# Enhanced Lepton Flavour Violation in the Supersymmetric Inverse Seesaw Model

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# Motivations

- Neutrino oscillations = Neutral lepton flavour violation
  Why not charged lepton flavour violation (cLFV) ?
- In the Standard Model: cLFV from higher order processes
  ⇒ negligible
- If cLFV observed:
  - Clear evidence of physics at a higher scale
  - Probe the origin of lepton mixing
  - Probe the origin of new physics
- Complementary to other New Physics searches
  - High energy: LHC
  - High intensity:
    - B factories: Rare decays, etc
    - Neutrino dedicated experiments: $U_{PMNS}$ non-unitarity, etc
    - Other low energy experiments: $(g-2)_\mu$, EDM, kaon decays(see Avelino's talk), 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: 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: New fields with a mass $M_R >$ EW scale and Majorana mass terms $\Rightarrow$ Generate $m_\nu$ in a renormalizable theory and at tree-level
- Type I seesaw $\mathcal{L}^{\text{leptons}}_{\text{mass}} = -Y^\ell \bar{L} H \ell_R - Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2} M_R \overline{\nu^C_R}\nu_R + \text{h.c.}$
  $\Rightarrow$ After EW symmetry breaking, a neutrino mass matrix appears $M^\nu_{6\times6}$

$$M^\nu = \begin{pmatrix} 0 & m_D \\ m_D^\intercal & M_R \end{pmatrix}$$

$m_D = \text{v}Y_\nu$ Dirac mass matrix
$M_R$ Majorana mass matrix $\to \text{Diag}\{m_{R_i}\}$

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

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

$$m_\nu^{\text{heavy}} \approx M_R \qquad \nu^{\text{heavy}} \approx \nu_R + \nu_R^C$$

- $M^\nu$ symmetric (Majorana $\nu$) $\Rightarrow M^\nu = Z D_\nu Z^\dagger$ with $Z$ unitary matrix $Z = \begin{pmatrix} V & Y \\ X & W \end{pmatrix}$

  The same goes for $M^\ell$ 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 $V_{CKM}$): potential source of cLFV

# Effective approach to seesaw mechanisms

- Notice that lepton number conservation is accidental in the SM (by construction of the SM: 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 $\geqslant 6$ operators effects $\rightarrow$ cLFV, precision test measurements, etc

# The Inverse Seesaw Mechanism

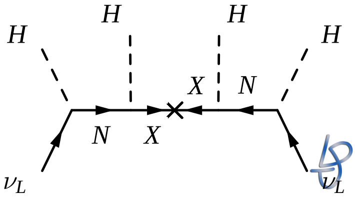
- Type I seesaw: $M_R \simeq 10^{15}$GeV with natural Yukawa $Y_\nu \sim \mathcal{O}(1)$ or $M_R \sim 1$TeV with Yukawa $Y_\nu \sim \mathcal{O}(10^{-6})$
  $\Rightarrow$ cLFV is suppressed ( dimension 6 operator $\propto \frac{Y_\nu^\dagger Y_\nu}{|M_R|^2}$ )
- Inverse seesaw: $M_R \simeq 1$ TeV with 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 (Belle II)
- 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 $m_D = Y_\nu \text{v}$

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

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



# 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 $\mathrm{sign}(\mu)$ $\rightarrow$ Nearly entirely excluded
  - Constrained MSSM: 5 free parameters $m_{1/2}$, $m_0$, $A_0$, $\tan(\beta)$ and $\mathrm{sign}(\mu)$ $\rightarrow$ Very restrictive boundary conditions

# Supersymmetric Seesaw Models

- No $\nu_R$ 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 $\nu_R$
- 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:

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

- Derive one of the new couplings:

$$Y_\nu^{ij}\varepsilon_{ab}\overline{\widetilde{H}_u^b}\widetilde{N}_j L_i^a + \text{h.c.} \in -\mathcal{L}$$

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

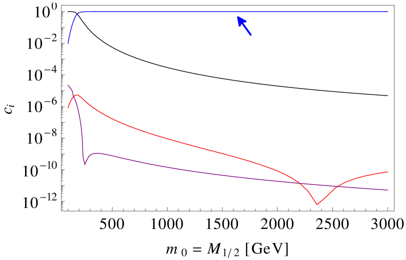
$$M_{\widetilde{N}}^2 = m_{\widetilde{N}}^2 + M_R^2 + Y_\nu^{ji*}Y_\nu^{ij}v_u^2 \sim M_{\text{SUSY}}^2 \sim (1\,\text{TeV})^2$$

# cLFV in Supersymmetric Seesaw Models

- Typically 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]
  $\Rightarrow (\Delta m^2_{\tilde{L}})_{ij} \propto (Y_\nu^\dagger Y_\nu)_{ij} \ln \frac{M_{GUT}}{M_R}$
- 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) $\rightarrow (\Delta m^2_{\tilde{L}})_{ij} \propto 30$
  $+ \tilde{N}$-mediated processes are no longer suppressed (since $M_{\tilde{N}} \sim 1$TeV)

# Z-mediated cLFV

- Photon and Higgs-mediated contributions usually dominate in the MSSM
  - In the SUSY inverse seesaw, 2 orders of magnitude enhancement of Higgs-mediated observables [A. Abada, D. Das and C. W., JHEP 1203 (2012) 100]
- Z-mediated contributions are suppressed in the MSSM through cancellations at leading order [Hirsch et al., 2012]
  - No longer true in the SUSY inverse seesaw due to new contributions from the right-handed sneutrino

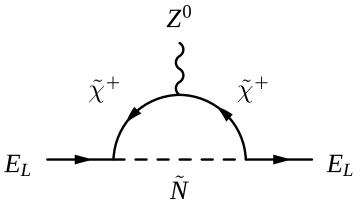



Relative contributions to $\mu - e$ conversion in $^{197}_{79}$Au

# Z-mediated cLFV domination explained

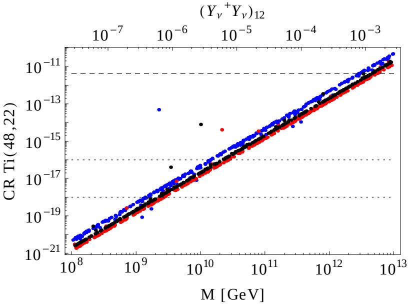
- Why is there a cancellation in the MSSM ?
  $\rightarrow$ Neglect chargino mixing: Masses cancel out in the combination of loop functions from different diagram
  $\Rightarrow$ cLFV$\propto (Z_{\tilde{\nu}}^{\dagger} Z_{\tilde{\nu}})_{ij} = 0$ [Hirsch et al., 2012]

- What happens in the SUSY inverse seesaw ?




- Diagrams with right-handed sneutrinos are no longer suppressed $\Rightarrow$ Spoils the cancellation
  cLFV$\propto \sum_i Z_{\tilde{\nu}}^{ik} Z_{\tilde{\nu}}^{ij*} Y_{\nu}^{ik*} Y_{\nu}^{ij}$
- Dominant contribution: Z-penguins scale like $m_Z^{-2}$ while $\gamma$-penguins scale like $m_{SUSY}^{-2}$

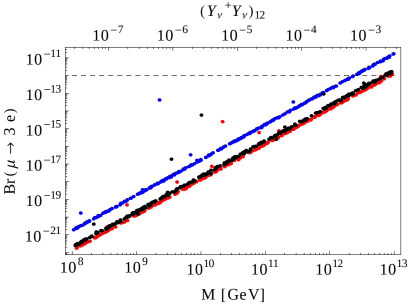
# $\mu - e$ Conversion



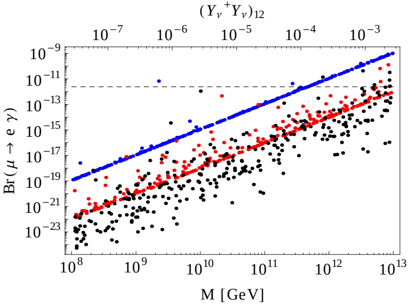

$\mu - e$ conversion rate in $\mathrm{Ti}(48, 22)$ as a function of $M = M_R^2/\mu_X$

- Different values of $M_R$: little impact on observables (blue: $M_R = 100$ GeV, red: $M_R = 1$ TeV, black: $M_R = 10$ TeV)
- Very little dependence on CMSSM parameters: points from random values of $m_0$ and $M_{1/2}$ in the range $[0, 3]$ TeV
- Current experimental limits $7 \times 10^{-13}$ (Au, SINDRUM II) $\Rightarrow (Y_\nu^\dagger Y_\nu)_{12} < 3 \times 10^{-4}$

# $\mu \to 3e$ VS $\mu \to e\gamma$




- Z-dominated observable: $\mu \to 3e$
- Slightly less constraining than $\mu - e$ conversion in Gold
- Small influence of $M_R$ and SUSY parameters




- Observable without any Z contribution: $\mu \to e\gamma$
- Below $\mu \to 3e$ (except for $M_R = 100$ GeV)
  $\Rightarrow$ Not constraining
- Strong influence of $M_R$ and SUSY parameters

# Other Observables and Comments

- Brs of observables like $\tau \to 3\mu$ or $\tau \to \mu\eta$ are dominated by Z-penguins and are of the same order as $\mathrm{Br}(\mu \to 3e)$
$\Rightarrow$ No chance to be observed at future B factories without specific textures of $Y_\nu$
- Collider observables like $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell_i \ell_j$ or $\Delta m_{\tilde{\ell}}$ are suppressed when compared to MSSM + type I seesaw due to constrained $Y_\nu$
- Non-degenerate singlets don't change the behaviour of observables dominated by Z-mediated contributions
- Higgs mass around $126$ GeV can be accomodated with large $A_0$ and moderately large $\tan\beta$ and singlets don't contribute much to Higgs mass because of the constraints on $Y_\nu$

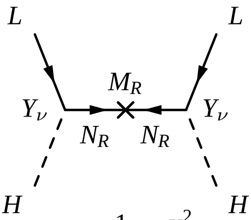
# Conclusion

- cLFV ⇒ Clear evidence of new physics
- Enhancement from the inverse seesaw ⇒ Put constraints on Yukawa couplings
- Most constraining observable: $\mu - e$ conversion
- Non-observation of cLFV ⇒ 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 ⇒ Interplay of cLFV with other observables will help to disentangle the type of neutrino mass generation mechanism and shed light on the new physics

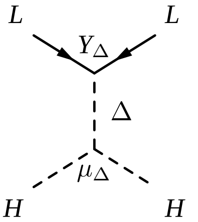
Thank you

# Three Seesaw Mechanisms

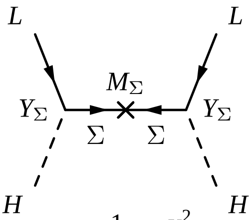
- Three classes of seesaw models at tree level ⇒ Three kinds of heavy fields
  - type I: RH neutrinos, SM gauge singlets
  - type II: scalar triplets
  - type III: fermionic triplets




$$m_\nu = -\frac{1}{2} Y_\nu^T \frac{v^2}{M_R} Y_\nu$$

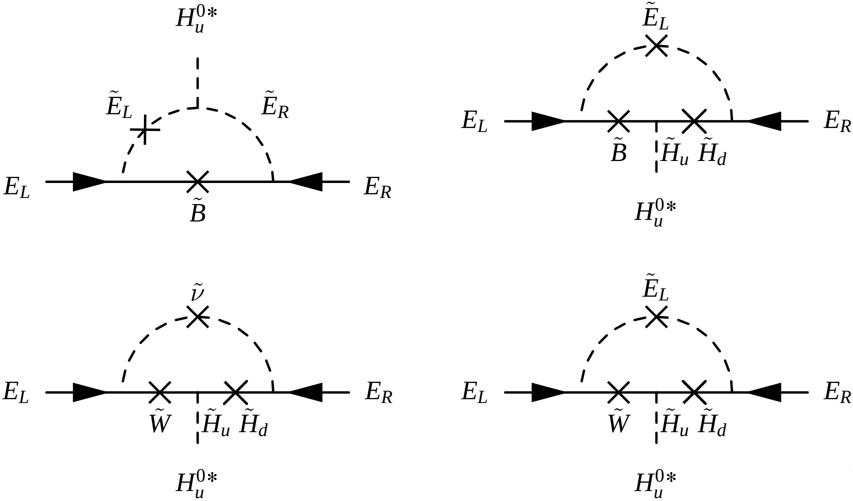



$$m_\nu = -2 Y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}$$




$$m_\nu = -\frac{1}{2} Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

# Higgs-mediated cLFV contribution through slepton mixing



- Soft SUSY breaking lagrangian :

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

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

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

- LFV coefficient :

$$\kappa^E_{ij} = \frac{\epsilon_{2ij}^{\rm tot} (Y_\nu^\dagger Y_\nu)_{ij}}{\left[ 1 + \left( \epsilon_1 + \epsilon_{2ii}^{\rm tot} (Y_\nu^\dagger Y_\nu)_{ii} \right) \tan\beta \right]^2}$$

- Branching ratios:

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

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

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

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

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

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

$$\mathrm{Br}(H_k \to \mu\tau) = \tan^2\beta\,(|\kappa^E_{\tau\mu}|^2)\,C_\Phi\,\mathrm{Br}(H_k \to \tau\tau)$$

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