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Flavour violation in SUSY seesaw models at colliders

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Outline

- Motivation
- SUSY seesaw models for neutrino masses and mixings
- LFV observables and constraints from low-energy experiments
- LFV observables at LHC and interplay with low-energy experiments
- Conclusions: What can we learn?

Collaborators: A. Abada, J. N. Esteves, A. J. R. Figueiredo, M. Hirsch, S. Kaneko, W. Porod, F. Staub
A. M. Teixeira, A. Vicente, A. Villanova del Moral

Papers:
arXiv:0903.1408 [JHEP05(2009)003], arXiv:0907.5090 [PRD80(2009)095003], arXiv:1007:4833 [JHEP10(2010)104]
arXiv:1010.6000 [PRD83(2011)013003], arXiv: 1011.0348 [JHEP12(2010)077], arXive: 1206.2306 [JHEP1208(2012)138]
arXive: 1402.1426

Understanding lepton flavour mixing

- **Flavour violated** in neutral leptons ($\nu_i \leftrightarrow \nu_j$ oscillations)

  What about charged lepton flavour violation? $\ell_i \to \ell_j \gamma, \ell_i \to 3\ell_j, \ldots$
  - No evidence, so far
  - Huge experimental effort: **MEG, PRISM/PRIME, SuperB, ...**

- **Charged LFV:** complementary to LHC searches and ν experiments
  - Use low-energy LFV observables, like BR($\ell_i \to \ell_j \gamma$)

    and
  - high-energy data, like slepton mass splittings at LHC

- **Use cLFV** complementarity to **disentangle** model of New Physics

cLFV ↔ New Physics (beyond SM+ν_R) mSUGRA-like SUSY (testable at LHC) + Lepton Flavour Mixing seesaw mechanism (suggested by ν mixing)

A unique source of flavour violation

- mSUGRA-like SUSY seesaw: Y_ν **unique source of LFV**

  All **LFV** observables strongly related

  - **low-energies:** $\ell_i \to \ell_j \gamma, \ell_i \to 3\ell_j, \mu - e$ in Nuclei

    → Large rates potentially observable (MEG, PRISM/PRIME, ...)

  - **high-energy:** look for charged slepton from $\chi_2^0 \to \ell^\pm \ell^\mp \chi_1^0$ decays

    → Possibly sizable $\tilde{e} - \tilde{\mu}$ mass differences, multiple edges, and direct LFV decays $\chi_2^0 \to \ell_i \ell_j \chi_1^0$

- Interplay **low- high-energy:**

  Low-energy: LFV observable (large BRs & CR) ↔ LHC: Interesting new phenomena

Lepton Flavour Violation (LFV) constraints

- All these seesaw models have built in LFV, as they are models for neutrino masses. LFV is highly constrained
- We summarize the current bounds on the LFV observables, as well as the future sensitivity:

LFV process	Present bound	Future sensitivity
BR($\mu \to e\gamma$)	5.7×10^{-13}	10^{-13}
BR($\tau \to e\gamma$)	3.3×10^{-8}	10^{-9}
BR($\tau \to \mu\gamma$)	4.4×10^{-8}	10^{-9}
BR($\mu \to 3e$)	1.0×10^{-12}	
BR($\tau \to 3e$)	2.7×10^{-8}	2×10^{-10}
BR($\tau \to 3\mu$)	2.1×10^{-8}	2×10^{-10}
CR($\mu - e$, Ti)	4.3×10^{-12}	$\mathcal{O}(10^{-16})(\mathcal{O}(10^{-18}))$
CR($\mu - e$, Au)	7×10^{-13}	
CR($\mu - e$, Al)		$\mathcal{O}(10^{-16})$

PDG: http://pdg.lbl.gov/

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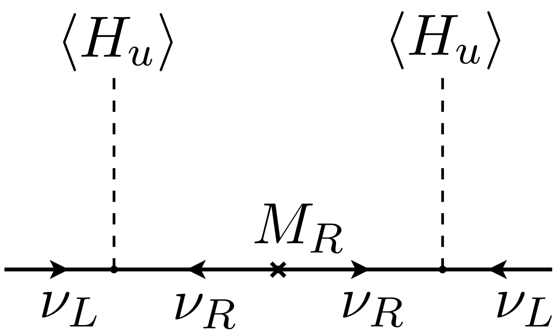
Seesaw models for neutrino masses: Type-I-II-III

$$\mathcal{L} = \cdots + H_u \overline{\nu_L} Y_\nu^{\mathrm{I}} \nu_R - \frac{1}{2} \nu_R^T C^{-1} M_R \nu_R$$

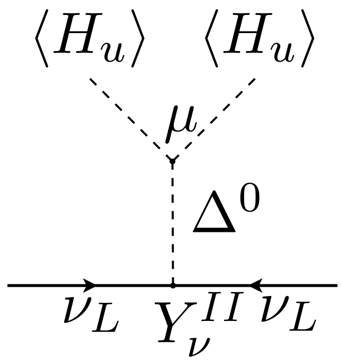
$$\mathcal{L} = \cdots - \frac{1}{2} Y_\nu^{\mathrm{II}} \overline{\nu_L^c} i\tau_2 \Delta_L \nu_L - \mu H_u^T \Delta_L H_u - M_\Delta^2 \Delta_L^\dagger \Delta_L$$

$$\mathcal{L} = \cdots + H_u \overline{W_M} Y_\nu^{\mathrm{III}} \nu_L - \frac{1}{2} W_M^T C^{-1} M_{W_M} W_M$$

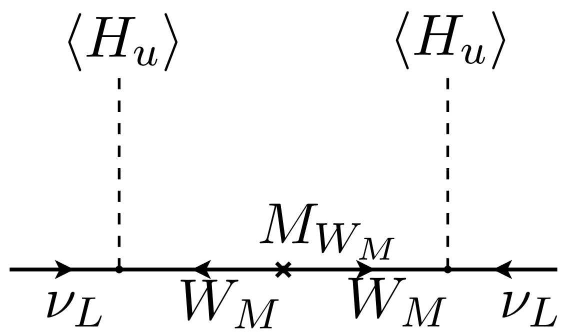
type-I



type-II



type-III



$$m_{\text{eff}}^{\mathrm{I}} = -(vY_\nu) M_R^{-1} (vY_\nu)^T$$

$$m_{\text{eff}}^{\mathrm{II}} = \frac{v^2 \mu Y_\nu^{\mathrm{II}}}{M_\Delta^2}$$

$$m_{\text{eff}}^{\mathrm{III}} = -(vY_\nu^{\mathrm{III}}) M_{W_M}^{-1} (vY_\nu^{\mathrm{III}})^T$$

- Exchanged particle: Type-I-III: neutral fermion. Type-II: neutral scalar
- Type-I: gauge singlet. Type-II-III; gauge triplet ➡ Stronger running
- $m_\nu \sim 1$eV and $Y_\nu \sim \mathcal{O}(1)$ ➡ $M_{\text{Seesaw}} \sim \mathcal{O}(10^{12-14})$GeV **Not directly observable**

Left-Right Model: breaking scales and neutrino mass

Outline

Motivation

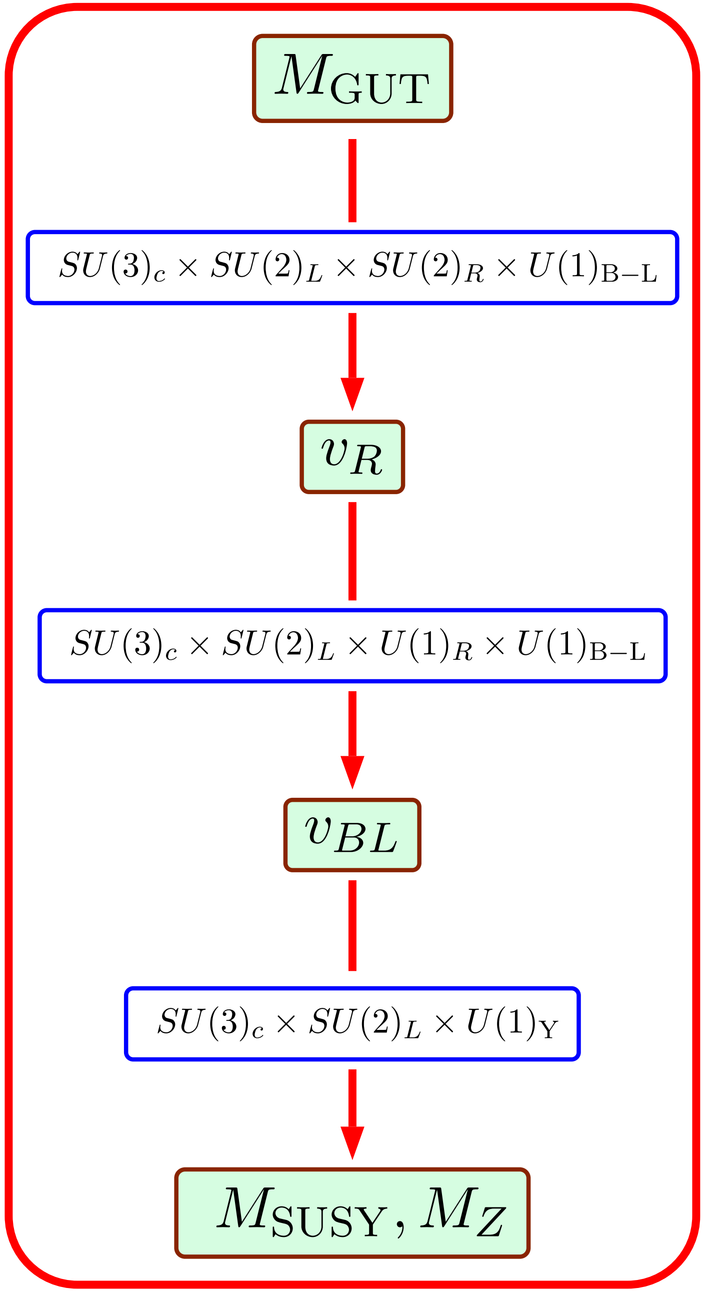
Models

- Type-I-II-III
- LR
- GUT scale
- Below GUT
- Effect on Spectra
- LFV

Low-Energy Obs.

LHC Observables

Conclusions



- Superpotential

$$\mathcal{W} = Y_L L \Phi L^c - f_c L^c \Delta^c L^c + \cdots$$

  - Y_L and f_c complex 3×3 matrices

- Lagrangian at $v_{BL} = \langle \Delta_c^0 \rangle$

$$\mathcal{L} = H_u \, \overline{\nu_L} \, Y_\nu^{\mathrm{I}} \, \nu_R - \tfrac{1}{2} \nu_R^T \, C^{-1} \left(f_c v_{BL} \right) \nu_R + \cdots$$

- Effective neutrino mass matrix (type-I)

$$m_{\mathrm{eff}}^{\mathrm{LR}} = -(v Y_\nu)(f_c v_{BL})^{-1} (v Y_\nu)^T$$

  - Y_ν fit $\to f_c = \mathbb{1}$, Y_ν arbitrary
  - f fit $\to Y_\nu = \mathbb{1}$, f_c arbitrary
  - Different imprints on RGE running

The Setup: GUT scale

At GUT scale the SU(5) invariant superpotentials are

- Type-I

$$W_{\rm RHN} = \mathbf{Y}_N^{\rm I}\, N^c\, \bar{5}\cdot 5_H + \frac{1}{2}\, M_R\, N^c N^c$$

- Type-II

$$W_{\rm 15H} = \frac{1}{\sqrt{2}}\mathbf{Y}_N^{\rm II}\; \bar{5}\cdot 15\cdot \bar{5} + \frac{1}{\sqrt{2}}\lambda_1 \bar{5}_H\cdot 15\cdot \bar{5}_H + \frac{1}{\sqrt{2}}\lambda_2 5_H\cdot \overline{15}\cdot 5_H$$
$$+\mathbf{Y}_5 10\cdot \bar{5}\cdot \bar{5}_H + \mathbf{Y}_{10} 10\cdot 10\cdot 5_H + M_{15} 15\cdot \overline{15} + M_5 \bar{5}_H\cdot 5_H$$

- Type-III

$$W_{\rm 24H} = \sqrt{2}\,\bar{5}_M Y^5 10_M \bar{5}_H - \frac{1}{4} 10_M Y^{10} 10_M 5_H + 5_H 24_M Y_N^{III} \bar{5}_M$$
$$+\frac{1}{2} 24_M M_{24} 24_M$$

The $SU(5)$-broken phase

Under $SU(3) \times SU_L(2) \times U(1)_Y$

- The $\mathbf{5}$, $\mathbf{10}$ and $\mathbf{5}_H$ contain

$$\bar{5} = (d^c, L), \;\; 10 = (u^c, e^c, Q), \;\; 5_H = (H^c, H_u), \;\; \bar{5}_H = (\bar{H}^c, H_d)$$

- The $\mathbf{15}$ decomposes as

$$\mathbf{15} = S(6, 1, -\frac{2}{3}) + T(1, 3, 1) + Z(3, 2, \frac{1}{6})$$

- The $\mathbf{24}$ decomposes as

$$\mathbf{24} = W_M(1, 3, 0) + B_M(1, 1, 0) + \overline{X}_M(3, 2, -\frac{5}{6}) + X_M(\bar{3}, 2, \frac{5}{6}) + G_M(8, 1, 0)$$

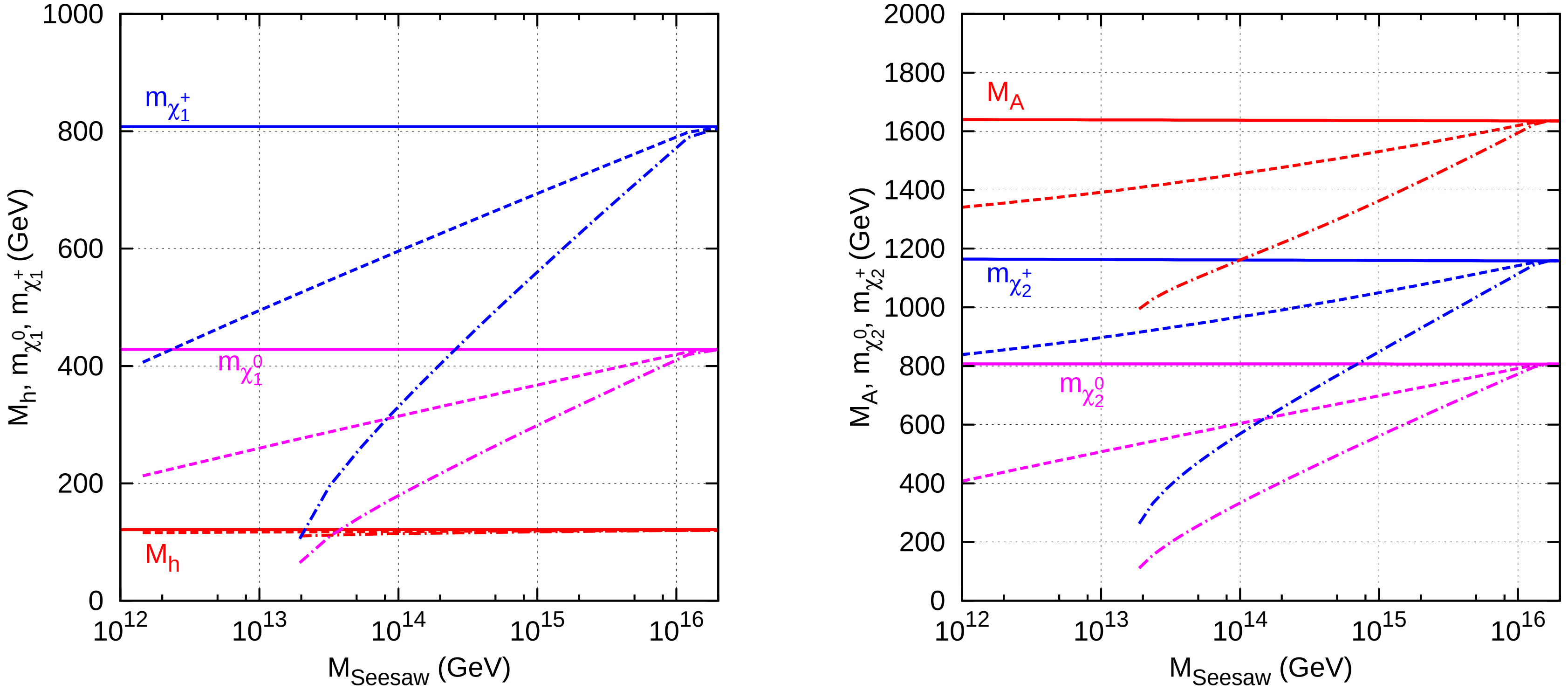
Effects of the heavy particles on the MSSM spectrum

The appearance of particles with charges under the gauge group at scales between M_{Seesaw} and M_{GUT} leads to changes in the beta functions of the gauge couplings

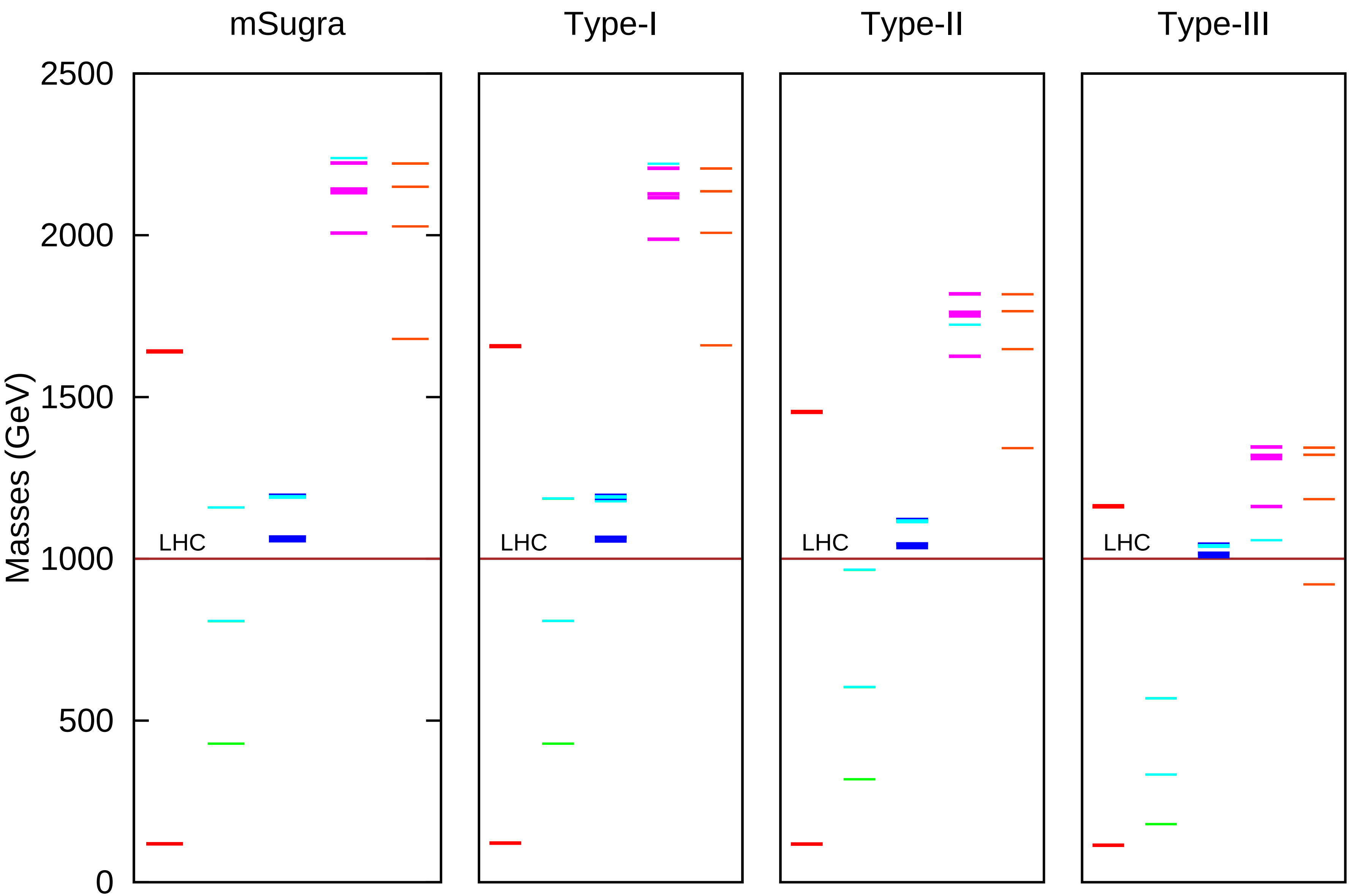
- In the MSSM the corresponding values at 1-loop level are $(b_1, b_2, b_3) = (33/5, 1, -3)$
- In case of one **15**-plet the additional contribution is $\Delta b_i = 7/2$ whereas in case of **24**-plet it is $\Delta b_i = 5$. This results in case of type-II in a total shift of $\Delta b_i = 7$ for the minimal model and in case of type-III in $\Delta b_i = 15$ assuming 3 generations of **24**-plets
- This does not only change the evolution of the gauge couplings but also the evolution of the gaugino and scalar mass parameters with profound implications on the spectra. Additional effects on the spectrum of the scalars can be present if some of the Yukawa couplings get large

Variation on the Spectra

- Example of spectra at $Q = 1$ TeV versus the seesaw scale
- SUSY parameters $m_0 = M_{1/2} = 1$ TeV, $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$
- Type-I (full lines), type-II (dashed) and type-III (dash-dotted)



After LHC: comparison for $M_{1/2}=m_0=1$ TeV ($M_{\rm SS}=10^{14}$ GeV)



$m_0 = 1$ TeV, $M_{1/2} = 1$ TeV, $\tan\beta = 10$, $A_0 = 0$ GeV, $\mu > 0$

LFV in the slepton sector: Approximate formulas for $\Delta m_{L,E}$

Starting with universal (mSUGRA) boundary conditions @ $M_{\rm GUT}$:

Seesaw type-I-II-III

$$\Delta m^2_{L,ij} \simeq -\frac{a_k}{8\pi^2}\left(3m_0^2+A_0^2\right)\left(Y_N^{k,\dagger} L Y_N^k\right)_{ij}, \qquad L=\ln\left(\frac{M_{\rm GUT}}{M_{\rm N}}\right)$$

$$\Delta m^2_{E,ij} \simeq 0 \qquad\qquad a_{\rm I}=1\,,\; a_{\rm II}=6 \text{ and } a_{\rm III}=\frac{9}{5}$$

Left-Right Model

$M_{\rm GUT}$ → v_R

$$\Delta m^2_L \simeq -\frac{1}{4\pi^2}\left(3ff^\dagger+Y_L^{(k)}Y_L^{(k)\,\dagger}\right)\left(3m_0^2+A_0^2\right)\ln\left(\frac{M_{\rm GUT}}{v_R}\right)$$

$$\Delta m^2_E \simeq -\frac{1}{4\pi^2}\left(3f^\dagger f+Y_L^{(k)\,\dagger}Y_L^{(k)}\right)\left(3m_0^2+A_0^2\right)\ln\left(\frac{M_{\rm GUT}}{v_R}\right)$$

v_R → v_{BL}

$$\Delta m^2_L \simeq -\frac{1}{8\pi^2}Y_\nu Y_\nu^\dagger\left(m_L^2|_{v_R}+A_e^2|_{v_R}\right)\ln\left(\frac{v_R}{v_{BL}}\right)$$

$$\Delta m^2_E \simeq 0$$

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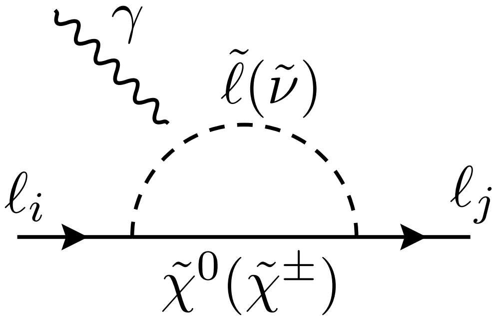
Radiative lepton decays $l_i \to l_j\gamma$: Approximate formulas

- BR($l_i \to l_j\gamma$): (**MEG**...)



$$\mathcal{L}_{eff} = e\frac{m_i}{2}\bar{l}_i\sigma_{\mu\nu}F^{\mu\nu}(A_L^{ij}P_L + A_R^{ij}P_R)l_j + h.c.$$

$$\text{BR}(l_i \to l_j\gamma) = \frac{48\pi^3\alpha}{G_F^2}\left(|A_L^{ij}|^2 + |A_R^{ij}|^2\right)\text{BR}(l_i \to l_j\nu_i\bar{\nu}_j)$$

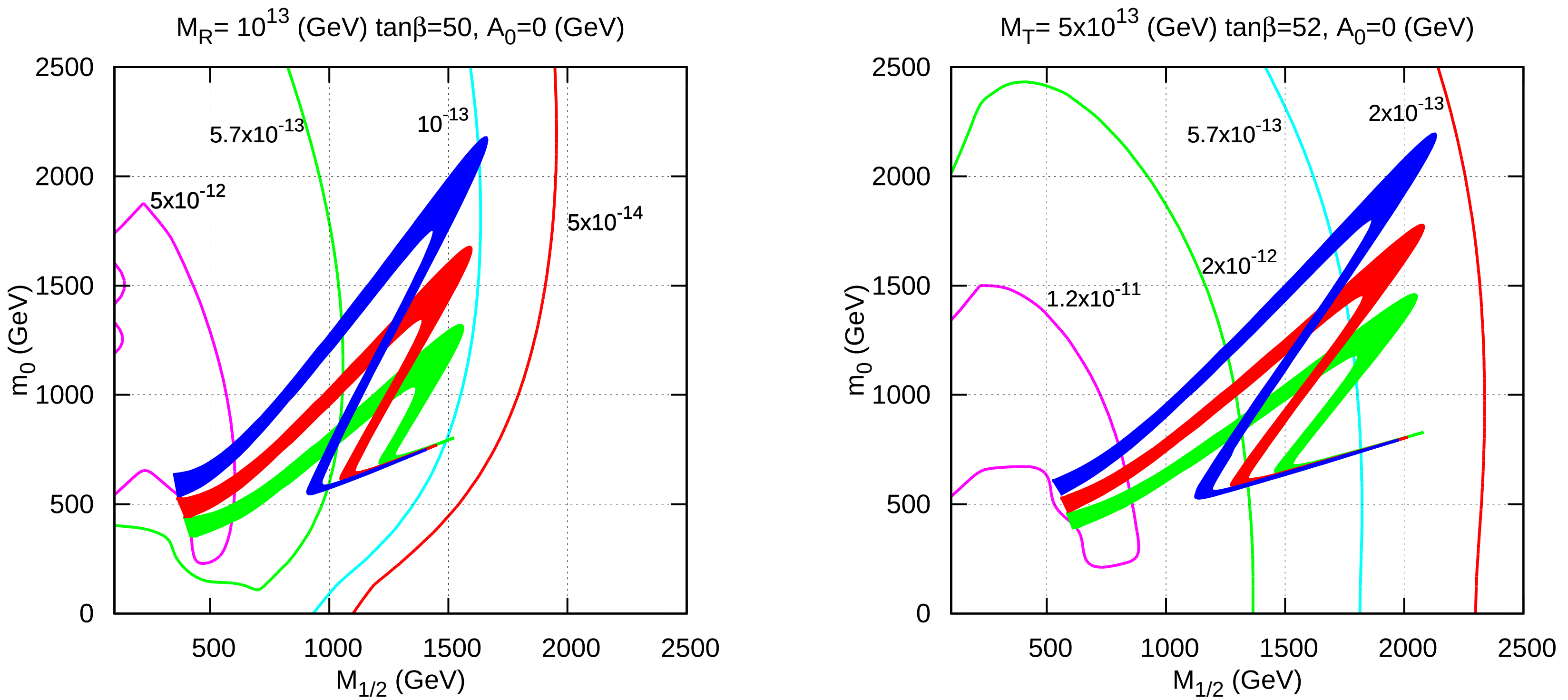
- For seesaw models: $A_L^{ij} \sim \frac{(\Delta m_L^2)_{ij}}{m_{SUSY}^4}, \quad A_R^{ij} \sim \frac{(\Delta m_E^2)_{ij}}{m_{SUSY}^4}$
  - type-I-II-III ➞ only A_L
  - Left-Right model: In principle **both** A_L and A_R
  - Distinguish models: ➞ Positron polarization asymmetry(**MEG**)

$$\mathcal{A}(\mu^+ \to e^+\gamma) = \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2} = \begin{cases} 1 & \text{type-I-II-III} \\ \neq 1 & \text{LR} \end{cases}$$

Low-Energy LFV constraints in SUSY seesaw models: type-I,II

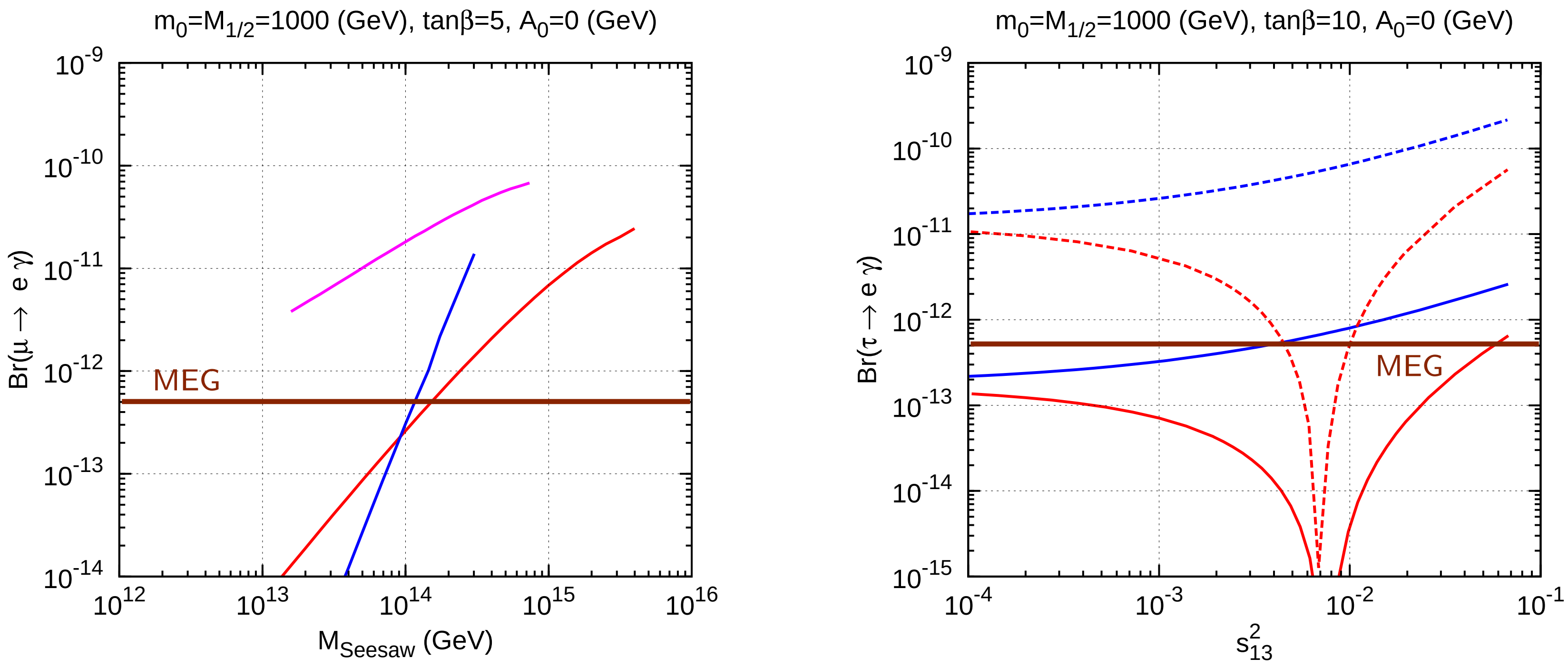
- Parameters: SUSY: $\{m_0, M_{1/2}, A_0 = 0, \tan\beta = 10, 52, \text{sign}(\mu) = +\}$
- Seesaw: $M_R = 10^{13}$ GeV and $M_T = 5 \times 10^{13}$ GeV
- Dark matter region: WMAP (3σ), $0.081 \le \Omega h^2 \le 0.129$
- SPheno(W.Porod), SARAH(F.Staub)

Higgs funnel



- $m_{top} = 169.1$ GeV (blue), 171.2 GeV (red), 173.3 GeV (green)
- Superimposed are the contour lines for the $Br(\mu \to e\gamma)$

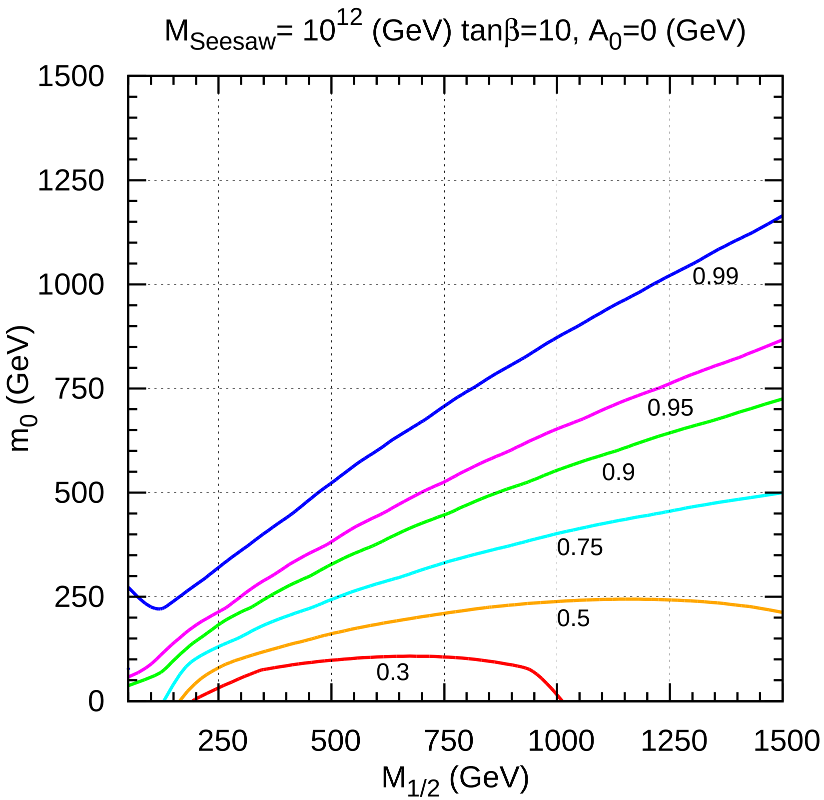
Comparison of $\mu \to e\gamma$ for the three sessaw types

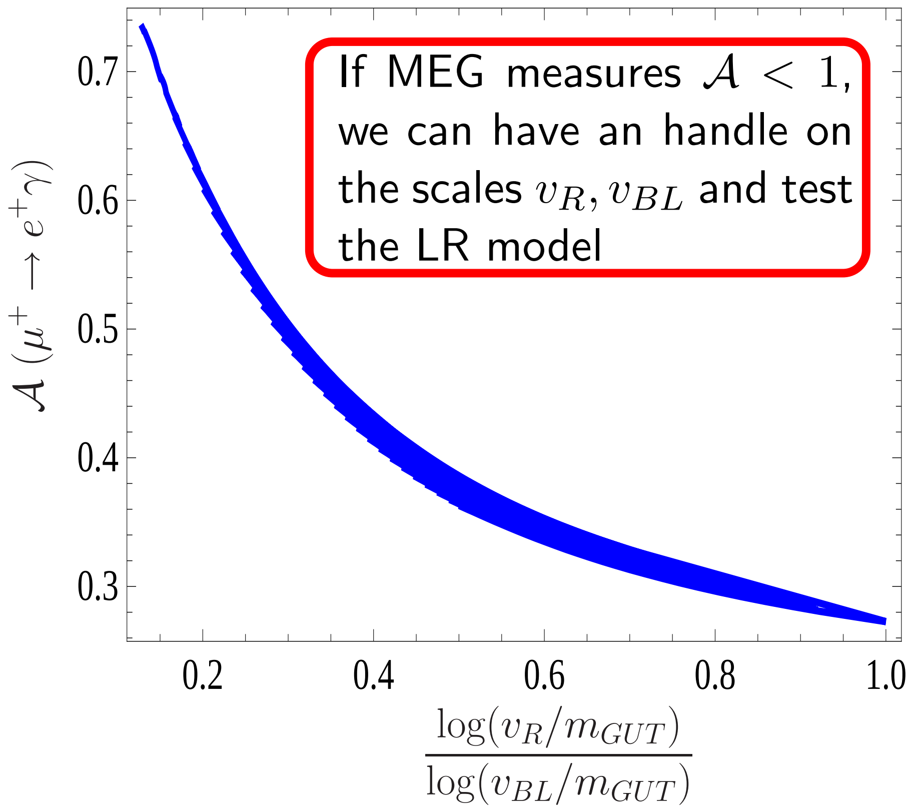


Left panel: $Br(\mu \to e\gamma)$ as a function of the seesaw scale for seesaw type-I (red line), seesaw type-II (blue line) and seesaw type-III (magenta line). Right panel: $Br(\mu \to e\gamma)$ (left) versus s^2_{13} for seesaw type-I (solid lines) and seesaw type-III (dashed lines), for $M_{\text{Seesaw}} = 10^{14}$ GeV. The curves shown are for 2 values of the Dirac phase: $\delta = 0$ (red) and $\delta = \pi$ (blue), both for normal hierarchy.

A low-energy observable for Left-Right model: $\mathcal{A}(\mu^+ \to e^+\gamma)$

- Positron polarization asymmetry: $\mathcal{A}(\mu^+ \to e^+\gamma) = \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2}$
- In seesaw type-I-II-III: $\mathcal{A}(\mu^+ \to e^+\gamma) = 1$, as $A_R \simeq 0$
- Parameters:
  - SUSY: SPS3 $\{m_0 = 90, M_{1/2} = 400, A_0 = 0, \tan\beta = 10, \text{sign}(\mu) = +\}$
  - LR: $v_{BL} = 10^{15}$ GeV, $v_R \in [10^{14}, 10^{15}]$ GeV, Y_ν fit





LHC Observables

At colliders we can look at LFV in the decays of different types of particles. Several types of observables have been considered:

- **Ratios of slepton branching ratios**

  arXiv: 0804.4072, 0903.1408

- **Slepton mass splittings**

  arXiv: 1007.4833, 1104.3962, 1206.2306, 1402.1426 and 1309.7951 (A.J.R. Figueiredo & A.M. Teixeira)

- In models that break R-parity we can look at the decays of the neutralino and correlate these decays with the solar and atmospheric angles. These models can be considered a kind of low scale seesaw and will also lead to signals of LFV at the colliders.

  W. Porod, M. Hirsch, JCR, J.W.F. Valle, PRD 63 (2001) 115004

Ratios of slepton branching ratios

- The charged slepton mass matrix is a 6×6 matrix. Taking into account that the running is more important for the left-sleptons, it is a reasonable first approximation just to consider the 3×3, LL block.

- This LL mass matrix is diagonalized by a matrix $R^{\tilde{l}}$. For small mixing

$$R^{\tilde{l}} \simeq \begin{bmatrix} 1 & \theta_{\tilde{e}\tilde{\mu}} & \theta_{\tilde{e}\tilde{\tau}} \\ -\theta_{\tilde{e}\tilde{\mu}} & 1 & \theta_{\tilde{\mu}\tilde{\tau}} \\ -\theta_{\tilde{e}\tilde{\tau}} & -\theta_{\tilde{\mu}\tilde{\tau}} & 1 \end{bmatrix}, \quad \theta_{ij} \simeq \frac{(\Delta M^2_{\tilde{L}})_{ij}}{(\Delta M^2_{\tilde{L}})_{ii} - (\Delta M^2_{\tilde{L}})_{jj}}$$

- To minimize the dependence of on SUSY parameters we take ratios

$$\frac{Br(\tilde{\tau}_2 \to e + \chi^0_1)}{Br(\tilde{\tau}_2 \to \mu + \chi^0_1)} \simeq \left(\frac{\theta_{\tilde{e}\tilde{\tau}}}{\theta_{\tilde{\mu}\tilde{\tau}}}\right)^2 \simeq \left(\frac{(\Delta M^2_{\tilde{L}})_{13}}{(\Delta M^2_{\tilde{L}})_{23}}\right)^2,$$

- To make estimates for the ratios of branching ratios we define

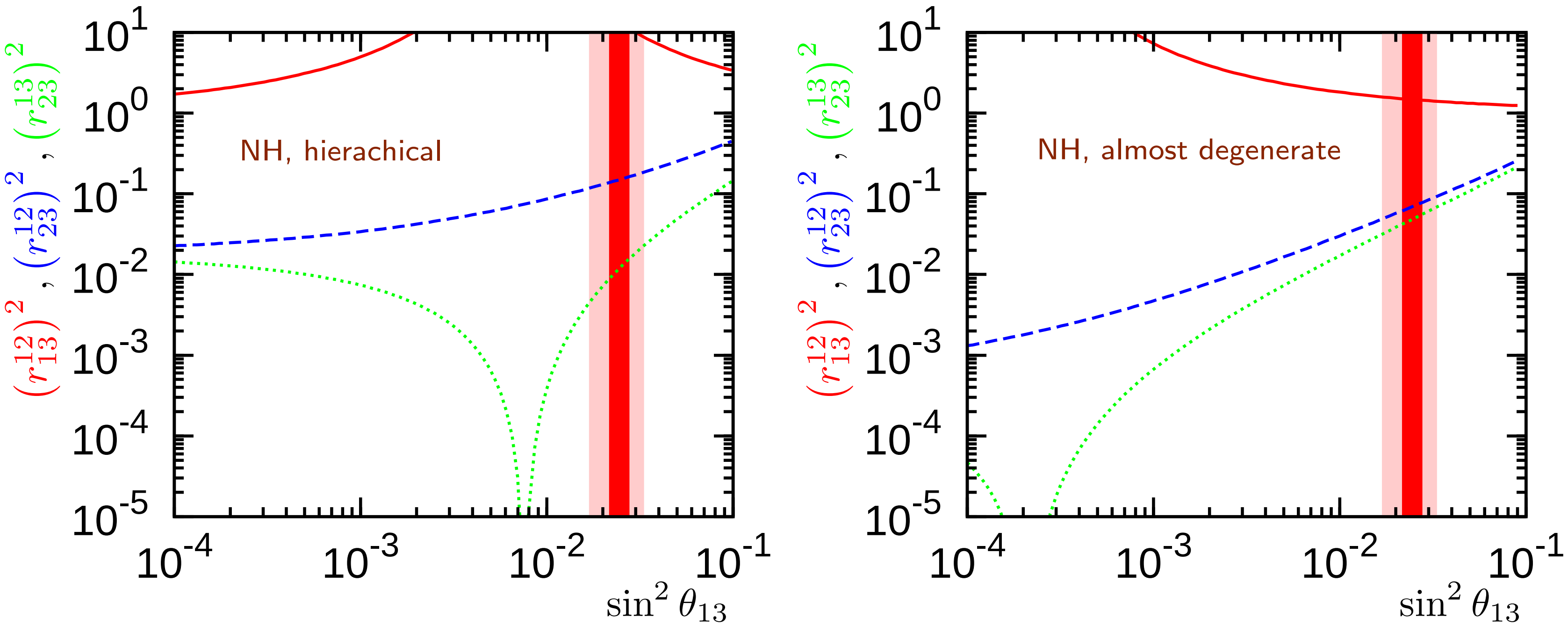
$$r^{ij}_{kl} \equiv \frac{|(\Delta M^2_{\tilde{L}})_{ij}|}{|(\Delta M^2_{\tilde{L}})_{kl}|}$$

→ **Largely independent of SUSY parameters**

where the observable quantity is $(r^{ij}_{kl})^2$

Ratios of slepton branching ratios

- We show the the ratios $(r_{kl}^{ij})^2$ as a function of $\sin^2\theta_{13}$ for two cases with normal hierarchy. On the **left panel we take $m_1 \sim 0$** and on the **right panel we have almost degenerate neutrinos**
- Right-handed neutrinos are taken degenerate and the other light neutrino parameters are at their best fit values with $\delta_{CP} = 0$
- Now that we have a measurement of $\sin\theta_{13}$, this will give a **prediction** on these ratios, under the above assumptions



Slepton Mass reconstruction at the LHC

- Di-lepton invariant mass distributions from $\chi_2^0 \to \tilde{\ell}^i_{L,R}\ell \to \chi_1^0 \ell\ell$

  For on-shell sleptons & isolated leptons with large $p_T > 10$ GeV

  - $m_{\ell\ell} = \frac{1}{m_{\tilde{\ell}}}\sqrt{\left(m^2_{\chi_2^0} - m^2_{\tilde{\ell}}\right)\left(m^2_{\tilde{\ell}} - m^2_{\chi_1^0}\right)}$ (0.1% precision at LHC)
  - Infer $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\ell}_i, \tilde{\ell}_j) = \frac{|m_{\tilde{\ell}_i} - m_{\tilde{\ell}_j}|}{<m_{\tilde{\ell}_{i,j}}>}$ @LHC: $\Delta m/m_{\tilde{\ell}}(\tilde{e}_L, \tilde{\mu}_L) \to \mathcal{O}(0.1\%)$, $\Delta m/m_{\tilde{\ell}}(\tilde{\mu}_L, \tilde{\tau}_L) \to \mathcal{O}(1\%)$

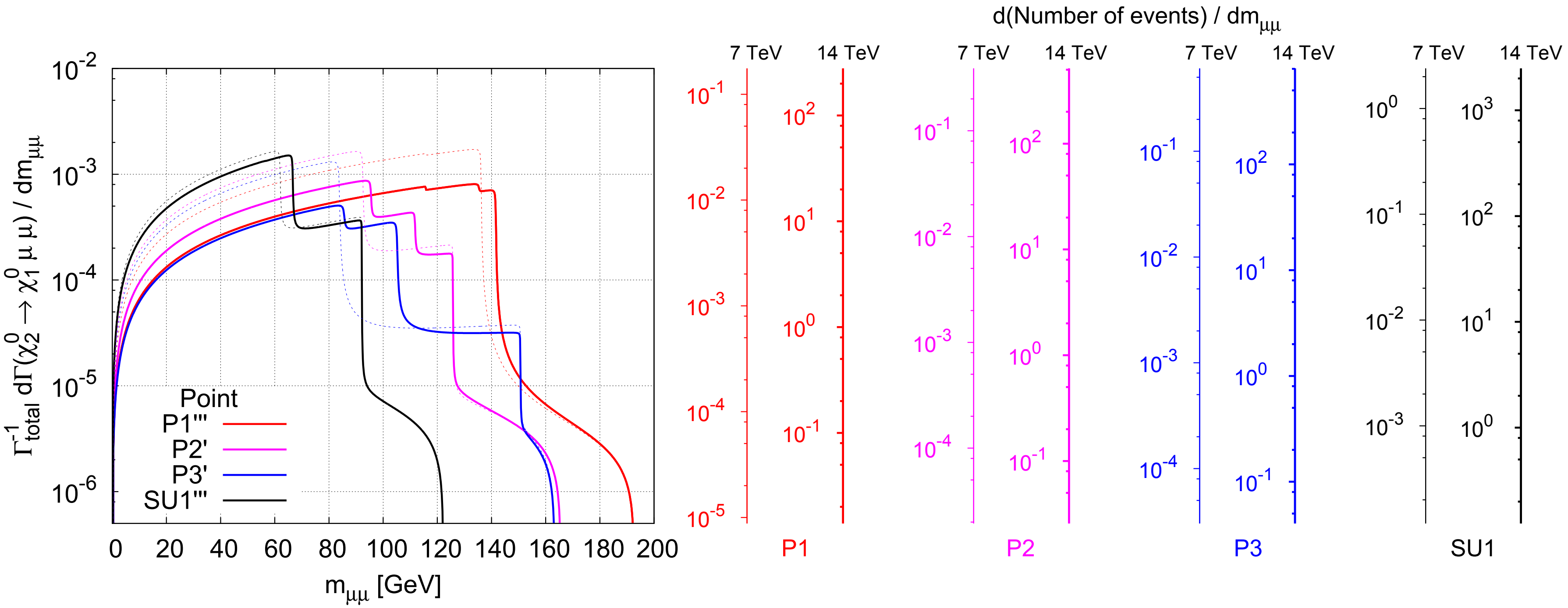
- Study points (good in 2012, mostly excluded today)

Point	$m_{\chi_2^0}$	$m_{\chi_1^0}$	$m_{\tilde{\ell}_L}$	$m_{\tilde{\ell}_R}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{\tau}_1}$	$< m_{\tilde{q}} >$
P1	410	217	374	231	375	224	1064
P2	356	191	338	212	335	198	963
P3	342	179	327	218	325	186	877
ATLAS-SU1	262	140	251	156	254	147	733

LFV at the LHC: di-lepton distributions in χ_2^0 decays (type-I)

Impact for di-lepton distributions $\chi_2^0 \to \tilde{\ell}^i_{L,R}\ell_i \to \chi_1^0 \ell_i \ell_i$

Seesaw: $M_N = \{10^{10}, 5\times 10^{10}(10^{12}), 5\times 10^{13}(10^{15})\}$ GeV, $\theta_{13} = 0.1^\circ$



- Displaced $m_{\mu\mu}$ and m_{ee} edges $(\ell_L) \Leftrightarrow$ sizable $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L)$
- Appearance of new edge in $m_{\mu\mu}$: intermediate $\tilde{\tau}_2$
- LFV at the LHC: e.g $\chi_2^0 \to \tilde{\tau}_2 \mu \to \chi_1^0 \mu\mu$

Mass splittings in view of the 2103 new results

- The discovery of the Higgs boson at 125 GeV together with the new bound from MEG in $\mu \to e\gamma$, the mesurement of $\theta_{13} \neq 0$ and an heavy spectra for SUSY put the **previous results under question**

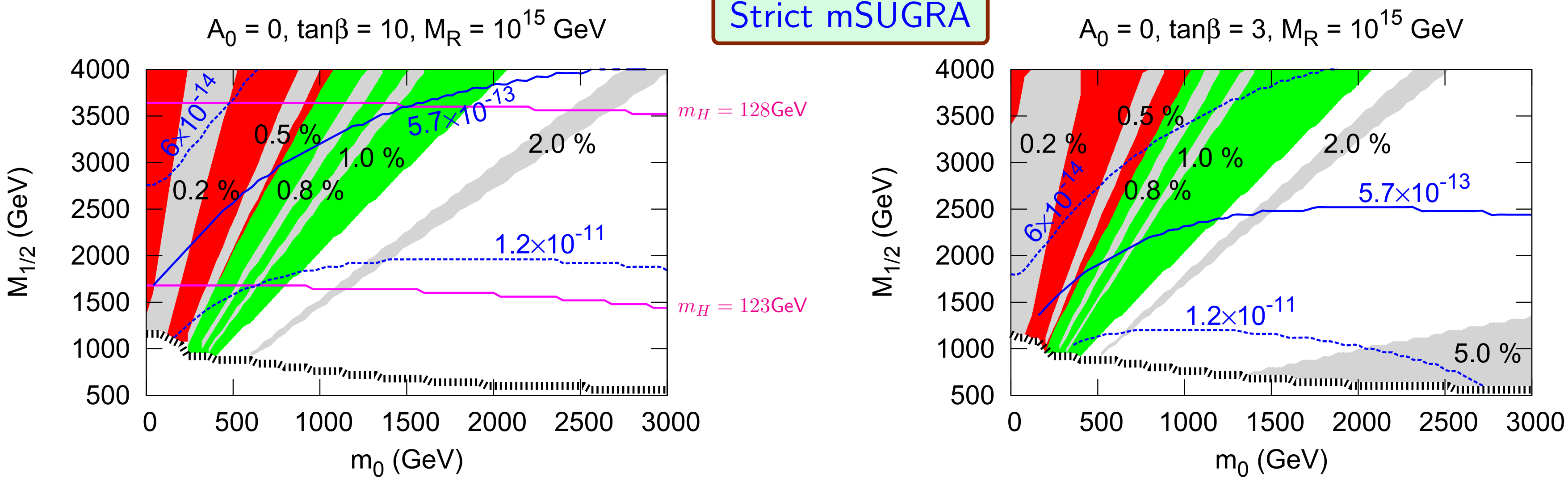
- An update was done by Figueiredo and Teixeira (JHEP 1401 (2014) 015) and we describe here their results:

  - **For constrained SUSY scenarios it is no more possible to have sizable mass splittings observable at LHC** in view of the LHC results on an heavy spectra, the 125 Higgs boson and the MEG result on $\mu \to e\gamma$

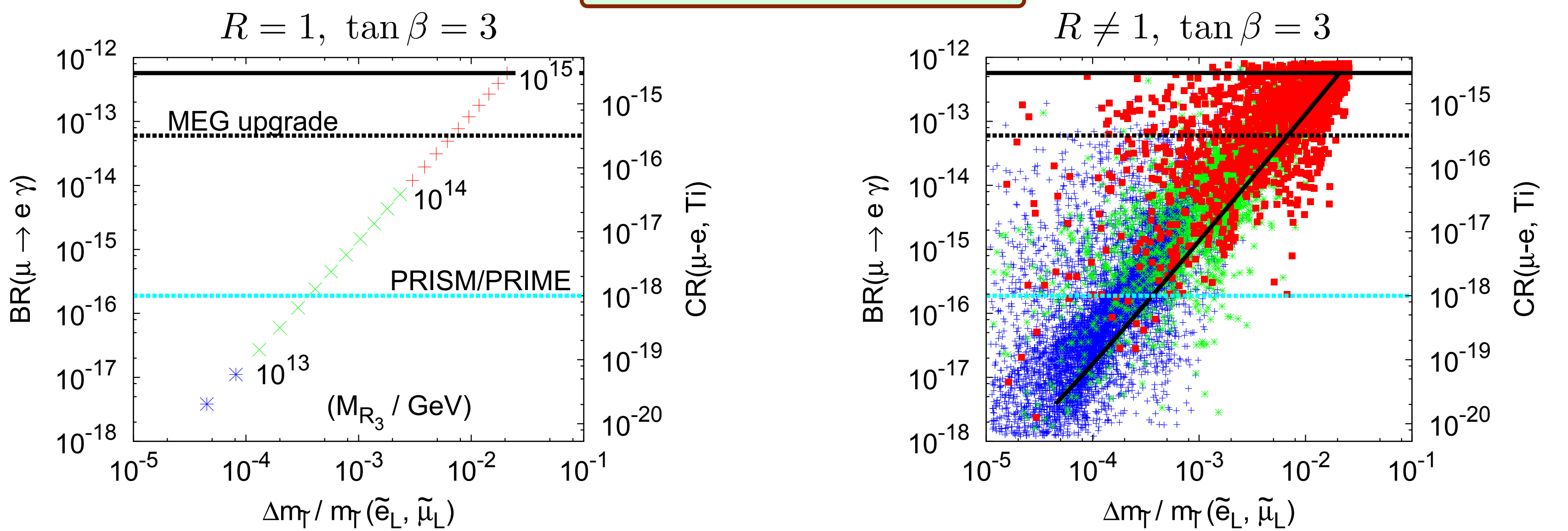
  - However **relaxing the strict universality** of SUSY soft breaking (but still preserving lepton universality), and exploring the heavy neutrino unknown dynamics $(R \neq 1)$ **we can still get slepton mass splittings of $\mathcal{O}$(few %) acessible at LHC** and with rates for $\mu \to e\gamma$ within the future sensitivity

Mass splittings @ LHC: 2014 update (Figueiredo & Teixeira)

Strict mSUGRA



Non-Universal soft masses



Figures from A.J.R. Figueiredo & Ana M. Teixeira, 1309.7951, JHEP 1401 (2014) 015

$[M_R = 10^{15}, 10^{14}, 10^{13}$ GeV$]$

Conclusions: What can we learn?

- **cMSSM:** no LFV, approximately degenerate $\tilde{e} - \tilde{\mu}$
- SUSY seesaw to account for neutrino masses and mixings:
  - $\dfrac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L)$ **within LHC sensitivity**
  - New edges in di-lepton distributions
  - Correlation of low- and high-energy LFV observables (e.g. **BR vs** $\Delta m_{\tilde{\ell}}$)
- Possible impact of experimental data:

BRs, CR and $\mathcal{A}(\mu^+ \to e^+\gamma)\vert_{\text{low-energy}}$	⟷	$\Delta m_{\tilde{\ell}}(\tilde{e}_L, \tilde{\mu}_L)$, LFV in decays@LHC

  - Substantiate seesaw hypothesis getting hints of the new physics
  - Disfavour SUSY seesaw as the (only) source of flavour violation

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Backup Slides

LFV in neutralino decays in broken R-parity models

- In the bilinear R-parity violation model the neutralino can decay in the following channels

$$\tilde{\chi}_1^0 \to \ \nu_i\,\nu_j\,\nu_k\ ,\nu_i\,q\,\bar{q}\ ,\nu_i\,l_j^+\,l_k^-\ \ ,l_i^\pm\,q\,\bar{q}'\ ,\nu_i\,\gamma$$

- These decays can be correlated with the solar and atmospheric angles