NSI in Electrophilic ν2HDM

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based on "**Non-standard Neutrino Interactions in a Modified ν2HDM**", Ujjal Dey, Newton Nath and Soumya Sadhukhan, Phys.Rev. D98 (2018) no.5, 055004

Introduction

• 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.

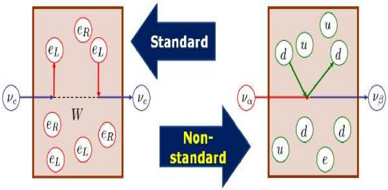
• Physics beyond the SM can appear in the form of new couplings involving neutrinos, which are usually referred to as non-standard neutrino interactions (NSIs).

• 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

$$L_{\mathrm{NSI}} = (\overline{\nu}_a \gamma^\alpha P_L \nu_b)(\bar{f}\gamma_\alpha P_c f) 2\sqrt{2} G_F \epsilon_{ab}^{fc} + \text{h.c.}$$

where $\epsilon_{\alpha\beta} = \sum_{f,C} \epsilon_{\alpha\beta}^{fC} \dfrac{N_f}{N_e}$ are NSI parameters, $a, b = e, \mu, \tau$, $c = L, R$, $f = u, d, e$.

ν two Higgs doublet model

• Symmetry of model: SM gauge symmetry $\times$ global $U(1)$ symmetry

Davidson, Logan

• SM + Second Higgs doublet (Φ_2) and a right handed neutrino ν_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 Φ_2.

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

• The neutrinos acquire masses much smaller than those of the quarks and charged leptons due to the tiny vev of Φ_2, when the global $U(1)$ is broken. In general ν2HDM, we require $v_2 \sim$ eV.

• This set up does not give rise to any NSI effects.

Electrophilic ν2HDM

• Here, along with Φ_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 Φ_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 $v_2 \sim 0.1$ MeV.

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

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

• $U(1)$ symmetry: λ_5 is zero. So the CP even scalar mass (m_H) is equal to CP odd scalar mass (m_A).

ν2HDM: Scalar sector

• In a CP-conserving 2HDM with a softly broken $U(1)$ symmetry, scalar potential is:

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

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

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

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

• For $\alpha, \beta << 1 : \cos(\beta - \alpha) \sim 1, \sin(\beta - \alpha)$ is very small; alignment limit is readily attained.

Fermion Mass Hierarchy and LFV Constraints

• For relatively larger $v_2 \sim 0.1$ MeV, $y_\nu \sim 10^{-6}$ which introduce fine tuning again for neutrino masses; still smaller hierarchy than the SM.

• The Φ_1 vev $v_1 \sim 250$ GeV gives mass to from top to μ, 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.

• $\ell_\alpha \to \ell_\beta \gamma$:

- MEG-2 (1303,0754) puts strongest constraints on the LFV processes as $\mathrm{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$. 1510.04284
- That translates to the tightest LFV constraint $\frac{1}{G_F m_{H^\pm}^2 v_2^2} \lesssim 1.2\,\mathrm{eV}^{-2}$ which does not put any significant bound for relatively larger $v_2 \sim$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.

• $\tau(\mu) \to 3e$: The LFV decays like $\tau(\mu) \to 3e$ are possible in the modified ν2HDM 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 $H^{\pm} \to l\nu$, where the LEP bound is $m_{H^{\pm}} > 80$ GeV. 1301.6065

• **Constraint from $e^+e^- \to l^+l^-$:** Measurement of $e^+e^- \to e^+e^-$ 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) 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, $e^+e^- \to \mu^+(\tau^+)\mu^-(\tau^-)$.

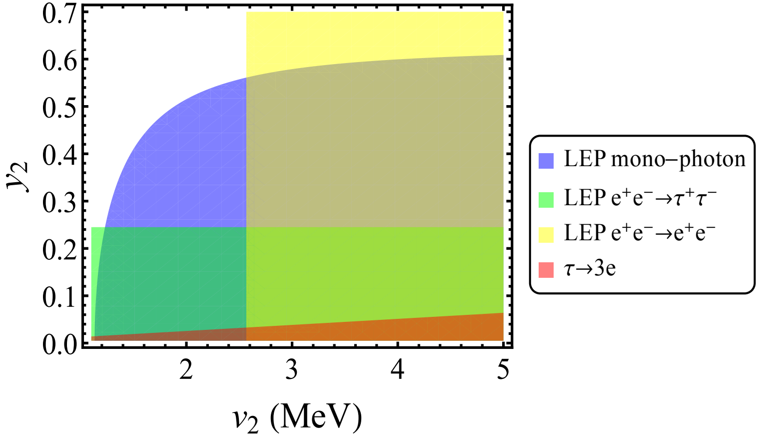
• **Mono-photon Constraint:** The mono-photon signal $e^+e^- \to$ DM DM γ used in LEP DM search can occur in modified ν2HDM as, $e^+e^- \to \nu_{e/\tau}\nu_{e/\tau}\gamma$ through the charged Higgs exchange. That translates to,

$$y_e^4 + 2y_e^2 y_2^2 + y_2^4 \leq \frac{16 m_{H_{\pm}}^4}{\Lambda_{DM}^4},$$

with $\Lambda_{DM} \approx 320$ GeV. Kopp et al

Results

- For $\mu \to 3e$ decay with $\text{BR}(\mu \to 3e) \leq 1 \times 10^{-12}$ will put bound on y_1 for moderate y_e and allowed m_H values, as $y_1 \sim 10^{-6}$.
- $\tau \to 3e$ is a tighter bound on y_e-y_2 plane compared to the LEP $e^+e^- \to l^+l^-$ and LEP mono-photon constraints.



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 ν2HDM.

• **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 ν2HDM. The $H^{\pm}$ and A mass difference is zero; modification to T negligible.

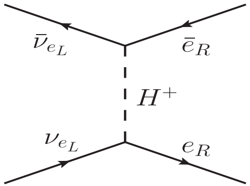
• **BBN:** Constraint from $\Delta N_{\rm eff} \equiv N_{\rm eff} - 3.046 = 0.10^{+0.44}_{-0.43}$ (Planck) translates to Davidson, Logan

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

, which, in the modified ν2HDM, is trivially satisfied due to the larger values of $v_2 \sim 0.1$ MeV.

• **Higgs invisible Width, Higgs diphoton Decay** etc

NSI in modified ν2HDM



- New vertex present: $\bar{\nu_{eL}} H^+ e_R$ 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:

$$L_{ee} = \frac{m_e^2}{v_2^2} \frac{1}{m_{H^+}^2} \left(\bar{\nu}_{eL} e_R\right) \left(\bar{e}_R \nu_{eL}\right)$$

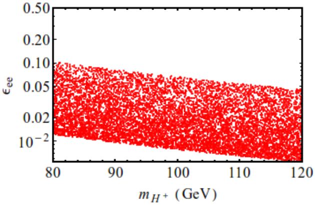
NSI in modified ν2HDM

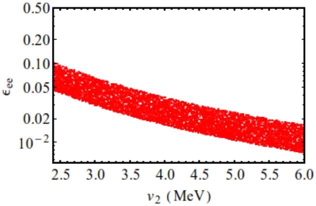
- After a fierz transformation the effective Lagrangian reads:

$$L_{ee} = \frac{1}{4}\frac{m_e^2}{v_2^2}\frac{1}{m_{H^+}^2}\left(\bar{\nu}_{eL}\gamma^\alpha\nu_{eL}\right)\left(\bar{e}_R\gamma_\alpha e_R\right)$$

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

$$\epsilon_{ee} = \frac{1}{4}\frac{m_e^2}{v_2^2}\frac{1}{m_{H^+}^2}\frac{1}{2\sqrt{2}G_F}$$





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

NSI Constraints and Results

- The model-independent bounds on NSI parameters are Ohlsson

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

Parameters	Benchmark Point-I	Benchmark Point-II	Benchmark Point-III
v_2	2.5 MeV	3 MeV	5 MeV
ϵ_{ee}	0.061-0.095	0.042-0.066	0.015-0.024

- 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.

BP-I ($v_2 = 2.5$ MeV)			
y_2	0.01	0.02	0.035
$\epsilon_{e\tau}$	0.0021 - 0.0033	0.0043 - 0.0067	0.0075 - 0.0117
BP-II ($v_2 = 3.0$ MeV)			
y_2	0.01	0.02	0.04
$\epsilon_{e\tau}$	0.0018 - 0.0028	0.0036 - 0.0056	0.0071 - 0.011

- The modified Hamiltonian in presence of propagation NSI, in the flavor basis:

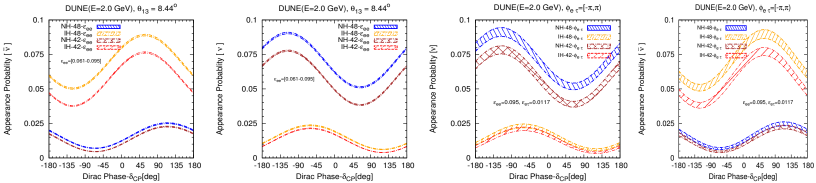
$$H = \frac{1}{2E}\left[U\mathrm{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})U^\dagger + \mathrm{diag}(A, 0, 0) + A\epsilon_{\alpha\beta}\right] \,, A \equiv 2\sqrt{2}G_F N_e E.$$

Appearance Probability at DUNE

- For normal hierarchy (NH) neutrino mode: Marfatia

$$\begin{aligned}
P_{\mu e} &= x^2 f^2 + 2xyfg\cos(\Delta+\delta_{CP}) + y^2 g^2 \\
&+ 4\hat{A}\epsilon_{e\tau} s_{23} c_{23}\{xf[f\cos(\phi_{e\tau}+\delta) - g\cos(\Delta+\delta+\phi_{e\tau})] - yg[g\cos\phi_{e\tau} - f\cos(\Delta-\phi_{e\tau})]\} \\
&+ 4\hat{A}^2(g^2+f^2)c_{23}^2 s_{23}^2|\epsilon_{e\tau}|^2 - 8\hat{A}^2 fg s_{23} c_{23} c_{23}\epsilon_{e\tau}^2\cos\Delta \\
&+ \mathcal{O}(s_{13}^2\epsilon, s_{13}\epsilon^2, \epsilon^3) \qquad \text{for} \quad x = 2s_{13}s_{23},\; y = 2r s_{12}c_{12}c_{23}, \\
\Delta &= \frac{\Delta m_{31}^2 L}{4E},\; \hat{A} = \frac{A}{\Delta m_{31}^2},\; f,\,\bar{f} = \frac{\sin[\Delta(1\mp\hat{A}(1+\epsilon_{ee}))]}{(1\mp\hat{A}(1+\epsilon_{ee}))},\; g = \frac{\sin[\hat{A}(1+\epsilon_{ee})\Delta]}{\hat{A}(1+\epsilon_{ee})}
\end{aligned}$$

- For inverted hierarchy (IH): $\Delta m_{31}^2 \to -\Delta m_{31}^2$. For antineutrino probability $\hat{A} \to -\hat{A}$.



Results

• Appearance channel probability suffers with degeneracy due to the presence of intrinsic $(\mathrm{NH}, \epsilon_{ee}) \to (\mathrm{IH}, -\epsilon_{ee} - 2)$, and $(\mathrm{NH}, \delta_{CP}) \to (\mathrm{IH}, \pi - \delta_{CP})$ degeneracy in presence of model-independent NSI parameters.

Marfatia, 2016; Coloma, 2016

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

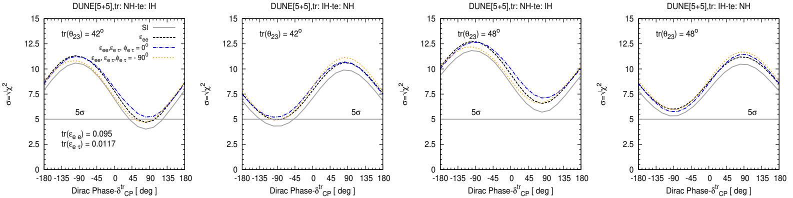
• We also observe that $P_{\mu e}$ has no hierarchy degeneracy even in the presence of off-diagonal NSI parameter, $\epsilon_{e\tau}$.

• 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 ϵ_{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.

Hierarchy Sensitivity

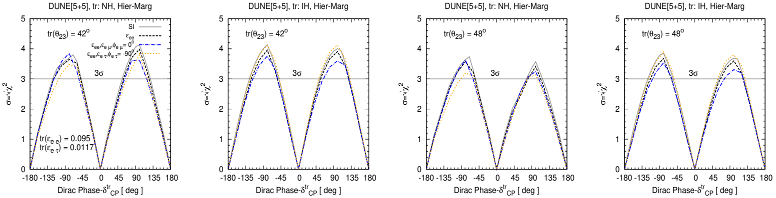
$$\chi^2_{\mathrm{NH-IH}} = \min \sum_i \frac{\left[N_i(\mathrm{NH^{tr}}, \epsilon^{\mathrm{tr}}, \phi^{\mathrm{tr}}) - N_i(\mathrm{IH^{te}}, \epsilon^{\mathrm{te}}, \phi^{\mathrm{tr}})\right]^2}{\sigma[N_i(\mathrm{NH^{tr}}, \epsilon^{\mathrm{tr}}, \phi^{\mathrm{tr}})]^2}$$



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

CPV Sensitivity

$$\chi^2_{\rm CPV} = \min \sum_i \frac{[N_i(\delta^{\rm tr}_{CP}, \epsilon^{\rm tr}, \phi^{\rm tr}) - N_i(\delta^{\rm te}_{CP}(0^\circ, \pm 180^\circ), \epsilon^{\rm te}, \phi^{\rm tr})]^2}{\sigma[N_i(\delta^{\rm tr}_{CP}, \epsilon^{\rm tr}, \phi^{\rm tr})]^2}$$



• DUNE achieves maximum CP violation discovery sensitivity for SI compared to when NSIs are present.

• Including diagonal NSI parameter ϵ_{ee}, the CPV sensitivity remail almost similar to SI case.

• For NH, CPV sensitivity considerbaly decreases when off-diagonal NSI $\epsilon_{e\tau}$ is added with ϵ_{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 ν2HDM, 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 violaton 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