Sensitivity to the Higgs Sector of the SUSY-Seesaw Models in the LFV $\tau \longrightarrow \mu f_0$ decay

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- M. J. Herrero, J. Portoles, A.M. Rodriguez-Sanchez, [arXiv:0903.5151[hep-ph]]
- E. Arganda, M. J. Herrero, J. Portoles, A. Rodriguez-Sanchez and A. M. Teixeira, [arXiv:0810.0163 [hep-ph]].
- E. Arganda, M. J. Herrero, J. Portoles, A. Rodriguez-Sanchez and A. M. Teixeira, [arXiv:0812.2692 [hep-ph]]

Why Lepton Flavour Violation (LFV)?

- LFV occurs in Nature:
  $\nu_i - \nu_j$ oscillations DO NOT conserve Lepton Flavour Number
- In SM:no LFV if $m_\nu = 0$ and extremely suppresed if $m_\nu \neq 0$
- LFV is very sensitive to SUSY: if Seesaw Mechanism for m_ν generation with Majorana $N_R \Rightarrow Y_\nu$ can be O(1). Large Y_ν induce, via SUSY loops, large LFV rates.
- Challenging exp. bounds : present/future sensitivities (?): MEGA, SINDRUM, BaBar, Belle / MEG, SuperB fact., PRISM/PRIME

  $\mathrm{BR}(\tau \to \mu\gamma) < 4.5 \times 10^{-8}/10^{-9}$ $\mathrm{BR}(\tau \to \mu f_0) < 3.4 \times 10^{-8}/10^{-9}$

  $\mathrm{BR}(\tau \to 3\mu) < 3.2 \times 10^{-8}/10^{-9}$ $\mathrm{BR}(\tau \to \mu\eta) < 5.1 \times 10^{-8}/10^{-9}$

  In the $\tau - \mu$ sector the semileptonic channels are already competitive with the leptonic ones.
- LFV bounds $\Rightarrow$ Bounds on SUSY and ν parameter space

Constrained SUSY-Seesaw models

- MSSM-Seesaw introduces too many new parameters due to the SOFT SUSY breaking terms.
- SOFT- SUSY breaking universality at the gauge coupling unification scale $M_x = 2x10^{16}$ GeV
- We work in CMSSM(M_0, $M_{1/2}$, A_0, $\tan\beta$, sign(μ)) and NUHM (previous and $M^2_{H_1} = M^2_0(1+\delta_1)$, $M^2_{H_2} = M^2_0(1+\delta_2)$) The main difference is that in NUHM a light Higgs sector can be obtained even for heavy SUSY.
- The low energy parameters are obtained by solving th RGE in two steps:
  - The full set of equations is run from M_x to m_M.At m_M the ν_R as well as $\tilde{\nu}_R$ decouple.
  - The RGE without the equations for the ν_R and $\tilde{\nu_R}$ are run from m_M to M_{EW}.The masses and couplings are computed.

How to generate LFV via SUSY loops?

- Need non vanishing off diagonal slepton mass entries.
- The flavor off diagonal mass entries $M_{\tilde{l}}^{ij}$ and $M_{\tilde{\nu}}^{ij}$ $(i \neq j)$ at M_{EW} are generated via RGE-running of Y_ν.

The LL off-diagonal entry of the slepton mass matrix in the Leading-Logarithmic (LLog) approximation:

$$M_{LL}^{ij2} = -\frac{1}{8\,\pi^2}\,(3\,M_0^2 + A_0^2)\,(Y_\nu^\dagger\,L\,Y_\nu)_{ij}\,;\; L_{kl} \equiv \log\left(\frac{M_X}{m_{M_k}}\right)\,\delta_{kl}$$

- Flavor changing sleptons propagators into loops then generate LFV
- δ_{LL}^{ij} useful phenomenologycal parameter that encodes the LFV in the i-j sector:

$$\delta_{LL}^{ij} = \frac{M_{LL}^{ij2}}{M_{SUSY}^2}$$

Our work

- Prediction of the LFV $\tau \to \mu f_0$ branching ratio in Constrained MSSM-Seesaw Models: CMSSM-NUHM.
- Full one loop computation of LFV rates. SPHENO 2.2.2.We do not use LLog nor MI approx.
- Require compatibility with ν data.
- Compare our prediction with present LFV bound.
- Explore sensitivity to SUSY, Higgs and heavy ν_R.
- Provide an approximate formulae useful for future analysis.
- Comparison with other Higgs's sensitive channels: $\tau \to 3\mu, \tau \to \mu\eta$.

Seesaw mechanism with $3\,\nu_R$ versus neutrino data

SeeSaw Mechanism with 3 ν_R:$(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}, m_{N_1}, m_{N_2}, m_{N_3})$

$m_\nu = -m_D^T\, m_N^{-1}\, m_D; m_N = m_M; m_D = Y_\nu < H_2 >$

Solution: $$\boxed{m_D = i\sqrt{m_N^{diag}}\, R\, \sqrt{m_\nu^{diag}}\, U^\dagger_{\rm PMNS}}$$ [Casas, Ibarra ('01)]

R is a 3×3 complex matrix and orthogonal

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

$c_i = \cos\theta_i,\quad s_i = \sin\theta_i,\quad \theta_{1,2,3}$ complex

Parameters: θ_{ij},δ,α,β,m_{ν_i},m_{N_i},θ_i **(18)** ; m_{N_i}, θ_i drive the size of Y_ν.

Hierarchical ν's :

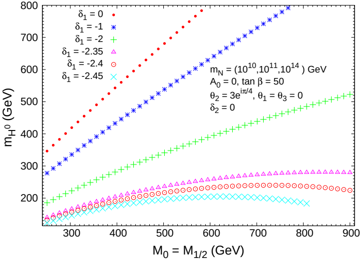
$m^2_{\nu_1} << m^2_{\nu_2} = \Delta m^2_{\rm sol} + m^2_{\nu_1} << m^2_{\nu_3} = \Delta m^2_{\rm atm} + m^2_{\nu_1}$

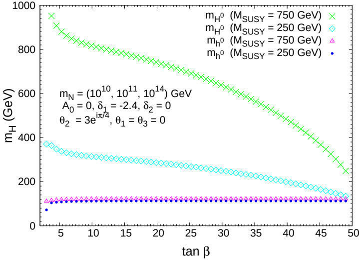
2 scenarios :

- Degenerate N's $\to m_{N_1} = m_{N_2} = m_{N_3} = m_N$
- Hierarchical N's $\to m_{N_1} << m_{N_2} << m_{N_3}$

Our choice of input parameters
Constrained MSSM $+3\nu_R$ (Majorana) $+ 3\tilde{\nu}_R$

- CMSSM:
  - SUSY parameters: M_0, $M_{1/2}$, A_0.
  - $\tan\beta$ $< H_2 > / < H_1 >$(at EW scale)
  - sign (μ) (μ derived from EW breaking)
- NUHM
  - CMSSM parameters: M_0, $M_{1/2}$, A_0, $\tan\beta$ and sign (μ).
  - Non Universal Higgs masses
    $M^2_{H_1} = M_0^2(1+\delta_1)$, $M^2_{H_2} = M_0^2(1+\delta_2)$
- Seesaw parameters
  - $m_{\nu_{1,2,3}}$ and U_{MNS} (set by data)
  - $m_{N_{1,2,3}}$ and $R(\theta_1, \theta_2, \theta_3)$ (input)
- For numerical estimates: $(\Delta m^2)_{12} = \Delta m^2_{\rm sol} = 8\times 10^{-5}$ eV^2
  $(\Delta m^2)_{23} = \Delta m^2_{\rm atm} = 2.5\times 10^{-3}$eV^2
  $\theta_{12} = 30^o$; $\theta_{23} = 45^o$; $\delta = \alpha = \beta = 0$; $0 \le \theta_{13} \le 10^o$
  $250\,{\rm GeV} < M_0, M_{1/2} < 1000\,{\rm GeV}$,
  $-500\,{\rm GeV} < A_0 < 500\,{\rm GeV}$ $5 < \tan\beta < 50$, $-2 < \delta_{1,2} < 2$



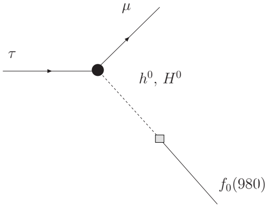


- In CMSSM a heavy soft SUSY spectrum $\Rightarrow$ heavy H_0.
- In NUHM, a proper choice of these non-universal parameters, δ_1 and δ_2, can lead us to light Higgs particles even for very large soft SUSY masses of $\mathcal{O}(1\ \text{TeV})$ if $tan\beta$ is large.
- m_{h^0} is independent of $tan\beta$ or M_{SUSY}.
- m_{H^0} becomes lighter with the increase of $tan\beta$.

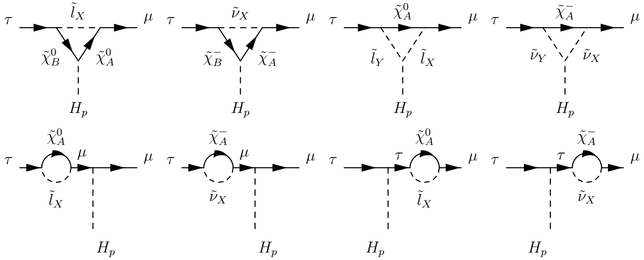
Results for $BR(\tau \to \mu f_0)$

- Analytical
  - Full
  - Approximate at large $tan\beta$ and large M_{SUSY}
- Numerical
- Comparison with other channels

Analytical computations



Higgs mediated $\tau \to \mu f_0$ decay



One loop SUSY LFV diagrams

Full Analytical Results

$$\mathrm{BR}(\tau \to \mu f_0) = \frac{1}{4\pi} \frac{(m_\tau^2 + m_\mu^2 - m_{f_0}^2)^2 - 4 m_\tau^2 m_\mu^2}{m_\tau^2 \Gamma_\tau} \frac{1}{2} \sum_{i,f} |T_H|^2 ,$$

$$\frac{1}{2} \sum_{i,f} |T_H|^2 = \frac{(m_\mu + m_\tau)^2 - m_{f_0}^2}{4\, m_\tau} |c_{h^0} + c_{H^0}|^2 .$$

$$c_p = \frac{g}{2 m_W} \frac{1}{2 M_{H_p}^2} \left(J_L^{(p)} + J_R^{(p)} \right) \left(H_R^{(p)} + H_L^{(p)} \right) ,$$

$H_{L,R}^{(h^0,H^0)} \to \tau \mu H^{(h^0,H^0)}$ SUSY one-loop LFV vertex functions

$J_{L,R}^{(h^0,H^0)} \to$ hadron form factors

Hadronisation $\to$ substitution of quarks bilinears by scalar currents

$f_0(980)$ state and hadron form factors

$f_0(980)$ isosinglet state $\rightarrow$ rotation of the octet R_8 and singlet R_0 components of the $R(0^+)$ nonet of resonances in the $N_C \rightarrow \infty$ limit:

$$\begin{pmatrix} R_8 \\ R_0 \end{pmatrix} = \begin{pmatrix} \cos\theta_S & \sin\theta_S \\ -\sin\theta_S & \cos\theta_S \end{pmatrix} \begin{pmatrix} f_0(1500) \\ f_0(980) \end{pmatrix}$$

θ_S mixing angle uncertain $\rightarrow$ $\theta_S = 7^o$ and $\theta_S = 30^o$

$$\begin{aligned} J_L^{(H^0)} \;\; = \;\; & \sqrt{2}\, c_m \left\{ \frac{\sin\alpha}{\sin\beta} \left[\frac{1}{2\sqrt{3}} \sin\theta_S + \frac{2}{3}\cos\theta_S \right] m_\pi^2 \;+ \right. \\ & \left. \frac{-\cos\alpha}{\cos\beta} \left[\frac{\sqrt{3}}{2} \sin\theta_S\, m_\pi^2 - \left(\frac{1}{\sqrt{3}} \sin\theta_S - \frac{2}{3}\cos\theta_S \right) 2\, m_K^2 \right] \right\} \end{aligned}$$

$J_R^{(H^0)} = J_L^{(H^0)*}$; $c_m = F/2$ where $F \sim F_\pi =$ pion decay constant

In the isospin limit:

$$B_0\, m_s = m_K^2 - \frac{1}{2}\, m_\pi^2 \, ; \; H^0 - f_0 \mathrm{coupling} \sim \mathrm{m_K^2 (H^0 ss \propto m_s)}$$

Approximate formulae of $\tau \to \mu f_0$ branching ratio

Approximate formulae valid at large $\tan\beta$ and heavy m_{SUSY}

- In this limit $H_L >> H_R$ and $H_L^{H^0} >> H_L^{h^0}$. We neglect H_R and $H_L^{h^0}$.
- This limit + MI approx $\Rightarrow$ chargino/neutralino contribution:

$$H_{L,c}^{(H^0)} = \frac{g^3}{16\pi^2}\frac{m_\tau}{12 m_W}\delta_{32}\tan^2\beta \; ; \; H_{L,n}^{(H^0)} = \frac{1}{2}(1 - 3\tan^2\theta_W)H_{L,c}^{(H^0)}$$

Non-decoupling of SUSY in Higgs mediated LFV processes

$$\mathrm{BR}(\tau \to \mu f_0(980))_{\mathrm{approx}} = \frac{1}{16\pi m_\tau^3}\left(m_\tau^2 - m_{f_0}^2\right)^2 \left| \frac{g}{2m_W}\frac{1}{m_{H^0}^2} J_L^{(H^0)} H_{L,c}^{(H^0)} \right|^2 \frac{1}{\Gamma_\tau}$$

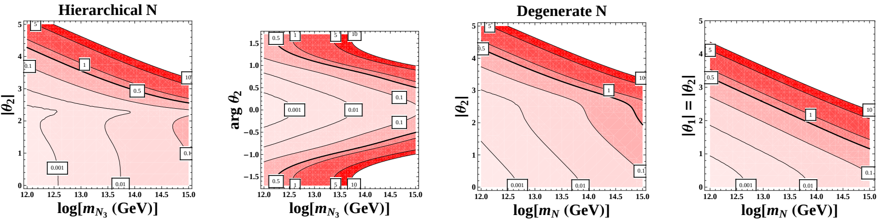
$$= \begin{pmatrix} 7.3\times 10^{-8}\ (\theta_S = 7^\circ) \\ 4.2\times 10^{-9}\ (\theta_S = 30^\circ) \end{pmatrix} |\delta_{32}|^2 \left(\frac{100}{m_{H^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 .$$

In contrast to $BR(\tau \to \mu\gamma) \propto \left(\frac{m_W}{M_{SUSY}}\right)^4$

Numerical results

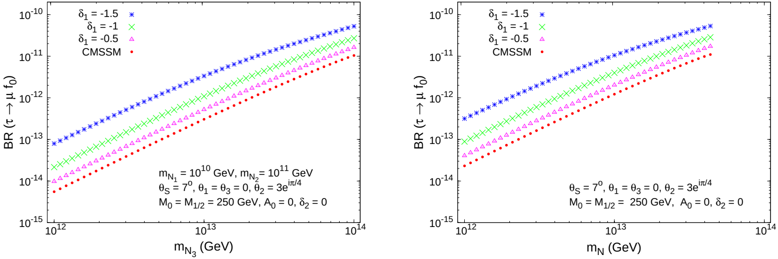
Size of δ_{32} in Constrained SUSY-Seesaw models

Hierarchical N   Degenerate N



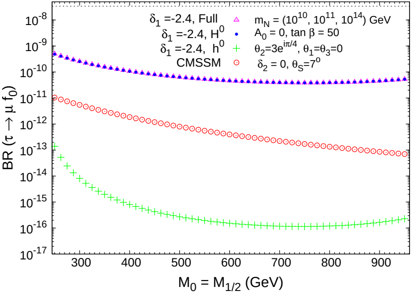
- Large size of $|\delta_{32}|$ for large $\theta_{1,2}$ and/or large m_N in the degenerate and large m_{N_3} in the hierarchical neutrino case.
- Complex $\theta_{1,2}$, with large modulus ($2 < |\theta_{1,2}| < 3$) and argument ($\pi/4 < \arg\theta_{1,2} < 3\pi/4$),and m_{N_3}between $10^{14} - 10^{15}$ GeV $\Rightarrow |\delta_{32}| \sim 1 - 10$.
- perturbativity in all the gauge and Yukawa couplings $\Rightarrow$ $|Y_\nu|^2/(4\pi) < 1.5$ and $|\delta_{32}| < 0.5$

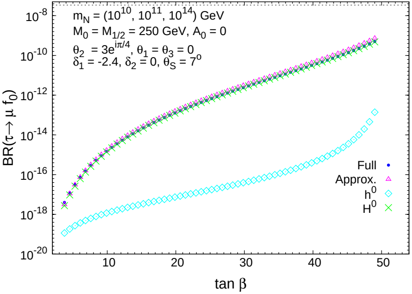
Results for $BR(\tau \to \mu f_0)$: CMSSM/NUHM, hierarchical/degenerate



- $BR(\tau \to \mu f_0)_{NUHM} > BR(\tau \to \mu f_0)_{CMSSM}$ due to $m_{H^0}|_{NUHM} < m_{H^0}|_{CMSSM}$
- $BR(\tau \to \mu f_0)$ grows with m_{N_3}/m_N
- Independence of $BR(\tau \to \mu f_0)$ with m_{N_1} and m_{N_2} if $m_{N_1} < m_{N_2} < m_{N_3}$
- $BR(\tau \to \mu f_0)_{deg} \geq BR(\tau \to \mu f_0)_{hierch}$ but hierarchical neutrino scenario more appealing for BAU

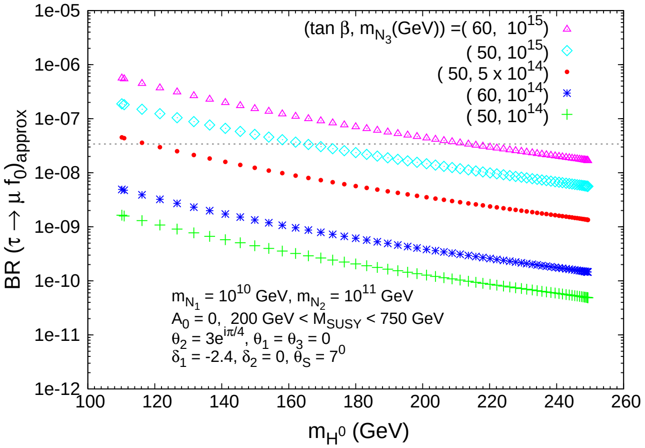
Getting larger $BR(\tau \to \mu f_0)$





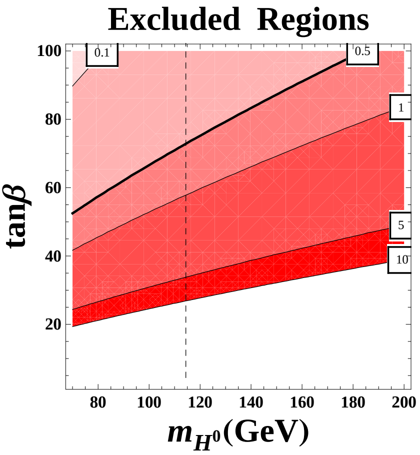
- Large BR for large $\tan\beta \sim 50$
- The total rates do not decrease with $M_{\rm SUSY}$ in the NUHM $\Rightarrow$SUSY particles do not decouple at large $M_{\rm SUSY}$ in this observable
- $BR(\tau \to \mu f_0)_{H^0} >> BR(\tau \to \mu f_0)_{h^0}$. At large $\tan\beta$ the H^0 contributions are enhanced by a $\tan^6\beta$ factor whereas the h^0 ones are suppressed
- $BR(\tau \to \mu f_0)_{Approx} \sim BR(\tau \to \mu f_0)_{Full}$

Sensitivity to H^0 in BR($\tau \to \mu f_0$) in the NUHM



- There is Higgs sensitivity in this channel.For large $m_{N_3} \sim 5 \times 10^{14} - 10^{15}$ GeV and large $\tan\beta \sim 50 - 60$ the rates are at the present experimental reach

Constraining the model parameters



- Sensitivity to Higgs sector ⇒ constraining mainly $\tan\beta$ and m_{H^0}
- For fixed δ_{32}, comparison with present exp bound ⇒ limits on large $\tan\beta$ and light m_{H^0}

Comparison with other LFV τ decays

$$\mathrm{BR}(\tau \to \mu f_0(980))_{\text{approx}} = \frac{1}{16\pi m_\tau^3}\left(m_\tau^2 - m_{f_0}^2\right)^2 \left|\frac{g}{2m_W}\frac{1}{m_{H^0}^2} J_L^{(H^0)} H_{L,c}^{(H^0)}\right|^2 \frac{1}{\Gamma_\tau}$$

$$= \begin{pmatrix} 7.3\times 10^{-8} \ (\theta_S = 7^\circ) \\ 4.2\times 10^{-9} \ (\theta_S = 30^\circ) \end{pmatrix} |\delta_{32}|^2 \left(\frac{100}{m_{H^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6.$$

$$\mathrm{BR}(\tau \to \mu\eta)_{H_{\text{approx}}} = \frac{1}{8\pi m_\tau^3}(m_\tau^2 - m_\eta^2)^2 \left|\frac{g}{2m_W}\frac{F}{m_{A^0}^2} B_L^{(A^0)}(\eta)\, H_{L,c}^{(A^0)}\right|^2 \frac{1}{\Gamma_\tau}$$

$$= \quad 1.2\times 10^{-7}(\theta = -18^o)\,|\delta_{32}|^2 \left(\frac{100}{m_{A^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6$$

$$\mathrm{BR}(\tau \to 3\mu)_{H_{\text{approx}}} = \frac{G_F^2}{2048\pi^3}\frac{m_\tau^7 m_\mu^2}{\Gamma_\tau}\left(\frac{1}{m_{H^0}^4} + \frac{1}{m_{A^0}^4} + \frac{2}{3m_{H^0}^2 m_{A^0}^2}\right)\left|\frac{g^2\delta_{32}}{96\pi^2}\right|^2 (\tan\beta)^6$$

$$= \quad 1.2\times 10^{-7}\,|\delta_{32}|^2 \left(\frac{100}{m_{A^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6$$

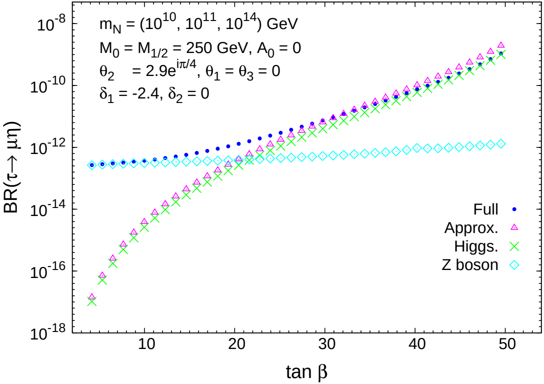
- $\tau \to \mu f_0$ is dominated by H^0 $\forall \tan\beta \Rightarrow$ more sensitive to H^0
- $\tau \to \mu\eta$ is dominated by A^0 (versus Z) only for $\tan\beta > 20$
- $\tau \to 3\mu$ is dominated by γ. H^0 and A^0 compete with γ only at large $\tan\beta > 60$

Conclusions

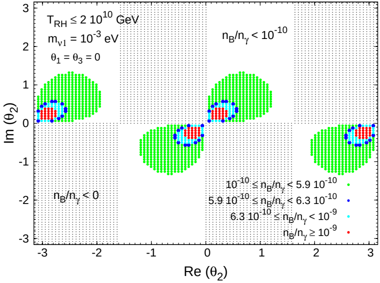
- BR($\tau \to \mu f_0$) grows with $\tan\beta$ as $\tan^6\beta$, with $1/m_{H^0}$ as $(1/m_{H^0})^4$, and it is approximately constant with $M_{\rm SUSY}$. The dependence with m_{N_3} and $\theta_{1,2}$ goes via the δ_{32} parameter as $BR \sim |\delta_{32}|^2 \sim |m_{N_3} \log m_{N_3}|^2$
- Much larger rates in the NUHM-seesaw than in the CMSSM-seesaw, due mainly to the lighter Higgs mass m_{H^0} in the NUHM-seesaw
- Challenging future sensitivities with SuperB factories

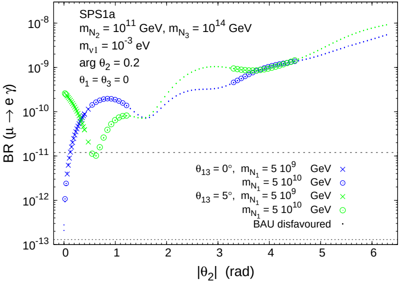
Additional transparencies

$BR(\tau \to \mu\eta)$ versus $\tan\beta$



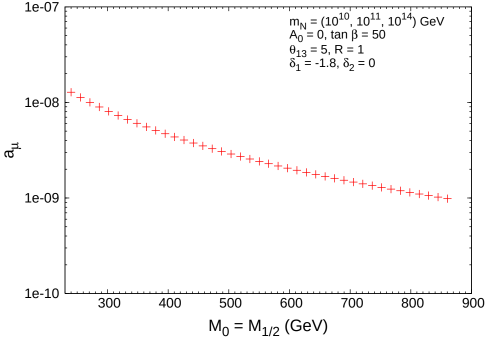
Constraints from 'viable' BAU





- BAU requires complex $R \neq 1 \Rightarrow$ complex $\theta_i \neq 0$. Most relevantly θ_2
- $n_B/n_\gamma \in [10^{-10}, 10^{-9}] \Rightarrow (Re(\theta_2), Im(\theta_2)) \in$ area ('ring') (WMAP in darkest ring)
- 'Optimal' m_{N_1} not far from 10^{10} GeV
- The BAU [fav] windows occur at small ($\neq 0$) $|\theta_2| \lesssim 1.5$
- **smaller $|\theta_2|$ $\Rightarrow$ smaller LFV rates**

Contributions to Δa_μ^{SUSY}



- $\Delta a_\mu^{\rm SUSY} \in \left[10^{-8}, 10^{-9}\right]$: compatible with $a_\mu^{EXP} - a_\mu^{SM} = 3.32 \times 10^{-9}$ (3.8σ)

Summary of our work

The results of this work have been summarised in the folowing references:

- E. Arganda, M. J. Herrero, J. Portoles, A. Rodriguez-Sanchez and A. M. Teixeira, "LFV in semileptonic τ decays and $\mu - e$ conversion in nuclei in SUSY-seesaw," Preprint IFT-UAM/CSIC-08-59, FTUAM/08-19. [arXiv:0810.0163 [hep-ph]].
- E. Arganda, M. J. Herrero, J. Portoles, A. Rodriguez-Sanchez and A. M. Teixeira, "Lepton Flavour Violation in charged leptons within SUSY-seesaw" Preprint IFT-UAM/CSIC-08-85, FTUAM/08-23. [arXiv:0812.2692 [hep-ph]]
- M. J. Herrero, J. Portoles, A.M. Rodriguez-Sanchez "Sensitivity to the Higgs sector of the SUSY-Seesaw Models in the Lepton Flavour Violating $\tau \to \mu f_0$ decay," Preprint IFT-UAM/CSIC-08-84, FTUAM/08-24.

Analytical results of $\mathrm{BR}(\tau \to \mu f_0)$

$$
\begin{aligned}
T_H &= T_{h^0} + T_{H^0} \\
&= \sum_{h^0, H^0} \frac{1}{M_{H_p}^2} \Big\{ H_L^{(p)} S_{L,q}^{(p)} [\bar{u}_\mu P_L u_\tau][\bar{u}_q P_L v_q] + H_R^{(p)} S_{R,q}^{(p)} [\bar{u}_\mu P_R u_\tau][\bar{u}_q P_R v_q] \\
&\quad + H_L^{(p)} S_{R,q}^{(p)} [\bar{u}_\mu P_L u_\tau][\bar{u}_q P_R v_q] + H_R^{(p)} S_{L,q}^{(p)} [\bar{u}_\mu P_R u_\tau][\bar{u}_q P_L v_q] \Big\}
\end{aligned}
$$

The Higgs boson couplings to quarks:

$$
i \left(S_{L,q}^{(p)} P_L + S_{R,q}^{(p)} P_R \right)
$$

$$
\begin{aligned}
S_{L,q}^{(p)} &= \frac{g}{2m_W} \left(\frac{-\sigma_2^{(p)*}}{\sin\beta} \right) m_q \ , \quad q = u \ , S_{R,q}^{(p)} = S_{L,q}^{(p)*} \\
S_{L,q}^{(p)} &= \frac{g}{2m_W} \left(\frac{\sigma_1^{(p)*}}{\cos\beta} \right) m_q \ , \quad q = d, s \ , S_{R,q}^{(p)} = S_{L,q}^{(p)*} .
\end{aligned}
$$

$$
\sigma_1^{(p)} = \begin{pmatrix} \sin\alpha \\ -\cos\alpha \\ i\sin\beta \end{pmatrix} , \quad \sigma_2^{(p)} = \begin{pmatrix} \cos\alpha \\ \sin\alpha \\ -i\cos\beta \end{pmatrix} , H_p = h^0, H^0, A^0
$$

Why seesaw mechanism for m_ν generation

- The seesaw is the simplest mechanism to explain small m_ν
- If Majonana ν, the seesaw allows for large Y_ν couplings
- If Majorana ν, L not preserved, viable BAU via Leptogenesis

$$-\mathcal{L}_{Y+M} = Y^e \bar{l}_L e_R H_1 + Y^\nu \bar{l}_L \nu_R H_2 + \frac{1}{2} m_M \nu_R^T C \nu_R + h.c.$$

where $m_D = Y_\nu < H_2 >$, $< H_2 >= v_2 \sin\beta$
Both Dirac mass m_D Majorana mass m_M involved $\leftrightarrow M_\nu$

$$\mathbf{M}_\nu = \begin{pmatrix} 0 & m_D^T \\ m_D & m_M \end{pmatrix}$$

$m_D << m_M \Rightarrow$ seesaw: $m_\nu = -m_D^T m_M^{-1} m_D$ (light), $m_N = m_M$ (heavy)

For $Y_\nu \sim \mathcal{O}(1)$, $m_M \sim 10^{14}$ GeV $\Rightarrow m_\nu \sim 0.1$ eV (OK) $m_N \sim 10^{14}$ GeV

Generalization to three generations also OK with data

MSSM spectrum and experimental constraints

Extended Standard Model spectrum	SUSY particles: $SU(3)_C \times SU(2)_L \times U(1)_Y$ interaction eigenstates — Notation	SUSY particles: interaction eigenstates — Name	SUSY particles: Mass eigenstates — Notation	SUSY particles: Mass eigenstates — Name
$q = u, d, s, c, b, t$ $l = e, \mu, \tau$ $\nu = \nu_e, \nu_\mu, \nu_\tau$	$\tilde{q}_L, \tilde{q}_R$ $\tilde{l}_L, \tilde{l}_R$ $\tilde{\nu}$	squarks sleptons sneutrino	$\tilde{q}_1, \tilde{q}_2$ $\tilde{l}_1, \tilde{l}_2$ $\tilde{\nu}$	squarks sleptons sneutrino
g	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$ $H_1^+ \supset H^+$ $H_2^- \supset H^-$	$\tilde{W}^\pm$ $\tilde{H}_1^+$ $\tilde{H}_2^-$	wino higgsino higgsino	$\tilde{\chi}_i^\pm$ $(i=1,2)$	charginos
γ Z $H_1^o \supset h^0, H^0, A^0$ $H_2^o \supset h^0, H^0, A^0$ W^3 B	$\tilde{\gamma}$ $\tilde{Z}$ $\tilde{H}_1^o$ $\tilde{H}_2^o$ $\tilde{W}^3$ $\tilde{B}$	photino zino higgsino higgsino wino bino	$\tilde{\chi}_j^o$ $(j=1,\ldots,4)$	neutralinos

- Mass bounds (95% C.L.) from direct searches (PDG 2008) in GeV

$$m_{h^0} > 92.8,\ m_{A^0} > 93.4,\ m_{\tilde{e}} > 73,\ m_{\tilde{\mu}} > 94,$$

$$m_{\tilde{\tau}} > 81.9,\ m_{\tilde{\nu}} > 94, m_{\tilde{\chi}_1^0} > 46,\ m_{\tilde{\chi}_1^\pm} > 94$$

Outline

- Motivation/Introduction
  - ⋆ Constrained SUSY Models
  - ⋆ Neutrino masses and Seesaw Mechanism
  - ⋆ Theoretical framework for LFV in semileptonic tau decays
  - ⋆ Hadronization of quark bilinears
  - ⋆ Experimental data (bound)
- Results:
  - ⋆ Analytical results
  - ⋆ Numerical results
  - ⋆ Full versus Approximate results
- Conclusions

Why SUSY?

- **Experimental evidence of Physics Beyond the SM**
  ⋆ Neutrino oscillations $\Rightarrow$ Neutrinos are massive
  ⋆ The SM can not explain the Baryon Asimmetry of the Universe
  ⋆ The SM does not incorporate gravitation
  ⋆ No understanding of dark matter and dark energy
- **SUSY solves the hierarchy problem of the SM and SM-Seesaw**
  ⋆ SUSY introduces a new symmetry between bosons and fermions

  fermionic dof = bosonic dof

  SUSY $\Rightarrow$ Cancellation of quadratic divergences of the Higgs mass

No experimental evidence of SUSY yet

- **Direct searches of SUSY particles at colliders**

best { ⋆But, not seen at LEP, Tevatron..⇒ Experimental constraints
⋆Some sparticles may not be produced at LHC if too heavy

- **Indirect searches of SUSY via radiative corrections**
  - ⋆ If SUSY particles not seen: Complementary to direct searches
  - ⋆ Similar to past LEP hints on top quark via $\Delta\ \rho$ etc

Hints on SUSY: virtual SUSY particles propagate into the loops

⇓

Look for observables enhanced in SUSY respect to SM prediction

⋆Involving **Higgs sector** ⋆ **FC and LFV** suppressed in SM

⇓ ⇓

Non-decoupling of heavy SUSY Window to new physics

Seesaw mechanism with $3\,\nu_R$

For 3 generations $\Rightarrow$ 6 physical neutrinos: 3 ν light, 3 N heavy

$$U^{\nu\,T} M^\nu U^\nu = \hat{M}^\nu = diag(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}, m_{N_1}, m_{N_2}, m_{N_3}).$$

$$m_D \ll m_M,\; m_D = Y_\nu < H_2 > \Rightarrow$$

$$\begin{aligned} m_\nu^{\rm diag} &= U_{\rm PMNS}{}^T m_\nu U_{\rm PMNS} = {\rm diag}\,(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})\,, \qquad (1)\\ m_N^{\rm diag} &= m_N = {\rm diag}\,(m_{N_1}, m_{N_2}, m_{N_3})\,, \end{aligned}$$

All, Y_ν, m_D, m_M, $U_{\rm PMNS}$, are 3×3 matrices; $c_{ij} \equiv \cos(\theta_{ij})$, $s_{ij} \equiv \sin(\theta_{ij})$

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\delta} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\delta} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\delta} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\delta} & c_{23}\,c_{13} \end{pmatrix} \times diag(1, e^{i\alpha}, e^{i\beta} \qquad (2)$$

Pontecorvo-Maki-Nakagawa-Sakata matrix: θ_{12}, θ_{13}, θ_{23}, δ, α, β