Neutrino Mass Ordering Using Synergy between ICAL, T2HK, and JUNO

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Abstract

In this work, we investigated mass ordering sensitivity using a combination of three experiments (ICAL, T2HK, and JUNO). All three differ in terms of baselines, energy range, and oscillation channels. All three have some limitations that can be addressed through a combined study. We obtained more than 5σ sensitivity for the unfavorable δ_{CP} phase, despite the JUNO detector's poor resolution (if $3\%/\sqrt{E}$ not achievable). We showed that increasing the run time for ICAL improves the overall sensitivity for MO measurement when combined with T2HK and JUNO. Our results demonstrate the power of combining multiple experiments to achieve more accurate and robust results in neutrino physics. We hope our work will contribute to future experimental efforts in this field and facilitate a deeper understanding of the fundamental properties of neutrinos.

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1. INTRODUCTION

The neutrino sector's unsolved problems include MO (mass ordering), CP phase, and the θ_{23} octant. MO has an impact on CP and octant measurements, which means that in order to properly understand the remaining parameters, we must fully understand MO. The solar neutrino experiments established that $m_2 > m_1$, resulting in $\Delta m^2_{21} > 0$. However, we do not have enough data to make such a claim for Δm^2_{31}. We still do not know what Δm^2_{31} means. The + sign represents NO ($m_3 > m_1$) and the - sign represents IO ($m_3 < m_1$) [1]. Many experiments are currently running and collecting data to determine MO. The atmospheric-based Super-Kamiokande [2], accelerator-based T2K [3], and NOVA [4] experiments, as well as a combined analysis of the data obtained from these experiments, show a preference for normal ordering over inverted ordering [5].

Many experiments are proposed to quantify MO with a higher level of significance. The ICAL [8], PINGU [9], HK [15], and some other experiments are for atmospheric neutrinos. T2HK [6] and DUNE [7] are two experiments suggested for long baseline neutrinos. JUNO [10] uses a suggested method for measuring MO in short baseline reactor antineutrino experiments.

In this work, we investigate the possibilities of the upcoming neutrino mass ordering experiments T2HK, JUNO, and ICAL. MO sensitivity enhancement has previously been accomplished by combining various types of experiments such as future atmospheric and future reactor experiments, future accelerator and future atmospheric neutrino experiments, and future accelerator and future reactor experiments to determine neutrino mass ordering. Reference [11] studies the combined study of PINGU and JUNO, reference [12] studies the combined data of reactor-based Daya Bay II [13] and PINGU, reference [14] studies the combination of T2HK, DUNE, and Hyper-Kamiokande, reference [15] studies the combination of accelerator-based ESSnuSB [16] and INO, and reference [17] studies the combination of T2K II, NOVA, and JUNO. DUNE's combined beam and atmospheric data combination is studied in [18], and ESSnuSB's combined beam and atmospheric data combination is studied in [19]. T2HK's mass ordering sensitivity is strongly δ_{CP} dependent, with MO sensitivity reaching 2σ in a specific small region.

The mass ordering sensitivity of JUNO is energy resolution dependent, whereas the mass ordering sensitivity of ICAL is independent of δ_{CP}. As a result, we will demonstrate in this work that by combining these three experiments, one can achieve mass ordering sensitivity at a significant confidence level regardless of JUNO's energy resolution or the value of δ_{CP}. The reactor experiment and the accelerator/atmospheric experiment share strong sensitivity to the parameter Δm^2_{31}. In addition, we will investigate (i) the effect of varying JUNO energy resolution, (ii) the effect of ICAL's longer run time, and (iii) the effect of octant degeneracy in the determination of neutrino mass ordering. More details can be found in our main papers given in [26, 27].

2. EXPERIMENTS AND ANALYSIS METHOD

2.1. ICAL

ICAL [8] is a 50 kt iron calorimeter capable of distinguishing between muons (μ^-) and antimuons (μ^+) in the presence of a 1.5-tesla magnetic field. It enables the detection of neutrinos and antineutrinos through the identification of muons and their antiparticles. We use the Honda fluxes, calculated for Theni (India), which include all types of neutrinos (ν_e, ν_μ, and ν_τ) and antineutrinos ($\bar{\nu}_e$, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$). To estimate neutrino nucleon scattering events, we employ the Monte Carlo application GE-

NIE. Further processing of these events was performed to obtain the expected events for 10 years of data [20, 21]. For more details on the binning and analysis, please refer to [23].

2.2. *JUNO*

JUNO is a liquid scintillator detector with an average baseline of 53 km that will detect reactor antineutrinos from several reactors, including the Yangjiang and Taishan nuclear power plants. The detector's energy resolution is $3\%/\sqrt{E}$, and the energy range, energy bins, background fluxes, systematics, and other characteristics for the fiducial volume (20 kt) are taken from [10]. In this work, we assume a 6-year run time for JUNO.

2.3. *T2HK*

T2HK is a long baseline water experiment with a fiducial volume of 187 kt (one detector). For our work, we used two detector setups. T2HK's baseline is 295 kilometers from the neutrino source at J-PARC [6]. We generated data for ten years of operation, with the dataset spanning five years of neutrino and antineutrino modes. The systematic errors are as follows: 4.71% (4.13%) overall normalization error for the appearance (disappearance) channel in the neutrino mode and 4.47% (4.15%) for the appearance (disappearance) channel in the antineutrino mode. Both the signal and the background have the same systematic errors. The remaining detector properties are taken from [6].

These configurations were used to generate a glb file, which was then used in GLoBES to generate and analyze data.

2.4. *Parameters*

The table presents the parameters utilized in the analysis for all experiments. We minimize δ_{CP} for T2HK in the range of $0°$ to $360°$. We also minimize JUNO data within the 3σ range of Δm^2_{21} and θ_{13} as given by NuFIT data. We combine all experiments in θ_{23} and Δm^2_{31} parameter space and then minimize over these experiments after combining all three experiments.

Δm^2_{21} (eV^2)	Δm^2_{31} (eV^2)	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2 2\theta_{13}$	δ_{CP}
7.42×10^{-5}	2.531×10^{-3}	0.33	0.5	0.0875	$0°$
fixed	2.38–2.6×10^{-3}	fixed	$40°$–$51°$	fixed	fixed

3. RESULTS

3.1. *Combined Sensitivity of ICAL, JUNO, and T2HK*

We have shown the mass ordering sensitivity χ^2 as a function of Δm^2_{31} in Figure 1. We considered $\delta_{CP} = 0°$ in the upper panel and $\delta_{CP} = -90°$ in the lower panel. We can see that the MO sensitivity χ^2 of ICAL is 9 and that it has minima at $\Delta m^2_{31}(\mathrm{IO}) = -2.419 \times 10^{-3}\,\mathrm{eV}^2$. For JUNO, the MO sensitivity χ^2 is 10 and the minima are at $\Delta m^2_{31}(\mathrm{IO}) = -2.503 \times 10^{-3}\,\mathrm{eV}^2$. We chose two δ_{CP} values for T2HK; each gives a different MO sensitivity and minima position. For $\delta_{CP} = 0°$, we have MO sensitivity $\chi^2 = 3.95$ and minima at $\Delta m^2_{31}(\mathrm{IO}) = -2.431 \times 10^{-3}\,\mathrm{eV}^2$, and for $\delta_{CP} = -90°$, we have MO sensitivity $\chi^2 = 3.95$ and minima at $\Delta m^2_{31}(\mathrm{IO}) = -2.428 \times 10^{-3}\,\mathrm{eV}^2$.

We discovered that the minimum values of the oscillation parameters obtained from the T2K, NOvA, and T2HK experiments are located at different points along the $\Delta m^2_{31}(\mathrm{IO})$ axis.

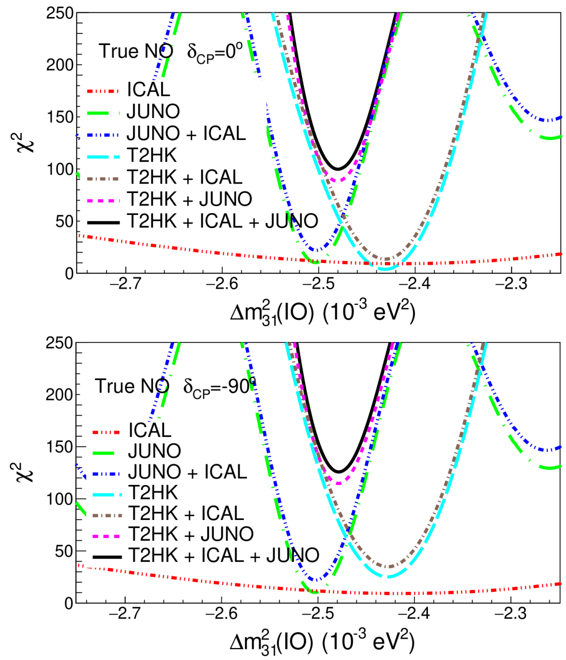

FIGURE 1: Mass ordering sensitivity as a function of Δm^2_{31} (test). The upper panel is for $\delta_{CP} = 0°$ and the lower panel is for $\delta_{CP} = -90°$ corresponding to T2HK.

Since all experiments are designed to constrain the value of Δm^2_{31}, we can combine them on the Δm^2_{31} axis to improve our sensitivity to this parameter. Due to the different locations of Δm^2_{31} for each experiment, we find that the combination of all three experiments provides complementary information, resulting in a significant improvement in our sensitivity to the mass ordering. Specifically, we obtained a combined sensitivity to the mass ordering of $\delta_{CP}(0°) = 99.76$ and $\delta_{CP}(-90°) = 125.8$, using the combined data from the T2K, NOvA, and T2HK experiments. This increase in sensitivity is reflected in a very large increase in χ^2, indicating a better fit to the observed data.

3.2. *Effect of the Energy Resolution of JUNO*

In the previous section, we made an assumption that the energy resolution of the JUNO detector would be $3\%/\sqrt{E}$, which is the best-case scenario proposed by the JUNO collaboration. However, we demonstrate in our work that even if Juno cannot achieve such a high level of energy resolution, it can still be used to measure mass ordering sensitivity when combined with T2HK and ICAL experiments. Figure 2 (upper plot) illustrates the effect of JUNO's energy resolution on mass ordering. Our results show that even with a resolution of 5%, the synergy effects between JUNO, ICAL, and T2HK experiments still provide a χ^2 value of 52 (76) for $\delta_{CP} = 0°(-90°)$, respectively. While JUNO alone would have no sensitivity for mass ordering at such a poor resolution, the combination of these experiments yields more than 7σ sensitivity.

3.3. *Effect of INO Run Time*

Since atmospheric neutrinos are abundant and free, experiments measuring them can be run for longer periods of time at a lower cost. This allows for more data to be collected over

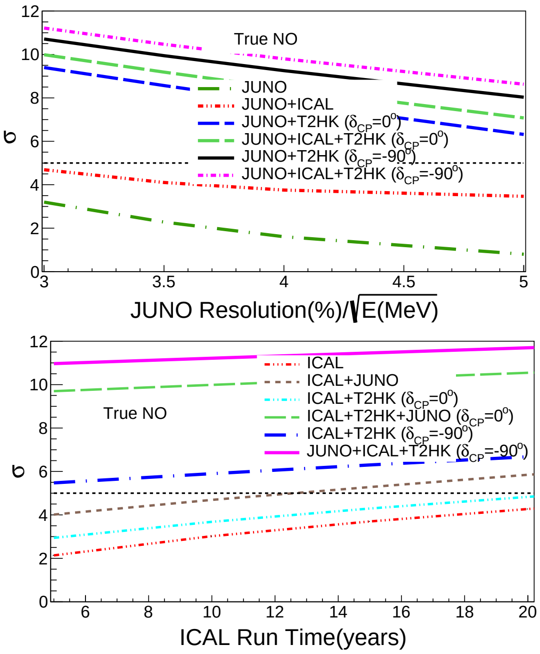

FIGURE 2: The upper plot is for the JUNO resolution effect on MO χ^2 and the lower plot is for the effect of ICAL run time on combined χ^2.

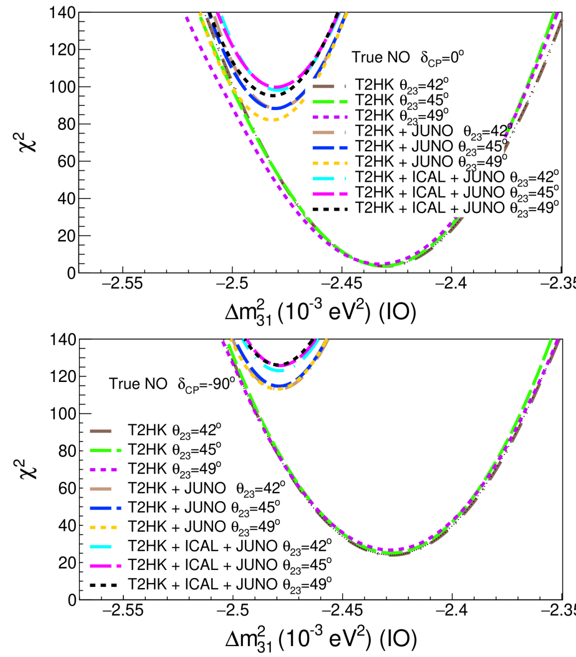

FIGURE 3: Neutrino mass ordering sensitivity as a function of Δm^2_{31}(IO) for LO, maximal, and HO values of θ_{23}. The upper panel is for $\delta_{CP} = 0°$ and the lower panel is for $\delta_{CP} = -90°$ corresponding to T2HK.

time. ICAL is also an atmospheric neutrino experiment, and as such, collecting data over a longer period of time can significantly improve mass ordering sensitivity measurements. Figure 2 (lower plot) demonstrates that as the run time for ICAL increases, the total sensitivity after combining all three experiments (ICAL + JUNO + T2HK) also increases.

Figure 2 shows that combining JUNO and ICAL alone requires 12 years of ICAL data to achieve 5σ sensitivity. This implies that no other experiment is required to achieve 5σ sensitivity.

3.4. Effect of Octant on MO Sensitivity

Figure 3 presents the χ^2 for mass ordering as a function of the true value of θ_{23}. The upper and lower panels correspond to δ_{CP} equal to 0° and −90°, respectively. It is clear from the figures that the sensitivity of individual experiments to the mass ordering increases with θ_{23}. However, this effect does not hold when combining the results of JUNO and T2HK.

4. CONCLUSION

Overall, the combination of ICAL, JUNO, and T2HK experiments provides a robust and powerful solution to establish mass ordering sensitivity greater than 5σ. This combination can achieve high C.L. sensitivity for all values of δ_{CP}, eliminating the δ_{CP} dependency associated with long baseline experiments. Additionally, it reduces the requirement for JUNO to have an extremely efficient energy resolution, as even with a poor resolution, high sensitivity can still be achieved. The results also suggest that with just two detectors, ICAL and JUNO, 5σ sensitivity can be achieved with 12 years of ICAL data and a high energy resolution JUNO detector.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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