Lepton Flavour Violation, (Dark Matter) & LHC

(A SUSY Perspective)

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Content

- $SU(5)$-inspired: seesaw implementations
- $SO(10)$-inspired: left-right symmetric models
- LHC: current bounds on sleptons

Lepton flavour violation, experimental data

Neutrinos: tiny masses — large mixings

$|\Delta m^2_{31}| \simeq 2.4 \cdot 10^{-3}$ eV^2 — $\sin^2\theta_{23} \simeq 0.57$ — $(\delta_{CP} \simeq 1.4\pi)$

$\Delta m^2_{21l} \simeq 7.6 \cdot 10^{-5}$ eV^2 — $\sin^2\theta_{12} \simeq 0.32$

^{3}H decay: $m_\nu \lesssim 2$ eV — $\sin^2\theta_{12} \simeq 0.023$

strong bounds for charged leptons

$BR(\mu \to e\gamma) \lesssim 4.2 \cdot 10^{-13}$ — $BR(\mu^- \to e^- e^+ e^-) \lesssim 10^{-12}$

$BR(\tau \to e\gamma) \lesssim 3.3 \cdot 10^{-8}$ — $BR(\tau \to \mu\gamma) \lesssim 4.4 \cdot 10^{-8}$

$BR(\tau \to l l l') \lesssim O(10^{-8})$ $(l, l' = e, \mu)$

$$|d_e| \lesssim 0.9 \cdot 10^{-28}\; e\; cm,\; |d_\mu| \lesssim 10^{-18}\; e\; cm,\; |d_\tau| \lesssim 10^{-15}\; e\; cm$$

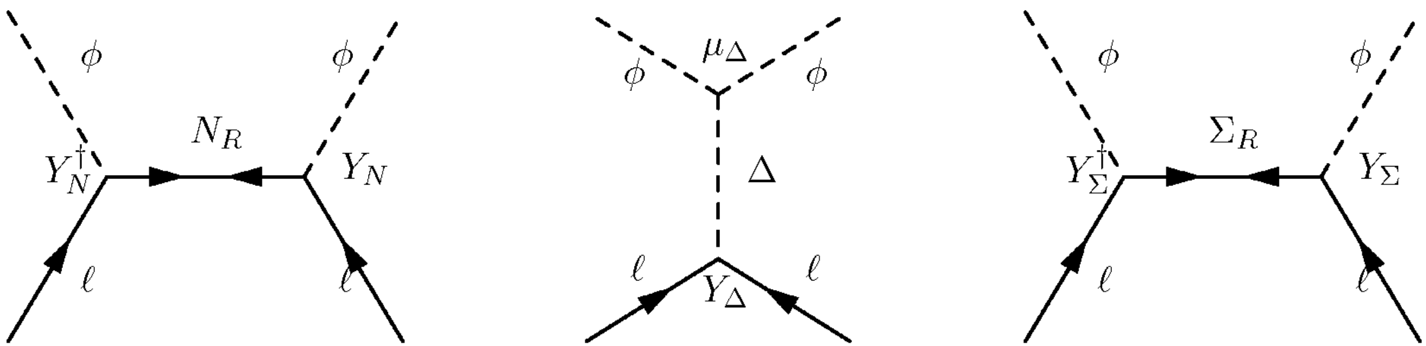
SUSY contributions to anomalous magnetic moments

$$|\Delta a_e| \leq 10^{-13},\;\; 0 \leq \Delta a_\mu \leq 34 \cdot 10^{-10},\;\; |\Delta a_\tau| \leq 0.058$$

Majorana neutrinos: Seesaw mechanism*

Neutrino masses due to

$$\frac{f}{\Lambda}(HL)(HL)$$



* P. Minkowski, Phys. Lett. B **67** (1977) 421; T. Yanagida, KEK-report 79-18 (1979); M. Gell-Mann, P. Ramond, R. Slansky, in *Supergravity*, North Holland (1979), p. 315; R.N. Mohapatra and G. Senjanovic, *Phys. Rev. Lett.* **44** 912 (1980); M. Magg and C.Wetterich, Phys. Lett. B 94 (1980) 61; G. Lazarides, Q. Shafi and C. Wetterich, Nucl. Phys. B 181 (1981) 287; J. Schechter and J. W. F. Valle, Phys. Rev. **D25**, 774 (1982); R. Foot, H. Lew, X. G. He and G. C. Joshi, Z. Phys. C 44 (1989) 441.

The Setup: GUT scale

Relevant SU(5) invariant parts of the superpotentials at M_{GUT}

- type-I

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

- type-II

$$W_{\rm 15H} = \frac{1}{\sqrt{2}} \mathbf{Y}_N^{\rm II}\, \overline{5}_M \cdot 15 \cdot \overline{5}_M + \frac{1}{\sqrt{2}} \lambda_1 \overline{5}_H \cdot 15 \cdot \overline{5}_H + \frac{1}{\sqrt{2}} \lambda_2 5_H \cdot \overline{15} \cdot 5_H + M_{15} 15 \cdot \overline{15}$$

- type-III

$$W_{\rm 24H} = 5_H 24_M Y_N^{III} \overline{5}_M + \frac{1}{2} 24_M M_{24} 24_M$$

The $SU(5)$-broken phase

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

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

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

- 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

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

Seesaw I, below M_{GUT}

$$W_I = W_{MSSM} + W_\nu \ ,$$
$$W_\nu = \widehat{N}^c Y_\nu \widehat{L} \cdot \widehat{H}_u + \frac{1}{2} \widehat{N}^c M_R \widehat{N}^c \ ,$$

Neutrino mass matrix

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

Inverting the seesaw equation gives Y_ν a la Casas & Ibarra

$$Y_\nu = \sqrt{2}\frac{i}{v_u}\sqrt{\hat{M}_R} \cdot R \cdot \sqrt{\hat{m}_\nu} \cdot U^\dagger$$

$\hat{m}_\nu$, $\hat{M}_R$ . . . diagonal matrices containing the corresponding eigenvalues
U . . . . neutrino mixing matrix
R . . . . complex orthogonal matrix.

Seesaw II, below M_{GUT}

$$
\begin{aligned}
W_{II} &= W_{MSSM} + \frac{1}{\sqrt{2}}(Y_T \widehat{L}\widehat{T}_1\widehat{L} + Y_S \widehat{D}^c \widehat{S}_1 \widehat{D}^c) + Y_Z \widehat{D}^c \widehat{Z}_1 \widehat{L} \\
&+ \frac{1}{\sqrt{2}}(\lambda_1 \widehat{H}_d \widehat{T}_1 \widehat{H}_d + \lambda_2 \widehat{H}_u \widehat{T}_2 \widehat{H}_u) + M_T \widehat{T}_1 \widehat{T}_2 + M_Z \widehat{Z}_1 \widehat{Z}_2 + M_S \widehat{S}_1 \widehat{S}_2
\end{aligned}
$$

fields with index 1 (2) originate from the 15-plet ($\overline{15}$-plet).

Neutrino mass matrix

$$
m_\nu = -\frac{v_u^2}{2}\frac{\lambda_2}{M_T} Y_T .
$$

Seesaw III, below M_{GUT}

$$W_{III} = W_{MSSM} + \widehat{H}_u(\widehat{W}_M Y_N - \sqrt{\frac{3}{10}}\widehat{B}_M Y_B)\widehat{L} + \widehat{H}_u \widehat{\bar{X}}_M Y_X \widehat{D}^c$$
$$+\frac{1}{2}\widehat{B}_M M_B \widehat{B}_M + \frac{1}{2}\widehat{G}_M M_G \widehat{G}_M + \frac{1}{2}\widehat{W}_M M_W \widehat{W}_M + \widehat{X}_M M_X \widehat{\bar{X}}_M$$

giving

$$m_\nu = -\frac{v_u^2}{2}\left(\frac{3}{10}Y_B^T M_B^{-1} Y_B + \frac{1}{2}Y_W^T M_W^{-1} Y_W\right) \simeq -v_u^2 \frac{4}{10} Y_W^T M_W^{-1} Y_W$$

last step: valid if $M_B \simeq M_W$ and $Y_B \simeq Y_W$
$\Rightarrow$ Casas-Ibarra parametrisation for Y_W as in type-I

Effect of heavy particles on MSSM parameters

MSSM: $(b_1, b_2, b_3) = (33/5, 1, -3)$

per 15-plet $\Delta b_i = 7/2$ $\Rightarrow$ type II model $\Delta b_i = 7$

per 24-plet $\Delta b_i = 5$ $\Rightarrow$ type III model $\Delta b_i = 15$

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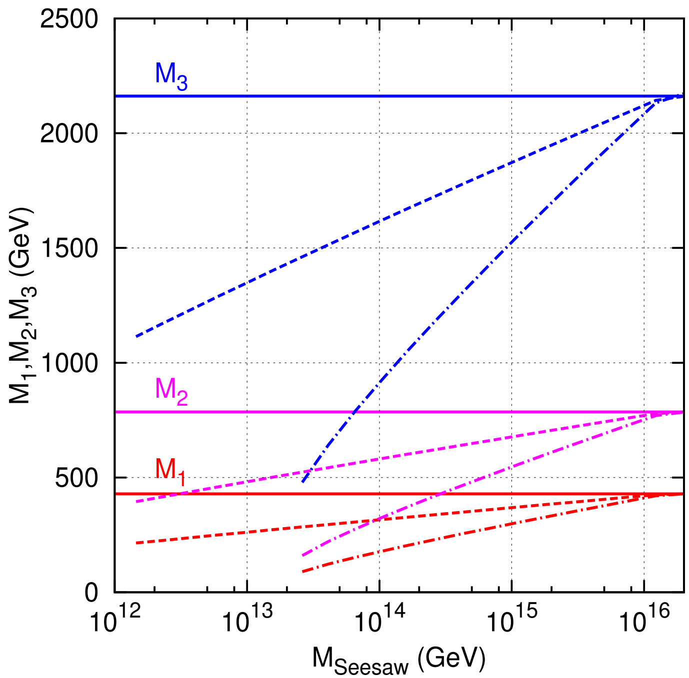
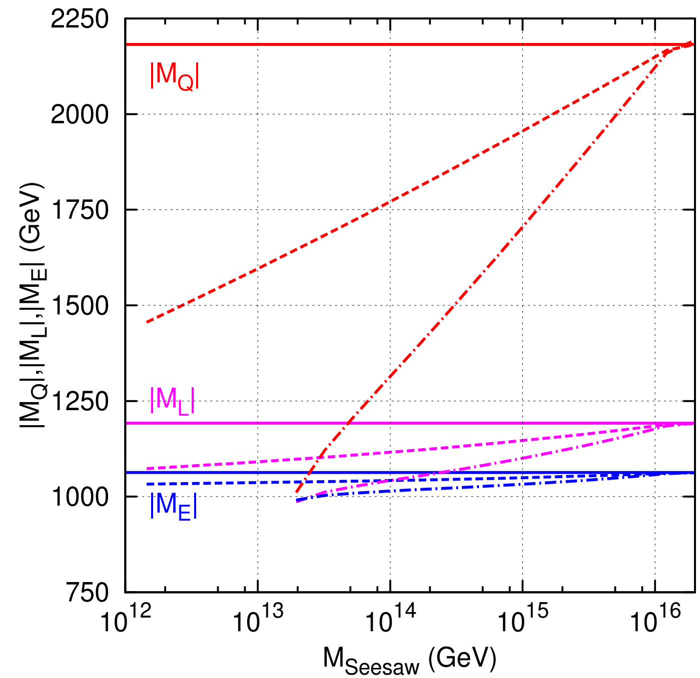


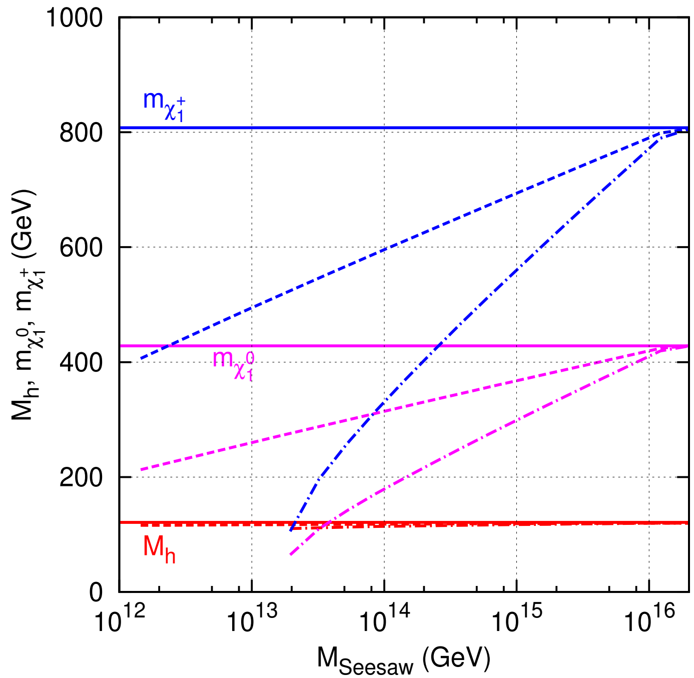


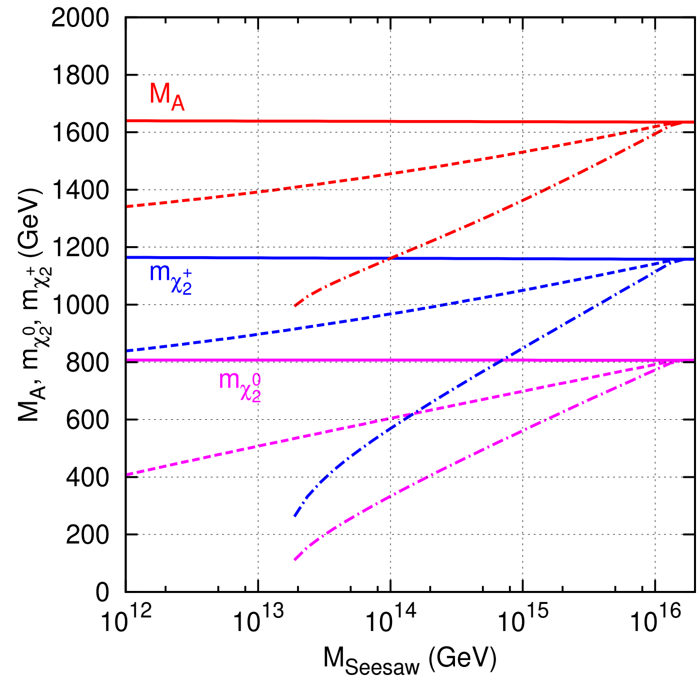
$Q = 1$ TeV, $m_0 = M_{1/2} = 1$ TeV, $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$

Full lines . . . seesaw type I, dashed lines . . . type II, dash-dotted lines . . . type III
degenerate spectrum of the seesaw particles

J. N. Esteves, M. Hirsch, W.P., J. C. Romão, F. Staub, arXiv:1010.6000

Effect on heavy particles on MSSM spectrum





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

Full lines ... seesaw type I, dashed lines ... type II, dash-dotted lines ... type III
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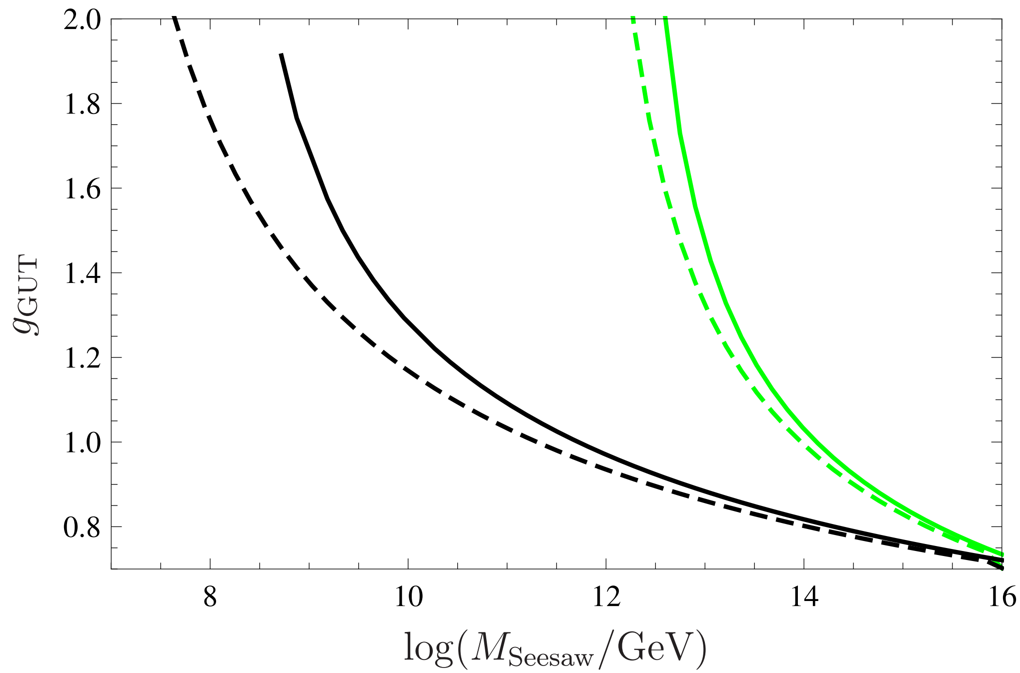
Landau Poles



$m_0 = M_{1/2} = 1$ TeV, $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$
$M_{GUT} = 2 \times 10^{16}$ GeV
black lines . . . seesaw type-II
green lines . . . seesaw type-III with three **24**-plets with degenerate mass spectrum
full (dashed) lines . . . 2-loop (1-loop) results

J. N. Esteves, M. Hirsch, W.P., J. C. Romão, F. Staub, arXiv:1010.6000

LFV in the slepton sector: approximate formulas, I

one-step integration of the RGEs assuming mSUGRA boundary

$$\Delta M^2_{L,ij} \simeq -\frac{a_k}{8\pi^2}\left(3m_0^2 + A_0^2\right)\left(Y_N^{k,\dagger} L Y_N^k\right)_{ij}$$

$$\Delta A_{l,ij} \simeq -a_k \frac{3}{16\pi^2} A_0 \left(Y_e Y_N^{k,\dagger} L Y_N^k\right)_{ij}$$

$$\Delta M^2_{E,ij} \simeq 0$$

$$L_{ij} = \ln(M_{GUT}/M_i)\delta_{ij}$$

for $i \neq j$ with Y_e diagonal

$$a_I = 1\ ,\ a_{II} = 6 \text{ and } a_{III} = \frac{9}{5}$$

LFV in the slepton sector: approximate formulas, II

$(\Delta M^2_{\tilde{L}})_{ij}$ and $(\Delta A_l)_{ij}$ induce

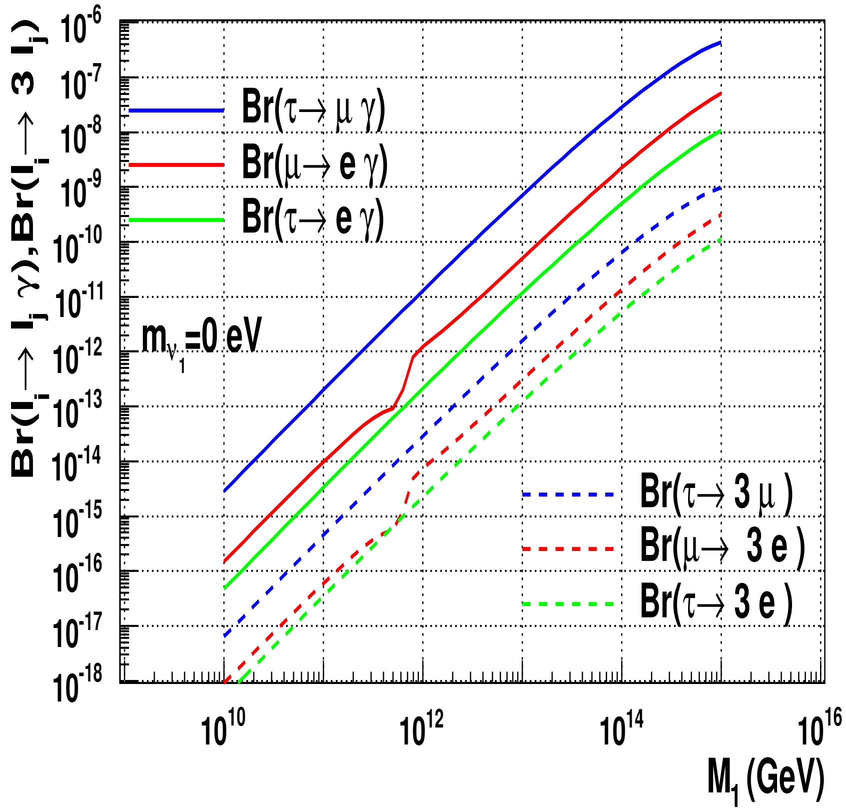
$$\begin{aligned} l_j &\to l_i\gamma\ ,\ l_i l_k^+ l_r^- \\ \tilde{l}_j &\to l_i\tilde{\chi}^0_s \\ \tilde{\chi}^0_s &\to l_i\tilde{l}_k \end{aligned}$$

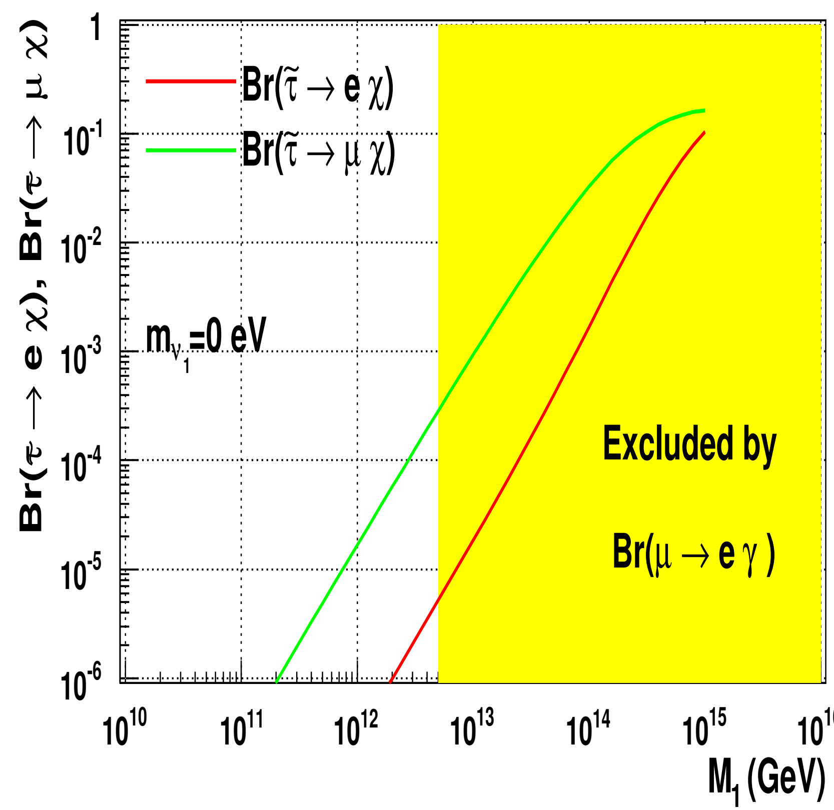
Neglecting L-R mixing:

$$\begin{aligned} BR(l_i \to l_j\gamma) &\propto \alpha^3 m^5_{l_i} \frac{|(\delta m^2_L)_{ij}|^2}{\widetilde{m}^8} \tan^2\beta \\ \frac{BR(\tilde{\tau}_2 \to e + \chi^0_1)}{BR(\tilde{\tau}_2 \to \mu + \chi^0_1)} &\simeq \left(\frac{(\Delta M^2_L)_{13}}{(\Delta M^2_L)_{23}}\right)^2 \end{aligned}$$

Moreover, in most of the parameter space

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





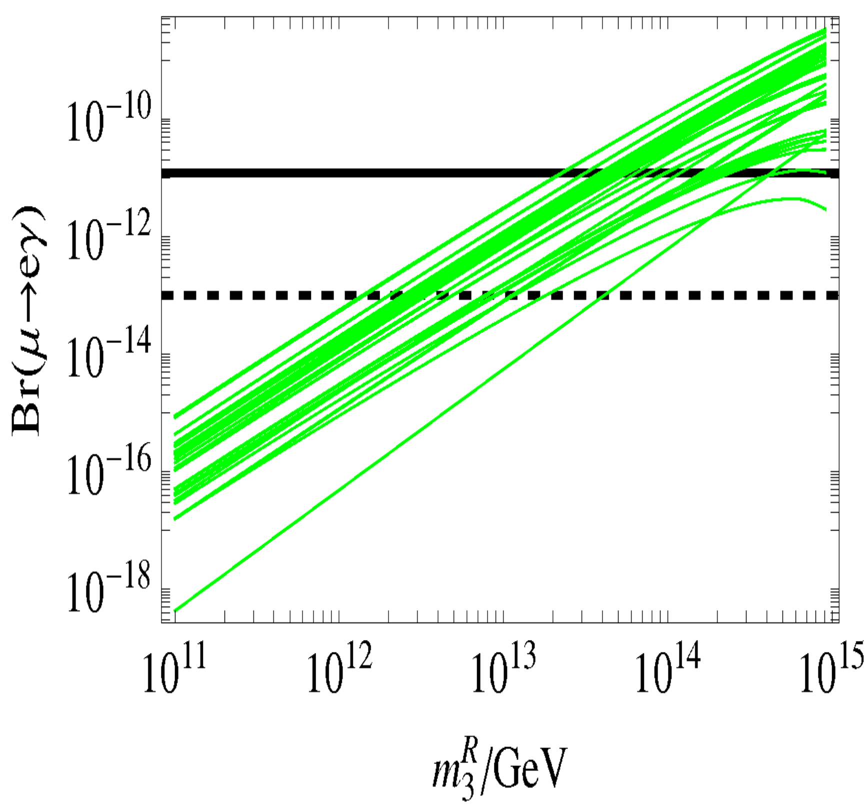
degenerate ν_R, $U_{\text{PMNS}} = U_{\text{TBM}}$, $R = \mathbb{1}$

SPS1a' ($M_0 = 70$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, $\mu > 0$)

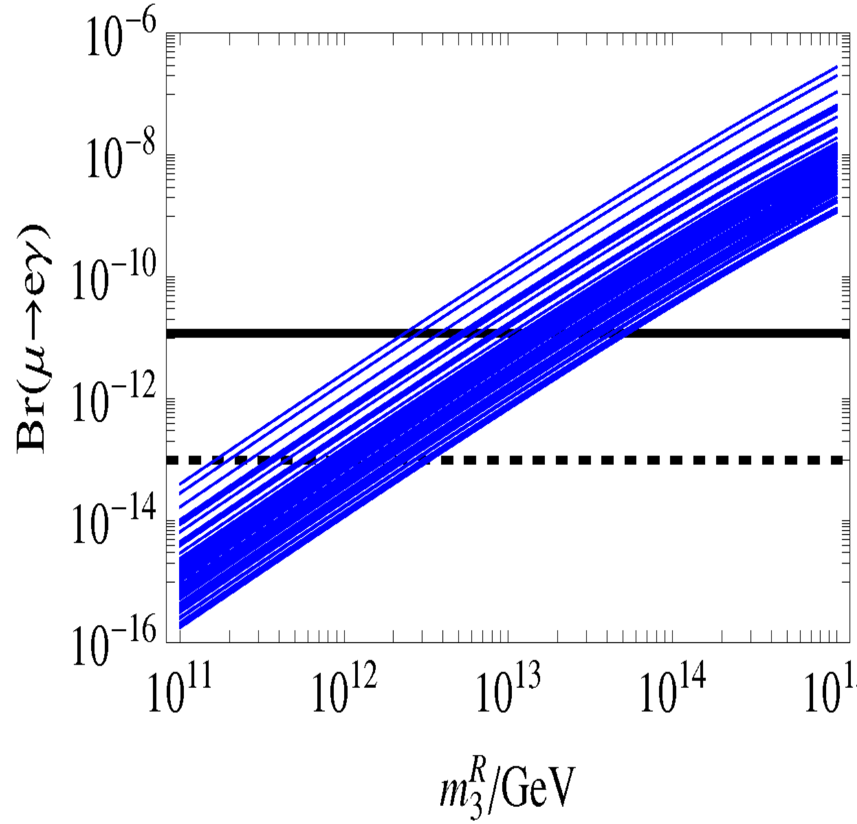
M. Hirsch, J. W. F. Valle, W.P., J. C. Romão and A. Villanova del Moral, arXiv:0804.4072

Texture models, hierarchical ν_R

real textures



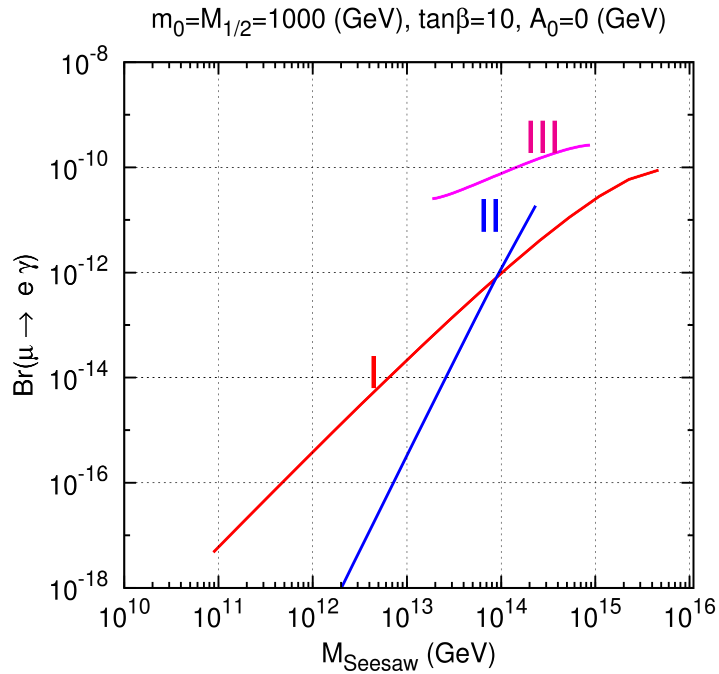
"complexification" of one texture

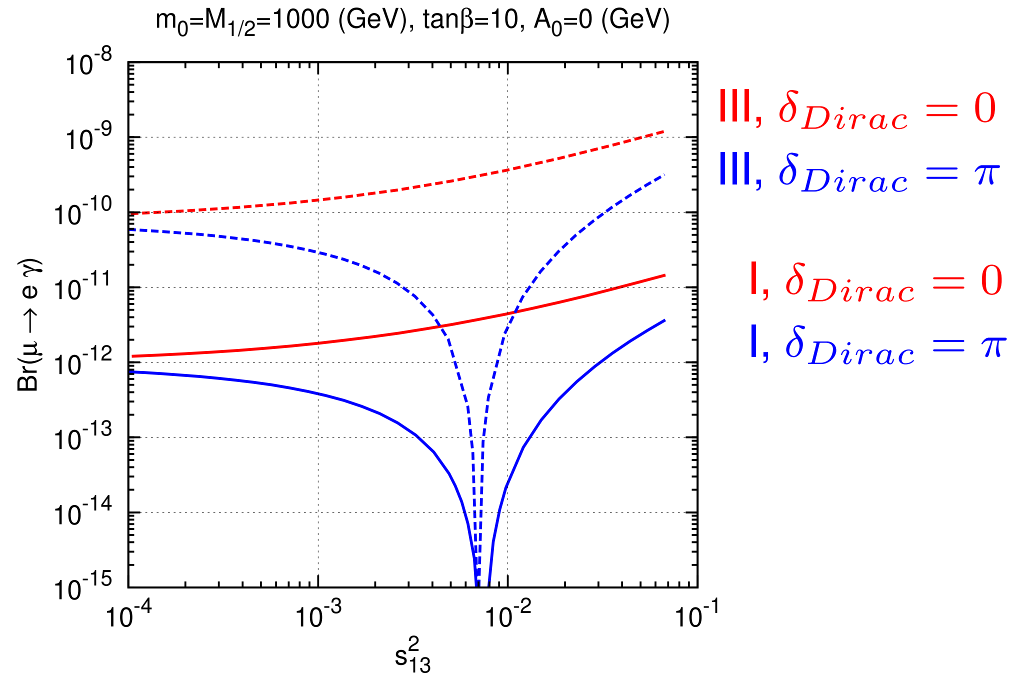


SPS1a' ($M_0 = 70$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, $\mu > 0$)

F. Deppisch, F. Plentinger, G. Seidl, arXiv:1011.1404

Seesaw I, II & III in comparison

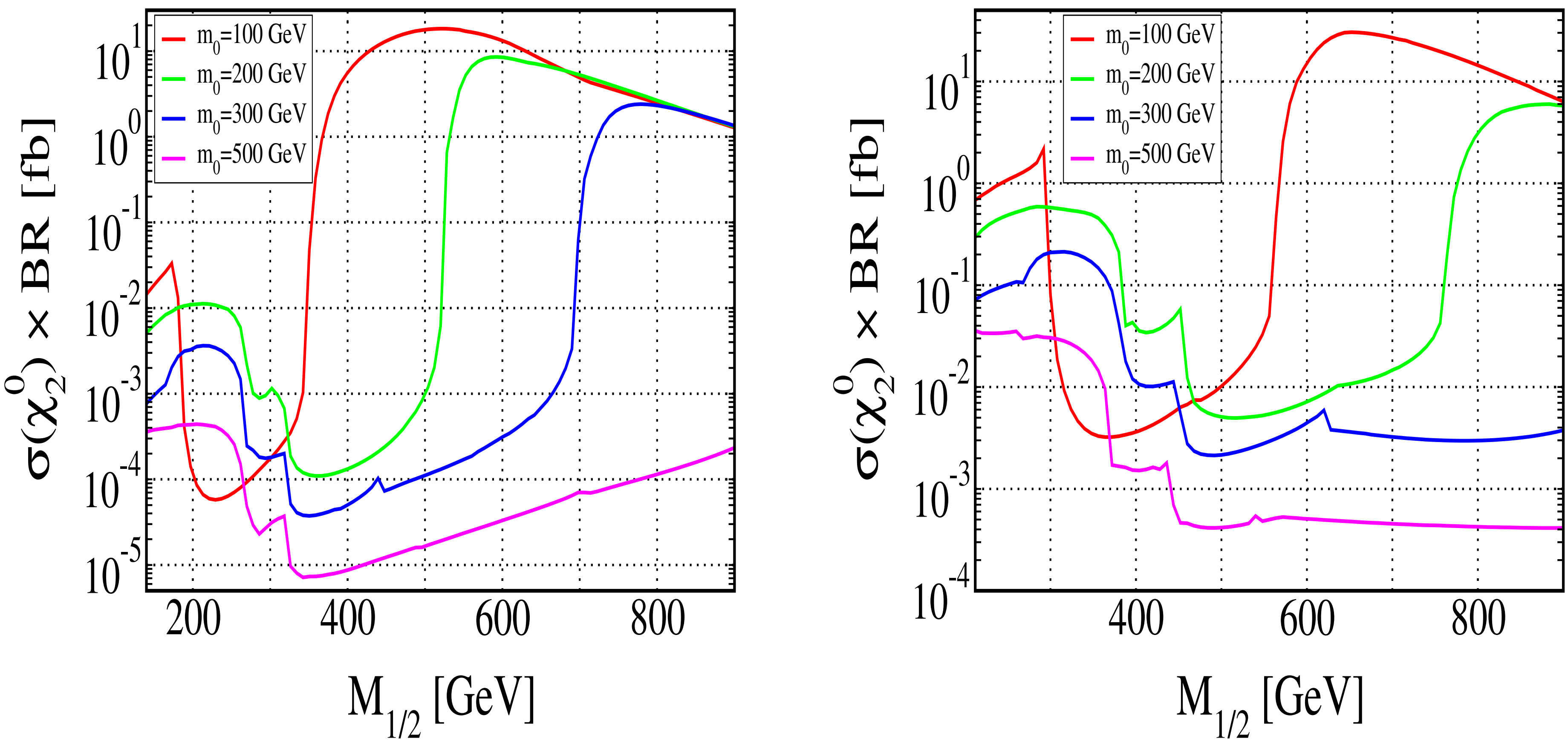




degenerate spectrum of the seesaw particles, $M_{seesaw} = 10^{14}$ GeV

J. Esteves, M.Hirsch, J. Romão, W.P., F. Staub, arXiv:1010.6000

Seesaw I + II, signal at LHC



$\sigma(pp \to \tilde{\chi}_2^0) \times BR(\chi_2^0 \to \sum_{i,j} \tilde{l}_i l_j \to \mu^{\pm}\tau^{\mp}\tilde{\chi}_1^0)$

$A_0 = 0$, $\tan\beta = 10$, $\mu > 0$ (Seesaw II: $\lambda_1 = 0.02$, $\lambda_2 = 0.5$)

J. N. Esteves, J. C. Romão, A. Villanova del Moral, M. Hirsch, J. W. F. Valle, W.P., arXiv:0903.1408

Extended gauge groups, motivation

- Origin of R-parity $R_P = (-1)^{2s+3(B-L)}$

  $\Rightarrow SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  $\to SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
  $\cong SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$
  or $E(8) \times E(8) \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

- Neutrino masses

  $B - L$ anomaly free $\Rightarrow \nu_R$
  usual seesaw, inverse seesaw

- low scale realisations:
  - additional D-term contributions to m_h at tree-level,
    extra $U(1)_\chi$ with new D-term contributions at tree-level: $m^2_{h,tree} \leq m^2_Z + \frac{1}{4} g^2_\chi v^2$
  - $\tilde{\nu}_R$ or other exotic neutral scalar as DM candidate
    $\Rightarrow$ interesting for (modified) Natural SUSY

$SO(10)$ left-right symmetric inspired model

Superfield	generations	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
Q	3	3	2	1	$\frac{1}{3}$
Q^c	3	$\bar{3}$	1	2	$-\frac{1}{3}$
L	3	1	2	1	-1
L^c	3	1	1	2	1
Φ	2	1	2	2	0
Δ	1	1	3	1	2
$\bar{\Delta}$	1	1	3	1	-2
Δ^c	1	1	1	3	-2
$\bar{\Delta}^c$	1	1	1	3	2
Ω	1	1	3	1	0
Ω^c	1	1	1	3	0

$$\begin{aligned} \mathcal{W} &= Y_Q Q\Phi Q^c + Y_L L\Phi L^c - \frac{\mu}{2}\Phi\Phi + f L\Delta L + f_c L^c\Delta^c L^c + a\Delta\Omega\bar{\Delta} + a^*\Delta^c\Omega^c\bar{\Delta}^c \\ &+ \alpha\Omega\Phi\Phi + \alpha^*\Omega^c\Phi\Phi + M_\Delta\Delta\bar{\Delta} + M_\Delta^*\Delta^c\bar{\Delta}^c + M_\Omega\Omega\Omega + M_\Omega^*\Omega^c\Omega^c\,. \end{aligned}$$

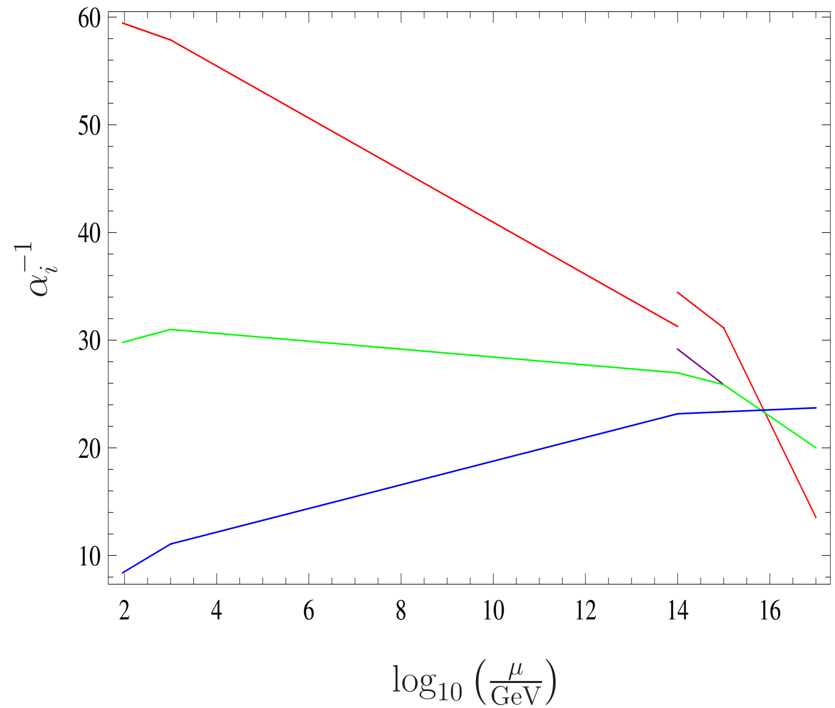
J.N. Esteves, J.C. Romão, M. Hirsch, A. Vicente, W.P., F. Staub, arXiv:1011.0348

Below $SO(10)$ scale

at the $SU(2)_R$ breaking scale v_R

$$
\begin{aligned}
Y_d &= Y_Q^1 \cos\theta_1 - Y_Q^2 \sin\theta_1 \\
Y_u &= -Y_Q^1 \cos\theta_2 + Y_Q^2 \sin\theta_2 \\
Y_e &= Y_L^1 \cos\theta_1 - Y_L^2 \sin\theta_1 \\
Y_\nu &= -Y_L^1 \cos\theta_2 + Y_L^2 \sin\theta_2
\end{aligned}
$$

at $B-L$ breaking scale v_{B-L}:
ν-masses: mainly seesaw I
ν_R-masses: $f_c v_{BL}, m_{\nu_R,1} := M_S$



J.N. Esteves, J.C. Romão, M. Hirsch, A. Vicente, W.P., F. Staub, arXiv:1109.6478

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\end{aligned}
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at $B-L$ breaking scale v_{B-L}:
ν-masses: mainly seesaw I
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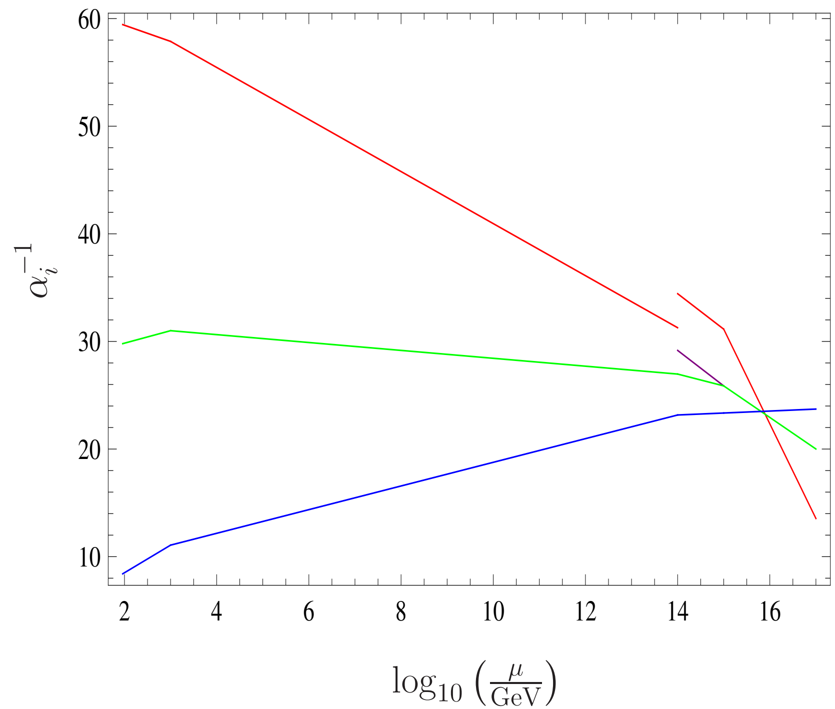
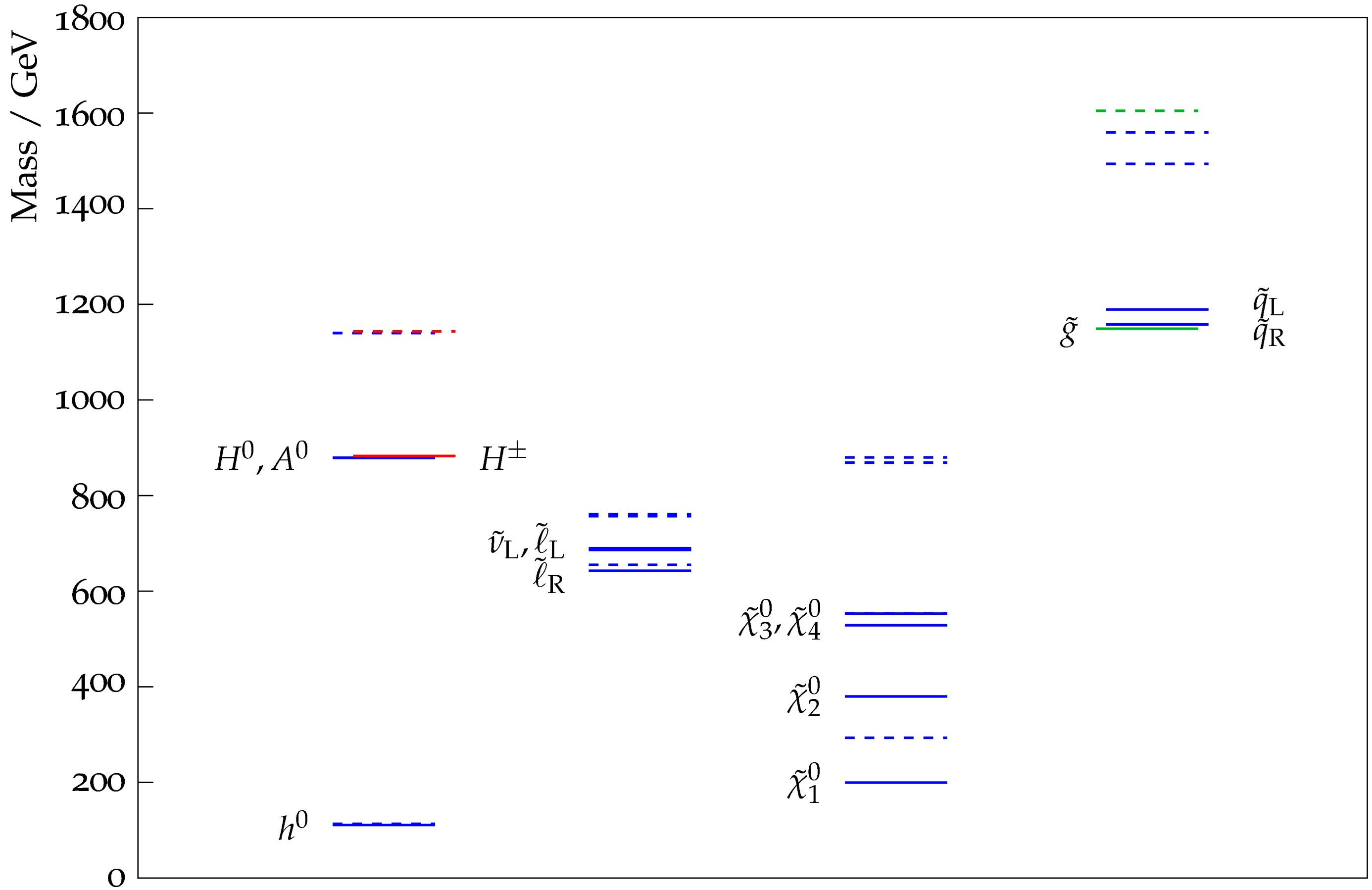


J.N. Esteves, J.C. Romão, M. Hirsch, A. Vicente, W.P., F. Staub, arXiv:1109.6478

$$
\begin{aligned}
(m_L^2)_{ij}|_{v_R} &= -\frac{1}{4\pi^2}\left(3ff^\dagger + \sum_{k=1}^{2} Y_L^{(k)} Y_L^{(k)\,\dagger}\right)_{ij} (3m_0^2 + A_0^2)\ln\left(\frac{m_{GUT}}{v_R}\right), \\
(m_{e^c}^2)_{ij}|_{v_R} &= -\frac{1}{4\pi^2}\left(3f^\dagger f + \sum_{k=1}^{2} Y_L^{(k)\,\dagger} Y_L^{(k)}\right)_{ij} (3m_0^2 + A_0^2)\ln\left(\frac{m_{GUT}}{v_R}\right)
\end{aligned}
$$

Example spectrum



$m_0 = 600$ GeV, $M_{1/2} = 700$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$ and $v_R = v_{BL} = 10^{14}$ GeV
full lines: LR-mdoel, dashed line pure CMSSM

J.N. Esteves, J.C. Romão, M. Hirsch, A. Vicente, W.P., F. Staub, arXiv:1011.0348

LFV decays

$$A_L^{ij} \sim \frac{(m_L^2)_{ij}}{m_{SUSY}^4} \quad , \quad A_R^{ij} \sim \frac{(m_{e^c}^2)_{ij}}{m_{SUSY}^4}$$

$$BR(l_i \to l_j \gamma) \propto \left(|A_L^{ij}|^2 + |A_R^{ij}|^2 \right)$$

LFV decays

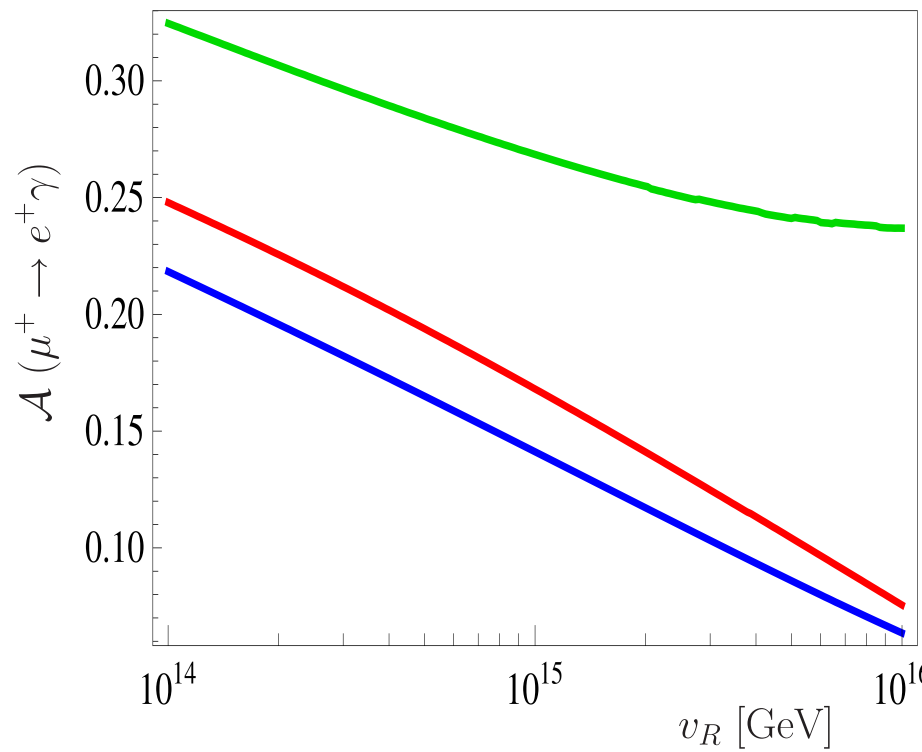
$$A_L^{ij} \sim \frac{(m_L^2)_{ij}}{m_{SUSY}^4} \quad , \quad A_R^{ij} \sim \frac{(m_{e^c}^2)_{ij}}{m_{SUSY}^4}$$

$$BR(l_i \to l_j \gamma) \propto \left(|A_L^{ij}|^2 + |A_R^{ij}|^2 \right)$$

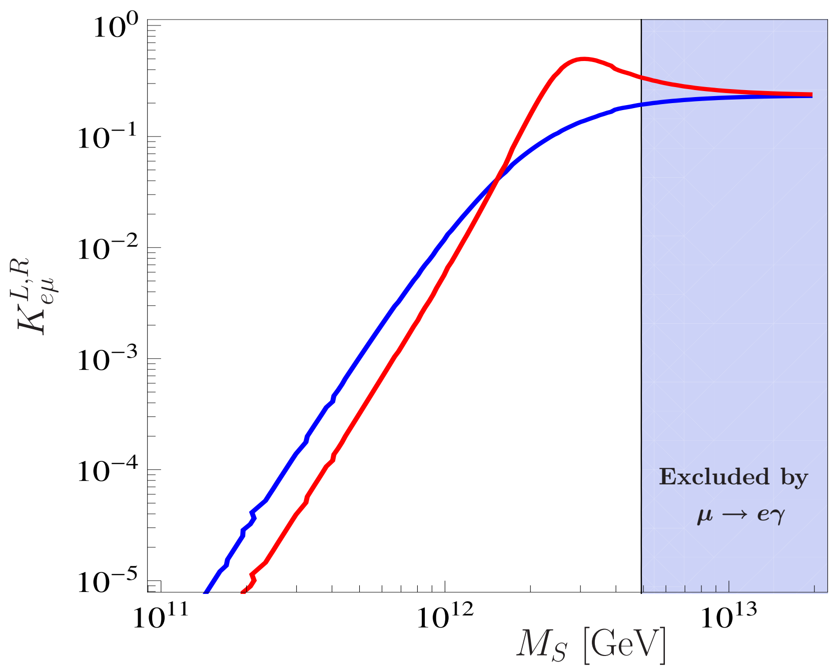
polarisation asymmetry

$$A_{LR} = \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2}$$

blue SPS1a', green SPS3, red SPS5



J.N. Esteves, J.C. Romão, M. Hirsch, A. Vicente, W.P., F. Staub, arXiv:1011.0348



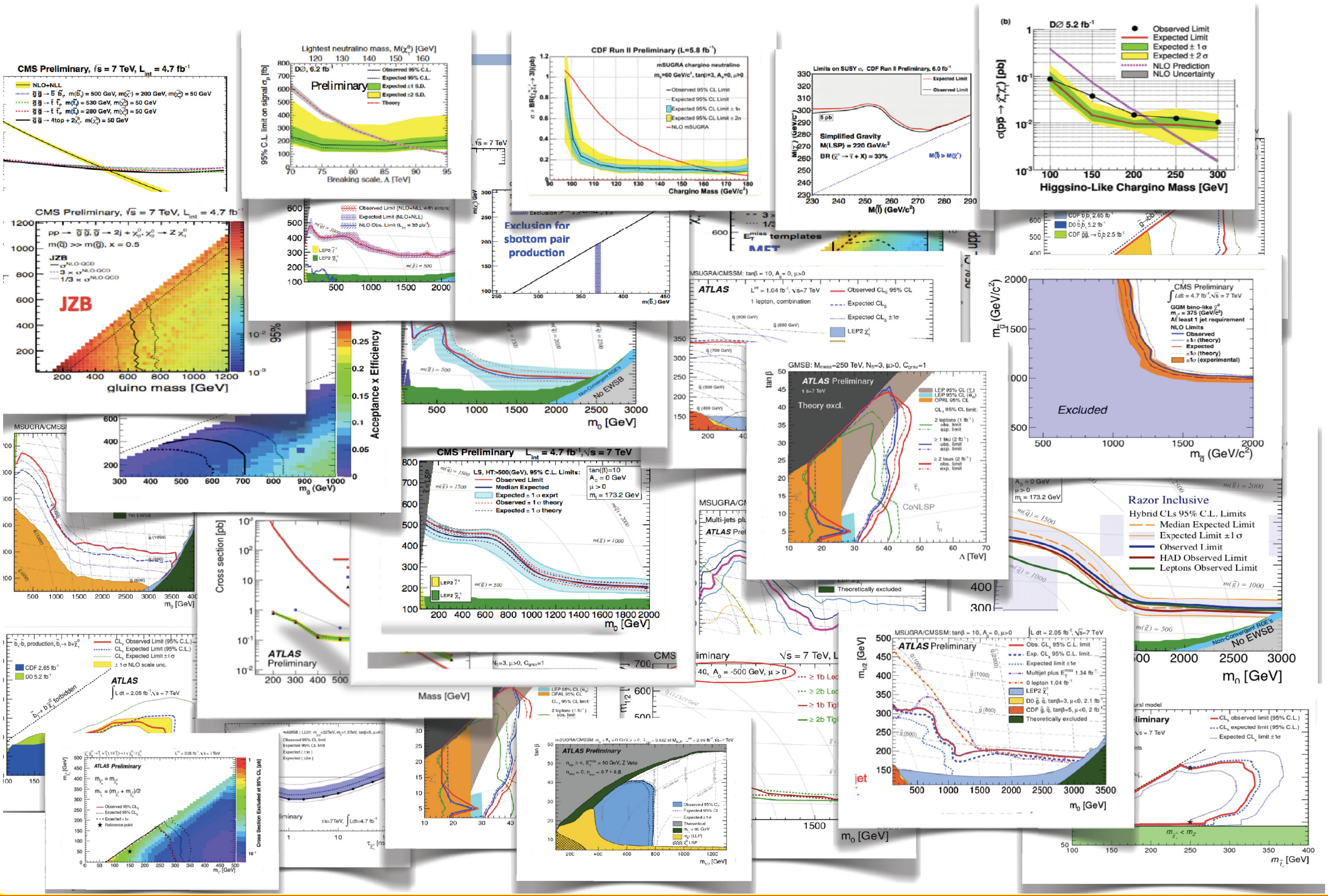
$$K_{e\mu} = \frac{BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 e\mu)}{BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 ee) + BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \mu\mu)}$$

$K_{e\mu}^L$: contributions via L-sleptons
$K_{e\mu}^R$: contributions via R-sleptons
assumption $m(\tilde{\chi}_2^0) > m(\tilde{l}_i) > m(\tilde{\chi}_1^0)$;
data point SPS3

J.N. Esteves, J.C. Romão, M. Hirsch, A. Vicente, W.P., F. Staub, arXiv:1011.0348

CMS studies: depending on the spectrum $K_{e\mu} > 0.04$ detectable for $\mathcal{L} = 10$ fb^{-1} at $\sqrt{s} = 14$ TeV

BSM searches, so far hardly anything ...



Natural SUSY + $\tilde{\nu}_R$: minimal inverse seesaw model

Natural SUSY: 100 GeV$\leq \mu \leq 500$ GeV, squarks except $\tilde{t}$ few TeV, $m_{\tilde{g}} \simeq 1-2$ TeV

$$\mathcal{W}_{eff} = \mathcal{W}_{\mathrm{MSSM}} + \frac{1}{2}(M_R)_{ij}\,\hat{\nu}_{R,i}\,\hat{\nu}_{R,j} + (Y_\nu)_{ij}\,\widehat{L}_i \cdot \widehat{H}_u\,\hat{\nu}_{R,j}$$

$$(Y_\nu)_{\ell 5} = \pm (Z_\ell^{\mathrm{NH}})^* \sqrt{\frac{2m_3 M_5}{v_u}} \cosh\gamma_{56}\, e^{\mp i\theta_{56}}$$

$$(Y_\nu)_{\ell 6} = -i (Z_\ell^{\mathrm{NH}})^* \sqrt{\frac{2m_3 M_6}{v_u}} \cosh\gamma_{56}\, e^{\mp i\theta_{56}}$$

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi_{56} & \sin\phi_{56} \\ 0 & -\sin\phi_{56} & \cos\phi_{56} \end{pmatrix}$$

$\phi_{56} \in \mathbb{C}$

$m_{\nu_h,i} \simeq M_{i-3}$, $M_4 = O$(keV),
$M_5 \simeq M_6 = O$(few - 100 GeV)

Natural SUSY + $\tilde{\nu}_R$: minimal inverse seesaw model

Natural SUSY: 100 GeV$\leq \mu \leq 500$ GeV, squarks except $\tilde{t}$ few TeV, $m_{\tilde{g}} \simeq 1-2$ TeV

$$\mathcal{W}_{eff} = \mathcal{W}_{\mathrm{MSSM}} + \frac{1}{2}(M_R)_{ij}\,\hat{\nu}_{R,i}\,\hat{\nu}_{R,j} + (Y_\nu)_{ij}\,\widehat{L}_i \cdot \widehat{H}_u\,\hat{\nu}_{R,j}$$

$$(Y_\nu)_{\ell 5} = \pm (Z_\ell^{\mathrm{NH}})^* \sqrt{\frac{2 m_3 M_5}{v_u}} \cosh\gamma_{56}\, e^{\mp i\theta_{56}}$$

$$(Y_\nu)_{\ell 6} = -i (Z_\ell^{\mathrm{NH}})^* \sqrt{\frac{2 m_3 M_6}{v_u}} \cosh\gamma_{56}\, e^{\mp i\theta_{56}}$$

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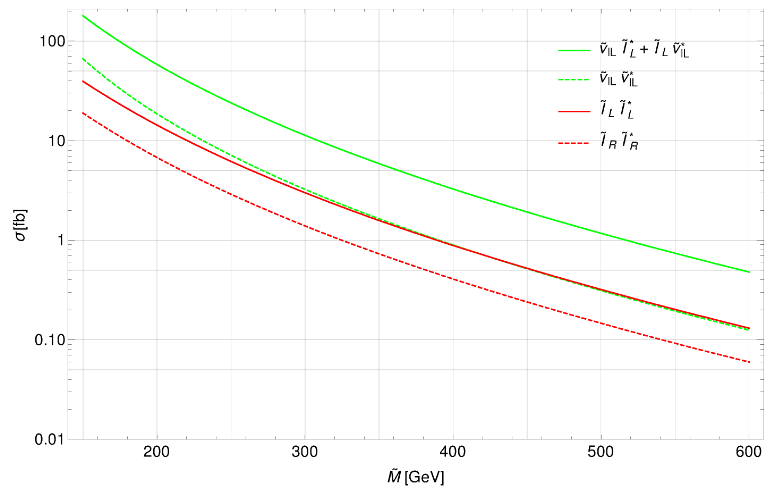
$\phi_{56} \in \mathbb{C}$

$m_{\nu_h,i} \simeq M_{i-3}$, $M_4 = O($keV$)$,
$M_5 \simeq M_6 = O($few - 100 GeV$)$

search for sleptons

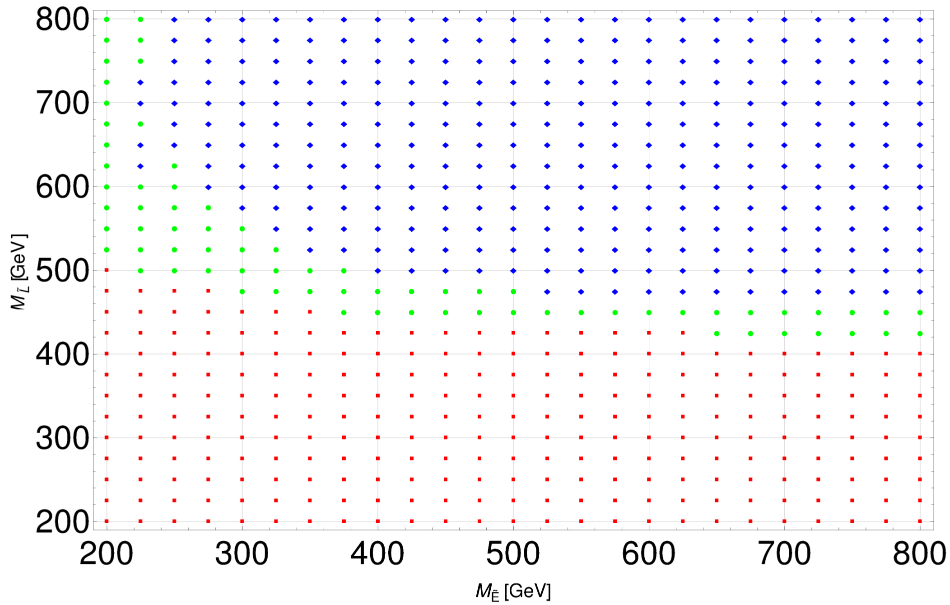


LHC, 13 TeV, tree-level
for searches: $\times$ K-factor 1.17
(B. Fuks et al., arXiv:1304.0790)

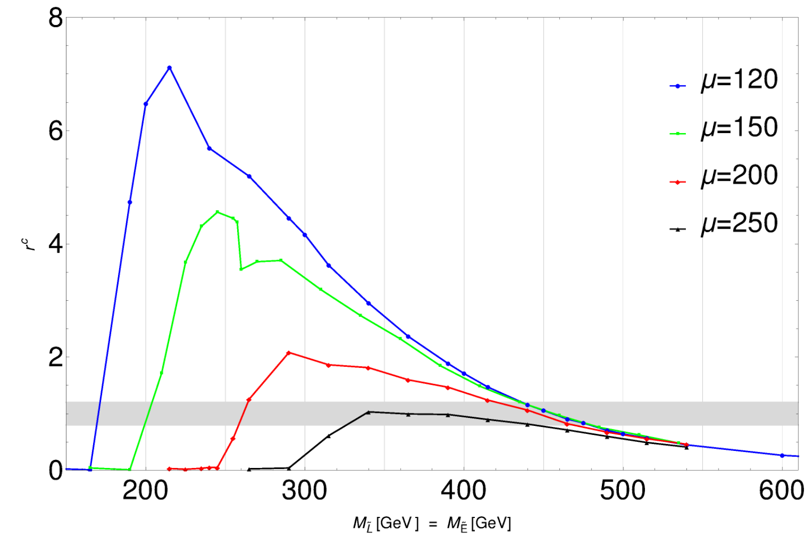
dominant decays:

$$\tilde{l}_L \to l\tilde{\chi}^0_1\ ,\ \nu\tilde{\chi}^-_1$$
$$\tilde{\nu}_L \to l^-\tilde{\chi}^+_1\ ,\ \nu\tilde{\chi}^0_1$$

Natural SUSY + $\tilde{\nu}_R$: Higgsino LSP



$\mu = 120$ GeV, $\tan\beta = 10$



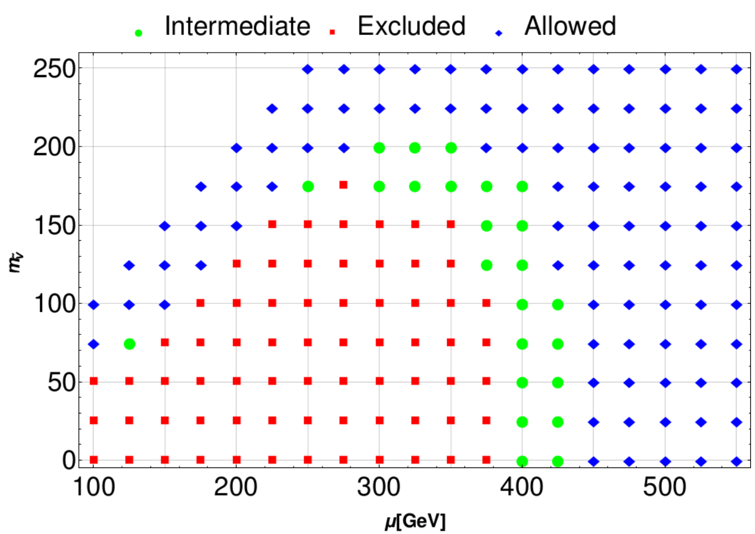
$M_{\tilde{L}} = M_{\tilde{E}}$, $\tan\beta = 10$

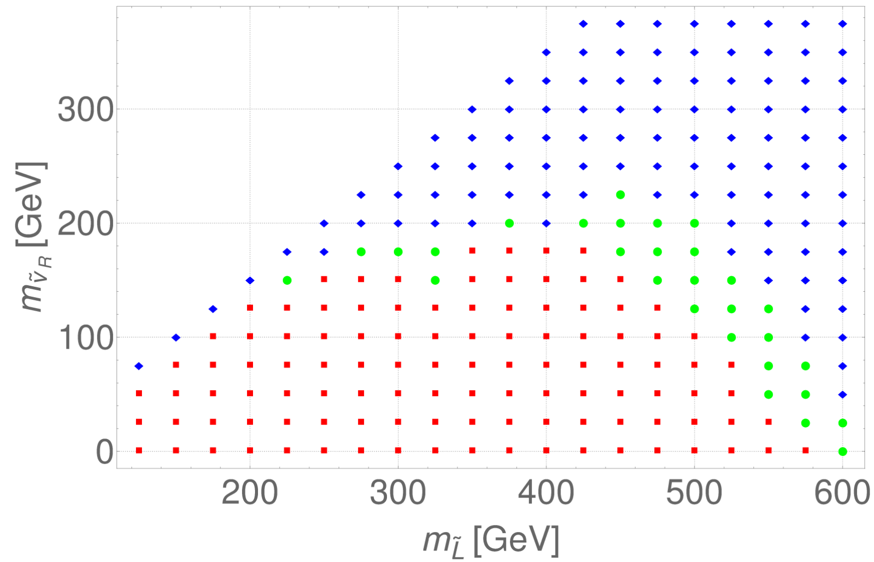
■ excluded, ● ambigous, ◇ allowed

8+13 TeV data (13.9 fb^{-1})

using `CheckMATE 2.0` Th. Faber, J. Jones, Nh. Cerna-Velazco, WP arXiv:1705.06583 additional constraint

$$pp \to \tilde\chi_1^+ \tilde\chi_1^- \to \ell^+ \ell^- \tilde\nu_R \tilde\nu_R^*$$





8+13 TeV data (13.9 fb^{-1})

using `CheckMATE 2.0`

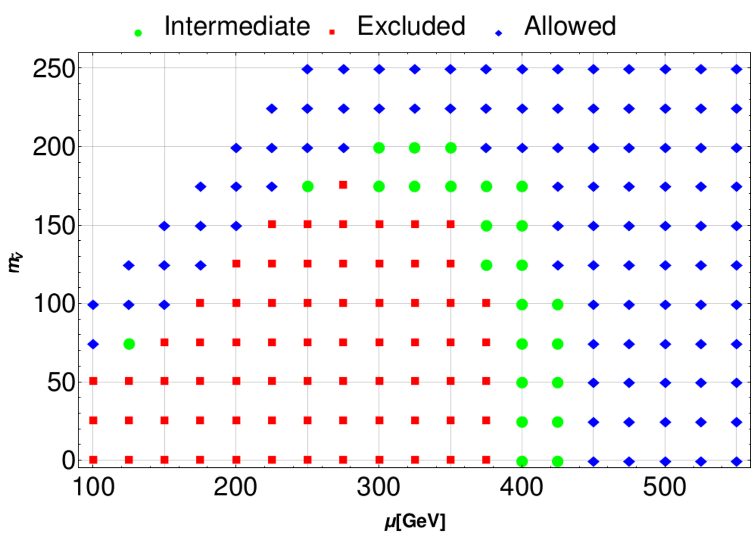
$$\mu = 25 + m_{\tilde\nu} < m_{\tilde l} = M_{\tilde L} = M_{\tilde E}$$

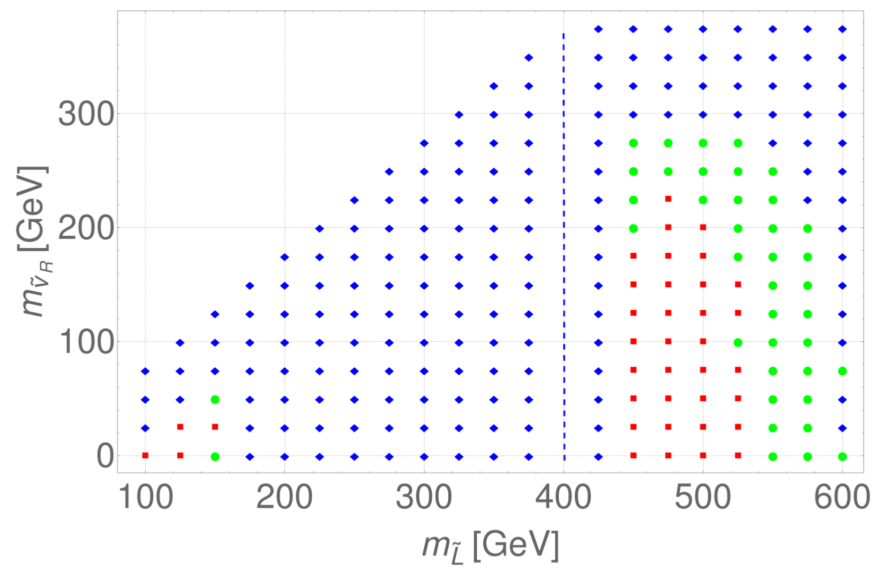
Th. Faber, J. Jones, Nh. Cerna-Velazco, WP arXiv:1705.06583

Natural SUSY + $\tilde{\nu}_R$: $\tilde{\nu}_R$-LSP

additional constraint

$$pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \ell^+ \ell^- \tilde{\nu}_R \tilde{\nu}_R^*$$





8+13 TeV data (13.9 fb^{-1}) $\mu = 400$ GeV

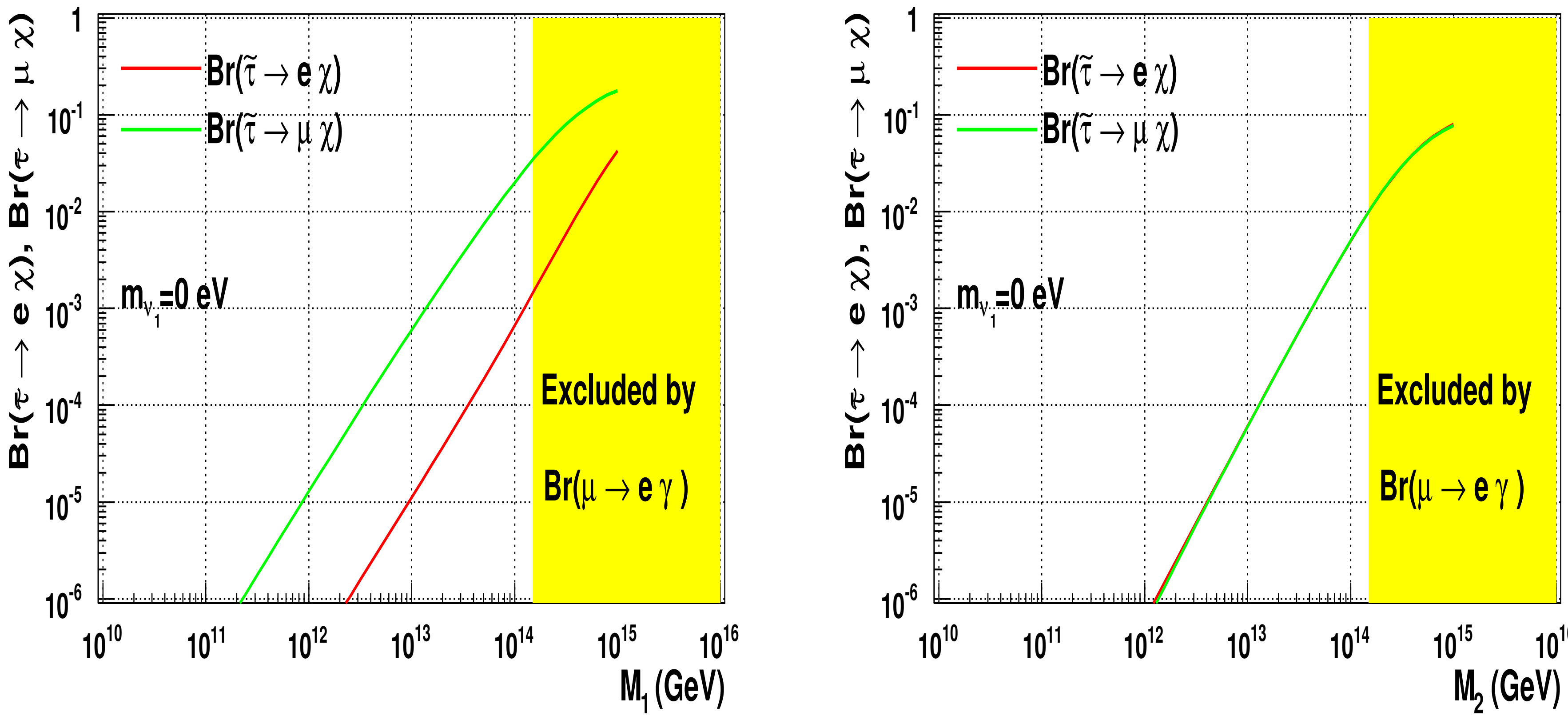
using `CheckMATE 2.0` Th. Faber, J. Jones, Nh. Cerna-Velazco, WP arXiv:1705.06583

Final remark

No signs for physics beyond the SM

But the hunt still continues, both at low energy experiments and the LHC

Seesaw I



degenerate ν_R

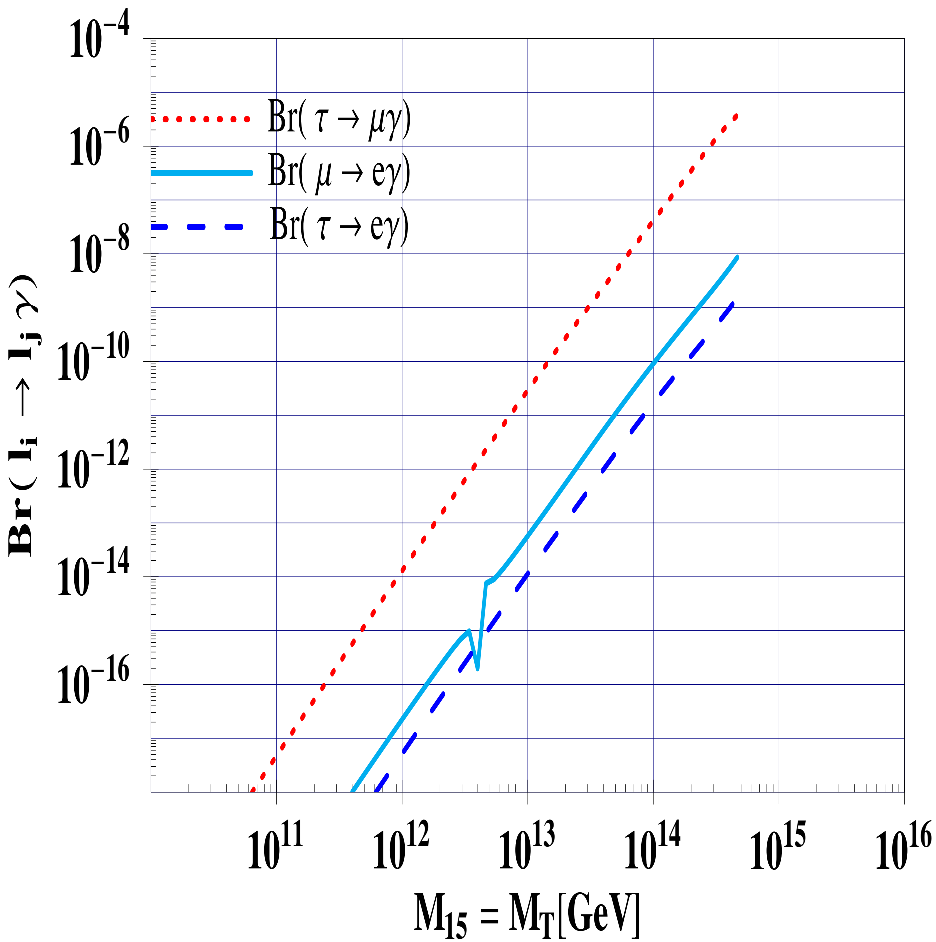
hierarchical ν_R

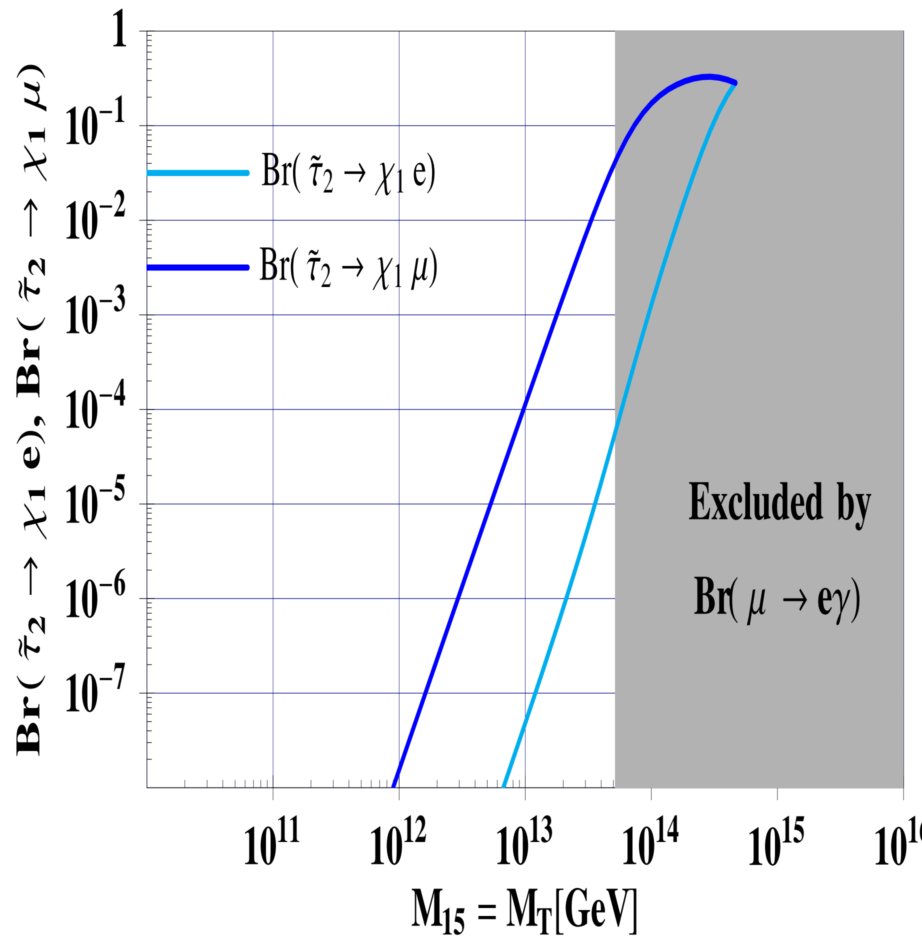
($M_1 = M_3 = 10^{10}$ GeV)

SPS3 ($M_0 = 90$ GeV, $M_{1/2} = 400$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, $\mu > 0$)

M. Hirsch et al. Phys. Rev. D **78** (2008) 013006

Seesaw II with a pair of 15-plets





$\lambda_1 = \lambda_2 = 0.5$

SPS3 ($M_0 = 90$ GeV, $M_{1/2} = 400$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, $\mu > 0$)

M. Hirsch, S. Kaneko, W. P., Phys. Rev. D **78** (2008) 093004.