Neutrino Mass Ordering - Circumventing the Challenges using Synergy between INO, T2HK and JUNO

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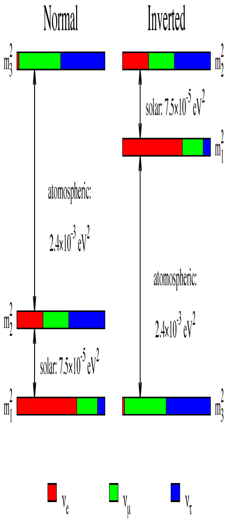
Neutrino mass ordering



- The neutrino mass ordering (NMO) is one of the most important questions to be solved in the field of neutrino oscillation physics.
- It impacts the limit on the absolute sum of neutrino masses from cosmology.
- important implications for the searches for neutrino-less double β decay .
- In addition, knowledge of the NMO is an important pre-requisite for unambiguously measuring leptonic charge-parity (CP) violation.
- For better understanding of the (flavor-mass) mixing in the lepton sector.

Experiments Features

Experiments			
Properties	INO@ICAL	JUNO	T2HK
Source	Atmospheric	Reactor	Accelerator
E range	0.5GeV-25GeV	2MeV-8MeV	0.2GeV-10GeV
Base line	0-12742 km	53 km	295 km
No of energy bins	15	200	98
Channels	$\nu_\mu/\bar{\nu}_\mu$ app. and dis.	$\bar{\nu}_e$ dis.	$\nu_\mu/\bar{\nu}_\mu$ dis. and $\nu_e/\bar{\nu}_e$ app.
Run time (years)	10	6	10
Matter effect	large	no	very small
Magnetic filed	1.5 Tesla	no	no
Fiducial volume	50kt	20kt	187kt

Experiments Physics Potential

Experiments		
INO	JUNO	T2HK
3σ MO	3σ MO	$2(5)\sigma$ MO
no CP sens	no CP sens	CP sens $>5\sigma$
poor octant sens	no octant sens	octant sens$>5\sigma$
-	θ_{13} precise measurement	-
NSI	NSI	NSI
LIV	LIV	LIV
Earth tomography	-	-
Sterile neutrino	Sterile neutrino	Sterile neutrino
-	proton decay	proton decay
indirect detection of DM	indirect detection of DM	indirect detection of DM
-	DSNB	DSNB

Simulating data for INO@ICAL

- We use honda fluxes calculated by honda etal. for theni site INDIA.
- We use full detector geometry developed by INO collaboration with geant4 detector simulation tool.
- We used Genie montecarlo event generator for neutrino nucleon interaction calculation and it generates events with unoscillated neutrino fluxes.
- We use re-weighting algorithm to include neutrino oscillation for different physics cases.
- We use muon and hadron look-up tables to include detector efficiency and resolution.
- We bin the data in specific binning scheme chosen for specific physics scenarios.
- We do statistical χ^2 analysis for hypothesis testing.

Simulating data for LBL end Reactor Experiments

- We use Globes software package to simulate events for long baseline experiments and reactor experiments.
- We use TDR(technical design reports) to make .glb file which includes detector configurations, neutrino channels for signals and backgrounds, baseline density profile, binning scheme etc.
- We add a new probability engine to calculate neutrino oscillation probability for BSM(LIV, NSI, LRF etc.) physics.

Binning Scheme for INO@ICAL

Marginalization is done only on θ_{23}. Rest of the parameters are fixed in whole analysis.

Observable	Range	Bin width	No. of bins
E_μ^{obs}(GeV) (15 bins)	[0.5,4]	0.5	7
	[4,7]	1	3
	[7,11]	4	1
	[11,12.5]	1.5	1
	[12.5,15]	2.5	1
	[15,25]	5	2
$cos\theta_\mu^{obs}$ (21 bins)	[-1.0,-0.4]	0.05	12
	[-0.4,0.0]	0.1	4
	[0,1]	0.2	5
E_{had}^{obs}(GeV)	[0,2]	1	2
	[2,4]	2	1
	[4,15]	11	1

Results

Mass Ordering Sensitivity - The Role of $|\Delta m^2_{31}|$

- From the figure we see that the minimum of $\Delta P_{\mu\mu}$ occurs at $\Delta m^2_{31}(\mathrm{IO}) \sim -2.300 \times 10^{-3}$ eV^2 (smaller values of $|\Delta m^2_{31}|$) for neutrinos and at $\Delta m^2_{31}(\mathrm{IO}) \sim -2.600 \times 10^{-3}$ eV^2 (larger values of $|\Delta m^2_{31}|$) for antineutrinos.

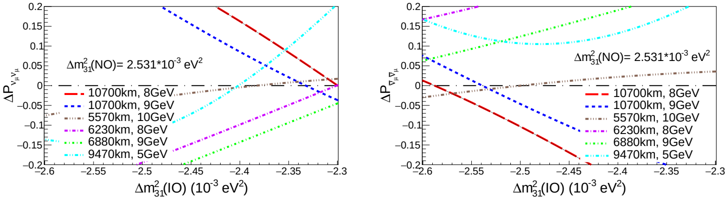


Figure 1: Left panel shows the $P_{\nu_\mu\nu_\mu}(NO) - P_{\nu_\mu\nu_\mu}(\mathrm{IO})$ for neutrino and right panel shows the $P_{\bar{\nu}_\mu\bar{\nu}_\mu}(NO) - P_{\bar{\nu}_\mu\bar{\nu}_\mu}(IO)$ for anti-neutrinos. These combinations of the energy and baseline have the maximum contribution towards the hierarchy sensitivity

MO sensitivity of INO as χ^2 plot

- From these curves we see that for neutrinos the χ^2 minimum is shifted towards $\Delta m^2_{31}(\text{test}) = -2.380 \times 10^{-3}$ eV^2 and for the antineutrinos the minimum is shifted towards $\Delta m^2_{31}(\text{test}) = -2.480 \times 10^{-3}$ eV^2.

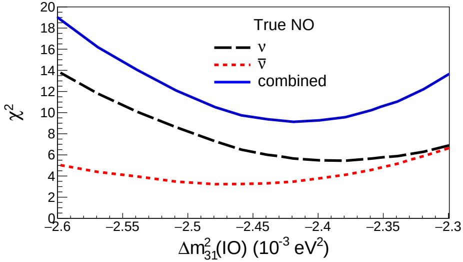


Figure 2: Mass ordering sensitivity χ^2 as a function of Δm^2_{31}(IO) forICALin ν , $\bar{\nu}$ and combined analysis. Red line is for $\bar{\nu_\mu}$ and black line for ν_μ data and combined results are shown in blue lines.

JUNO

- The reactor antineutrino event spectrum that we consider for JUNO varies between $E = 1.8$ MeV to 8 MeV and is divided into 200 equispaced bins, with bin width 0.031 MeV.
- The different E bins give χ^2 minimum at different values of $\Delta m^2_{31}(\mathrm{IO})$ and $\chi^2_{min} \simeq 0$ in each of the individual bins, albiet at a different value of $\Delta m^2_{31}(\mathrm{IO})$.

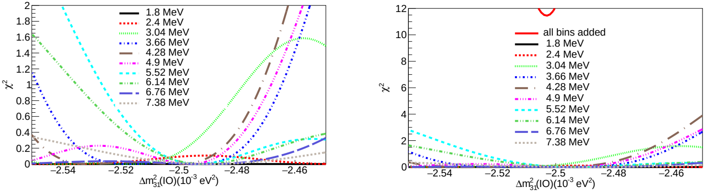


Figure 3: Mass ordering χ^2 in JUNO for 10 energy bins out of the total 200 energy bins. Systematic uncertainties are neglected.

T2HK

- the effect of combining the disappearance and the appearance channels in T2HK in a χ^2 plot. One can see that the minima in Δm^2_{31}(IO) for the disappearance channel comes very close to that predicted and different as compared to the assumed true value.
- Combining both channels gives us the final χ^2 which higher to simple sum of both the channels.

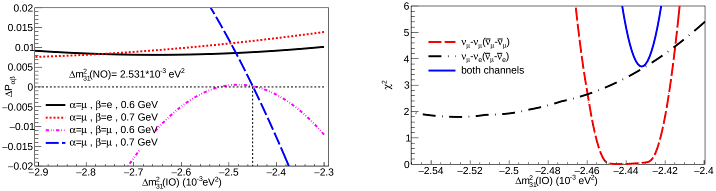


Figure 4: Mass ordering sensitivity χ^2 as a function of Δm^2_{31}(IO) for T2HK. Red dotted line is for ν_μ and $\bar{\nu}_\mu$ disappearance channel. The black dotted line is for ν_e and $\bar{\nu}_e$ appearance channel. Blue solid line is for after combining all channels.

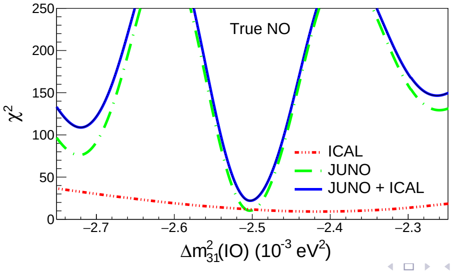
Juno and ICAL

Δm^2_{31} (True)	Δm^2_{31} (JUNO)	Δm^2_{31} (ICAL)	Δm^2_{31} (Combined)
2.531	-2.503	-2.419	-2.503

Table 1: Δm^2_{31}(IO) (in units of 10^{-3} eV^2)

JUNO	ICAL	JUNO+ICAL	Combined	% increase
10.23	9.12	19.35	22.01	13.7

Table 2: Mass-ordering χ^2 for true NO and test IO.



ICAL and T2HK

	Δm^2_{31} (True)	Δm^2_{31} (ICAL)	Δm^2_{31} (T2HK)	Δm^2_{31} (Combined)
$\delta_{CP} = 0$	2.531	-2.419	-2.431	-2.431
$\delta_{CP} = -90$	2.531	-2.419	-2.428	-2.428

Table 3: Δm^2_{31}(IO) (in units of 10^{-3} eV^2)

	ICAL	T2HK	T2HK+ICAL	Combined	% increase
$\delta_{CP} = 0$	9.12	3.77	12.89	13.55	5
$\delta_{CP} = -90$	9.12	25.09	34.21	34.84	1.8

Table 4: Mass-ordering χ^2 for true NO and test IO.

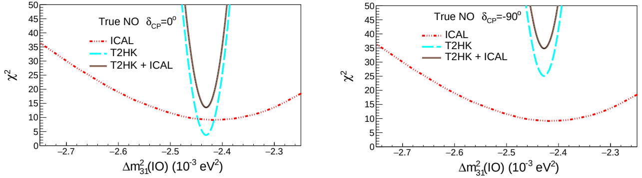


Figure 6: Mass ordering sensitivity as a function of Δm^2_{31} (test).

JUNO and T2HK

	JUNO	T2HK	Combined	True value
$\delta_{\rm CP} = 0°$	-2.503	-2.432	-2.481	2.531
$\delta_{\rm CP} = -90°$	-2.503	-2.429	-2.479	2.531

Table 5: Values of Δm^2_{31}(IO) (in units of 10^{-3} eV^2).

NH	χ^2_J	χ^2_T	$\chi^2_J + \chi^2_T$	$\chi^2_{Comb.}$	% increase
$\delta_{\rm CP} = 0$	10.23	3.70	13.93	86.87	523
$\delta_{\rm CP} = -90$	10.23	25.07	35.30	113.22	220

Table 6: Mass ordering χ^2 for true NO and test IO.

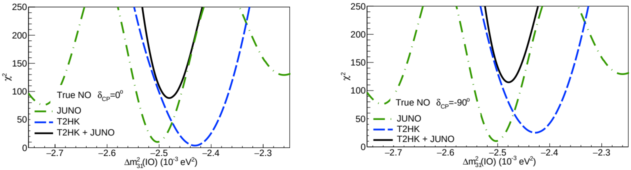


Figure 7: Mass ordering sensitivity expected from a combined analysis.

ICAL, JUNO and T2HK combined

- All three experiments has $\Delta m^2_{31}(test)$ minima at different location.
- First χ^2 of ICAL and T2HK minimize over θ_{23} and $\Delta m^2_{31}(test)$ then JUNO is added and minimized over $\Delta m^2_{31}(test)$.

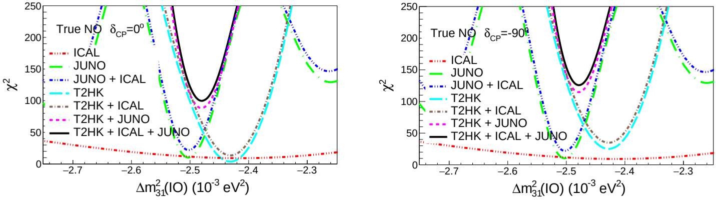


Figure 8: Mass ordering sensitivity as a function of Δm^2_{31} (test). Left panel is for $\delta_{\rm CP} = 0^\circ$ and the right panel is for $\delta_{\rm CP} = -90^\circ$ corresponding to T2HK.

- As we discussed earlier, for JUNO, the mass-ordering χ^2 is around 10 and for ICAL the mass ordering sensitivity is around 3σ. The sensitivity of T2HK is around 2σ for $\delta_{\rm CP} = 0^\circ$ and 5σ for $\delta_{\rm CP} = -90^\circ$.
- The true value of Δm^2_{31} is same for all these experiments, the χ^2 minimum occurs at different values of Δm^2_{31} (IO) for different experiments.

	Δm^2_{31}(True value)	Δm^2_{31}(ICAL)	Δm^2_{31}(JUNO)	Δm^2_{31}(T2HK)	Δm^2_{31}(Combined)
NH($\delta_{CP} = 0$)	2.531	-2.419	-2.503	-2.431	-2.48
NH($\delta_{CP} = -90$)	2.531	-2.419	-2.503	-2.428	-2.479

Table 7: Values of Δm^2_{31}(IO) (in units of 10^{-3} eV^2), for which we get mass-ordering χ^2 minimum.

	ICAL	JUNO	T2HK	JUNO +T2HK +ICAL	Combined	% increase
NH($\delta_{CP} = 0$)	9.12	10.23	3.77	23.12	99.76	331
NH($\delta_{CP} = -90$)	9.12	10.23	25.09	44.44	125.79	183

Table 8: Mass-ordering χ^2 for true NO and test IO.

JUNO Resolution effect

- The sensitivity of JUNO goes from $\chi^2 = 10$ to almost zero when the energy resolution is varied from $3\%/\sqrt{E(MeV)}$ to $5\%/\sqrt{E(MeV)}$.
- For ICAL+JUNO+T2HK the χ^2 is around 52 (76) for $\delta_{\rm CP} = 0^\circ(-90^\circ)$ even if the JUNO energy resolution is $5\%/\sqrt{E(MeV)}$.

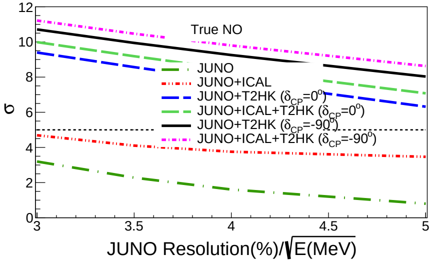


Figure 9: Neutrino mass ordering sensitivity as a function of energy resolution of JUNO.

ICAL run time effect

- For a 20 years running of ICAL, the χ^2 for ICAL goes up to 16. When it is added with JUNO the χ^2 reaches 36.
- For the combination of ICAL+JUNO+T2HK one can have a mass-ordering χ^2 of 100 (144) for $\delta_{\rm CP} = 0^\circ(-90^\circ)$ for 20 years running of ICAL.

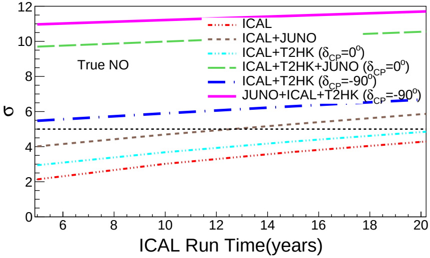


Figure 10: Neutrino mass ordering sensitivity as a function of run-time of ICAL.

θ_{23} true effect on MO

- The χ^2 increases as θ_{23} increases from 42° to 45° and when θ_{23} increases further from 45°, the sensitivity decreases.

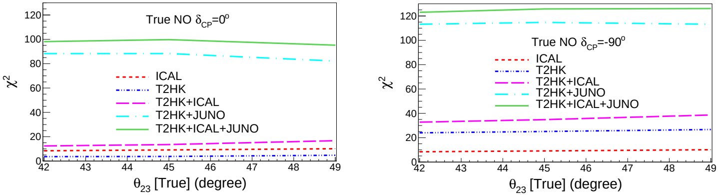


Figure 11: Neutrino mass ordering sensitivity as a function of θ_{23} true. Left panel is for $\delta_{\rm CP} = 0°$ and the right panel is for $\delta_{\rm CP} = -90°$ corresponding to T2HK.

- For $\delta_{\rm CP} = 0°$, we note that though χ^2 for T2HK increases as θ_{23} increases, the χ^2 minimum tends to shift towards the left.
- For $\delta_{\rm CP} = -90°$, the shift of the T2HK curve towards left for the value of $\theta_{23} = 49°$ is less prominent as compared to $\delta_{\rm CP} = 0°$. As a result,

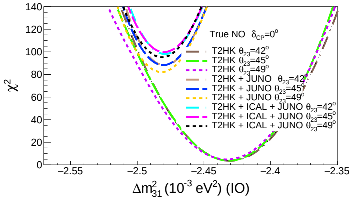


Figure 12: Mass ordering sensitivity as a function of Δm^2_{31} (test) for different values of θ_{23}. Left panel is for $\delta_{\rm CP} = 0°$ and the right panel is for $\delta_{\rm CP} = -90°$ corresponding to T2HK.

Octant effect on MO sensitivity

- For true θ_{23} in the lower octant, the χ^2 minimum always occurs with the correct octant for both T2HK and ICAL.
- For θ_{23} in the higher octant, the χ^2 minimum occurs at the wrong octant for ICAL. But when ICAL is added with T2HK, the minimum of the combined χ^2 occurs at the correct octant.

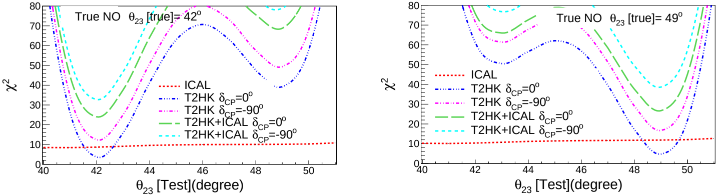


Figure 13: Neutrino mass ordering sensitivity as a function of θ_{23} test. Left panel is for $\delta_{\rm CP} = 0^\circ$ and the right panel is for $\delta_{\rm CP} = -90^\circ$ corresponding to T2HK.


Thank You

References I

[CGR22] Sandhya Choubey, Monojit Ghosh, and Deepak Raikwal. *Neutrino Mass Ordering – Circumventing the Challenges using Synergy between T2HK and JUNO*. 2022. DOI: 10.48550/ARXIV.2207.04784. URL: https://arxiv.org/abs/2207.04784.

[RCG22] Deepak Raikwal, Sandhya Choubey, and Monojit Ghosh. *Determining Neutrino Mass Ordering with ICAL, JUNO and T2HK*. 2022. DOI: 10.48550/ARXIV.2207.06798. URL: https://arxiv.org/abs/2207.06798.