CP violation and mass hierarchy with a combined sensitivity of T2K-II, NOνA and JUNO

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Abstract

Recent T2K data indicates a CP violation in the neutrino oscillations and mildly favours the normal neutrino mass hierarchy. This work explores the physics potentials with a combined sensitivity of T2K-II, NOνA, and JUNO experiments. T2K-II, a proposed run extension up to 2026 by T2K collaboration, is sensitive to CP violation at a level of 3σ or higher if $\delta_{CP} \sim -\pi/2$. NOνA, proposed to run until 2024, provides a significant sensitivity to both mass hierarchy and CP violation. JUNO, expected to take data for six years starting from 2021, has 3σ or higher sensitivity to the mass hierarchy and 1% or better precision measurement of solar parameters and atmospheric mass splitting. It is shown that the joint analysis can determine definitely the neutrino mass hierarchy. Also it provides $> 4\sigma$ to exclude CP conserving values if $\delta_{CP} \sim -\pi/2$ and $> 50\%$ fractional region of δ_{CP} can be explored at $\geq 3\sigma$ significance.

Objectives

Neutrino oscillations establish that **neutrinos have mass and the leptons are mixed**. Lepton mixing matrix, which connects the mass eigenstates and flavor eigenstates of neutrinos, is presumed to be unitary 3×3 matrix, which are commonly parameterized by three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$, one Dirac CP-violation phase $\delta_{CP}{}^a$. The probability for a α-flavor to oscillate into β-flavor, $P_{(\nu_\alpha \to \nu_\beta)}$, depends on these four parameters, two mass square splitting $\Delta m^2_{21}, \Delta m^2_{31}$, its energy, E_ν, propagation distance L, and amount of matter it passing through, ρ:

$$P_{(\nu_\alpha \to \nu_\beta)} = f\left(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}; \Delta m^2_{21}, \Delta m^2_{31}; E_\nu, L, \rho\right) \quad (1)$$

- Experiments basically measures the oscillation probabilities to extract parameters, e.g T2K, NOvA measure $P_{(\nu_\mu \to \nu_\mu)}$ (ν_μ *disappearance*), $P_{(\nu_\mu \to \nu_e)}$ (ν_e *appearance*), and corresponding processes with $\overline{\nu}_\mu$; JUNO will measure $P_{(\overline{\nu}_e \to \overline{\nu}_e)}$
- Each experiment is sensitive to a specific set of parameters, e.g T2K, NOvA are sensitive to $(\theta_{13}, \theta_{23}, \delta_{CP}, \Delta m^2_{31})$; JUNO $(\theta_{12}, \theta_{13}, \Delta m^2_{21}, \Delta m^2_{31})$. Also there are degeneracy among parameters, challenging the precision measurements from single experiment.

It is essential to combine data from multiple experiments to attain a precision measurement. Main objectives of T2K-2, NOvA and JUNO joint analysis are to *(i) determine the neutrino mass hierarchy (MH), (ii) enhance sensitivity to CP violation, (iii) precision measurement of other oscillation parameters, and (iv) to test the unitary of the lepton mixing matrix.*

[a] If neutrino is Majorana particle, two additional Majorana-CP-violation phases are included but these are irrelevant for neutrino oscillation

Experimental and Simulation Details

GLoBES [1] is used for simulating the experiments and calculating the statistical significance. **We describe the experiments closely as much as possible by using the updated information of flux, signal/background efficiency, and systematic error. Each experimental setup is validated at the event rate level and sensitivity level.** An overview of experimental specification is shown in Table 1 and details are described below:

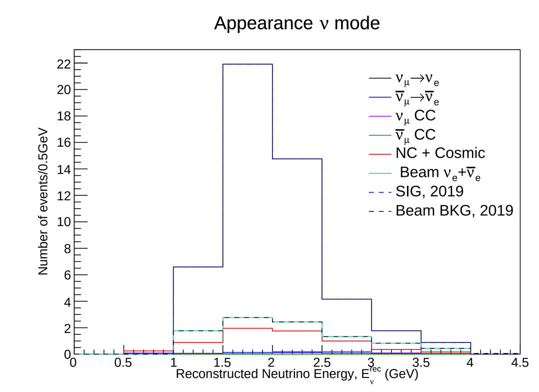
Parameters	T2K-II	NOνA	JUNO
Exposure (POT)	20×10^{21}	7.2×10^{21}	6 yrs. @ 36 GW-th
Baseline (km)	295	810	52.5
Energy peak/range	~0.6 GeV	~2.0 GeV	1-8 MeV
(Far) Det. Type	WC	LS	LS
(Far) Det. Mass	50 kt	14kt	20kt

Table 1: Experimental Specifications

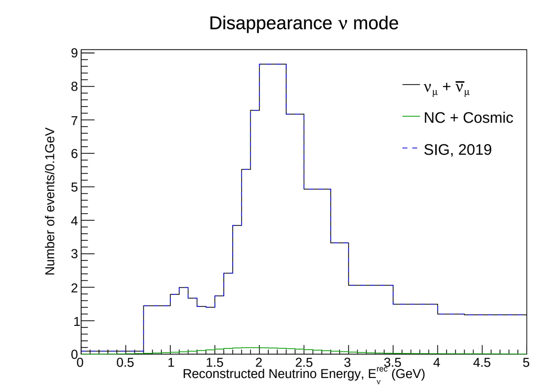
T2K-II An exposure of 20×10^{21} proton-on-target (POT) equally divided among ν and $\overline{\nu}$ running modes. The signal/background efficiency and spectral information for T2K-II is obtained by scaling the 2017 analysis [2] to same exposure as T2K proposal [3]. Four data samples are used: ν_μ disappearance, ν_e appearance in both ν-mode and $\overline{\nu}$-mode. A 3% systematic error for all samples and 3% energy resolution are used.

NOνA w/ run extension A total exposure of 7.2×10^{21} POT equally divided among ν and $\overline{\nu}$ modes; We closely followed [4] to obtain the flux information and [5] to obtain the signal, background efficiency and spectral information. A 5% systematic error for all samples and energy resolution from $8-10\%$ are assigned. Fig. 1 shows an example of comparing event rate obtained by our setup and real NOvA simulation.

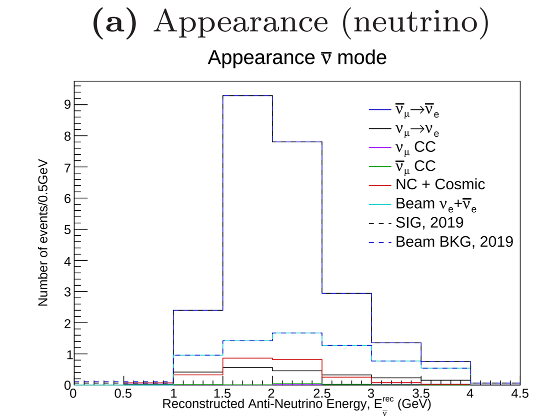
JUNO Neutrinos flux is simulated with four isotopes of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu with an efficiency of 73%, predicting 60 IBD events per day. Detector setup is simplified with a single reactor core of 36 GW-th and no simulation of background. This simplification affects the solar parameter precision, but less on the MH sensitivity. A 3% energy resolution and 1% error for flux and detector uncertainties are used.



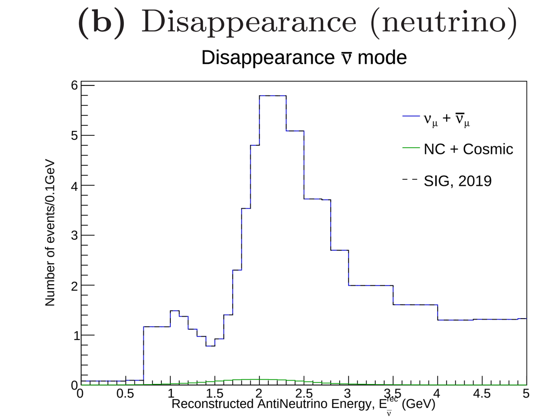
(a) Appearance (neutrino)



(b) Disappearance (neutrino)



(c) Appearance (antineutrino)



(d) Disappearance (antineutrino)

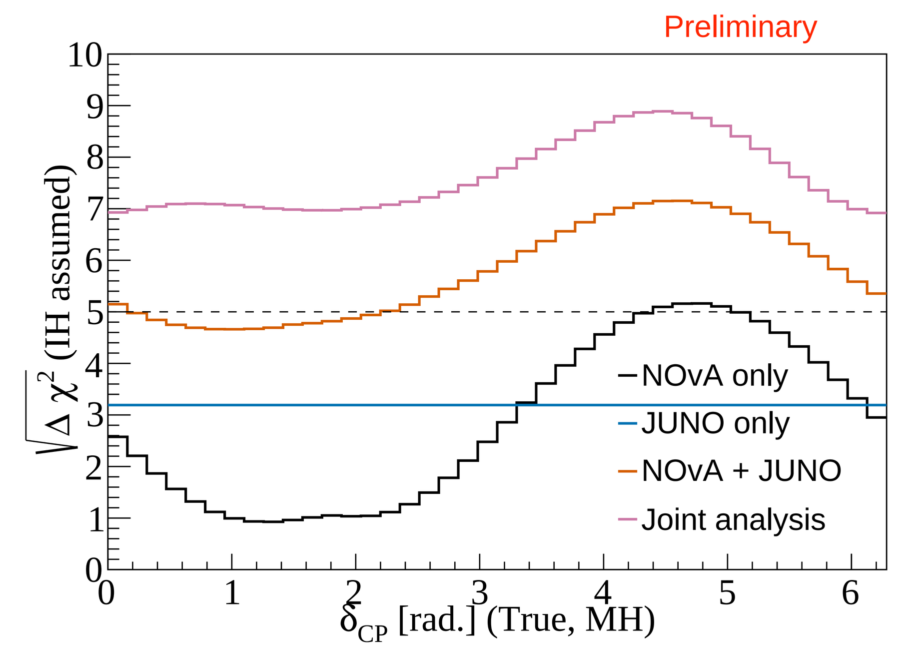
Figure 1: NOνA FD event spectra: our setup w/ GLoBES compared to [5]

Result

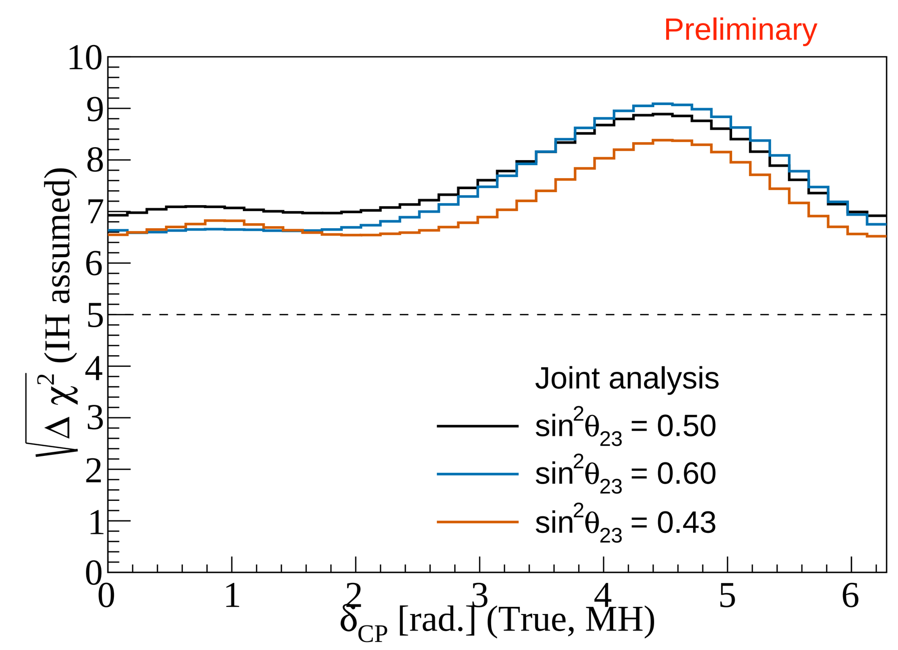
Unless mentioned, the following values (mostly from global analysis [6]) are taken as the truth for sensitivity studies:

$$(\sin^2\theta_{12}, \sin^2\theta_{13}, \sin^2\theta_{23}, \delta_{CP}) = (0.310, 0.02241, 0.5, -\pi/2)$$
$$(\Delta m^2_{21}, \Delta m^2_{31}) = (7.39 \times 10^{-5} eV^2, 2.523 \times 10^{-3} eV^2)$$

Mass Hierarchy (MH) Sensitivity Assume neutrino MH is normal, statistical significance χ^2 to exclude the inverted MH is calculated at each possible true value of δ_{CP}.



(a) Individual and combined sensitivity to MH at $\sin^2\theta_{23} = 0.5$

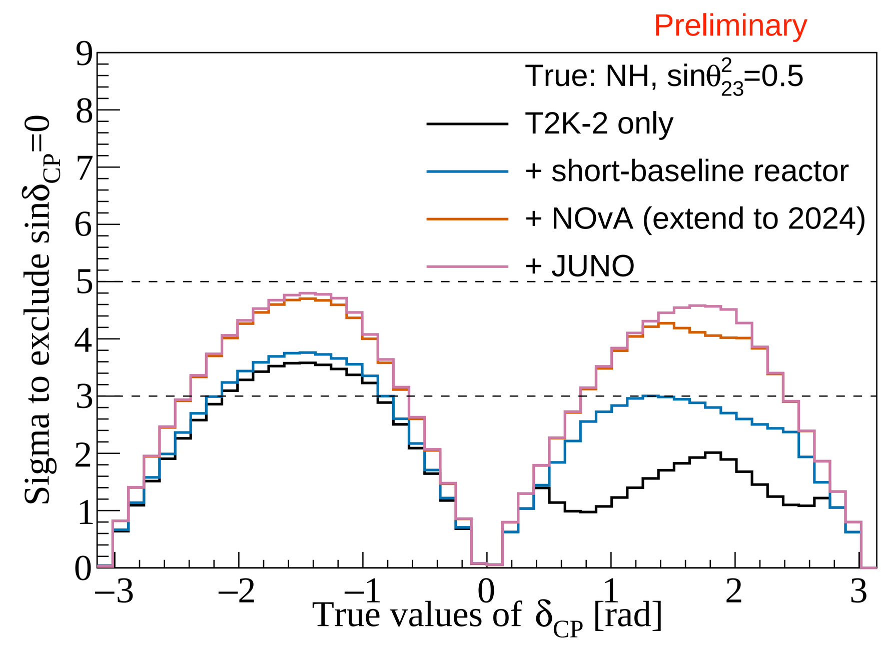


(b) Combined sensitivity for three values of $\sin^2\theta_{23}$

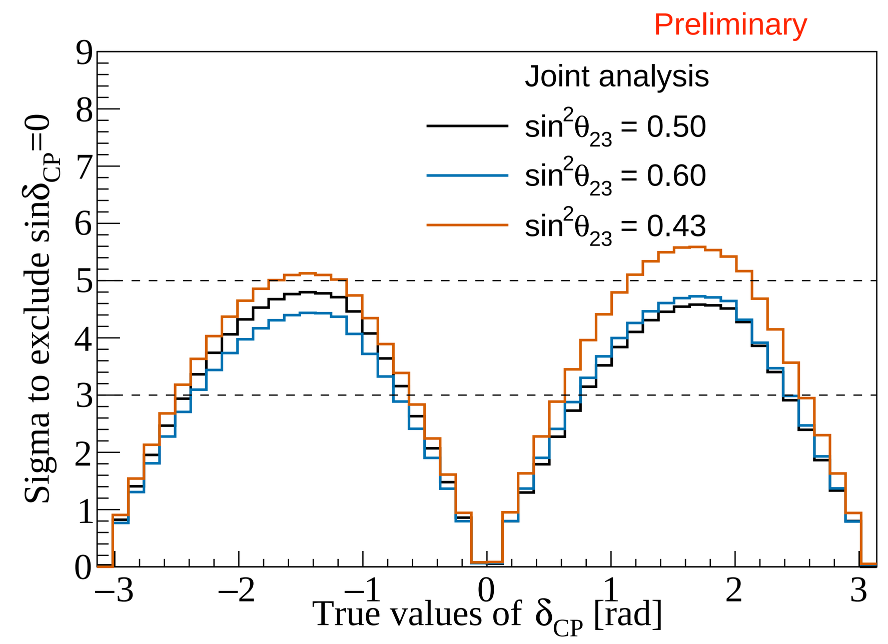
Figure 2: Mass hierarchy resolving as a function of true δ_{CP}

Fig.2(a) shows sensitivity to mass hierarchy from different experiment and combination at $\sin^2\theta_{23} = 0.5$. The combined sensitivity for different values of $\sin^2\theta_{23}$ is shown in Fig.2(b).

CP Violation Sensitivity Considering δ_{CP} can be varied between $(-\pi, +\pi)$, the statistical significance of excluding the CP-conserving values, $\delta_{CP} = 0, \pi$, is calculated assuming either the MH is known or not known. Although the result below is tagged as with "unknown" MH, it should be closely equivalent to "known" MH when all experiments are combined since MH is solved definitely in this case.



(a) For $\theta_{23} = \frac{\pi}{4}$, MH is not known



(b) For different values of θ_{23}, MH is not known

Figure 3: Sensitivity to CP violation

Fig. 3(a) shows the sensitivity to the leptonic CP violation for the case when $\theta_{23} = \frac{\pi}{4}$ and the MH is assumed to be *"not known"* by adding up experiments starting from T2K-2. Fig. 3(b) shows the combined sensitivity to CP violation at different values of $\sin^2\theta_{23}$. Table 2 shows the fractional region of δ_{CP} in which CP violation can be explored with 3σ or higher significance.

$\sin^2\theta_{23}$	0.43	0.50	0.60
Fraction of δ_{CP}	61.6%	54.6%	53.3%

Table 2: Fractional region of δ_{CP}, depending on $\sin^2\theta_{23}$, can be explored with 3σ or higher significance

Summary and Discussion

- **Mass hierarchy** will be determined with this joint analysis
- **CP violation** can be explored $> 4\sigma$ if $\delta_{CP} \sim -\pi/2$ (T2K data indication) and $> 50\%$ fractional region of δ_{CP} with $\geq 3\sigma$ significance.
- (Not shown in the poster), a joint analysis provides a great improvement in solving the θ_{23} **octant degeneracy**, more precise measurements on other oscillation parameters and provide a **great test to the standard neutrino oscillation paradigm.**
- **Further consideration**: background simulation for JUNO; systematic modeling; correlation among experiments)

References

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