The effective $H\tau\mu$ vertex from heavy SUSY and implications for $H \to \tau\mu$ decays

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References

Work based on:

- E. Arganda, M. J. Herrero, R. Morales and A. Szynkman, "Analysis of the $h, H, A \to \tau\mu$ decays induced from SUSY loops within the Mass Insertion Approximation", arXiv:1510.04685[hep-ph]

  In continuation to:

- M. Arana-Catania, E. Arganda and M. J. Herrero, "Non-decoupling SUSY in LFV Higgs decays: a window to new physics at the LHC", arXiv:1304.3371 [hep-ph], JHEP 1309 (2013) 160, JHEP 1510 (2015) 192.

Motivation

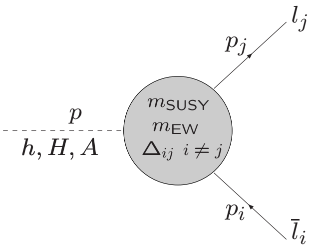
- The use of effective vertices is very usefull for pheno. The $H\tau\mu$ effective vertex will help in LFV pheno.
- Why LFV?: Lepton Flavor Violation occurs in Nature. Neutrino oscillations $\Rightarrow$ LFV.
- LFV opens a new window to look for BSM physics: In particular to SUSY (No LFV within SM).
- SUSY not seen yet at LHC (m_{SUSY} into multi-TeV range?).
- Higgs mediated processes very sensitive to SUSY, via loops. LFV Higgs decays (LFVHD) induced by SUSY at one loop: sizeable even at very heavy $m_{\text{SUSY}} \simeq \mathcal{O}(5\ \text{TeV})$.

Main here: The use of the MIA will allow us to derive the $H\tau\mu$ one-loop effective vertex from heavy SUSY

Our aim

Get the effective vertex from an expansion valid for heavy SUSY

$m_{\rm SUSY} > p_{\rm ext}, m_{\rm EW}, m_{h,H,A}$



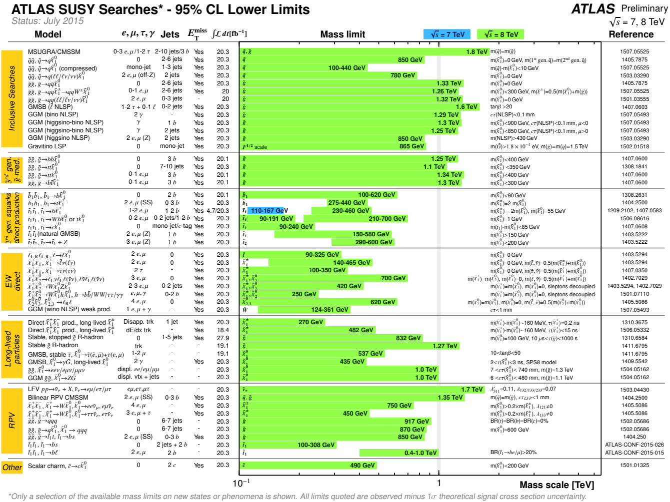
With flavor changing insertions Δ_{ij} treated pertubatively (MIA)

$$\Delta_{ij} F(p_{\rm ext}, m_{H_x}, m_{\rm EW}, m_{\rm SUSY}) \sim \Delta_{ij}\left[F|_{p_{\rm ext}=0} + \mathcal{O}(m_{H_x}^2/m_{\rm SUSY}^2) + \mathcal{O}(m_{\rm EW}^2/m_{\rm SUSY}^2)\right]$$

$F|_{p_{\rm ext}=0} \sim \mathcal{O}((m_{H_x}/m_{\rm SUSY})^0)$ Non-decoupling
$\mathcal{O}(m_{H_x}^2/m_{\rm SUSY}^2)$ and $\mathcal{O}(m_{\rm EW}^2/m_{\rm SUSY}^2)$ decoupling
We wish to compute analytically both contributions to $\mathcal{O}(\Delta_{ij})$ (single MIA)

Present Status: SUSY searches (summary)

SUSY not seen yet. Present (95% CL) bounds (similar in ATLAS and CMS):



SQCD $m_{\rm SUSY} > 1.8$ TeV

SEWinos $m_{\rm SUSY} > 0.7$ TeV

Sleptons $m_{\rm SUSY} > 0.3$ TeV

$\Longrightarrow$ Heavy SUSY

LFV Present Bounds versus Future Sensitivities

LFV (in charged leptons) not seen yet. Intense program. Some searched processes:
(updated as reported in EPS 2015)

LFV process	Present bound $(90\% CL)$	Future sensitivity (?)
BR$(\mu \to e\,\gamma)$	5.7×10^{-13} (MEG 2013)	5×10^{-14} MEGup
BR$(\tau \to e\,\gamma)$	3.3×10^{-8} (BaBar 2010)	3×10^{-9} SuperB
BR$(\tau \to \mu\,\gamma)$	4.4×10^{-8} (BaBar 2010)	2.4×10^{-9} SuperB
BR$(\mu \to e\,e\,e)$	1×10^{-12} (SINDRUM 1988)	10^{-16} Mu3E (PSI)
BR$(\tau \to e\,e\,e)$	2.7×10^{-8} (Belle 2010)	$10^{-9,-10}$ Belle2, SuperB
BR$(\tau \to \mu\,\mu\,\mu)$	2.1×10^{-8} (Belle 2010)	$10^{-9,-10}$ Belle2, SuperB
BR$(\tau \to \mu\eta)$	2.3×10^{-8} (Belle 2010)	$10^{-9,-10}$ Belle2, SuperB
CR$(\mu - e, \mathrm{Au})$	7.0×10^{-13} (SINDRUM2 2006)	
CR$(\mu - e, \mathrm{Al})$		3.1×10^{-15} COMET-I (J-PARC)
		2.6×10^{-17} COMET-II (J-PARC)
		6×10^{-17} Mu2E (Fermilab)
CR$(\mu - e, \mathrm{Ti})$	4.3×10^{-12} (SINDRUM2 2004)	10^{-18} PRISM (J-PARC)

New input from LHC: LFV Higgs decays

$\mathrm{Br}(H \to \tau\mu) < 1.51 \times 10^{-2}\ (95\% CL)$ [CMS, 2015] (2.4σ excess?)

$\mathrm{Br}(H \to \tau\mu) < 1.85 \times 10^{-2}\ (95\% CL)$ [ATLAS, 2015]

Our work here

- Assume heavy SUSY $\gtrsim \mathcal{O}(1\,\mathrm{TeV})$
- Focus on LFV Higgs decays (LFVHD): $h, H, A \to l_k \bar{l}_m$.
- Work within the MSSM with general slepton flavor mixing: Assume NMFV instead of the most commonly used MFV.
- In contrast to previous works:
  Use the MIA for the 1-loop diagramatic computation.
  Work with single/linear insertions, i.e., $\mathcal{O}(\Delta_{mk})$, $m \neq k$.
- Perform an analytic expansion of all the form factors involved in powers of the external momenta:
  Capture the non-decoupling and decoupling contributions.
- Explore the goodness of the MIA results:
  Systematic comparison MIA/Full 1-loop computation
- Perform a numerical study of maximum $h, H, A \to \tau\mu$ rates, allowed by exp. $\tau \to \mu\gamma$ constraints. Pheno implications.

The MSSM with general slepton mixing

We use a low energy parametrization for general slepton mixing:

Model Independent Approach

LFV is orginated from the off-diagonal δ_{ij}^{AB}'s via loops of SUSY.

Model parameters: MSSM + slepton flavor mixing parameters δ_{ij}^{AB}.

$$m^2_{\tilde{L}} = \left(\begin{array}{ccc} m^2_{\tilde{L}_1} & \delta_{12}^{LL} m_{\tilde{L}_1} m_{\tilde{L}_2} & \delta_{13}^{LL} m_{\tilde{L}_1} m_{\tilde{L}_3} \\ \delta_{21}^{LL} m_{\tilde{L}_2} m_{\tilde{L}_1} & m^2_{\tilde{L}_2} & \delta_{23}^{LL} m_{\tilde{L}_2} m_{\tilde{L}_3} \\ \delta_{31}^{LL} m_{\tilde{L}_3} m_{\tilde{L}_1} & \delta_{32}^{LL} m_{\tilde{L}_3} m_{\tilde{L}_2} & m^2_{\tilde{L}_3} \end{array} \right),$$

$$v_1 \mathcal{A}^l = \left(\begin{array}{ccc} m_e A_e & \delta_{12}^{LR} m_{\tilde{L}_1} m_{\tilde{R}_2} & \delta_{13}^{LR} m_{\tilde{L}_1} m_{\tilde{R}_3} \\ \delta_{21}^{LR} m_{\tilde{L}_2} m_{\tilde{R}_1} & m_\mu A_\mu & \delta_{23}^{LR} m_{\tilde{L}_2} m_{\tilde{R}_3} \\ \delta_{31}^{LR} m_{\tilde{L}_3} m_{\tilde{R}_1} & \delta_{32}^{LR} m_{\tilde{L}_3} m_{\tilde{R}_2} & m_\tau A_\tau \end{array} \right),$$

$$m^2_{\tilde{R}} = \left(\begin{array}{ccc} m^2_{\tilde{R}_1} & \delta_{12}^{RR} m_{\tilde{R}_1} m_{\tilde{R}_2} & \delta_{13}^{RR} m_{\tilde{R}_1} m_{\tilde{R}_3} \\ \delta_{21}^{RR} m_{\tilde{R}_2} m_{\tilde{R}_1} & m^2_{\tilde{R}_2} & \delta_{23}^{RR} m_{\tilde{R}_2} m_{\tilde{R}_3} \\ \delta_{31}^{RR} m_{\tilde{R}_3} m_{\tilde{R}_1} & \delta_{32}^{RR} m_{\tilde{R}_3} m_{\tilde{R}_2} & m^2_{\tilde{R}_3} \end{array} \right).$$

We assume real δ's ($\delta_{ij}^{AB} = \delta_{ji}^{BA}$) $\Rightarrow$ 12 independent δ_{ij}^{AB}'s.

Physical mass basis usually used (full diagonalization): 6 sleptons $\tilde{l}_\alpha$ and 3 sneutrinos $\tilde{\nu}_\beta$. Dependence on δ_{ij}^{AB} hidden inside masses and rotations.

Mass Insertions Changing SUSY-Flavor: Δ_{mk}^{AB} $(m \neq k)$

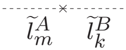
$$\Delta_{mk}^{LL} \equiv (m_{\tilde{L}}^2)_{mk} = \delta_{mk}^{LL} m_{\tilde{L}_m} m_{\tilde{L}_k}$$

$$\Delta_{mk}^{RR} \equiv (m_{\tilde{R}}^2)_{mk} = \delta_{mk}^{RR} m_{\tilde{R}_m} m_{\tilde{R}_k}$$

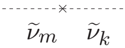
$$\Delta_{mk}^{LR} \equiv (v_1 \mathcal{A}^l)_{mk} = \tilde{\delta}_{mk}^{LR} v_1 \sqrt{m_{\tilde{L}_m} m_{\tilde{R}_k}}$$

$$\Delta_{mk}^{RL} \equiv (v_1 \mathcal{A}^l)_{km} = \tilde{\delta}_{mk}^{RL} v_1 \sqrt{m_{\tilde{R}_m} m_{\tilde{L}_k}}$$

$$\delta_{mk}^{LR} = \tilde{\delta}_{mk}^{LR} \frac{v_1}{\sqrt{m_{\tilde{L}_m} m_{\tilde{R}_k}}} \; ; \; v_{1,2} = < H_{1,2} > ; \; \tan\beta = v_2/v_1$$



$-i\Delta_{mk}^{AB}$



$-i\Delta_{mk}^{LL}$

MIA: works with the EW int. basis, $\tilde{l}_i^{L,R}$, $\tilde{\nu}_i^L$ ($\tilde{\nu}_i$ for short). Pert. $\mathcal{O}(\Delta_{mk}^{AB})$. $|\delta| \leq 1$.

Full: works with the mass basis. Full diagonalisation of mass matrix (non-pert).

Updated constraints on general slepton mixing

(M.Arana-Catania,S.Heinemeyer and M.J.H, PRD 88(2013)015026)

Systematic study of constraints on all δ_{ij}^{AB} slepton mixing parameters from selected LFV processes:

- Radiative LFV decays: $\mu \to e\gamma$, $\tau \to e\gamma$ and $\tau \to \mu\gamma$
- Leptonic LFV decays: $\mu \to 3e$, $\tau \to 3e$ and $\tau \to 3\mu$
- Semileptonic LFV tau decays: $\tau \to \mu\eta$ and $\tau \to e\eta$
- Conversion of μ into e in heavy nuclei

And requiring present experimental LFV bounds on their BRs.

The first are usually the most constraining, but the others can be mediated by Higgs bosons, then access to different δ_{ij}^{AB}'s

Summary of bounds on δ_{ij}^{AB} for selected points

[See details in: Arana-Catania, Heinemeyer, M.J.H, PRD 88 (2013) 015026]

For S1...S6: $500 < m_{\tilde{l},\tilde{\nu}}(\mathrm{GeV}) < 1500$; $300 < m_{\tilde{\chi}}(\mathrm{GeV}) < 900$

$|\delta_{23}^{LL}| < \mathcal{O}(10^{-1})$ $|\delta_{23}^{LR}| < \mathcal{O}(10^{-1})$ $|\delta_{23}^{RR}| < \mathcal{O}(1)$

$|\delta_{13}^{LL}| < \mathcal{O}(10^{-1})$ $|\delta_{13}^{LR}| < \mathcal{O}(10^{-1})$ $|\delta_{13}^{RR}| < \mathcal{O}(1)$

$|\delta_{12}^{LL}| < \mathcal{O}(10^{-4})$ $|\delta_{12}^{LR}| < \mathcal{O}(10^{-5})$ $|\delta_{12}^{RR}| < \mathcal{O}(10^{-3})$

If S7: $m_{\tilde{l},\tilde{\nu}} \sim 10\mathrm{TeV}$, $m_{\tilde{\chi}} \sim 2\mathrm{TeV}$, all $\delta_{23} \lesssim \mathcal{O}(1)$ allowed.

General : Heavy SUSY implies weaker bounds on δ_{ij}^{AB}'s

Results for LFV Higgs decays in the MIA

[Arganda, M.J.H, Morales and Szynkman, arXiv:1510.04685]

Work with simple heavy SUSY scenarios: just one $m_{\rm SUSY}$

1) *Equal masses* scenario

$$M_1 = M_2 = M_3 = \mu = m_{\tilde{L}_i} = m_{\tilde{R}_i} = A_\mu = A_\tau = m_{\rm SUSY}\,.$$

2) *GUT approximation* scenario

$$\begin{aligned} M_2 &= 2M_1 = M_3/4 \\ m_{\tilde{L}_i} &= m_{\tilde{R}_i} = M_2 = A_\mu = A_\tau = \mu/a = m_{\rm SUSY}\,, a = \frac{3}{4}, \frac{4}{3}, .. \end{aligned}$$

3) *Generic* scenario

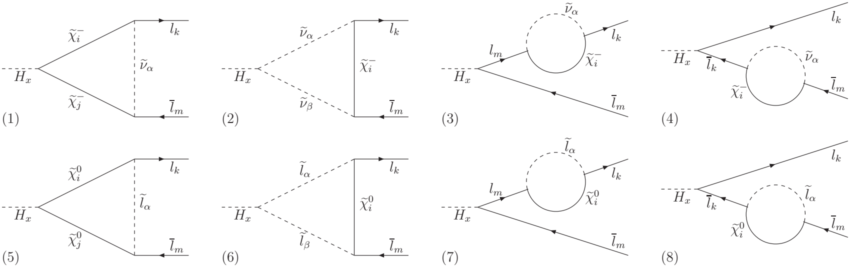
$$\begin{aligned} M_1 &= 2.2\,m_{\rm SUSY}\,, M_2 = 2.4\,m_{\rm SUSY}\,, M_3 = 2.6\,m_{\rm SUSY}\,, \mu = 2.1\,m_{\rm SUSY} \\ m_{\tilde{L}_1} &= 2\,m_{\rm SUSY}\,, m_{\tilde{L}_2} = 1.8\,m_{\rm SUSY}\,, m_{\tilde{L}_3} = 1.6\,m_{\rm SUSY}\,, \\ m_{\tilde{R}_1} &= 1.4\,m_{\rm SUSY}\,, m_{\tilde{R}_2} = 1.2\,m_{\rm SUSY}\,, m_{\tilde{R}_3} = m_{\rm SUSY}\,, \\ A_\mu &= 0.6\,m_{\rm SUSY}\,, A_\tau = 0.8\,m_{\rm SUSY}\,. \end{aligned}$$

Checked that all these provide a m_h prediction within (125 ± 3) GeV (adjusting the parameters in the squark sector, irrelevant for LFV)

One-loop diagrams for the Full results (for comparison)

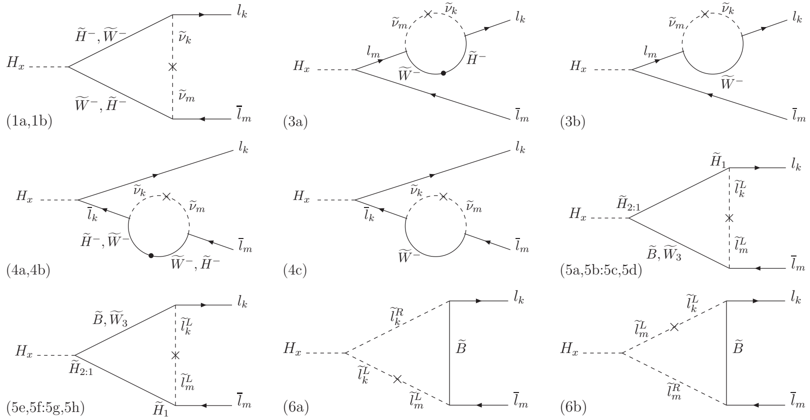
Use mass basis for the internal SUSY particles: sleptons, sneutrinos, charginos, neutralinos.

[Arganda, Curiel, M.J.H, Temes, PRD71(2005)035011]

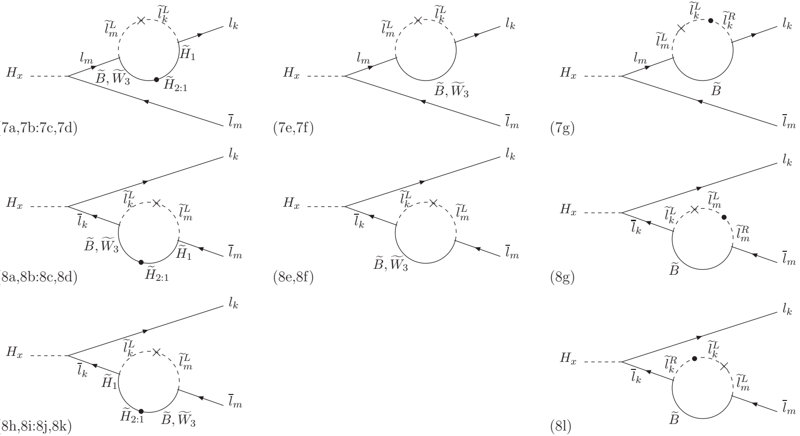


Relevant one-loop diagrams for the MIA : $\times = \Delta_{mk}^{LL}$ (1)

Other diagrams suppressed by extra factors of $(m_{\rm EW}/m_{\rm SUSY})^n$ and/or $(m_l/M_W)^m$



Relevant one-loop diagrams for the MIA : $\times = \Delta^{LL}_{mk}$ (2)

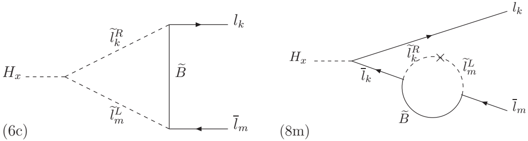


(7a,7b:7c,7d) (7e,7f) (7g)

(8a,8b:8c,8d) (8e,8f) (8g)

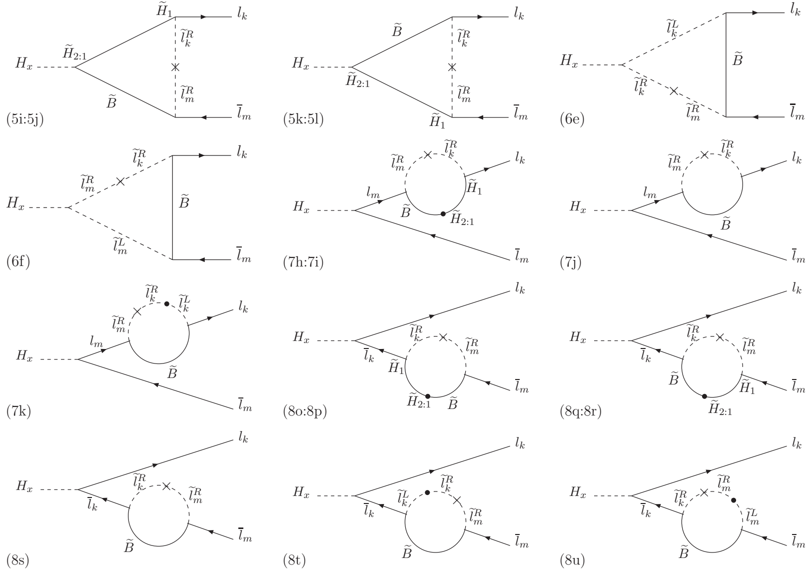
(8h,8i:8j,8k) (8l)

Relevant one-loop diagrams for the MIA : $\times = \Delta_{mk}^{LR}$



Similarly for $\times = \Delta_{mk}^{RL}$ changing $L \leftrightarrow R$

Relevant one-loop diagrams for the MIA : $\times = \Delta^{RR}_{mk}$



Analytical results of the LFV form factors in the MIA (1)

$H_x(p_1) \to l_k(-p_2)\bar{l}_m(p_3)$, $H_x = h, H, A$, described by:

$$i\mathcal{M} = -ig\bar{u}_{l_k}(-p_2)(F_L^{(x)}P_L + F_R^{(x)}P_R)v_{l_m}(p_3)\,,$$

$$\Gamma(H_x \to l_k\bar{l}_m) = \frac{g^2}{16\pi m_{H_x}}\sqrt{\left(1-\left(\frac{m_{l_k}+m_{l_m}}{m_{H_x}}\right)^2\right)\left(1-\left(\frac{m_{l_k}-m_{l_m}}{m_{H_x}}\right)^2\right)}$$
$$\times\left((m_{H_x}^2 - m_{l_k}^2 - m_{l_m}^2)(|F_L^{(x)}|^2 + |F_R^{(x)}|^2) - 4m_{l_k}m_{l_m}Re(F_L^{(x)}F_R^{(x)*})\right)\,,$$

$$F_{L,R}^{(x)} = \Delta_{mk}^{LL}F_{L,R}^{(x)LL} + \Delta_{mk}^{LR}F_{L,R}^{(x)LR} + \Delta_{mk}^{RL}F_{L,R}^{(x)RL} + \Delta_{mk}^{RR}F_{L,R}^{(x)RR}\,,$$

$F_{L,R}^{(x)LL}$, $F_{L,R}^{(x)LR}$, $F_{L,R}^{(x)RL}$, $F_{L,R}^{(x)RR}$ computed in terms (see paper) of scalar one-loop functions: C_0, C_2, D_0, $\tilde{D}_0$: all UV convergent!
We perfom a systematic expansion of all them in powers of $p_{\rm ext}$, and keep: leading $\mathcal{O}(p_{\rm ext}^0)$ and next-to-leading $\mathcal{O}(p_1^2)$.

Analytical results of the LFV form factors in the MIA (2)

$$\left(\Delta_{23}^{LL} F_L^{(x)LL}\right)_{\rm ND} = \left(\frac{g^2}{16\pi^2}\frac{m_\tau}{2M_W}\right)\left[\frac{\sigma_2^{(x)} + \sigma_1^{(x)^*} t_\beta}{c_\beta}\right](\delta_{23}^{LL} m_{\tilde{L}_2} m_{\tilde{L}_3})$$

$$\mathcal{O}(m_{H_x}^0/m_{\rm SUSY}^0) \quad \times\left[\frac{3}{2}\mu M_2 D_0(0,0,0,m_{\tilde{L}_2},m_{\tilde{L}_3},\mu,M_2) - \frac{t_W^2}{2}\mu M_1 D_0(0,0,0,m_{\tilde{L}_2},m_{\tilde{L}_3},\mu,M_1) - t_W^2 \mu M_1 D_0(0,0,0,m_{\tilde{L}_2},m_{\tilde{L}_3},m_{\tilde{R}_3},M_1)\right]$$

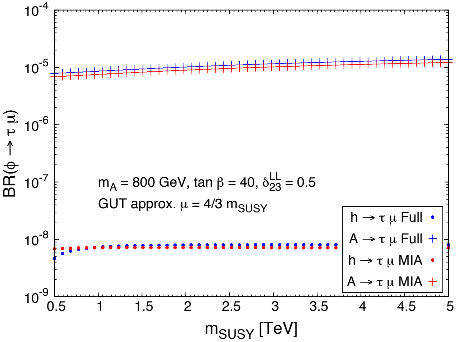
$$\left(\Delta_{23}^{RR} F_R^{(x)RR}\right)_{\rm ND} = \left(\frac{g^2 t_W^2}{16\pi^2}\frac{m_\tau}{2M_W}\right)\left[\frac{\sigma_2^{(x)^*} + \sigma_1^{(x)} t_\beta}{c_\beta}\right](\delta_{23}^{RR} m_{\tilde{R}_2} m_{\tilde{R}_3})$$

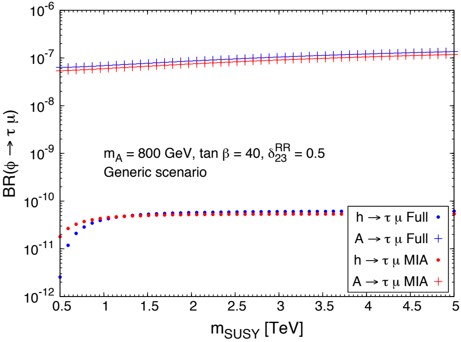
$$\mathcal{O}(m_{H_x}^0/m_{\rm SUSY}^0) \quad \times\left[\mu M_1 D_0(0,0,0,m_{\tilde{R}_2},m_{\tilde{R}_3},\mu,M_1) - \mu M_1 D_0(0,0,0,m_{\tilde{R}_2},m_{\tilde{R}_3},m_{\tilde{L}_3},M_1)\right]$$

$$\left(\Delta_{23}^{LR} F_L^{(x)LR}\right)_{\rm D} = \frac{g^2 t_W^2}{16\pi^2}(\tilde{\delta}_{23}^{LR} v_1 \sqrt{m_{\tilde{L}_2} m_{\tilde{R}_3}})\frac{M_1 \sigma_1^{(x)^*}}{2M_W c_\beta}$$

$$\mathcal{O}(m_{H_x}^2/m_{\rm SUSY}^2) \quad \times\left(-C_0(p_2,p_1,M_1,m_{\tilde{R}_3},m_{\tilde{L}_2}) + C_0(p_3,0,M_1,m_{\tilde{L}_2},m_{\tilde{R}_3})\right)$$

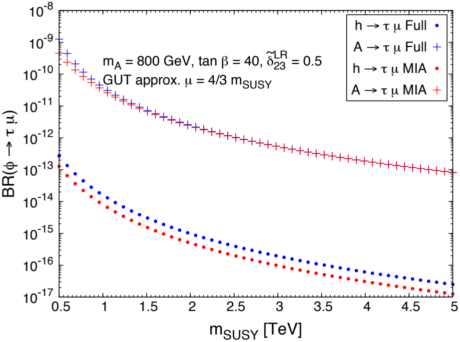
Numerical results: Non-decoupling LL and RR

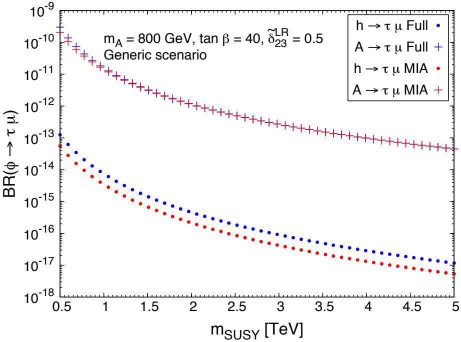




- Non-decoupling behavior of BR($h, H, A \to \tau\mu$) with m_{SUSY}
  In contrast with decoupling behavior of BR($\tau \to \mu\gamma$) $\sim 1/m^4_{\text{SUSY}}$
- MIA very close to the Full (in each diag and in total)
- Largest rates for LL and large $\tan\beta$: BR($H, A \to \tau\mu$) $\propto (\tan\beta)^2$
- Similar results in other scenarios

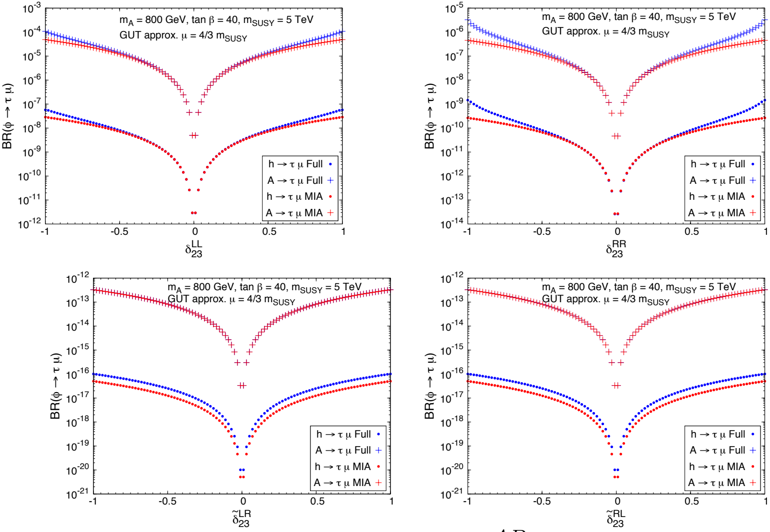
Numerical results: Decoupling LR (and RL)





- Decoupling behavior of BR$(h, H, A \to \tau\mu)$ with m_{SUSY}
  Strong cancellations between (non-decoupling) diagrams.
  BR$(h, H, A \to \tau\mu) \sim 1/m^4_{\text{SUSY}}$ (similar to $\tau \to \mu\gamma$)
- MIA agrees with Full.
- Very small LFV rates for LR (and RL)
- Similar results in other scenarios

Limitations of the MIA results



Seems to work reasonably well within $|\delta_{23}^{AB}| \leq \mathcal{O}(1)$

Simplest effective vertices: *Equal masses* scenario (1)

$$F_{L,R}^{(x)} = \delta_{23}^{LL} \hat{F}_{L,R}^{(x)LL} + \tilde{\delta}_{23}^{LR} \hat{F}_{L,R}^{(x)LR} + \tilde{\delta}_{23}^{RL} \hat{F}_{L,R}^{(x)RL} + \delta_{23}^{RR} \hat{F}_{L,R}^{(x)RR} .$$

$$\hat{F}_L^{(x)LL} = \frac{g^2}{16\pi^2} \frac{m_\tau}{2M_W c_\beta} \left[\left(\sigma_2^{(x)} + \sigma_1^{(x)^*} t_\beta \right) \frac{1 - t_W^2}{4} + \frac{m_{H_x}^2}{m_{\text{SUSY}}^2} \left(\sigma_2^{(x)} \frac{3 - 5t_W^2}{120} + \sigma_1^{(x)^*} \frac{9 - 11t_W^2}{240} \right) \right] \quad \rightarrow \text{ND}$$

$$\hat{F}_R^{(x)RR} = -\frac{g^2 t_W^2}{16\pi^2} \frac{m_\tau}{2M_W c_\beta} \frac{m_{H_x}^2}{m_{\text{SUSY}}^2} \left[\frac{2\sigma_2^{(x)^*} + \sigma_1^{(x)}}{120} \right] \quad \rightarrow \text{D}$$

$$\hat{F}_L^{(x)LR} = \frac{g t_W^2}{16\pi^2} \frac{1}{24\sqrt{2}} \frac{m_{H_x}^2}{m_{\text{SUSY}}^2} \left[\sigma_1^{(x)^*} \right] \quad \rightarrow \text{D}$$

$H_x = (h, H, A)$, $\sigma_1^{(x)} = (s_\alpha, -c_\alpha, is_\beta)$, $\sigma_2^{(x)} = (c_\alpha, s_\alpha, -ic_\beta)$

Simplest effective vertices: *Equal masses* scenario (2)

The dominant effective vertex and most relevant for phenomenology is originated from δ_{23}^{LL} mixing: $(-igV^{\rm eff}_{H_x\tau\mu}P_L)$

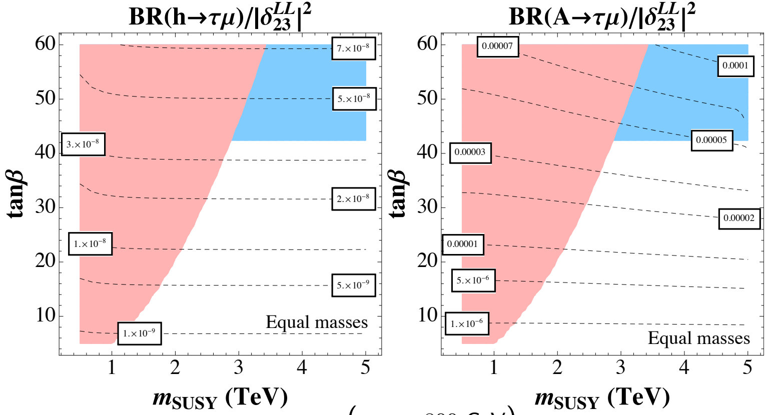
$$V^{\rm eff}_{H_x\tau\mu} = \frac{g^2}{16\pi^2}\frac{m_\tau}{2M_W}\left[\frac{\sigma_2^{(x)}+\sigma_1^{(x)*}t_\beta}{c_\beta}\right]\left(\frac{1-t_W^2}{4}\right)\delta_{23}^{LL}$$

$$V^{\rm eff}_{H\tau\mu}|_{t_\beta\gg1} = -iV^{\rm eff}_{A\tau\mu}|_{t_\beta\gg1} = -\frac{g^2}{16\pi^2}\frac{m_\tau}{2M_W}t_\beta^2\left(\frac{1-t_W^2}{4}\right)\delta_{23}^{LL}$$

$$V^{\rm eff}_{h\tau\mu}|_{t_\beta\gg1} = -\frac{g^2}{16\pi^2}\frac{m_\tau}{M_W}\frac{M_Z^2}{m_A^2}t_\beta\left(\frac{1-t_W^2}{4}\right)\delta_{23}^{LL}$$

Similar results for A and H: LFV eff. vertex enhanced by t_β^2.
For h: LFV eff. vertex suppressed by (M_Z^2/m_A^2): h resembles $H_{\rm SM}$

Implications for phenomenology (1)

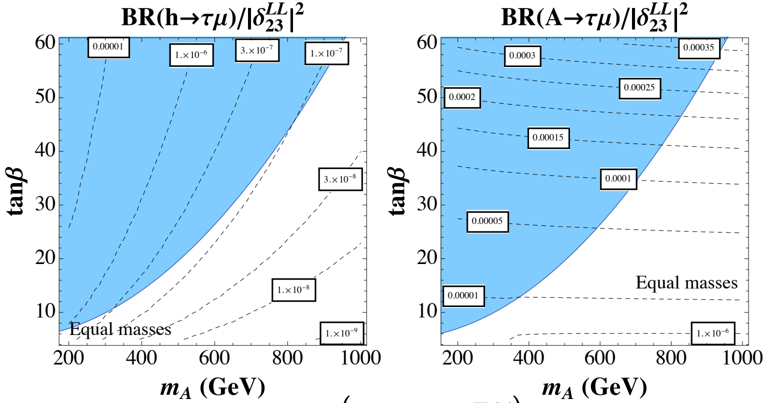


$\left(m_A = 800\ \text{GeV}\right)$

Shaded pink/red area: excluded by BR$(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$.
Shaded blue area: excluded by negative searches by ATLAS and CMS of neutral MSSM Higgs bosons decaying to tau pairs.

Max. allowed rates are for H, A. For this input: $\sim 5 \times 10^{-5}$ below LHC sensitivity.

Implications for phenomenology (2)

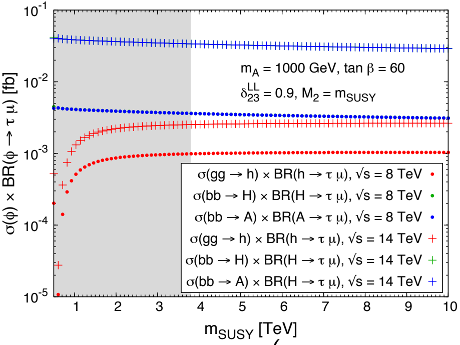


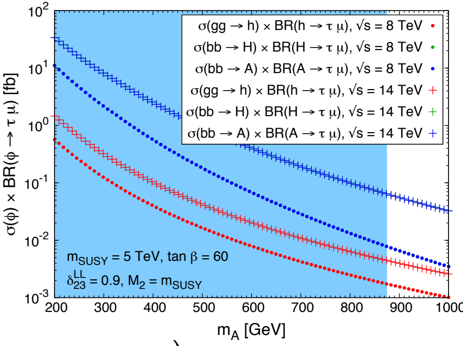
$\left(m_{\rm SUSY} = 4\ \text{TeV}\right)$

If very heavy SUSY, no constraints from $\tau \to \mu\gamma$
Shaded blue area: excluded by negative searches by ATLAS and CMS of neutral MSSM Higgs bosons decaying to tau pairs.
Max. allowed rates are for H, A. Upper right corner: $\sim 3.5 \times 10^{-4}$.

If both channels $\tau\bar{\mu}$, $\mu\bar{\tau}$ added: BR up to $\sim 10^{-3}$, closer to LHC sensitivity!!.

LFV rates at LHC from $h, H, A \to \tau\mu$





(Cross sections computed with *FeynHiggs*)

Shaded gray area excluded by $\tau \to \mu\gamma$.
Shaded blue area excluded by CMS and ATLAS searches.
Best expectations are for H, A (no chances for h).

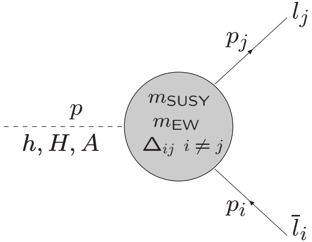
For $\sqrt{s} = 14$ TeV and $\mathcal{L} \sim 100$ fb^{-1} we predict a few events $\mathcal{O}(1-10)$, in the region:

$\tan\beta \sim 40-60$, $m_A \sim 800-1000$ GeV, even if very heavy SUSY, $m_{\rm SUSY} \gtrsim 4$ TeV.

Conclusions

- In case SUSY is not seen at LHC, exploring LFV may provide an alternative test of SUSY *via* exotic channels like $h, H, A \to \tau\mu$.
- We have computed the relevant effective vertices by means of the MIA with single sflavor changing insertions Δ_{ij}:

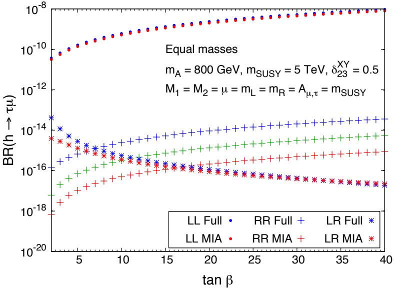
$$V^{\text{eff}}_{H_x l_i l_j} =$$

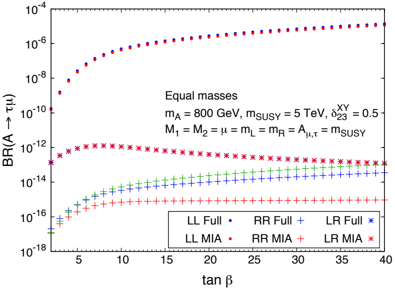


- We found very simple analytical results which are very useful for phenomenology and comparison with data. Predicted 1-10 events at LHC from $H, A \to \tau\mu$.

Backup slides

On the subleading $\mathcal{O}(M_W^2/m_{\rm SUSY}^2)$ contributions





$$
\begin{aligned}
\tilde{F}_R^{(x)\,RR} \;=\;& \frac{g^2 t_W^2}{16\pi^2}\,\frac{m_\tau}{2M_W c_\beta}\,\frac{M_W^2}{m_S^2}\,\frac{t_\beta^2}{1+t_\beta^2}\left[\left(\frac{\sigma_1^{(x)}}{60}\left(3t_W^2+13-4t_W^2 t_\beta-12t_\beta\right)\right.\right.\\
&\left. -\frac{\sigma_1^{(x)*}}{5}-\frac{4\sigma_2^{(x)}}{15}-\frac{2\sigma_2^{(x)*}}{15}+\frac{\sigma_3^{(x)}\sqrt{1+t_\beta^2}}{12t_\beta}\left(1+t_W^2\right)\right)\\
&+\left(\frac{1+t_W^2}{60t_\beta}\left(-8\sigma_1^{(x)}+4\sigma_1^{(x)*}+\sigma_2^{(x)}+\sigma_2^{(x)*}\right)+\frac{\sigma_3^{(x)}\sqrt{1+t_\beta^2}}{12t_\beta^2}\left(-1+5t_W^2\right)\right)\\
&\left.+\left(\frac{1+t_W^2}{30t_\beta^2}\left(-\sigma_1^{(x)}+\sigma_1^{(x)*}+\sigma_2^{(x)}-\sigma_2^{(x)*}\right)\right)\right].
\end{aligned}
$$

Present Status: LFV in Neutrino oscillations

- Neutrino oscillations imply non-vanishing
  ν mass differences $\Delta m^2_{kj} = m^2_k - m^2_j$ and mixings θ_{ij}

- Best fit (nu-fit.org) (NuFit 1.3 (2014))

$$\sin^2\theta_{12} = 0.304^{+0.012}_{-0.012}\,, \qquad \Delta m^2_{21} = 7.50^{+0.19}_{-0.17} \times 10^{-5}\ \mathrm{eV}^2\,,$$
$$\sin^2\theta_{23} = 0.451^{+0.001}_{-0.001}\,, \qquad \Delta m^2_{31} = 2.458^{+0.002}_{-0.002} \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NH}),$$
$$\sin^2\theta_{13} = 0.0219^{+0.0010}_{-0.0011}\,, \qquad \Delta m^2_{32} = -2.448^{+0.047}_{-0.047} \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IH}).$$

Therefore, large flavor mixings (i.e. large LFV in ν sector)

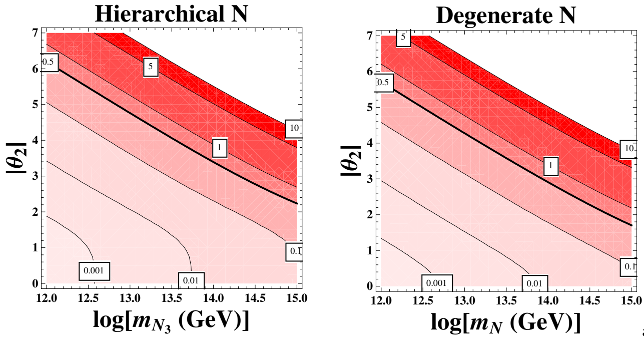
solar	$\theta_{12} \simeq 33.5^o$	large
atmospheric	$\theta_{23} \simeq 42.2^o$	almost maximal
reactor	$\theta_{13} \simeq 8.5^o$	not small

- Interesting connections between LFV and neutrino oscillations in specific models. Particularly via Y_ν if Seesaw Mechanism: Seesaw Models (I, II, III, Linear, Inverse, non-SUSY, SUSY...)

Size of δ_{32}^{LL} in SUSY-Seesaw

M.J.H, J.Portoles, A.Rodriguez-Sanchez, PRD80(2009)015023, (Seesaw I)

Contour lines of δ_{32}^{LL} for heavy N_i (full 1-loop RGE and compatibility with ν data)



$\arg(\theta_2) = \pi/4$

Large δ_{23}^{LL} for $m_{N_i} \sim 10^{14} - 10^{15}$ GeV $\Rightarrow |\delta_{32}^{LL}| \sim 0.1 - 10$ ($|\delta_{12}^{LL}| < 10^{-3}$)

Perturbativity constraints (solid line): $|\frac{Y_\nu^2}{4\pi}| < 1.5 \Rightarrow |\delta_{23}^{LL}| < 0.5$

Larger δ_{32}^{LL} ($\sim \times 6$) and LFV rates in low scale SUSY-Seesaw models, like SUSY-ISS [Deppisch,Valle,2005; Hirsch et al,2010; Abada et al 2012; Ilakovac et al,2012...]

(Meta)stability bounds on $\mathcal{A}^l_{ij}$

If $\mathcal{A}^l_{ij}$ too large, MSSM scalar potential develops charge and/or colour breaking (CCB) minimum deeper than SM-like local minimum or unbounded from below (UFB) directions

[Casas, Dimopoulos (1996)]

$$|\mathcal{A}^l_{23}| \leq y_\tau \sqrt{m^2_{\tilde{L}_2} + m^2_{\tilde{E}_3} + m^2_1}\,, \text{ with } \quad y_\tau = \frac{g m_\tau}{\sqrt{2} M_W \cos\beta}$$

In our simplified SUSY scenarios:

$$|\delta^{LR}_{23}| \leq \frac{m_\tau}{m_{\mathsf{SUSY}}} \sqrt{2 + \frac{m_1^2}{m^2_{\mathsf{SUSY}}}}\,, \quad |\tilde{\delta}^{LR}_{23}| \leq y_\tau \sqrt{2 + \frac{m_1^2}{m^2_{\mathsf{SUSY}}}}.$$

- **Stability:** for $m_{\mathsf{SUSY}} = m_A = 1$ TeV, $|\tilde{\delta}^{LR}_{23}| \lesssim \mathcal{O}(0.1)$ $(\tan\beta \simeq 5)$ and $|\tilde{\delta}^{LR}_{23}| \lesssim \mathcal{O}(1)$ $(\tan\beta \simeq 50)$.
- **Metastability:** for $3 \leq \tan\beta \leq 30$ and $m_{\mathsf{SUSY}} \leq 10$ TeV, $|\tilde{\delta}^{LR}_{23}| \leq 5$ [Jae-hyeon Park (2011)]. Weaker $\times$ factor $\sim (4-8)$.

Selected MSSM points allowed by present data

[Arana-Catania, Heinemeyer, M.J.H, 2013]

	S1	S2	S3	S4	S5	S6
$m_{\tilde{L}_{1,2}}$	500	750	1000	800	500	1500
$m_{\tilde{L}_3}$	500	750	1000	500	500	1500
M_2	500	500	500	500	750	300
A_τ	500	750	1000	500	0	1500
μ	400	400	400	400	800	300
$\tan\beta$	20	30	50	40	10	40
M_A	500	1000	1000	1000	1000	1500
$m_{\tilde{Q}_{1,2}}$	2000	2000	2000	2000	2500	1500
$m_{\tilde{Q}_3}$	2000	2000	2000	500	2500	1500
A_t	2300	2300	2300	1000	2500	1500
$m_{\tilde{l}_1} - m_{\tilde{l}_6}$	489-515	738-765	984-1018	474-802	488-516	1494-1507
$m_{\tilde{\nu}_1} - m_{\tilde{\nu}_3}$	496	747	998	496-797	496	1499
$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_2^\pm}$	375-531	376-530	377-530	377-530	710-844	247-363
$m_{\tilde{\chi}_1^0} - m_{\tilde{\chi}_4^0}$	244-531	245-531	245-530	245-530	373-844	145-363
M_h	126.6	127.0	127.3	123.1	123.8	125.1
M_H	500	1000	999	1001	1000	1499
M_A	500	1000	1000	1000	1000	1500
$M_{H^\pm}$	507	1003	1003	1005	1003	1502
$m_{\tilde{u}_1} - m_{\tilde{u}_6}$	1909-2100	1909-2100	1908-2100	336-2000	2423-2585	1423-1589
$m_{\tilde{d}_1} - m_{\tilde{d}_6}$	1997-2004	1994-2007	1990-2011	474-2001	2498-2503	1492-1509
$m_{\tilde{g}}$	2000	2000	2000	2000	3000	1200

Heavy SUSY ok with LHC, h identified with observed Higgs ($M_h \in (123, 127)$ GeV), $(g-2)_\mu$ OK with data.

Bounds on δ_{12}^{LL} for selected S1,..,S6 points

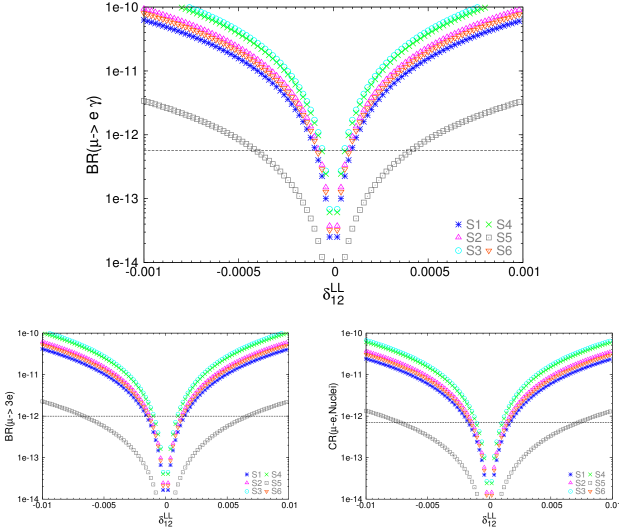
[Arana-Catania, Heinemeyer, M.J.H, 2013]

$$|\delta_{12}^{LL}| < \mathcal{O}(10^{-4})$$

All 12 mixings are strongly restricted

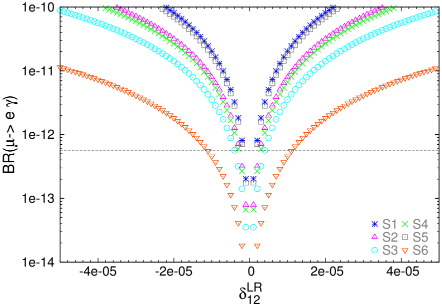
$\mathrm{BR}(\mu \to e\gamma)$ the most restrictive observable at present

$\mu - e$ conversion also competitive, with best future prospects



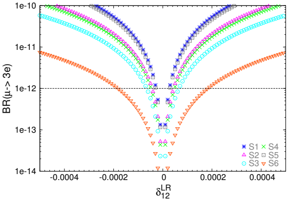
Bounds on δ_{12}^{LR} for selected S1,..,S6 points

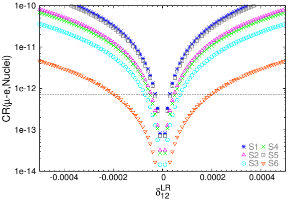
[Arana-Catania, Heinemeyer, M.J.H, 2013]



$|\delta_{12}^{LR}| < \mathcal{O}(10^{-5})$

δ_{12}^{LR} highly restricted !!

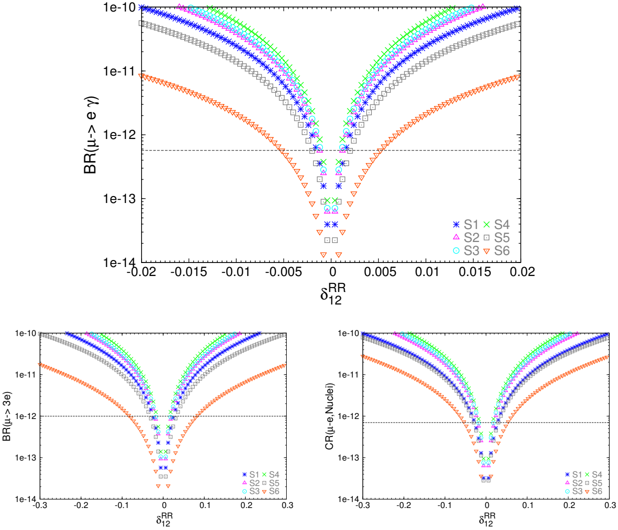




Bounds on δ_{12}^{RR} for selected S1,..,S6 points

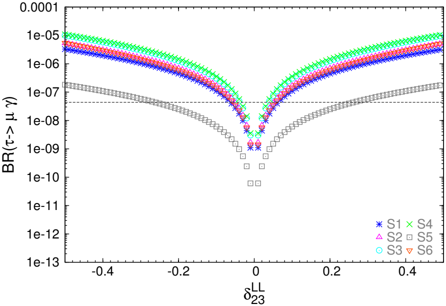
[Arana-Catania, Heinemeyer, M.J.H, 2013]

$$|\delta_{12}^{RR}| < \mathcal{O}(10^{-3})$$



Bounds on δ_{23}^{LL} for selected S1,..,S6 points

[Arana-Catania, Heinemeyer, M.J.H, 2013]

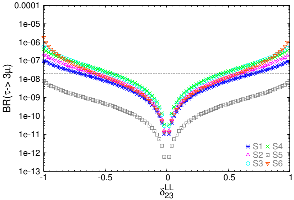


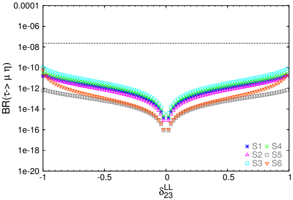
$|\delta_{23}^{LL}| < \mathcal{O}(10^{-1})$

$\mathrm{BR}(\tau \to \mu\gamma)$ most restrictive observable

Similar bounds for δ_{13}^{LL}

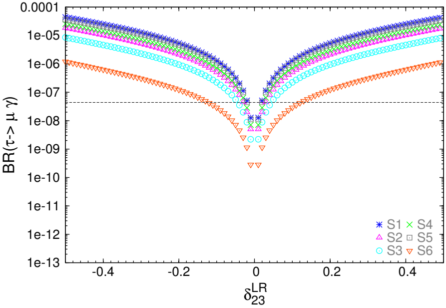
Higgs mediated $\tau \to 3\mu$ and $\tau \to \mu\eta$ less constraining (even at large $\tan\beta$)





Bounds on δ_{23}^{LR} for selected S1,..,S6 points

[Arana-Catania, Heinemeyer, M.J.H, 2013]

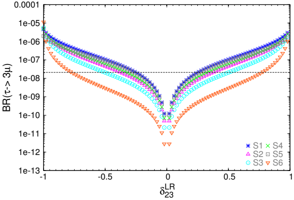


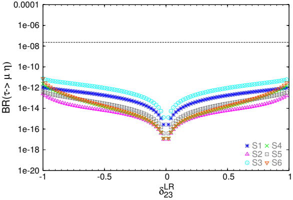
$$|\delta_{23}^{LR}| < \mathcal{O}(10^{-1})$$

$\mathrm{BR}(\tau \to \mu\gamma)$ the most restrictive observable

Similar bounds for δ_{13}^{LR}

Higgs mediated $\tau \to 3\mu$ and $\tau \to \mu\eta$ less constraining





Bounds on δ_{23}^{RR} for selected S1,..,S6 points

[Arana-Catania, Heinemeyer, M.J.H, 2013]

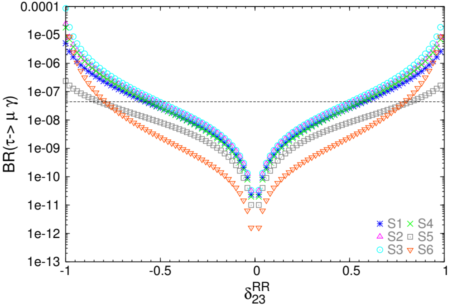
$|\delta_{23}^{RR}| < \mathcal{O}(1)$

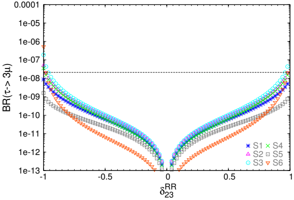
The less constrained mixing

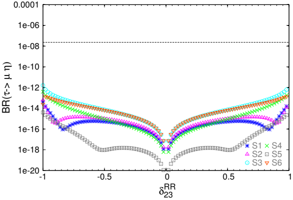
$\mathrm{BR}(\tau \to \mu\gamma)$ the most restrictive observable

Similar bounds for δ_{13}^{RR}

Higgs mediated $\tau \to 3\mu$ and $\tau \to \mu\eta$ less constraining







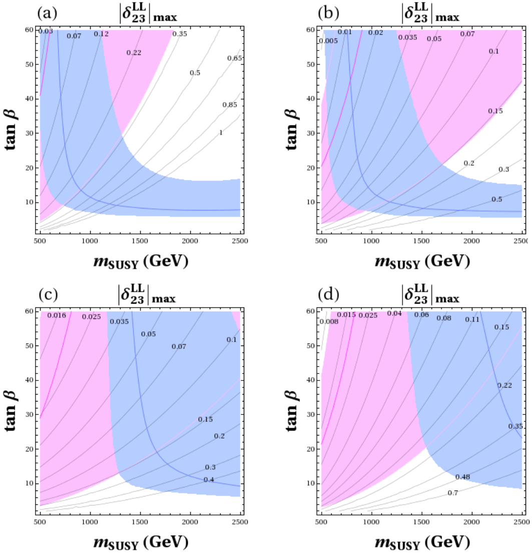
$|\delta_{23}|_{\max}$ in $(m_{SUSY}, \tan\beta)$ plane, versus $(g-2)_\mu$ and m_h

Max allowed by $\tau \to \mu\gamma$

Tension in MSSM versus data

$(g-2)_\mu$ requires a light SUSY-EW sector and large $\tan\beta$; m_h requires a heavy SUSY-QCD sector.

$|\delta_{23}^{LL}|_{\max} \sim \mathcal{O}(10^{-1})$



$m_{\tilde L} = m_{\tilde E} = m_{SUSY-EW}$
$m_{\tilde Q} = m_{\tilde U} = m_{\tilde D} = m_{SUSY-QCD}$

a) $M_2 = m_{SUSY-EW}$, $A_t = 1.3\, m_{SUSY-QCD}$, $m_{SUSY-QCD} = 2\, m_{SUSY-EW}$

b) $M_2 = m_{SUSY-EW}/5$, $A_t = m_{SUSY-QCD}$, $m_{SUSY-QCD} = 2\, m_{SUSY-EW}$

c) $M_2 = 300$ GeV, $A_t = m_{SUSY-QCD}$, $m_{SUSY-QCD} = m_{SUSY-EW}$

d) $M_2 = m_{SUSY-EW}/3$, $A_t = m_{SUSY-QCD}$, $m_{SUSY-QCD} = m_{SUSY-EW}$

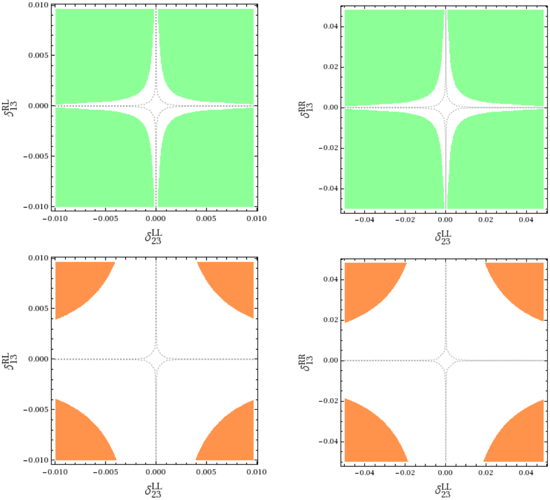
Pink area allowed by $(g-2)_\mu$

Blue area allowed by m_h

LFV constraints on double delta

More stringent bounds than single delta case.

Same conclusions for $(\delta_{13}^{LL}, \delta_{23}^{LL})$ and $(\delta_{13}^{RR}, \delta_{23}^{RR})$.



Disallowed by $\mathrm{BR}(\mu \to e\gamma)$

Disallowed by $\mu - e$ conversion

LFV constraints on double delta $(\delta_{23}^{LR}, \delta_{23}^{LL})$

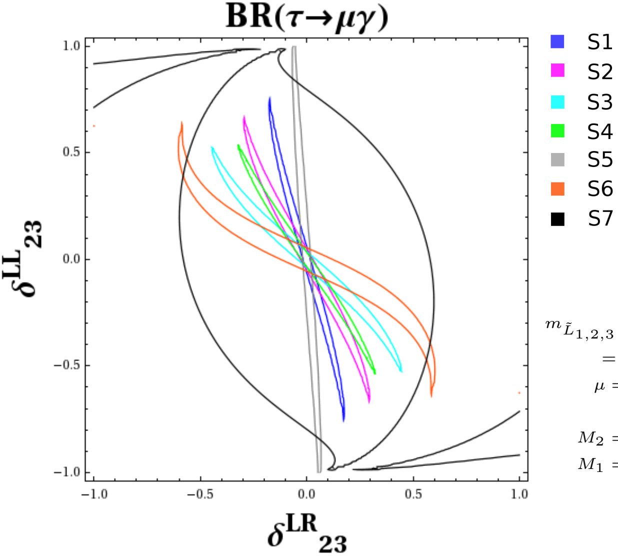
Constructive or destructive interference depending on relative sign of deltas

Allowed areas inside contour lines

Large deltas $\sim \pm 0.5$ still allowed.

Even larger $\sim \pm 0.9$ for S7

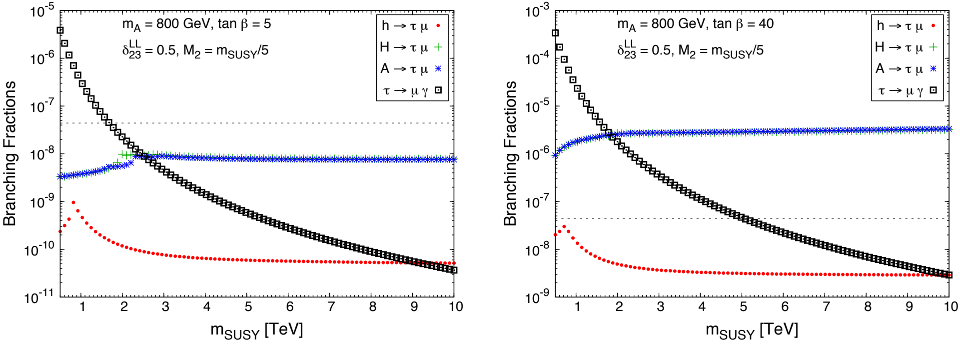
Heavy SUSY decoupling in $\tau \to \mu\gamma$



$S7$

$m_{\tilde{L}_{1,2,3}} = m_{\tilde{E}_{1,2,3}}$
$= 10000$ GeV
$\mu = 2000$ GeV
$\tan\beta = 60$
$M_2 = 2000$ GeV
$M_1 = 1000$ GeV

Full one-loop LFV rates versus m_{SUSY} ($\delta_{23}^{LL} = 0.5$)



- Constant non-decoupling behavior of BR($\phi \to \tau\mu$) with m_{SUSY}.
- In contrast with decoupling behavior of BR($\tau \to \mu\gamma$) $\sim 1/m_{\text{SUSY}}^4$.
- Large ratios at large $\tan\beta$: BR($\delta_{23}^{LL} \neq 0$) grow with $\tan\beta$
- BR($H, A \to \tau\mu$) close to $\sim 10^{-5}$ for $\tan\beta = 40$ in allowed region ($m_{\text{SUSY}} \geq 5\,\text{TeV}$) by BR($\tau \to \mu\gamma$) exp. upper bound (dashed line)

One example: SUSY-Seesaw with heavy ν_R (N_i)

Slepton flavor mixing δ_{ij}^{AB} generated radiatively.

[Borzumati,Masiero,1988; Hisano et al,1996; Hisano,Nomura,1999]

Connection between LFV and neutrino physics comes via Y_ν.
RGE running from $M_X = 2 \times 10^{16}$ GeV down to m_{N_i}:

$$\begin{aligned}
\delta_{ij}^{LL} &= -\frac{1}{8\pi^2}\frac{(3M_0^2 + A_0^2)}{M_{\rm SUSY}^2}(Y_\nu^+ L Y_\nu)_{ij} \\
\delta_{ij}^{LR} &= -\frac{3}{16\pi^2}\frac{A_0 v_1 Y_{l_i}}{M_{\rm SUSY}^2}(Y_\nu^+ L Y_\nu)_{ij} \\
\delta_{ij}^{RR} &= \mathcal{O}(\frac{m_l^2}{M_{\rm SUSY}^2}) \simeq 0\ ;\ L_{ii} \equiv \log\left(\frac{M_X}{m_{N_i}}\right);\ (\text{LLog Approx})
\end{aligned}$$

Large δ_{32}^{LL} for $m_{N_i} \sim 10^{14} - 10^{15}$ GeV $\Rightarrow |\delta_{32}^{LL}| \sim 0.1 - 10$ $(|\delta_{12}^{LL}| < 10^{-3})$

Perturbativity: $|\frac{Y_\nu^2}{4\pi}| < 1.5 \Rightarrow$ SUSY-Seesaw I: $|\delta_{23}^{LL}| < 0.5$ [Arganda et al 2005..]

Larger δ_{32}^{LL} $(\sim \times 6)$ and LFV rates in low scale SUSY-Seesaw models, like SUSY-ISS

[Deppisch,Valle,2005; Hirsch et al,2010; Abada et al 2012; Ilakovac et al,2012,..]

Recently: large BR$(h \to \tau\mu)$ up to $\sim 10^{-2}$ found in SUSY-ISS [Arganda et al 2015]

Results for LFV Higgs decays, $h, H, A \to l_k \bar{l}_m$, in the MIA

[Arganda, M.J.H, Morales and Szynkman, arXiv:1510.04685]

- Work in simple scenarios for heavy SUSY:
  all masses heavy by means of a single mass parameter $m_{\rm SUSY}$
- Analytical results in the MIA for all involved form factors:
  computation of all relevant one-loop diagrams
  with one insertion, $\mathcal{O}(\Delta_{mk}^{AB})$
- Perform a systematic comparison of one-loop resuts:
  MIA versus Full
- Numerical results for BR$(h, H, A \to \tau\mu)$
  and constraints from BR$(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$.
- Earlier estimates of loop-induced LFV Higgs decay rates
  within MSSM: did not work with the MIA

  [Brignole, Rossi, 2003], [Diaz-Cruz, 2003], [Kanemura et al 2004],..

  Full one-loop computation in [Arganda, Curiel, M.J.H, Temes, 2005]