NSI in Electrophilic $\nu$2HDM

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based on "Non-standard Neutrino Interactions in a Modified $\nu$2HDM", Ujjal Dey, Newton Nath and Soumya Sadhukhan, Phys.Rev. D98 (2018) no.5, 055004
Experiments establish the SM to be the complete theory of particle physics. The missing one predicted by the SM, a (spin 0) Higgs boson is also recently found at the LHC.

Major issues not resolved in the SM include:

- Non-zero and tiny neutrino mass
- Dark matter candidate
- CP violation not enough for baryon asymmetry
- Fermion mass hierarchy problem etc.

Physics beyond the SM can appear in the form of new couplings involving neutrinos, which are usually referred to as non-standard neutrino interactions (NSIs).

Moreover, the next generation experiments like DUNE have improved sensitivity to look at the oscillation effects more precisely i.e. to probe for NSI effects.

New models with NSI and connection to other BSM issues: neutrinophilic 2HDM as a test case.
Non-Standard Interactions (NSI)

- Neutrino oscillation is established to be the 'standard' phenomenon to explain the results of various experiments. There is still possibility of extra sub-leading effects originating from new physics beyond the Standard Model (SM).

- Only the effect of matter NSI on neutrino oscillation and mass ordering is studied here, leaving the production and detection NSI effects.
- NSI effects can be described in the effective operator form as: Wolfenstein, 1978

\[
L_{\text{NSI}} = (\bar{\nu}_a \gamma^\alpha P_L \nu_b)(\bar{f} \gamma^\alpha P_c f)2\sqrt{2}G_F \epsilon_{abc} + \text{h.c.}
\]

where \(\epsilon_{\alpha\beta} = \sum_f, c \epsilon^f_{\alpha\beta} \frac{N_f}{N_e}\) are NSI parameters, \(a, b = e, \mu, \tau, c = L, R, f = u, d, e\).
two Higgs doublet model

- Symmetry of model: SM gauge symmetry × global $U(1)$ symmetry

Davidson, Logan

- SM + Second Higgs doublet ($\Phi_2$) and a right handed neutrino $\nu_R$ introduced. Both are charged +1 under $U(1)$ while the SM particles are $U(1)$ neutral.

- The SM left-handed neutrinos, together with the right-handed neutrino added here, couple only to the Higgs doublet $\Phi_2$.

$$L_Y = y_l \bar{L}_l \tilde{\Phi}_2 \nu_R + \text{h.c.},$$

- The neutrinos acquire masses much smaller than those of the quarks and charged leptons due to the tiny vev of $\Phi_2$, when the global $U(1)$ is broken. In general $\nu2HDM$, we require $v_2 \sim \text{eV}$.

- This set up does not give rise to any NSI effects.
Here, along with $\Phi_2$ and right handed neutrinos, the $e_R$ is charged odd under global $U(1)$, providing extra interaction apart from neutrinophilic Yukawa. Yukawa interactions involving $\Phi_2$ are,

$$L \supset y_e \bar{L}_e \Phi_2 e_R + y_1 \bar{L}_\mu \Phi_2 e_R + y_2 \bar{L}_\tau \Phi_2 e_R + h.c.,$$

This term will give mass term to the electron. For order one Yukawa coupling $\nu_2 \sim 0.1$ MeV.

This new construction does not affect $h^{SM} e_L e_R$ Yukawa coupling: matches SM value.

softly broken $U(1)$ symmetry: $m^2_{12}$ non zero. So the non-SM CP even scalar ($H$) can be heavy i.e. around TeV scale.

$U(1)$ symmetry: $\lambda_5$ is zero. So the CP even scalar mass ($m_H$) is equal to CP odd scalar mass ($m_A$).
• In a CP-conserving 2HDM with a softly broken $U(1)$ symmetry, scalar potential is:

\[ V_H = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 + m_{12}^2 \left[ \Phi_1^\dagger \Phi_2 + h.c. \right] + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \]

• The fields parametrized in terms of the mass eigenstates $H^\pm$, $h$, $H$, $A$ in unitary gauge:

\[
\Phi_1 = \begin{pmatrix} -s_\beta H^+ \\ \frac{1}{\sqrt{2}} [v_1 + (-s_\alpha h + c_\alpha H) - is_\beta A] \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} c_\beta H^+ \\ \frac{1}{\sqrt{2}} [v_2 + (c_\alpha h + s_\alpha H) + ic_\beta A] \end{pmatrix}
\]

• $\tan \beta = \frac{v_2}{v_1}, \tan \alpha = O(v_2/v_1)$; $\beta, \alpha$ are very small. Two scalar doublets mix minimally in this setup.

• For $\alpha, \beta << 1 : \cos(\beta - \alpha) \sim 1, \sin(\beta - \alpha)$ is very small; alignment limit is readily attained.
• For relatively larger $\nu_2 \sim 0.1$ MeV, $y_\nu \sim 10^{-6}$ which introduce fine tuning again for neutrino masses; still smaller hierarchy than the SM.

• The $\Phi_1$ vev $\nu_1 \sim 250$ GeV gives mass to from top to $\mu$, varying the Yukawa coupling $y \sim 1$ to $y \sim 10^{-3}$, requiring fine tuning of order $10^{-3}$ is required, which is an improvement.

• $\ell_\alpha \rightarrow \ell_\beta \gamma$:
  - MEG-2 (1303,0754) puts strongest constraints on the LFV processes as $\text{BR}(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13}$. 
  - 1510.04284
    - That translates to the tightest LFV constraint $\frac{1}{G_F m_{H^\pm}^2} \lesssim 1.2 \text{eV}^{-2}$ which does not put any significant bound for relatively larger $\nu_2 \sim \text{MeV}$ in this case.
  - Other LFV constraints of this kind do not put any lower bound on $m_{H^\pm}$.
    - Allowing smaller values of $m_{H^\pm}$ has implication on NSI values.

• $\tau(\mu) \rightarrow 3e$: The LFV decays like $\tau(\mu) \rightarrow 3e$ are possible in the modified $\nu_2$HDM through the neutral scalar ($H, A$) mediation at tree level, putting stringent constraints on the Yukawa couplings.
LEP Constraints

- **Charged Higgs mass**: $H^\pm$ decays mostly to the leptonic channels $H^\pm \rightarrow l\nu$, where the LEP bound is $m_{H^\pm} > 80$ GeV.

- **Constraint from $e^+e^- \rightarrow l^+l^-$**: Measurement of $e^+e^- \rightarrow e^+e^-$ cross section at LEP can be expressed in terms of a limit on the scale of an effective 4e interaction as $\Lambda > 9.1$ TeV ([SLD EW result](1301.6065)) which for this case, with

\[ \mathcal{L}_{\text{eff}} \supset \frac{y_e^2}{4m_H^2} (\bar{e}_L \gamma \rho e_L)(\bar{e}_R \gamma \rho e_R), \]

translates to $y_e^2 \leq 8\pi m_H^2/\Lambda^2$.

- Limits on other Yukawas $y_1, y_2$ appear from LEP measurement in other processes like, $e^+e^- \rightarrow \mu^+(\tau^+)\mu^- (\tau^-)$.

- **Mono-photon Constraint**: The mono-photon signal $e^+e^- \rightarrow \text{DM DM} \gamma$ used in LEP DM search can occur in modified $\nu 2HDM$ as, $e^+e^- \rightarrow \nu_e/\tau \nu_e/\tau \gamma$ through the charged Higgs exchange. That translates to,

\[ y_e^4 + 2y_e^2y_2^2 + y_2^4 \leq \frac{16m_{H^\pm}^4}{\Lambda_{DM}^4}, \]

with $\Lambda_{DM} \approx 320$ GeV. 

Kopp et al
Results

- For $\mu \rightarrow 3e$ decay with $\text{BR}(\mu \rightarrow 3e) \leq 1 \times 10^{-12}$ will put bound on $y_1$ for moderate $y_e$ and allowed $m_H$ values, as $y_1 \sim 10^{-6}$.

- $\tau \rightarrow 3e$ is a tighter bound on $y_e$-$y_2$ plane compared to the LEP $e^+ e^- \rightarrow l^+ l^-$ and LEP mono-photon constraints.

![Graph showing constraints on $y_2$ vs $v_2$ (MeV)]
Other Constraints

- **(g-2):** The $H^\pm$ contribution to muon and electron g-2 at one loop is negligible due to a suppression factor $m_l^4/m_{H^\pm}^2$. Unlike a 2HDM, two loop contributions are tiny as charged lepton couplings to $H,A$ are suppressed by a factor $\tan \beta$ in $\nu 2HDM$.

- **S and T parameter:** Presence of a sufficiently heavy scalar does not contribute much to the $S$ parameter and therefore makes this case better than a $Z_2$ symmetric $\nu 2HDM$. The $H^\pm$ and $A$ mass difference is zero; modification to $T$ negligible.

- **BBN:** Constraint from $\Delta N_{\text{eff}} \equiv N_{\text{eff}} - 3.046 = 0.10^{+0.44}_{-0.43}$ (Planck) translates to

  $$y_{\nu_i} \leq 0.05 \times \left[ \frac{m_{H^\pm}}{100 \text{ GeV}} \right] \left[ \frac{1/\sqrt{2}}{|U_{ei}|} \right] .$$

  which, in the modified $\nu 2HDM$, is trivially satisfied due to the larger values of $\nu_2 \sim 0.1 \text{ MeV}$.

- **Higgs invisible Width, Higgs diphoton Decay etc**
New vertex present: $\bar{\nu}_e L H^+ e_R$ with vertex factor $\frac{m_e}{v^2}$. Other vertices like $y_1 \bar{\nu}_\mu L H^+ e_R$, $y_2 \bar{\nu}_\tau L H^+ e_R$ will also be present.

The effective vertex that appears from the t-channel diagrams:

$$L_{ee} = \frac{m_e^2}{v^2} \frac{1}{m_{H^+}^2} (\bar{\nu}_e L e_R) (\bar{e}_R \nu_e L)$$
NSI in modified $\nu 2$HDM

- After a fierz transformation the effective Lagrangian reads:

$$L_{ee} = \frac{1}{4} \frac{m_e^2}{v^2} \frac{1}{m_{H^+}^2} (\bar{\nu}_e \gamma^\alpha \nu_{eL}) (\bar{\nu}_{eR} \gamma^\alpha \nu_{eL})$$

- As $e$ is the only fermion involved, NSI definition gives,

$$\epsilon_{ee} = \frac{1}{4} \frac{m_e^2}{v^2} \frac{1}{m_{H^+}^2} \frac{1}{2\sqrt{2} G_F}$$

$$\epsilon_{e\mu} = \frac{1}{2\sqrt{2} G_F} \frac{y_e y_1}{4 m_{H^\pm}^2}, \quad \epsilon_{e\tau} = \frac{1}{2\sqrt{2} G_F} \frac{y_e y_2}{4 m_{H^\pm}^2},$$
NSI Constraints and Results

- The model-independent bounds on NSI parameters are

\[ |\epsilon_{ee}| < 4.2, \ |\epsilon_{e\mu}| < 0.33, \ |\epsilon_{e\tau}| < 3.0, \]
\[ |\epsilon_{\mu\mu}| < 0.07, \ |\epsilon_{\mu\tau}| < 0.33, \ |\epsilon_{\tau\tau}| < 21. \]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Benchmark Point-I</th>
<th>Benchmark Point-II</th>
<th>Benchmark Point-III</th>
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<tbody>
<tr>
<td>(v_2)</td>
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<td>3 MeV</td>
<td>5 MeV</td>
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<tr>
<td>(\epsilon_{ee})</td>
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<td>0.042-0.066</td>
<td>0.015-0.024</td>
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- The charged Higgs mass is varied from 80 GeV to 100 GeV, keeping in mind mass splitting allowed from oblique parameter considerations and mass splitting required for satisfying LEP limit.

<table>
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<th>BP-I ((v_2 = 2.5) MeV)</th>
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<tr>
<td>(y_2)</td>
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<td>(\epsilon_{e\tau})</td>
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<tr>
<th>BP-II ((v_2 = 3.0) MeV)</th>
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<tr>
<td>(\epsilon_{e\tau})</td>
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- The modified Hamiltonian in presence of propagation NSI, in the flavor basis:

\[ H = \frac{1}{2E} \left[ U \text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) U^\dagger + \text{diag}(A, 0, 0) + A\epsilon_{\alpha\beta} \right], A \equiv 2\sqrt{2}G_F N_e E. \]
Appearance Probability at DUNE

- For normal hierarchy (NH) neutrino mode:

\[ P_{\mu e} = x^2 f^2 + 2xyfg \cos(\Delta + \delta_{CP}) + y^2 g^2 \]

\[ + 4\hat{A}\epsilon_{e\tau}s_{23}c_{23}\{xf[f \cos(\phi_{e\tau} + \delta) - g \cos(\Delta + \delta + \phi_{e\tau})] - yg[g \cos \phi_{e\tau} - f \cos(\Delta - \phi_{e\tau})]\} \]

\[ + 4\hat{A}^2(g^2 + f^2)c_{23}^2|\epsilon_{e\tau}|^2 - 8\hat{A}^2fgs_{23}c_{23}\epsilon_{e\tau}^2 \cos \Delta \]

\[ + O(s_{13}^2, s_{13}^2\epsilon^2, \epsilon^3) \quad \text{for} \quad x = 2s_{13}s_{23}, \ y = 2rs_{12}c_{12}c_{23}, \]

\[ \Delta = \frac{\Delta m_{31}^2 L}{4E}, \ \hat{A} = \frac{A}{\Delta m_{31}^2}, \ f, \ \bar{f} = \frac{\sin[\Delta(1 \mp \hat{A}(1 + \epsilon_{ee}))]}{(1 \mp \hat{A}(1 + \epsilon_{ee}))}, \ g = \frac{\sin[\hat{A}(1 + \epsilon_{ee})\Delta]}{\hat{A}(1 + \epsilon_{ee})} \]

- For inverted hierarchy (IH): \( \Delta m_{31}^2 \rightarrow -\Delta m_{31}^2 \). For antineutrino probability \( \hat{A} \rightarrow -\hat{A} \).
• Appearance channel probability suffers with degeneracy due to the presence of intrinsic \((\text{NH}, \epsilon_{ee}) \rightarrow (\text{IH}, -\epsilon_{ee} - 2)\), and \((\text{NH}, \delta_{CP}) \rightarrow (\text{IH}, \pi - \delta_{CP})\) degeneracy in presence of model-independent NSI parameters.
  
  Marfatia, 2016; Coloma, 2016

• In our model-dependent constrained parameter space of \(\epsilon_{ee}\), DUNE has no hierarchy degeneracy. The NH bands (blue, brown) have no intersection with IH bands (yellow, red).

• We also observe that \(P_{\mu e}\) has no hierarchy degeneracy even in the presence of off-diagonal NSI parameter, \(\epsilon_{e\tau}\).

• Similar results are also observed for antineutrinos as shown by right panel and conclusion made for neutrinos remain same for antineutrinos.

• For allowed values of \(\epsilon_{ee}\) values, DUNE has no octant degeneracy. In presence of off-diagonal NSI parameter \(\epsilon_{e\tau}\), non-degeneracy of octant is not very clear for inverted hierarchy for neutrino mode and for normal hierarchy for anti-neutrino mode.
\[ \chi^2_{\text{NH-IF}} = \min \sum_i \left[ \frac{N_i(\text{NH}^\text{tr}, \epsilon^\text{tr}, \phi^\text{tr}) - N_i(\text{IH}^\text{te}, \epsilon^\text{te}, \phi^\text{tr})}{\sigma[N_i(\text{NH}^\text{tr}, \epsilon^\text{tr}, \phi^\text{tr})]^2} \right]^2 \]

- With standard neutrino interaction DUNE can reach 5\(\sigma\) sensitivity for higher octant for both NH, IH for all \(\delta_{\text{CP}}\) values. For lower octant 5\(\sigma\) is reached for all values except \(\delta_{\text{CP}} = +90^\circ\).
- Presence of \(\epsilon_{ee}\) increases DUNE sensitivity. Considering \(\epsilon_{e\tau}\) with CP conservation pushes the DUNE sensitivity over 5\(\sigma\) for all \(\delta_{\text{CP}}\) values.
- For NH, CP violating phases \((\phi_e = -90^\circ)\) worsens the sensitivity while for IH, it improves sensitivity for positive \(\delta_{\text{CP}}\) values.
CPV Sensitivity

\[ \chi^2_{\text{CPV}} = \min \sum_i \left[ \frac{N_i(\delta_{CP}^{\text{tr}}, \epsilon_{\text{tr}}, \phi_{\text{tr}}) - N_i(\delta_{CP}^{\text{te}}, \epsilon_{\text{te}}, \phi_{\text{tr}})}{\sigma[N_i(\delta_{CP}^{\text{tr}}, \epsilon_{\text{tr}}, \phi_{\text{tr}})]^2} \right]^2 \]

- DUNE achieves maximum CP violation discovery sensitivity for SI compared to when NSIs are present.
- Including diagonal NSI parameter \( \epsilon_{ee} \), the CPV sensitivity remain almost similar to SI case.
- For NH, CPV sensitivity considerbably decreases when off-diagonal NSI \( \epsilon_{e\tau} \) is added with \( \epsilon_{ee} \). For IH, presence of CP violating phase enhances the sensitivity.
Summary and Conclusion

• We can have sizable NSI parameter while maintaining LFV constraints, by assigning a charge to $e_R$ under a global U (1) symmetry.

• Allowed range of different NSI parameter values cuts short in electrophilic $\nu 2$HDM, due to tight constraints from LFV and LEP constraints.

• The effect of any NSI parameter involving $y_1$, i.e. $\epsilon_{\mu\mu}, \epsilon_{e\mu}$ etc become negligible, leaving $\epsilon_{e\tau}$ as only dominant off-diagonal NSI parameter.

• Inclusion of NSI parameter with extra CP phase confuses the Dirac CP measurement and therefore affects overall CP violatlon sensitivity.

• At the probability level, considering model-dependent NSIs, we observe no wrong hierarchy degeneracy even in the presence of off-diagonal NSI parameter.
Thank You