LFV in the MSSM and non-decoupling

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References

Work based on:

- M. A.-C., 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.
- M. A.-C., S. Heinemeyer and M. J. Herrero,
  "New Constraints on General Slepton Flavor Mixing",
  arXiv:1304.2783 [hep-ph], Phys.Rev. D88 (2013) 015026.

Motivation

- Lepton Flavor Violation (LFV) occurs in Nature:
  Seen in neutral leptons: Neutrino oscillations ⇒ LFV.
- LFV rates in SM extremely supressed:
  zero if massless neutrinos, tiny with present massive neutrinos.
- If LFV exists in neutral sector why not in charged sector.
  Intense present and future programs for exp. LFV searches.
- LFV opens a new window to look for BSM physics: in particular SUSY.
- Higgs boson seen at the LHC, with $m_H \simeq 125$ GeV, opens new channels for LFV searches.
- SUSY not seen yet at LHC ($m_{\rm SUSY}$ into multi-TeV range?).
- Higgs physics/mediated processes very sensitive to SUSY.

Here: LFV Higgs decays induced by SUSY at one loop:
sizeable even at very heavy $m_{\rm SUSY} \simeq \mathcal{O}(5$ TeV$)$.

Present Status: LFV experimental searches

LFV not seen yet. Intense program. Present (90%CL) bounds:

- Radiative decays,
  $\mathrm{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ [MEG, 2013]

  $\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$, $\mathrm{Br}(\tau \to e\gamma) < 3.3 \times 10^{-8}$ [BaBar, 2010]
- 3-body lepton decays,
  $\mathrm{Br}(\mu \to 3e) < 1.0 \times 10^{-12}$ [SINDRUM, 1988]

  $\mathrm{Br}(\tau \to 3\mu) < 2.1 \times 10^{-8}$, $\mathrm{Br}(\tau \to 3e) < 2.7 \times 10^{-8}$ [Belle, 2010]
- Semileptonic tau decays,

  $\mathrm{Br}(\tau \to \mu\eta) < 2.3 \times 10^{-8}$, $\mathrm{Br}(\tau \to e\eta) < 4.4 \times 10^{-8}$ [Belle, 2010]
- muon-electron conversion in heavy nuclei,

  $\mathrm{CR}(\mu - e, \mathrm{Au}) < 7.0 \times 10^{-13}$ [SINDRUM II, 2006]
- Meson decays, $\mathrm{Br}(B_d^0 \to e\mu) < 2.8 \times 10^{-9}$ [LHCb, 2013]
- Z decays, $\mathrm{Br}(Z \to \mu e) < 1.7 \times 10^{-6}$ [OPAL, 1995]
- H decays, $\mathrm{Br}(H \to \tau\mu) < 1.57\%$ $(95\%CL)$ LHC New! [CMS, 2014]
  Estimated $(8\,\mathrm{TeV}, 20\,\mathrm{fb}^{-1})$ sensitivity 4.5×10^{-3} [Davidson,Verdier 1211.1248]

LFV Present Bounds versus Future Sensitivities

LFV process	Present bound	Future sensitivity (?)
$\mathrm{BR}(\mu \to e\,\gamma)$	5.7×10^{-13} (MEG 2013)	5×10^{-14} MEGup
$\mathrm{BR}(\tau \to e\,\gamma)$	3.3×10^{-8} (BaBar 2010)	3×10^{-9} SuperB
$\mathrm{BR}(\tau \to \mu\,\gamma)$	4.4×10^{-8} (BaBar 2010)	2.4×10^{-9} SuperB
$\mathrm{BR}(\mu \to e\,e\,e)$	1×10^{-12} (SINDRUM 1988)	10^{-16} Mu3E (PSI)
$\mathrm{BR}(\tau \to e\,e\,e)$	2.7×10^{-8} (Belle 2010)	$10^{-9,-10}$ Belle2, SuperB
$\mathrm{BR}(\tau \to \mu\,\mu\,\mu)$	2.1×10^{-8} (Belle 2010)	$10^{-9,-10}$ Belle2, SuperB
$\mathrm{BR}(\tau \to \mu\eta)$	2.3×10^{-8} (Belle 2010)	$10^{-9,-10}$ Belle2, SuperB
$\mathrm{CR}(\mu - e, \mathrm{Au})$	7.0×10^{-13} (SINDRUM2 2006)	
$\mathrm{CR}(\mu - e, \mathrm{Al})$		3.1×10^{-15} COMET-I (J-PARC)
		2.6×10^{-17} COMET-II (J-PARC)
		2.5×10^{-17} Mu2E (Fermilab)
$\mathrm{CR}(\mu - e, \mathrm{Ti})$	4.3×10^{-12} (SINDRUM2 2004)	10^{-18} PRISM (J-PARC)

(?) = Future sensitivities are under discussion
(updated here as reported in presentations at ICHEP 2014)

Our proposal and work

- Present data suggests soft masses above TeV scale.
- Accept the tension between this heavy SUSY $\gtrsim \mathcal{O}(1\,\text{TeV})$ and the SUSY solution to the hierarchy problem with $\lesssim \mathcal{O}(1\,\text{TeV})$.
- Look for specific observables where there are relevant contributions from SUSY, even if heavy.
- Look at Higgs observables to one-loop since Higgs couplings to all particles grow with the particle mass:
  hence more sensitive to 'internal' Sparticles in the loops.
- Full 1-loop computation of LFV Higgs decay rates with internal sleptons ($\tilde{l}$, $\tilde{\nu}$) and inos ($\tilde{\chi}^0$,$\tilde{\chi}^\pm$).
- Work within the MSSM with general slepton flavor mixing.
- Focus on LFV Higgs decays with taus: $\phi \to \tau\mu$ ($\phi = h, H, A$)
  $\phi \to \mu e$ rates suppressed by $(m_\mu/m_\tau)^n$
  $\phi \to \tau e$ rates similar to $\tau\mu$ with close detection prospects.
- Impose all the present constraints: both on LFV and SUSY

The MSSM with general slepton mixing

We use a low energy parametrization for general slepton mixing, with no particular assumption on the off-diagonal (in flavor) soft terms.
LFV is orginated from these non-diagonal soft terms (via loops of SUSY).
Model parameters: MSSM + slepton flavor mixing parameters δ^{AB}_{ij}(real).

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

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

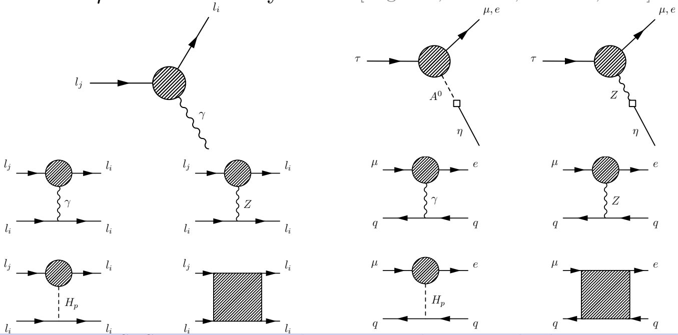
$$m^2_{\tilde{E}} = \left(\begin{array}{ccc} m^2_{\tilde{E}_1} & \delta^{RR}_{12} m_{\tilde{E}_1} m_{\tilde{E}_2} & \delta^{RR}_{13} m_{\tilde{E}_1} m_{\tilde{E}_3} \\ \delta^{RR}_{21} m_{\tilde{E}_2} m_{\tilde{E}_1} & m^2_{\tilde{E}_2} & \delta^{RR}_{23} m_{\tilde{E}_2} m_{\tilde{E}_3} \\ \delta^{RR}_{31}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

Hermiticity of $\mathcal{M}^2_{\tilde{l}}$ and $\mathcal{M}^2_{\tilde{\nu}}$ and $SU(2)_L$ invariance $\Rightarrow$ 12 independent δ^{AB}_{ij}'s.
6 charged sleptons and 3 sneutrinos with intergenerational mixing

Selected LFV processes and framework for computation of

MSSM spectra with Spheno. Full 1-loop calculation using a FORTRAN code by Arganda, Herrero. Updated constraints in M.A.-C.,S.Heinemeyer and Herrero, PRD 88(2013)015026)

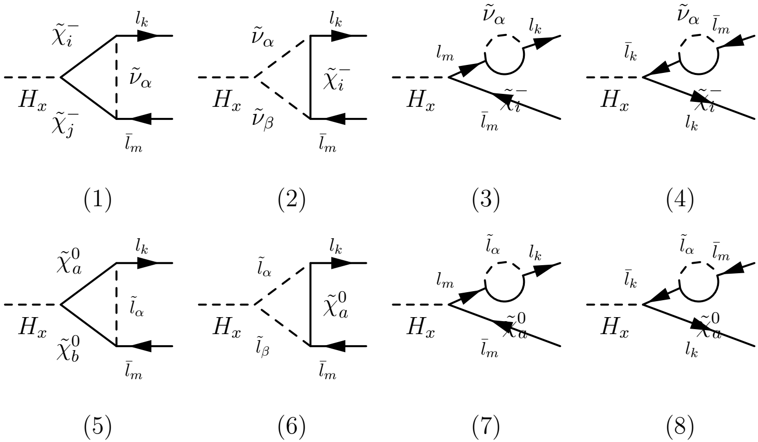
- Radiative LFV decays: $\mu \to e\gamma$, $\tau \to e\gamma$ and $\tau \to \mu\gamma$ [Hisano et al, 1996]
- Leptonic LFV decays: $\mu \to 3e$, $\tau \to 3e$ and $\tau \to 3\mu$ [Arganda, Herrero, 2006]
- Semileptonic LFV τ decays: $\tau \to \mu\eta$ and $\tau \to e\eta$ [Arganda, Herrero, Portoles, 2008]
- Conversion of μ into e in heavy nuclei [Arganda, Herrero, Teixeira, 2007]



One-loop LFV SUSY-induced Higgs decay diagrams

We work with MSSM particle content and explore, either 1) selected MSSM points, or 2) simple MSSM scenarios with few parameters.

[A.-C.,Arganda,Herrero,2013] [Arganda et al,2005]



Selected MSSM points allowed by present data

[A.-C., Heinemeyer, Herrero, 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

[A.-C., Heinemeyer, Herrero, 2013]

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

BR($\mu \to e\gamma$) most restrictive observable.

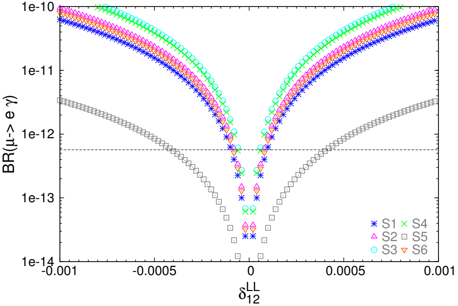
Most stringent bounds for 12 mixing

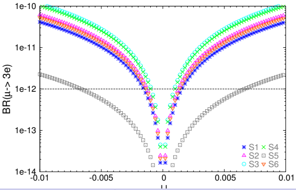
S3 (largest $\tan\beta$) is the most constrained for δ_{12}^{LL} and δ_{12}^{RR}.

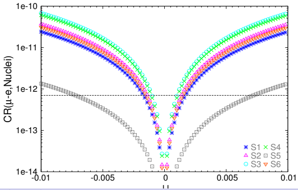
dominance of photonic-mediated channel leading to correlation

$$\frac{\mathrm{BR}(l_j \to 3l_i)}{\mathrm{BR}(l_j \to l_i\gamma)} = \frac{\alpha}{3\pi}\left(\log\frac{m_{l_j}^2}{m_{l_i}^2} - \frac{11}{4}\right)$$

Same with $\mu - e$ conversion. Competitive, with best future prospects.

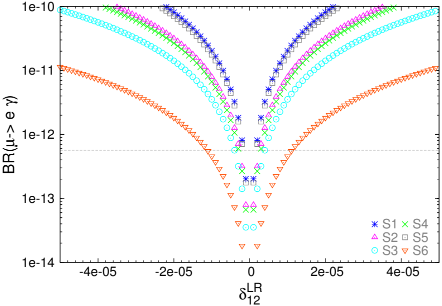






Bounds on δ_{12}^{LR} for selected S1,..,S6 points

[A.-C., Heinemeyer, Herrero, 2013]

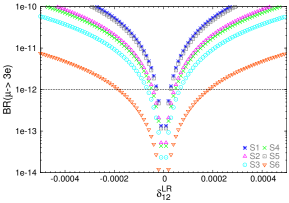


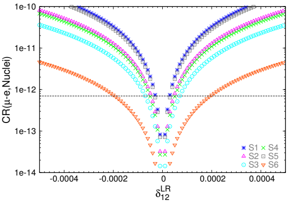
$|\delta_{12}^{LR}| < \mathcal{O}(10^{-5})$

δ_{12}^{LR} most restricted delta

No observed dependence with $\tan\beta$.

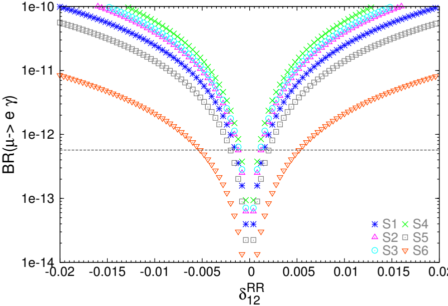
S1 and S5 are the most restricted because of lighter sleptons



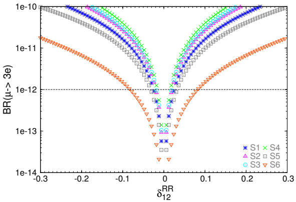


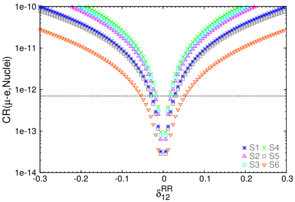
Bounds on δ_{12}^{RR} for selected S1,..,S6 points

[A.-C., Heinemeyer, Herrero, 2013]



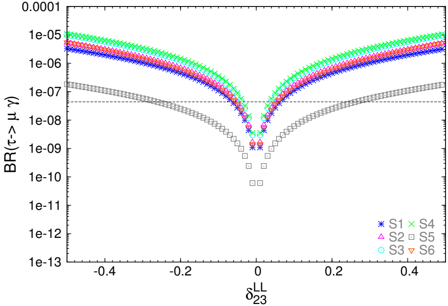
$|\delta_{12}^{RR}| < \mathcal{O}(10^{-3})$





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

[A.-C., Heinemeyer, Herrero, 2013]

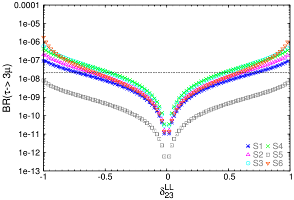


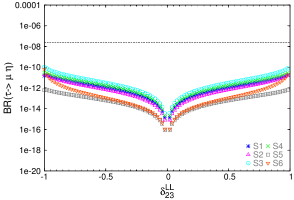
$|\delta_{23}^{LL}| < \mathcal{O}(10^{-1})$

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

13 mixing rates and bounds very similar to 23 mixing.

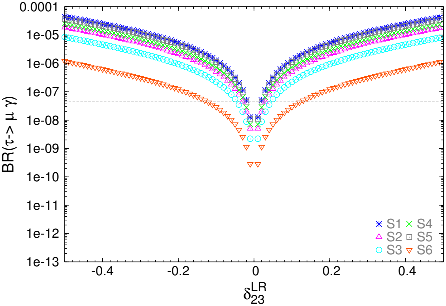
Higgs mediated $\tau \to 3\mu$ and $\tau \to \mu\eta$ less constraining due to heavy A^0 (even at large $\tan\beta$)



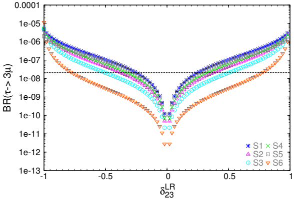


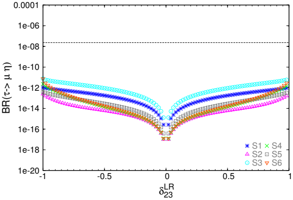
Bounds on δ_{23}^{LR} for selected S1,..,S6 points

[A.-C., Heinemeyer, Herrero, 2013]



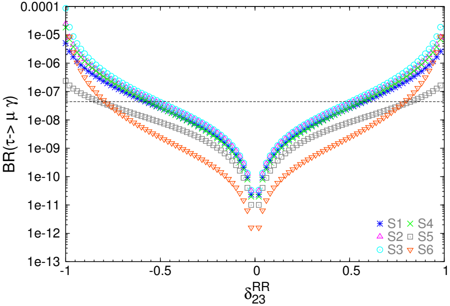
$|\delta_{23}^{LR}| < \mathcal{O}(10^{-1})$





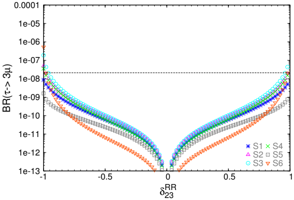
Bounds on δ_{23}^{RR} for selected S1,..,S6 points

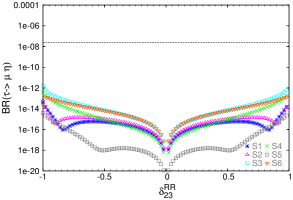
[A.-C., Heinemeyer, Herrero, 2013]



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

The less constrained mixing





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

Constructive or destructive interference depending on relative sign of deltas

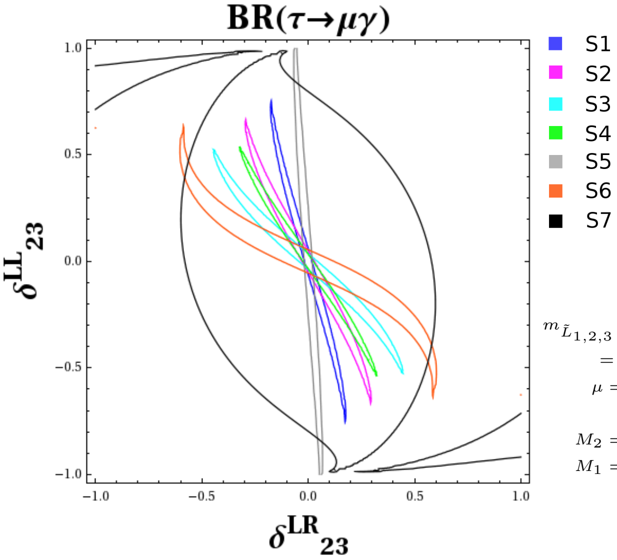
Allowed areas inside contour lines

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

Even larger $\sim \pm 0.9$ for S7

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

Shapes not explained by MIA.



$S7$

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

Results for LFV Higgs decays: BR($h, H, A \to \tau\mu$)

[A.-C., Arganda, Herrero, 2013]

- Complete 1-loop formulas and full set of diagrams.
- Work with MSSM particle content. Consider heavy SUSY.
- Work in physical basis: δ_{ij}^{AB}'s transmitted to LFV rates via physical slepton and sneutrino masses and their rotations.
- Real δ_{ij}^{AB}'s imply BR($\phi \to l_i \bar{l}_j$) = BR($\phi \to \bar{l}_i l_j$).
  But: we do not $\times 2$.
- We perform a systematic comparison of BR($\phi \to \tau\mu$) and BR($\tau \to \mu\gamma$), and require BR($\tau \to \mu\gamma$) $< 4.4 \times 10^{-8}$.
- Earlier estimates of loop-induced LFV Higgs decay rates within MSSM:

  [Brignole, Rossi, 2003], [Diaz-Cruz, 2003], [Kanemura et al 2004], [Arganda, Curiel, Herrero, Temes, 2005],....
- Recent studies of sensitivity to LFV Higgs decays at LHC:

  [Davidson, Verdier, 2012], [Blankenburg, Ellis, Isidori, 2012]

Work with simple heavy SUSY scenarios

Take all soft-mass parameters relevant for LFV related to just one $m_{\rm SUSY}$:

$$\begin{aligned} m_{\tilde L} &= m_{\tilde L_1} = m_{\tilde L_2} = m_{\tilde L_3} = m_{\rm SUSY}\,, \\ m_{\tilde E} &= m_{\tilde E_1} = m_{\tilde E_2} = m_{\tilde E_3} = m_{\rm SUSY}\,, \\ \mu &= M_2 = a\, m_{\rm SUSY} \quad (a = 1/5, 1/3, 1)\,, \end{aligned}$$

with the approximate GUT relation for the gaugino masses:

$$M_2 = 2M_1 = M_3/4\,.$$

($A_\tau = A_\mu = A_e = m_{\rm SUSY}$, $m_{\tilde Q} = m_{\tilde U} = m_{\tilde D} = A_t = A_b = 5$ TeV)
(checked that all these provide a m_h prediction close to exp. ± 2 GeV)

$$\mathcal{A}^l_{23} = \tilde\delta^{LR}_{23} m_{\rm SUSY}\,, \quad \mathcal{A}^l_{32} = \tilde\delta^{LR}_{32} m_{\rm SUSY}\,,$$

Simply related to the previous ones by:

$$\delta^{LR}_{23} = \left(\frac{v_1}{m_{\rm SUSY}}\right)\tilde\delta^{LR}_{23}\,, \quad \delta^{LR}_{32} = \left(\frac{v_1}{m_{\rm SUSY}}\right)\tilde\delta^{LR}_{32}.$$

Input parameters for LFV Higgs decays

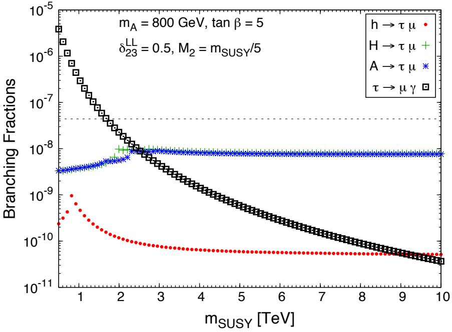
Explore wide intervals:

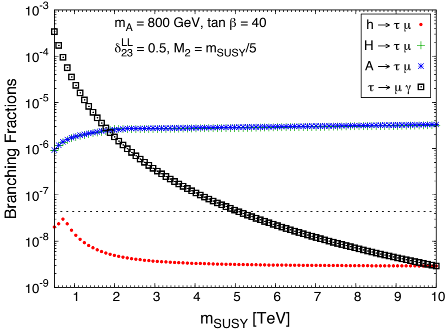
- 200 GeV $\leq m_A \leq$ 1000 GeV,
- $1 \leq \tan\beta \leq 60$,
- 0.5 TeV $\leq m_{\rm SUSY} \leq$ 10 TeV   HEAVY SUSY!!,
- $-1 \leq \delta_{23}^{LL}, \delta_{23}^{RR} \leq 1$,
- $-5 \leq \tilde{\delta}_{23}^{LR}, \tilde{\delta}_{23}^{RL} \leq 5$,
  ($|\delta_{23}^{LR}|, |\delta_{23}^{RL}| \leq 0.0043$ for $m_{\rm SUSY} = 5$ TeV and $\tan\beta = 40$)

Respect constraints from:

1) Experimental bounds on BR($\tau \to \mu\gamma$)
2) LHC direct SUSY searches and ($m_A, \tan\beta$) plane
3) Vacuum Metastability [Jae-hyeon Park (2011)]

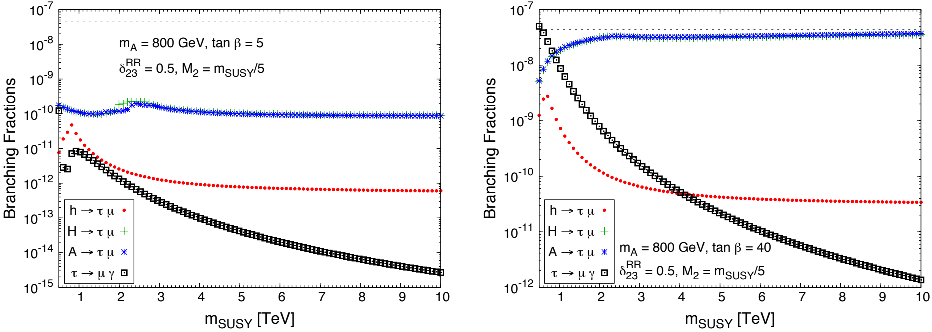
Results: LFV rates versus m_{SUSY} ($\delta_{23}^{LL} = 0.5$)





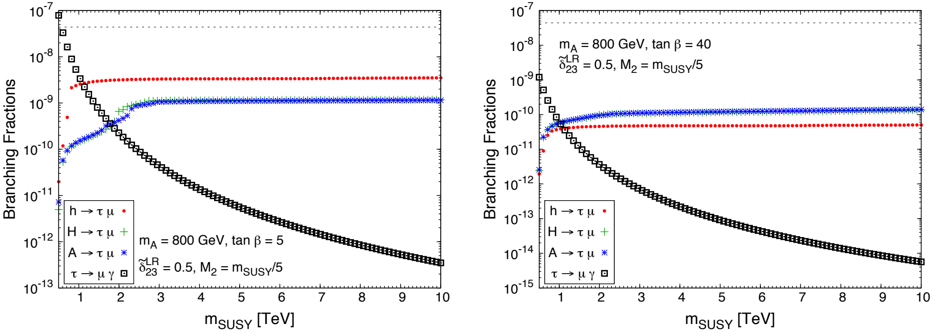
- Constant non-decoupling behavior of $\text{BR}(\phi \to \tau\mu)$ with m_{SUSY}.
- In contrast with decoupling behavior of $\text{BR}(\tau \to \mu\gamma) \sim 1/m_{\text{SUSY}}^4$.
- Large ratios at large $\tan\beta$: $\text{BR}(\delta_{23}^{LL} \neq 0)$ grow with $\tan\beta$
- $\text{BR}(H, A \to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

Results: LFV rates versus $m_{\rm SUSY}$ ($\delta_{23}^{RR} = 0.5$)



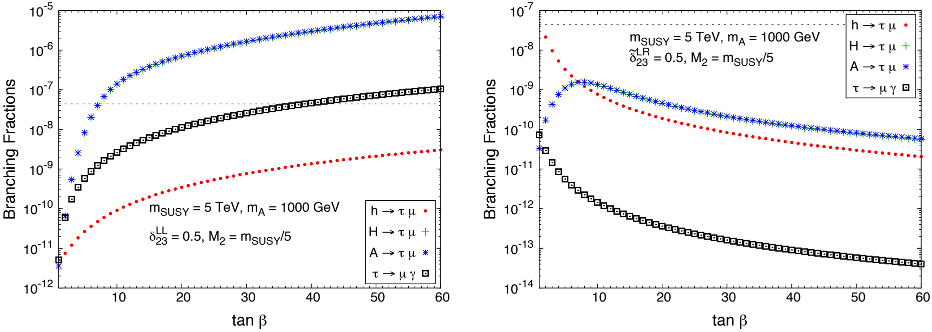
- Similar behavior with $m_{\rm SUSY}$ for δ_{23}^{RR} as for δ_{23}^{LL}
- But lower LFV rates for δ_{23}^{RR} than for δ_{23}^{LL}
- Strong decoupling behaviour of BR$(\tau \to \mu\gamma) \sim 1/m_{\rm SUSY}^4$.
- All BR$(\tau \to \mu\gamma)$ allowed.

Results: LFV rates versus m_{SUSY} ($\tilde{\delta}_{23}^{LR} = 0.5$)



- Again: Non-decoupling constant behaviour of LFV H decays for $\tilde{\delta}_{23}^{LR}$, versus decoupling behaviour of LFV τ decays.
- In contrast: BR($\delta_{23}^{LR} \neq 0$) decrease with $\tan\beta$. Large LFV rates at the low $\tan\beta$ region.

LFV rates as functions of $\tan\beta$



- δ_{23}^{LL} (and δ_{23}^{RR}): Larger ratios at large $\tan\beta$: $\tan\beta = 40$ optimal !
  $\text{BR}(\delta_{23}^{LL} \neq 0) \sim (\tan\beta)^2$ for $\tan\beta \gtrsim 10$.
- δ_{23}^{LR} (and δ_{23}^{RL}): Lower ratios at large $\tan\beta$: $\tan\beta \lesssim 5$ optimal !
  $\text{BR}(\delta_{23}^{LR} \neq 0) \sim (\tan\beta)^{-2}$ for $\tan\beta \gtrsim 10$.

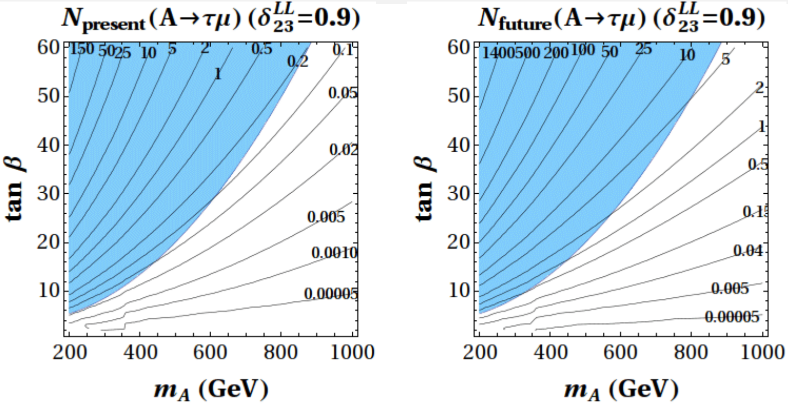
Results for the LFV Higgs mediated event rates at the LHC

- Focus on largest rates allowed by $\tau \to \mu\gamma$
  We chose: $m_{\rm SUSY} \gtrsim 5$ TeV, $M_2 = m_{\rm SUSY}$, $\delta_{23}^{LL} = 0.9$ and $\tilde{\delta}_{23}^{LR} = \tilde{\delta}_{23}^{RL} = \pm 5$. Predictions for other choices easily derived from previous plots.
- Low $\tan\beta$: $\sigma(h, H, A)$ dominated by gluon fusion.
- Large $\tan\beta$ ($\gtrsim 10$): $\sigma(H, A)$ dominated by bottom-antibottom quark annihilation.
- We use FeynHiggs to compute the Higgs cross sections.

Phases of the LHC

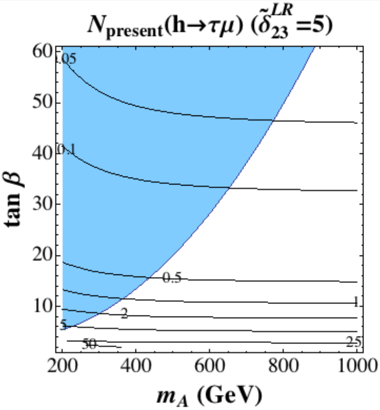
- Present: $\sqrt{s} = 8$ TeV and $\mathcal{L} = 25\ {\rm fb}^{-1}$.
- Future: $\sqrt{s} = 14$ TeV and $\mathcal{L} = 100\ {\rm fb}^{-1}$.

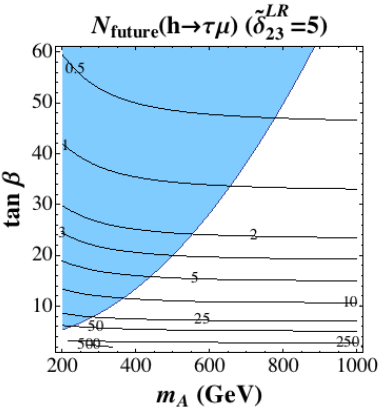
Predictions in $(m_A, \tan\beta)$ plane for LL mixing



- The needed large $\tan\beta$ is excluded (blue area) by present LHC searches. No LFV mediated $A\,(\sim H)$ events in present phase of LHC if δ_{23}^{LL} responsible for $\tau - \mu$ transitions. Worse for h.
- Better expectations in future phase: up to $A\,(\sim H)$ 5 events for large $\tan\beta \gtrsim 50$ and $800 < m_A(\mathrm{GeV}) < 1000$

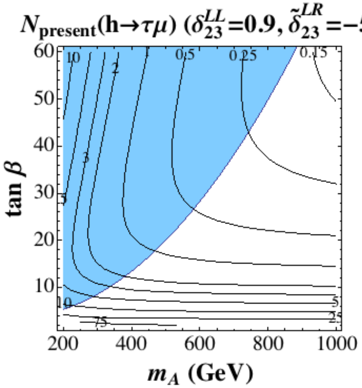
Predictions in $(m_A, \tan\beta)$ plane for LR mixing

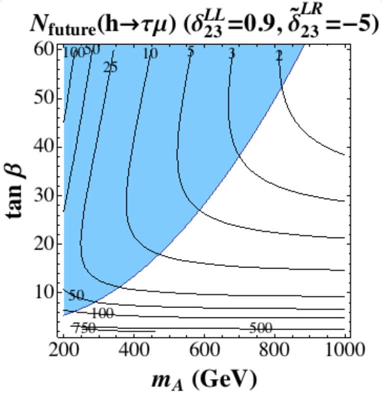




- Maximum allowed number of events are obtained in the low $\tan\beta$ region, softly dependent on m_A.
- For instance: 25 (250) LFV events in the present (future) LHC phase for $\tan\beta \sim 3$ and all $200 < m_A(\text{GeV}) < 1000$.

Predictions in $(m_A, \tan\beta)$ plane for LL-LR mixing





- Maximum rates predicted when combining both LL and LR deltas.
- For instance: 50 (500) LFV h events in the present (future) LHC phase for low $\tan\beta \sim 3$ and all $200 < m_A(\text{GeV}) < 1000$
- Conclusions apply to both choices for the sign of LR/RL mixings, i.e. here for ± 5.

Conclusions

If m_{SUSY} is too heavy, as the present experiments are pointing out, and the SUSY particles cannot be directly reachable at the present or next future LHC energies, LFV Higgs decays could provide an unique window to explore new physics and to find some hint of very heavy SUSY at the LHC.

If LFV Higgs decays not seen at the LHC, then extract new bounds on slepton δ_{ij}^{AB} mixings, some more restrictive than from other LFV processes

Future work

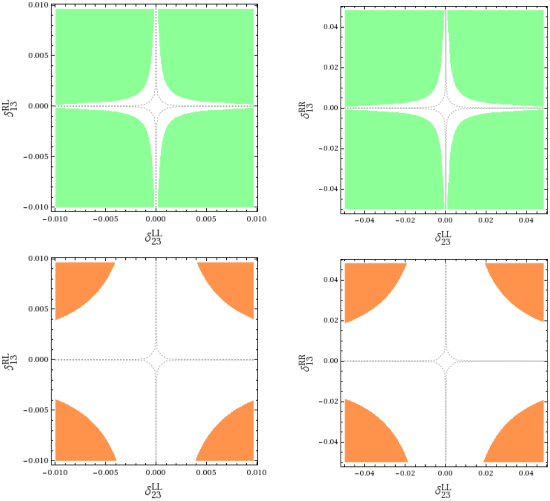
- Analytical formulas from mass insertion approximation (MIA) in order to understand better the non-decoupling behavior of LFVHD.
- Search strategies for $\phi \to \tau\mu$ processes at the LHC, especially for the LFV decays of the heavy Higgs boson states, $H \to \tau\mu$ and $A \to \tau\mu$.

There is always more...

LFV constraints on various double delta

More stringent bounds than single delta case.

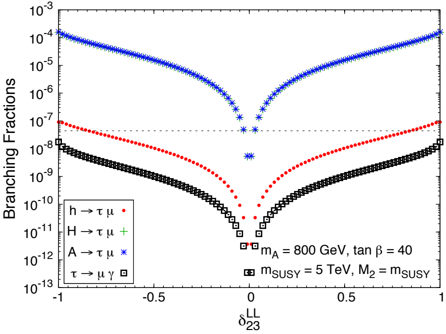
Same conclusions for $(\delta_{13}^{LL}, \delta_{23}^{LL})$ and $(\delta_{13}^{RR}, \delta_{23}^{RR})$.

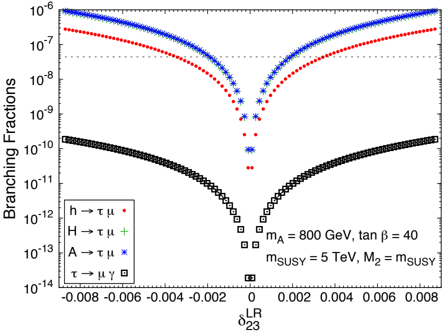


Disallowed by $BR(\mu \to e\gamma)$

Disallowed by $\mu - e$ conversion

Increasing the LFV rates with δ_{23}^{LL} and δ_{23}^{LR}





- Found growing behaviour as BR $\sim |\delta_{23}^{AB}|^2$, as expected.
- $|\delta_{23}^{LL}| \leq 1$ allowed by $\tau \to \mu\gamma$. Going to max.rates for: $\tan\beta = 40$ we get BR$(h \to \tau\mu) \sim 10^{-7}$, BR$(H, A \to \tau\mu) \sim 10^{-4}$.
- $|\tilde{\delta}_{23}^{LR}| \leq 5$ (or $|\delta_{23}^{LR}| \leq 0.0043$) allowed by $\tau \to \mu\gamma$. Going to max.rates, for: $|\tilde{\delta}_{23}^{LR}| = |\tilde{\delta}_{23}^{RL}| = 5$ and $\tan\beta = 5$, we get BR$(h, H, A \to \tau\mu) \sim 10^{(-5,-4)}$
- Switching both δ_{23}^{LL} and δ_{23}^{LR}: $\mathrm{BR}_{\mathrm{max}} \sim 10^{-4}$ for all ϕ; both large/low $\tan\beta$

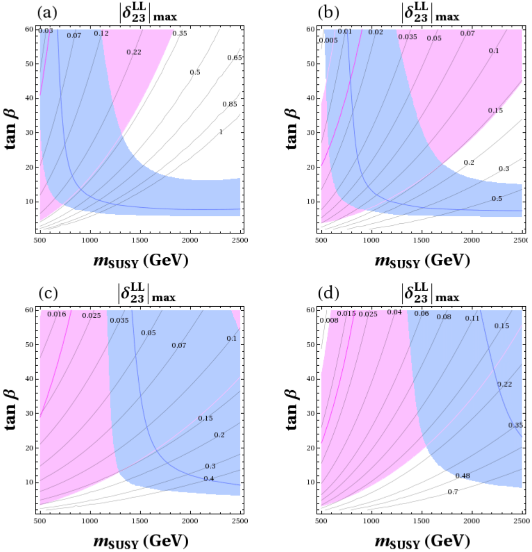
$|\delta_{23}|_{\max}$ in $(m_{SUSY}, \tan\beta)$ plane, versus $(g-2)_\mu$ and m_h

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.

$|\delta_{23}^{LL}|_{\max} \sim \mathcal{O}(10^{-1} - 10^{-2})$



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

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

(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)]

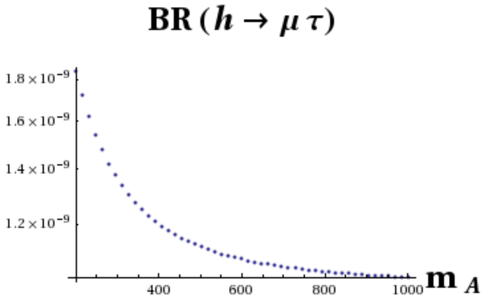
$$|\mathcal{A}^l_{23}| \leq y_\tau \sqrt{m^2_{\tilde{L}_2} + m^2_{\tilde{E}_3} + m^2_1}\,, \text{ with} \quad y_\tau = \frac{g m_\tau}{\sqrt{2} M_W \cos\beta}$$

In our simplified SUSY scenarios:

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

- **Stability:** for $m_{\text{SUSY}} = m_A = 1$ 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 $m_{\text{SUSY}} \leq 10$ TeV, $|\tilde{\delta}^{LR}_{23}| \leq 5$ [Jae-hyeon Park (2011)]. Weaker $\times$ factor $\sim (4-8)$.

Remark on the 'Decoupling Limit' in LFV Higgs decays



($\delta_{23}^{LR} = 0.9$, $\delta_{23}^{LL} = \delta_{23}^{RR} = 0$, $m_{\rm SUSY} = 5$ TeV, $\tan\beta = 60$)

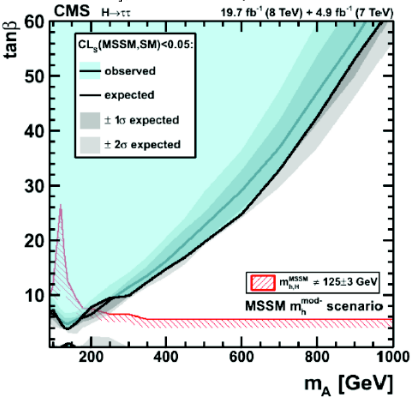
The LFV ratios for the lightest Higgs boson decays, $h \to \tau\mu$,..,
manifest decoupling behaviour, as expected, for $m_A >> m_Z$
i.e in the so-called decoupling limit: h behaves as $H_{\rm SM}$ (OK!)

Experimental constraints over the parameter space

- B. Aubert *et al.*, [BABAR Collaboration], Phys. Rev. Lett. **104**, 021802 (2010) [arXiv:0908.2381 [hep-ex]]:

$$\mathrm{BR}(\tau^{\pm} \to \mu^{\pm}\gamma) < 4.4 \times 10^{-8}\,.$$

- Searches for MSSM neutral Higgs bosons decaying to τ pairs in pp collisions (M.Carena *et al.* [arXiv:1302.7033], also talk by A.Nikitenko SUSY2014).



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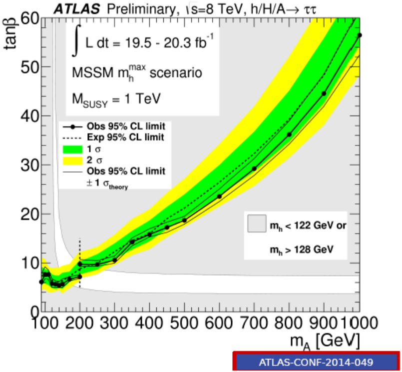
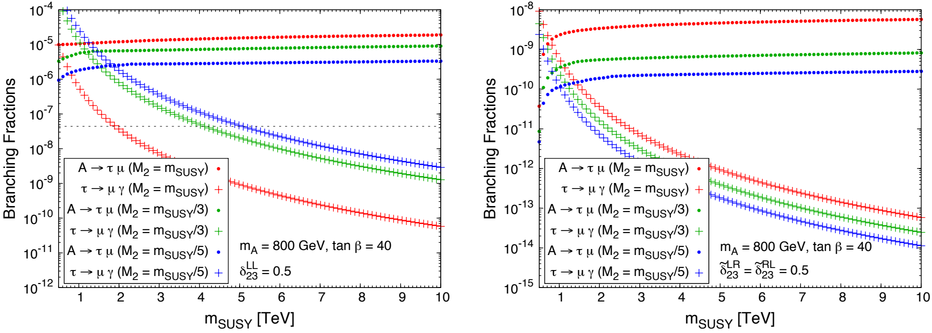
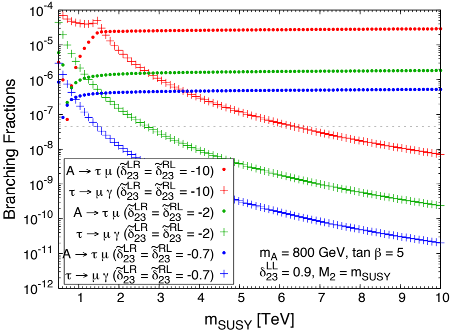


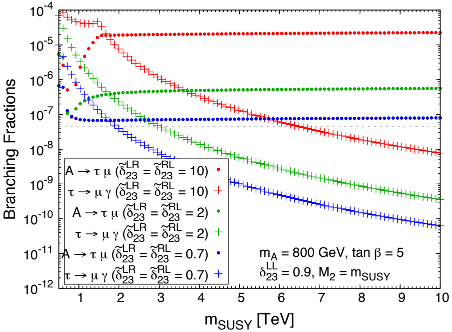
LFV rates as functions of m_{SUSY} $(M_2 = a\, m_{\mathrm{SUSY}})$



- LL case: the larger M_2 is, the larger the LFV Higgs branching ratios are and the lower $\mathrm{BR}(\tau \to \mu\gamma)$ is.
- LR case: $\mathrm{BR}(h, H, A \to \tau\mu)$ rise as a grows but $\mathrm{BR}(\tau \to \mu\gamma)$ increases too.
- $M_2 = m_{\mathrm{SUSY}}$ in order to obtain the largest LFVHD rates.

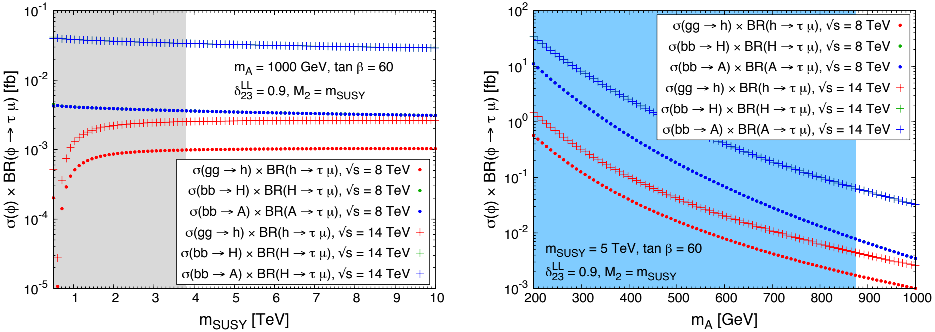
LFV rates combining δ_{23}^{LL} and $\tilde{\delta}_{23}^{LR} = \tilde{\delta}_{23}^{RL}$





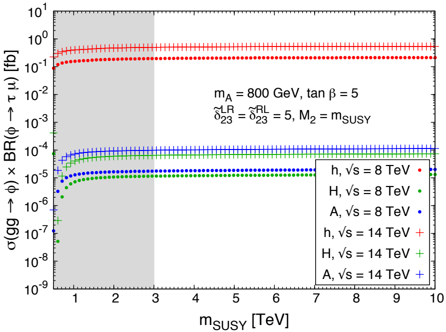
- LFV rates increase as $|\tilde{\delta}_{23}^{LR}| = |\tilde{\delta}_{23}^{RL}|$ grows and slightly higher than for single LL or LR mixings: BR$(h \to \tau\mu) \simeq 10^{-4}$ and BR$(H, A \to \tau\mu)$ $\simeq 3 \times 10^{-5}$.
- LFVHD rates from negative LR mixings slightly larger than positive ones. Opposite behavior for $\tau \to \mu\gamma$.

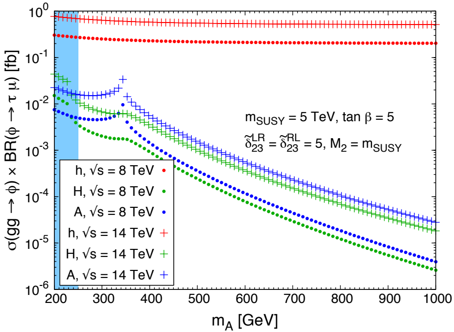
Predictions for single LL mixing



- Shaded gray area excluded by $\tau \to \mu\gamma$ upper bound and shaded blue area excluded by CMS searches.
- $H, A \to \tau\mu$: $\mathcal{L} \gtrsim 100$ fb^{-1} (present) and $\mathcal{L} \gtrsim 20$ fb^{-1} (future).
- $h \to \tau\mu$: $\mathcal{L} \gtrsim 500$ fb^{-1} (present) and $\mathcal{L} \gtrsim 200$ fb^{-1} (future).
- Large m_A and large $\tan\beta$: h behaves as SM-like Higgs with no LFV couplings (decoupling limit).

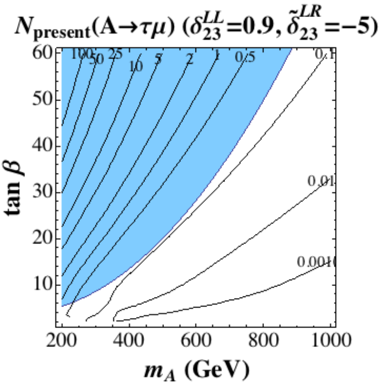
Predictions for single LR mixing

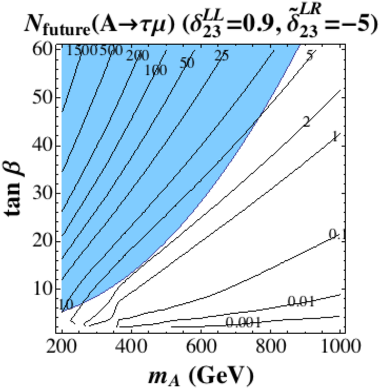




- $\sigma(gg \to h) \times \mathrm{BR}(h \to \tau\mu)$ reach values around 0.2 fb in the present LHC phase and up to 0.5 fb in the future one.
- LFV A cross sections of 0.01 fb (0.04 fb) in the present (future) LHC phase ($t\bar{t}$ threshold effect).
- Largest LFV H cross section is 0.004 fb (0.01 fb) in the present (future) phase of the LHC ($m_A \simeq 250$ GeV).

Predictions in $(m_A, \tan\beta)$ plane for LL-LR mixing





- Event rates increase as $\tan\beta$ grows and are reduced as m_A gets bigger.
- Present: no events. Future: up to about 5 LFV events for large $\tan\beta$ and m_A and up to 10 in the low $\tan\beta$ region with $m_A \simeq 200$ GeV.
- Similar conclusions are found for the case of positive LR.

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}:

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

The size of neutrino masses and mixings drive the size of Y_ν, hence, δ_{ij}^{AB} and the LFV rates

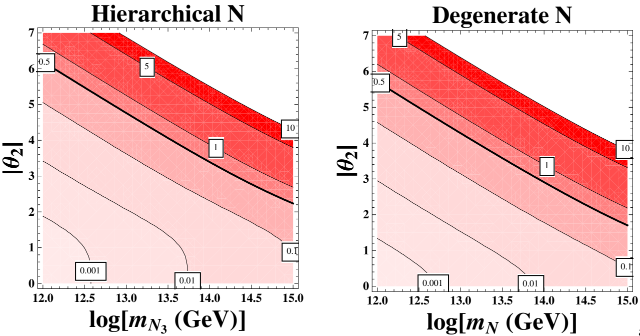
$$m_D = Y_\nu v_2 = i\sqrt{m_N^{diag}}\,R(\theta_i)\,\sqrt{m_\nu^{diag}}\,U_{\rm PMNS}^\dagger$$

Within SUSY-Seesaw: $\delta^{LL} > \delta^{LR} > \delta^{RR}$ and $\delta_{32}, \delta_{31} > \delta_{21}$, hence, larger $\tau - \mu$ and $\tau - e$ than $\mu - e$ rates

Size of δ_{32}^{LL} in SUSY-Seesaw

M.J.Herrero, 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...]