PROCEEDINGS OF SCIENCE

PoS(HQL2023)022

Neutrino Oscillation Parameters: Present and Future

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

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

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

Neutrino oscillation experiments, both ongoing and upcoming, alongside their synergies, lay the cornerstone for resolving key issues within the framework of the three-flavor neutrino paradigm. The present complementarities between atmospheric and long-baseline experiments have reduced the span in atmospheric oscillation parameters and the CP phase. Further, the persistent discrepancy between Solar and KamLAND data regarding Δm^2_{21} has now been almost resolved. The remarkable precision on θ_{13} attained by the current reactor experiment, Daya Bay is unprecedented. The notable precision attained in ongoing oscillation experiments not only lays a solid foundation for future research but also offers the potential for substantial advancements and the revelation of significant phenomena within the neutrino sector. This work briefly highlights the recent advancements and outlines the promising future directions in the field of neutrino oscillations.

16th International Conference on Heavy Quarks and Leptons (HQL2023)
28 November-2 December 2023
TIFR, Mumbai, Maharashtra, India

---

[*] Speaker

1. Introduction

In recent decades, extensive experimental efforts and theoretical advancements have deepened our understanding of neutrino oscillations. Notably, in the past few decades, precision studies focusing on the interactions of first and second-generation neutrinos have led to two Nobel prizes in this field. This talk will analyze recent measurements from global experiments and explore how upcoming experiments will continue to enhance our understanding of neutrino properties.

2. Present synergies and tensions in neutrino oscillation parameters

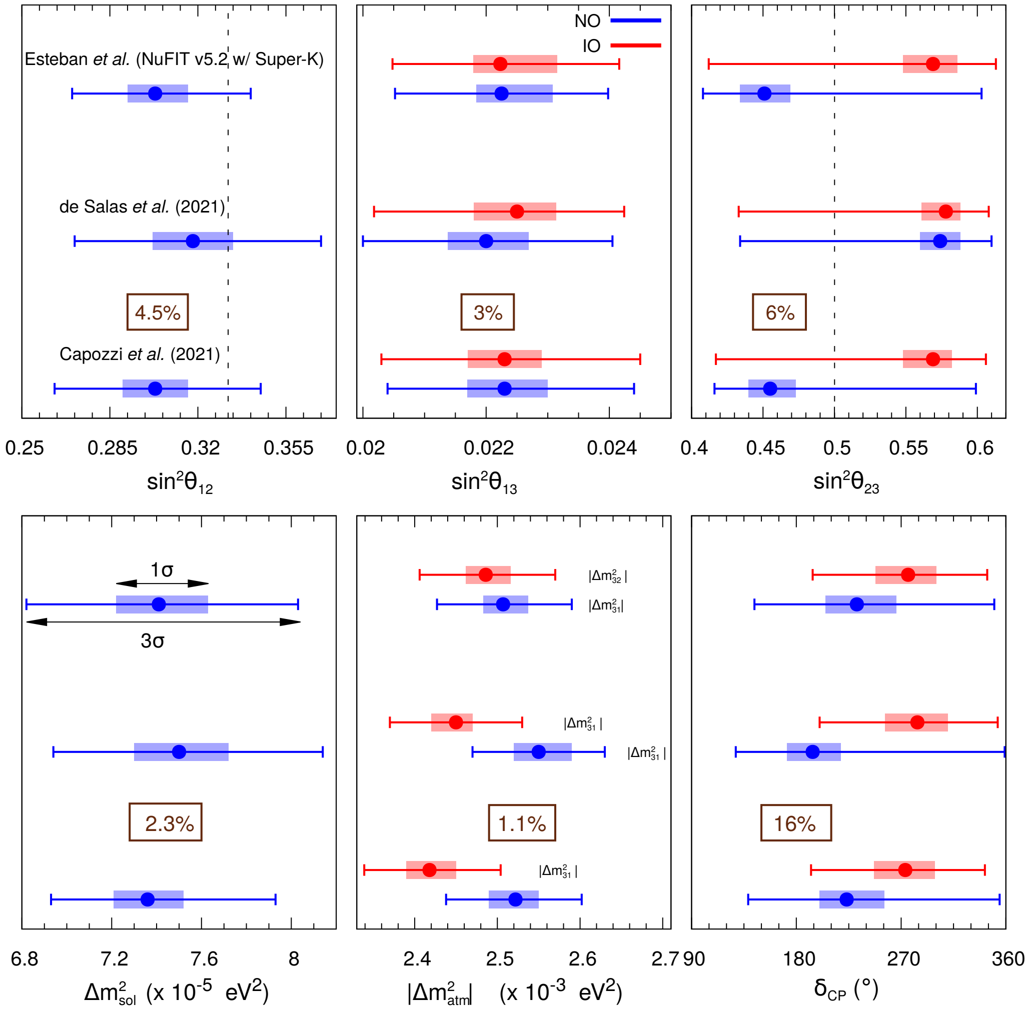

Figure 1: Present 1σ and 3σ allowed ranges, following global neutrino oscillation data in Ref. [1–3].

Figure 1 provides an overview of our current knowledge on the six parameters governing neutrino oscillations within the standard 3ν framework by three global fit studies [1–3]. It highlights the remarkable precision in determining solar oscillation parameters: Δm^2_{21} (4.5%) and $\sin^2\theta_{12}$ (3%), atmospheric mass splitting: $|\Delta m^2_{31}|$ (~1%), and reactor mixing angle: θ_{13} (3%). However, the atmospheric mixing angle ($\sin^2\theta_{23}$) and CP phase ($\delta_{\rm CP}$) remain the most uncertain parameters.

By comparing the 1σ confidence levels (C.L.) and the 3σ allowed regions, we offer a comprehensive overview of the parameter space of the global oscillation data by the three global fit studies, thus confirming to the robustness of our current understanding of neutrino oscillations. Following [1], we find that there is a slight preference for normal ordering (NO) at approximately 2.5σ, preference, at a 90% C.L. for the angle $\sin^2\theta_{23}$ to be in the lower octant (LO) compared to the secondary best fit in the higher octant (HO), and for $\delta_{\rm CP}$ to be approximately 1.24 times π, deviating from the CP-conserving value of π. Conversely, having maximal $\sin^2\theta_{23}$ mixing is less likely by about 1.8σ, and the range of $\delta_{\rm CP}$ between 0 and 0.77π is unlikely by more than 3σ under NO. These achievements have laid the foundation for neutrino research to enter a new era of precision.

2.1 The Solar and KamLAND

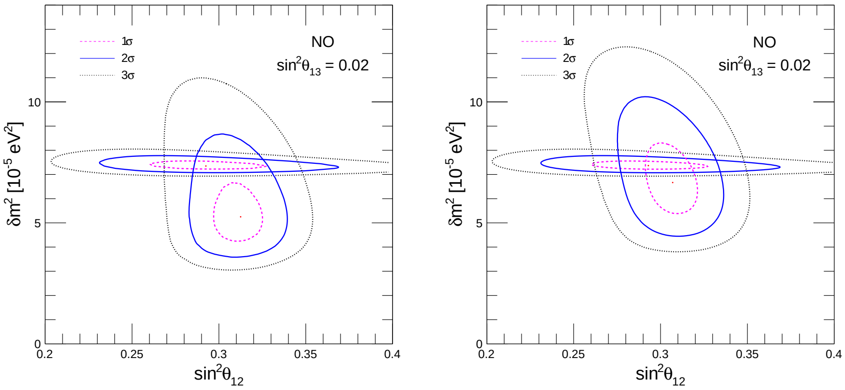

Figure 2: Previous [4] and present [1] allowed regions in the solar oscillation parameters, using Solar and KamLAND experiments.

The joint assessments from the Solar and KamLAND experiments have been pivotal in determining solar parameters. Over the past decade, there has been a notable discrepancy at about 2σ globally in the preferred best fit for Δm^2_{21} between these experiments, with KamLAND favoring a relatively higher value. This tension arises from two significant disparities [4]: (a) Solar experiments (SNO, SK, and Borexino) found no evidence of the low-energy upturn predicted by the standard LMA-MSW solution for the favored Δm^2_{21} value by KamLAND. (b) Super-K observed a non-vanishing day-night asymmetry, supporting a higher Δm^2_{21} value compared to KamLAND. With the addition of the latest Super-K solar data that prefers smaller day-night asymmetry, the gap in Δm^2_{21} measurements has decreased to around 1.1σ [1] (refer to Fig. 2).

2.2 Correlation between $\sin^2\theta_{23}$ and $\delta_{\rm CP}$

The octant ambiguity results in two nearly equally favorable solutions, each surrounded by permissible regions that converge at 2σ or 3σ C.L. (refer to Fig. 3) [1]. While the Inverted Ordering (IO) consistently leans towards $\delta_{\rm CP} = \pi/2$ across all data combinations, indicating a negligible correlation with $\sin^2\theta_{23}$, the NO exhibits a broader range for $\delta_{\rm CP}$, encompassing the CP-conserving scenario $\delta_{\rm CP} = \pi$ at 2σ. Furthermore, with the addition of short-baseline (SBL) reactor data, NO exhibits best-fit around $\delta_{\rm CP} = \pi$, disfavoring $\delta_{\rm CP} = 3\pi/2$ at $\sim 2\sigma$. In terms of numerical assessment, the likelihood of the CP-conserving value $\delta_{\rm CP} = \pi$ stands at a 90%

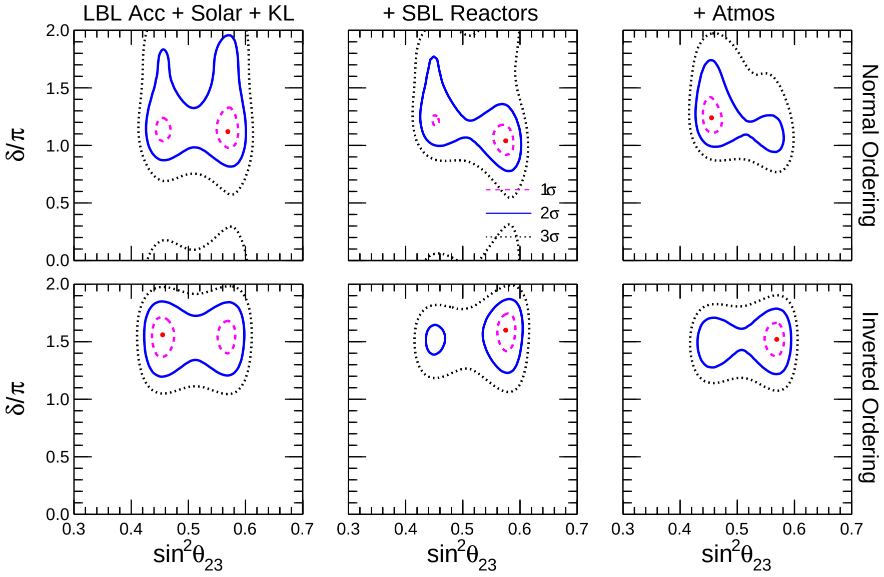

Figure 3: Current allowed regions in ($\delta_{\rm CP} - \sin^2\theta_{23}$) plane, using global oscillation data [1].

C.L. corresponding to approximately 1.6σ deviation from the favored range. However, recent analyses that omitted SK-IV atmospheric data allowed for acceptance of this value with less than 1σ significance [2, 3]. Despite the current data showing relatively minor correlation effects, these effects are expected to become more pronounced with the advancement of statistical precision and accuracy in long-baseline (LBL) accelerator experiments.

2.3 Results from T2K and NOνA

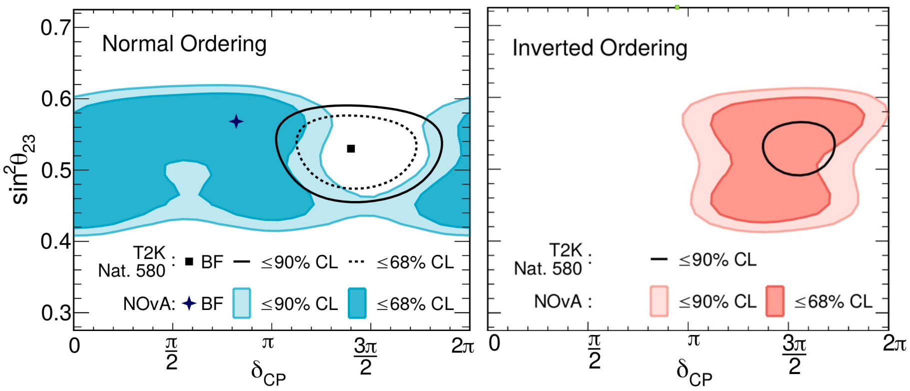

Figure 4: Allowed regions in ($\delta_{\rm CP} - \sin^2\theta_{23}$) plane, exhibiting current tension in T2K-NOνA [6].

The two ongoing LBL experiments exhibit both tension and complementarity while determining the two most uncertain parameters: $\sin^2\theta_{23}$ and $\delta_{\rm CP}$. These experiments have access to both $\nu_\mu \to \nu_e$ appearance and $\nu_\mu \to \nu_\mu$ disappearance channels with a very well-determined initial muon neutrino flux (the same is true for the antineutrino mode as well). While both T2K and NOνA have a slight preference for NO over IO and HO over LO, the preference for CP phase defers under the NO assumption [5, 6]. As illustrated in the left panel of Fig. 4, the T2K experiment's optimal fit point aligns with the NO but falls within a region that is disfavored by NOνA. Nevertheless, there are still areas of overlap between the two experiments. The right panel in Fig. 4 confirms that both the experiments consistently favor $\delta_{\rm CP} \in [\pi, 2\pi]$. However, both experiments are currently statistically limited. Recently, they announced the results from their joint-fit analysis [7].

2.4 Latest Oscillation Results from IceCube DeepCore

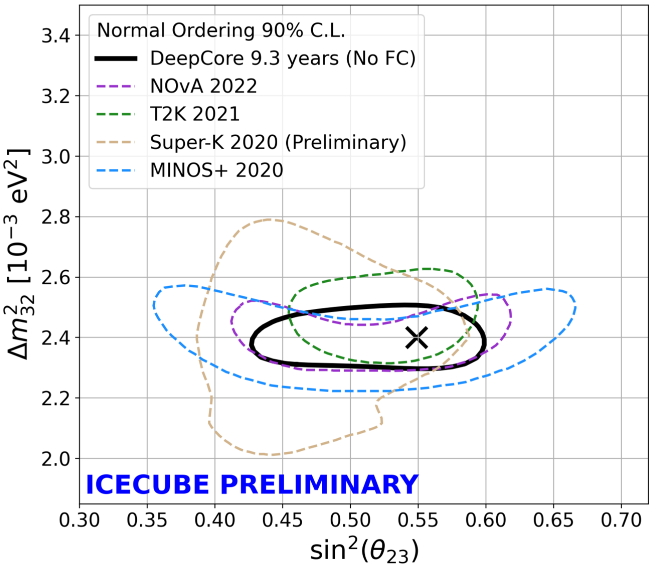

Figure 5: Comparing IceCube DeepCore with other oscillation experiments at 90% C.L. assuming NO [8].

LBL experiments in operation have established set baselines and neutrino beam energies that are finely tuned to enhance the examination of neutrino oscillations. Conversely, atmospheric experiments like Super-Kamiokande, KM3NeT-ORCA [9], and IceCube DeepCore have access to a wide range of energies (E) and baselines (L). This allows them to probe neutrino oscillation at several L/E values in presence of Earth matter effect. In Fig. 5, we exhibit the currently allowed ranges in ($\sin^2\theta_{23} - \Delta m^2_{32}$) at 90% C.L. from all the leading oscillation experiments, assuming NO [8].

The competitive sensitivity of DeepCore compared to the other leading measurements worldwide has reduced the span in Δm^2_{32} the most. Notably, the analysis in IceCube explores a higher energy (5-100) GeV range compared to other experiments and utilizes a unique detector technology, introducing a distinct set of systematic uncertainties. Therefore, the observed consistency serves as robust validation for the standard model of three massive neutrino oscillations.

3. Upcoming experiments and their physics reach

As the quest for deeper understanding and precision studies continues, a new wave of upcoming neutrino oscillation experiments emerges, promising unprecedented insights into the uncertainties of neutrino physics. There are several candidates like Deep Underground Neutrino Experiment

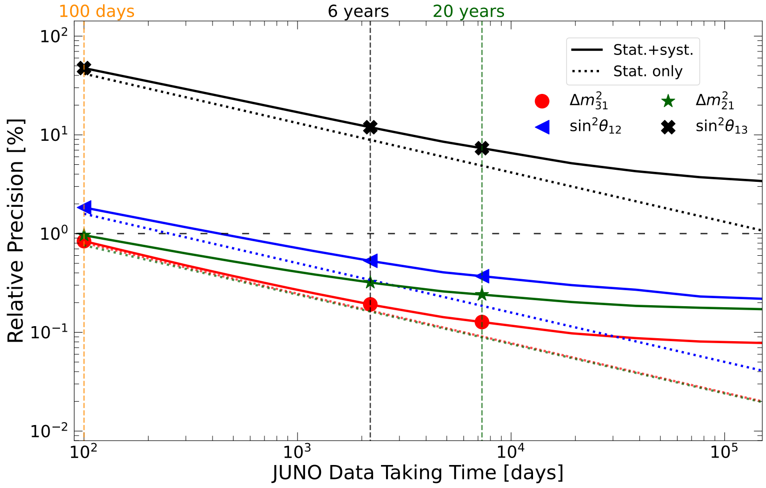

Figure 6: Relative precision of the oscillation parameters as a function of runtime in JUNO [9].

(DUNE), Tokai-to-Hyper-Kamiokande (T2HK), T2HK with a second detector in Korea (T2HKK), Jiangmen Underground Neutrino Observatory (JUNO), IceCube Upgrade, India-based Neutrino Observatory (INO), and the next-to-next generation European Spallation Source neutrino Super Beam (ESSνSB). Armed with cutting-edge technology and innovative methodologies, these experiments are poised to extend the frontiers of knowledge, probing elusive phenomena such as neutrino mass ordering, leptonic CP violation (CPV), and precision measurements of oscillation parameters. In the subsequent sections, we explore the exciting landscape of some of these experiments.

3.1 JUNO

JUNO, situated in Kaiping, Jiangmen, within China's Guangdong province, is a reactor neutrino experiment currently in the deployment phase. Positioned at a distance of 52.5 km from two nuclear power plants, its primary objective is to ascertain the neutrino mass ordering through the observation of reactor antineutrino disappearance. It can detect not only $\bar{\nu}_e$ neutrinos from reactors and Earth but also the atmospheric neutrinos. JUNO is poised to achieve world-leading precision measurements with sub-percent in Δm^2_{21}, Δm^2_{31}, and θ_{12} measurements, as depicted in Fig. 6 [9]. Collaborating with TAO, a satellite detector stationed adjacent to the Taishan reactors to regulate the flux, JUNO anticipates achieving a 3σ C.L. in NO with six years of exposure equivalent to 26.6 GW.

3.2 IceCube Upgrade

For the past decade, the IceCube Neutrino Observatory has been actively monitoring atmospheric neutrinos within the GeV energy range, utilizing its low-energy extension known as DeepCore. To enhance its capabilities, a new extension named the IceCube Upgrade is set to be deployed during the polar season of 2025/26. This upgrade involves the installation of seven additional strings within the DeepCore fiducial volume. By more than tripling the number of Photomultiplier Tube channels compared to the current IceCube setup, the Upgrade will significantly bolster its capabilities within the GeV energy range, lowering the threshold value to approximately 3GeV. Figure 7 depicts the sensitivity achieved at the 90% C.L. following three years of operation with the new strings. Crucially, the addition of new strings boosts IceCube's sensitivity to atmospheric

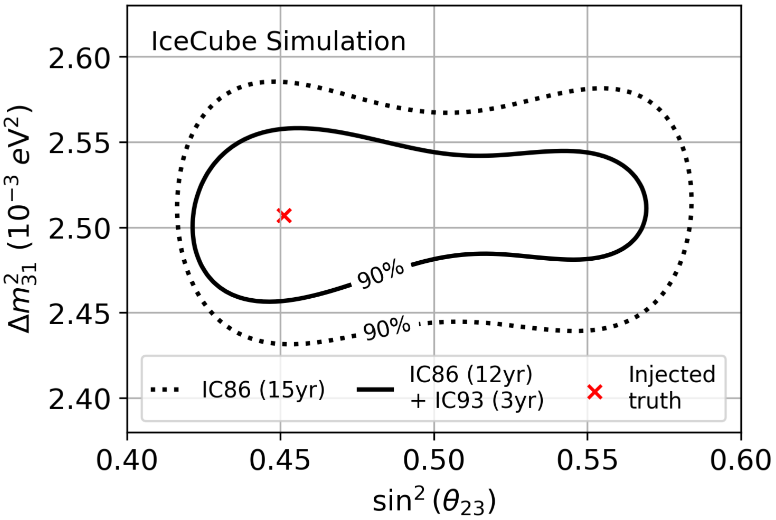

Figure 7: Joint projection of DeepCore and upcoming Upgrade in ($\Delta m^2_{31} - \sin^2\theta_{23}$) plane assuming NO [10].

parameters by around (20-30)% and increases its capability to resolve the mass ordering by a factor of four [10].

3.3 DUNE, T2HK, and their complementarity

DUNE and T2HK represent the next-generation LBL experiments, offering unprecedented statistics, intense beams, and reduced systematic uncertainties. These advancements promise to greatly improve precision measurements in oscillation parameters and may open avenues for exploring New Physics in the lepton sector. With a proposed long baseline of 1285 km, DUNE will be heavily influenced by matter effects, while T2HK, with a shorter baseline of 295 km, will experience conditions closer to vacuum. DUNE's flux peaks at higher energies (around 2.5 GeV), allowing for potential ν_τ appearance searches, whereas T2HK's flux peaks around 0.6 GeV. DUNE's far-detector, a 40 kt LArTPC, offers remarkable imaging capabilities, reducing signal normalization uncertainties to 2% in appearance and 5% in disappearance. Conversely, T2HK's 187 kt water Cherenkov detector will accumulate extensive statistics, albeit with slightly higher expected signal normalization uncertainties (5% in appearance and 3.5% in disappearance). T2HK's proposed runtime ratio, operating in a 1:3 ratio of $\nu : \bar{\nu}$ mode, contrasts with DUNE's approach [11, 12]. In the subsequent sections, we detail the potentials of DUNE and T2HK, both independently and in combination, highlighting their complementary nature.

3.3.1 Leptonic CP violation

The strong correlation between $\sin^2\theta_{23}$ and $\delta_{\rm CP}$ ensures large uncertainties in the measurements of the CP phase in the present generation of experiments (Sec. 2.2). The superior detector systematics and ability to probe varied L/E ratios in DUNE, coupled with the shorter baseline and larger fiducial volume in T2HK, promises substantial complementarity in resolving the ($\sin^2\theta_{23} - \delta_{\rm CP}$) degeneracy. In Fig. 8, left, we depict this in terms of CP coverage, which denotes the values of true $\delta_{\rm CP}$ (in %) in its entire range of [−180°, 180°], for which leptonic CPV can be established at $\geq 3\sigma$ confidence level. We observe that around maximal mixing (MM) choices of $\sin^2\theta_{23}$, CP coverage tends to reduce in

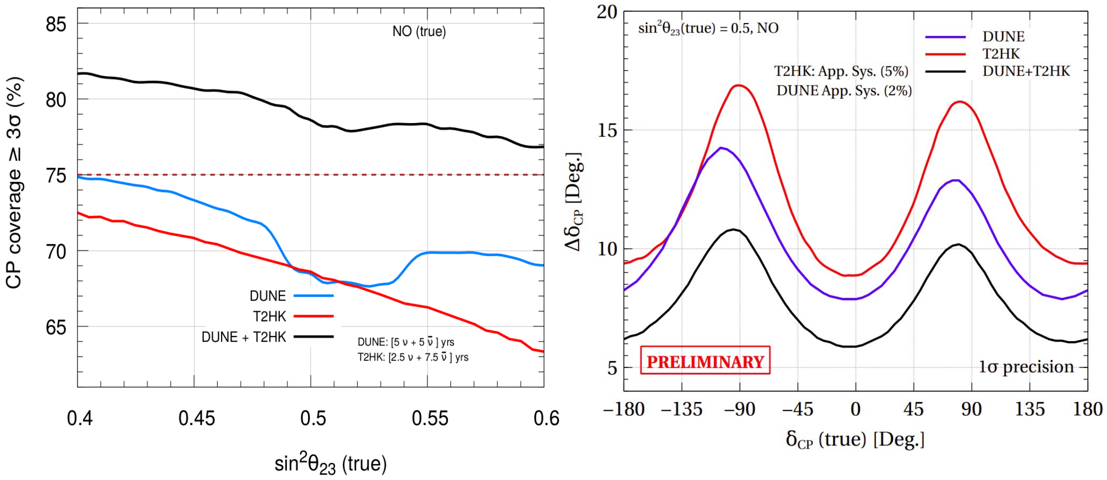

Figure 8: Left panel: coverage in $\delta_{\rm CP}$ for $\geq 3\sigma$ leptonic CP violation as a function of $\sin^2\theta_{23}$ [13]. Right panel shows the relative 1σ precision in $\delta_{\rm CP}$ assuming NO, which is taken from a work in preparation [14].

DUNE because of the extrinsic CP phase that induces ($\sin^2\theta_{23} - \delta_{\rm CP}$) degeneracy. However, T2HK with a smaller baseline remains unaffected, attaining better CP coverage than DUNE around MM. Furthermore, the complementarity between DUNE + T2HK can enable us to achieve more than 77% CP coverage irrespective of the values of θ_{23} and mass ordering. For more insights, refer [13]. On the right panel of Fig. 8, we exhibit relative 1σ precision in $\delta_{\rm CP}$. For a fixed $\delta_{\rm CP}$ (true), $\Delta\delta$ is defined as one-half of the reconstructed 1σ range (1 d.o.f.), after marginalizing over atmospheric parameters and systematic uncertainties. We find that DUNE + T2HK can measure any value of $\delta_{\rm CP}$ with a relative 1σ precision of $\leq \sim 10°$.

3.3.2 Deviation from maximal $\sin^2\theta_{23}$

Several neutrino mixing models have ruled out the MM of θ_{23} due to $\mu - \tau$ asymmetry. DUNE and T2HK individually have bright prospects to establish this non-maximality with more than 3σ C.L. based on the present global fit [1, 15] in NO. The left panel in fig. 9 depicts that the combination of DUNE and T2HK has the potential to establish this phenomenon at more than 7σ C.L. whereas, the full exposures expected from the currently running LBL experiments: T2K and NOνA can jointly attain sensitivity of only 1.6σ. T2HK's huge statistics have a crucial input in enhancing this potential. Conversely, if the best fit of $\sin^2\theta_{23}$ shifts to the upper bound of present 1σ fluctuations, then DUNE + T2HK remains the only solution to obtain non-maximality at 3σ.

3.3.3 Discovery of 2-3 octant

The ambiguity of θ_{23} octant remains unsolved with current oscillation experiments. Utilizing either T2HK or DUNE can resolve this issue with more than 4σ, using the current global oscillation data from Ref. [1] in NO. Moreover, the right panel in fig. 9 depicts that their complementarity can excel from their standalone capabilities in excluding wrong octant exclusion by ~1.5 times. This is mostly because of their upgraded systematics in the appearance channel. T2HK plays the leading role in resolving the issue of octant at lower significance due to its dominance in statistics. Whereas improved systematic uncertainties in ν appearance channel enable DUNE to perform well

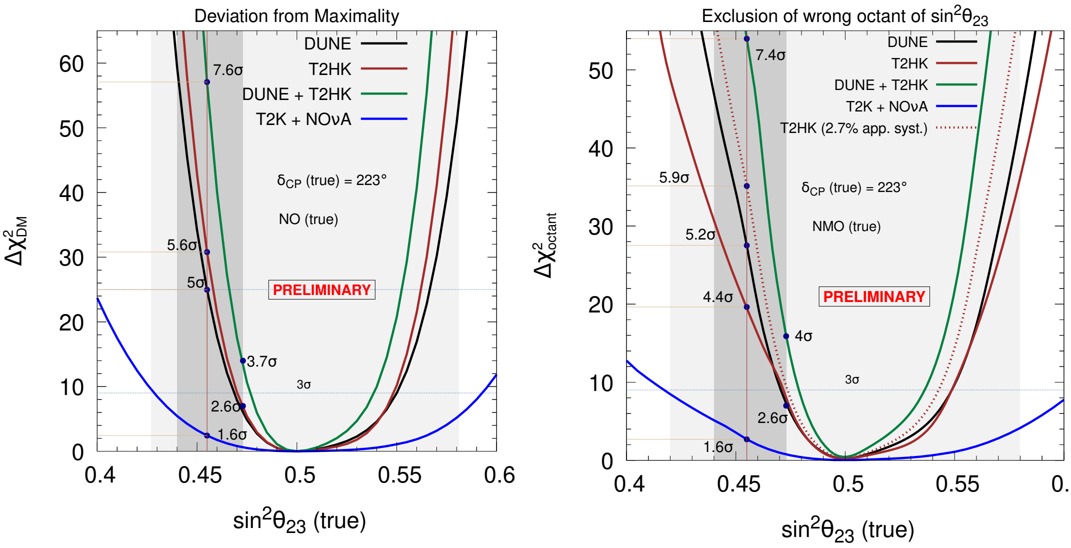

Figure 9: Sensitivity towards establishing deviation from maximal mixing of $\sin^2\theta_{23}$ (left) and resolving the issue of octant of $\sin^2\theta_{23}$ (right) assuming NO. These figures are taken from a work in progress [16].

at a higher C.L. Furthermore, considering better systematics in T2HK ($\sim 2.7\%$) [17] will enhance its capability even better than DUNE.

3.3.4 Precision measurements in atmospheric oscillation parameters

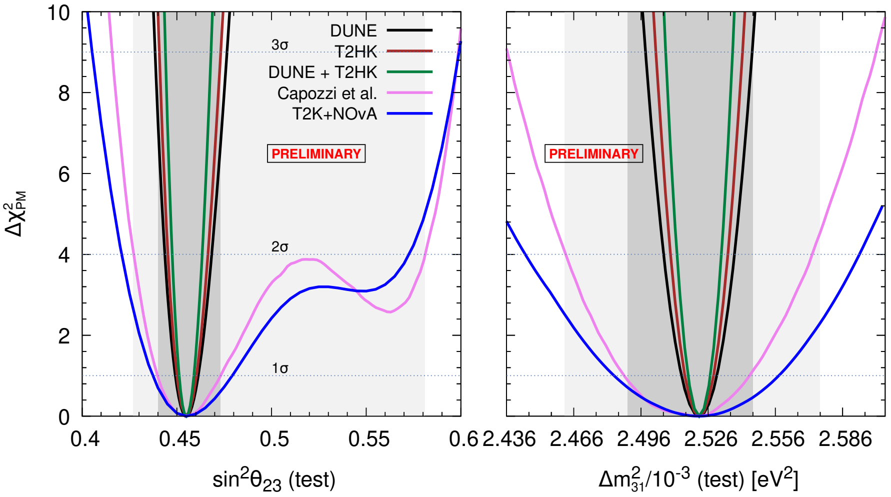

Figure 10: Precision in atmospheric oscillation parameters assuming NO. These figures are taken from a work in preparation [16].

DUNE and T2HK will be the pioneers in achieving precision at high C.L. Figure 10 reveals that the solo performance of T2HK in achieving precisions on $\sin^2\theta_{23}$ and Δm^2_{31} is better than DUNE. This is because of its huge statistics and lesser systematics in the disappearance channel. Remarkably, the combined setup of DUNE and T2HK improves the present precision status (in [1]) of $\sin^2\theta_{23}$ and Δm^2_{31} by 7 and 5 times, respectively [15].

4. Concluding Remarks

Present and future neutrino oscillation experiments establish the cornerstone to address the pressing issues in the three-flavor neutrino paradigm. Besides the achievement of excellent precision on θ_{13} by Daya-Bay, the long-standing tension between Solar and KamLAND on Δm^2_{21} also got resolved with the inclusion of Super-K solar data. The precision currently achieved in ongoing oscillation experiments has paved the way for future experiments to make substantial improvements and potentially uncover significant discoveries in the neutrino sector.

Acknowledgements : S.K.A. acknowledges financial support from the DAE, DST, DST-SERB, Govt. of India, and USIEF. M.S. acknowledges financial support from the DST, Govt. of India. The numerical simulations are performed using SAMKHYA: High-Performance Computing Facility at the Institute of Physics, Bhubaneswar.

References

[1] Capozzi *et al.*, Phys.Rev.D 104 (2021) 8, 083031; 2107.00532 [hep-ph].

[2] Esteban *et al.*, JHEP 09 (2020) 178; 2007.14792 [hep-ph].

[3] De Salas *et al.*, JHEP 02 (2021) 071; 2006.11237 [hep-ph].

[4] Capozzi *et al.*, Prog. Part. Nucl. Phys. 102 (2018) 48-72; 1804.09678 [hep-ph].

[5] T2K Collaboration: Abe *et al.*, Nature 583 (2020) 7814, E16 (erratum); 1910.03887 [hep-ex].

[6] NOνA Collaboration: Acero *et al.*, Phys.Rev.D 106 (2022) 3, 032004; 2108.08219 [hep-ex].

[7] Ed Atkins: J-PARC Seminar, Zoya Vallari: Wine and Cheese Seminar, Feb. 16, 2024.

[8] IceCube Collaboration: Yu *et al.*, PoS ICRC(2023); 2307.15855 [hep-ex].

[9] KM3NeT Collaboration: Eur. Phys. J. C 82, 26 (2022); 2103.09885 [hep-ex].

[9] JUNO Collaboration: Abusleme *et al.*, Chin.Phys.C 46 (2022) 12, 123001; 2204.13249 [hep-ex].

[10] IceCube Collaboration: Eller *et al.*, PoS ICRC2023 (2023) 1036; 2307.15295 [astro-ph.HE].

[11] DUNE Collaboration: Abi *et al.*, 2103.04797 [hep-ex].

[12] T2HK Collaboration: Abi *et al.*, PTEP 2018 (2018) 6, 063C01; 1611.06118 [hep-ex].

[13] S. K. Agarwalla *et al.*, Eur.Phys.J.C 83 (2023) 8, 694; 2211.10620 [hep-ph].

[14] S. K. Agarwalla, S. Das, A. Giarnetti, D. Meloni, and M. Singh, in preparation, 2024.

[15] S. K. Agarwalla *et al.*, JHEP 03 (2022) 206, 2111.11748 [hep-ph].

[16] S. K. Agarwalla, R. Kundu, and M. Singh, in preparation, 2024.

[17] T2HK Collaboration: Laura-Iuliana Munteanu, PoS NuFact2021 (2022) 056.