Chapter 5

Octant Degeneracy and Precision Measurements of Oscillation Parameters in T2K-II, NOνA-II and JUNO

Besides the neutrino mass hierarchy and CP violation in the lepton sector, the other outstanding problem that demands attention is the true octant of θ_{23} mixing angle. In section 5.1, we present the importance and present status of the neutrino oscillation parameters. The allowed regions of $\sin^2\theta_{13}$-$\delta_{\rm CP}$ and $\sin^2\theta_{23} - \Delta m^2_{31}$ constrained by T2K-II, NOνA-II and JUNO, are present in sections 5.2 and 5.3. We conclude the chapter by presenting the results on octant resolving sensitivity in the section 5.4.

5.1 Introduction

Based on their predictions of various oscillation parameters, many BSM models can either be accepted or rejected. So, a precise measurement of the oscillation parameters can guide us towards a successful BSM theory. Determination of δ_{CP}

can also give clue in understanding the present matter-antimatter asymmetry of the universe. The matter-antimatter asymmetry of the universe can be explained by the process of baryogenesis. But the baryogenesis in SM is not sufficient to explain the observed baryon asymmetry of the universe. One option to create additional baryon asymmetry is via leptogenesis in which the decay of heavy right handed neutrinos (for instance, those belonging to the See-Saw models) can create lepton asymmetry, which can be converted to baryon asymmetry. Different studies show that under certain conditions, it may be possible to connect the leptonic CP phase δ_{CP} to leptogenesis.

As per the global analysis from experimental data available upto July 2020, for the allowed 3σ ranges of the oscillation parameters [1, 2], the present status of the magnitude of the elements of the PMNS matrix is given as,

$$|U|^{3\sigma}_{PMNS} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.143 \to 0.156 \\ 0.233 \to 0.507 & 0.461 \to 0.694 & 0.631 \to 0.778 \\ 0.261 \to 0.526 & 0.471 \to 0.701 & 0.611 \to 0.761 \end{pmatrix} \tag{5.1}$$

The θ_{13} mixing angle is well-measured by reactor-based neutrino experiments, dominated by Daya Bay. The solar mass-squared difference are independently well constrained by the Solar experiments and VLBL reactor experiment KamLAND data. T2K and NOνA are the only ongoing LBL experiments, although in the global fits K2K and MINOS results besides them are also considered. The LBL experiments are sensitive to θ_{23} and Δm^2_{31} through the disappearance sample $\nu_\mu \to \nu_\mu$ ($\bar{\nu_\mu} \to \bar{\nu_\mu}$), to θ_{13} and δ_{CP} though their appearance $\nu_e \to \nu_\mu$ ($\bar{\nu_\mu} \to \bar{\nu_e}$) samples and to mass-heirarchy resolution due to the matter effect potentials the neutrinos (anti-neutrinos) experience in their propagation to the detectors through Earth matter. However, MINOS/MINOS+ is sensitive to $|\Delta m^2_{31}|$ but not to θ_{13} and δ_{CP} due to its operation for muon neutrino disappearance search only.

θ_{23} octant degeneracy: In equation 2.77, the uncertainty in appearance measurement comes from θ_{23}, apart from $\sin\delta_{CP}$. In ν_μ disappearance measurement, given by Equation 2.74, the amplitude gives the measurement of $\sin^2 2\theta_{23}$ at the oscillation maxima $\Phi_{31} = \frac{\pi}{2}$. There are two possible values of

$\sin^2\theta_{23}$ for a given value of $\sin^2 2\theta_{23}$ from the disappearance measurement [3], given by

$$\sin^2\theta_{23} = \frac{1 \pm \sqrt{1 - \sin^2 2\theta_{23}}}{2} \tag{5.2}$$

As the difference between the two solutions is $\sqrt{1 - \sin^2 2\theta_{23}}$, it can be large even if the term is small. For example, if $(1 - \sin^2 2\theta_{23})$ is measured to be $\sin^2 2\theta_{23} > 0.97$, the possible range of $\sin\theta_{23}$ is between 0.41 and 0.59, which allows both the octants. This is called the octant θ_{23} degeneracy problem. To solve this problem, it is necessary to show that $\sin^2 2\theta_{23}$ is ~ 1 or determine which solution/octant is correct by combining oscillation measurements from different experiments. As the disappearance sample is sensitive to $\sin^2 2\theta_{23}$, ocatnt can't be resolved by this sample alone in LBL i.e. whether $\theta_{23} < \pi/4$ or $> \pi/4$ can't be answered. However, the octant degeneracy can be resolved by adding appearance sample as the term $\sin^2\theta_{23}$ appears and also by considering SuperKamiokande and Ice Cube DeepCore data. The present best fit of θ_{23} lies in the upper octant (see Table 1.3). The lower octant is allowed at $\sim 2.4\sigma$ confidence level from the global data fits. Maximal mixing is now disfavoured with a significance of $\Delta\chi^2 = 3.9$, including Super-K data.

5.2 Allowed regions of θ_{13} mixing angle and δ_{CP}

The θ_{13} mixing angle can be constrained precisely by measuring the disappearance of $\overline{\nu}_e$ in the R-SBL neutrino experiment. The A-LBL experiments, on the other hand, can provide a constraint of θ_{13} mixing angle correlated to $\delta_{\rm CP}$, mainly thank to the measurements of the appearance of $\nu_e(\overline{\nu}_e)$ from the beam of $\nu_\mu(\overline{\nu}_\mu)$ respectively. The sensitivities are calculated at three different *true* values of $\delta_{\rm CP}$ $(0, \pm\frac{\pi}{2})$. A 3σ C.L. range of $\sin^2\theta_{13}$ $[0.02046, 0.02440]$ is taken from Ref. [4]. Fig. 5-1 shows the 3σ C.L. allowed region of $\sin^2\theta_{13}$-$\delta_{\rm CP}$ obtained with a joint analysis of the T2K-II and NOνA-II. The precision of $\sin^2\theta_{13}$ can be achieved between 6.5% and 10.7% depending on the *true* value of $\delta_{\rm CP}$. It will be interesting to compare the measurements of θ_{13} from R-SBL experiments and from the A-LBL experiments with such high precision.

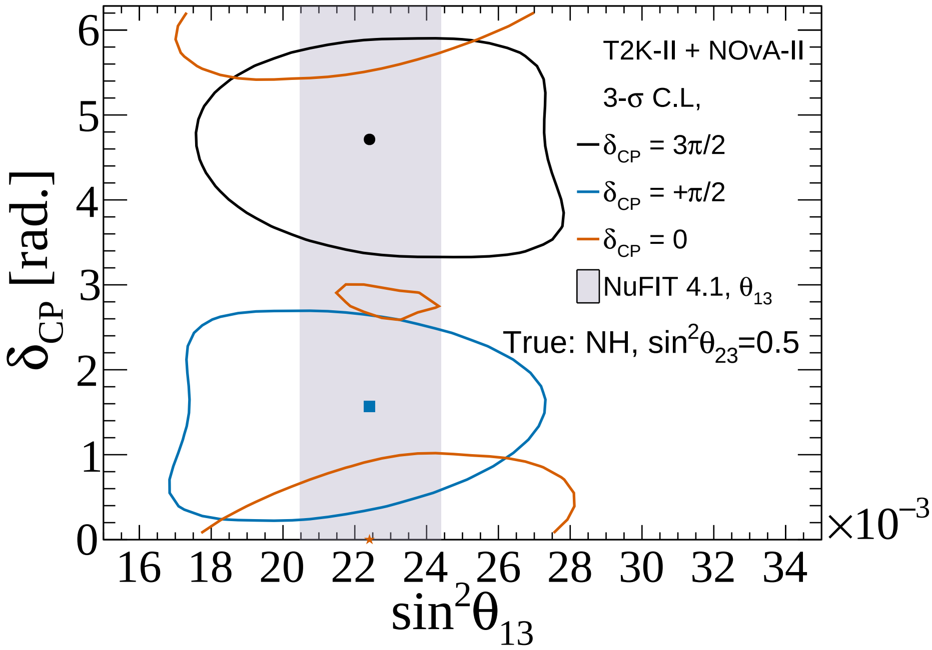

Figure 5-1: Allowed region of $\sin^2\theta_{13}$-δ_{CP} at the 3σ C.L. compared between a joint analysis of T2K-II and NOνA-II and the present constraint from the global data [4].

5.3 Allowed regions of θ_{23} mixing angle and Δm^2_{31}

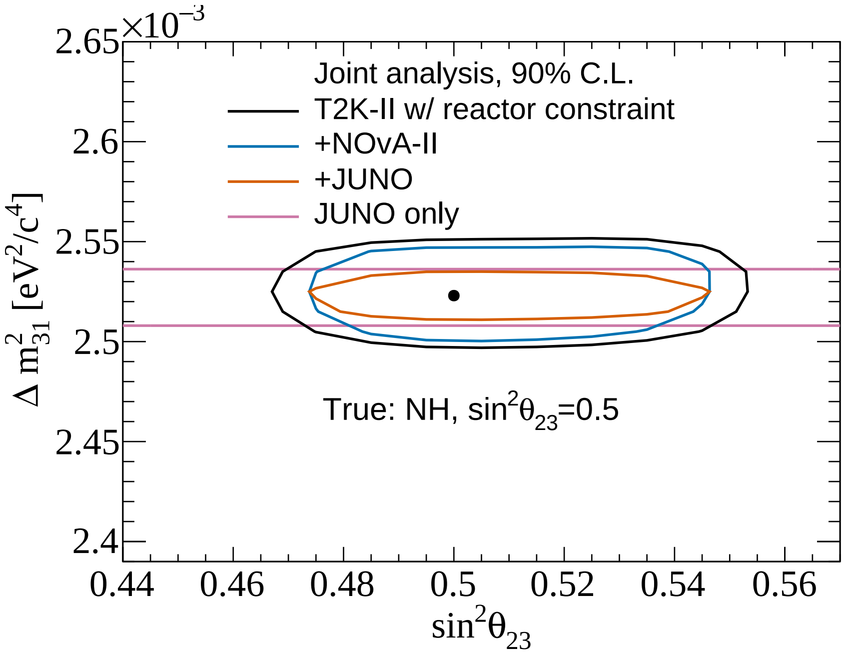

Figure 5-2: Allowed region in the $\sin^2\theta_{23} - \Delta m^2_{31}$ space at 90% C.L. with various experimental setups. *Normal* MH and $\sin^2\theta_{23} = 0.5$ are assumed to be true.

As shown in Fig. 5-2, both JUNO alone and a combined sensitivity of T2K-II and

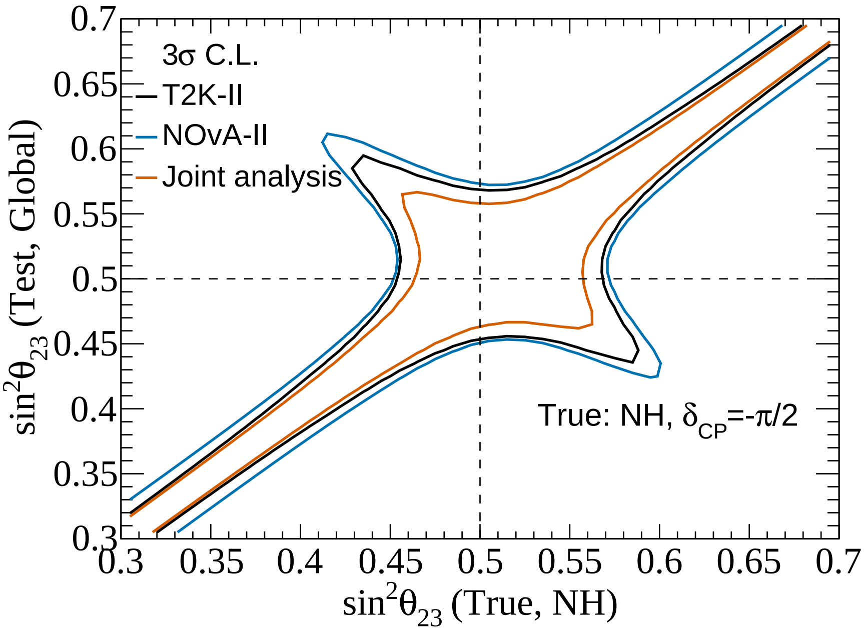

Figure 5-3: Allowed region of *test* $\sin^2\theta_{23}$ at 3σ C.L as a function of *true* $\sin^2\theta_{23}$. *Normal* MH and $\delta_{\mathrm{CP}} = -\frac{\pi}{2}$ are assumed to be true.

NOνA-II experiments can reach a sub-percent-level precision on the atmospheric mass-squared splitting Δm^2_{31}. A comparison at such precision may provide a very good test for the PMNS framework. Besides, assuming a maximal mixing $\sin^2\theta_{23} = 0.5$, a combined sensitivity of T2K-II and NOνA-II can achieve approximately 6% and 3% precision for the upper and lower limit on $\sin^2\theta_{23}$ respectively. A capability to solve the θ_{23} octant in case the mixing angle θ_{23} is not maximal in the next section.

5.4 Resolving the octant of the θ_{23} mixing angle:

We consider a range [0.3, 0.7] of possible *true* $\sin^2\theta_{23}$ values and that the *true* MH is *normal*. For each *true* $\sin^2\theta_{23}$ value, the marginalized χ^2 is calculated at various values of *test* value θ_{23} with both possibilities of the MH. The minimization over the MH options is firstly performed to obtain global minimum χ^2 for any combination of the *true* and *test* values of θ_{23}. The allowed regions of test $\sin^2\theta_{23}$ as a function of true $\sin^2\theta_{23}$ can be obtained, e.g. at the 3σ C.L, as shown in Fig. 5-3.

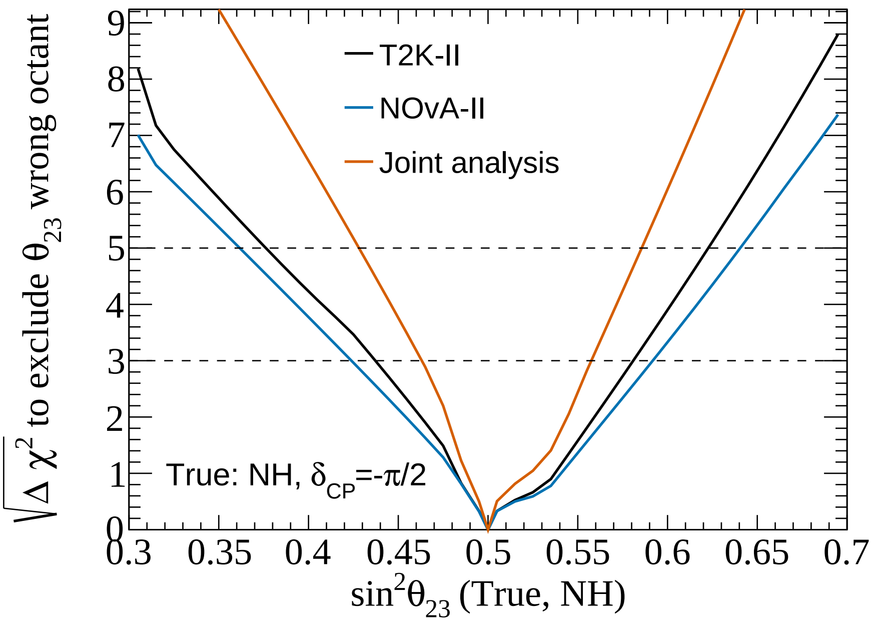

Figure 5-4: Statistical significance to exclude the *wrong* octant as a function of $\sin^2\theta_{23}$. *Normal* MH and $\delta_{\rm CP} = -\frac{\pi}{2}$ are assumed to be true.

The statistical significance to exclude the *wrong* octant given a *true* (non-maximal) value of θ_{23} is calculated by taking the difference between the mimimal value of the global χ^2 in the *wrong* octant and the *true* octant of θ_{23}. The octant resolving sensitivities with T2K-II, NOνA-II alone or with a combined analysis is shown in Fig. 5-4. The θ_{23} octant resolving power can be enhanced significantly when combining T2K-II and NOνA-II data samples, particularly the θ_{23} octant can be determined at 3σ C.L or higher if $\sin^2\theta_{23}$ is ≤ 0.46 or ≥ 0.56.

5.5 Discussion

Regarding the octant of the θ_{23} mixing angles, T2K, NOνA, SK, and MINOS(+) data prefer non-maximal mixing with statistical significance between 0.5σ to 1.5σ C.L. If the *true* value of θ_{23} is close to the best fit in the global data fit [2], θ_{23}= 0.57, a combined analysis of T2K-II, NOνA-II and JUNO can exclude the *wrong* octant with 3σ C.L. There is a room for improvement in the above-mentioned physic potentials, for example, by adding an atmospheric neutrino data sample from the SK experiment. There are on-going efforts to combine data from T2K and SK along with a joint analysis of T2K and NOνA. Such activities are vital to realizing a grand framework for combining the special-but-statistically-limited neutrino data in the future.

Bibliography

[1] Gonzalez-Garcia, M. C. & Pena-Garay, C. Three neutrino mixing after the first results from K2K and KamLAND. *Phys. Rev. D* **68**, 093003, 2003. hep-ph/0306001.

[2] Esteban, I. *et al.* The fate of hints: updated global analysis of three-flavor neutrino oscillations. *JHEP* **09**, 178, 2020. 2007.14792.

[3] Suekane, F. *Neutrino Oscillations: A Practical Guide to Basics and Applications*, vol. 898, 2015.

[4] Esteban, I. *et al.* Global analysis of three-flavour neutrino oscillations: synergies and tensions in the determination of θ_{23}, δ_{CP}, and the mass ordering. *JHEP* **01**, 106, 2019. 1811.05487.