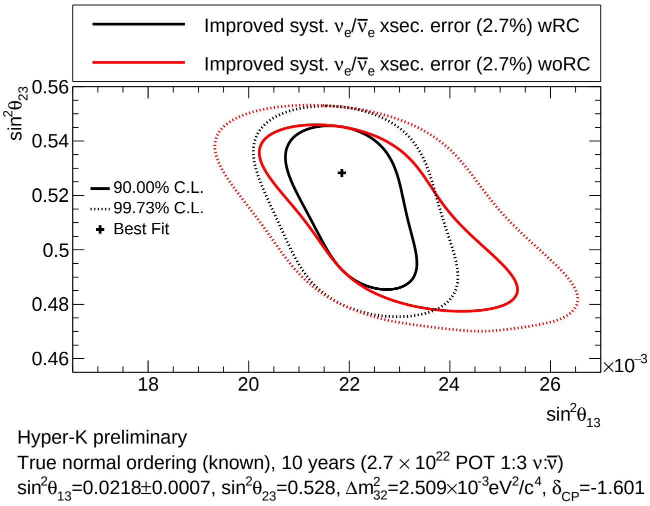

Figure 4: 2D contours, made with and without including constraints from reactor experiments, in $\sin^2\theta_{13} - \sin^2\theta_{23}$ with the improved systematics model for 10 years of statistics.

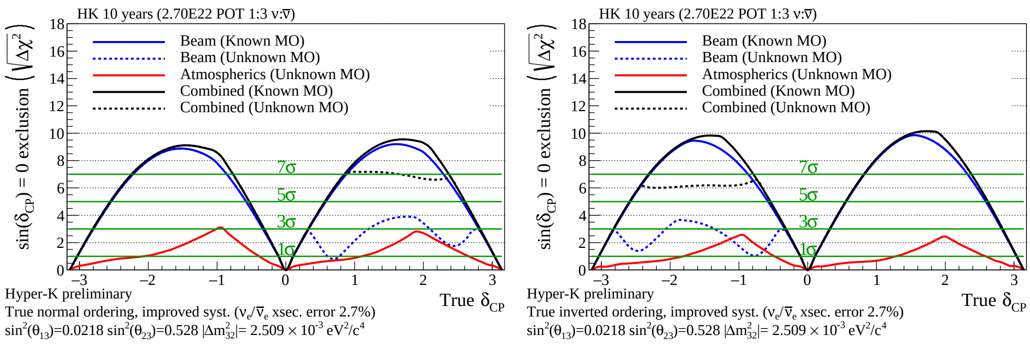

Figure 5: Sensitivity to exclude $\sin(\delta_{CP}) = 0$, as a function of true δ_{CP} value, for 10 HK-years in the case of normal (left) or inverted (right) mass ordering.

a complementary data set. In particular multi-GeV upward-going neutrinos are subject to the matter effect as they pass through earth, whilst the beam baseline of 295 km is too short to experience measurable matter effects. Note that figures 1 and 2 assume a known mass ordering, but if this is still unknown at the time of HK data taking, δ_{CP} sensitivity from beam measurements alone drops to that shown by the blue dashed lines in figure 5 for true normal ordering (left) and true inverted ordering (right). The red line shows the lower but complementary sensitivity of atmospheric neutrinos alone, and the black dashed lines show that by combining atmospheric data with beam data, exclusion sensitivity across the δ_{CP} phase space is dramatically improved. Combining atmospheric and beam data will also result in improved sensitivity to the θ_{23} octant.

3. Experiment Construction

At the time of the conference (September 2024) roughly half of the 20,000 inner detector PMTs have been delivered and tested. Mass production of these 50 cm-diameter box and line dynode PMTs commenced in 2021 and is due to complete by September 2026. In addition to these 50 cm

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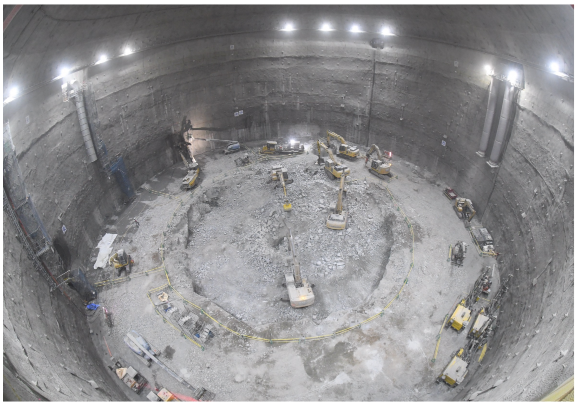

Figure 6: Photograph of the HK detector cavern during construction in July 2024, when the cavern depth was approximately half that of the final size.

PMTs, 800 multi-PMT units, consisting of 19 8 cm diameter PMTs and their electronics arranged inside a pressure resistant vessel, will also be installed in the HK inner detector to provide additional directional information, and improved spatial and timing resolution. The first ~100 mPMT units have been produced and deployed in a 4 m-scale Water Cherenkov Test Experiment (WCTE) at CERN, which will validate the performance of the mPMTs and the IWCD approach.

Excavation of the cavern for the HK detector had reached a depth of 37 m at the time of the conference, over half-way towards the final cavern height needed to accommodate the 71 m high detector. Figure 6 shows an image of the cavern as of July 2024.

Cavern excavation is scheduled to complete by the end of 2024, with construction of the tank scheduled for 2025. Installation of the PMTs and other instrumentation will commence mid 2026, with water filling scheduled in 2027.

4. Summary

Construction of the Hyper Kamiokande experiment is progressing rapidly and the collaboration are preparing for data taking to commence at the end of 2027. With a 260 kton water Cherenkov far detector, 1.3 MW beam and upgraded suite of near detectors, HK aims to reveal the full picture of neutrino oscillations, including CP violation, mass ordering, the θ_{23} octant, and more!

References

[1] The T2K Collaboration. Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations. Nature 580, 339–344 (2020). https://doi.org/10.1038/s41586-020-2177-0