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Measurement of the CP violation in neutrino flavour oscillations with Hyper-Kamiokande

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Long baseline neutrino oscillation experiments have a high sensitivity to the CP violation phase of the neutrino mixing matrix through the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance channels. For instance, the measurements of the T2K experiment in Japan, using Super-Kamiokande as a far detector, favour a close to maximal CP violation and excluded the CP conserving values at a 90% CL. However, these results are largely limited by statistics. With a fiducial volume approximately 8 times larger than the existing Super-Kamiokande, the future water Cherenkov detector Hyper-Kamiokande (HK) being built in Japan is one example of a next generation of long-baseline neutrino experiment. Thanks to a bigger far detector (8 times larger) and an upgraded beam facility (3 times more intense), using the same baseline as the current T2K experiment, HK will improve the measurements of neutrino oscillation parameters. With this increased statistics, the CP violation phase measurement will be limited by the poor understanding of systematic effects among which the neutrino interaction modelling is a major source of uncertainties. To improve the measurement of the CP violation phase, the HK collaboration is studying in depth the systematics errors that impact the measurements. At the same time it is upgrading the near detectors suite to be able to improve the knowledge of the neutrino flux and cross-section before oscillations. In particular, HK plans to measure the ν_e and $\bar{\nu}_e$ cross-sections (that are expected to be a major source of uncertainty for the measurement of the CP violation phase) with a new intermediate water Cherenkov detector located at 850 m from the neutrino source and an upgraded near detector (inherited from the T2K experiment) at 280 m. Depending on the true value of the CP violation phase, the measurement could also be impacted by degeneracy with the neutrino Mass Ordering. This obstacle can be overcome using the combined analysis of accelerator and atmospheric neutrinos in HK.

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1. Introduction

Hyper-Kamiokande (HK) [1] is the third generation of water Cherenkov detector being built in Japan for nucleon decay search and neutrino studies. With a fiducial volume of around 190 kt, approximately 8 times larger than its predecessor Super-Kamiokande [2], it will accumulate statistics much faster increasing the sensitivity to all signals, including the Charged Parity (CP) symmetry violation in neutrino flavour oscillation.

We use the Pontecorvo-Maki-Nagawa-Sakata (PMNS) parametrisation of the mixing matrix between the neutrino flavour states and mass states [3, 4] to describe the flavour oscillation. The PMNS matrix includes 4 free parameters, three mixing angles θ_{12}, θ_{23} and θ_{13} and a complex phase δ_{CP} called CP violation phase because if $\sin\delta_{CP} \neq 0$, neutrino oscillation violates CP symmetry. The oscillation probabilities also depend on the neutrino energy, the propagation lenght and the difference between the square of the neutrino masses $\Delta m^2_{ij} = m^2_j - m^2_i$ adding 2 free parameters to the minimal list of oscillation parameters to be measured experimentally.

Neutrino oscillations will be studied in Hyper-Kamiokande using two main sources of neutrinos: the atmospherics ones and the artificial neutrinos produced by the accelerator (JPARC) at 295 km (LBL). In both cases, the disappearance of ν_μ ($\bar{\nu}_\mu$) and the appearance of ν_e ($\bar{\nu}_e$) is measured in either the neutrinos produced in the cosmic rays induced hadronic showers in the atmosphere or the beam of neutrinos produced at the Japan Proton Accelerator Research Complex (J-PARC). The second one is more sensitive to CP violation as J-PARC provides either a ν_μ or a $\bar{\nu}_\mu$ beam so one can better compare oscillation in neutrinos to oscillation in anti-neutrinos. Also, the propagation lenght is relatively small (295 km) so that matter effects have a sub-leading impact on the difference of oscillation between neutrinos and anti-neutrinos.

The LBL program will re-use the same baseline as T2K with some upgrades. The J-PARC Facility is under-going upgrades to increase the beam power but the neutrino beam will have the same narrow energy band peaked at 600 MeV. The same set of near detectors as in T2K, including ND280 upgrade [5], will be used to measure the neutrino flux before oscillation and interaction cross section in order to constrain systematic effects. In addition, a new Intermediate Water Cherenkov Detector (IWCD) is being built at 850 m from the neutrino beam production facility.

The oscillation analysis of the LBL data will allow precision measurement of $|\Delta m^2_{32}|$ through the muon flavour disappearance channel, of $\sin^2\theta_{23}$ through both the muon disappearance and electron flavour appearance channels and of δ_{CP} via the difference of electron flavour appearance in neutrino and anti-neutrino mode. Regarding this last parameter, the goal is a 5σ discovery of CP violation in neutrino oscillation. The T2K experiment obtained a 2σ exclusion result that is limited by statistics [6] whereas the NOvA experimental results show no preference for CP violating values of δ_{CP} [7].

2. Hyper-Kamiokande's sensitivity to CP violation

Because the anti-neutrino cross section is approximately 3 times lower than the neutrino cross section, it is planned to run the LBL program only one fourth of the time in neutrino mode and the rest in anti-neutrino mode. Ignoring possible CP violation, this allows to expect approximately the same event rate in e-like samples in both neutrino and anti-neutrino mode. A negative $\sin\delta_{CP}$

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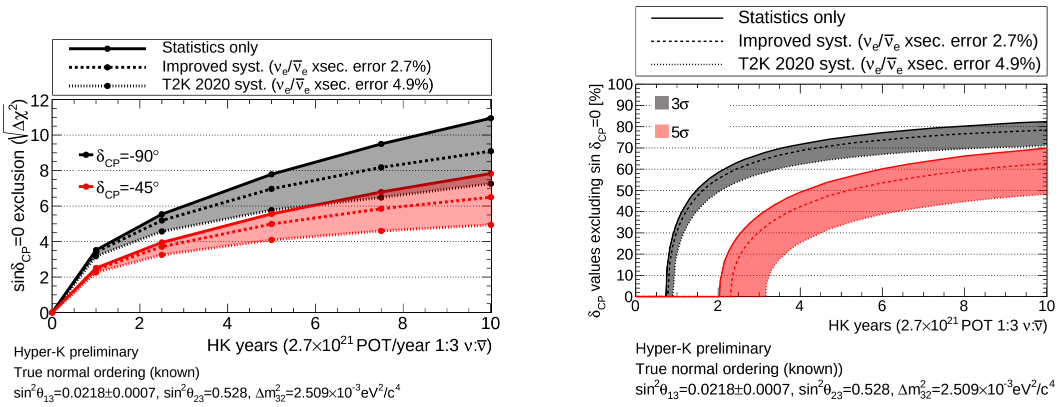
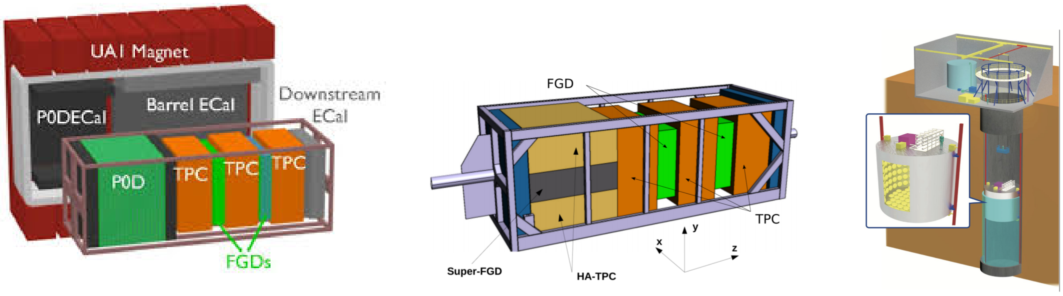


Figure 1: HK sensitivity to CP violation as a function of the number of years of accumulated statistics. The different line styles correspond to the three secnarios of level of systematic uncertainties. Left: Sensitivity to exclude $\sin\delta_{CP} = 0$ for $\delta_{CP} = -90°$ (black) or $\delta_{CP} = -45°$ (red). Right: number of values of δ_{CP} in percentage for which a 3σ (black) or a 5σ (red) exclusion of $\sin\delta_{CP} = 0$ is achievable.

would lead to an enhancement $\nu_\mu \to \nu_e$ oscillation compared to $\bar{\nu}_\mu \to \bar{\nu}_e$ whereas a positive $\sin\delta_{CP}$ would do the contrary.

However, one must also take into account systematic effects. Three level of systematic uncertainties are considered here: Statistical errors only (no systematics), T2K systematic uncertainties as in one of the latest T2K analysis [6], HK improved systematics. The last one was calculated considering the increased statistics at the near detectors and the improvements coming from ND280 upgrade and the addition of IWCD. More details on the improvements can be found in [8].

HK's sensitivity to CP symmetry violation can be estimated using the likelihood as a function of δ_{CP} obtained when fitting the simulated LBL data. More precisely, we consider the square root of the difference between the log-likelihood at $\sin\delta_{CP} = 0$ and the minimum log-likelihood which should be at the the true value of δ_{CP}. Figure 1 shows the predicted sensitivity of HK as a function of the accumulated statistics in number of years of data-taking, assuming that we always keep the 1:3 ratio between neutrino and anti-neutrino beam modes. For the left plot, we assumed that the true value of δ_{CP} to be either $-90°$ (black) or $-45°$ and we look at the significance of exclusion in number of σ for the three different levels of systematic uncertainties. In the right plot, we consider all possible values of δ_{CP} and we count the number of them for which a 3σ (black) and a 5σ (red) exclusion can be obtained. Taking into account the expected improvements of systematic uncertainties, the 5σ exclusion could happen after less than 2.5 years of accumulated statistics in case of maximal CP violation. After 10 years, the 5σ exclusion will have been obtained in more than 60% of the most favourable cases. However, if the systematic uncertainties are not reduced, this last number could drop down to 50% and, for instance, the 5σ exclusion for $\delta_{CP} = -45°$ would take 10 years of data instead of 5 years. Systematic uncertainties could thus soon limit the ultimate sensitivity to the oscillation phenomena in HK.



(a) ND280 pre-upgrade **(b)** ND280 upgrade **(c)** IWCD

Figure 2: Schemes of the pre-upgrade ND280 (left), ND280 upgrade (middle) and IWCD (right) detectors.

3. Systematic uncertainties reduction

HK's plan to reduce systematic uncertainties is mostly based on using and improving the capabilities of the near detectors. Compared to the T2K analysis used as reference here, the ND280 detector has been upgraded for the second phase of T2K [5] and HK will start its data-taking with this upgraded detector. As shown in Figure 2 (left and middle), the pre-upgrade π^0 detector (POD) was replaced by a Super-Fine-Grained Detector (SFGD) composed of 2.1 million of 1 cm^3 scintillating cubes and two high angle TPCs. The upgrade multiplied by 2 the fiducial mass of the detector, increased the angular coverage and allowed a lower proton detection threshold. R&D is currently ongoing to decide on a possible further upgrade of the second half of the detector to further increase the mass and the detection capabilities. The upgrade should be installed during HK's lifetime.

Furthermore, IWCD, shown in the right panel of Figure 2, is being built to bring complementary measurements of neutrino cross section and further reduce related systematic uncertainties. Using the same target and the same detector technology as the far detector it will significantly help the extrapolation of the near detector constraints to the far detector measurements. Additionally, the plan is to built a system of water lift to vertically move the detector and change its off-axis angle with respect to the average neutrino beam direction. Going to higher off-axis angle allows a purer selection of lower energy neutrinos and, consequently, Charged Current Quasi-Elastic (CCQE) interactions that dominate the LBL signal region. On the other hand, going to lower off-axis angles will increase the statistics at higher energy (above 1 GeV) and improve constraints on other processes (e.g., Charged Current interaction with pion production) that can typically lead to biases in the energy reconstruction.

More precisely, for the measurement of CP violation, any systematic effect that could mimic the impact of δ_{CP} on the ν_e and $\bar{\nu}_e$ event rates could become limiting. A good example is the cross sections of ν_e and $\bar{\nu}_e$: if $\sigma(\nu_e)$ is slightly higher than expected and $\sigma(\bar{\nu}_e)$ slightly lower, this could be mistaken for a negative value of $\sin\delta_{CP}$. One can therefore guess that the ratio $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ is an important systematic parameter to constrain in order to maximise our sensitivity to CP violation. In the current T2K analysis, $\sigma(\nu_e)$ and $\sigma(\bar{\nu}_e)$ are constrained by theory via the measurement of $\sigma(\nu_\mu)$ and $\sigma(\bar{\nu}_\mu)$ by the near detectors. It is indeed very challenging to directly measure $\sigma(\nu_e)$ and $\sigma(\bar{\nu}_e)$ at the near detectors because of the low statistics (low ν_μ and $\bar{\nu}_\mu$ beam contamination) and

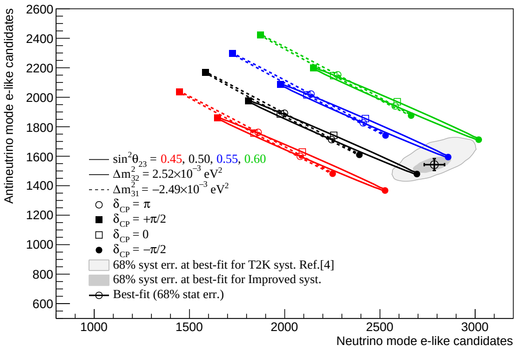


Figure 3: Expected event rates in HK in the e-like anti-neutrino beam mode versus neutrino beam mode samples. The values of various oscillation parameters are varied: the different colours corrspond to different values of $\sin^2\theta_{23}$, the marker shapes to the value of δ_{CP} and the line style to the assumed Mass Ordering (solid for Normal and dashed for Inverted).

the pre-upgrade ND280 performance of $\nu_e/\bar{\nu}_e$ selection. However, adding IWCD and the upgraded ND280, HK will improve the constraint on $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$. Indeed, first sensitivity studies suggested that IWCD alone could provide a constraint below 4% with a statistics of the order of 10^3 ν_e and $\bar{\nu}_e$. Simulation using the Fine Grained Detectors of ND280 but the ν_e and $\bar{\nu}_e$ statistics expected for the SFGD in HK, also demonstrated that ND280 upgrade could achieve a constraint close to 5%. By combining the two detectors' measurements, an even better constrained might be achieved. In this analysis, the ultimate goal after 10 years of data-taking was set to 2.7% constraint on $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ compared to the 4.9% constraint currently used by T2K.

4. Degeneracy between CP violation and Mass Ordering

Apart from statistics and systematic uncertainties, the sensitivity to CP violation in LBL experiments can be limited by the degeneracy with mass ordering (the sign of Δm^2_{31} or Δm^2_{21}). In the previous sections, Mass Ordering (MO) was assumed to be known and Normal ($\Delta m^2_{31} > 0$). Indeed, thanks to the many current and next generation neutrino oscillation experiments sensitive to the MO (e.g, Super-Kamiokande [9], NOVA, KM3NeT/ORCA [10], JUNO [11], DUNE [12] and HK atmospherics program), it will likely have been determined before 10 years of running with HK. In this section, let us consider the limitations to HK's sensitivity to CP violation if the MO is unknown.

As the oscillation happens in matter, the ν_μ ($\bar{\nu}_\mu$) to ν_e ($\bar{\nu}_e$) is also impacted by so-called matter effects. Matter effects can mimic the effect of δ_{CP} on the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations depending on the Mass Ordering (MO). In case of Normal Ordering ($\Delta m^2_{31} > 0$) NO, the electron flavour appearance is reduced (respectively increased) in neutrino (respectively anti-neutrino) mode whereas the contrary happens in case of Inverted Ordering ($\Delta m^2_{31} < 0$) IO. In T2K and HK, the propagation lenght is relatively small so that matter effects are a sub-leading effect in the ν_e and $\bar{\nu}_e$ event rates allowing a good sensitivity to δ_{CP} and a poor sensitivity to MO. However, there still exist a degeneracy between the two in some cases: NO with $\sin\delta_{CP} > 0$ and IO with $\sin\delta_{CP} < 0$.

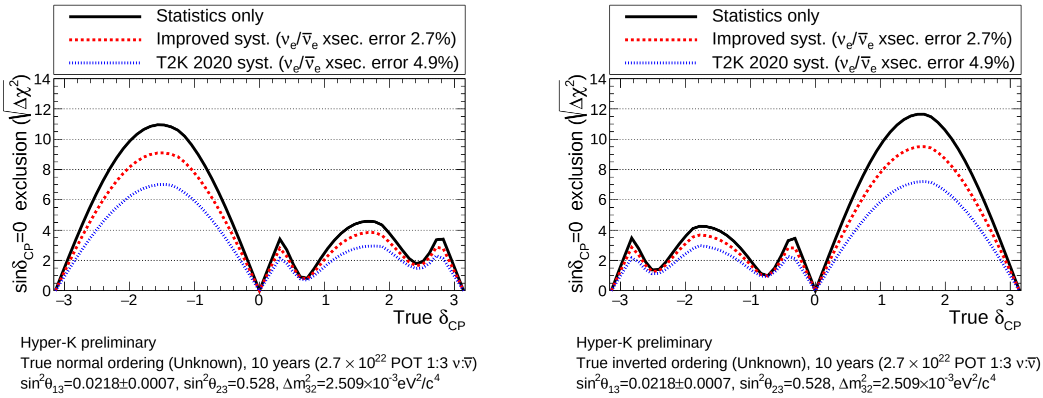


Figure 4: HK sensitivity to exclude $\sin\delta_{CP} = 0$ as a function of the true value of δ_{CP} after 10 years of accumulated statistics in case of Normal (left) or Inverted (right) MO. In both cases, the knowledge of the Mass Ordering is not assumed. The different lines correspond to different levels of systematic uncertainties.

This is illustrated by Figure 3 showing the expected event rates in e-like LBL HK samples in anti-neutrino mode versus neutrino mode for various values of the oscillation parameters and the two possible Mass Orderings. When varying only δ_{CP}, the relative variation of event rates forms an ellipse. When switching from NO (solid line) to IO (dashed line), the ellipse is displaced to the top left (lower event rate in neutrino mode and higher event rate in anti-neutrino mode). The small overlaps between the NO and IO ellipses illustrates the degeneracy: for instance the scenarios (NO, $\delta_{CP} = \pi/4$) and (IO, $\delta_{CP} = 0$) are not distinguishable in Figure 3.

The degeneracy can greatly reduce the sensitivity to CP violation in the so-called degenerate regions. This effect is illustrated in Figure 4 showing the exclusion limit of $\sin\delta_{CP} = 0$ after 10 years of accumulated statistics at HK as a function of the true value of δ_{CP} assuming the true MO is Normal (left) or Inverted (right). If MO is not known, no 5σ exclusion of $\sin\delta_{CP} = 0$ is possible in the region $\sin\delta_{CP} > 0$ (respectively $\sin\delta_{CP} < 0$) in case of Normal (respectively Inverted) Ordering even after 10 years of accumulated statistics at HK.

Performing a joint oscillation analysis of LBL and atmospheric neutrinos samples in HK will help overcome this issue. Indeed, thanks to a much longer propagation lenght, the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation for neutrinos produced in the atmosphere at the other side of the earth compared to HK is much more sensitive to matter effect and therefore the MO. A first iteration of a joint fit between T2K and SK atmospherics samples was published in 2025 and demonstrated a significant increase of sensitivity to CP violation compared to T2K only [13]. A previous more simplified analysis showed that a joint fit, after 10 years, would allow the same 5σ exclusion potential of CP symmetry in both the degenerate and non-degenerate regions. This is illustrated by Figure 5 that shows the expected sensitivity to exclude $\sin\delta_{CP} = 0$ after 10 years of LBL (blue) or atmospheric (red) or both (black) data as a function of the true value of δ_{CP} and assuming the MO to be known (solid line) or unknown (dashed line). Indeed, in the MO unknown scenario, the joint fit significantly increases the sensitivity compared to LBL only.

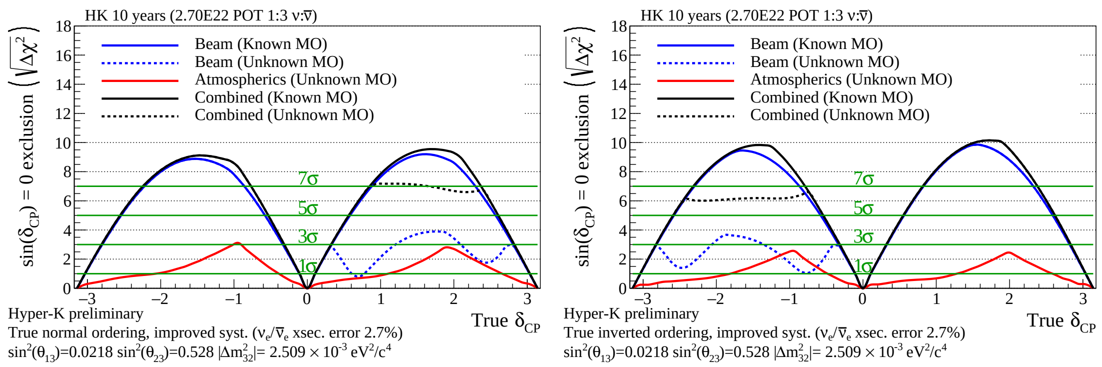


Figure 5: HK sensitivity to exclude $\sin\delta_{CP} = 0$ as a function of the true value of δ_{CP} after 10 years of accumulated statistics in case of Normal (left) or Inverted (right) MO and with improved levels of systematic uncertainties. The true MO is either assumed known (solid lines) or unknown (dashed lines). The results are obtained using either only the LBL samples (blue), only the atmospheric samples (red) or a joint fit of LBL and atmospheric samples (black).

5. Conclusions

The HK long baseline program will have an unprecedented sensitivity to CP violation allowing a 5σ exclusion of CP symmetry conservation after a few years of data only, if CP violation is close to maximal and non degenerate with the Mass Ordering. This is due to three main factors discussed here. First, with a 8 times larger fiducial volume and a higher beam intensity, it will accumulate statistics 10 times faster than T2K that holds today the most precise measurement of δ_{CP} limited by statistics. With the fast accumulation of statistics, the result will soon become limited by systematic uncertainties. Better constraints of systematic uncertainties will be obtained thanks to the continuing operation of the T2K near detectors, an upgrade of ND280 during HK's lifetime and the addition of a new Water Cherenkov Detector at 850 m from the beam production facility. For instance, it is estimated that the constraint on $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ will be reduced from 4.9% to 2.7% after 10 years of data-taking. Finally, in case of degeneracy between δ_{CP} and MO, a joint fit with atmospheric samples will significantly increase the sensitivity to CP violation allowing after 10 years the same 5σ potential of exclusion of CP symmetry as if the MO was known.

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