In the present paper, we have studied that the implication of a large value of the effective Majorana neutrino mass in case of neutrino mass matrices having either two equal elements and one zero element (popularly known as hybrid texture) or two equal cofactors and one zero minor (popularly known as inverse hybrid texture) in the flavor basis. In each of these cases, four out of sixty phenomenologically possible patterns predict near maximal atmospheric neutrino mixing angle in the limit of large effective Majorana neutrino mass. This feature remains irrespective of the experimental data on solar and reactor mixing angles. In addition, we have also performed the comparative study of all the viable cases of hybrid and inverse hybrid textures at 3σ CL.

1 Introduction

In leptonic sector, the reactor mixing angle (θ_{13}) has been established to a reasonably good degree of precision \cite{1-5}, and its non zero and relatively large value has not only provided an opportunity in exploring CP violation and the neutrino mass ordering in the future experiments, but has also highlighted the puzzle of neutrino mass and mixing pattern. In spite of the significant developments made over the years, there are still several intriguing questions in the neutrino sector which remain unsettled. For instance, the present available data is unable to throw any light on the neutrino mass spectrum, which may be normal/inverted and may even be degenerate. Another important issue is the determination of octant of atmospheric mixing angle θ_{23}, which may be greater than or less than or equal to 45°. The determination of the nature of neutrinos whether Dirac or Majorana also remains an open question. The observation of neutrinoless double beta (0νββ) decay would eventually establish the Majorana nature of neutrinos.

The effective Majorana mass term related to 0νββ decay can be expressed as

\[ |M|_{ee} = |m_1 c_{12} c_{13} e^{2i\rho} + m_2 s_{12} c_{13} e^{2i\sigma} + m_3 s_{13}|. \]  

Data from KamLAND-Zen experiment has presented an improved search for neutrinoless double-beta (0νββ) decay \cite{6} and it is found that \[|M|_{ee} < (0.061 - 0.165)\text{eV} \text{ at } 90\% \text{ (or } < 2\sigma\text{) CL.}

For recent reviews on 0νββ
In the lack of any convincing theory, several phenomenological ideas have been proposed in the literature so as to restrict the form of neutrino mass matrix, such as some elements of neutrino mass matrix are considered to be zero or equal [11–14] or some co-factors of neutrino mass matrix to be either zero or equal [12, 15–17]. Specifically, mass matrices with zero textures (or cofactors) have been extensively studied [11, 15] due to their connections to flavor symmetries. In addition, texture structures with one zero element (or minor) and an equality between two independent elements (or cofactors) in neutrino mass matrix have also been studied in the literature [13, 14, 17]. Such form of texture structures sets to one constraint equation and thus reduces the number of real free parameters of neutrino mass matrix to seven. Hence they are considered as predictive as the well-known two-zero textures and can also be realised within the framework of seesaw mechanism. Out of sixty possibilities, only fifty four are found to be compatible with the neutrino oscillation data [14] for texture structures having one zero element and an equal matrix elements in the neutrino mass matrix (1TEE), while for texture with one vanishing minor and an equal cofactors in the neutrino mass matrix (1TEC) only fifty two cases are able to survive the data [17].

The purpose of present paper is to investigate the implication of large effective neutrino mass $|M|_{ee}$ on 1TEE and 1TEC structures of neutrino mass matrix, while taking into account the assumptions of Refs. [18, 19]. The consideration of large $|M|_{ee}$ is motivated by the extensive search for this parameter in the ongoing $0\nu\beta\beta$ experiments. The implication of large $|M|_{ee}$ has earlier been studied for the viable cases of texture two zero and two vanishing minor, respectively [18, 19]. Grimus et. al [20] also predicted the near maximal atmospheric mixing for two zero textures when supplemented with the assumption of quasi degenerate mass spectrum. However the observation made in all these analyses are independent of solar and reactor mixing angles. Motivated by these works, we find that only four out of sixty cases are able to predict near maximal $\theta_{23}$ for 1TEE and 1TEC, respectively. In addition, the analysis also hints towards the indistinguishable feature of 1TEE and 1TEC. To present the indistinguishable nature of the 1TEE and 1TEC texture structures, we have then carried out a comparative study of all the viable cases of 1TEE and 1TEC at 3$\sigma$ CL. The similarity between texture zero structures with one mass ordering and corresponding cofactor zero structures with the opposite mass ordering has earlier been noted in Refs. [21, 22]. In Ref. [12], the strong similarities have also been noted between the texture structures with two equalities of elements and structures with two equalities of cofactors in neutrino mass matrix, with opposite mass ordering.

The rest of the paper is planned in following manner: In Section 2, we shall discuss the methodology to obtain the constraint equations. Section 3 is devoted to numerical analysis. Section 4 will summarize our result.

2 Methodology

The effective Majorana neutrino mass matrix ($M_\nu$) contains nine parameters which include three neutrino masses ($m_1$, $m_2$, $m_3$), three mixing angles ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$) and three CP violating phases ($\delta$, $\rho$, $\sigma$). In the flavor basis, the Majorana neutrino mass matrix can be expressed as,

$$M_\nu = P_l P_\nu M^{\text{diag}} P_\nu^T U^T P_l^T,$$

(2)
where $M^{\text{diag}} = \text{diag}(m_1, m_2, m_3)$ is the diagonal matrix of neutrino masses and $U$ is the flavor mixing matrix, and

$$P_\nu = \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad P_1 = \begin{pmatrix} e^{i\phi_\nu} & 0 & 0 \\ 0 & e^{i\phi_\nu} & 0 \\ 0 & 0 & e^{i\phi_\nu} \end{pmatrix};$$

(3)

where $P_\nu$ is diagonal phase matrix containing Majorana neutrinos $\rho, \sigma$. $P_1$ is unobservable phase matrix and depends on phase convention. Eq. (2) can be re-written as

$$M_\nu = P_1 U \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix} U^T P_1^T,$$

(4)

where $\lambda_1 = m_1 e^{2i\rho}, \lambda_2 = m_2 e^{2i\sigma}, \lambda_3 = m_3$. For the present analysis, we consider the following parameterization of $U$ [13]:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}s_{23}s_{13} - c_{12}c_{23}e^{-i\delta} & -s_{12}s_{23}s_{13} + c_{12}c_{23}e^{-i\delta} & s_{23}c_{13} \\ -c_{12}s_{23}s_{13} + s_{12}c_{23}e^{-i\delta} & -s_{12}s_{23}s_{13} - c_{12}c_{23}e^{-i\delta} & c_{23}c_{13} \end{pmatrix},$$

(5)

where, $c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij}$. Here, $U$ is a $3 \times 3$ unitary matrix consisting of three flavor mixing angles ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$) and one Dirac CP-violating phase $\delta$.

For hybrid texture structure (1TEE) of $M_\nu$, we can express the ratios of neutrino mass eigenvalues in terms of the mixing matrix elements as [14]

$$\frac{\lambda_1}{\lambda_3} = \frac{P(U_{a3}U_{b3}U_{a2}U_{b2} - U_{a2}U_{b3}U_{a3}U_{b1}) + (U_{a2}U_{b2}U_{c3}U_{d3} - U_{a3}U_{b3}U_{c2}U_{d2})}{P(U_{a2}U_{b2}U_{a1}U_{b1} - U_{a1}U_{b2}U_{a3}U_{b3}) + (U_{a1}U_{b1}U_{c2}U_{d2} - U_{a2}U_{b2}U_{c1}U_{d1})},$$

(6)

$$\frac{\lambda_2}{\lambda_3} = \frac{P(U_{a1}U_{b1}U_{a3}U_{b3} - U_{a3}U_{b3}U_{a1}U_{b1}) + (U_{a3}U_{b3}U_{c1}U_{d3} - U_{a1}U_{b1}U_{c3}U_{d3})}{P(U_{a2}U_{b2}U_{a1}U_{b1} - U_{a1}U_{b2}U_{a3}U_{b3}) + (U_{a1}U_{b1}U_{c2}U_{d2} - U_{a2}U_{b2}U_{c1}U_{d1})},$$

(7)

where $P = e^{i(\rho_\nu + \phi_\nu - \phi_e - \phi_e)}$ is a phase factor. Similarly, in case of inverse hybrid texture structure (ITEC) of $M_\nu$, we can express the ratios of mass eigenvalues as [14] follows

$$\frac{\lambda_1}{\lambda_3} = \frac{A_1B_2 - A_2B_1}{A_2B_3 - A_3B_2},$$

(8)

$$\frac{\lambda_2}{\lambda_3} = \frac{A_1B_2 - A_2B_1}{A_3B_1 - A_4B_3},$$

(9)

where

$$A_i = (U_{p_j}U_{q_j}U_{r_k}U_{s_k} - U_{r_j}U_{s_j}U_{t_k}U_{u_k}) + (j \leftrightarrow k)$$

(10)

$$B_i = (-1)^{m+n}Q(U_{a_j}U_{b_j}U_{c_k}U_{d_k} - U_{c_j}U_{d_j}U_{e_k}U_{f_k}),$$

$$-(-1)^{m'+n'}(U_{a'_{j'}}U_{b'_{j'}}U_{c'_{k'}}U_{d'_{k'}} - U_{c'_{j'}}U_{d'_{j'}}U_{e'_{k'}}U_{f'_{k'}}) + (j \leftrightarrow k),$$

(11)

with $(i, j, k)$ a cyclic permutation of $(1, 2, 3)$ and $Q = e^{i(\phi_e + \phi_\nu + \phi_e - \phi_e)}$ is phase factor.

Using above expressions, we can obtain the magnitude of neutrino mass ratios, $\alpha \equiv \frac{|\lambda_1|}{|\lambda_3|}$ and $\beta \equiv \frac{|\lambda_2|}{|\lambda_3|}$ in each texture structure, and the Majorana phases $(\rho, \sigma)$ can be given as $\rho = \frac{1}{2}\text{arg} \left( \frac{\lambda_1}{\lambda_3} \right)$ and $\sigma = \frac{1}{2}\text{arg} \left( \frac{\lambda_2}{\lambda_3} \right)$. 

3
The solar and atmospheric mass squared differences \( (\delta m^2, \Delta m^2) \), where \( \delta m^2 \) corresponds to solar mass-squared difference and \( \Delta m^2 \) corresponds to atmospheric mass-squared difference, can be defined as [13]

\[
\delta m^2 = (m_2^2 - m_1^2),
\]

\[
\Delta m^2 = m_3^2 - \frac{1}{2}(m_1^2 + m_2^2).
\]

The experimentally determined solar and atmospheric neutrino mass-squared differences can be related to neutrino mass ratios \((\alpha, \beta)\) and the three neutrino masses can be determined in terms of \(\alpha, \beta\) as

\[
R_\nu \equiv \frac{\delta m^2}{|\Delta m^2|} = \frac{2(\beta^2 - \alpha^2)}{|2 - (\beta^2 + \alpha^2)|},
\]

and the three neutrino masses can be determined in terms of \(\alpha, \beta\) as

\[
m_3 = \sqrt{\frac{\delta m^2}{\beta^2 - \alpha^2}}, \quad m_2 = m_3\beta, \quad m_1 = m_3\alpha.
\]

Among the sixty logically possible cases of 1TEE or 1TEC texture structures, there are certain pairs, which exhibit similar phenomenological implications and are related via permutation symmetry [14, 17]. This corresponds to permutation of the 2-3 rows and 2-3 columns of \(M_\nu\). The corresponding permutation matrix can be given by

\[
P_{23} = \begin{pmatrix}
1 & 0 & 0 \\
0 & 0 & 1 \\
0 & 1 & 0
\end{pmatrix}.
\]

With the help of permutation symmetry, one obtains the following relations among the neutrino oscillation parameters

\[
\theta_{12}^X = \theta_{12}^Y, \quad \theta_{23}^X = 90^\circ - \theta_{23}^Y, \quad \theta_{13}^X = \theta_{13}^Y, \quad \delta^X = \delta^Y - 180^\circ,
\]

where \(X\) and \(Y\) denote the cases related by 2-3 permutation. The following pair among sixty cases are related via permutation symmetry:

\[(A_1, A_2); (A_2, A_8); (A_3, A_7); (A_4, A_6); (A_5, A_3); (A_9, A_{10}); (B_1, C_1);
\]
\[(B_2, C_7); (B_3, C_6); (B_4, C_5); (B_5, C_4); (B_6, C_3); (B_7, C_2); (B_8, C_{10});
\]
\[(B_9, C_9); (B_{10}, C_8); (D_1, F_2); (D_2, F_1); (D_3, F_4); (D_4, F_3);
\]
\[(D_5, F_5); (D_6, F_9); (D_7, F_8); (D_8, F_7); (D_9, F_6); (D_{10}, F_{10});
\]
\[(E_1, E_2); (E_3, E_4); (E_5, E_5); (E_6, E_9); (E_7, E_8); (E_{10}, E_{10}).\]

Clearly we are left with only thirty two independent cases. It is worthwhile to mention that cases \(A_1, A_5, E_5\) and \(E_{10}\) are invariant under the permutations of 2- and 3-rows and columns.

### 3 Numerical analysis

The experimental constraints on neutrino parameters at 3\(\sigma\) confidence levels (CL) are given in Table I. The classification of sixty phenomenologically possible cases of 1TEE and 1TEC is done in the the nomenclature, given by W. Wang in Ref. [17]. All the sixty cases are divided into six categories A, B, C, D and E [Table 2]. In [17], it is found that the phenomenological results of cases belonging to 1TEC (or 1TEE) are almost similar to each other due to permutation symmetry. For the purpose of calculation, we have used the latest experimental data on neutrino mixing angles \((\theta_{12}, \theta_{23}, \theta_{13}, \delta m^2)\) and mass squared differences \((\Delta m^2, \delta)\) at 3\(\sigma\) CL [5].
| Parameter                        | Best Fit   | 3σ         |
|---------------------------------|------------|------------|
| $\delta m^2 \left[10^{-5}\text{eV}^2\right]$ | 7.50       | 7.03 - 8.09 |
| $|\Delta m^2_{31}| \left[10^{-3}\text{eV}^2\right]$ (NO) | 2.52       | 2.407 - 2.643 |
| $|\Delta m^2_{31}| \left[10^{-3}\text{eV}^2\right]$ (IO) | 2.52       | 2.39 - 2.63  |
| $\theta_{12}$                  | 33.56°     | 31.3° - 35.99° |
| $\theta_{23}$ (NO)             | 41.6°      | 38.4° - 52.8° |
| $\theta_{23}$ (IO)             | 50.0°      | 38.8° - 53.1° |
| $\theta_{13}$ (NO)             | 8.46°      | 7.99° - 8.90° |
| $\theta_{13}$ (IO)             | 8.49°      | 8.03° - 8.93° |
| $\delta$ (NO)                  | 261°       | 0° - 360°  |
| $\delta$ (IO)                  | 277°       | 145° - 391° |

Table 1: Current neutrino oscillation parameters from global fits at 3σ confidence level [5]. NO(IO) refers to normal (inverted) neutrino mass ordering.

Figure 1: Correlation plots for textures $B_2$ [(a) NO (b)IO] and $C_7$ for [(c) NO (d) IO] at 3σ CL for 1TEE. The symbols have their usual meaning. The horizontal line indicates the upper limit on effective neutrino mass term $|M|_{ee}$ (i.e $|M|_{ee} < 0.165\text{eV}$) at 90% CL, given in KamLAND-Zen experiment [6].

3.1 Near maximal atmospheric mixing for 1TEE and 1TEC texture structures

As a first step of the analysis, all the sixty cases of 1TEE and 1TEC have been investigated in the limit of large $|M|_{ee}$. For the analysis, we have incorporated the assumptions of Refs. [18][19], wherein authors have considered...
Figure 2: Correlation plots for textures $B_2$ [(a) NO (b) IO] and $C_7$ [(c) NO (d) IO] at $3\sigma$ CL for 1TEE.

The symbols have their usual meaning. The horizontal line indicates the upper limit on reactor mixing angle $\theta_{13} < 8.9^0$, as given in Table 1.

the lower bound on $|M|_{ee}$ to be large (i.e. $|M|_{ee} > 0.08eV$). The upper bound on $|M|_{ee}$ is choosen to be more conservative i.e. $|M|_{ee} < 0.5eV$ at $3\sigma$ CL [9]. The input parameters ($\theta_{12}, \theta_{23}, \theta_{13}, \delta m^2, \Delta m^2, \delta$) are generated by the method of random number generation. The three neutrino mixing angles and Dirac-type CP-violating phase $\delta$ are varied between $0^0$ to $90^0$ and $0^0$ to $360^0$, respectively. However, the mass-squared differences ($\delta m^2, \Delta m^2$) are varied randomly within their $3\sigma$ experimental range [5]. For the numerical analysis, we follow the same procedure as discussed in [13]. The main results and discussion are summarized as follows:

In Fig. 1, Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6 it is explicitly shown that the octant of $\theta_{23}$ is well restricted for $B_2, C_7, D_3, F_4$ of 1TEE and 1TEC texture structures, respectively. However, for the remaining cases, the value of $\theta_{23}$ is unconstrained like other oscillation parameters. Apart from restricting the octant of $\theta_{23}$, the analysis also ensures the quasi degenerate mass ordering for these cases similar to the observation of Refs. [18–20]. From Fig. 1(a, b) and Fig. 3(a, b), it is clear that for increasing value of $|M|_{ee}$, atmospheric mixing angle $\theta_{23}$ approaches to maximal value for the structure $B_2$ of 1TEE and 1TEC for both normal (NO) as well as inverted (IO) ordering. In Fig. 2 and Fig. 4 it is explicitly shown that for cases $B_2$ and $C_7$ the quadrant of $\theta_{23}$ is already decided without the experimental input of the mixing angles. For 1TEE we have $\theta_{23} < 45^0$ for NO, while $\theta_{23} > 45^0$ for IO, whereas for 1TEC, $\theta_{23} > 45^0$ for NO, while $\theta_{23} < 45^0$ for IO [Fig. 2(a, b), Fig. 4(a, b)]. Clearly the correlation plots of case $B_2$ are indistinguishable for 1TEE and 1TEC, if neutrino mass ordering is not considered as also pointed out earlier. Similar conclusion can be drawn for structure $C_7$ since both are related through 2-3 exchange symmetry [Fig. 2(c, d), Fig. 4(c, d)]. Apart from the prediction of near
maximality of $\theta_{23}$, cases $B_2$ and $C_7$ also predict $\delta \simeq 90^0, 270^0$ for 1TEE and 1TEC respectively, if experimental range of mixing angles are considered Table [2]. Figs. [2] [(a), (c)] for NO and Figs. [2] (b), (d)] for IO, depict the 2-3 interchange symmetry between the cases $B_2$ and $C_7$ for 1TEE. Similar phenomenological observation is shown for 1TEC in Fig. [4] (a, c) and Fig. [4] (b, d), respectively.

Similarly, cases $D_3$ and $F_4$ of 1TEE also predict near maximal atmospheric mixing angle ($\theta_{23}$) for IO [Fig. 5(a, b)]. Interestingly the parameter space of reactor mixing angle $\theta_{13}$ is found to be constrained between $0^0$ and $35^0$ [Figs. [5] (c), (d)]. In Figs. [5] (c, d), it is clear that for the allowed experimental range of $\theta_{13}$ ($8.5^0 - 9.8^0$), $\theta_{23}$ inches closer to $45^0$. Similar predictions have been noted for cases $D_3$ and $F_4$ of 1TEC, however for normal mass ordering (NO) [Figs. 5(a, b, c, d)].

### 3.2 Comparing the results for 1TEE and 1TEC texture structures

In this subsection, we compare the results of all the viable structures of 1TEE and 1TEC in neutrino mass matrix. It is worthwhile to mention that the present refinements of the experimental data does not limit the number of viable cases in 1TEE and 1TEC textures respectively. The number of viable cases obtained are same as predicted in Refs. [14] and [17] for 1TEE and 1TEC, respectively. For executing the analysis, we vary the allowed ranges of three neutrino mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and mass squared differences ($\delta m^2, \Delta m^2$) within their $3\sigma$ confidence level. To facilitate the comparison, we have encapsulated the the predictions regarding three
CP violating phases ($\rho, \sigma, \delta$) and neutrino masses $m_{1,2,3}$ for all the allowed texture structures of 1TEE and 1TEC respectively [Table 3, 4, 5, 6].

**Category A:** In Category A, there are 10 possible cases out of which only four ($A_{1,4,5,6}$) are allowed for 1TEE at 3$\sigma$ CL, and in addition, inverted mass ordering (IO) is ruled out for all these cases. On the other hand, only three ($A_{1,4,6}$) are allowed for 1TEC with current oscillation data, while normal mass ordering (NO) is ruled out for these cases. For 1TEE, $\rho, \sigma, \delta$ remain unconstrained, however for 1TEC, only $\delta$ remains unconstrained, while Majorana phases ($\rho, \sigma$) are restricted near $0^0$ pertaining to viable cases. From Table 3 it is clear that lower bound on lowest neutrino mass ($m_1$ (NO) or $m_3$ (IO)) is nearly equal or less than 1meV for 1TEE and 1TEC.

**Category B (C):** In Category B, all the ten possible cases are allowed for both 1TEE and 1TEC, respectively at 3$\sigma$ CL, however cases $B_{1,6,7}$ allow only NO for 1TEE, while the same allow only IO for 1TEC [Table 4]. Cases $B_{2,3,4,5,8,9,10}$ allow both NO as well as IO for 1TEE and 1TEC, respectively. As mentioned in Ref. [17], cases of Category B are related to the cases belonging to Category C through permutation symmetry, therefore we can obtain the results for Category C from B. We find that cases $C_{1,2,3}$ allow only NO for 1TEE, while the same allow IO for 1TEC. Textures $B_1$(NO), $B_3$ (NO, IO), $B_5$(NO, IO), $B_6$(NO), $B_7$(NO), $B_8$(NO), $B_{10}$ (NO), $C_1$(NO), $C_2$(NO), $C_3$(NO), $C_4$(NO, IO), $C_6$(NO, IO), $C_9$(NO), $C_{10}$(NO) held nearly no constraint on Dirac CP violating phase ($\delta$) for 1TEE and 1TEC respectively, however with opposite neutrino mass ordering [Table 4]. Only cases $B_2$ (NO), $B_4$ (IO),
Figure 5: Correlation plots for textures $D_{3}$ [(a),(c)] and $F_{4}$ [(b),(d)] with IO for 1TEE at 3σ CL. The symbols have their usual meaning. In Figs. (a) and (b), colored horizontal line indicates the upper limit on effective neutrino mass term $|M|_{ee}$ (i.e $|M|_{ee} < 0.165eV$) at 90 ($< 2\sigma$)% CL, given in KAMLAND-Zen experiment [6]. In Figs.(c) and (d), we have shown the upper limit on reactor mixing angle $\theta_{13}$.

$C_{7}$(NO), $C_{5}$(IO) for 1TEE, and $B_{2}$(IO),$B_{4}$(NO), $C_{7}$(IO), $C_{5}$(NO) for 1TEC show significant reduction in the parameter space of $\delta$. It is found that $\delta$ is restricted near 90° and 270° for 1TEE and 1TEC, respectively [Table 4]. These predictions are significant considering the latest hint on $\delta$ near 270° [5]. Therefore all the above cases discussed are almost indistinguishable for 1TEE and 1TEC, if neutrino mass ordering is not considered.

Category D (F): All the ten possible cases belonging to Category D are acceptable with neutrino oscillation data at 3σ CL for 1TEE and 1TEC, respectively [Table 5]. However cases $D_{1,2,4,5,6,7,9}$ favor both NO and IO for 1TEE and 1TEC, while $D_{3,8}$ and $D_{10}$ are acceptable only for IO in case of 1TEE, however same cases are allowed for NO in case of 1TEC. Similarly, the results for cases belonging to Category F can be derived from Category D.

Cases $D_{1}$(IO), $D_{2}$(IO), $D_{3}$(IO), $D_{4}$(IO), $D_{5}$(NO, IO), $D_{6}$(IO), $D_{7}$(NO, IO), $D_{8}$(IO), $D_{9}$(NO, IO), $D_{10}$(IO), $F_{1}$(IO),$F_{2}$(IO), $F_{3}$(IO), $F_{4}$(IO), $F_{5}$(NO, IO), $F_{6}$(IO), $F_{7}$(NO, IO), $F_{8}$(IO), $F_{9}$(NO, IO), $F_{10}$(IO) predict literally no constraints on $\delta$ for 1TEE. These cases give identical predictions for 1TEC, however for opposite mass ordering. On the other hand, for $D_{1}$(NO), $D_{2}$(NO), $D_{4}$(NO), $D_{6}$(NO), $F_{1}$(NO),$F_{2}$(NO), $F_{4}$(NO), $F_{6}$(NO) $\delta$ is notably constrained for 1TEE, and same is true for 1TEC, however for opposite mass ordering.

Category E: In Category E, all the ten possible cases are allowed for 1TEE at 3σ CL, while only nine other than $E_{5}$ are acceptable in case of 1TEC [Table 6]. Cases $E_{1,2,3,4,6,7,8,9}$ allow only inverted mass ordering (IO) for 1TEE, while same textures allow only normal mass ordering (NO) for 1TEC. Cases $E_{5}$ and $E_{10}$ allow both NO
and IO for 1TEE, however $E_5$ is ruled out for both NO and IO for 1TEC at 3σ CL. Similar to cases belonging to Category D, $E_{1,2,3,4,5,6,7,8,9}$ (IO) cover full range of $\rho, \sigma, \delta$ for 1TEE, whereas same cases (except $E_5$) give identical predictions for 1TEC, however for NO. For $E_{5,10}$ (NO), phases $\rho, \sigma, \delta$ are somewhat restricted at 3σ CL for 1TEE, while only for $E_{10}$ (IO), the parameter space of $\rho, \sigma, \delta$ seem to be restricted for 1TEC [Table 6].

To summarize our discussion, we have investigated all the viable cases of 1TEE and 1TEC texture structures in the limit of large effective neutrino mass $|M_{ee}|$. It is found that only four cases are able to produce near maximal atmospheric mixing for 1TEE and 1TEC, respectively. However, the predictions remain true irrespective of the experimental data on solar and reactor mixing angle. The observation also hints towards the indistinguishable feature of 1TEE and 1TEC texture structures, however for opposite mass ordering. In order to depict the indistinguishability, we have carried out a comparative study of 1TEE and 1TEC texture structures using the current experimental data at 3σ CL. From our discussion we find that most of the cases belonging to 1TEE and 1TEC are almost indistinguishable as far as the neutrino oscillation parameters are concerned, however with opposite neutrino mass ordering. The indistinguishable nature of 1TEE and 1TEC is more prominent for quasi degenerate mass ordering. For the cases where lower bound on lowest neutrino mass is very small ($<1meV$), there is noticeable deviation in the predictions for 1TEE and 1TEC [Table 3, 4, 5, 6, and 7]. This point is also discussed by Liao et. al. in Ref. [21]. In addition, the parameter space of $\delta$ for most of the cases belonging to
1TEE and 1TEC remain unrestricted, while only eight cases show maximal restriction for $\delta$. Since no presently feasible experiment has been able to determine the neutrino mass ordering, therefore we cannot distinguish 1TEE and 1TEC structures using the present oscillation data. However, the currently running and forthcoming neutrino experiments aimed at distinguishing the mass ordering of neutrinos will test our phenomenological results. Also the ongoing and future neutrinoless double beta decay experiments are capable of measuring $|M_{ee}|$ term, which would, in turn either confirm or rule out our assumption of large $|M_{ee}|$.

**Conflicts of Interest**

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

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|   | A             | B             | C             | D             | E             | F             |
|---|---------------|---------------|---------------|---------------|---------------|---------------|
| 1 | \( \Delta \Delta \) | \( \Delta \ 0 \ 0 \) | \( \Delta \ 0 \ 0 \) | \( \Delta \ 0 \ 0 \) | \( \Delta \ 0 \ 0 \) | \( \Delta \ 0 \ 0 \) |
|   | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
| 2 | \( \Delta \ 0 \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
|   | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
| 3 | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
|   | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
| 4 | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
|   | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
| 5 | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
|   | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
| 6 | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
|   | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
| 7 | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
|   | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
| 8 | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
|   | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
| 9 | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
|   | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
| 10| \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |
|   | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) | \( \Delta \times \times \) |

Table 2: Sixty phenomenologically possible hybrid texture structures of \( M_3 \) at 3\( \sigma \) C.L where the triangles ”\( \Delta \)” denote equal and non-zero elements (or cofactors), and ”0” denotes the vanishing element (or minor).”\( \times \)” denote the non-zero elements or cofactor.
| Cases | 1TEE | 1TEC |
|-------|------|------|
|       | NO   | IO   | NO   | IO   |
| A1    | ρ = −90° − 90° × × | ρ = −0.0277° −0.0220° −0.0214° −0.0274° |
|       | σ = −90° − 90° × × | σ = −0.0273° −0.0271° |
|       | δ = 0° − 360° × × | δ = 0° − 360° |
|       | m₁ = 0.00147 − 0.0106 × × | m₁ = 0.0430 − 0.0534 |
|       | m₂ = 0.00849 − 0.0139 × × | m₂ = 0.0439 − 0.0541 |
|       | m₃ = 0.0437 − 0.0551 × × | m₃ = 0.000904 − 0.00004 |
| A₂(Å₈) | ×   | ×   | ×   | ×   |
| A₃(Å₇) | ×   | ×   | ×   | ×   |
| A₄(Å₆) | ρ = −90° − 90° × × | ρ = −0.0273° −0.0220° −0.0215° −0.0260° |
|       | σ = −90° − 90° × × | σ = −0.0273° −0.0268° |
|       | δ = 0° − 360° × × | δ = 0° − 360° |
|       | m₁ = 0.00148 − 0.0106 × × | m₁ = 0.0431 − 0.0534 |
|       | m₂ = 0.00850 − 0.0139 × × | m₂ = 0.0439 − 0.0540 |
|       | m₃ = 0.0437 − 0.0551 × × | m₃ = 0.000950 − 0.00004 |
| A₅(Å₅) | ×   | ×   | ×   | ×   |
| A₆(Å₄) | ρ = −90° − 90° × × | ×   |
|       | σ = −90° − 90° × × | ×   |
|       | δ = 0° − 360° × × | ×   |
|       | m₁ = 0.00163 − 0.0105 × × | ×   |
|       | m₂ = 0.00854 − 0.0137 × × | ×   |
|       | m₃ = 0.0438 − 0.0545 × × | ×   |
| A₇(Å₃) | ×   | ×   | ×   | ×   |

Table 3: The allowed ranges of Dirac CP-violating phase δ, the Majorana phases ρ, σ, three neutrino masses m₁, m₂, m₃ for the experimentally allowed cases of Category A. Masses are in eV. "×" denotes the non-viability of case for a particular mass ordering.
Table 4: The allowed ranges of Dirac CP-violating phase $\delta$, the Majorana phases $\rho, \sigma$, three neutrino masses $m_1, m_2, m_3$ for the experimentally allowed cases of Category B(C). Masses are in eV. " $\times$ " denotes the non-viability of case for a particular mass ordering.
### Table 5: The allowed ranges of Dirac CP-violating phase $\delta$, the Majorana phases $\rho, \sigma$, three neutrino masses $m_1, m_2, m_3$ for the experimentally allowed cases of Category D(F). Masses are in eV. "×" denotes the non-viability of case for a particular mass ordering.
Table 6: The allowed ranges of Dirac CP-violating phase $\delta$, the Majorana phases $\rho, \sigma$, three neutrino masses $m_1, m_2, m_3$ for the experimentally allowed cases of Category E. Masses are in eV. "×" denotes the non-viability of case for a particular mass ordering.
KamLand-Zen at 90% CL
