PROCEEDINGS OF SCIENCE

Oscillation Physics with Hyper-Kamiokande

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Hyper-Kamiokande (HK) is a next-generation water Cherenkov neutrino experiment, which aims to start taking data in 2027. It will use the J-PARC neutrino beam, which will be upgraded to 1.3 MW. The upgraded near detector ND280 and new Intermediate Water Cherenkov Detector (IWCD) will constrain the flux and cross section systematic uncertainties. Atmospheric neutrinos are sensitive to the Mass Ordering (MO), which in combination with accelerator neutrinos will allow for the possibility of a 5-σ sensitivity to CP-violation regardless of the true MO. Moreover, HK also aims to make precision measurements of the neutrino oscillation parameters, which require a precise understanding of the systematic uncertainties in HK.

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1. Introduction

1.1 Neutrino Oscillation

The oscillation of neutrinos indicates that the neutrinos have mass and has been discovered by experiments like Super-Kamiokande (SK) [1] and SNO [2]. Current-generation experiments, such as T2K [3] and NOvA [4], are making measurements of long-baseline neutrino oscillations. The long baseline T2K experiment uses the beam of $\nu_\mu(\bar{\nu}_\mu)$ from J-PARC and the water Cherenkov detector SK 295 km away as the far detector, which measures the disappearance of $\nu_\mu(\bar{\nu}_\mu)$ and appearance of $\nu_e(\bar{\nu}_e)$. Hyper-Kamiokande (HK) [5] is a next generation water Cherenkov neutrino experiment which has the potential to make precision measurements of $\sin^2\theta_{23}$, Δm^2_{32}, δ_{CP}, as well as CP violation and MO discovery.

1.2 Hyper-Kamiokande

The HK far detector located in Kamioka, 295 km from the J-PARC beam is 68 m in diameter and 71 m in height and is 8.4 times the fiducial volume of SK.

The Inner Detector (ID) of HK which is the volume used for physics analyses includes approximately 20,000 50 cm box and line PMTs and additional multi-PMTs (mPMTs). The 50 cm PMTs are 2 times more efficient of those used in SK. The addition of mPMTs (which consist of 19 8 cm PMTs for each module) will have also the benefit of measuring directional information of arrival photons. The mPMTs have accurate photon counting and excellent timing resolution.

The Outer Detector (OD), which consists of 8 cm PMTs and wavelength shifting plates, is used to reject cosmic ray muons to constrain the external background.

The aforementioned photon sensors, together with the electronics, will then be installed on the frame in HK. HK aims to elucidate the Grand Unified Theory and the history of the evolution of the universe through an investigation of proton decay and CP violation (the difference between neutrinos and antineutrinos), precision measurements of oscillation parameters, together with the observation of neutrinos from supernova explosions.

1.3 J-PARC Upgrade

J-PARC is located in Tokai and will provide the neutrino beam, where the flux $\nu/\bar{\nu}$ peak at 0.6 GeV to maximize the sensitivity to oscillation. The HK far detector is 2.5° off-axis from the J-PARC beam.

J-PARC has upgraded the magnet PS to 1.36 s cycle and is in the process of upgrading the RF system. In the future, with the RF system upgrade and the cycle further upgraded to 1.16 s, the neutrino beam from J-PARC is expected to reach 1.3 MW by 2028, corresponding to 2.7×10^{22} proton on target (POT) in 10 HK running years.

1.4 ND280

ND280 is one of the near detectors which is located 280 m away and at 2.5° of axis from the neutrino beam at J-PARC. ND280 currently is part of T2K, and is used to constrain the flux and cross-section systematic uncertainties. It will then be used in HK when it will start taking data. ND280 will be soon upgraded adding a Super Fine-Grained Detector (Super-FGD module), sandwiched between 2 High-Angle Time Projection Chambers, all of which will improve the ND280 4π acceptance and lower energy threshold. These will enable the upgraded ND280 to measure more hadronic final states.

1.5 Intermediate Water Cherenkov Detector (IWCD)

HK will include an additional intermediate water Cherenkov detector, which aims to constrain the systematic uncertainties of cross sections. The IWCD will be a tall vertical shaft, instrumented by mPMTs, located approximately 1 km from the beam source. The IWCD is designed to have $1\sim4^\circ$ off-axis angle. In addition, it will detected the large fraction at the far-OA angle and constrain $\nu_e/\bar{\nu}_e$ cross sections in water.

2. Long-Baseline Programs in HK

2.1 Accelerator Neutrinos from J-PARC

The beam from J-PARC is expected to provide 2.7×10^{21} POT per year. The sensitivity to δ_{CP} mainly comes from $\nu_\mu \rightarrow \nu_e$ appearance, while the sensitivity to $\sin^2\theta_{23}$ and Δm^2_{32} mainly comes from ν_μ disappearance. The oscillation parameters used to build the true Monte Carlo data are based mainly on the previous T2K experiment [8] and also refer to some other experiments [9], as shown in Table 1. HK has simulated the event rates by the SK Monte Carlo method and SK selection method, where the amount of events signals assumes 2.7×10^{22} POT with a run plan $1\nu : 3\bar{\nu}$.

δ_{CP}	$-\pi/2$
$\sin^2\theta_{23}$	0.528
Δm^2_{32}	2.509×10^{-3}
$\sin^2\theta_{13}$	0.0218
Δm^2_{21}	7.53×10^{-5}
$\sin^2\theta_{12}$	0.307

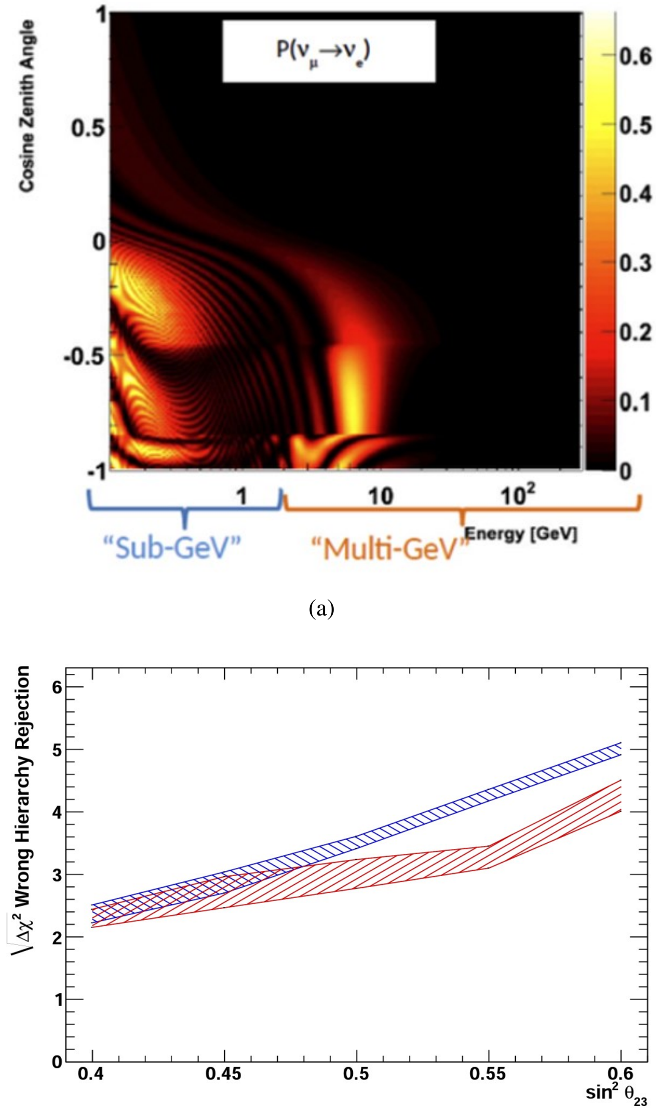
Table 1: The oscillation parameters of HK Long-baseline event rate.

2.2 Atmospheric Neutrinos

The simulation of atmospheric neutrinos events in HK is based on SK Monte Carlo and assumes a HK exposure of 1.9×10^6 events in total.

Since the up-going neutrino events have traveled through the earth, some muon neutrinos transmute into tau neutrinos. The size of the decrease in disappearance channel is sensitive to $sin^2\theta_{23}$ but not to Δm^2_{32}. Figure 1(a) shows the oscillation probability for the channel $\nu_\mu \rightarrow \nu_e$. If the mass ordering is normal there are some peaks of the probability in the high energy (multi-GeV) upward-going appearance electron neutrinos. Otherwise, this area is empty. SK measurements [6] prefer normal MO and reject the inverted MO at 93% confidence level.

Therefore, HK is expected to have strong significance to determine the neutrino mass ordering from atmospheric neutrinos alone.



(a)

(b)

Figure 1: (a) The oscillation probability of $\nu_\mu \rightarrow \nu_e$ assuming the MO is normal with the effect by earth density. (b) Neutrino MO sensitivity as a function of the true value of $sin^2\theta_{23}$ for a single detector after 10 years, where the blue (red) bands denotes the normal (inverted) MO and the width of the band indates the uncertainty from δ_{CP}.

2.3 Systematic Uncertainties

For atmospheric samples, HK estimates the systematic uncertainties to HK size and exposure according to SK information, assuming 10 running years. The systematic uncertainties from the beam are based on T2K systematic uncertainties [8] and have been reduced based on projected sensitivity of the ND280 upgrade and IWCD (which constrain the cross-section and flux uncertainties) and increased exposure to atmospheric neutrinos (which constrain the detector uncertainties). Those systematic uncertainties have also been reduced based on the assumed decrease in statistical error from the increased running time. The detailed systematic uncertainties errors are given in Table 2.

	1-ring ν_μ-like		1-ring ν_e-like			
Error source	ν-mode CCQE-like	$\bar{\nu}$-mode CCQE-like	ν-mode CCQE-like	$\bar{\nu}$-mode CCQE-like	ν-mode CC1π-like	ν-/$\bar{\nu}$-mode CCQE-like
Flux+Cross-section	0.81%	0.72%	2.07%	1.88%	2.21%	2.28%
Detector+FSI+SI	1.68%	1.58%	1.54%	1.72%	5.21%	0.97%
All systematics	1.89%	1.74%	2.56%	2.53%	5.63%	2.45%

Table 2: HK beam neutrinos systematic uncertainties.

To do the joint fit, some correlation between the systematic uncertainties of atmospheric samples and beam samples will be further studied.

3. Sensitivity to CP-Violation

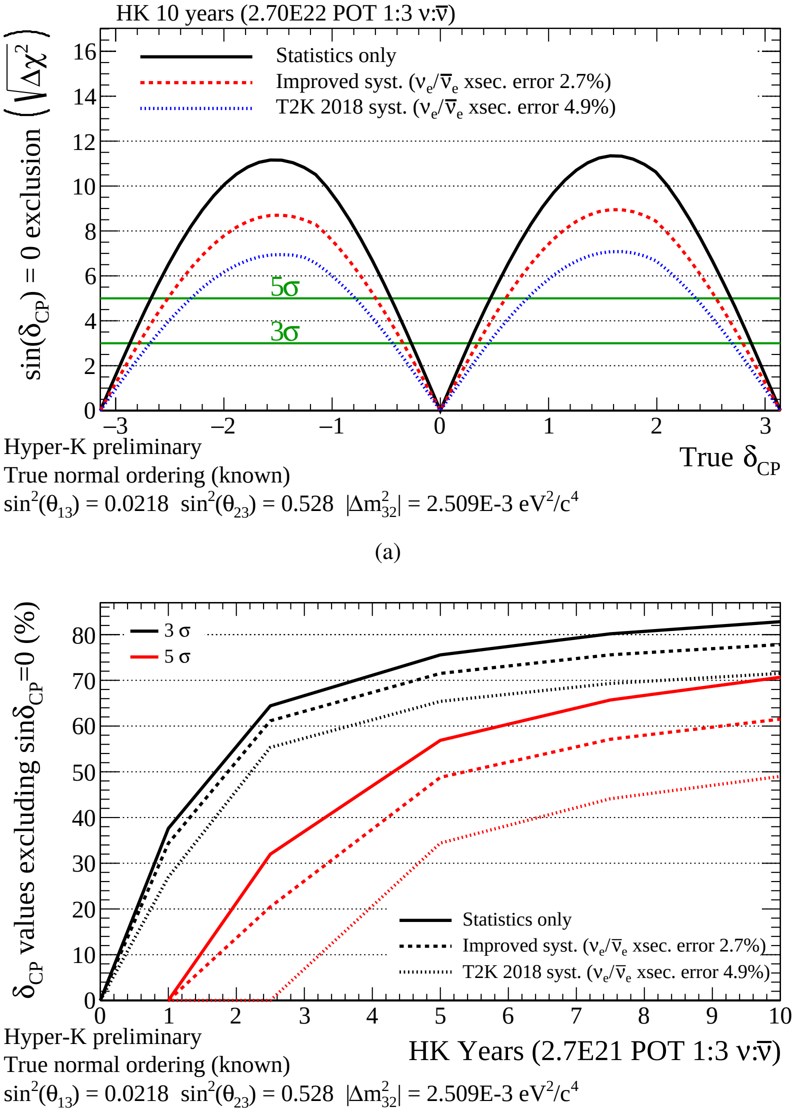
Figure 2 shows the significance to exclude the CP-conserving case that $sin(\delta_{CP} = 0)$ assuming the MO is normal and known, where the sensitivity to CP violation is improved by the HK systematic uncertainties.

HK is sensitive to CP-violation and can get a higher than 8-σ significance for excluding CP conservation, assuming the MO is known. However, sensitivity to CP violation is significantly reduced if the MO is unknown, because the baseline of HK is not long enough to be sensitive to MO. However, including information from atmospheric neutrinos, which are sensitive to MO as indicated in section 2.2, will get a $5 - \sigma$ sensitivity to CP violation, as shown in Figure 3. After 10 years of data taking, CP conservation will be excluded for 61% of true values of δ_{CP} with the improved HK systematic uncertainties assuming the MO is normal.

4. Precision Measurement

HK is not limited to measure δ_{cp}, it can also measure other oscillation parameters such as $sin^2\theta_{23}$ and Δm^2_{32}. Figure 4(a) shows the wrong octant can be excluded at 3-σ for true $sin^2\theta_{23} < 0.47$ and true $sin^2\theta_{23} > 0.55$. In addition, Figure 4(b) indicates HK has the potential of precision measurements of Δm^2_{32}.

However, some systematic uncertainties will impact the sensitivity of the precision measurement, for example, reconstructed energy scale uncertainties which are the scaling of bin edges of



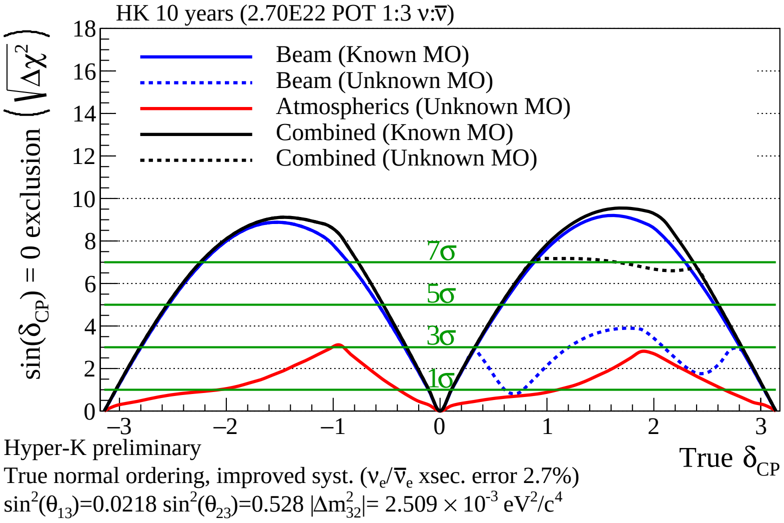
(a)

(b)

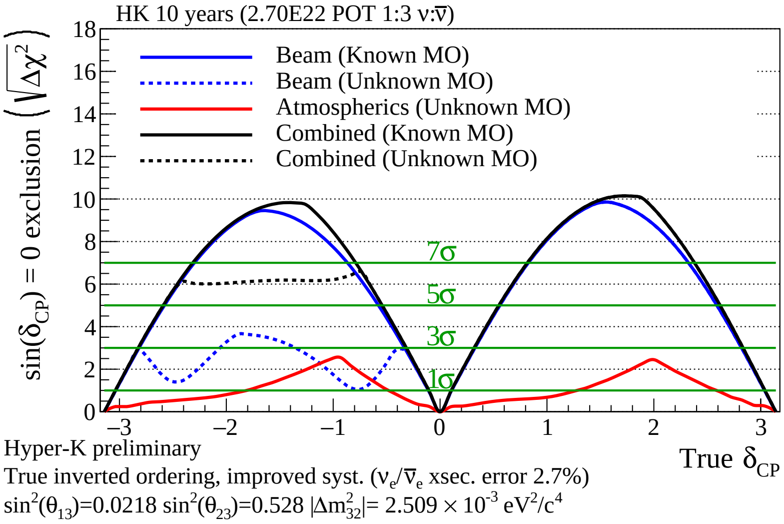
Figure 2: Sensitivity to CP violation in 10 years, assuming the MO is normal.

neutrino reconstructed energy. The impact of shifting 12° on δ_{CP} is similar to the 0.5% variation of energy scale uncertainties as shown in Figure 5(a). Therefore, the IWCD have the requirement of the energy scale 1-σ error to be lower than 0.5%. However, since the implementation of mPMTs improves the detector measurement of the electron neutrinos and muon neutrinos, the free degree of measuring electron neutrinos and muon neutrinos will be different, which requires the analysis using different methods to estimate the energy scale uncertainties of electron neutrinos and muon neutrinos. From sensitivity to δ_{CP} measurement shown in Figure 5, though the impact is small, either increasing the error or separate energy scale uncertainties of electron neutrinos and muon neutrinos cause a reduction in sensitivity.

To achieve the target, the calibration procedure should be able to disentangle and precisely



(a)



(b)

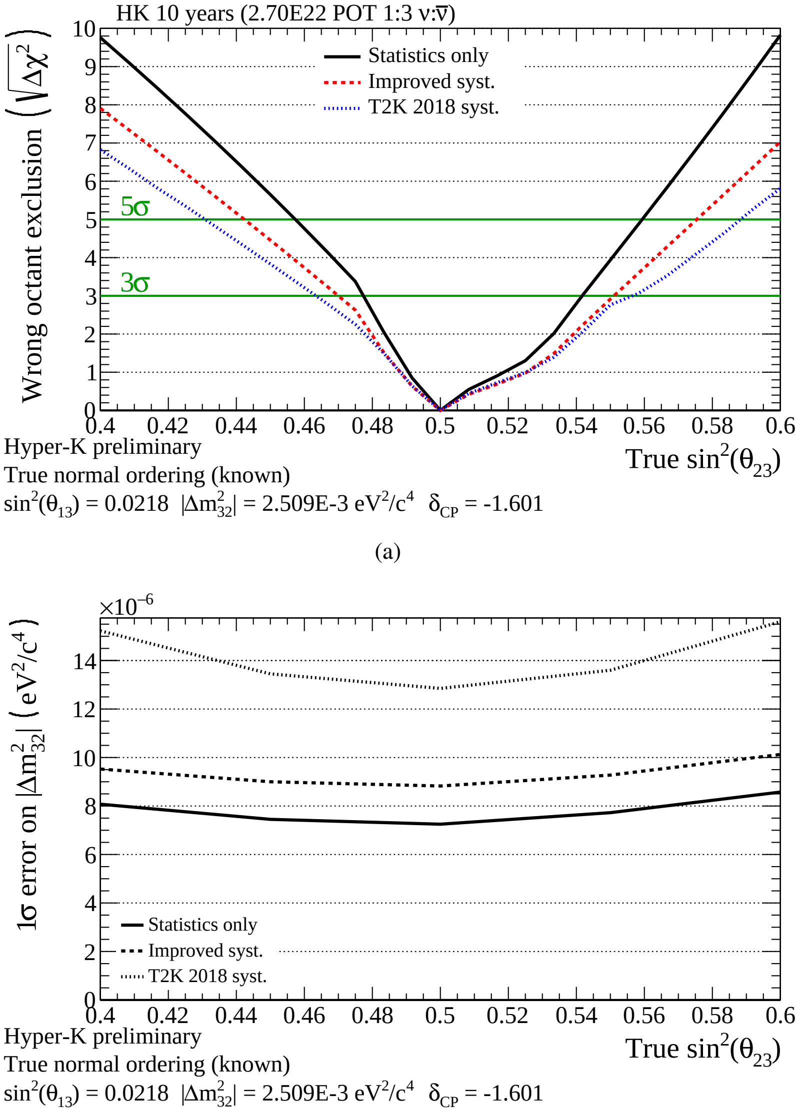
Figure 3: Sensitivity to CP-violation in 10 years, (a) is true normal MO, and (b) is true inverted MO.

model all fundamental causes of energy scale uncertainties as a function of energy and neutrino flavor.

5. Conclusion

HK is the next generation water Cherenkov neutrino experiment, having a 295 km baseline and 8.4 times the fiducial volume of SK, which is expected to make precision measurements of the neutrino oscillation parameters.

With the combination of beam and atmospheric neutrinos, HK is expected to get a 5-σ sensitivity to CP-violation regardless of MO. In addition, after 10 HK years, 61% of the value of



(a)

(b)

Figure 4: (a) Sensitivity to exclude the wrong $sin^2\theta_{23}$ octant, as a function of true $sin^2\theta_{23}$, for 10 HK-years. (b) 1 σ resolution of Δm^2_{32} as a function of true $sin^2\theta_{23}$, after 10 HK-years.

δ_{CP} will be excluded with the improved HK systematic uncertainties assuming the MO is normal. Moreover, wrong octant can be excluded at 3-σ for true $sin^2\theta_{23} < 0.47$ and true $sin^2\theta_{23} > 0.55$.

Furthermore, HK has multiple physics targets, which also have the potential to measure proton decay, supernova neutrinos, solar neutrinos, etc.

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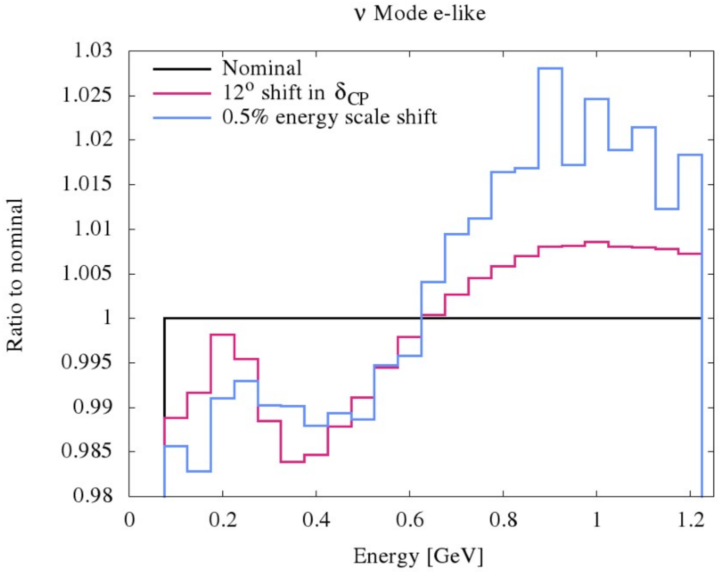
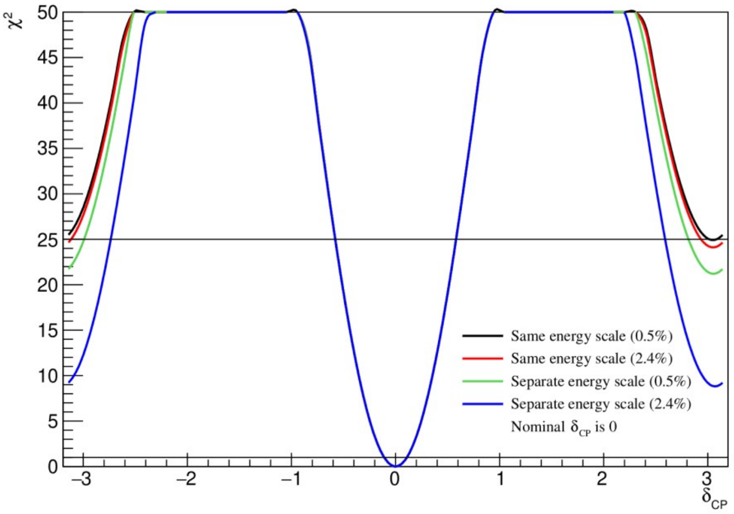


(a)



(b)

Figure 5: (a) is the fractional variation of the 1-ring electron-like sample prediction of shifting δ_{CP} 12° and energy scale 0.5% variation. (b) is sensitivity to δ_{CP} assuming true $\delta_{CP} = 0$ after 10 HK-years.

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