Sensitivity to leptonic CP violation at Hyper-Kamiokande

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Abstract. Hyper-Kamiokande is a next generation water Cherenkov detector, an order of magnitude larger than Super-Kamiokande, capable of large and diverse physics studies. Among these, it will study long baseline oscillation physics with great detail, thanks not only to a larger volume and higher detection efficiency, but also to an improved accelerator and near detector system at J-PARC. We study the effect of a new systematic error model on the overall sensitivity of the experiment to the neutrino oscillation parameters, with particular care for the CP violating phase. A variety of theoretical models will benefit from a precise measurement of $\delta_{\text{CP}}$, which Hyper-Kamiokande has the capability of constraining, with good precision. The accuracy of the measurement, however, is dictated by the systematic uncertainties and hence it is essential to assess the impact of the new error model on the sensitivity.

1. Introduction

The violation of the CP symmetry is a well-known process in the quark sector of the standard model (SM), giving clear evidence that the Cabibbo-Kobayashi-Maskawa matrix is complex. As three generations exist, an entirely analogous phenomenon is expected to arise in the lepton sector. The leptonic mass mixing matrix, the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, is usually parameterised as

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\gamma_1} & 0 \\ 0 & 0 & e^{i\gamma_2} \end{pmatrix}$$

where $c_{ij} \equiv \cos \theta_{ij}$ and $s_{ij} \equiv \sin \theta_{ij}$. The angle $\delta_{\text{CP}}$ is the phase responsible for CP violation, whereas the additional phases $\gamma_1$ and $\gamma_2$ bring about CP violation if the neutrinos are Majorana.

CP and CP violation are some of the conditions required in order to generate an asymmetry between matter and antimatter particles, together with baryon number violation and interactions out of thermal equilibrium [1]. The amount of CP violation in the quark sector is not enough to describe the observed baryon asymmetry within the SM. An asymmetry in the lepton sector, however, could be translated into baryogenesis, via non-perturbative sphaleronic processes [2]. This process, called lepto genesis, would be allowed by the addition of right-handed Majorana neutrinos to the SM, which can violate lepton number. This elegant solution to explain the baryon asymmetry is a strong motivation for searches of signals of CP violation in the lepton sector.
Figure 1: Effect of $\delta_{\text{CP}}$ on the normalised asymmetry from Eq. 3.

Figure 2: Expected significance to exclude CP conservation, in case of normal hierarchy, where the mass hierarchy is assumed to be known [8].

The best probe to discover CP violation is neutrino oscillation, being a purely weak process in which CP-conjugate processes can be easily studied. The PMNS matrix relates flavour states $\alpha = e, \mu, \tau$ with mass eigenstates $i = 1, 2, 3$ as $|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$. The probability of flavour oscillation in vacuum is hence computed as

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \langle \nu_\alpha | e^{-i\mathcal{H}t} | \nu_\beta \rangle \right|^2 = \sum_{i,j} U_{i\alpha}^* U_{\beta j} U_{\alpha j}^* \exp \left( -\frac{i\Delta m_{ij}^2 L}{2E} \right),$$

(2)

where $\mathcal{H}$ is the Hamiltonian, $t \simeq L$ and $\Delta m_{ij}^2 = m_j^2 - m_i^2$, and it depends on the physical angles and phases of the PMNS matrix, with the exception of the Majorana phases $\gamma_{1,2}$. The CP-conjugate of a neutrino with negative helicity is an antineutrino with positive helicity, which, in terms of neutrino oscillations, means transforming the $\nu_\alpha \rightarrow \nu_\beta$ oscillation channel into the $\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$ channel. The violation of CP in neutrino oscillation can be quantified by the asymmetry in oscillation probabilities between neutrinos and antineutrinos

$$A_{\alpha\beta}^{\text{CP}} = P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = 4 \sum_{i>j} 3 |U_{i\alpha}^* U_{\beta j} U_{\alpha j}^*| \sin \left( -\frac{i\Delta m_{ij}^2 L}{2E} \right).$$

(3)

It follows that CP violation can only be measured in “appearance” channels, as the argument of the imaginary part of Eq. 3 is real for $\alpha = \beta$. Furthermore, given the parametrisation in Eq. 1, this asymmetry is not measurable if the phase is trivial, i.e. $\delta_{\text{CP}} = 0$ or $\pm \pi$, or if $\theta_{13}$ is vanishing. From a model building point of view, however, a successful leptogenesis requires the parameters to satisfy $|\sin \theta_{13} \sin \delta_{\text{CP}}| \gtrsim 0.09$ when the Majorana phases are vanishing [3]. The value of $\theta_{13}$ has been measured to be non-zero [4–7] and for this reason it is expected that on-going and future generation neutrino experiments will also constrain the value of $\delta_{\text{CP}}$. The effect of the CP-violating phase on the asymmetry of Eq. 3 can be appreciated from the plot in Fig. 1.

2. Hyper-Kamiokande experiment

Hyper-Kamiokande (HK) [8] will be the next-generation water Cherenkov detector, starting taking data from 2027. Similar in concept to its predecessor, Super-Kamiokande (SK), the cylindrical tank of HK will be 72m high and 68m in diameter, with a fiducial volume of 188.4 kton, around 8.4 times the fiducial volume of SK. The photo-coverage of the inner detector region will be 40%, the same of SK, but it translates to roughly forty thousands photomultipliers (PMTs). New PMTs, with twice the quantum efficiency of the previous generation and
improved charge and timing resolution, will be employed. Thanks to incredible statistics and cutting edge resolutions, HK will be capable of a vast variety of physics studies, from accelerator and atmospheric neutrinos to solar and supernova neutrinos. Besides detecting proton decay, the main goal of HK is to measure $\delta_{\text{CP}}$ and constrain the other oscillation parameters with high precision. This is achievable by studying accelerator neutrinos, and to this end the possibility of installing a second detector in Korea, at the secondary oscillation peak, is being investigated.

HK will be located 295 km away from the target and $2.5^\circ$ off-axis with respect to the beamline. The neutrino beam is generated by a 30 GeV proton beam colliding on a fixed graphite target; a focusing horn selects positively charged ($\nu$ mode) or negatively charged ($\bar{\nu}$ mode) pions, which decay leptonically, to obtain an almost pure muon neutrino or antineutrino beam, peaking at 600 MeV. The accelerator facility at J-PARC will undergo a planned upgrade to increase the beam power up to 1.3 MW, before HK starts operation. The T2K near detector system, comprised of the two modules ND280 and INGRID, will be refurbished and the new Intermediate Water Cherenkov Detector, possibly gadolinium-loaded, will be located around 1 km from the target.

HK will take data for ten years, collecting a total of $2.7 \times 10^{22}$ Protons On Target, divided between $\nu$ and $\bar{\nu}$ beam modes. Assuming the design report configuration [8], $\nu : \bar{\nu} = 1 : 3$ and $\delta_{\text{CP}} = 0$, the expected number of fully-contained events in the fiducial volume for the channels $\nu_{\mu} \rightarrow \nu_{e}$ and $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ are respectively 1643 and 15 in $\nu$ mode and 206 and 1183 in $\bar{\nu}$ mode, assuming CP conservation. Deviations from these expected numbers could be indication of CP violation. A preliminary study for the HK design report [8], using a different analysis, estimated a significance well-above 5$\sigma$ after ten years of data taking, as can be seen in Fig. 2.

3. Sensitivity to $\delta_{\text{CP}}$

The sensitivity of HK to oscillation parameters is assessed by a combined fit of beam and atmospheric samples. For the atmospheric part, SK atmospheric Monte Carlo (MC) is adapted and scaled to HK statistics. A total of 2224 bins are used, divided in several two-dimensional histograms of log $p$ and cos $\theta$, where $\theta$ is the zenith angle. The beam sample uses four histograms in reconstructed energy with 87 bins for each of the four event samples, 1 ring $e$-like and 1 ring $\mu$-like events in $\nu$ and $\bar{\nu}$ mode. The event rates at the far detector are estimated with a flux prediction tuned with near detector constraints and smeared to obtain the reconstructed energy spectra. The event distributions are then weighted by the corresponding oscillation probabilities for each point of the oscillation space, using the true neutrino energy.

The oscillation space spans four variables, $\Delta m_{32}^2$, $\sin^2\theta_{13}$, $\sin^2\theta_{23}$, and $\delta_{\text{CP}}$, on a grid of respectively $13 \times 13 \times 13 \times 61$ points. The CP phase is varied on the interval $[-\pi, +\pi]$, whereas the other three parameters are centred around the best fit points from T2K [9] and reactor experiments [10, 11]. The number of events on each point of such space is compared to the number of events of a selected point, which is referred to as the true set of oscillation parameters. A $\chi^2$-test is used to test CP conservation. The sensitivity of HK to exclude the null hypothesis, i.e. $\delta_{\text{CP}} = 0, \pm \pi$, is quantified by changing the true value of $\delta_{\text{CP}}$ and by computing

$$\sigma = \sqrt{\min_{\delta_{\text{CP}}=0,\pm\pi} \chi^2 - \chi^2_{\text{true}}}$$

for each point, where $\chi^2_{\text{true}}$ is evaluated at the true point.

The test statistics of this analysis is defined as a "pull approach" $\chi^2$ [12], in the following way

$$\chi^2_{\text{tot}} = \sum_{n} \left[ E_{\text{obs}}(1 + \sum_{j} f_{j}^{\text{obs}} \varepsilon_{j}) - O_{n} + O_{n} \log \left( \frac{E_{n}(1 + \sum_{j} f_{j}^{n} \varepsilon_{j})}{O_{n}} \right) \right] + \sum_{ij} \varepsilon_{i} \rho_{ij}^{-1} \varepsilon_{j}$$

where $O_{n}$ and $E_{n}$ are respectively the number of observed and expected events in the $n$-th bin and $\rho^{-1}$ is the inverse of the correlation matrix of the systematic errors. The systematic
uncertainties are embedded in the $f^n_j$ term, which is the fractional change induced on the $n$-th bin by a 1σ variation of the $j$-th systematic; the amount of the shift is quantified by the “pull” $\varepsilon_j$ in units of the uncertainty $\sigma_j$. For most of the systematic parameters, a linear response is assumed. This means that varying of the $j$-th systematic by a known amount, $\beta_j \rightarrow \beta_j + \varepsilon_j \sigma_j$, the number of expected events changes as $E_n \rightarrow E_n (1 + \varepsilon_j f^n_j)$. Certain systematic uncertainties do not present a linear behaviour for small values of $\varepsilon$ and they are better described by a linear interpolation between four different $f^n_j$ histograms, computed at $\pm 1\sigma$ and $\pm 3\sigma$. For each point of the oscillation parameter space, the $\chi^2$ is profiled with respect to the pulls. This leads to a set of $j$ non-linear equations, which can be solved iteratively if the condition $\sum_j f^n_j \varepsilon_j < 1$ holds.

We adopt 67 systematics for the atmospheric sample from SK atmospheric studies [13]. For the beam part, the T2K (2018) error model is employed [14], initially uncorrelated with the atmospheric systematic set. There are 74 uncertainties for flux and cross-section parameters, from near detector constraints. They are grouped in 50 systematics—25 for the $\nu$ mode and 25 for the $\bar{\nu}$ mode—for the main flux components ($\nu_e$, $\nu_\mu$, $\nu_\tau$, and $\bar{\nu}_e$), and 24 systematics for cross-section parameters. There are also 45 uncertainties for SK detector efficiencies and Final State Interactions, which parameterise the uncertainties on the four final state event selections at the far detector: 1 ring $e$-like and 1 ring $\mu$-like in both $\nu$ and $\bar{\nu}$ modes. Among these, one systematic describes the energy scale uncertainty.

4. Systematic studies and conclusions

It is expected that larger systematic errors will result in a worse sensitivity, but certain uncertainties affect the measurement of CP violation more than others. For example, these can be the $\nu_e$ and $\bar{\nu}_e$ charged-current cross sections, the transverse flux model, the pion absorption probability, the total energy scale in SK, or the flux alignment. We study the impact of these selected systematics by modifying them one by one with respect to the nominal model and comparing the overall sensitivities to CP violation in these different scenarios. Doing so, it is possible to determine which systematics have the most important repercussion on the sensitivity, since it is fundamental to understand their effect at all phases of the experiment.

CP violation in the leptonic sector is plausible and it is also a necessary ingredient for leptogenesis. Neutrino oscillation experiments can lead to the discovery of CP violation, and it is foreseen that HK will determine the value of $\delta_{CP}$, a milestone which requires precise measurements and a deep understanding of the systematic errors.

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