PROCEEDINGS OF SCIENCE

Bridging Experiments, Narrowing Uncertainties: When DUNE Meets Hyper-K to unveil insights into 2–3 Oscillation Sector

Sanjib Kumar Agarwalla,[a,b,d] **Ritam Kundu,**[a,b,*] **and Masoom Singh**[a,c]

[a] *Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India*
[b] *Homi Bhabha National Institute, Anushakti Nagar, Mumbai 400094, India*
[c] *Department of Physics, Utkal University, Vani Vihar, Bhubaneswar 751004, India*
[d] *Department of Physics & Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin, Madison, WI 53706, U.S.A*

E-mail: sanjib@iopb.res.in, ritam.k@iopb.res.in, masoom@iopb.res.in

A meticulous determination of Δm^2_{31} and θ_{23} is indispensable for accurately evaluating the Earth's matter effect in long-baseline experiments, a key element in resolving the neutrino mass ordering conundrum and in measuring the CP phase in the 3ν paradigm. By reviewing the footprints of previous and ongoing experiments and considering the anticipated sensitivities from the upcoming IceCube Upgrade and KM3NeT/ORCA, we examine the expected advancements in the precision of 2–3 oscillation parameters that the next-generation long-baseline experiments, DUNE and Hyper-K, are set to provide, either independently or in combination. We underscore the significance of the complementarity between these two experiments, which substantially enhances the sensitivity to deviations from maximal mixing in θ_{23}, decisively excludes the wrong-octant solutions for θ_{23}, and enables exceptionally refined measurements of the 2–3 oscillation parameters, surpassing the capabilities of each experiment when considered in isolation. Our analysis shows that, for the current best-fit values of the oscillation parameters and assuming normal mass ordering (NMO), the combination of DUNE and Hyper-K can confirm a non-maximal θ_{23} and exclude the wrong octant solution with a statistical significance of approximately 7σ with their nominal exposures. Furthermore, we find that DUNE and Hyper-K together can enhance the existing 1σ precision on $\sin^2\theta_{23}$ and Δm^2_{31} by factors of 7 and 5, respectively, assuming NMO. Given the financial hurdles and the prolonged commitment required for the full 10-year operation of DUNE and Hyper-K, our study highlights that even with less than half of their nominal exposures, the collaboration between DUNE and Hyper-K can still achieve sensitivities in our phenomenological analyses that are on par with those expected from their full exposures individually. Finally, we highlight how the synergistic interplay between DUNE and Hyper-K can offer more stringent constraints on the $(\sin^2\theta_{23}, \delta_{\rm CP})$ plane, outstripping the reach of the standalone experiments.

The European Physical Society Conference on High Energy Physics (EPS-HEP2025)
7-11 July 2025
Marseille, France

*Speaker

PoS(EPS-HEP2025)164

1. Introduction

Complementarity and synergy among various datasets from several oscillation experiments have played an important role in shaping our present knowledge about the six oscillation parameters in the three-flavor neutrino oscillation paradigm [1]. In addition to increasing the statistical strength, combining various datasets in a single experiment or multiple experiments helps to remove parameter degeneracies by exploring the sub-leading three-flavor effects in the 3ν oscillation framework [2, 3]. Focusing on these sub-leading three-flavor effects, we have conducted a detailed study of the sensitivity of the upcoming high-precision long-baseline experiment, DUNE [4], to detect deviations from maximal mixing in θ_{23} and to determine its octant based on the current knowledge of other oscillation parameters [5]. We have thoroughly investigated the potential complementarities and synergies between DUNE and another next-generation long-baseline experiment in Japan, Hyper-K [6]. Our focus has been on how the combination of these two experiments can enhance sensitivities in the search for leptonic CP violation [7] and identify possible deviations from maximal mixing of θ_{23} and its octant [8], suppressing various parameter degeneracies in the three-flavor framework. In this short proceeding, based on our recent publication [8], we highlight the importance of combining the future long-baseline data from DUNE and Hyper-K to achieve high precision in the measurements of $\sin^2\theta_{23}$ and Δm^2_{31}. We also show how the possible complementarities between DUNE and Hyper-K enhance the sensitivities in establishing non-maximal θ_{23} and resolving its correct octant and constraining the allowed regions in the plane of $\sin^2\theta_{23}$ and δ_{CP}.

2. Our Results

We evaluate the performance of DUNE and Hyper-K, either individually or in combination, to measure the potential deviation of θ_{23} from maximal mixing. Our analysis focuses on eliminating incorrect octant solutions for θ_{23}, as well as on achieving precise measurements of $\sin^2\theta_{23}$ and Δm^2_{31}. A precise measurement of any deviation from maximal mixing of θ_{23} and its correct octant may assist us in testing various theoretical neutrino mixing models, such as bimaximal, tri-bimaximal, tri-bimaximal-Cabibbo, and bi-large within the three-neutrino 3ν framework. For the DUNE experiment, we estimate the aforementioned sensitivities using a baseline of 1285 km, with a wide-band, on-axis neutrino beam, and a far detector with a fiducial volume of 40 kilotons, assuming 5 years of neutrino ν running followed by 5 years of antineutrino $\bar{\nu}$ running. Regarding the Hyper-K setup, we consider a baseline of 295 km, utilizing a narrow-band, off-axis neutrino beam, a water Cherenkov far detector with a fiducial volume of 187 kilotons, and operating for 2.5 years in neutrino mode and 7.5 years in antineutrino mode.

We consider the benchmark values of oscillation parameters and their allowed ranges obtained from the global fit of world neutrino oscillation data [12], assuming the normal mass ordering. We simulate our results using the publicly available GLoBES software [13, 14]. In the top left panel of Fig. 1, we see that individually DUNE and Hyper-K have a bright prospect to establish non-maximal θ_{23} with exceptional significance ($> 5\sigma$) with their full exposures at the best-fit value of $\sin^2\theta_{23} = 0.455$, but the combined analysis of data from DUNE and Hyper-K surpasses the sensitivity achieved individually. A notable finding in this regard is, *if in Nature,* $\sin^2\theta_{23}$ *is around the upper value of its current 1*σ *uncertainty (*~ 0.473*), then the combination of DUNE and Hyper-K*

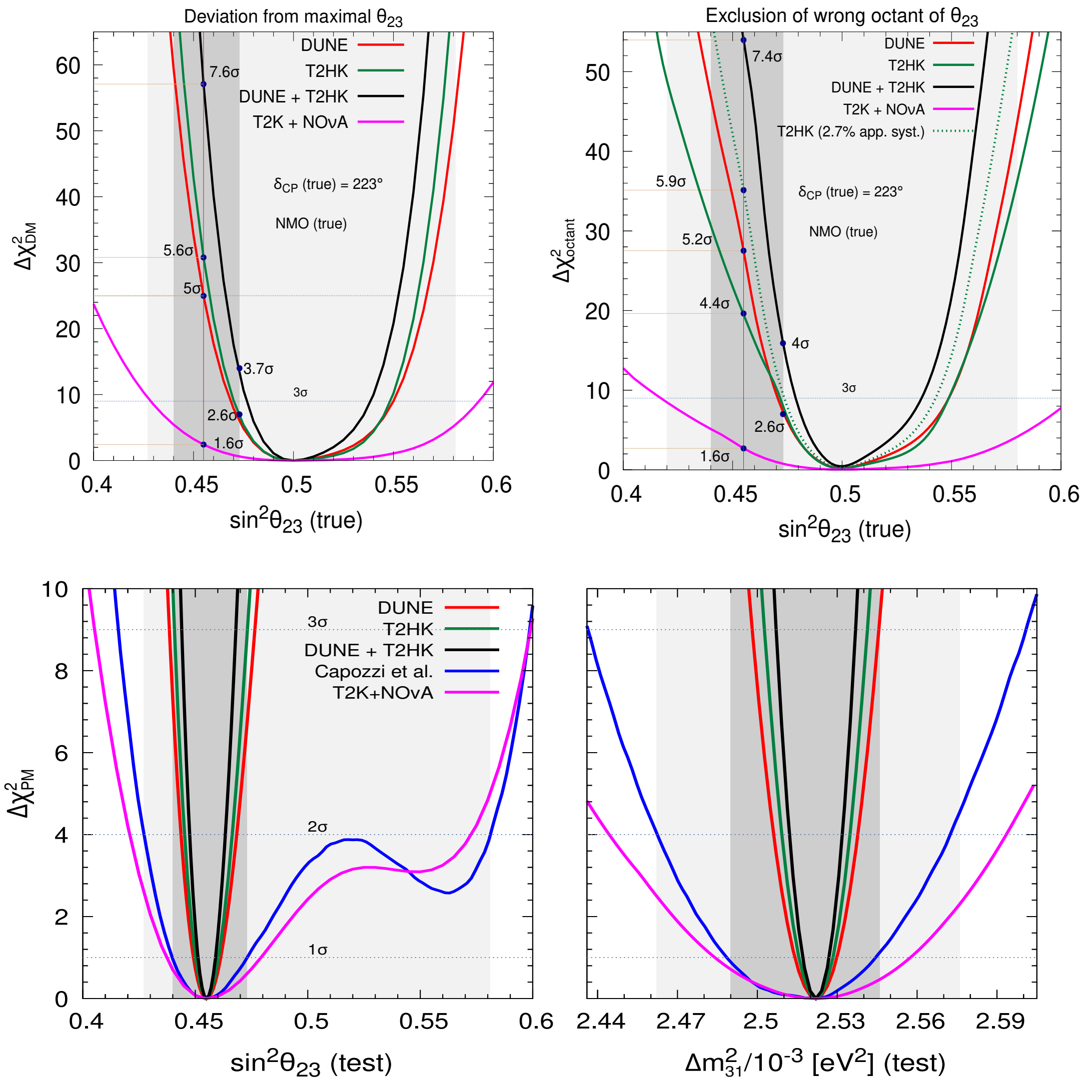

Figure 1: Upper panel: Sensitivity of DUNE, Hyper-K, and T2K+NOνA in testing non-maximal θ_{23} (left) and excluding the wrong octant (right). Lower panel: Precision on $\sin^2\theta_{23}$ (left) and Δm^2_{31} (right). Red, green, and magenta curves denote DUNE, Hyper-K, and T2K [9]+NOνA [10, 11]; black shows DUNE+Hyper-K; blue (lower panel) indicates global-fit precision [12]. Vertical brown line marks our $\sin^2\theta_{23}$ best fit (0.455). Dark (light) gray bands show $1\sigma(2\sigma)$ global-fit ranges. Benchmark values: $\delta_{CP} = 223°$, $\Delta m^2_{31} = 2.522 \times 10^{-3}$ eV^2 (NMO). Upper-panel sensitivities are marginalized over Δm^2_{31}, δ_{CP}; lower-panel precisions over δ_{CP} and the complementary parameter. See Ref. [8] for details.

is the only way to achieve sensitivity $> 3\sigma$ with our benchmark choices of oscillation parameters. As this study is mostly a disappearance-driven phenomenon, Hyper-K performs better than DUNE owing to its greater statistics due to a larger detector volume and smaller systematic uncertainties in the $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ disappearance channels. The top right panel of Fig. 1 depicts the sensitivity in ruling out the incorrect choice of the θ_{23} octant for a true $\delta_{CP} = 223°$ assuming true NMO. Since it is mostly an appearance-driven phenomenon, DUNE performs better than Hyper-K, especially at a high confidence level, due to its less systematic uncertainty (2%) in the $\nu_\mu \to \nu_e$ and

PoS(EPS-HEP2025)164

$\bar{\nu}_\mu \to \bar{\nu}_e$ appearance channels.

In the lower panel of fig.1, we depict the precision measurements of $\sin^2\theta_{23}$ (one of the most uncertain neutrino oscillation parameters) and Δm^2_{31} around their best-fit values [*i.e.*, $\sin^2\theta_{23} = 0.455$ and $\Delta m^2_{31} = 2.522 \times 10^{-3}$ eV^2] in true NMO. Precision measurement generally gets improved in the presence of higher statistics, or in turn, $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ disappearance channel in LBL experiments. We tabulate the relative 1σ precision of the 2-3 parameters in different experimental setup in Table 1. The relative 1σ precision is defined as,

$$p\,(\alpha) \;=\; \frac{\alpha^{\max} - \alpha^{\min}}{6.0\,\times\,\alpha^{\text{true}}} \;\times\; 100\%\,. \tag{1}$$

Here, $\alpha^{\max}$ and $\alpha^{\min}$ depict the allowed upper and lower test values of each curve in the corresponding parameters (as shown in figure 1) at 3σ, respectively. Being the precision measurement a disappearance-driven phenomenon, Hyper-K performs better than DUNE due to its enlarged statistics. A noteworthy point is, combined DUNE + Hyper-K improves the present-day achievable precision [12] on $\sin^2\theta_{23}$ and Δm^2_{31} by a factor of $\sim$7 and $\sim$5, respectively. The notable precision on Δm^2_{31} by DUNE + Hyper-K is comparable with the projected precision of JUNO [15] experiment. In figure 1, the joint performance of T2K + NOνA deteriorates than DUNE and Hyper-K, irrespective of any true values of $\sin^2\theta_{23}$. This happens due to their larger systematic uncertainties in both appearance and disappearance channels. The smaller detector volumes compared to the future LBL experiments of our study are also responsible for this deterioration in their sensitivities. In Ref. [12], we found that when true inverted mass ordering (IMO) is assumed, the projected best-fit of $\sin^2\theta_{23}$ gets shifted towards the higher octant (HO), at 0.569. Furthermore, we observe an almost similar confidence level in probing the sensitivity of non-maximal θ_{23} and precision of $\sin^2\theta_{23}$ for true IMO. Considering that the best-fit value of δ_{CP}, assuming true IMO, shifts to 274° [12], we observe little shift in the sensitivity study of exclusion of wrong θ_{23} octant.

Parameter	Relative 1σ precision (%)					
	HK	DUNE	HK+DUNE	T2K+NOνA	Capozzi *et al.*	JUNO
$\sin^2\theta_{23}$	1.18	1.40	0.88	7.10	6.72	—
Δm^2_{31}	0.25	0.31	0.20	0.99	1.09	0.2

Table 1: Relative 1σ precision calculated from figure 1 using Eq. 1, assuming true NMO. Furthermore, we also depict current global-fit precision from ref. [12] and expected relative 1σ precision using JUNO with an estimated 6 years of run [15].

In figure 2, we show the nature of our phenomenological studies at 3σ and 5σ as a function of scaled exposure for the standalone DUNE, Hyper-K, and their combination. The quantity of exposure is often considered interchangeably with runtime in phenomenological aspects of neutrino oscillation. Some experiments (e.g.- DUNE) plan to take the staged approach by adding up the detector volume cumulatively to reach the full detector volume. Hence, our studies become pertinent for varying exposures of the experiments. In the upper panel of fig.2, we show that although with an increment in exposure, the sensitivity to non-maximal θ_{23} increases initially, it attains saturation after reaching half of their individual benchmark exposures. Based on the benchmark choices of

PoS(EPS-HEP2025)164

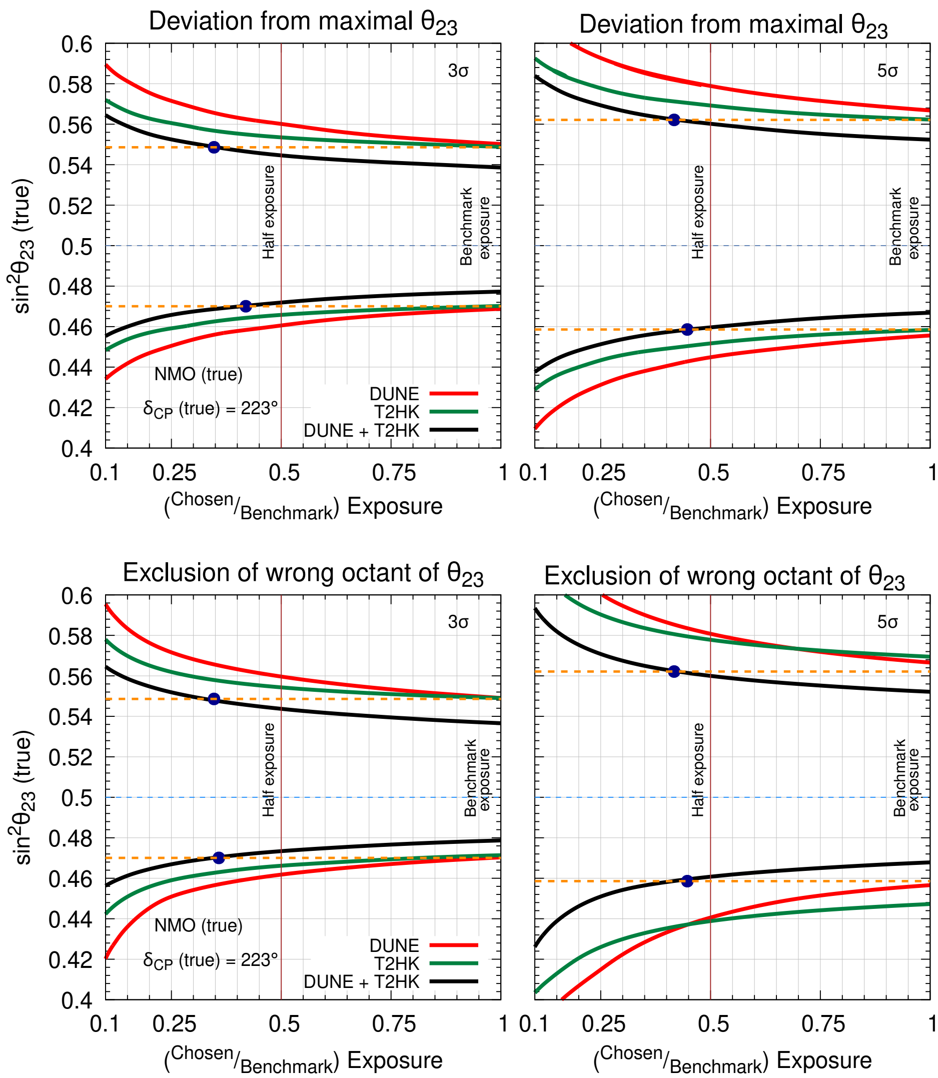

Figure 2: Sensitivity to non-maximal $\sin^2\theta_{23}$ (upper) and wrong-octant exclusion (lower) vs. scaled (ratio of the chosen to the benchmark value of) exposure, assuming true NMO. Left (right): 3σ (5σ). Dashed orange lines: maximum standalone sensitivity of DUNE and Hyper-K at nominal exposure; solid blue dots: reduced DUNE+Hyper-K exposure giving the same. The ratio touches 1 at the benchmark choices [12] of the corresponding experimental setups. Only $\sim 40\%$ of nominal exposure with DUNE+Hyper-K matches standalone results, and their combination uniquely attains 5σ octant exclusion.

oscillation parameters [12], we find that the range of true values of $\sin^2\theta_{23}$ that can be differentiated from maximal mixing, by DUNE + Hyper-K with just ~ 0.5 of their nominal exposures, cannot be achieved by either of the individual experiments even with their respective projected exposures. At lower exposure, Hyper-K always performs better than DUNE to establish non-maximal $\sin^2\theta_{23}$, irrespective of the lower or higher octant of true choices of $\sin^2\theta_{23}$, because of better systematic uncertainties in disappearance rates and its larger detector volume than DUNE. The complementarity between DUNE and Hyper-K is essential to achieve a significant sensitivity at 5σ, even with high exposure. In the left (right) figure of the lower panel of figure 2, we show the exclusion of the wrong octant solution of $\sin^2\theta_{23}$ as a function of exposure with 3σ (5σ) C.L. for true $\delta_{\rm CP}$ = 223° and assuming the true NMO. We find that with 0.25 times of their nominal exposures, DUNE alone will be able to differentiate about 45% of $\sin^2\theta_{23}$ from the wrong octant solutions; this improves to $\sim$ 50% in Hyper-K, while their combination, DUNE + Hyper-K can differentiate $\sim$ 60%. So with just 0.25 of their individual exposures, it is possible in the combined setup to exclude the wrong θ_{23} octant for more than half of currently allowed $\sin^2\theta_{23}$. Increasing beyond half of the nominal exposure does not help much, as the exclusion of the wrong octant solutions no longer remains statistics-driven. We also notice that at 3σ confidence, around 73% of $\sin^2\theta_{23} \in 0.4, 0.6$ can differentiate between the correct and the wrong octant solutions of θ_{23} using the combined DUNE + Hyper-K setup, given the current benchmark values and projected exposure. For a larger confidence level (5σ), DUNE + Hyper-K is the only way to avoid choosing the wrong octant of θ_{23} at lower exposure. We also show that the discovery potential of DUNE + Hyper-K in excluding the wrong octant solutions of $\sin^2\theta_{23}$, achievable with just $\sim$0.45 times of their individual exposures, is comparable to the sensitivity attained by standalone experiments using their nominal exposures.

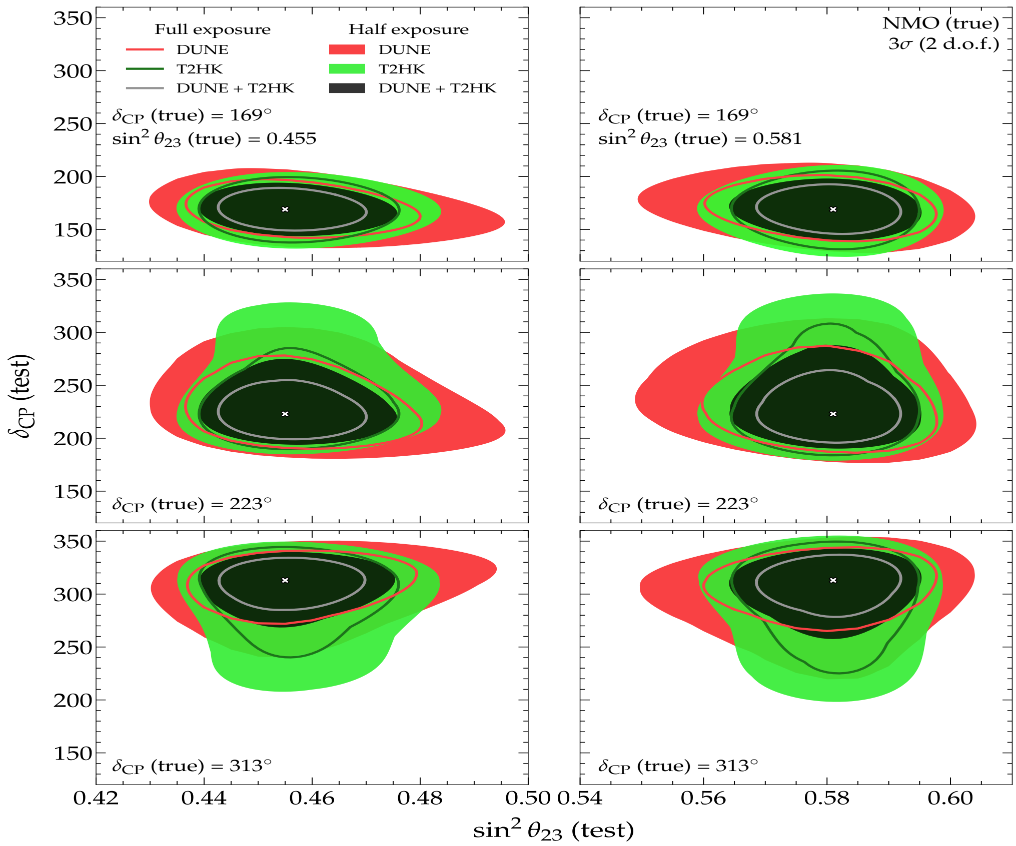

Figure 3: Allowed regions in $\sin^2\theta_{23}$–$\delta_{\rm CP}$ for benchmark choices [12] (true NMO). Scanned over both parameters within 3σ, marginalizing Δm^2_{31}. Solid colors (thin lines) show half (full) exposures. Only DUNE+Hyper-K can eliminate clone solutions left by standalone experiments at half exposure.

In figure 3, the importance of complementarity between DUNE and Hyper-K becomes apparent in giving the bound on the ($\sin^2\theta_{23}$ $-$ $\delta_{\rm CP}$) plane. Here we see, due to the small appearance systematic uncertainty (2%), DUNE can give better precision on $\delta_{\rm CP}$ whereas, due to larger statistics, Hyper-K gives better bound on $\sin^2\theta_{23}$. Besides, Hyper-K's smaller matter effect can probe intrinsic $\delta_{\rm CP}$ better. In the upper panel, we observe that the allowed region is more or less similar in DUNE, Hyper-K, and the combination for the CP phase but varies with the uncertainty of $\sin^2\theta_{23}$. This is because both DUNE and Hyper-K have better precision on $\delta_{\rm CP}$ when it is away from the CP-violating phases. In the middle panel, we see that the individual experiments are suffering from clone solutions — Hyper-K in $\delta_{\rm CP}$ and DUNE in $\sin^2\theta_{23}$, only the combined DUNE + Hyper-K is able to precisely measure around the true values. The case in the lower panel is similar. Therefore, with half the exposures of each experiment, the combination is the only solution for better precision around the illustrative true values considered.

3. Conclusion

In this study, we find the perspectives of the next-generation high-precision LBL experiments DUNE and Hyper-K, focusing how their collaborative setups and hence, the possible complementarities among them may alleviate the need of a very large exposure from these individual experiments in obtaining the desired sensitivities towards the atmospheric oscillation parameters, *i.e.*, Δm^2_{31} and $\sin^2\theta_{23}$. We also highlight how the degree of achievable precision is upgraded in DUNE and Hyper-K compared to the present measurements. Furthermore, we also show how, even only at half-exposure, the synergy among DUNE and Hyper-K help to lift the degeneracies between $\sin^2\theta_{23}$ and $\delta_{\rm CP}$ and bring more stringent constraints in ($\sin^2\theta_{23} - \delta_{\rm CP}$) plane which was difficult for the either of the standalone experimental setups of DUNE and Hyper-K.

Acknowledgments

We acknowledge financial support from the DST-SERB, DAE, DST, Govt. of India, INSA, and the USIEF. R.K acknowledges the support of the ANRF grant, Govt. of India (File No.:-ITS/2025/002283). S.K.A. and R.K. acknowledge the support of the Department of Atomic Energy (DAE), Govt. of India, under the Project Identification no. RIO 4001. S.K.A. acknowledges the financial support from the Swarnajayanti Fellowship (sanction order no. DST/SJF/PSA- 05/2019-20) provided by the Department of Science and Technology (DST), Govt. of India, and the Research Grant (sanction order no. SB/SJF/2020-21/21) provided by the Science and Engineering Research Board (SERB), Govt. of India, under the Swarnajayanti Fellowship project. The numerical simulations were performed using the SAMKHYA: High-Performance Computing Facility at the Institute of Physics, Bhubaneswar.

References

[1] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. P. Pinheiro, and T. Schwetz, "NuFit-6.0: updated global analysis of three-flavor neutrino oscillations," JHEP **12**, 216 (2024), [arXiv:2410.05380 [hep-ph]], doi:10.1007/JHEP12(2024)216.

[2] S. K. Agarwalla, S. Prakash, and S. U. Sankar, "Resolving the octant of θ_{23} with T2K and NOvA," JHEP **07**, 131 (2013), [arXiv:1301.2574 [hep-ph]], doi:10.1007/JHEP07(2013)131.

[3] S. K. Agarwalla, S. Prakash, and S. U. Sankar, "Exploring the three flavor effects with future superbeams using liquid argon detectors," JHEP **03**, 087 (2014), [arXiv:1304.3251 [hep-ph]], doi:10.1007/JHEP03(2014)087.

[4] B. Abi *et al.* [DUNE Collaboration], "Long-baseline neutrino oscillation physics potential of the DUNE experiment," Eur. Phys. J. C **80**, 978 (2020), [arXiv:2006.16043 [hep-ex]], doi:10.1140/epjc/s10052-020-08456-z.

[5] S. K. Agarwalla, R. Kundu, S. Prakash, and M. Singh, "A close look on 2-3 mixing angle with DUNE in light of current neutrino oscillation data," JHEP **03**, 206 (2022), [arXiv:2111.11748 [hep-ph]], doi:10.1007/JHEP03(2022)206.

[6] K. Abe *et al.* [Hyper-Kamiokande Proto- Collaboration], "Physics potential of a long-baseline neutrino oscillation experiment using a J-PARC neutrino beam and Hyper-Kamiokande," PTEP **2015**, 053C02 (2015), [arXiv:1502.05199 [hep-ex]], doi:10.1093/ptep/ptv061.

[7] S. K. Agarwalla, S. Das, A. Giarnetti, D. Meloni, and M. Singh, "Enhancing sensitivity to leptonic CP violation using complementarity among DUNE, T2HK, and T2HKK," Eur. Phys. J. C **83**, 694 (2023), [arXiv:2211.10620 [hep-ph]], doi:10.1140/epjc/s10052-023-11863-7.

[8] S. K. Agarwalla, R. Kundu, and M. Singh, "Improved precision on 2–3 oscillation parameters using the synergy between DUNE and T2HK," JHEP **10**, 243 (2024), [arXiv:2408.12735 [hep-ph]], doi:10.1007/JHEP10(2024)243.

[9] K. Abe *et al.* [T2K], "Neutrino oscillation physics potential of the T2K experiment," PTEP **2015**, no.4, 043C01 (2015), doi:10.1093/ptep/ptv031, [arXiv:1409.7469 [hep-ex]].

[10] D. S. Ayres *et al.* [NOvA], "The NOvA Technical Design Report," FERMILAB-DESIGN-2007-01 (2007), doi:10.2172/935497.

[11] R. B. Patterson [NOvA], "The NOvA Experiment: Status and Outlook," Nucl. Phys. Proc. Suppl. **235-236**, 151–157 (2013), doi:10.1016/j.nuclphysbps.2013.04.005, [arXiv:1209.0716 [hep-ex]].

[12] F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri and A. Palazzo, "Unfinished fabric of the three neutrino paradigm," Phys. Rev. D **104**, no.8, 083031 (2021), doi:10.1103/PhysRevD.104.083031, [arXiv:2107.00532 [hep-ph]].

[13] P. Huber, M. Lindner and W. Winter, "Simulation of long-baseline neutrino oscillation experiments with GLoBES (General Long Baseline Experiment Simulator)," Comput. Phys. Commun. **167**, 195 (2005), doi:10.1016/j.cpc.2005.01.003, [arXiv:hep-ph/0407333].

[14] P. Huber, J. Kopp, M. Lindner, M. Rolinec and W. Winter, "New features in the simulation of neutrino oscillation experiments with GLoBES 3.0: General Long Baseline Experiment Simulator," Comput. Phys. Commun. **177**, 432–438 (2007), doi:10.1016/j.cpc.2007.05.004, [arXiv:hep-ph/0701187].

[15] D. Navas Nicolas [JUNO], "Prospects of oscillation physics with JUNO," PoS **NOW2022**, 034 (2023), doi:10.22323/1.421.0034.

PoS(EPS-HEP2025)164