Higgs Mediated LFV in the Supersymmetric Inverse Seesaw Model

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Plan

Motivations

- Neutrino oscillations = Neutral lepton flavour violation.
  Why not have charged lepton flavour violation (cLFV) ?
- cLFV arises from higher order processes
  $\Rightarrow$ negligible in the Standard Model
- If observed:
  - Clear evidence of physics at a higher scale
  - Probe the origin of lepton mixing
  - Probe the origin of new physics
- Complementary to (other) neutrino and collider experiments
  $\Rightarrow (g-2)_\mu$, EDM, U_{PMNS} non-unitarity, etc

Motivations

- BSM to generate $m_\nu \neq 0$
  - Radiative models
  - Extra dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanism $\rightarrow$ BAU through leptogenesis ?
- The SM doesn't only lack neutrino masses $\Rightarrow$ The hierarchy problem
  - Strongly coupled theories : Technicolor, Composite Higgs
  - Extra-dimensions : Randall-Sundrum, Large extra dimension
  - Extending the SM field content/gauge group : 2HDM, Little Higgs, 4th generation, etc
  - Supersymmetric extensions : MSSM, NMSSM $\rightarrow$ Gauge coupling unification, DM candidate, graviton in local SUSY

The Seesaw Mechanisms

- $m_\nu \neq 0 \Rightarrow$ New physics at a high scale ($>$ SM)
- Seesaw mechanism: Consider new fields at this scale ($\sim M_R$) and Majorana mass terms $\Rightarrow$ Generate m_ν in a renormalizable way
- Example: Type I seesaw $\mathcal{L}^{\text{leptons}}_{\text{mass}} = -Y^\ell \bar{L}\Phi\ell_R - Y^\nu \bar{L}\tilde{\Phi}\nu_R - \frac{1}{2}M_R\overline{\nu_R^C}\nu_R + \text{h.c.}$
  $\Rightarrow$ After EW symmetry breaking, a neutrino mass matrix appears $M^\nu_{6\times6}$

  $M^\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}$ $\quad$ $m_D = \text{v}Y^\nu$ Dirac mass matrix; M_R Majorana mass matrix $\rightarrow \text{Diag}\{m_{R_i}\}$

  $\Rightarrow$ Seesaw limit $M_R \gg m_D$

  $m_\nu^{\text{light}} \approx -m_D M_R^{-1} m_D^T$ $\quad$ $\nu^{\text{light}} \approx \nu_L + \nu_L^C$

  $m_\nu^{\text{heavy}} \approx M_R$ $\quad$ $\nu^{\text{heavy}} \approx \nu_R + \nu_R^C$
- M^ν symmetric (Majorana ν) $\Rightarrow M^\nu = Z D_\nu Z^\dagger$ with Z unitary matrix $Z = \begin{pmatrix} V & Y \\ X & W \end{pmatrix}$

  The same goes for M^ℓ the charged leptons mass matrix $\Rightarrow M^\ell = A_R D_\ell A_L^\dagger$ with $A_{R,L}$ unitary matrices

  $\Rightarrow U_{PMNS} = A_L^\dagger V$ leptonic mixing matrix (similar to V_{CKM})

Effective approach to seesaw mechanisms

- Notice that lepton number conservation is accidental in the SM (from the gauge group, field content and renormalizability)
- Need to violate L conservation to generate $m_\nu \Rightarrow$ Effective non-renormalizable operators
- Unique dimension 5 operator for all seesaw mechanisms $\rightarrow$ Violates lepton number L $\Rightarrow$ Majorana neutrinos

$$\delta\mathcal{L}^{d=5} = \frac{1}{2} c_{ij} \frac{(H \cdot L_i)^\dagger (H \cdot L_j)}{\Lambda} + \text{h.c.}$$

- To distinguish the several seesaw mechanisms, either
  - Directly produce the heavy states (LHC, ILC)
  - Look for dimension 6 (or higher) operators effects $\rightarrow$ LFV

The Inverse Seesaw Mechanism

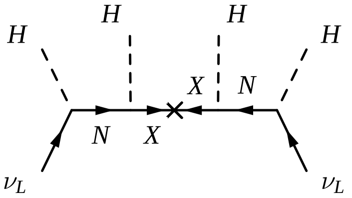
- Type I seesaw: $M_R \simeq 10^{14}$GeV with natural Yukawa $Y_\nu \sim \mathcal{O}(1)$ or $M_R \sim 1$TeV with Yukawa $Y_\nu \sim \mathcal{O}(10^{-6})$
  $\Rightarrow$ cLFV is suppressed
- Inverse seesaw: $M_R \simeq 1$ TeV with natural Yukawa $Y_\nu \sim \mathcal{O}(1)$
  $\Rightarrow$ cLFV is much less suppressed
  $\rightarrow$ Might be testable at the LHC and future B factories (SuperB)
- Inverse seesaw $\Rightarrow$ Consider fermionic gauge singlets N_i ($L = -1$, $i = 1, 2, 3$) and X_i ($L = +1$, $i = 1, 2, 3$) [Mohapatra and Valle, 1986]

$$\mathcal{L}_{inverse} = Y^\nu_{ij} H \cdot L_i N_j - (M_R)_{ij} N_i X_j - \frac{1}{2} (\mu_X)_{ij} X_i X_j + \text{h.c.}$$

With $m_D = Y^\nu \mathrm{v}$

$$m_\nu \approx \frac{m_D^2 \mu_X}{m_D^2 + M_R^2}$$

$$m_{1,2} \approx \mp\sqrt{m_D^2 + M_R^2} + \frac{M_R^2 \mu_X}{2(m_D^2 + M_R^2)}$$



The Minimal Supersymmetric Model

- Same gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$
- Field content $=$ SM fields and their SUSY partners
  $\Rightarrow$ Except for the Higgs sector $\rightarrow$ Up- and down-type Higgs
- More than a 100 free parameters, most of them from soft SUSY breaking terms
  $\Rightarrow$ Work in constrained frameworks (or find a SUSY breaking mechanism)
  - mSUGRA: 4 free parameters $m_{1/2}$, m_0, A_0 and $\text{sign}(\mu)$ $\rightarrow$ Nearly entirely excluded
  - Constrained MSSM: 5 free parameters $m_{1/2}$, m_0, A_0, $\tan(\beta)$ and $\text{sign}(\mu)$ $\rightarrow$ Very restrictive boundary conditions
  - Non-Universal Higgs Mass model (NUHM): 7 free parameters $m_{1/2}$, m_0, m_{H_u}, m_{H_d}, A_0, $\tan(\beta)$ and $\text{sign}(\mu)$ $\rightarrow$ Still verify the MFV paradigm

Supersymmetric Seesaw Models

- No ν_R in the MSSM $\Rightarrow m_\nu = 0$
  $\rightarrow$ Implement a seesaw mechanism
- Non diagonal neutrino Yukawa couplings
  $\Rightarrow$ LFV in the slepton mass matrices (radiatively induced)
  $\Rightarrow$ LFV at low energies through RGE
- Amount of cLFV proportional to the Yukawa couplings
  $\Rightarrow$ In the usual seesaw (type I), large scale to accommodate natural Yukawa couplings
  $\Rightarrow$ Impossible to directly produce ν_R
- Embed the inverse seesaw in the MSSM
  $\Rightarrow$ Natural Yukawa couplings with a TeV new Physics scale

The Supersymmetric Inverse Seesaw Model

- MSSM extended by singlet chiral superfields $\widehat{N}_i$ and $\widehat{X}_i$ ($i = 1, 2, 3$) with respectively $L = -1$ and $L = +1$
- Defined by the superpotential:

$$\mathcal{W} = \varepsilon_{ab}\Big[Y_d^{ij}\widehat{H}_d^a\widehat{Q}_i^b\widehat{D}_j + Y_u^{ij}\widehat{Q}_i^a\widehat{H}_u^b\widehat{U}_j + Y_e^{ij}\widehat{H}_d^a\widehat{L}_i^b\widehat{E}_j + Y_\nu^{ij}\widehat{L}_i^a\widehat{H}_u^b\widehat{N}_j - \mu\widehat{H}_d^a\widehat{H}_u^b\Big] + M_{R_i}\widehat{N}_i\widehat{X}_i + \frac{1}{2}\mu_{X_i}\widehat{X}_i\widehat{X}_i$$

- Derive one of the new couplings:

$$A_{Y_\nu}Y_\nu^{ij}\varepsilon_{ab}\widetilde{L}_i^a\widetilde{N}_jH_u^b + \text{h.c.} \in -\mathcal{L}$$

- Work with a flavour-blind mechanism for SUSY breaking
- Derive the right-handed sneutrino mass:

$$M_{\tilde{N}}^2 = m_{\tilde{N}}^2 + M_R^2 + Y_\nu^{ji*}Y_\nu^{ij}v_u^2 \sim M_{\text{SUSY}}^2 \sim (1\text{TeV})^2$$

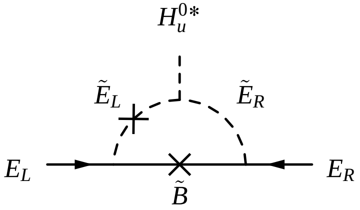
cLFV in Supersymmetric Seesaw Models

- In SUSY, cLFV appears at the one-loop level through RGE-induced slepton mixing $(\Delta m^2_{\tilde{L}})_{ij}$
  [Borzumati and Masiero, 1986, Hisano et al., 1996, Hisano and Nomura, 1999]
  $\Rightarrow (\Delta m^2_{\tilde{L}})_{ij} \propto (Y^\dagger_\nu Y_\nu)_{ij} \ln \frac{M_{GUT}}{M_R}$
- Contribute to all cLFV observables
  $\rightarrow$ Dominant in most of the SUSY seesaw models
- Type I seesaw ($Y_\nu \sim 1$, $M_R \sim 10^{14}$GeV) $\rightarrow (\Delta m^2_{\tilde{L}})_{ij} \propto 5$
- Inverse seesaw ($Y_\nu \sim 1$, $M_R \sim 1$TeV) $\rightarrow (\Delta m^2_{\tilde{L}})_{ij} \propto 30$
  $\rightarrow \tilde{N}$-mediated processes are no longer suppressed

Higgs-mediated cLFV

- Higgs mediated contributions dominant at large $\tan\beta = \frac{v_u}{v_d}$
  $\Rightarrow$ described by the effective Lagrangian [Babu and Kolda, 2002]

$$-\mathcal{L}^{\text{eff}} = \bar{E}_R^i Y_e^{ii} \left[\delta_{ij} H_d^0 + \left(\epsilon_1 \delta_{ij} + \epsilon_2 (Y_\nu^\dagger Y_\nu)_{ij}\right) H_u^{0*}\right] E_L^j + \text{h.c.}$$



Inverse seesaw

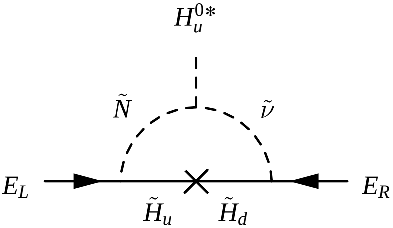
$$\epsilon_1 \simeq 0.003$$
$$\epsilon_2 \simeq -0.0002$$

Type I seesaw

$$\epsilon_1 \simeq 0.003$$
$$\epsilon_2 \simeq -0.00004$$

Higgs-mediated cLFV

- $M_{\tilde{N}} \sim 1\text{TeV} \Rightarrow$ New contribution, dominant in the SUSY Inverse Seesaw model



Inverse seesaw

$$\epsilon_2' \simeq -0.0006$$

Type I seesaw

$$\epsilon_2' \simeq -1 \times 10^{-23}$$

- Comparing type I and inverse seesaw

$$\epsilon_{2\,\text{type I}}^{\text{tot}} \simeq -2 \times 10^{-4} \qquad \epsilon_{2\,\text{inverse}}^{\text{tot}} \simeq -4 \times 10^{-3}$$

- $\Rightarrow$ Two orders of magnitude enhancement of all Higgs mediated cLFV observables

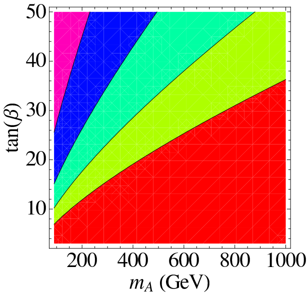
Results

- Most relevant parameters: m_A and $\tan(\beta)$

Br$(\tau \to 3\mu)$:

UL@90%CL $= 2.1 \times 10^{-8}$

$$\text{Br}(\tau \to 3\mu) \approx \frac{G_F^2\, m_\mu^2\, m_\tau^7\, \tau_\tau}{768\, \pi^3\, M_A^4} |\kappa^E_{\tau\mu}|^2 \tan^6\beta$$



- Benchmark points used for numerical evaluation :

Point	$\tan\beta$	$m_{1/2}$	m_0	$m^2_{H_U}$	$m^2_{H_D}$	A_0	μ	m_A
CMSSM-A	10	550	225	$(225)^2$	$(225)^2$	0	690	782
CMSSM-B	40	500	330	$(330)^2$	$(330)^2$	-500	698	604
NUHM-C	15	550	225	$(652)^2$	$-(570)^2$	0	478	150

Results

- Higgs-mediated contributions to some cLFV processes branching ratios are given in the following table

LFV Process	Present Bound	Future Sensitivity	CMSSM-A	CMSSM-B	NUHM-C
$\tau \to \mu\mu\mu$	2.1×10^{-8}	8.2×10^{-10}	1.4×10^{-15}	3.9×10^{-11}	8.0×10^{-12}
$\tau^- \to e^-\mu^+\mu^-$	2.7×10^{-8}	$\sim 10^{-10}$	1.4×10^{-15}	3.4×10^{-11}	8.0×10^{-12}
$\tau \to eee$	2.7×10^{-8}	2.3×10^{-10}	3.2×10^{-20}	9.2×10^{-16}	1.9×10^{-16}
$\mu \to eee$	1.0×10^{-12}		6.3×10^{-22}	1.5×10^{-17}	3.7×10^{-18}
$\tau \to \mu\eta$	2.3×10^{-8}	$\sim 10^{-10}$	8.0×10^{-15}	3.3×10^{-10}	4.6×10^{-11}
$\tau \to \mu\eta'$	3.8×10^{-8}	$\sim 10^{-10}$	4.3×10^{-16}	1.1×10^{-10}	3.1×10^{-12}
$\tau \to \mu\pi^0$	2.2×10^{-8}	$\sim 10^{-10}$	1.8×10^{-17}	8.5×10^{-13}	1.0×10^{-13}
$B_d^0 \to \mu\tau$	2.2×10^{-5}		2.7×10^{-15}	8.5×10^{-10}	2.7×10^{-11}
$B_d^0 \to e\mu$	6.4×10^{-8}	1.6×10^{-8}	1.2×10^{-17}	3.1×10^{-12}	1.2×10^{-13}
$B_s^0 \to \mu\tau$			7.7×10^{-14}	2.5×10^{-8}	7.8×10^{-10}
$B_s^0 \to e\mu$	2.0×10^{-7}	6.5×10^{-8}	3.4×10^{-16}	8.9×10^{-11}	3.4×10^{-12}
$h \to \mu\tau$			1.3×10^{-8}	2.6×10^{-7}	2.3×10^{-6}
$A, H \to \mu\tau$			3.4×10^{-6}	1.3×10^{-4}	5.0×10^{-6}

- Most promising channel: $\tau \to \mu\eta$
- Low $\tan\beta \Rightarrow$ Large contribution from γ- and Z-penguin diagrams $\Rightarrow$ Conservative estimates in the table (see Avelino's talk)

Results

- Just a curiosity: strong dependence of Higgs-mediated processes on the heaviest lepton chirality
  → For instance, Br($\tau_L \to \mu_R X$) suppressed by $\frac{m_\mu^2}{m_\tau^2}$ when compared to Br($\tau_R \to \mu_L X$).

$$\left(-\mathcal{L}^{\text{eff}} = \bar{E}_R^i Y_e^{ii} \left[\delta_{ij} H_d^0 + \left(\epsilon_1 \delta_{ij} + \epsilon_2 (Y_\nu^\dagger Y_\nu)_{ij}\right) H_u^{0*}\right] E_L^j + \text{h.c.}\right)$$

⇒ Asymmetry that can be used to identify the relative contribution from Higgs-mediated processes
⇒ Enhanced in the SUSY inverse seesaw

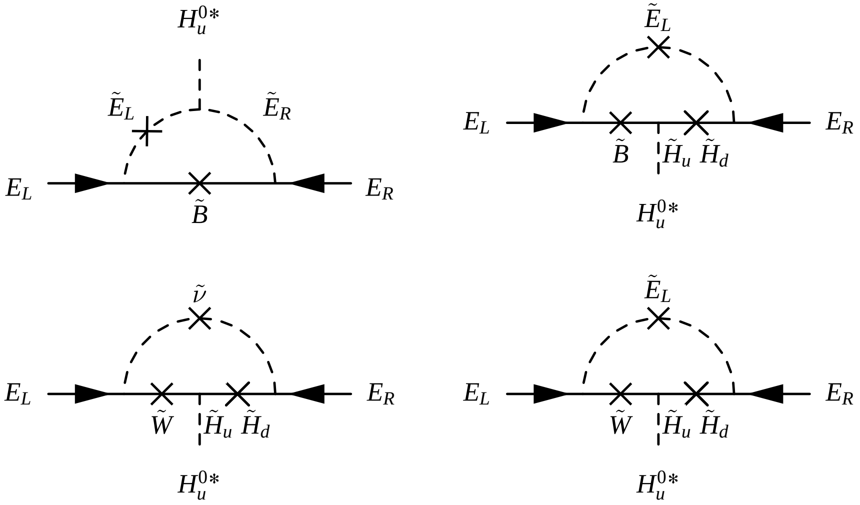
- If photon penguins dominate ⇒ $\frac{\text{Br}(\tau\to 3\mu)}{\text{Br}(\tau\to\mu\gamma)} \sim 0.003$
  [Hisano et al., 1996, Hisano and Nomura, 1999]
  → No longer holds if Higgs mediated processes dominate

Conclusion

- cLFV $\Rightarrow$ Clear signal of new physics
- Enhancement from the inverse seesaw $\Rightarrow$ Model can be tested at future low energy experiments
- If nothing is detected $\Rightarrow$ Strong constraints on the SUSY inverse seesaw, maybe exclusion if coupled with LHC (absence of) results on SUSY
- If cLFV is detected in the predicted range $\Rightarrow$ Interplay of cLFV with other observables will help to disentangle the type of neutrino mass generation mechanism and shed light on the new physics
- Enhancement of Z-mediated diagrams $\Rightarrow$ Under study (see Avelino's talk for further details)


Thank you !

Higgs-mediated cLFV contribution through slepton mixing



- Soft SUSY breaking lagrangian :

$$-\mathcal{L}_{\rm soft} = -\mathcal{L}_{\rm soft}^{\rm MSSM} + m_{\widetilde{N}}^2 \widetilde{N}_i^\dagger \widetilde{N}_i + m_X^2 \widetilde{X}_i^\dagger \widetilde{X}_i + \Big(A_\nu Y_\nu^{ij} \varepsilon_{ab} \widetilde{L}_i^a \widetilde{N}_j H_u^b + B_{M_{R_i}} \widetilde{N}_i \widetilde{X}_i + \frac{1}{2} B_{\mu_{X_i}} \widetilde{X}_i \widetilde{X}_i + \text{h.c.} \Big)$$

- RGE corrections to the left-handed slepton soft-breaking masses :

$$(\Delta m_{\widetilde{L}}^2)_{ij} \simeq -\frac{1}{8\pi^2} (3 m_0^2 + A_0^2) (Y_\nu^\dagger L Y_\nu)_{ij} \,, \quad L = \ln \frac{M_{GUT}}{M_R}$$
$$= \xi (Y_\nu^\dagger Y_\nu)_{ij}$$

- LFV coefficient :

$$\kappa_{ij}^E = \frac{\epsilon_{2ij}^{\text{tot}} (Y_\nu^\dagger Y_\nu)_{ij}}{\Big[1 + \Big(\epsilon_1 + \epsilon_{2ii}^{\text{tot}} (Y_\nu^\dagger Y_\nu)_{ii} \Big) \tan\beta \Big]^2}$$

- Branching ratios:

$$\text{Br}(\tau \to 3\mu) \approx \frac{G_F^2\, m_\mu^2\, m_\tau^7\, \tau_\tau}{768\, \pi^3\, M_A^4} |\kappa^E_{\tau\mu}|^2 \tan^6\beta$$

$$\begin{aligned}
\text{Br}(B_s \to \ell_i \ell_j) &= \frac{G_F^4\, M_W^4}{8\, \pi^5} \, |V_{tb}^* V_{ts}|^2 \, M_{B_s}^5 \, f_{B_s}^2 \, \tau_{B_s} \left(\frac{m_b}{m_b + m_s} \right)^2 \\
&\times \sqrt{\left[1 - \frac{(m_{\ell_i} + m_{\ell_j})^2}{M_{B_s}^2}\right]\left[1 - \frac{(m_{\ell_i} - m_{\ell_j})^2}{M_{B_s}^2}\right]} \\
&\times \left\{ \left(1 - \frac{(m_{\ell_i} + m_{\ell_j})^2}{M_{B_s}^2}\right) |c_S^{ij}|^2 + \left(1 - \frac{(m_{\ell_i} - m_{\ell_j})^2}{M_{B_s}^2}\right) |c_P^{ij}|^2 \right\}
\end{aligned}$$

$$c_S^{\mu\tau} = c_P^{\mu\tau} \approx \frac{8\, \pi^2\, m_\tau\, m_t^2}{M_W^2} \frac{\epsilon_Y\ \kappa^E_{\tau\mu}\ \tan^4\beta}{\left[1 + (\epsilon_0 + \epsilon_Y Y_t^2) \tan\beta\right] \left[1 + \epsilon_0 \tan\beta\right]} \frac{1}{M_A^2}$$

$$\frac{\text{Br}(\tau \to \mu\eta)}{\text{Br}(\tau \to 3\mu)} \simeq 36\,\pi^2 \left(\frac{f_\eta^8\, m_\eta^2}{m_\mu\, m_\tau^2}\right)^2 (1 - x_\eta)^2 \left[\xi_s + \frac{\xi_b}{3}\left(1 + \sqrt{2}\,\frac{f_\eta^0}{f_\eta^8}\right)\right]^2$$

$$\frac{\text{Br}(\tau \to \mu\eta')}{\text{Br}(\tau \to \mu\eta)} \simeq \frac{2}{9}\left(\frac{f_{\eta'}^0}{f_\eta^8}\right)^2 \frac{m_{\eta'}^4}{m_\eta^4}\left(\frac{1 - x_{\eta'}}{1 - x_\eta}\right)^2 \left[\frac{1 + \frac{3}{\sqrt{2}}\frac{f_{\eta'}^8}{f_{\eta'}^0}\left(\frac{\xi_s}{\xi_b} + \frac{1}{3}\right)}{\frac{\xi_s}{\xi_b} + \frac{1}{3} + \frac{\sqrt{2}}{3}\frac{f_\eta^0}{f_\eta^8}}\right]^2$$

$$\frac{\text{Br}(\tau \to \mu\pi)}{\text{Br}(\tau \to \mu\eta)} \simeq \frac{4}{3}\left(\frac{f_\pi}{f_\eta^8}\right)^2 \frac{m_\pi^4}{m_\eta^4}(1 - x_\eta)^{-2}\left[\frac{\frac{\xi_d}{\xi_b}\frac{1}{1+z} + \frac{1}{2}\left(1 + \frac{\xi_s}{\xi_b}\right)\frac{1-z}{1+z}}{\frac{\xi_s}{\xi_b} + \frac{1}{3} + \frac{\sqrt{2}}{3}\frac{f_\eta^0}{f_\eta^8}}\right]^2$$

$$\text{Br}(H_k \to \mu\tau) = \tan^2\beta\,\left(|\kappa_{\tau\mu}^E|^2\right) C_\Phi\ \text{Br}(H_k \to \tau\tau)$$

$$C_h = \left[\frac{\cos(\beta - \alpha)}{\sin\alpha}\right]^2, \quad C_H = \left[\frac{\sin(\beta - \alpha)}{\cos\alpha}\right]^2, \quad C_A = 1$$