PROCEEDINGS OF SCIENCE

Long-baseline neutrino oscillation sensitivities with Hyper-Kamiokande

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Neutrino oscillation physics is entering the precision measurement era. The focus of next generation neutrino experiments will be to determine the parameters governing neutrino oscillations precisely. The Hyper-Kamiokande experiment, currently under construction in Japan, includes a long-baseline neutrino oscillations program. Its main goals will be to determine whether CP violation occurs in neutrino oscillations and to provide precise measurements of neutrino oscillation parameters. To achieve this, Hyper-Kamiokande will have a large fiducial volume (8 times that of Super-Kamiokande) and will benefit from the upgrade of the J-PARC neutrino beam, enabling it to collect an unprecedented amount of data. A thorough knowledge of systematic effects and powerful near detectors are needed to match this level of precision. This talk presents the expected sensitivity of Hyper-K to oscillation parameters, notably CP violation, using a combination of accelerator and atmospheric neutrino information.

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1. Introduction

Many unanswered questions about the properties of neutrinos still exist, despite remarkable progress over the past few decades. Some of these include determining whether CP symmetry is violated in neutrino oscillations and whether the neutrino masses follow the same mass ordering (MO) as their charged lepton counterparts.

Hyper-Kamiokande (Hyper-K) [1] is a next-generation neutrino detector aiming to address the above mentioned open issues. It is a large-scale water Cherenkov detector, currently under construction in Japan. The Hyper-K collaboration has a rich and diverse physics program. It will study both neutrinos from the J-PARC neutrino beam, as well as solar, atmospheric and astrophysical neutrinos. Furthermore, it will also search for proton decay.

2. The Hyper-Kamiokande Long-Baseline Physics Program

An important part of the Hyper-K scientific agenda is its long-baseline (LBL) neutrino program. Some of the aims of the latter are to determine whether CP symmetry is violated in neutrino oscillations, and determining the precise values of neutrino oscillation parameters.

Hyper-K was proposed as a natural successor to the Super-Kamiokande detector. Like the latter, Hyper-K will be used to detect neutrino oscillations in a pure muon (anti-)neutrino beam produced at the J-PARC complex, located at a distance of 295 km. As such, it will be able to study neutrino oscillations in the same oscillation regime as T2K, with greater precision.

Before the scheduled start of Hyper-K data taking in 2027, the J-PARC beam power will be upgraded to 1.3 MW (up from the current 500 kW). This, combined with the 188 kton Hyper-K fiducial volume (8 times that of Super-Kamiokande), will yield an event rate 20 times higher than that recorded by T2K to date.

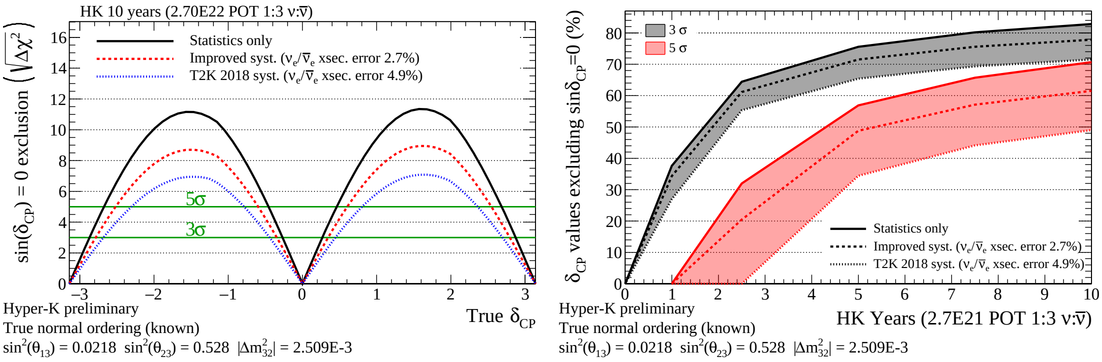
However, at this unprecedented level of statistics, systematic effects start to become important. The Hyper-K LBL program will follow the same strategy as T2K to control systematic effects related to the neutrino beam and neutrino interactions, namely by obtaining constraints with a set of near detectors located close to the beam production point. The first of these is INGRID, located on the beam axis to monitor its position and stability. Second, the T2K magnetized off-axis near detector at 280 m (ND280) will undergo a series of upgrades in 2022 [2]. The planned upgrades will double its fiducial mass and use new and improved detectors. As a result, the upgraded ND280 will be able to achieve full 4π coverage, matching that of Hyper-K. Furthermore, its new 3D scintillating tracker will lower the detection thresholds for protons and neutrons [3], thus giving access to more complex neutrino interaction final states. Finally, the third detector in the series is the Intermediate Water Cherenkov Detector, placed at $\sim$1 km from the beam. The IWCD will have the possibility to move at different off-axis angles with respect to the beam and construct linear combinations of (anti-)neutrino energy spectra enriched in different beam components.

3. Sensitivity to Oscillation Parameter Measurements

Hyper-K will be located at a distance of 295 km from J-PARC, at an off-axis angle of 2.5° with respect to the beam direction. The muon neutrino beam energy is peaked at 600 MeV, which is the energy at which the oscillation probability is maximized. In the muon neutrino disappearance channel, to first order, the amplitude of the oscillations is proportional to the mixing angle θ_{23}, and the position of the disappearance dip in the spectrum depends on the mass splitting Δm^2_{32}. The asymmetry between the electron neutrino and electron anti-neutrino appearance channels gives access to the CP violating phase $\delta_{\rm CP}$.

Hyper-K uses the simulation of the T2K experiment, scaled to account for the Hyper-K size and exposure. The simulation is split into 5 single-ring samples based on the Cherenkov ring pattern (electron-like or muon-like) and neutrino beam mode. The fifth sample consists of ν_e interactions with pion production, where the pion is tagged by the presence of a Michel electron. The number of expected events in the muon-like and electron-like samples for 10 years of Hyper-K data taking, corresponding to 2.7×10^{22} POT with a ν:$\bar{\nu}$ fraction of 1:3, is of the order of $O(10000)$ and $O(2000)$ events, corresponding to a statistical uncertainty of the level of $O(1\%)$ and $O(2\%)$, respectively. The statistical power is enough to determine whether CP violation occurs for a large fraction of $\delta_{\rm CP}$ values, and also to precisely measure the value of $\delta_{\rm CP}$. The increase in statistical power will also require a corresponding reduction in the size of systematic uncertainties.

To estimate its sensitivity to oscillation parameters quantitatively, the Hyper-K LBL studies use the same oscillation analysis pipeline as T2K. Dedicated flux and neutrino interaction models are fit to simulated near detector data and the results of the fit are used to constrain systematic uncertainties propagated to the far detector prediction. Two systematic error models have been compared in these sensitivity studies. The first one is based on the T2K 2018 [4] near detector fit results ('T2K 2018' model). The second one incorporates target improvements to the systematic error model based on the expected performance of the upgraded ND280 detector and the IWCD ('Hyper-K improved' model). Detector systematic errors were scaled to the Hyper-K size and exposure, and individual systematic errors were not allowed to go below 1%.

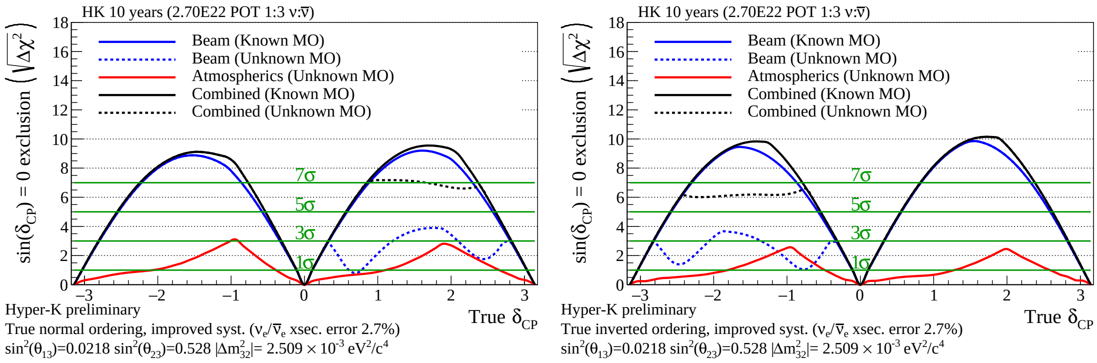


(a) **(b)**

Figure 1: (a) Sensitivity to exclude CP violation as a function of the true value of $\delta_{\rm CP}$. The solid black line shows the case where no systematics are considered (statistics only), the dotted red line represents the Hyper-K improved model and the dashed blue line shows the T2K 2018 model. (b) Percentage of $\delta_{\rm CP}$ values excluding $\sin\delta_{\rm CP} = 0$ at 3σ (black) and 5σ (red) significance, as a function of accumulated Hyper-K data. The line styles represent different systematic models.

The sensitivity to measure CP violation is shown in Figure 1a. The systematic error model significantly influences the range of excluded $\delta_{\rm CP}$ values. Considering that the $\nu_\mu/\bar{\nu}_\mu$ model of flux and cross-section will be well constrained by the near detectors, the main remaining uncertainty concerns the residual $\nu_e/\bar{\nu}_e$ uncertainty which could be partially uncorrelated with the ν_μ counterpart. Figure 1b shows that Hyper-K can detect CP violation within two years if $\delta_{\rm CP} = -\pi/2$, and can exclude CP conservation at the 5σ level for more than 60% of $\delta_{\rm CP}$ values after 10 years of operation. Similarly, the speed at which CP violation can be discovered depends on the systematic error model. Other oscillation parameters to which Hyper-K is sensitive are impacted similarly by the systematic error model.

The sensitivity to CP violation also depends on whether the MO is known. The 295 km baseline between Hyper-K and J-PARC cannot lift the degeneracy between the normal and inverted ordering (NO and IO, respectively) scenarios. However, Hyper-K can benefit from its strong atmospheric neutrino physics program. Unlike beam neutrinos, atmospheric neutrinos can have baselines up to the order of $O(10^4)$ km. This introduces significant matter effects, which offer additional sensitivity to the MO. Although atmospheric neutrinos themselves are less sensitive to CP violation than beam neutrinos, performing a combined analysis using beam and atmospheric neutrinos makes it possible to obtain a very good sensitivity to CP violation over a large fraction of $\delta_{\rm CP}$ values, independent on whether the MO will be determined by external experiments. The combined sensitivity is illustrated in Figure 2. This will allow Hyper-K to reach a 5σ statement on CP violation regardless of the true MO.

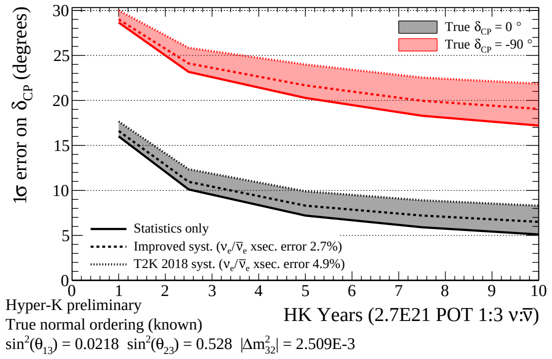


(a) **(b)**

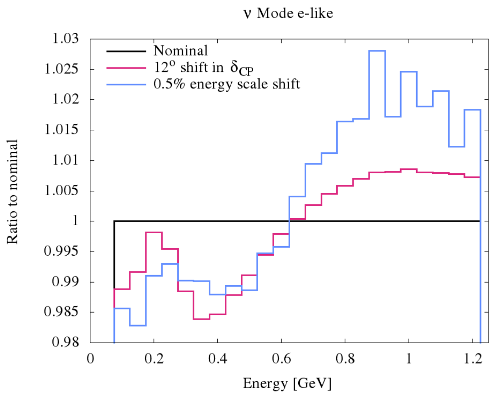
Figure 2: Sensitivity to exclude CP violation using beam neutrinos (blue), atmospheric neutrinos (red) and the combination of the two (black). Solid (dashed) lines indicate that the MO is known (unknown). (a) Assuming true NO. (b) Assuming true IO.

4. Prospects for Precision Measurements

Performing precision measurements of neutrino oscillation parameters is crucial to identify underlying symmetries which explain neutrino mass generation and mixing. The precision with which an oscillation parameter can be determined depends on its true value, but also on the assumptions on the systematic error model. Figure 3a shows the precision on $\delta_{\rm CP}$ as a function of accumulated data using the T2K 2018 systematic model and the Hyper-K improved model. Systematic effects become particularly important when they present degeneracies with oscillation parameters. This is illustrated in Figure 3b, comparing the effect of a shift in the detector energy



(a)



(b)

Figure 3: (a) 1σ error on δ_{CP} as a function of Hyper-K accumulated data. The red (black) color assumes the true value of δ_{CP} is $-90°(0°)$. Solid lines represent the systematics-only case, dashed lines the Hyper-K improved model, and finely dotted lines the T2K 2018 model. (b) Fractional variation of the 1-ring electron-like sample prediction with respect to the nominal spectrum for a 12° shift in δ_{CP} (magenta) and a 0.5% variation of the energy scale (blue).

scale to the size of the precision on δ_{CP}. A 0.5% shift in the absolute energy scale is degenerate with δ_{CP}. A careful calibration program is under development to this end, using in-situ measurements.

5. Conclusion

Hyper-K has a rich and diverse physics program, including an ambitious long-baseline neutrino oscillation physics agenda. The fiducial volume of Hyper-K, combined with the upgrade of the J-PARC neutrino beam, will allow this program to gather unprecedented statistics. As the statistical power increases, systematic effects need to be precisely controlled and better understood. If CP violation occurs in neutrino oscillations, Hyper-K will be able to detect it within the first few years of operation. Combining beam and atmospheric neutrinos will further enhance Hyper-K's sensitivity to CP violation, regardless of the neutrino mass ordering. Hyper-K will also perform precision measurements of neutrino oscillation parameters. To mitigate systematic effects which hinder these measurements, Hyper-K is developing robust analysis methods and calibration strategies.

References

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