Can nonstandard interactions jeopardize the hierarchy sensitivity of DUNE?

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We study the effect of non-standard interactions (NSIs) on the propagation of neutrinos through the Earth matter and how it affects the hierarchy sensitivity of the DUNE experiment. We emphasize on the special case when the diagonal NSI parameter $\epsilon_{ee} = -1$, nullifying the standard matter effect. We show that, in addition, CP violation is maximal then this gives rise to an exact intrinsic hierarchy degeneracy in the appearance channel, irrespective of the baseline and energy. Introduction of off-diagonal NSI parameter, $\epsilon_{e\tau}$, shifts the position of this degeneracy to a different $\epsilon_{ee}$. Moreover the unknown magnitude and phases of the off-diagonal NSI parameters can give rise to additional degeneracies. Overall, given the current model independent limits on NSI parameters, the hierarchy sensitivity of DUNE can get seriously impacted. However, a more precise knowledge on the NSI parameters, specially $\epsilon_{ee}$, can give rise to an improved sensitivity. Alternatively, if NSI exists in nature, and still DUNE shows hierarchy sensitivity, certain ranges of the NSI parameters can be excluded. Additionally, we briefly discussed the implications of $\epsilon_{ee} = -1$ (in the Earth) on MSW effect in the Sun.

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Introduction: Phenomenal experiments over the past decades have established neutrino oscillations and led us into an era of precision measurements in the leptonic sector. Current data determines the two mass squared differences ($\Delta m^2_{23} = m^2_2 - m^2_1$, $|\Delta m^2_{31}| = |m^2_2 - m^2_1|$), $m_1$, $m_2$, $m_3$ being the mass states) and three leptonic mixing angles ($\theta_{12}$, $\theta_{23}$, $\theta_{13}$) with considerable precision \[1\]. This leaves determination of neutrino mass hierarchy i.e. whether $m_3 > m_2 > m_1$ (normal hierarchy (NH)) or $m_3 < m_2 \approx m_1$ (inverted hierarchy (IH)), octant of $\theta_{23}$ i.e whether $\theta_{23} < \pi/4$ and lies in lower octant (LO) or it is $> \pi/4$ and is in the higher octant (HO) and measurement of $\delta_{CP}$ as the major objectives of ongoing and future experiments. Recently, the on-going T2K experiment \[2\] and global analysis of data \[1\] have hinted that the Dirac CP phase is maximal i.e. $\delta_{CP} = -\pi/2$ although at $3\sigma$ the full range ($0 - 2\pi$) remains allowed. Whereas, recent NOvA result \[3\] suggested that there are two best fit points if neutrinos obey normal hierarchy, (i) $\sin^2 \theta_{23} = 0.404$, $\delta_{CP} = 1.48\pi(\sim 90^0)$ and (ii) $\sin^2 \theta_{23} = 0.623$, $\delta_{CP} = 0.74\pi(\sim 135^0)$. Also, inverted mass hierarchy with $\theta_{23} < 45^0$ is disfavoured at 93% C.L. for all values of $\delta_{CP}$.

Although neutrino oscillation has been identified as the dominant phenomenon to explain the results of various experiments, the possibility of sub-leading effects originating from new physics beyond the Standard Model (SM) cannot be ignored. Among these, non-standard interactions have received a lot of attention lately specially with the emergence of proposed next generation experiments like DUNE, T2HK, T2HKK etc. \[14\].

In this work, we emphasize on an interesting case when standard matter effects during neutrino propagation through the Earth matter gets nullified due to NSI effects \[1\], creating degeneracies which affect the determination of hierarchy in any long-baseline (LBL) experiment. Though additional hierarchy degeneracy in LBL experiments due to NSI have been discussed earlier \[14\] the new points that we make are: (i) if the NSI parameter $\epsilon_{ee}$ characterizing new interactions between electrons neutrinos and electrons has the value $\epsilon_{ee} = -1$, the NSI effect cancels the standard matter effect; (ii) if in addition $\delta_{CP} = \pm \pi/2$, there exists an exact intrinsic hierarchy degeneracy in the appearance channel, which is independent of baseline and the neutrino beam energy making it unsolvable in LBL experiments, in particular DUNE. Note that this degeneracy cannot be lifted even if $\epsilon_{ee}$ and $\delta_{CP}$ are precisely measured around these values. This result assumes more importance in the light of current data from the T2K experiment hinting at $\delta_{CP} \sim -\pi/2$. We also consider the simultaneous presence of $\epsilon_{ee}$ and non-zero values of the NSI parameter $\epsilon_{e\tau}$ and show that the intrinsic degeneracy still exists, albeit at a different $\epsilon_{ee}$. Moreover, given the current model independent bounds on the NSI parameters, hierarchy sensitivity in DUNE does not improve. Rather the phases associated with $\epsilon_{e\tau}$ can give rise to additional degeneracies which seriously impact the sensitivity.

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1 We neglect the production and detection NSI, bounds on which are stronger by an order of magnitude than matter NSI \[10\].
We focus on the matter NSI effects on the neutrino propagation. This is described by dimension-six four-fermion operators of the form $^{17}$

$$L_{NSI}^{NC} = (\pi_\alpha^\gamma \rho P_L \nu_\beta)(\hat{f} \gamma_\rho P_C f)2\sqrt{2}G_F \alpha_{\alpha\beta} + \text{h.c.} \tag{1}$$

where $\alpha_{\alpha\beta}$ are NSI parameters, $\alpha, \beta = e, \mu, \tau$, $C = L, R$ denotes the chirality, $f = u, d, c, e$, and $G_F$ is the Fermi constant. The Hamiltonian in the flavor basis can be written as,

$$H = \frac{1}{2E} [U \text{diag}(0, \Delta m_{31}^2, \Delta m_{32}^2)] U^\dagger + V \tag{2}$$

where $U$ is the PMNS mixing matrix having three mixing angles ($\theta_{ij}$, $i < j = 1, 2, 3$) and a CP phase $\delta_{CP}$. $V$ is the matter potential due to the the interactions of neutrinos,

$$V = A \left( \begin{array}{lll} 1 + \epsilon_{ee} & \epsilon_{e\mu} e^{i\phi_{e\mu}} & \epsilon_{e\tau} e^{i\phi_{e\tau}} \\ \epsilon_{e\mu} e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau} e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau} e^{i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{array} \right) \tag{3}$$

where, $A = 2\sqrt{2}G_F N_e(r)E$. The unit contribution to the (1,1) element of the $V$ matrix is the usual matter term arising due to the standard charged-current interactions.

$$P_{\mu e} = x^2 f^2 + 2xy fg \cos(\Delta + \delta_{CP}) + y^2 g^2 + O(\epsilon_{en})$$

$$+ 4A_{ee} e^{2x} (x[f \cos(\phi_e + \delta) - g \cos(\Delta + \delta + \phi_e)]) - yg [g \cos(\phi_e + \delta) - f \cos(\Delta - \phi_e)]) - 8A^2 f^2 s_{23}^2 \cos \Delta + O(s_{13}^2 \epsilon_{ee}, s_{13}^2 \epsilon_{ee}, \epsilon_{e\tau}) \tag{5}$$

$$x = 2s_{13}s_{23}, \quad y = r c_{23} \sin 2\theta_{12}, \quad \Delta = \frac{\Delta m_{31}^2 L}{4E}, \quad \bar{A} = \frac{A}{\Delta m_{31}^2}, \quad f, \bar{f} = \frac{\sin[\Delta(1 + \bar{A})(1 + \epsilon_{ee})]}{1 + \bar{A}(1 + \epsilon_{ee})}, \quad g = \sin[\bar{A}(1 + \epsilon_{ee})] \tag{6}$$

This has a $\Delta \to -\Delta$ and $\delta_{CP} \to -\delta_{CP}$ degeneracy. If $\delta_{CP}$ is measured accurately such that $\pi - \delta_{CP}$ is not allowed then this degeneracy can be alleviated. However for true value of $\delta_{CP} = \pm \pi/2$ since both $\delta_{CP}$ and $\pi - \delta_{CP}$ are same there is an intrinsic degeneracy which cannot be removed even if $\delta_{CP}$ is measured precisely around these values. Note that for $\delta_{CP} = \pm \pi/2$, the third term becomes $\sin^2 \Delta$ and there is no hierarchy sensitivity. Note that this is a special case of the $\epsilon_{ee} = -1$, $\epsilon_{e\tau} = 0$ degeneracy discussed in $^{14}$. We emphasize on the intrinsic nature of this degeneracy for $\epsilon_{ee} = -1$ $^3$ and $\delta_{CP} = \pm \pi/2$.

In the above expressions $s_{ij} = \sin \theta_{ij}, c_{ij} = \cos \theta_{ij}, i < j, i = 1, 2, 3$. The expressions for IH can be obtained by replacing $\Delta m_{31}^2 \to -\Delta m_{31}^2$ (implying $\Delta \to -\Delta$, $\bar{A} \to -\bar{A}$ (i.e. $f \to -\bar{f}$ and $g \to -g$), $y \to -y$). Similar expressions for anti neutrino probability ($P_{\mu e}^{\bar{e}}$) can be obtained by replacing $\bar{A} \to -\bar{A}$ (i.e. $f \to \bar{f}$), $\delta_{CP} \to -\delta_{CP}$, $\phi_{e\beta} \to -\phi_{e\beta}$. From eq. $^3$ the only diagonal parameter to which appearance channel is sensitive is $\epsilon_{ee}$. Also note that since $P_{\mu e}$ contains terms of the form $\sin 2\theta_{12}$ the $s_{12} \leftrightarrow c_{12}$ transformation is not very important in our discussion and we concentrate on the region $\theta_{12} < \pi/4$ $^4$.

While assuming the presence of only the diagonal NSI parameters if $\epsilon_{ee} = -1$, we observe from eq. $^3$ that the NSI effect cancels the standard matter effect and $P_{\mu e}$, for NH, can be expressed as $^2$:

$$P_{\mu e} = x^2 \sin^2 \Delta + y^2 + 2xy g \sin \Delta \cos(\delta_{CP} + \Delta). \tag{7}$$

$^2$ At $\epsilon_{ee} = -1$, $f = \sin \Delta (\pm \sin \Delta)$ and $g = 1(1)$ for NH (IH).

$^3$ In $^{15}$, a fit to the SuperKamiokande data assuming NSI gives the best-fit as $\epsilon_{ee}^{\odot} = -1, |\epsilon_{\mu\tau}^{\odot}| = 0$. However, the author mentions that this could be because of the discrepancies between the Monte Carlo simulation of the Superkamiokande group and theirs.
The behaviour of $P_{\mu e}$ as a function of $\epsilon_{ee}$ is shown in fig. (1) for a fixed energy $E = 2$ GeV and $\delta_{CP} = -\pi/2$ for DUNE experiment. The 4 bands correspond to different combinations of hierarchy and octant as labelled in the figure. The width of the bands are due to variation over $\theta_{23}$. We observe that the probability is a rising (falling) function of $\epsilon_{ee}$ for NH (IH) for both the octants. The value $\epsilon_{ee} = 0$, represents the standard oscillation case for which a huge separation between NH and IH bands can be seen for neutrinos, as the DUNE baseline has large matter effect.

![FIG. 1: $P_{\mu e}$ vs $\epsilon_{ee}$ for DUNE. The bands are over $\theta_{23}$, for LO($\theta_{23} = 39^\circ - 42^\circ$) and for HO($\theta_{23} = 48^\circ - 51^\circ$).](image)

But in presence of NSI, DUNE loses hierarchy sensitivity due to additional degeneracy creaping in through the NSI parameters. The figure exhibits the $\epsilon_{ee} \rightarrow -\epsilon_{ee} - 2$ degeneracy discussed in [14]. One further observes that, for $\epsilon_{ee} = -1$, the bands for NH-LO(NH-HO) overlap with those of IH-LO(IH-HO) demonstrating the intrinsic nature of the hierarchy degeneracy.

It’s also noteworthy that this degeneracy will be there for all baselines and hence no LBL experiment will be able to resolve this degeneracy. We have checked that similar plots for antineutrinos show that the nature of the octant degeneracy as a function of $\epsilon_{ee}$ is opposite and hence, running in ($\nu + \bar{\nu}$) mode will take care of the wrong octant solutions. For known octant, the probability figures show the absence of hierarchy degeneracy for $\epsilon_{ee} > 2$.

So far we have discussed hierarchy degeneracy for $\delta_{CP} = -\pi/2$. In fig. (2), we have plotted the probability vs $\delta_{CP}$ for various values of $\epsilon_{ee}$ to understand the degeneracies due to $\delta_{CP}$ in presence of NSI. The various degenerate solutions observed are, (i) The WH-RO-R$\delta_{CP}$ solution, discussed above, occurs at $\delta_{CP} = \pm \pi/2$. This is seen by comparing the blue and magenta bands or the brown and the grey bands. Mathematically the above implies $P_{\mu e}^{NH}(\epsilon_{ee}, \delta_{CP} = \pm \pi/2) = P_{\mu e}^{IH}(\epsilon_{ee} - 2, \delta_{CP} = \pm \pi/2)$. (ii) The WH-RO-W$\delta_{CP}$ solutions which can be observed by comparing the blue band with magenta band or brown band with grey band by drawing a horizontal line corresponding to a given probability. This can be defined as $P_{\mu e}^{NH}(\epsilon_{ee}, \delta_{CP}) = P_{\mu e}^{IH}(\epsilon_{ee} - 2, \delta_{CP})$. (iii) Apart from the degenerate solutions corresponding to $\epsilon_{ee} \rightarrow -\epsilon_{ee} - 2$ one can have a more general form of the degeneracy $P_{\mu e}^{NH}(\epsilon_{ee}, \delta_{CP}) = P_{\mu e}^{IH}(\epsilon_{ee}, \delta_{CP})$. This can be seen by comparing the yellow band with the dark red band. The conclusions made above are also true for antineutrinos.

![FIG. 2: $P_{\mu e}$ vs $\delta_{CP}$ for DUNE. The bands are for $\theta_{23} \in$ LO.](image)

**Off-diagonal NSI** : We also study the cases of whether inclusion of off-diagonal NSI parameter $\epsilon_{\tau\tau}$ can resolve the intrinsic hierarchy degeneracy occurring at $\epsilon_{ee} = -1$ and $\delta_{CP} = -\pi/2$. From eq. (5) the difference in hierarchy for $\epsilon_{ee} = -1$ and $\delta_{CP} = -\pi/2$ and same $\epsilon_{\tau\tau}$ in both NH and IH can be expressed as,

$$P_{\mu e}^{NH} - P_{\mu e}^{IH} = 8 A \sin \Delta c_{23} s_{23} (x \sin \Delta - x \cos \Delta + y \sin \Delta \epsilon_{\tau\tau} \sin \phi_{\tau\tau} \epsilon_{\tau\tau}) \epsilon_{\tau\tau}. \quad (8)$$

Thus, we can see that there is a finite difference between the NH and IH probabilities which vanishes if $\phi_{\tau\tau}$ is zero or if $\phi_{\tau\tau} \rightarrow -\phi_{\tau\tau}$. However, the intrinsic degeneracy may shift by an amount which depends on the values of the off-diagonal NSI parameters. For instance, assuming a small shift ‘q’ in presence of $\phi_{\tau\tau}$ one can write $P_{\mu e}^{NH}(\epsilon_{ee} + q, \epsilon_{\tau\tau}, \delta_{CP} = \pm \pi/2) = P_{\mu e}^{IH}(\epsilon_{ee} + q, \epsilon_{\tau\tau}, \delta_{CP} = \pm \pi/2)$. Then assuming $\delta = -\pi/2$ and $\theta_{23} = \pi/4$, $q$ can be calculated at the oscillation maxima ($\sin \Delta \sim \pi/2$) as,

$$q = -\frac{0.23 \sin \phi_{\tau\tau}}{0.044 - 0.03 \cos \phi_{\tau\tau} + 0.01 \epsilon_{\tau\tau}^2} \epsilon_{\tau\tau}. \quad (9)$$

For instance, for $\epsilon_{\tau\tau} = 0.05(0.5)$ and $\phi_{\tau\tau} = -90^\circ$, eq. (9) gives $q \approx 0.25(2.37)$. This shift can be observed from the green(blue) dashed and solid lines of fig. (3). These two cases demonstrate degeneracy of the

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4 Note that WH = Wrong Hierarchy, RO = Right Octant, R$\delta_{CP}$ = Right $\delta_{CP}$, W$\delta_{CP}$ = Wrong $\delta_{CP}$.

5 Since, the bounds on $\epsilon_{\tau\tau}$ are more tightly constrained than $\epsilon_{\tau\tau}$ we consider the effect of latter.
form \( P_{\mu e}^{NH}(\epsilon_{ee}, \delta_{CP}, \epsilon_{\tau}, \phi_{e\tau}) = P_{\mu e}^{IH}(\epsilon_{ee}, \delta_{CP}, \epsilon_{\tau}, \phi_{e\tau}) \) with \( \epsilon_{ee} \neq -1 \) and \( \delta_{CP} = \pm \pi/2 \).

Additionally, we can also observe more general degeneracies of the form \( P_{\mu e}^{NH}(\epsilon_{ee}, \delta_{CP}, \epsilon_{\tau}, \phi_{e\tau}) = P_{\mu e}^{IH}(\epsilon_{ee}', \delta_{CP}, \epsilon_{\tau}', \phi_{e\tau}) \) by drawing horizontal lines intersecting the green(blue)-dashed and blue(green)-solid lines. Fig 3 is drawn for fixed values of \( \delta_{CP} \) and \( \epsilon_{\tau} \). Allowing these parameters to vary can generate additional degeneracies.

Note that eq (9) and fig. 3) correspond to the energy at which the oscillation maxima occurs. We have verified that in general the amount of this shift depends on the energy and for a different energy the intrinsic degeneracy occurs at a different value of \( \epsilon_{ee} \).

![Graph: P_{\mu e} vs \epsilon_{ee} for different \epsilon_{\tau} values.](image)

Thus the intrinsic degeneracy becomes energy dependent in presence of \( \epsilon_{\tau} \) and hence spectrum information can be useful for removal of these degeneracies.

In fig. 4, we plot hierarchy \( \chi^2 \) Vs \( \epsilon_{ee} \) (Test) to understand how the diagonal and off-diagonal NSI affect the mass hierarchy sensitivity of DUNE while assuming NSI in nature.

![Graph: Hierarchy \chi^2 vs \epsilon_{ee} (Test)](image)

We have used General Long baseline Experiment Simulator (GLoBES) [19] with additional tools from [20] in our numerical calculations. The experimental specifications and other numerical details are taken from [21] except that this analysis is done for 40 kt detector mass. The true values that we have considered are, \( \sin^2 \theta_{12} = 0.297 \), \( \sin^2 2\theta_{13} = 0.085 \), \( \theta_{23} = 45^\circ \), \( \delta_{CP} = -\pi/2 \), \( \Delta m^2_{32} = 7.37 \times 10^{-5} \text{eV}^2 \) and \( \Delta m^2_{21} = 2.50 \times 10^{-3} \text{eV}^2 \) [1]. Different true values of NSI parameters are as mentioned in the fig. 4). We marginalize over \( \theta_{13} \), \( \delta_{CP} \), \( \epsilon_{\tau} \) and \( \phi_{e\tau} \). The remaining NSI parameters are taken to be zero. The bounds on NSI parameters [16, 22] that occur in \( P_{\mu e} \), eq. (5), at 90% C.L. are considered to be \( |\epsilon_{ee}| \leq 4 \) and \( \epsilon_{\tau} \leq 3.0 \) and the corresponding off-diagonal phase \( \phi_{e\tau} = [-\pi, \pi] \).

The black solid curve shows that there is no hierarchy sensitivity for \( \epsilon_{ee} = -1 \) in the absence of other NSI parameters because of the intrinsic degeneracy in the appearance channel. Here, the small non-zero \( \chi^2 \) at \( \epsilon_{ee} = -1 \) arises from the disappearance channel \( P_{\mu e} \). Because of the intrinsic nature of this degeneracy, if hierarchy sensitivity is observed in DUNE and NSI exists in nature then certain ranges of NSI parameters will be ruled out. For instance assuming existence of only diagonal NSI, the range \(-1.6 < \epsilon_{ee} < -0.8 \) will be ruled out if DUNE observes 3\( \sigma \) hierarchy sensitivity. For other true values of \( \epsilon_{ee} \) the corresponding degenerate parameter space will be excluded. The magenta curve shows the hierarchy sensitivity for a non-zero true value of \( \epsilon_{\tau} = 0.5 \) and \( \phi_{e\tau} = -\pi/2 \). We find that for this the global minima comes at \( \epsilon_{ee} = -0.8 \) and there is no hierarchy sensitivity.

Note that there is also a local minima for \( \epsilon_{ee} = 1 \), where we observed an intrinsic degeneracy in fig. 3. The reasons for which we do not get the global minima at this value are (i) marginalization over the phase \( \phi_{e\tau} \), which had been kept fixed in fig. 3. (ii) the broadband nature of the beam at DUNE. The green dotted curve depicts the hierarchy sensitivity for a different true value of \( \epsilon_{ee} = 1 \). The global minima comes at \( \epsilon_{ee} = -2 \) as well as a very close minima near \( \epsilon_{ee} = -1 \) and several other local minima. Here the global minima exhibits the most general form of the degeneracy: \( P_{\mu e}^{NH}(\epsilon_{ee}, \delta_{CP}, \epsilon_{\tau}, \phi_{e\tau}) = P_{\mu e}^{IH}(\epsilon_{ee}', \delta_{CP}, \epsilon_{\tau}', \phi_{e\tau}') \). However in this case 2\( \sigma \) sensitivity can be achieved by DUNE if the region \( \epsilon_{ee} < 0.8 \) is excluded.

Our study shows that in presence of true non-zero NSI parameters DUNE will not have any hierarchy sensitivity if marginalized over the model independent ranges of NSI parameters. If however, we use the more restrictive model dependent bounds then the hierarchy sensitivity of DUNE can improve considerably. For instance assuming only diagonal NSI and the model dependent bound \(-0.9 < \epsilon_{ee} < 0.75 \) [16], 3\( \sigma \) hierarchy sensitivity can be achieved for \(-0.7 < \epsilon_{ee} \) and it can be very large for higher values of \( \epsilon_{ee} \) [11].

**Implications of \( \epsilon_{ee} = (\epsilon_{ee}^0) = -1 \) in the Sun**:
Neutrinos, while travelling through the matter of varying density possibly undergo resonant flavor transitions through Mikheyev–Smirnov–Wolfenstein (MSW) effect. This resonance phenomenon accounts for the flavor
transitions of solar neutrinos while they propagate from the core to the surface of the Sun.

The solar neutrino evolution equation can be written in an effective two flavor model under one-mass scale dominance (OMSD) approximation $|\Delta m_{31}^2| \rightarrow \infty$ as:

$$
\frac{d}{dr} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = H_{eff} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}
$$

where $r$ is the coordinate along the neutrino trajectory and $H_{eff}$ is the effective hamiltonian given by sum of vacuum, standard matter potential and NSI parts as

$$
H_{eff} = U_{12} \begin{bmatrix} 0 & 0 \\ 0 & \Delta_{21} \end{bmatrix} U_{12}^\dagger + \sum f V_f \begin{pmatrix} C_{13}^2 \delta_{12} & \epsilon_D^f \\ \epsilon_N^f & \epsilon_D^f \end{pmatrix}
$$

where $U_{12} = \begin{bmatrix} c_{12} & \s_{12} \\ -\s_{12} & c_{12} \end{bmatrix}$, $\Delta_{21} \equiv \Delta m_{21}^2/(4E)$ and $V_f = V_f(r) = \sqrt{2}G_F N_f(r)$ Here, the usual MSW effect induced by standard matter potential $V_e(r)$ is in the $(1, 1)$ element of the second term in $H_{eff}$. The diagonal $\epsilon_D^f$ (real) and off-diagonal $\epsilon_N^f$ (complex) NSI parameters are related to $\epsilon_{\alpha\beta}$ by $[23, 24]$.

$$
\epsilon_D^f = c_{13}s_{13} \text{Re}[e^{i\delta_{CP}}(s_{23}^2 \epsilon_{\mu\tau} + c_{23}^2 \epsilon_{\nu\tau})]
- (1 + s_{13}^2) c_{23} s_{23} \text{Re}(\epsilon_{\mu\tau})
- \frac{1}{2}(\epsilon_{\tauee} - \epsilon_{\mu\tau})
+ s_{23}^2 - s_{23}^2 c_{23}^2 (\epsilon_{\nu\tau} - \epsilon_{\nu\tau}^*)
+ \frac{1}{2}(\epsilon_{\nu\tau} - \epsilon_{\nu\tau}^*) + c_{23} s_{23} (\epsilon_{\nu\tau} - \epsilon_{\nu\tau}^*)
$$

The survival probability of solar neutrinos under OMSD approximation is given by:

$$
P_{ee} = s_{13}^2 + c_{13}^2 P_{eff}
$$

where $P_{eff}$ can be obtained by solving eq. (10) in the effective 2-flavor system. By diagonalizing the effective hamiltonian in eq. (11) one can obtain the effective mixing angle $\theta_{eff}$ in the matter as:

$$
\tan \theta_{eff} = \frac{2(\Delta_{21} \sin 2\theta_{12} + \sum_f V_f \epsilon_N^f)}{2\Delta_{21} \cos 2\theta_{12} - \sum_f V_f (s_{13}^2 \delta_{12} - 2\epsilon_D^f)}
$$

It can be noted that the eq. (14) reduces to the effective mixing angle $\tan \theta_{M}$ of a neutrino encountering only the standard matter potential when the NSIs cease to exist i.e. $\epsilon_{\alpha\beta} = 0$.

In the previous section, while considering the presence of only diagonal NSI parameter $\epsilon_{ee}$ we have taken a special case of $\epsilon_{ee} = -1$ for the Earth. Below, we have explored how this choice of NSI parameters would affect the MSW resonance in the Sun.

For the matter composition of the Earth the average of $Y_n$ is given by the PREM model as $Y_n = 1.051$. Thus from eq. (14) we have

$$
\epsilon_{ee} = \epsilon_{ee}^\prime + 3\epsilon_{ee}^\mu + 3\epsilon_{ee}^\nu
$$

Whereas, in the Sun, $Y_n(r)$ varies from 1/2 in the core to 1/6 at the surface. Relevant expression for $\epsilon_{ee}^\nu$ can be obtained by substituting these values in eq. (14).

For instance, let us consider $\epsilon_{ee}^\mu = -1/3$ and $\epsilon_{ee}^\mu = 0$ which are within 1σ allowed region of CHARM results $[25]$. Substituting $\epsilon_{ee}^\mu = -1/3$ and $Y_n = 1/2$ (at the core), in eq. (14) gives

$$
\epsilon_{ee}^\nu = (2 + 1/2)\epsilon_{ee}^\mu = -\frac{5}{6}
$$

Thus, eq. (14) reduces to

$$
\epsilon_{ee} = -\frac{\epsilon_{ee}^\mu}{2} \epsilon_{ee}^\nu = \frac{c_{13}^2}{6} ; \epsilon_{ee}^\mu = 0.
$$

Now, by substituting the above equations in eq. (14) one can obtain a simplified form of

$$
\tan \theta_{M} = \frac{2\Delta_{21} \sin 2\theta_{12}}{2\Delta_{21} \cos 2\theta_{12} - V_e c_{13}^2/6}
$$

or

$$
\tan \theta_{M} = 1 - \frac{N_{e, res}}{c_{13}^2/6}.
$$

Thus, MSW resonance in Sun occurs when the condition $\Delta_{21} \cos 2\theta_{12} = V_e c_{13}^2/12$, is satisfied. The electron density at resonance is,

$$
N_{e, res} = 3\Delta m_{12}^2 \cos 2\theta_{12}/\sqrt{2}G_F E c_{13}^2.
$$

We have observed that for neutrino energy $E \geq 7.2$ MeV MSW resonance occurs in the Sun, i.e. the matter mixing angle is $\cos 2\theta_M \sim -1$ and the corresponding survival probability is $P_{ee} \sim 0.3$ for $\Delta m_{21}^2 \sim 4 \times 10^{-6} eV^2$ and Large Mixing Angle solution with $\sin^2 \theta_{12} = 0.3$. This analysis can be extrapolated to the case of non-zero off-diagonal NSI parameters (say $|\epsilon_{ee}^\nu| \neq 0$). However, this would require a thorough study of non-standard neutrino interactions in the Sun which is beyond the scope of this paper.

**Conclusions**: In this paper, we make the striking observation that if the parameter $\epsilon_{ee} = -1$, the standard matter effect gets cancelled by the NSI effects and the probability $P_{ee}$ is just the vacuum oscillation probability in absence of off-diagonal NSI parameters. If in addition, the CP phase $\delta_{CP} = \pm \pi/2$ one gets an intrinsic hierarchy degeneracy which cannot be removed even if both $\epsilon_{ee}$ and $\delta_{CP}$ are known precisely. This result acquires more relevance in the light of the preference of T2K data and global oscillation analysis results implying $\delta_{CP} \sim -\pi/2$. Although this is a special case of the generalized hierarchy degeneracy $\epsilon_{ee} \rightarrow -\epsilon_{ee} - 2$, $\delta_{CP} \rightarrow \pi - \delta_{CP}$, considered in $[14]$ for any other value of $\epsilon_{ee}$ and $\delta_{CP}$, a precise measurement of these parameters will alleviate the degeneracies. However for $\epsilon_{ee} = -1$ together with $\delta_{CP} = \pm \pi/2$ that is not true. To the best of our knowledge this particular point has not been highlighted before. This conclusion, being independent of baseline and energy, can seriously impact the hierarchy sensitivity of the DUNE experiment.

The matter effects can reappear, if for instance, the off-diagonal NSI parameter $\epsilon_{ee}$ is included. But we show
that for this case the intrinsic hierarchy degeneracy is transported from $\epsilon_{ee} = -1$ to a different value depending on the off-diagonal NSI parameters as well as energy. Moreover the uncertainty in the magnitude and phase of the off-diagonal NSI parameters can give rise to additional degeneracies affecting the hierarchy sensitivity. A more precise knowledge of the parameter $\epsilon_{ee}$, can however, give rise to an enhanced sensitivity provided $\epsilon_{ee} \neq -1$. This underscores the importance of independent measurement of the NSI parameters from non-oscillation experiments \[20\]. Furthermore, we also discussed the implications of $\epsilon_{ee} = -1$ (in the earth) on the matter effect in the Sun.

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