Octant Degeneracy, Quadrant of Leptonic CPV phase at Long Baseline ν Experiments and Baryogenesis

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1. Introduction

- Today, Neutrino physics is going through precision era.
- With the measurement of reactor mixing angle θ_{13} [1–3] precisely by reactor experiments, the unknown quantities left to be measured in neutrino sector are:

- leptonic CP violating phase [4–9],
- octant of atmospheric angle θ_{23} [10–15],
- mass hierarchy, nature of neutrino etc.

- Long baseline neutrino experiments (LBNEs [16, 17], NOνA [18] , T2K [19], MINOS [20], LBNO [21] etc) may be very promising, in measuring many of these sensitive parameters.
- The relatively large value of the reactor mixing angle θ_{13} measured with a high precision in neutrino experiments [1] has opened up a wide range of possibilities to examine CP violation in the lepton sector

- Measuring leptonic CP violation (CPV) is one of the most demanding tasks in future neutrino experiments [22].
- The leptonic CPV phase can be induced by the PMNS neutrino mixing matrix [23] which holds, in addition to the three mixing angles, a Dirac type CP violating phase in general as it exists in the quark sector, and two extra phases if neutrinos are Majorana particles.

- The current global fit to available neutrino data manifests nontrivial values of the Dirac-type CP phase [24, 25].
- Recently in [4], we have explored possibilities of improving CP violation discovery potential of newly planned Long-Baseline Neutrino Experiments (earlier LBNE, now called DUNE) in USA.

- In neutrino oscillation probability expression $P(\nu_\mu \to \nu_e)$ relevant for LBNEs, the term due to significant matter effect, changes sign when oscillation is changed from neutrino to antineutrino mode, or vice-versa.
- Therefore in presence of matter effects, CPV effect is entangled and hence, one has two degenerate solutions :

- **One due to CPV phase and another due to its entangled value.**

- It has been suggested to resolve this issue by combining two experiments with different baselines [26, 27].
- Precise measurement of θ_{13} plays crucial role in its CPV measurements.
- This fact was utilized recently by us [4], where we have explored different possibilities of improving CPV sensitivity for LBNE, USA.

- We considered both appearance P($\nu_\mu \rightarrow \nu_e$) and disappearance P ($\nu_\mu \rightarrow \nu_\mu$) channels in both neutrino and antineutrino modes. Some of the observations made in [4] are:
- CPV discovery potential of LBNE increases significantly when combined with near detector and reactor experiments.
- CPV violation sensitivity is more in LO (lower octant) of atmospheric angle θ_{23} , for any assumed true hierarchy.

- CPV sensitivity increases with mass of FD (far detector).
- Adding data from reactors to LBNE improves its CPV sensitivity irrespective of octant.
- Aim of this work is to critically analyze the results presented in [4], in context of entanglement of quadrant of CPV phase and octant of θ_{23} , and hence study the role of baryogenesis in resolving this enganglement.

- Following the results of [4], either of the two octants is favoured, and the enhancement of CPV sensitivity with respect to its quadrant is utilized here to calculate the values of lepton-antilepton symmetry.
- This is done considering two cases of the rotation matrix for the fermions - CKM only, and CKM+PMNS.

- Then, this is used to calculate the value of BAU within the nonsupersymmetric S0(10) model [28], characterized by the presence of an intermediate mass scale where both the lepton number conservation and quark-lepton symmetry are broken.

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- This is an era of precision measurements in neutrino physics. We therefore consider variation of Δm^2_{31} at its 3σ C.L. vs δ_{CP} range at $\geq 2\sigma$ over the corresponding distribution of χ^2–minima from fig. 2

  We calculate baryon to photon ratio, and compare with its experimentally known best fit value. As, constrained by the latest updated BAU limits, $5.7*10^{-10} < \text{BAU} < 6.7*10^{-10}$, we plot θ_{13} range at its 3σ C.L [2] from its central δ_{CP} range at $\geq 2\sigma$ over the corresponding distribution of χ^2–minima from fig. 2.

2. CPV Phase and Octant of θ_{23}

- By combining with ND and reactor experiments, CPV sensitivity of LBNE improves more for LO (lower octant) than HO (higher octant), for any assumed true hierarchy [4].
- In Fig. 1 below we plot CP asymmetry,

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\overline{\nu_\mu} \to \overline{\nu_e})} \tag{1}$$

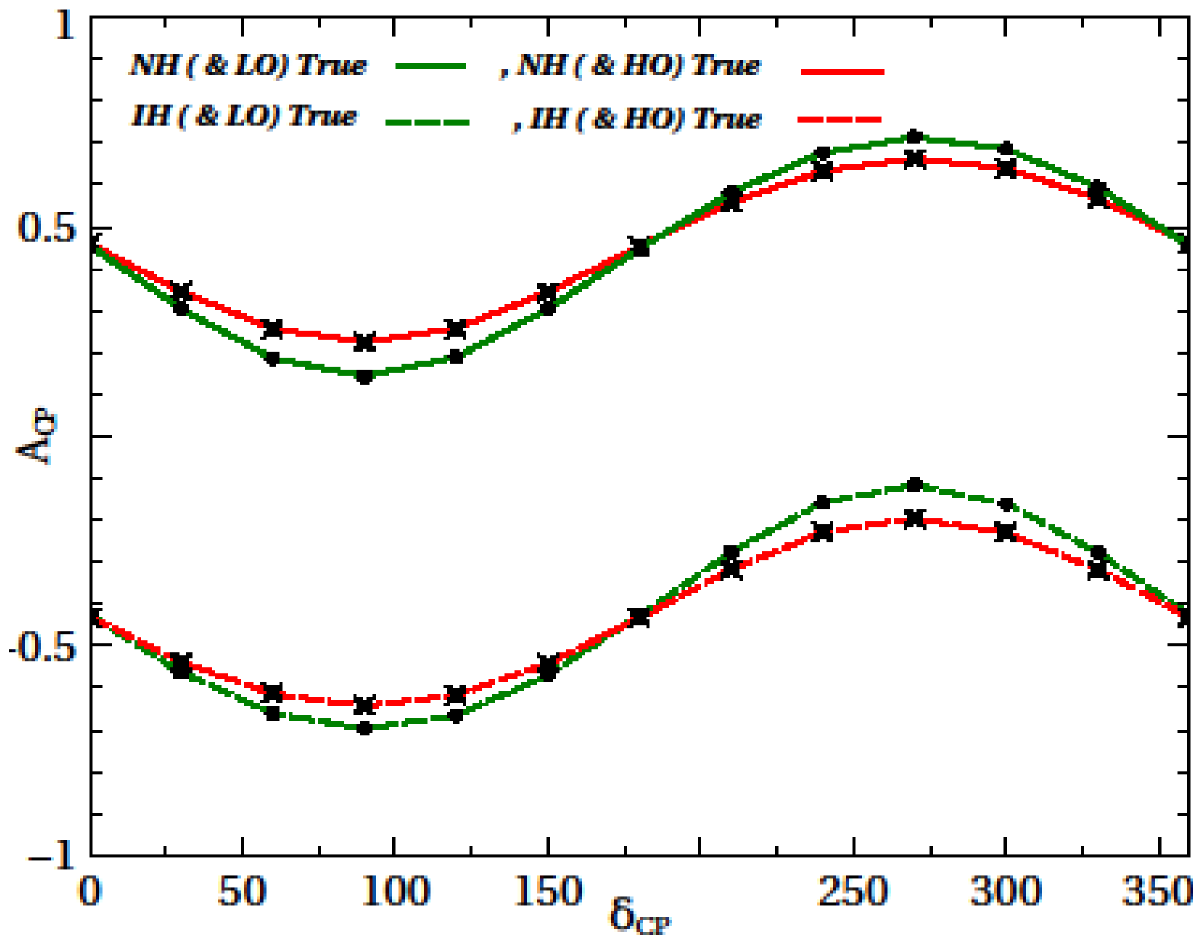

Fig1:
CP asymmetry vs δ_{CP} at DUNE/LBNE, for both the hierarchies. In Fig. 1 red and green solid (dotted) lines are for NH (IH) with types of curve to distinguish HO and LO as the true octant respectively.

- CP asymmetry also depends on the mass hierarchy.
- In this work we have used above information to calculate dependance of leptogenesis on octant of θ_{23} and quadrant of CPV phase.
- From Fig. 1and Fig. 2 we see that

A_{CP} (LO) > A_{CP} (HO) (2)

- For a given true hierarchy, there are eight degenerate solutions:

δ_{CP} (first quadrant)– θ_{23} (lower octant)
δ_{CP} (second quadrant)– θ_{23} (lower octant)
δ_{CP} (third quadrant)– θ_{23} (lower octant)
δ_{CP} (fourth quadrant)– θ_{23} (lower octant)

δ_{CP} (first quadrant)– θ_{23} (higher octant)
δ_{CP} (second quadrant)– θ_{23} (higher octant)
δ_{CP} (third quadrant)– θ_{23} (higher octant)
δ_{CP} (fourth quadrant)– θ_{23} (higher octant)

(3)

This eight-fold degeneracy can be viewed as

Quadrant of CPV phase – Octant of θ_{23} entanglement

(4)

- Out of these eight degenerate solutions, only one should be true solution.
- To pinpoint one true solution, this entanglement has to be broken. We have shown [4] that sensitivity to discovery potential of CPV at LBNEs in LO is improved more, if data from near detector of LBNEs, or from Reactor experiments is added to data from FD of LBNEs.

- Therefore 8-fold degeneracy of (3) gets reduced to 4-fold degeneracy, with our proposal [4].

Following this 4-fold degeneracy still remains to be resolved.

δ_{CP}(first quadrant) - θ_{23} (lower octant)

δ_{CP}(second quadrant) - θ_{23} (lower octant)

δ_{CP} (third quadrant) - θ_{23} (lower octant)

δ_{CP} (fourth quadrant) - θ_{23} (lower octant)..(5)

The possibility of $\theta_{23} > 45^0$, i.e. HO of θ_{23} is also considered in this work:

δ_{CP} (first quadrant)– θ_{23} (higher octant)
δ_{CP} (second quadrant)– θ_{23} (higher octant)
δ_{CP} (third quadrant)– θ_{23} (higher octant)
δ_{CP} (fourth quadrant)– θ_{23} (higher octant)..

(6)

- Leptogenesis can be used to break above mentioned 4-fold degeneracy of Eq. (5), (6).
- It is known that observed baryon asymmetry of the Universe (BAU) can be explained via leptogenesis [33-37].
- In leptogenesis, the lepton-antilepton asymmetry can be explained, if there are complex Yukawa couplings or complex fermion mass matrices

- This in turn arises due to complex leptonic CPV phases, δ_{CP}, in fermion mass matrices.
- If all other parameters except leptonic CP phase in the formula for lepton - antilepton asymmetry are fixed, for example, then

observed value of BAU from experimental observation can be used to constrain quadrant of CP , and hence 4-fold entanglement of (5), (6) can be broken.

- To elucidate this proposal, we consider nonsupersymmetric SO(10) models, in which BAU arises due to leptogenesis,
- This lepton–antilepton asymmetry [39] is generated by the out of equilibrium decay of the right handed, heavy Majorana neutrinos, which form an integral part of seesaw mechanism for neutrino masses and mixings.
- We consider type I seesaw mechanism, just for simplicity.

3. Leptogenesis and Baryogenesis using Type I Seesaw in SO(10) models

- In Grand Unified theories like SO(10), one right handed heavy Majorana neutrino per generation is added to Standard Model and they couple to left handed ν via Dirac mass matrix $m_{D.}$
- When the neutrino mass matrix is diagonalized, we get two eigenvalues – light neutrino – $\frac{m^2{}_D}{M_R}$ and a heavy neutrino state $M_{R.}$

- This is called type I See Saw mechanism.
- Here, decay of the lightest of the three heavy RH Majorana neutrinos M_1, i.e $M_{3,}M_2 >> M_1$ will contribute to $l - \bar{l}$ asymmetry [40] (for leptogenesis), i.e ε_{CP}^{l}
- Some results on leptogenesis in the context of SO(10) Models have been discussed earlier in [41, 42]

- In the basis where RH ν mass matrix is diagonal, the type I contribution to CP asymmetry ε^{l}_{CP} is given by decay of M_1

$$\varepsilon^{l}_{CP} = \frac{\Gamma(M_1 \to lH) - \Gamma(M_1 \to lH)}{\Gamma(M_1 \to lH) + \Gamma(M_1 \to lH)} \quad \ldots\ldots\ldots \qquad \ldots(7)$$

$\Gamma(M_1 \to lH) \to$ decay rate of heavy Majorana RH ν of mass M_1 to a lepton and Higgs.

- We assume a normal mass hierarchy for heavy Majorana neutrinos.

- In this scenario the lightest of heavy Majorana neutrinos is in thermal equilibrium while the heavier neutrinos, M_2 and M_3, decay.

- Any asymmetry produced by the out of equilibrium decay of M_2 and M_3 will be washed away by the lepton number violating interactions mediated by M_1.
- Therefore, the final lepton-antilepton asymmetry is given only by the CP-violating decay of M_1 to standard model leptons (l) and Higgs (H).

- This contribution is [43]:

- $$\varepsilon_l = \frac{-3M_1 \operatorname{Im}(\Delta m_e{}^2 R^2{}_{12} + \Delta m_A{}^2 R^2{}_{13})}{8\pi \upsilon^2 \Sigma |R_{1j}|^2 m_j} \quad \ldots\ldots(8)$$

- where υ is the vev of the SM Higgs doublet that breaks the SM gauge group to $U(1)_{em}$.

- R is a complex orthogonal matrix with the property that $RR^T = 1$

- R can be parameterized as [44]:

$$R = D_{\sqrt{M^{-1}}} Y_{\nu} U D_{\sqrt{K^{-1}}} \quad \text{.........(9)}$$

- where Y_{ν} is the matrix of neutrino Yukawa couplings.
- In the flavor basis, where the charged-lepton Yukawa matrix, Y_e and gauge interactions are flavour-diagonal, $D_K = U^T K U$,

- K = $Y^T{}_\nu M^{-1}{}_R Y_\nu$
- U is the PMNS matrix and
- M_R is the RH neutrino Majorana scale
- In the basis of right handed neutrinos,

D_M = Diag(M_1, M_2, M_3) where M_3, M_2 >> M_1. Eqn. (8) relates the lepton asymmetry to both the solar ($\Delta m^2{}_{21}$) and atmospheric ($\Delta m^2{}_A$) mass squared differences.

- In SO(10) models, the right handed neutrino M_R is generated from the Yukawa coupling of right handed neutrinos with the Higgs field that breaks the unification or intermediate symmetry down to the standard model [45].
- When such a Higgs field takes a VEV, the right handed neutrinos get a Majorana mass. This happens because lepton number is broken at that scale.

- It has been discussed in [42], that in the super symmetric case the mass scale of the right-handed neutrino is similar to the unification scale, $M_R \sim M_U \sim 10^{16}$ GeV
- In the non-supersymmetric case, the majorana scale is about intermediate scale, $M_R \sim M_I \sim 10^{11}$ GeV [46], M_I being the scale of the quark – lepton symmetry [47].

- Following [51], in this work we choose a basis where the complex orthogonal matrix R takes the form, $R = V_{CKM} \times U_{PMNS}$, where V_{CKM} is the CKM matrix containing the quark mixing angles,
- U_{PMNS} is the PMNS matrix containing neutrino mixing parameters. In equation (9) and (15) of [51], if V is taken as quark mixing matrix (where, in SO(10) theories, as quarks and leptons appear in same representaion, neutrino mixing matrix can be taken to be same as quark mixing matrix at high scales.

- If U is taken as PMNS matrix at low energies, then we get the relation

$$R = V_{CKM} \times \; U_{PMNS}$$

This assumption can also be justified, as it is well known that quark mixing CKM phase alone is not sufficient to explain the BAU, and leptonic CPV phase are needed to generate the observed BAU.

- Here, the matrix R is orthogonal since, $R^{\dagger}R = U^{\dagger}V^{\dagger}V U = 1$ (because $U^{\dagger}U = V^{\dagger}V = 1$) .
- Both the quark sector (quark mixing angles, phase) and the neutrino sector (mixing angles and the leptonic CPV phase) appear in the expression for R.
- In that case R can be parameterized as for example,

- $R_{13} = e^{-i\delta_q} c23_l c13_l s13_q - c13_q c13_l s12_q s23_l - e^{-i\delta_l} c12_q c13_q s13_l$……… (10)

- Here, $c23_l$, $s12_l$, $c13_l$, etc represents the cosine of atmospheric mixing angle, sine of solar mixing angle and cosine of reactor mixing angle respectively.
- Similarly 23_q, 12_q, 13_q are the quark mixing angles. δ_l and δ_q are the leptonic CPV phase and quark CPV phase respectively.

- Here the R equation presumably holds at the GUT scale but weak scale values can be used in the calculations since it is well known that mass mixing parameters do not change much under RG evolution in hierarchical mass spectrum of SO(10) theories.
- Hence CKM matrix at high scales can be used at low energies also and U is taken as PMNS matrix at low energies. We also consider $R = U_{PMNS}$ only, where R matrix consists of mixing angles and the leptonic CPV phase.
- Thus when left-right symmetry is broken at high intermediate mass scale M_R in SO(10) theory, CP asymmetry in this case is given by

- $$\varepsilon_l = \frac{-3M_1 \operatorname{Im}(\Delta m_A{}^2 R^2{}_{13})}{8\pi\upsilon^2 \Sigma |R_{1j}|^2 m_j} \qquad \ldots(11)$$

- Where for example, $|R_{13}|^2$ goes like

$$|R_{13}|^2 = \cos^2(\delta_l)\sin^2(\theta^l{}_{13}) + \sin^2(\delta_l)\sin^2(\theta^l{}_{13}) \ldots(12)$$

The neutrino oscillation data used in our numerical calculations are [29].

$$\Delta m^2_{21}[10^{-5}eV^2] = 7.60^{+0.19}_{-0.18}$$

$$|\Delta m^2_{31}|[10^{-3}eV^2] = 2.48^{+0.05}_{-0.07}(2.38^{+0.05}_{-0.06})$$

$$\sin^2\theta_{12} = 0.323\pm 0.016$$

$$\sin^2\theta_{23} = 0.567^{+0.032}_{-0.124}(0.573^{+0.025}_{-0.039})$$

$$\sin^2\theta_{13} = 0.0226\pm 0.0012(0.0229\pm 0.0012) \tag{13}$$

- The origin of the baryon asymmetry in the universe (baryogenesis) is a very interesting topic of current research.
- A well known mechanism is the baryogenesis via leptogenesis, in which lepton asymmetry is transformed into a baryon asymmetry [51] by electroweak sphaleron processes [52-55].

The BAU can be defined as

$$Y_B = \frac{\eta_B - \eta_{\overline{B}}}{s} = \frac{\eta_B - \eta_{\overline{B}}}{7\eta_\gamma} = \frac{\eta_B}{7} \tag{14}$$

- where η_B , $\eta_{\overline{B}}$, η_γ are the number densities of baryons, antibaryons and photons respectively, s is the entropy density. The best fit value used is

- $5.7 \times 10^{-10} \leq \eta_B \leq 6.7 \times 10^{-10}$ (95 % C.L)

[56]

The baryon asymmetry Y_B is related to the lepton asymmetry Y_L as :

$$Y_B = \frac{a}{a-1} Y_L, a = \frac{8N_F + 4N_H}{22N_F + 13N_H}, \quad \ldots\ldots \qquad (15)$$

here, N_f is the number of families

N_H is the number of light Higgs doublets.

In case of SM,

$N_f = 3$ and $N_H = 1$.

The lepton asymmetry is defined as follows:

$$Y_L = d \frac{\epsilon_l}{g^*}. \quad \ldots\ldots \qquad (16)$$

- The parameter k [42] is

$$k = \frac{M_P (M_D^{\dagger} M_D)_{11}}{1.7 \upsilon^2 32\pi \sqrt{g^*} M_1}$$

- here M_P is the Planck mass.
- We have used the form of Dirac neutrino mass matrix M_D from [28].

- d is a dilution factor and g* = 106.75 in the standard case [42], is the effective number of light degrees of freedom in the theory, defined as

$$d = \frac{0.24}{k(lnk)^{0.6}} \text{ for } k \geq 10$$

and,

$$d = \frac{1}{2k}, d = 1 \text{ for } 1 \leq k \leq 10 \text{ and } 0 \leq k \leq 1$$

respectively

4. Calculations, Results and Discussions

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- We use the current experimental data for three neutrino mixing angles as inputs.
- We explore the baryon asymmetry of the universe within nonsupersymmetric SO(10) models [28] using Eq. (7)–Eq. (16) of the two hierarchies (NH and IH), two octants – LO and HO, w ND, w/o ND (with and without near detector)

- and δ_{CP} range at $\geq 2\sigma$ over the corresponding distribution of χ^2 –minima (for maximum sensitivity from Fig. 2(a), 2(b), for which the CP discovery potential of the DUNE is maximum).
- For our purpose, we have carried out a general scanning of the parameters: δ_{CP} range at $\geq 2\sigma$ (from Fig. 2(a), 2(b)), θ_{13} in its 3σ C.L and Δm_{31}^2 in its 3σ C.L using the data given by the oscillation experiments [1, 2, 29].

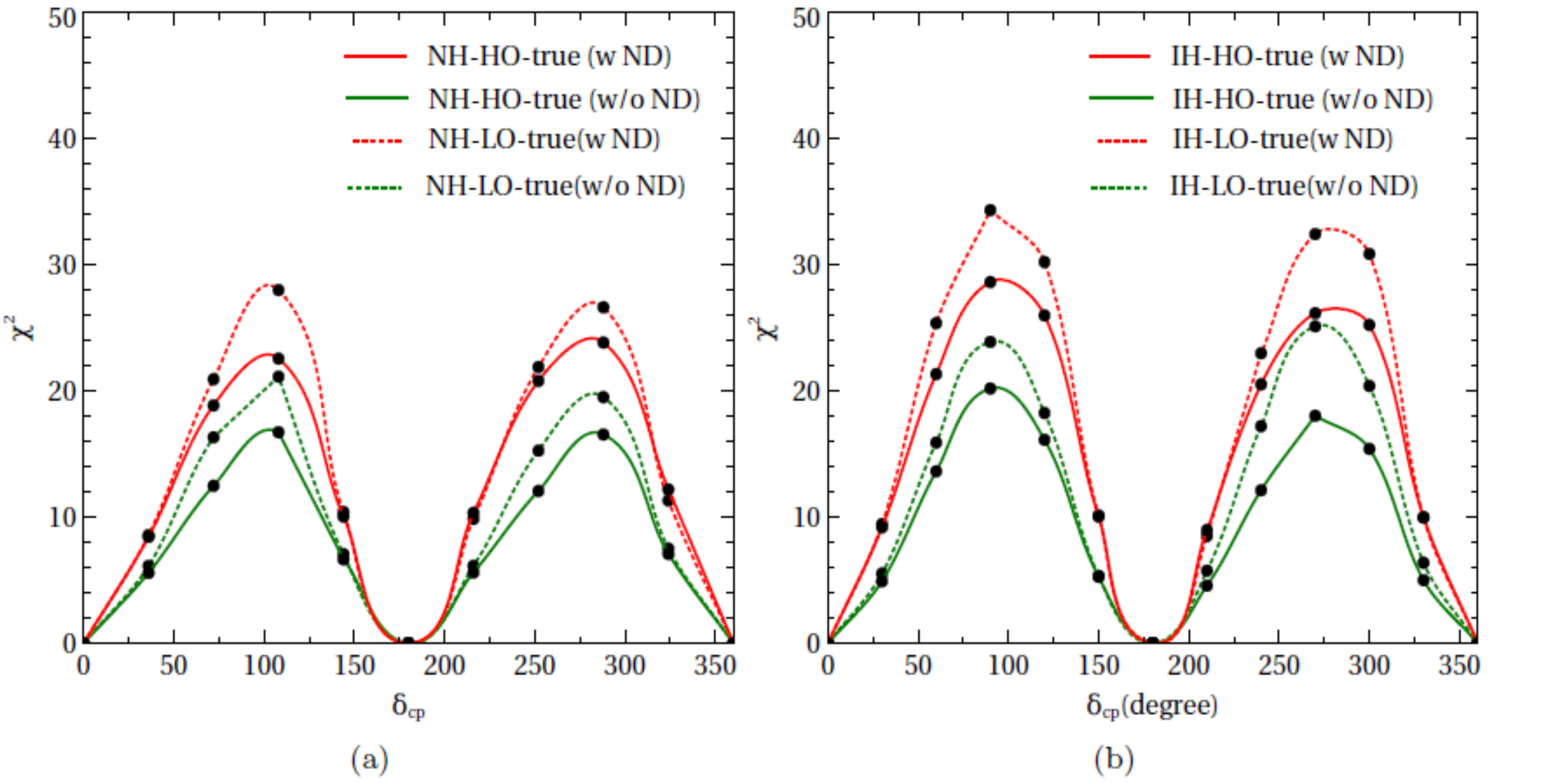


Fig 2: In Fig. 2a and 2b CP Vs δ_{CP} sensitivity corresponding to CP discovery potential at LBNEs, for both the hierarchies and octant is shown.

- In this calculation, we have chosen, $M_1 \approx 2.154 \times 10^{11}$ GeV for which the baryon asymmetry becomes lower than the observed value.
- We scan the parameter space for IH, HO/LO in the light of recent ratio of the baryon to photon density bounds [56]
- The range of other parameters are (IH) :

$$\delta_{CP} \in [0, 2\pi]$$

$$\theta_{13} \in [7.8^0, 9.9^0]$$

$$\Delta m_{31}^2 \in [-2.54 * 10^{-3}, -2.20 * 10^{-3}]eV^2 \quad \text{......(17)}$$

Similarly constrained by the present BAU bounds we perform random scans for the following range of parameters in NH, HO/LO case:

$$\delta_{CP} \in [0,\ 2\pi]$$

$$\theta_{13} \in [7.7^0,\ 9.9^0]$$

$$\Delta m^2_{31} \in [2.30 * 10^{-3},\ 2.65 * 10^{-3}] eV^2 \quad .....(18)$$

We find above analysis puts significant constraints on the $\delta_{CP} - \theta_{13}$ parameter space in the IH, LO case.

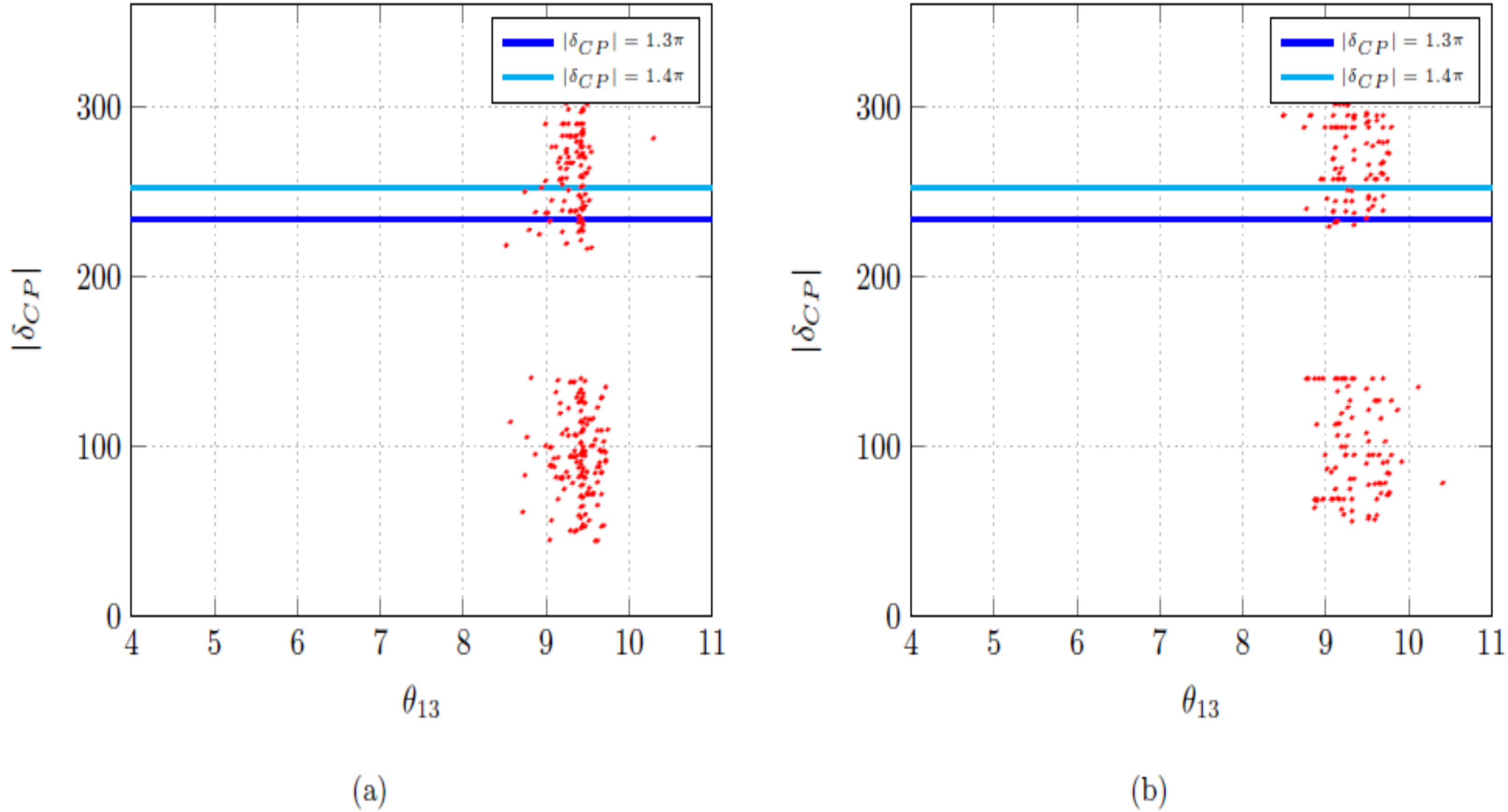


Figure 3: Allowed region constrained by the present BAU bounds, $5.7 \times 10^{-10} < \eta_B < 6.7 \times 10^{-10}$ for δ_{CP}, θ_{13} for the case when R matrix consists of both V_{CKM} and U_{PMNS}. The regions are obtained by varying δ_{CP} range at $\geq 2\sigma$ over the corresponding χ^2 minima distribution from fig. 2 and θ_{13} with its experimental values varied within 3σ. In Fig. 3a (3b) we show the plot for the IH, LO case (IH, HO case). The blue (cyan) horizontal line represents $\delta_{CP} = 1.3\pi(1.4\pi)$ around which the best fit values of CPV phase δ_{CP} are assumed to lie.

- For, NH, LO only a particular value of CP violating phase, $\delta_{CP} = 258.5^0$ corresponding to $\theta_{13} = 9.02375^0$ is consistent with the BAU constraint.

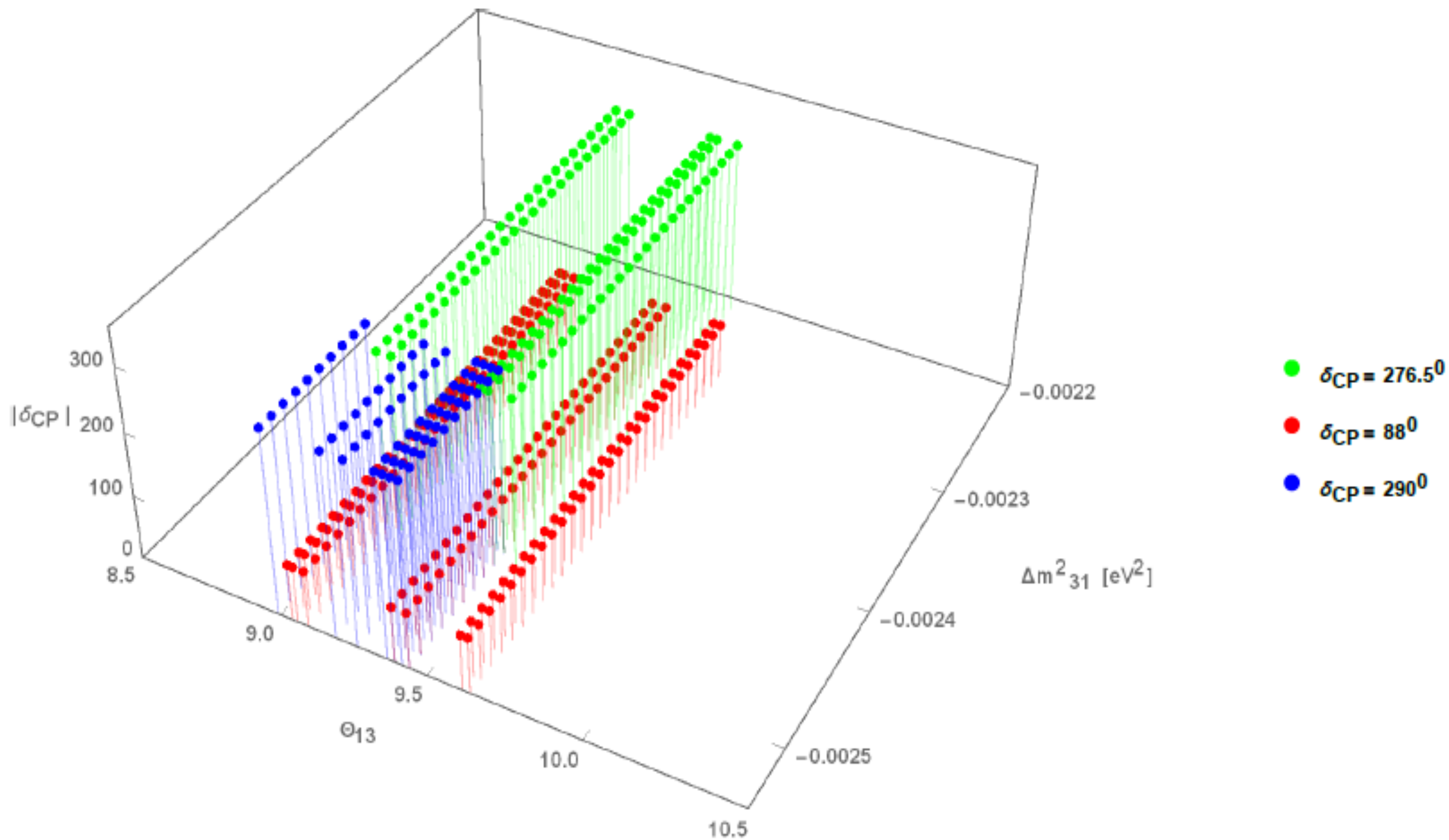
But, for IH, many values of δ_{CP} are found to comply with the BAU limits.

δ_{CP} θ_{13}

This indicates that IH is the most favoured hierarchy for breaking the 4-fold degeneracy Of equation (5-6). All the analysis presented above is for the case when R matrix consists of both V_{CKM} and U_{PMNS}

- No points in the (δ_{CP} ,θ_{13}) parameter space, consistent with the BAU constraint, is able to break the entanglement of the quadrant of δ_{CP} and octant of θ_{23} , when R matrix consists of U_{PMNS} only.
- In Fig. 4, 5 we display the allowed 3D-space (δ_{CP} , θ_{13} , $\Delta m^2{}_{31}$) for breaking the 4-fold degeneracy of Eqn (5), (6)

Figure 4: Allowed region constrained by the present BAU bounds, $5.7 \times 10^{-10} < \eta_B < 6.7 \times 10^{-10}$ for δ_{CP}, θ_{13} and Δm^2_{31} for the case when R matrix consists of both V_{CKM} and U_{PMNS}. The regions are obtained by varying δ_{CP} range at $\geq 2\sigma$ over the corresponding χ^2 minima distribution from fig. 2 and θ_{13} with its experimental values varied within 3σ and Δm^2_{31} at its 3σ C.L. The results of our calculation are presented for IH, LO case.



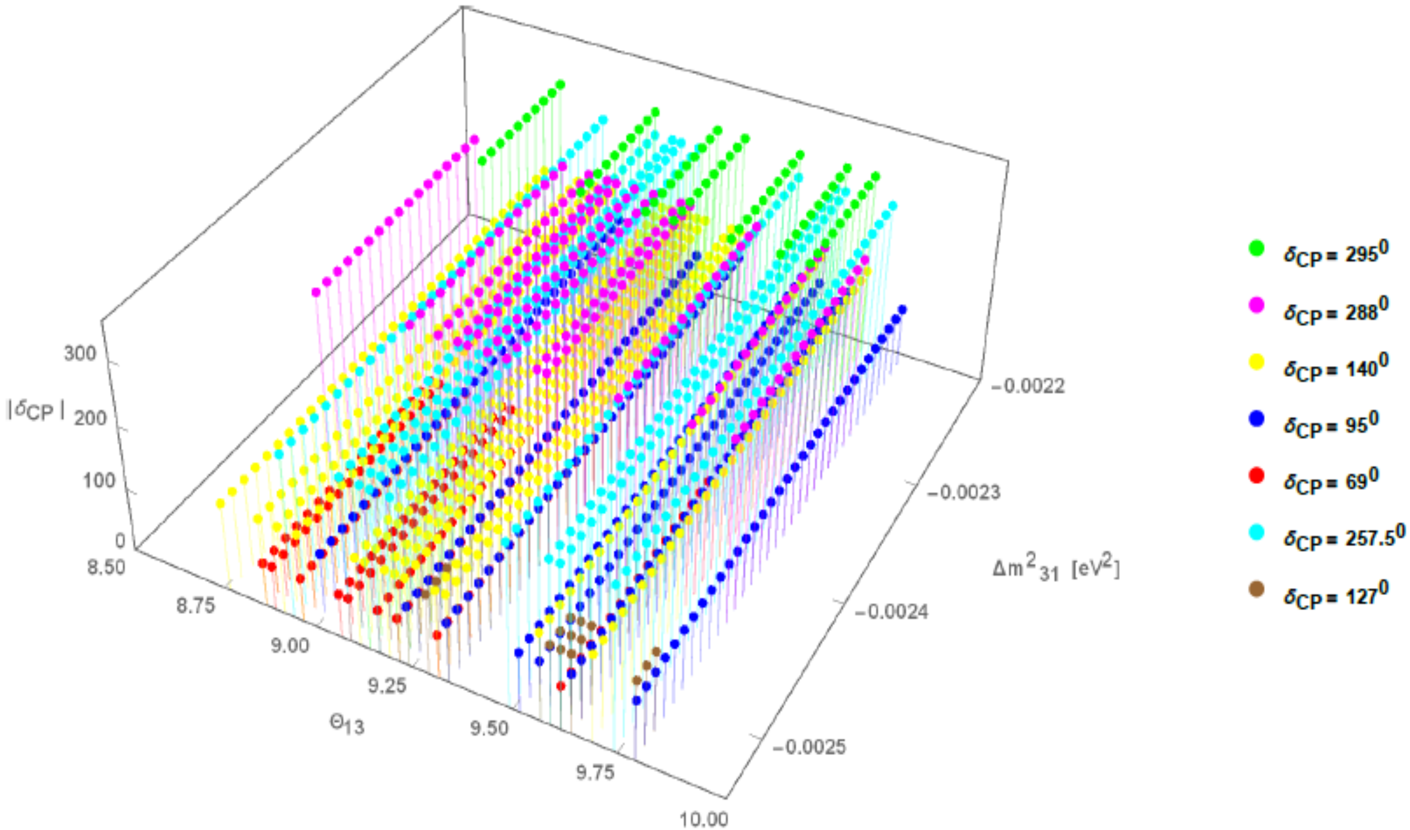


Figure 5: Allowed 3-D region constrained by the present BAU bounds, $5.7 \times 10^{-10} < \eta_B < 6.7 \times 10^{-10}$ for δ_{CP}, θ_{13} and Δm^2_{31} for the case when R matrix consists of both V_{CKM} and U_{PMNS}. The regions are obtained by varying δ_{CP} range at $\geq 2\sigma$ over the corresponding χ^2 minima distribution from fig. 2, θ_{13} with its experimental values varied within 3σ from its central values and Δm^2_{31} at its 3σ C.L. The results of our calculation are presented for IH, HO case.

- From Figure 4 one can easily see the favoured values of δ_{CP} ,and $\Delta m^2{}_{31}$ for IH, LO case, allowed by the updated recent ratio of photon density to baryon density bounds, $5.7*10^{-10} \leq \eta_B \leq 6.7*10^{-10}$ (shown in Table I).

- For IH, HO case, the results of our numerical analysis are shown in Fig. 5 which shows allowed (δ_{CP}, θ_{13} , $\Delta m^2{}_{31}$) space as allowed by the current BAU bounds.

- The values of δ_{CP}, θ_{13} and Δm^2_{31} which are favoured simultaneously in consistent with η_B constraints, $5.7*10^{-10} \leq \eta_B \leq 6.7*10^{-10}$ [56], are as shown in Table II.

- For NH case we get only one point as shown in Eq. (19).

NH, HO, III quadrant of Leptonic CP phase

$\delta_{CP} = 258.4^0$ or $1.436\,\pi$ ......(19)

S.No	Leptonic CPV Phase δ_{CP}	$[\Delta m_{31}^2]eV^2$	θ_{13}	Quadrant of δ_{CP}
1	$\delta_{CP} = 88^0$	$[-2.54 * 10^{-3},\ -2.21 * 10^{-3}]$	$9.0417^0, 9.0697^0, 9.0974^0,$ $9.3917^0, 9.4417^0, 9.6167^0,$ 9.6417^0	I
2	$\delta_{CP} = 276.5^0$	$[-2.45 * 10^{-3},\ -2.21 * 10^{-3}]$	$9.0667^0, 9.0974^0,$ $9.3167^0 - 9.4417^0, 9.5167^0$	IV
3	$\delta_{CP} = 290^0$	$[-2.42 * 10^{-3},\ -2.54 * 10^{-3}]$	$9^0, 9.1817^0, 9.2667^0,$ $9.3667^0 - 9.4417^0$	IV

Table I: The summary of our calculated values of δ_{CP}, θ_{13} and Δm_{31}^2 in case of IH, LO for R_{1j} elements of R Matrix comprising of U_{PMNS} and V_{CKM}.

S.No	δ_{CP}	$[\Delta m^2_{31}] eV^2$	θ_{13}	Quadrant of δ_{CP}
1	95^0	$[-2.54 * 10^{-3},\ -2.21 * 10^{-3}]$	$8.9917^0, 9.2417^0, 9.352^0, 9.5167^0, 9.567^0, 9.6417^0, 9.7917^0$	II
2	69^0	$[-2.54 * 10^{-3},\ -2.38 * 10^{-3}]$	$8.8667^0, 8.8917^0, 8.9667^0, 9.0667^0, 9.0917^0, 9.1667^0, 9.2167^0, 9.3167^0, 9.6167^0$	I
3	140^0	$[-2.54 * 10^{-3},\ -2.21 * 10^{-3}]$	$8.7667^0, 8.8667^0, 8.9167^0, 8.9667^0, 9.1167^0, 9.1417^0, 9.1917^0 - 9.2417^0, 9.3167^0, 9.3417^0, 9.5667^0, 9.6917^0$	II
4	257.5^0	$[-2.54 * 10^{-3},\ -2.21 * 10^{-3}]$	$8.9667^0, 9.0974^0, 9.1417^0, 9.1667^0, 9.2167^0, 9.4917^0, 9.5917^0, 9.6167^0, 9.7417^0$	III
5	295^0	$[-2.3 * 10^{-3},\ -2.21 * 10^{-3}]$	$8.4917^0, 8.8167^0, 9.0917^0, 9.2667^0, 9.4917^0, 9.6167^0$	IV
6	288^0	$[-2.44 * 10^{-3},\ -2.28 * 10^{-3}]$	$8.7817^0, 8.9917^0, 9.0667^0, 9.1167^0, 9.1417^0, 9.1917^0, 9.2417^0, 9.3167^0, 9.3417^0, 9.5167^0, 9.6917^0, 9.7917^0$	IV

Table II: The summary of our calculated values of δ_{CP}, θ_{13} and Δm^2_{31} in case of IH, HO for R_{1j} elements of R Matrix comprising of U_{PMNS} and V_{CKM}.

5. Summary

- A systematic study of the CP sensitivity of the current and upcoming LBNE/DUNE is done in our earlier work [4] which may help a
  precision measurement of leptonic phase.
- In this work, we show how the $\delta_{CP} - \theta_{23}$

entanglement of the quadrant of leptonic CPV phase and octant of atmospheric mixing angle at LBNE/DUNE, can be broken via leptogenesis and baryogenesis.

- Here, we have considered the effect of ND only in LBNE, on sensitivity of CPV phase measurement, but similar conclusions would hold for the effect of reactor experiments as well.
- This study is done for both the octants and hierarchies. We considered two cases of fermion rotation matrix – PMNS only, and CKM+PMNS.

- We have made a complete numerical analysis of the 3 dimensional parameters $\delta_{CP}, \theta_{13}, \Delta m^2{}_{31}$ that encode the breaking of the entanglement of the quadrant of CPV phase and Octant of θ_{23} in presence of the latest constraints on η_B.

- We pinpoint the values of CPV phase that comply with BAU of the universe, shown in Tables I and II, which are the highlight of this work

- These results could be important, as the

quadrant of leptonic CPV phase, and octant of atmospheric mixing angle θ_{23} are yet not fixed experimentally.

- Also, they are significant in context of precision measurements of neutrino

  oscillation parameters like the reactor angle

  θ_{13}

- Future experiments like DUNE/LBNEs and Hyper-Kamionande [57] looking for the leptonic CPV phase δ_{CP} together with an improvement in the precision determination on the mixing angles would certainly provide worthy information to support or rule out the scenario presented in this work for breaking the entanglement of quadrant of

CPV phase and Octant of θ_{23}

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THANK YOU

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