Radiatively-induced LFV Higgs Decays from Massive ISS Neutrinos

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References

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Motivation

Signals of new physics

- Discovery of SM Higgs boson: $m_h^{\text{ATLAS}} = 125.5 \pm 0.6$ GeV [ATLAS, 2012] and $m_h^{\text{CMS}} = 125.7 \pm 0.4$ GeV [CMS, 2012], $J^P = 0^+$, $\Gamma_h < 17.4$ MeV (4.2 times the SM value).
- Some years ago, first signal of BSM physics: LFV in neutrino oscillations.
- SM must be modified to include $\nu$’s masses and oscillations according to data.
- Simplest extensions: seesaw models can induce non-zero contributions to LFV processes via radiative corrections mediated by $Y_\nu$ couplings.

Open possibility of exploring at the LHC

LFV Higgs decays (LFVHD): $H \rightarrow \mu e, \tau e, \tau \mu$. 
Introduction

- Inverse Seesaw Model (ISS) extends SM adding pairs of RH neutrinos with opposite lepton number, whose masses and couplings produce correct physical light neutrino masses and oscillations.
- Smallness of light neutrino masses is associated to smallness of Majorana mass parameters (in contrast to Type-I seesaw).
- ISS allows large $Y_\nu$ with RH neutrinos masses of $\mathcal{O}(\text{TeV})$ reachable at present colliders, leading to new rich LFV phenomenology.
- Full 1-loop computation of LFV partial decay widths, $\Gamma(H \rightarrow l_k \bar{l}_m)$, within ISS context with 3 extra pairs of RH neutrinos.
The Inverse Seesaw Model

ISS extends SM Lagrangian with the following neutrino Yukawa interactions and mass terms of fermionic gauge singlets $\nu_{Ri}$ ($L = +1$) and $X_i$ ($L = -1$) [Mohapatra and Valle, 1986],

$$\mathcal{L}_{\text{ISS}} = -Y_{\nu}^{ij} \bar{L}_i \tilde{\Phi} \nu_{Rj} - M_{Ri}^{ij} \nu_{Ri}^C X_j - \frac{1}{2} \mu_X^{ij} X_i^C X_j + h.c.,$$

(1)

where

- $M_R$ is a lepton number conserving complex $3 \times 3$ mass matrix,
- $\mu_X$ is a Majorana complex $3 \times 3$ symmetric mass matrix that violates lepton number conservation by 2 units.

After EW symmetry breaking, the $9 \times 9$ neutrino mass matrix in the EW basis ($\nu_L^C$, $\nu_R$, $X$) reads

$$M_{\text{ISS}} = \begin{pmatrix}
0 & m_D & 0 \\
0 & m_T^D & M_R \\
m_T^D & 0 & M_R^T \\
0 & M_R & \mu_X
\end{pmatrix}.$$  

(2)

In the one generation case, the mass eigenvalues are given by:

$$m_\nu = \frac{m_D^2}{m_D^2 + M_R^2} \mu_X, \quad m_{N_1,N_2} = \pm \sqrt{M_R^2 + m_D^2} + \frac{M_R^2 \mu_X}{2(m_D^2 + M_R^2)}. \quad (3)$$
The Inverse Seesaw Model

By means of the Casas-Ibarra parametrization [Casas and Ibarra, 2001]:

\[ m^T_D = V^\dagger \text{diag}(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3}) \ R \ \text{diag}(\sqrt{m_{\nu_1}}, \sqrt{m_{\nu_2}}, \sqrt{m_{\nu_3}}) U_{\text{PMNS}}^\dagger, \]

where \( V \) diagonalizes \( M = M_R \mu^{-1}_X M^T_R \), \( U_{\text{PMNS}} \) diagonalizes \( M_{\text{light}} \approx m_D M^T_R \mu X M^{-1}_R m^T_D \), and \( R \) is:

\[
R = \begin{pmatrix}
    c_2 c_3 & -c_1 s_3 - s_1 s_2 c_3 & s_1 s_3 - c_1 s_2 c_3 \\
    c_2 s_3 & c_1 c_3 - s_1 s_2 s_3 & -s_1 c_3 - c_1 s_2 s_3 \\
    s_2 & s_1 c_2 & c_1 c_2
\end{pmatrix}
\]

(4)

where \( c_i \equiv \cos \theta_i \) and \( s_i \equiv \sin \theta_i \) with \( \theta_1, \theta_2 \) and \( \theta_3 \) complex angles.

Input ISS parameters

- Light neutrino masses \( m_{\nu_1,2,3} \).
- \( \mu_X = \text{diag}(\mu_X_1, \mu_X_2, \mu_X_3) \).
- \( M_R = \text{diag}(M_{R_1}, M_{R_2}, M_{R_3}) \).
- \( R \)-matrix complex angles \( \theta_{1,2,3} \).
- \( \text{PMNS} \)-matrix angles \( \theta_{12}, \theta_{13}, \theta_{23} \) and \( \delta \).
Remarks on the LFVHD computation: 1-loop diagrams

- Calculated in the Feynman-’t Hooft gauge.
- Formulae taken from [Arganda et al., 2005] and adapted for ISS.
- Diagrams 1, 8 and 10 dominant at large $M_R$. 
Remarks on the LFVHHD computation: constraints

- Perturbatibity of Yukawa couplings: $\frac{|Y_{ij}|^2}{4\pi} < 1.5$.
- Neutrino data: differences between input $m_{\nu 1,2,3}$ and output $m_{\nu 1,2,3}$ below 10% and unitarity of $U_\nu$.
- Predictions of LFV radiative decays compatible with their present experimental 90% C.L. upper bounds:
  \[
  \begin{align*}
  \text{BR}(\mu \to e\gamma) & \leq 5.7 \times 10^{-13} \text{ [MEG, 2013]}, \\
  \text{BR}(\tau \to e\gamma) & \leq 3.3 \times 10^{-8} \text{ [BaBar, 2010]}, \\
  \text{BR}(\tau \to \mu\gamma) & \leq 4.4 \times 10^{-8} \text{ [BaBar, 2010]}. 
  \end{align*}
  \]
- Invisible Higgs decays: Higgs decay into sterile neutrinos kinematically closed ($M_R > 200$ GeV).
- EDMs: zero with real PMNS and mass matrices.
- Lepton Flavor Universality: less constraining than $\mu \to e\gamma$ decay.

Most stringent constraints:
Yukawa coupling perturbatibitivity and $\mu \to e\gamma$ upper bound.
Dependence of LFV rates on $M_R$

$\text{BR} \ (H \to l_k \bar{l}_m)$

$\text{BR} \ (l_m \to l_k \gamma)$

Dotted lines: non-perturbative Yukawa couplings.
Horizontal dashed lines: upper bounds of LFV radiative decays.

- Enhancement from $Y_\nu$ of $\mathcal{O}(1)$ and neutrino masses at TeV scale.
- Dips in LFVHD coming from interferences between diagrams.
- Apparent non decoupling in radiative decays: artefact originating from Casas-Ibarra parametrization.
- All LFV rates allowed by data with this choice of ISS parameters.
Behavior of LFV rates at large $M_R$

- Radiative decays constant with $M_R$ since $|\langle Y_\nu Y_{\nu}^{\dagger}\rangle_{km}|^2$ grow as $M_R^4$.
- LFVHD fit reproduces extremely well contributions from dominant diagrams.
- LFVHD fit also pretty good to reproduce the two different $M_R$ regions: flat or $\sim M_R^4$. 
Dependence of LFV rates on $\mu_X$

- Both LFV rates decrease as $\mu_X$ grows: radiative decays as $\mu_X^{-2}$; LFVHD as $\mu_X^{-4}$ for large $Y_\nu$ and as $\mu_X^{-2}$ for small $Y_\nu$.
- Dips: consequence of destructive interferences among the various contributing diagrams.
- Smallest value of $\mu_X$ allowed by $\mu \to e\gamma$ upper bound is $\sim 10^{-8}$ GeV.

Dotted lines: non-perturbative Yukawa couplings.
Horizontal red dashed line: upper bound of $\mu \to e\gamma$.

$m_{\nu_1} = 0.1$ eV
$R = I$
Maximum allowed LFVHD rates: degenerate case

$\log_{10} \text{BR}(H \to \mu \tau)$

Excluded by $\mu \to e\gamma$
Non-perturbative $Y_\nu$

Maximum allowed LFVHD rate is $\text{BR}(H \to \mu \bar{\tau}) \sim 10^{-10}$ for $M_R \sim 2 \times 10^4$ GeV and $\mu_X \sim 5 \times 10^{-8}$ GeV.
Searching for the largest LFVHD: full scan

Excluded by $\mu \rightarrow e\gamma$. Allowed by all the constraints.

- $M_R$ diagonal, real and degenerate; $\mu_X$ non-diagonal, real, random and degenerate.
- Largest LFVHD rates: $\text{BR}(H \rightarrow \mu \bar{\tau}) \sim 10^{-10}$, $\text{BR}(H \rightarrow e \bar{\tau}) \sim 10^{-10}$ and $\text{BR}(H \rightarrow e \bar{\mu}) \sim 10^{-13}$. No enhancement in complex case.
Maximum allowed LFVHHD rates: hierarchical case

Log_{10} BR (H \rightarrow \mu \bar{\tau})

Excluded by $\mu \rightarrow e\gamma$

Non-perturbative $Y_\nu$

Enhancement of one order of magnitude compared to degenerate case:
\[ \text{BR}(H \rightarrow \mu \bar{\tau}) \sim 10^{-9}. \]
Conclusions

• Detailed study of LFVHD within the ISS context with 3 pairs of right-handed singlet neutrinos.
• Most relevant ISS parameters: $M_{R_{1,2,3}}$ and $\mu_{X_{1,2,3}}$.
• Impressive enhancement of LFVHD rates with respect to Type-I seesaw predictions, due to $O(1) Y_\nu$ and TeV-scale neutrino masses.
• Largest rates: $\text{BR}(H \to \mu \bar{\tau}, e \bar{\tau}) \sim 10^{-10}$ (degenerate case) and $\text{BR}(H \to \mu \bar{\tau}, e \bar{\tau}) \sim 10^{-9}$ (hierarchical case). Larger values excluded by $\mu \to e\gamma$.

LFVHD rates, although many orders of magnitude larger than in other models of massive neutrinos, are however yet unreachable at present colliders.
Backup slides
Neutrino data

The lightest neutrino mass $m_{\nu_1}$ is assumed as a free input parameter in agreement with the upper limit on the effective electron neutrino mass in $\beta$ decays from the Mainz [C. Kraus et al., 2005] and Troitsk [V. N. Aseev et al., 2011] experiments,

$$m_\beta < 2.05 \text{ eV at 95\% CL}.$$  \hspace{1cm} (5)

The other two light masses are obtained from:

$$m_{\nu_2} = \sqrt{m_{\nu_1}^2 + \Delta m_{21}^2}, \quad m_{\nu_3} = \sqrt{m_{\nu_1}^2 + \Delta m_{31}^2}.$$ \hspace{1cm} (6)

For simplicity, we set to zero the CP-violating phase of the $U_{PMNS}$ matrix and we have used the results of the global fit [M. C. Gonzalez-Garcia et al., 2012] leading to:

$$\sin^2 \theta_{12} = 0.306^{+0.012}_{-0.012}, \quad \Delta m_{21}^2 = 7.45^{+0.19}_{-0.16} \times 10^{-5} \text{ eV}^2,$$

$$\sin^2 \theta_{23} = 0.446^{+0.008}_{-0.008}, \quad \Delta m_{31}^2 = 2.417^{+0.014}_{-0.014} \times 10^{-3} \text{ eV}^2,$$

$$\sin^2 \theta_{13} = 0.0231^{+0.0019}_{-0.0019},$$ \hspace{1cm} (7)

where we have assumed a normal hierarchy.
Examples of ISS neutrino mass spectrum

<table>
<thead>
<tr>
<th>ISS examples</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{R_1}$ (GeV)</td>
<td>$1.5 \times 10^4$</td>
<td>$1.5 \times 10^2$</td>
<td>$1.5 \times 10^2$</td>
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<tr>
<td>$M_{R_2}$ (GeV)</td>
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<td>$1.5 \times 10^3$</td>
<td>$1.5 \times 10^3$</td>
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<tr>
<td>$M_{R_3}$ (GeV)</td>
<td>$1.5 \times 10^4$</td>
<td>$1.5 \times 10^4$</td>
<td>$1.5 \times 10^4$</td>
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<tr>
<td>$\mu X_{1,2,3}$ (GeV)</td>
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<td>$5 \times 10^{-8}$</td>
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<td>$m_{\nu_1}$ (eV)</td>
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<td>0.1</td>
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<td>$\theta_{1,2,3}$ (rad)</td>
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<td>0, 0, 0</td>
<td>$\pi/4, 0, 0$</td>
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<td>$</td>
<td>(Y_\nu Y^{\dagger}<em>\nu)</em>{23}</td>
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<tr>
<td>$</td>
<td>(Y_\nu Y^{\dagger}<em>\nu)</em>{12}</td>
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<tr>
<td>$</td>
<td>(Y_\nu Y^{\dagger}<em>\nu)</em>{13}</td>
<td>$</td>
<td>0.2</td>
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Relevant neutrino interactions for LFVHD

Following the notation in [A. Ilakovac and A. Pilaftsis, 1995] and [Arganda et al., 2005], the relevant interactions are given in the mass basis by the following terms of the Lagrangian:

\[
\mathcal{L}^{W\pm}_{\text{int}} = \frac{-g}{\sqrt{2}} W^\mu \bar{l}_i B_{l_i n_j} \gamma^\mu P_L n_j + h.c,
\]

\[
\mathcal{L}^H_{\text{int}} = \frac{-g}{2m_W} H \bar{n}_i C_{n_i n_j} [m_{n_i} P_L + m_{n_j} P_R] n_j,
\]

\[
\mathcal{L}^{G\pm}_{\text{int}} = \frac{-g}{\sqrt{2}m_W} G^- [\bar{l}_i B_{l_i n_j} (m_{l_i} P_L - m_{n_j} P_R) n_j] + h.c,
\]

where the coupling factors \( B_{l_i n_j} \) \((i = 1, 2, 3, j = 1, \ldots, 9)\) and \( C_{n_i n_j} \) \((i, j = 1, \ldots, 9)\) are defined in terms of the \( U_\nu \) matrix such that \( U_\nu^T M_{\text{ISS}} U_\nu = \text{diag}(m_{n_1}, \ldots, m_{n_9}) \) by:

\[
B_{l_i n_j} = U_{i j}^{\nu*},
\]

\[
C_{n_i n_j} = \sum_{k=1}^{3} U_{k i}^{\nu} U_{k j}^{\nu*}.
\]

(8)

(9)

(10)