Testing the flavour sector of SUSY models @ LHC

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Overview

- Flavour, Generalities
- LFV signals in models with
  - Dirac neutrinos
  - Majorana neutrinos
  - General MSSM + extensions
- Squark flavour at LHC
- Conclusions

More in: F. del Aguila *et al.*, EPJC **57** (2008) 183 [arXiv:0801.1800]

Supersymmetry, MSSM

	Standard Model		MSSM
matter:	e d d d	$\Leftrightarrow$	$\tilde{e}$ $\tilde{d}$ $\tilde{d}$ $\tilde{d}$
	ν_e u u u		$\tilde{\nu}_e$ $\tilde{u}$ $\tilde{u}$ $\tilde{u}$
gauge sector:	γ Z^0 $W^\pm$ g	$\Leftrightarrow$	$\tilde{\gamma}$ $\tilde{z}^0$ $\tilde{w}^\pm$ $\tilde{g}$
Higgs sector:	h^0 H^0 A^0 $H^\pm$	$\Leftrightarrow$	$\tilde{h}^0_d$ $\tilde{h}^0_u$ $\tilde{h}^\pm$

assume conserved R-Parity: $(-1)^{(3(B-L)+2s)}$

$(\tilde{\gamma}, \tilde{z}^0, \tilde{h}^0_d, \tilde{h}^0_u) \rightarrow \tilde{\chi}^0_i$, $(\tilde{w}^\pm, \tilde{h}^\pm) \rightarrow \tilde{\chi}^\pm_j$

Flavour, Generalities

- SM: Higgs doublet + Yukawa couplings
  $\Rightarrow$ after EWSB, CKM- and PMNS matrices
  $\Rightarrow$ excellent agreement with data, e.g.
  - BR($b \to s\gamma$), BR($B_u^+ \to \tau^+\nu$), BR($B_s \to \mu^+\mu^-$), BR($B \to D\tau\nu$), BR($b \to s\mu^+\mu^-$), BR($B_d \to \mu^+\mu^-$), BR($B_d \to \mu^+\mu^-$), ΔM_{B_s}, ΔM_{B_d}
  - BR($D_s \to \tau\nu$), BR($D_s \to \mu\nu$), ΔM_D
  - BR($K \to \mu\nu$), BR($K_L^0 \to \pi^0\nu\nu$), BR($K^+ \to \pi^+\nu\nu$), Δm_K, ϵ_K
  - $BR(\tau \to e\gamma)$, $BR(\tau \to \mu\gamma)$, $BR(\tau \to lll')$ $(l, l' = e, \mu)$
  - $BR(\mu \to e\gamma)$, $BR(\mu^- \to e^-e^+e^-)$
  - electric dipolemoments, e.g. d_n, d_e

  However: no clue what determines sizes of masses and mixing angles
- Supersymmetry, e.g. MSSM

$$\begin{aligned} W_{MSSM} &= \hat{H}_d\hat{L}Y_e\hat{E}^C + \hat{H}_d\hat{Q}Y_d\hat{D}^C + \hat{H}_u\hat{Q}Y_u\hat{U}^C - \mu\hat{H}_d\hat{H}_u \\ V_{soft} &= H_d\tilde{L}T_e\tilde{e}^* + H_d\tilde{Q}T_d\tilde{d}^* + H_u\tilde{Q}T_u\tilde{u}^* \\ &+ \sum_{\tilde{f}=\tilde{L},\tilde{e},\tilde{Q},\tilde{d},\tilde{u}} \tilde{f}^* M_{\tilde{f}}^2 \tilde{f} + M_{H_d}^2|H_u|^2 + M_{H_u}^2|H_u|^2 - B\mu H_d H_u \end{aligned}$$

Flavour, Generalities

- Pragmatic approach, Minimal Flavour Violation[†]
  express all additional flavour structures in terms of 'known' Yukawas
  e.g. at some (high) scale

$$T_f = A_{0,f} Y_f \ , \ M^2_{\tilde{f}} = M^2_{0,f} \mathbf{1}_3 + \alpha Y_f^\dagger Y_f$$

  where $A_{0,f}$ and $M^2_{0,f}$ are scalars
  generic prediction for squarks*: FV decays are governed by $|V_{CKM,ij}|^2$, e.g.

$$\begin{aligned} BR(\tilde{t} \to \tilde{\chi}^+_1 s) &\simeq |V_{CKM,ts}|^2 BR(\tilde{t} \to \tilde{\chi}^+_1 s) \\ BR(\tilde{t} \to \tilde{\chi}^0_{1,2} c) &\lesssim 10^{-7} \end{aligned}$$

  Sleptons: depend on mechanism for neutrino masses

† A.J. Buras et al., PLB **500** (2001) 161; G. D'Ambrosio et al., NPB **645** (2002) 155
* E. Lunghi, W.P., O. Vives, PRD **74** (2006) 075003

Flavour, Generalities

- more ambitious: new symmetries, e.g. Abelian or non-Abelian, gauge or discrete ...
  $SU(3)$ flavour example*

$$W_Y = H\psi_i\psi^c_j\left[\theta^i_3\theta^j_3 + \theta^i_{23}\theta^j_{23}\left(\theta_3\overline{\theta}_3\right) + \epsilon^{ikl}\overline{\theta}_{23,k}\overline{\theta}_{3,l}\theta^j_{23}\left(\theta_{23}\overline{\theta}_3\right) + \ldots\right],$$

$$Y_d \propto \begin{pmatrix} 0 & x^d_{12}\,\bar{\varepsilon}^3 & x^d_{13}\,\bar{\varepsilon}^3 \\ x^d_{12}\,\bar{\varepsilon}^3 & \bar{\varepsilon}^2 & x^d_{23}\,\bar{\varepsilon}^2 \\ x^d_{13}\,\bar{\varepsilon}^3 & x^d_{23}\,\bar{\varepsilon}^2 & 1 \end{pmatrix}, \quad Y_u \propto \begin{pmatrix} 0 & x^u_{12}\,\varepsilon^3 & x^u_{13}\,\varepsilon^3 \\ x^u_{12}\,\varepsilon^3 & \varepsilon^2 & x^u_{23}\,\varepsilon^2 \\ x^u_{13}\,\varepsilon^3 & x^u_{23}\,\varepsilon^2 & 1 \end{pmatrix},$$

$$(M^2_{\tilde{f}})^j_i = m^2_0\Big(\delta^j_i + \frac{1}{M^2_f}\left[\theta^\dagger_{3\,i}\theta^j_3 + \overline{\theta}_{3,i}\overline{\theta}^{\dagger\,j}_3 + \theta^\dagger_{23\,i}\theta^j_{23} + \overline{\theta}_{23,i}\overline{\theta}^{\dagger\,j}_{23} + \theta^\dagger_{123\,i}\theta^j_{123} + \overline{\theta}_{123,i}\overline{\theta}^{\dagger\,j}_{123}\right] + \frac{1}{M^4_f}(\epsilon_{ikl}\overline{\theta}^{\dagger\,k}_3\overline{\theta}^{\dagger\,l}_{23})(\epsilon^{jmn}\overline{\theta}_{3,m}\overline{\theta}_{23,n}) + \ldots\Big)$$

LHC: similar to MFV approach although somewhat larger effects

* G.G. Ross, L. Velasco-Sevilla, O. Vives, NPB **692**, 50 (2004); L. Calibbi, J. Jones-Perez, O. Vives, PRD **78** (2008) 075007; L. Calibbi et al., NPB **831** (2010) 26

Lepton flavour violation, experimental data

Neutrinos: tiny masses

$\Delta m^2_{atm} \simeq 3 \cdot 10^{-3}$ eV^2

$\Delta m^2_{sol} \simeq 7 \cdot 10^{-5}$ eV^2

^{3}H decay: $m_\nu \lesssim 2$ eV

Neutrinos: large mixings

$|\tan\theta_{atm}|^2 \simeq 1$

$|\tan\theta_{sol}|^2 \simeq 0.4$

$|U_{e3}|^2 \lesssim 0.05$

strong bounds for charged leptons

$BR(\mu \to e\gamma) \lesssim 1.2 \cdot 10^{-11}$

$BR(\mu^- \to e^- e^+ e^-) \lesssim 10^{-12}$

$BR(\tau \to e\gamma) \lesssim 1.1 \cdot 10^{-7}$

$BR(\tau \to \mu\gamma) \lesssim 6.8 \cdot 10^{-8}$

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

$$|d_e| \lesssim 10^{-27}\ e\ cm,\ |d_\mu| \lesssim 1.5 \cdot 10^{-18}\ e\ cm,\ |d_\tau| \lesssim 1.5 \cdot 10^{-16}\ e\ cm$$

SUSY contributions to anomalous magnetic moments

$$|\Delta a_e| \leq 10^{-12},\ \ 0 \leq \Delta a_\mu \leq 43 \cdot 10^{-10},\ \ |\Delta a_\tau| \leq 0.058$$

Dirac neutrinos, MFV scenario

analog to leptons or quarks

$$Y_\nu \, H \, \bar\nu_L \, \nu_R \to Y_\nu \, v \, \bar\nu_L \, \nu_R = m_\nu \, \bar\nu_L \, \nu_R$$

requires $Y_\nu \ll Y_e$

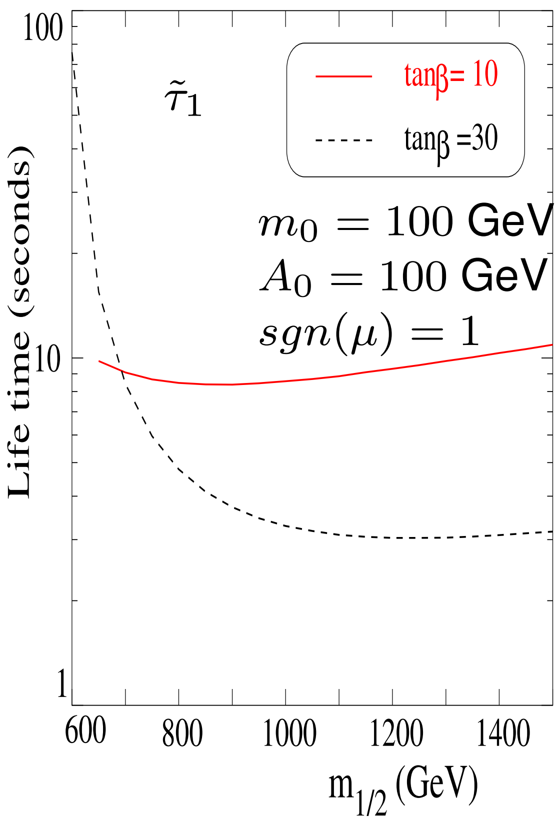
$\Rightarrow$ no impact for future collider experiments

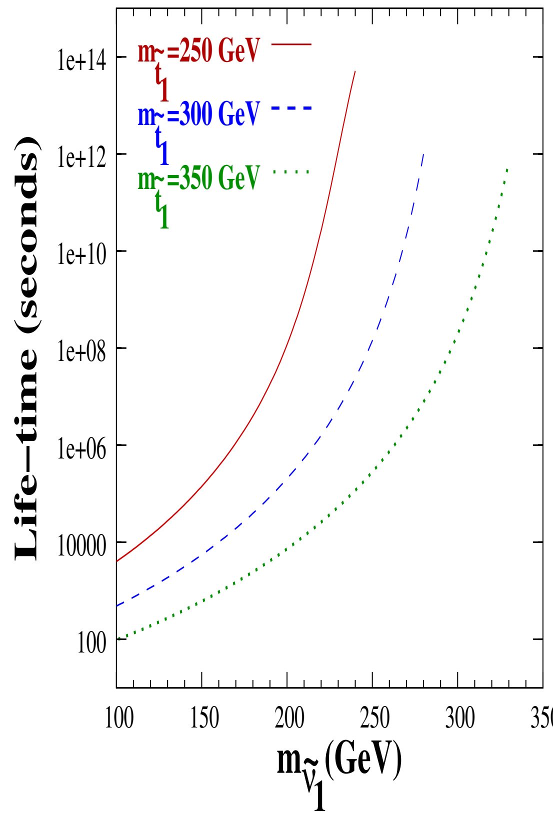
Exception: $\tilde\nu_R$ is LSP and thus a candidate for dark matter
$\Rightarrow$ long lived NLSP, e.g. $\tilde t_1 \to l^+ b \tilde\nu_R$

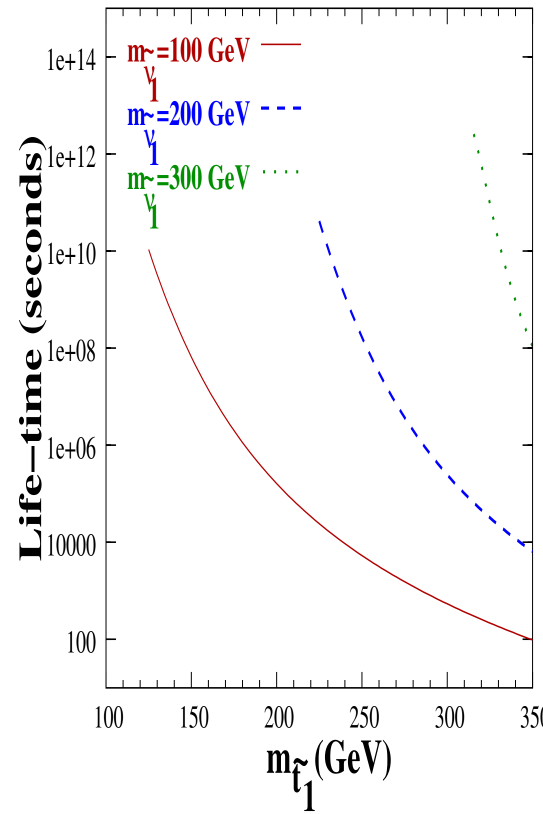
Remark: $m_{\tilde\nu_R}$ hardly runs $\Rightarrow$ e.g. $m_{\tilde\nu_R} \simeq m_0$ in mSUGRA
$m_{\tilde\nu_R} \simeq 0$ in GMSB

S. Gopalakrishna, A. de Gouvea and W. P., JCAP **0605** (2006) 005, JHEP **0611** (2006) 050

Dirac neutrinos, NLSP life times







general signature: two long lived particles + multi jets and/or multi lepton

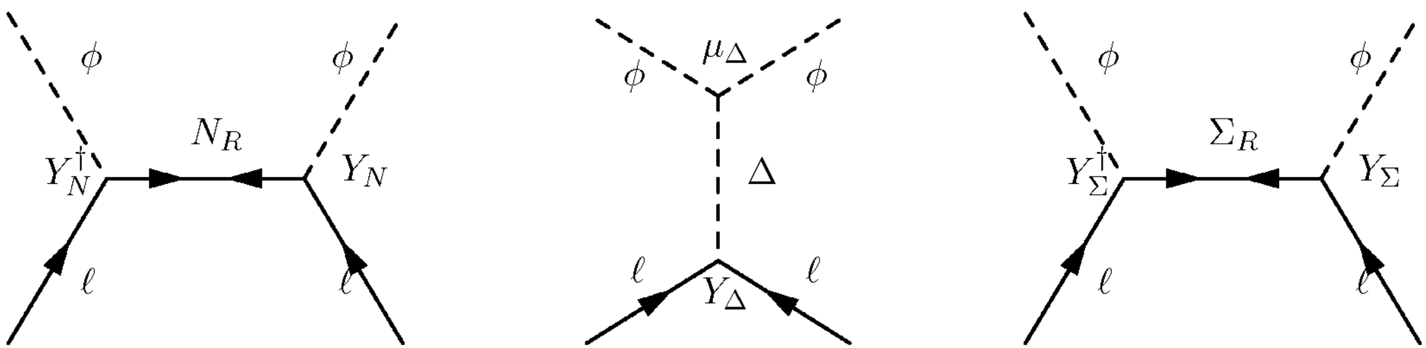
S. K. Gupta, B. Mukhopadhyaya, S. K. Rai, PRD **75** (2007) 075007

D. Choudhury, S. K. Gupta, B. Mukhopadhyaya, PRD **78** (2008) 015023

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

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

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

$$\overline{5}_M = (\widehat{D}^c, \widehat{L}),\; 10 = (\widehat{U}^c, \widehat{E}^c, \widehat{Q}),\; 5_H = (\widehat{H}^c, \widehat{H}_u),\; \overline{5}_H = (\widehat{\overline{H}}^c, \widehat{H}_d)$$

- The $\mathbf{15}$ decomposes as

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

- The $\mathbf{24}$ decomposes as

$$\mathbf{24}_M = \widehat{W}_M(1,3,0) + \widehat{B}_M(1,1,0) + \widehat{\overline{X}}_M(3,2,-\frac{5}{6}) + \widehat{X}_M(\overline{3},2,\frac{5}{6}) + \widehat{G}_M(8,1,0)$$

Seesaw I

Postulate very heavy right-handed neutrinos yielding the following superpotential 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} the superpotential reads

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

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

The effective mass matrix is

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

Note that

$$\hat{Y}_T = U^T \cdot Y_T \cdot U \ ,$$

Seesaw III

In the $SU(5)$ broken phase the superpotential becomes

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

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 decomposition for Y_W as in type-I up to factor $4/5$

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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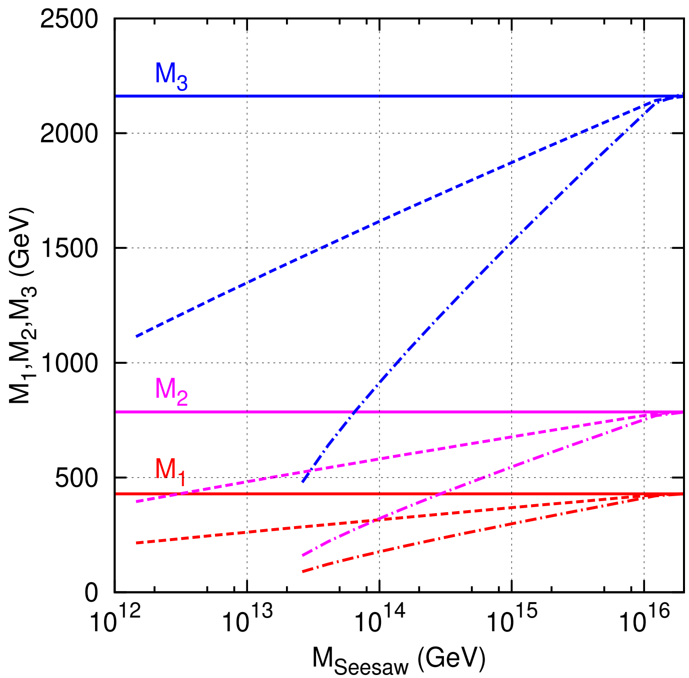
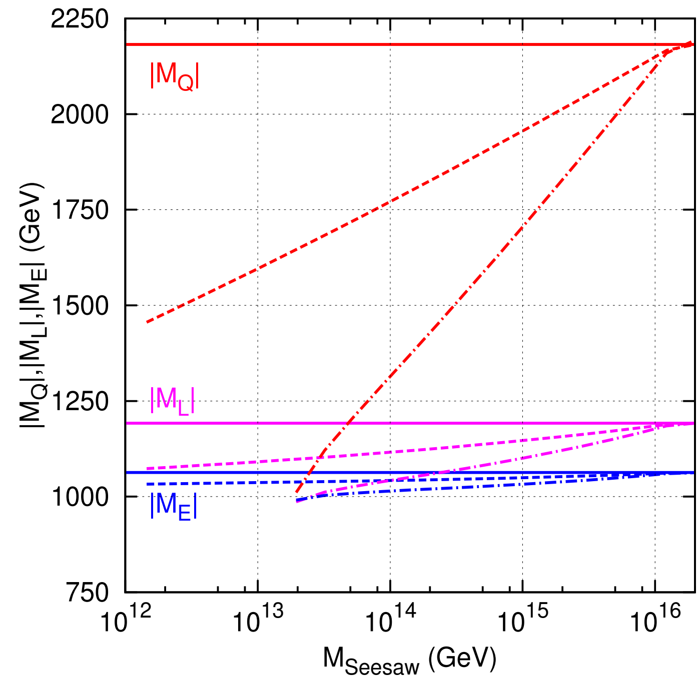


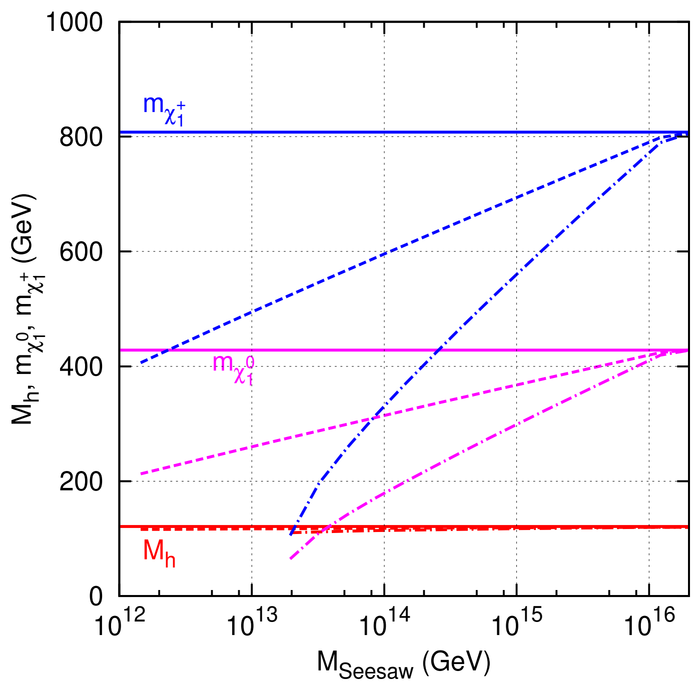


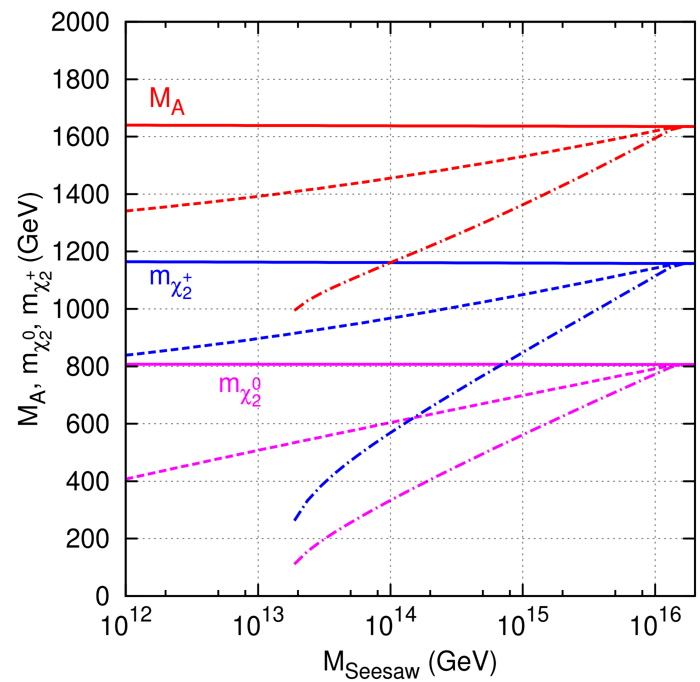
$Q = 1$ TeV, $m_0 = M_{1/2} = 1$ TeV, $A_0 = 0$, $\tan\beta = 10$ and $\mu > 0$

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. Romao, F. Staub, Phys. Rev. D**83** (2011) 013003

Effect on heavy particles on MSSM spectrum, I





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

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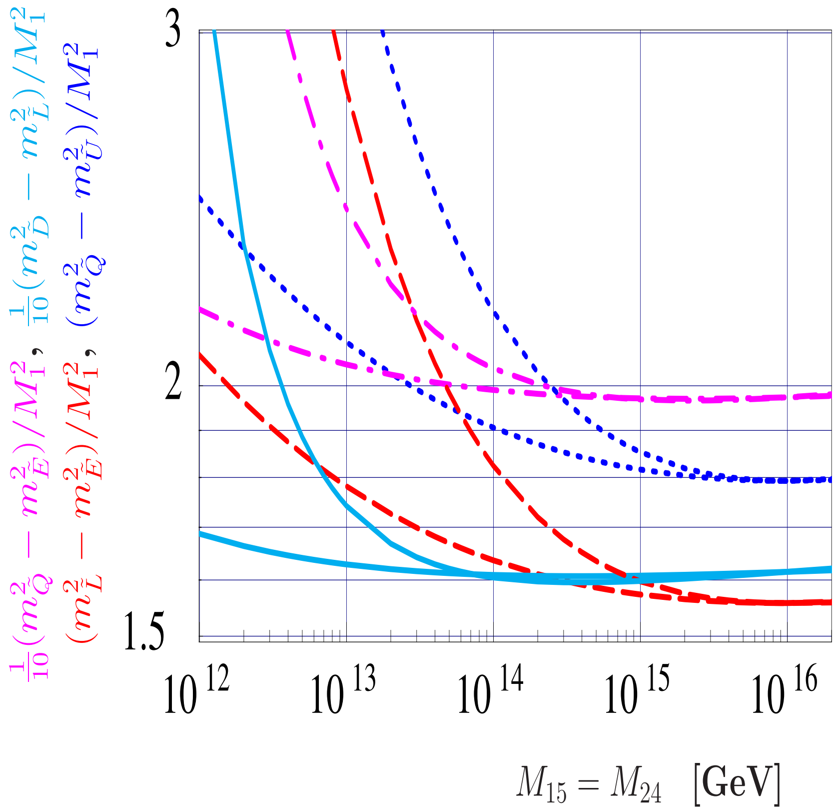
”Invariants”



Seesaw I ($\simeq$ MSSM)

$\frac{m_Q^2 - m_E^2}{M_1^2} \simeq 20$, $\frac{m_D^2 - m_L^2}{M_1^2} \simeq 18$

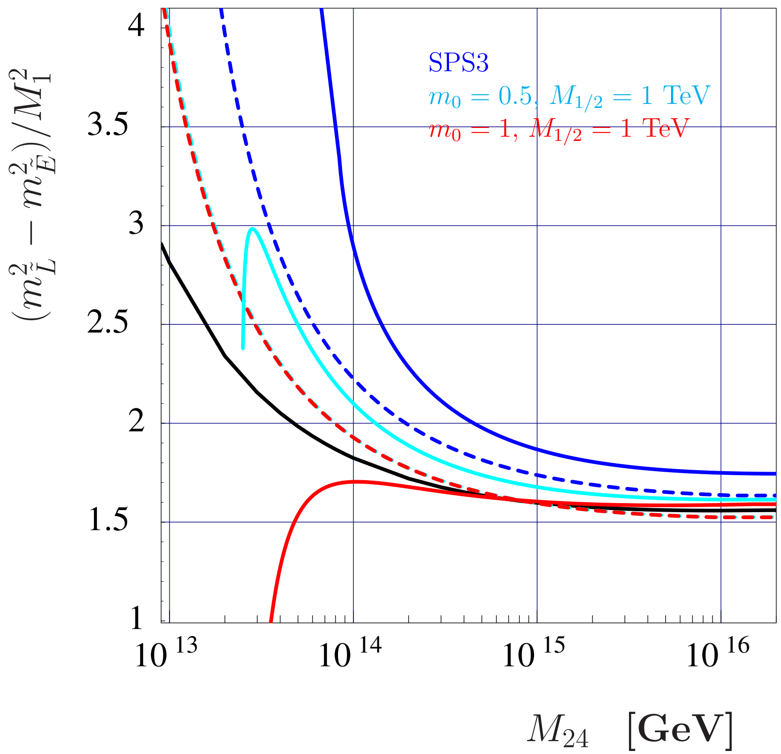
$\frac{m_L^2 - m_E^2}{M_1^2} \simeq 1.6$, $\frac{m_Q^2 - m_U^2}{M_1^2} \simeq 1.55$

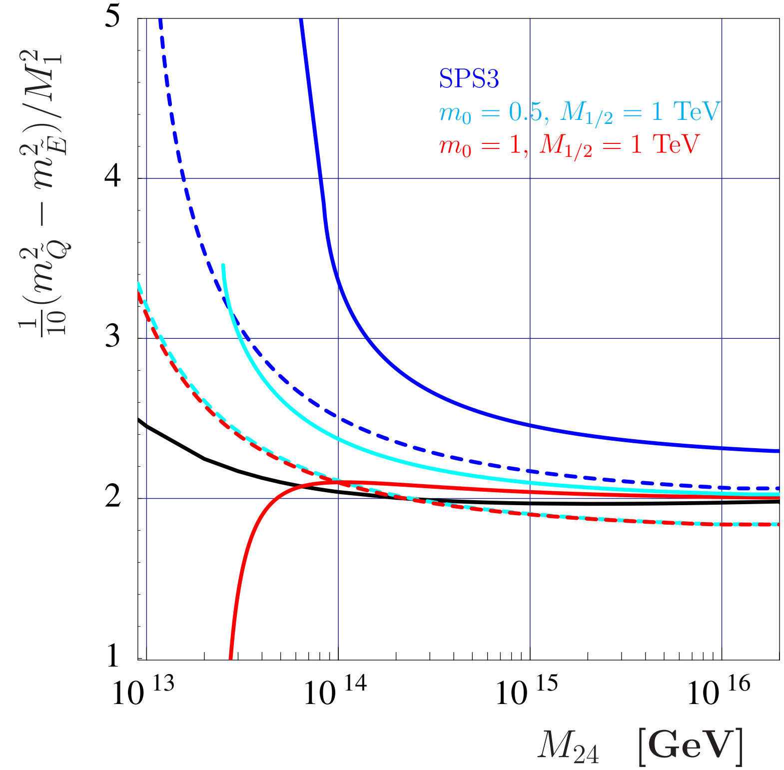
(solution of 1-loop RGEs)

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

J. Esteves, M.Hirsch, J. Romão, W. P., F. Staub, Phys. Rev. D**83** (2011) 013003

”Invariants”, limits for seesaw type-III models





blue lines . . . SPS3

light blue lines . . . $m_0 = 500$ GeV and $M_{1/2} = 1$ TeV

red lines . . . $m_0 = M_{1/2} = 1$ TeV

black line . . . analytical approximation

full (dashed) lines . . . 2-loop (1-loop) results

LFV in the slepton sector: approximate formulas, I

one-step integration of the RGEs assuming mSUGRA boundary

$$\begin{aligned}
\Delta M^2_{L,ij} &\simeq -\frac{a_k}{8\pi^2}\left(3m_0^2 + A_0^2\right)\left(Y_N^{k,\dagger} L Y_N^k\right)_{ij} \\
\Delta A_{l,ij} &\simeq -a_k \frac{3}{16\pi^2} A_0 \left(Y_e Y_N^{k,\dagger} L Y_N^k\right)_{ij} \\
\Delta M^2_{E,ij} &\simeq 0 \\
L_{ij} &= \ln(M_{GUT}/M_i)\delta_{ij}
\end{aligned}$$

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, I

$(\Delta M^2_{\tilde{L}})_{ij}$ 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:

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

Moreover, in most of the parameter space

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

Seesaw I

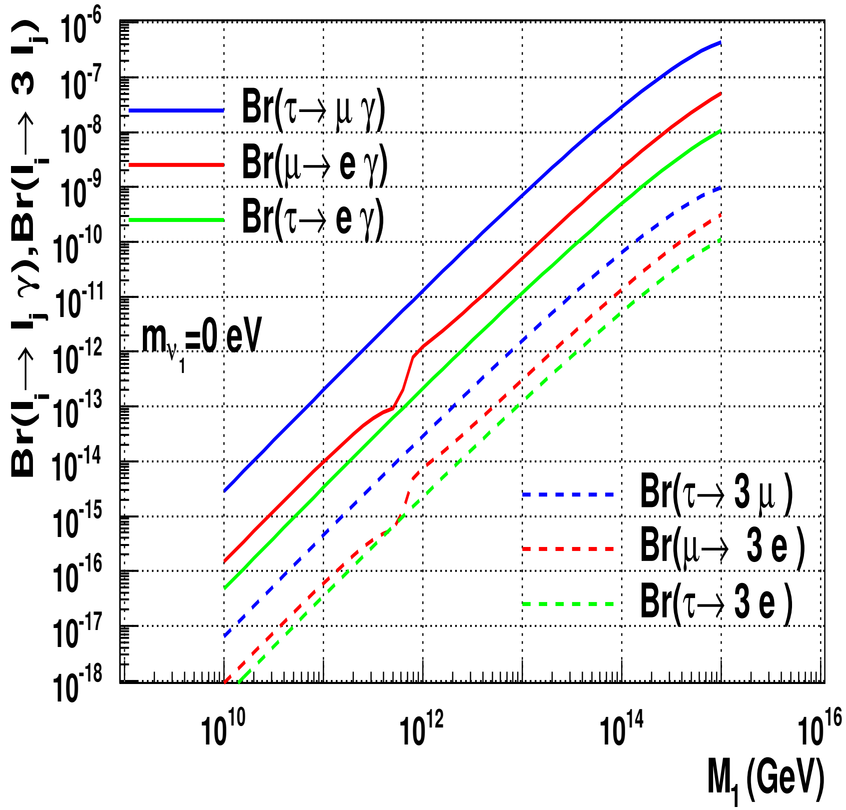
take all parameters real

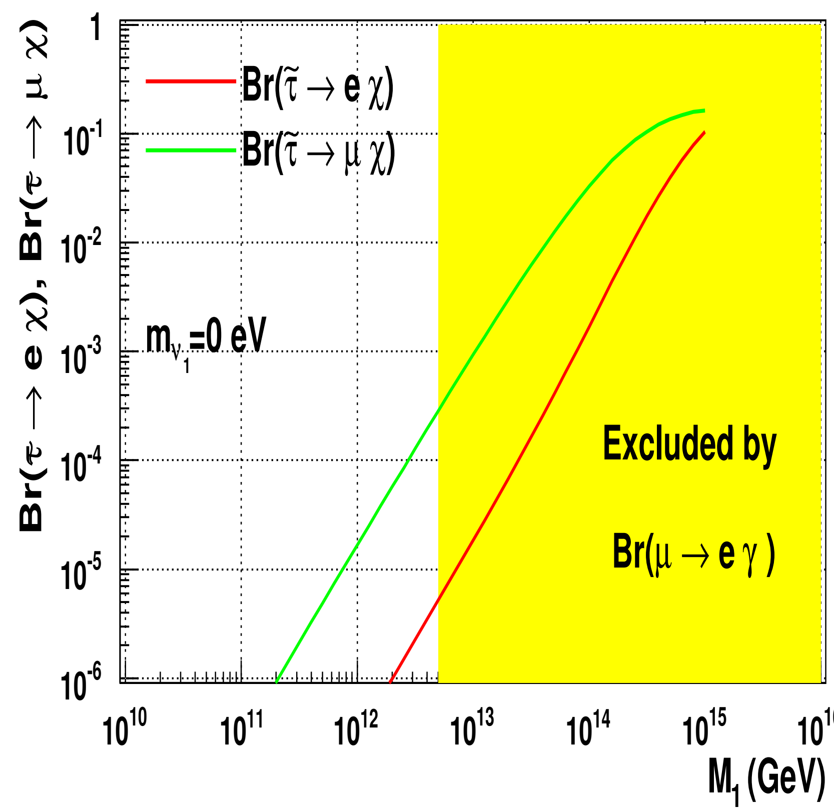
$$U = U_{\text{TBM}} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Use 2-loop RGEs and 1-loop corrections including flavour effects

Seesaw I



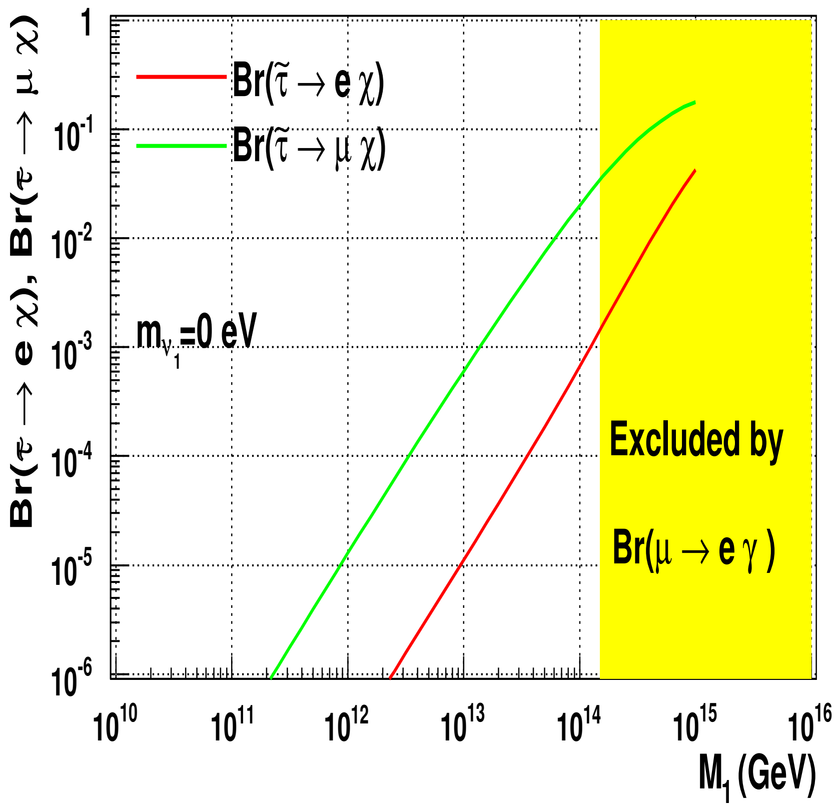


degenerate ν_R

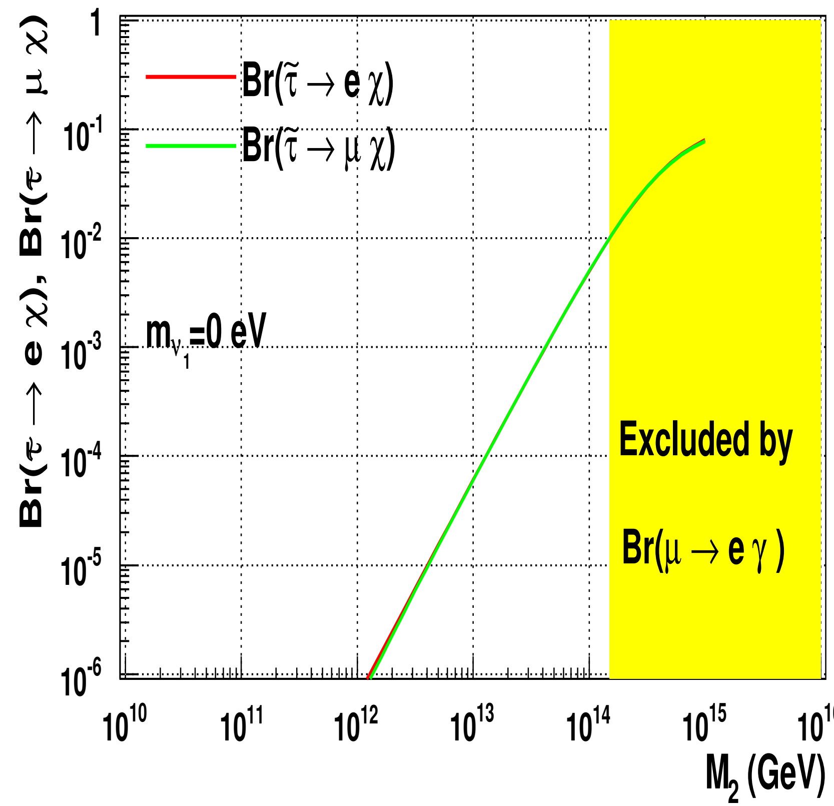
SPS1a' ($M_0 = 70$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, $\mu > 0$)

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

Seesaw I



degenerate ν_R



hierarchical ν_R

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

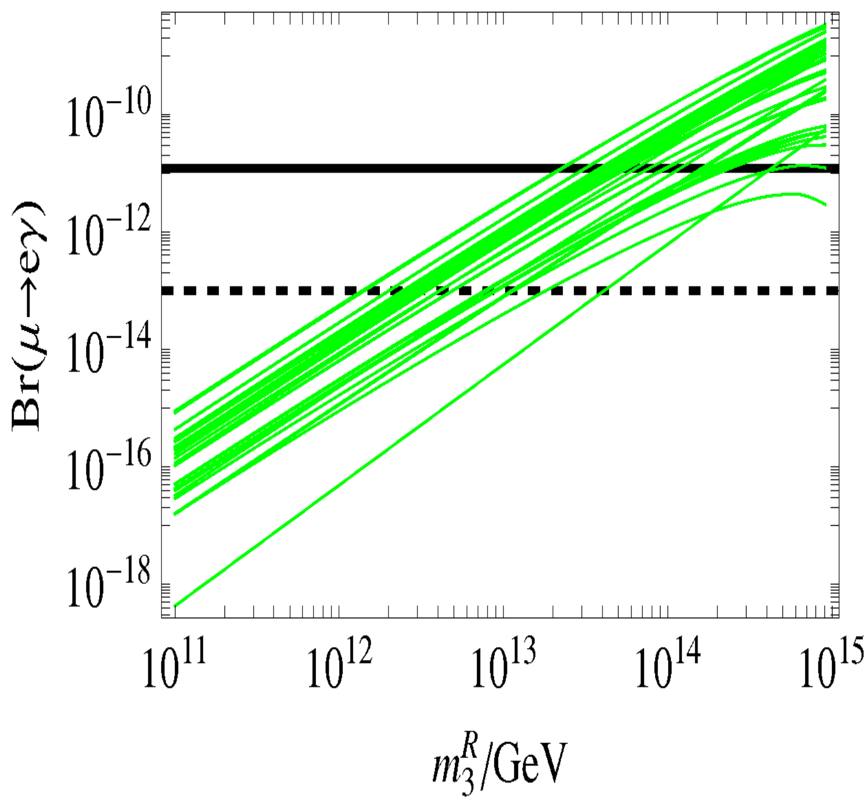
SPS3 ($M_0 = 90$ GeV, $M_{1/2} = 400$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, $\mu > 0$)

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

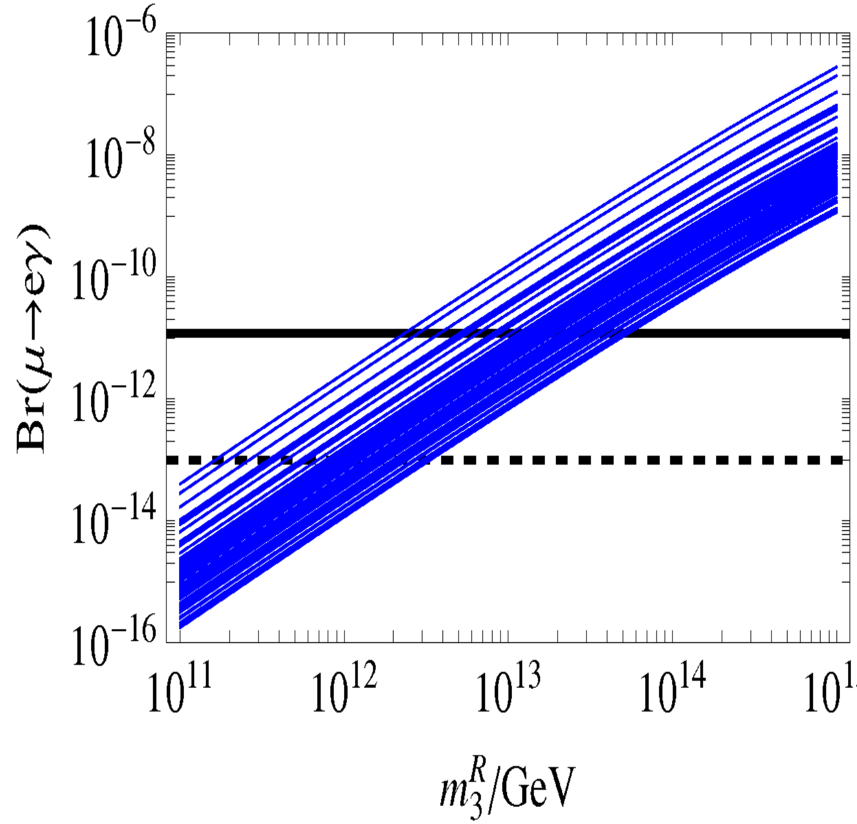
Seesaw I

Texture models, hierarchical ν_R

real textures



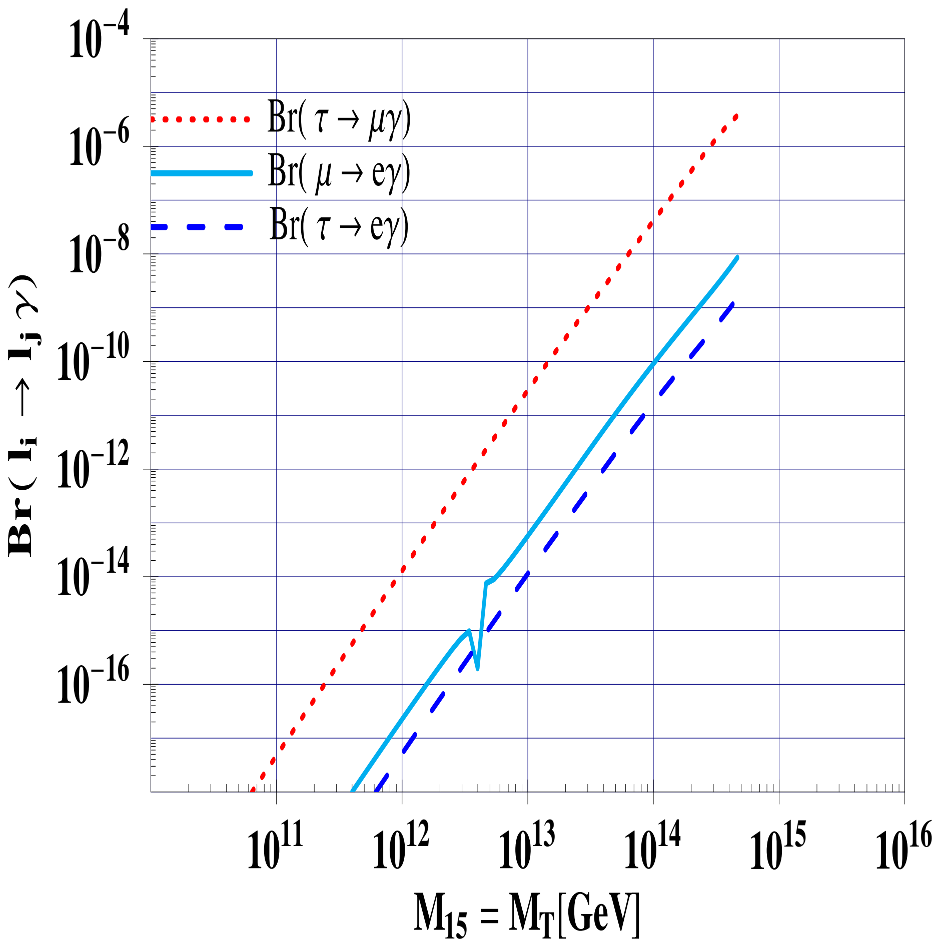
"complexification" of one texture

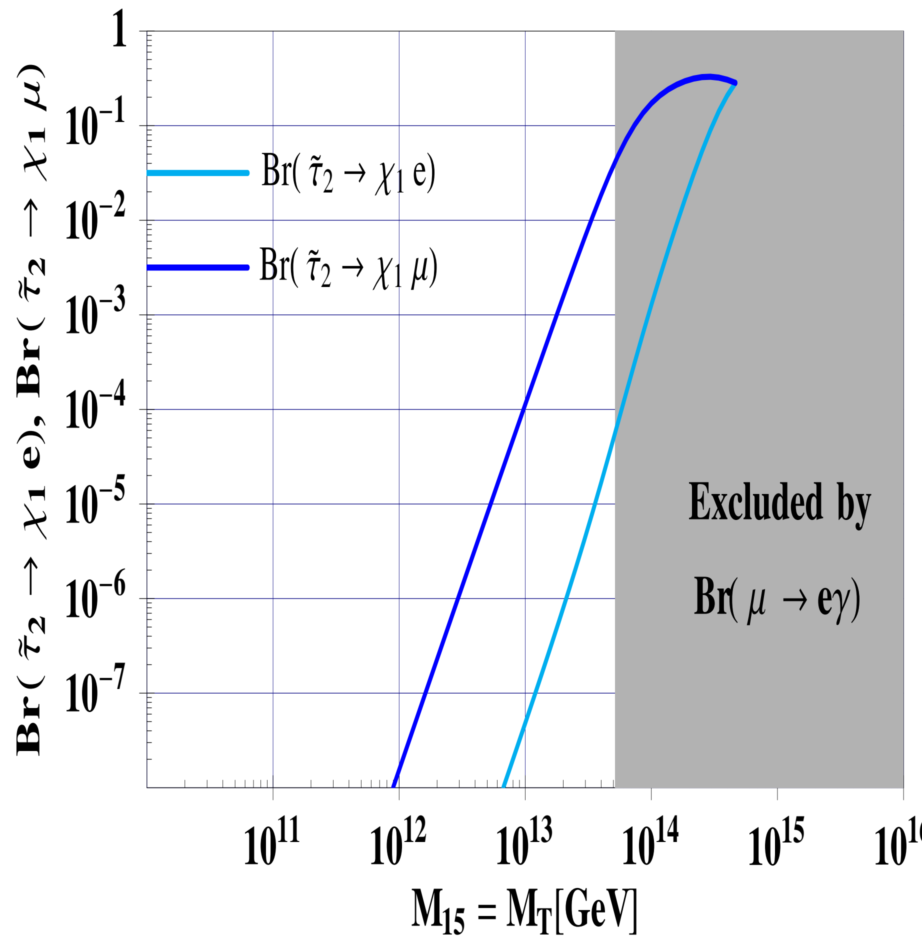


SPS1a' ($M_0 = 70$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, $\mu > 0$)

F. Deppisch, F. Plentinger, G. Seidl, JHEP **1101** (2011) 004

Seesaw II with a pair of 15-plets



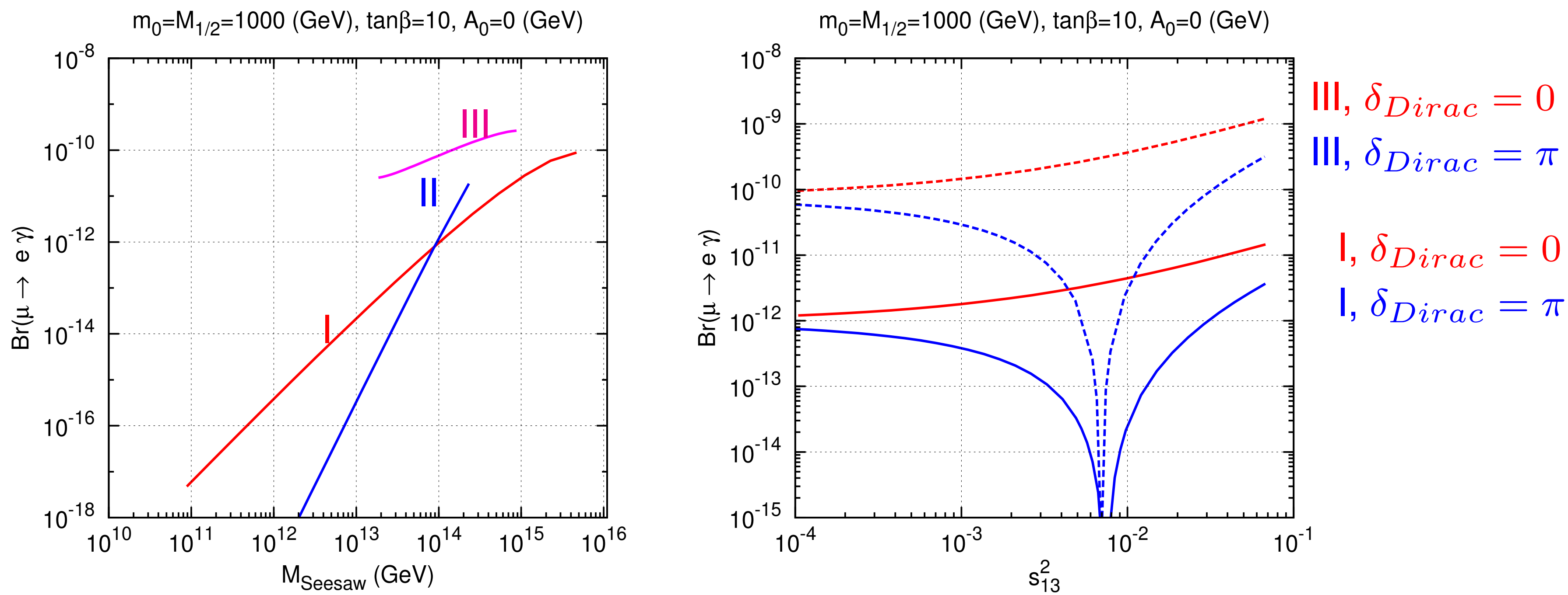


$\lambda_1 = \lambda_2 = 0.5$

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.

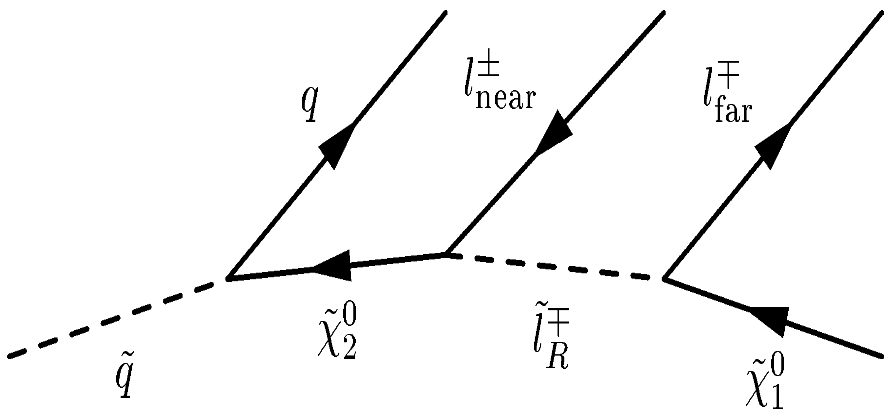
Seesaw III in comparison



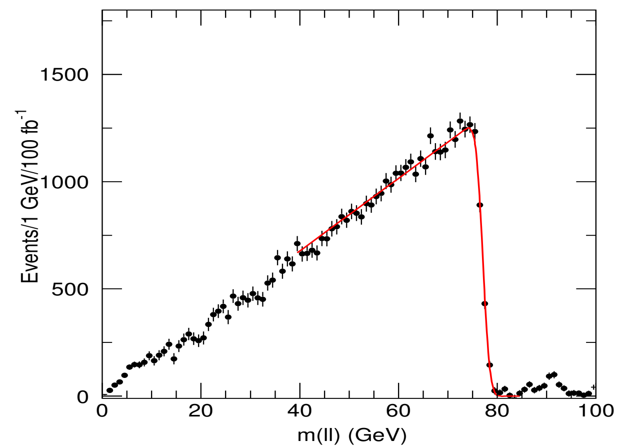
degenerate spectrum of the seesaw particles, $M_{seesaw} = 10^{14}$ GeV

J. Esteves, M.Hirsch, J. Romão, W.P., F. Staub, Phys. Rev. D**83** (2011) 013003

Masses at LHC



G. Polesello



5 kinematical observables depending on 4 SUSY masses

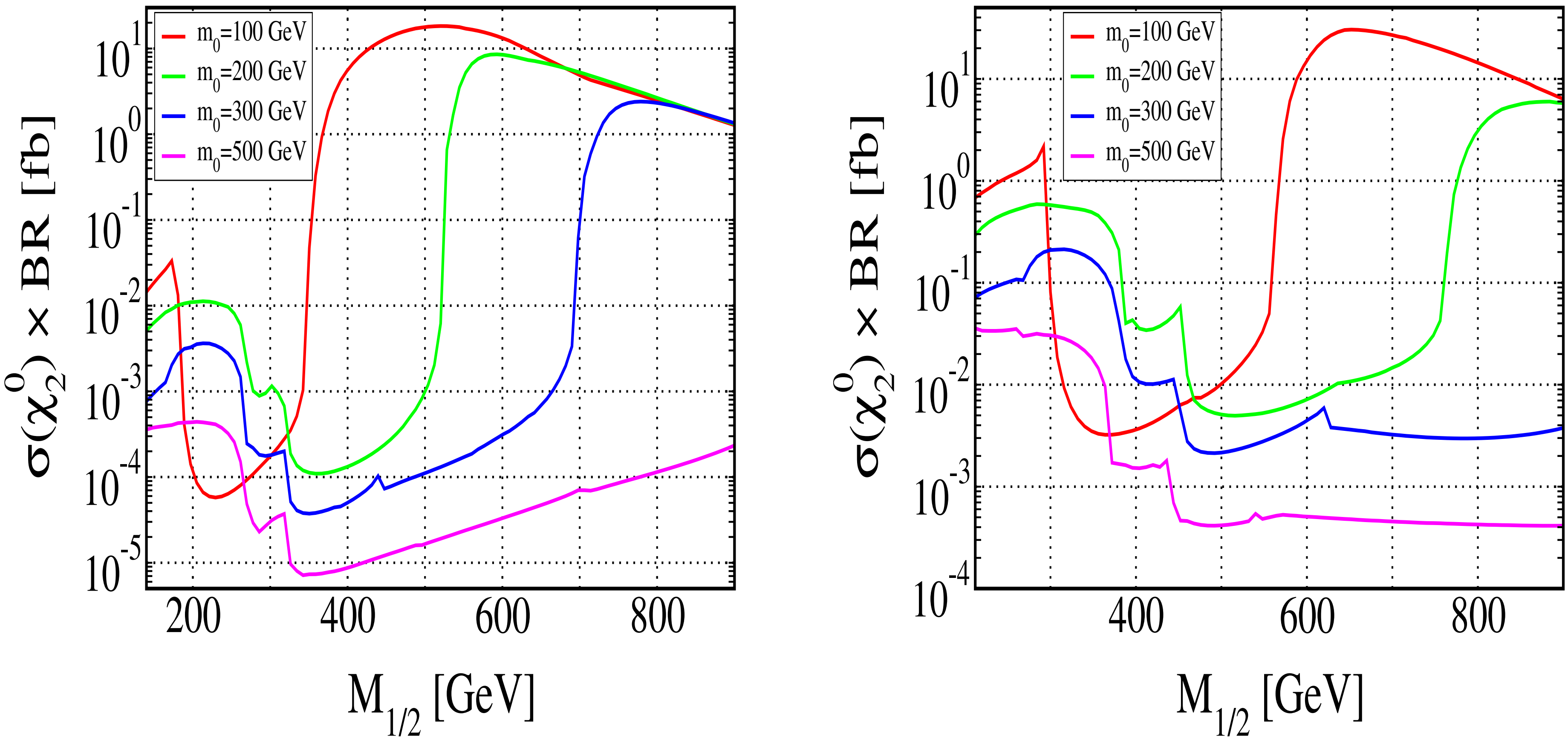
e.g.: $m(ll) = 77.02 \pm 0.05 \pm 0.08$

$\Rightarrow$ mass determination within 2-5%

For background suppression

$$N(e^+e^-) + N(\mu^+\mu^-) - N(e^+\mu^-) - N(\mu^+e^-)$$

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 et al., JHEP **0905**, 003 (2009)

Low scale Seesaw

general problem up to now: $m_\nu \simeq 0.1$ eV $\Rightarrow Y^2/M$ fixed

However: dim-5 operator might be forbidden due to symmetries,

- e.g. Z_3 + NMSSM[†]

$$\frac{(LH_u)^2 S}{M_6^2} \quad , \quad \frac{(LH_u)^2 S^2}{M_7^3}$$

solves at the same time the μ-problem

$$W_{MSSM} = \hat{H}_d \hat{L} Y_e \hat{E}^C + \hat{H}_d \hat{Q} Y_d \hat{D}^C + \hat{H}_u \hat{Q} Y_u \hat{U}^C - \lambda \hat{H}_d \hat{H}_u \hat{S} + \frac{\kappa}{3} \hat{S}^3$$

- flavour symmetries + extra $SU(2)$ doublets + singletts
  or linear or inverse seesaw $\Rightarrow$ see talk by M. Krauss

† I. Gogoladze, N. Okada, Q. Shafi, PLB **672** (2009) 235

NMSSM phenomenology in a nut-shell

- Higgs sector: h_i^0 (i=1,2,3), a_i^0 (i=1,2)
  non-standard Higgs decays*:

$$h_i^0 \rightarrow a_1^0 a_1^0 \rightarrow 4b, 2b\tau^+\tau^-, \tau^+\tau^-\tau^+\tau^-$$

- Neutralinos, Singlino LSP $|\lambda| \ll 1 \Rightarrow$ displaced vertex†, e.g.

$$\Gamma(\tilde{\tau}_1 \rightarrow \tilde{\chi}_1^0 \tau) \propto \lambda^2 \sqrt{m_{\tilde{\tau}_1}^2 - m_{\tilde{\chi}_1^0}^2 - m_\tau^2}$$

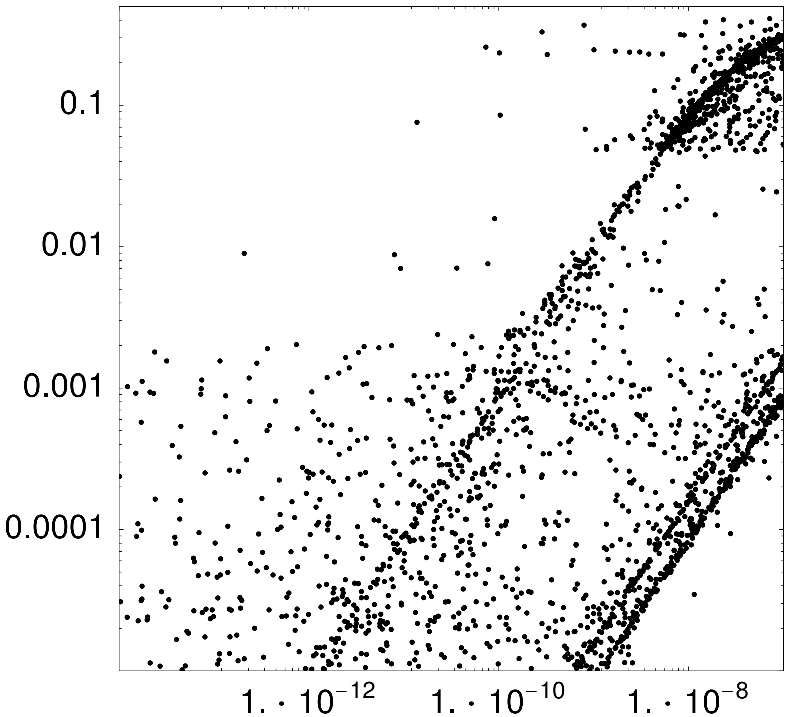
  Note: $\mu = \lambda v_s$

* see e.g. U. Ellwanger, J. F. Gunion and C. Hugonie, JHEP **0507** (2005) 041

† see e.g. U. Ellwanger and C. Hugonie, Eur. Phys. J. C **5** (1998) 723
S. Hesselbach, F. Franke and H. Fraas, Phys. Lett. B **492** (2000) 140

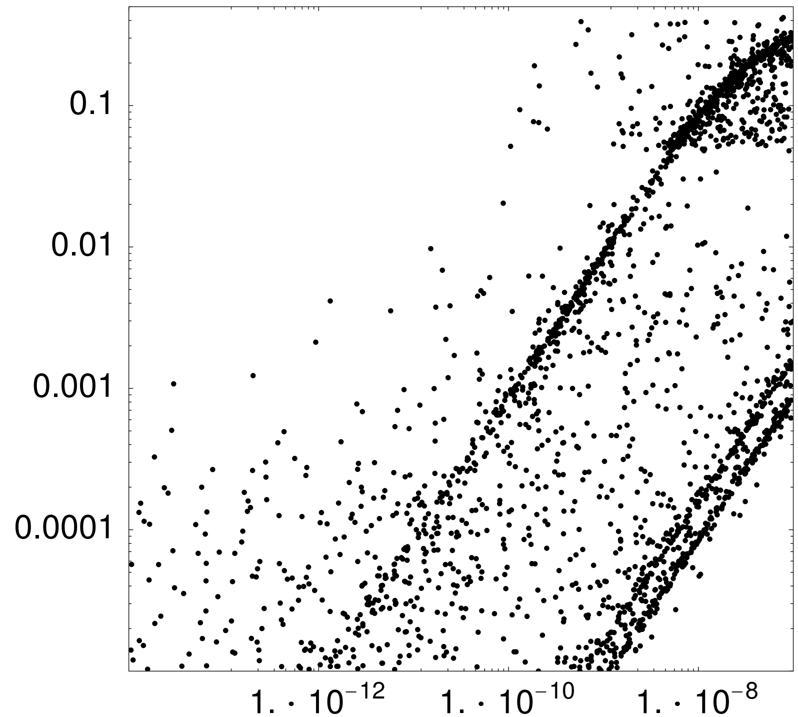
arbitrary $M^2_{E,ij}$, $M^2_{L,ij}$, $A_{l,ij}$: $\tilde{\chi}^0_2 \to \tilde{l}_i l_j \to l_k l_j \tilde{\chi}^0_1$

BR$(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\, e^{\pm}\, \tau^{\mp})$



BR$(\tau \to e\gamma)$

BR$(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\, \mu^{\pm}\, \tau^{\mp})$

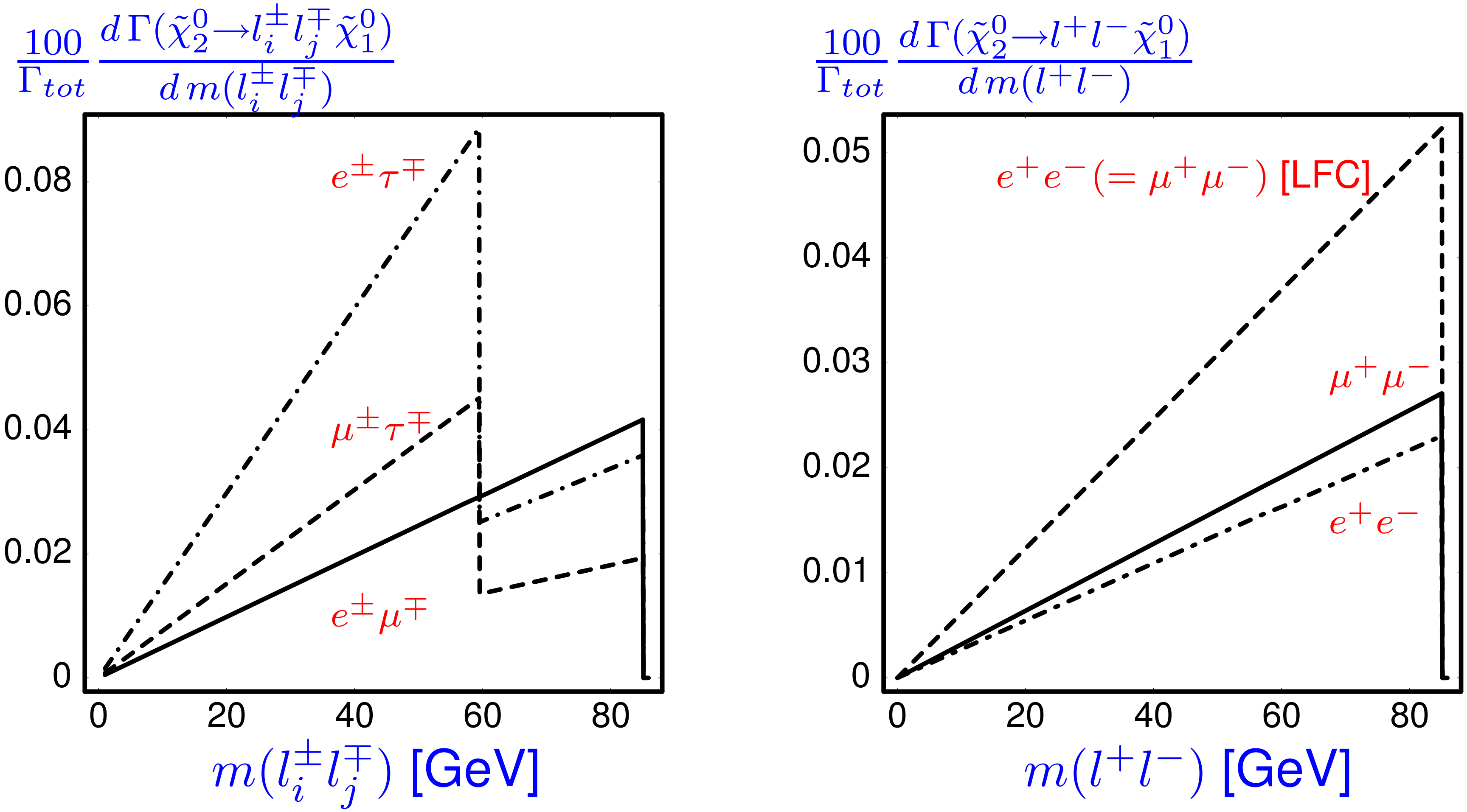


BR$(\tau \to \mu\gamma)$

Variations around SPS1a

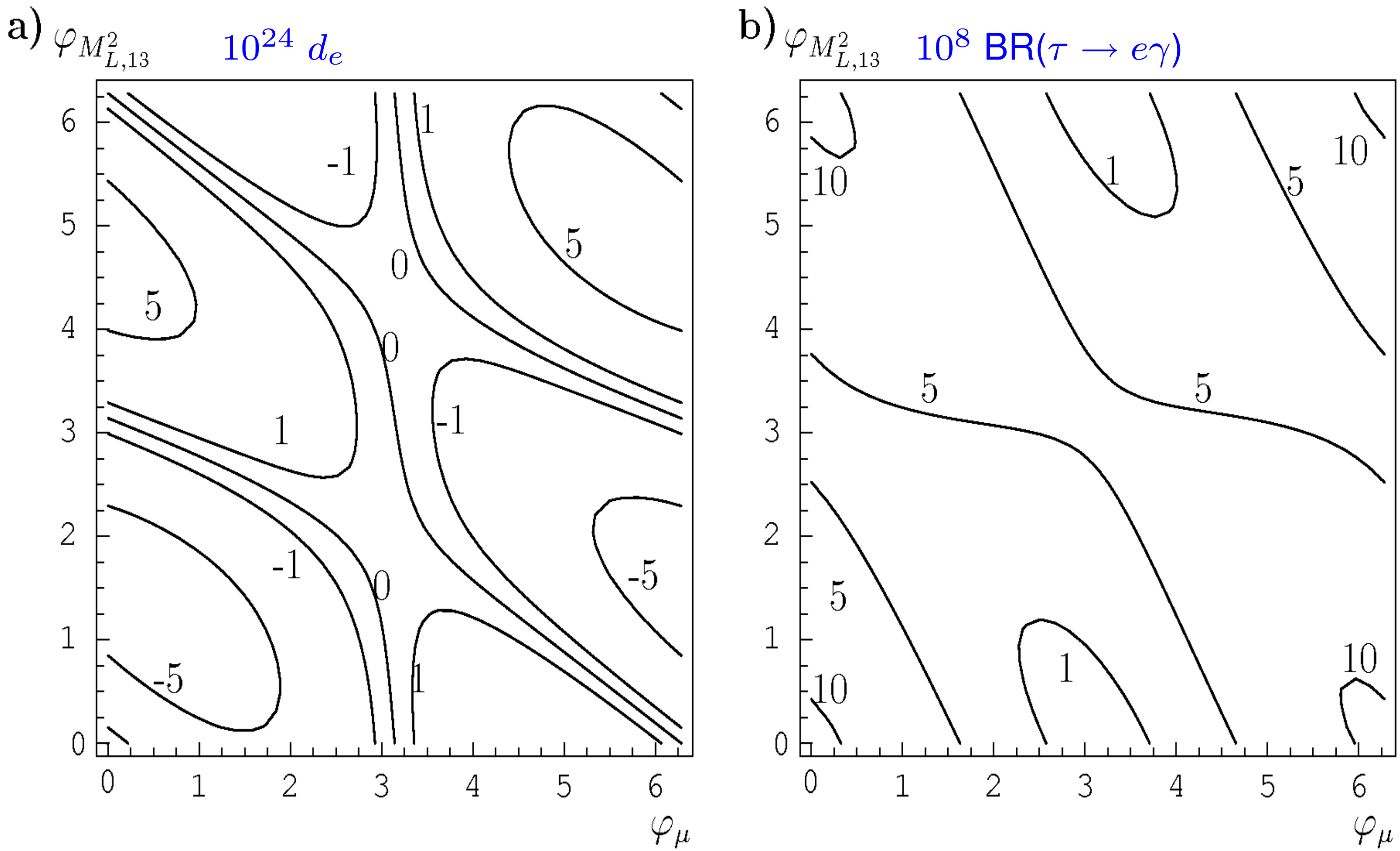
($M_0 = 100$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -100$ GeV, $\tan\beta = 10$)

Flavour mixing and edge variables



A. Bartl et al., Eur. Phys. J. C **46** (2006) 783

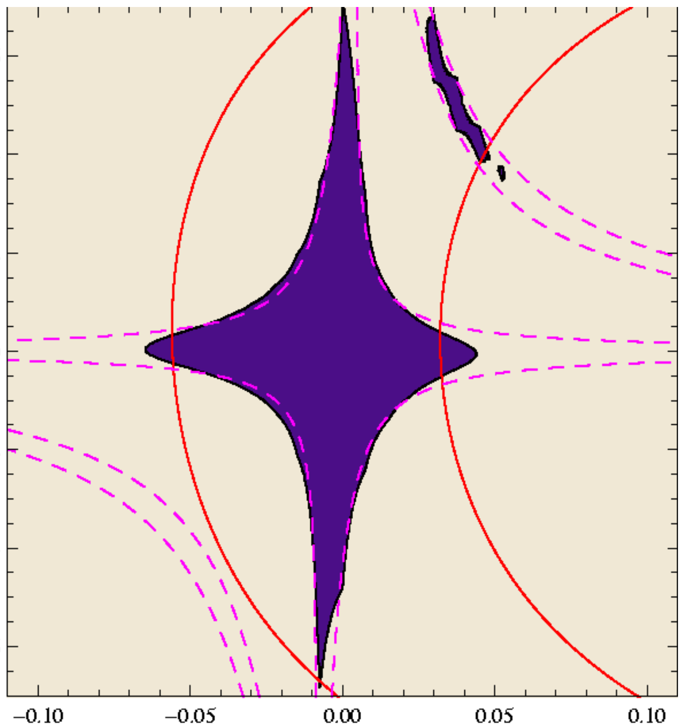
Phases: special cancelation regions

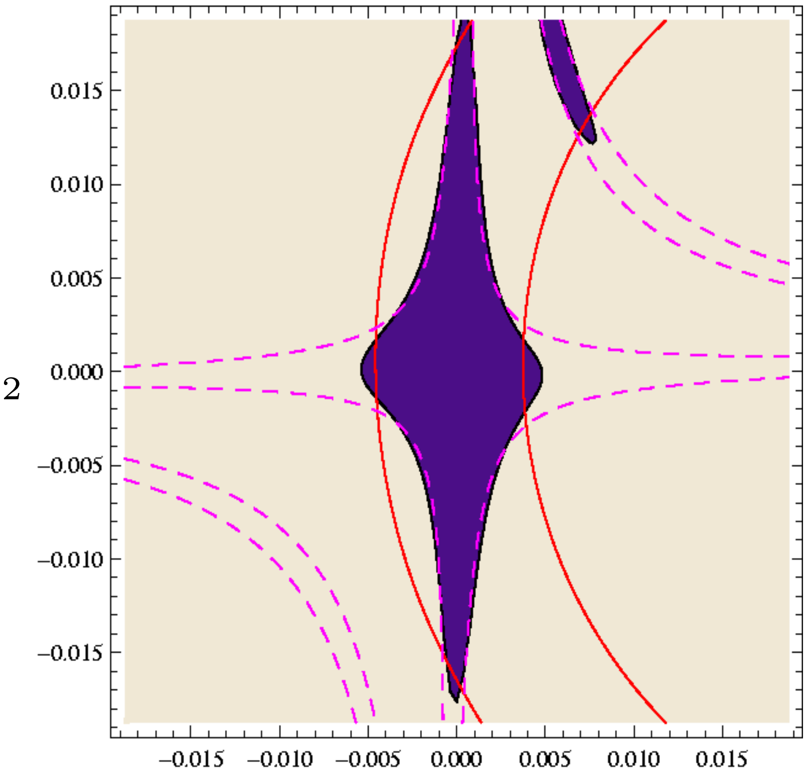


Variations around SPS3

see also A. Bartl, W. Majerotto, W.P., D. Wyler, PRD **68** (2003) 053005

Squarks, variations around SPS1a'



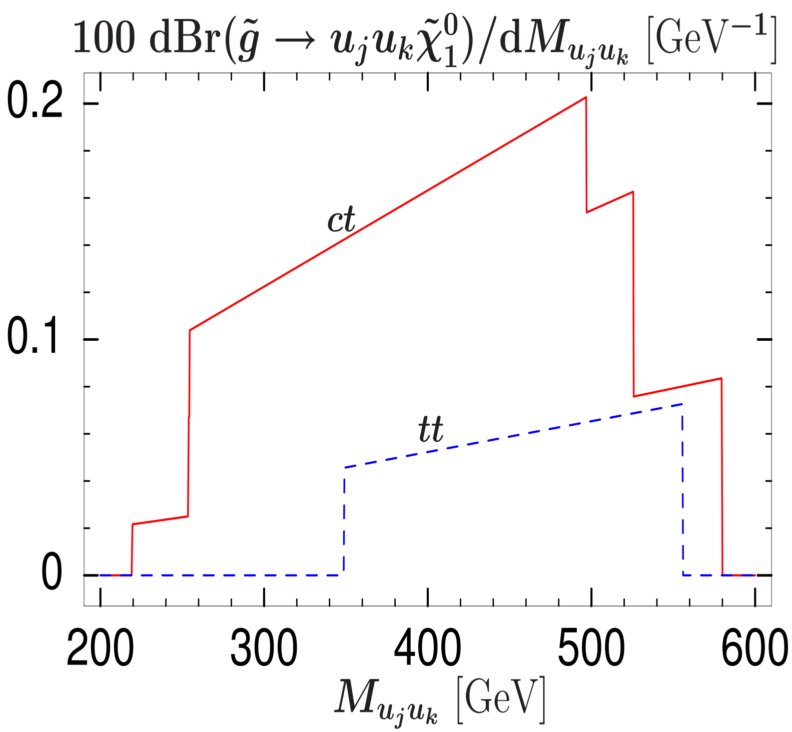


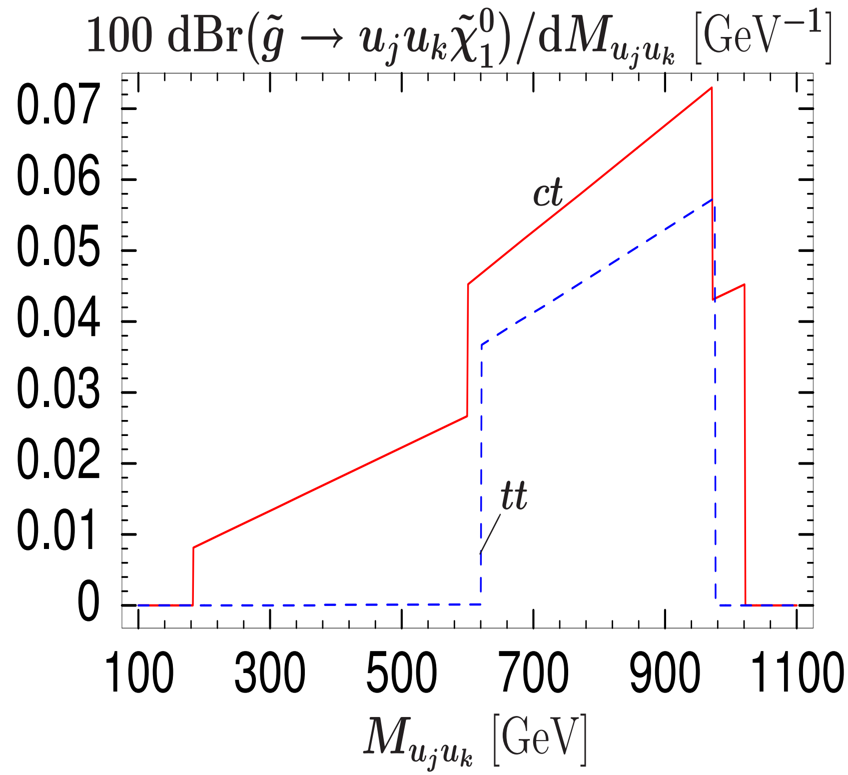
$2.7 \cdot 10^{-4} \leq BR(b \to s\gamma) \leq 4.3 \cdot 10^{-4}$, $13.5\ \text{ps}^{-1} \leq |\Delta_{M_{B_s}}| \leq 21.1\ \text{ps}^{-1}$

$$\delta_{LL,ij} = \frac{(M^2_{q,\,LL})_{ij}}{m^2_{\tilde{q}}}\,, \qquad \delta_{q,RR,ij} = \frac{(M^2_{q,\,RR})_{ij}}{m^2_{\tilde{q}}}\,, \qquad \delta_{q,LR,ij} = \frac{(M^2_{q,\,LR})_{ij}}{m^2_{\tilde{q}}}\,, \qquad (i \neq j)$$

T. Hurth, W.P. JHEP **0908** (2009) 087

Edge variables in the squark sector





$m_{\tilde{g}} = 800$ GeV, $m_{\tilde{u}_j} \gtrsim 560$ GeV

$\delta_{LL,ij} = 0.06, , \delta_{RR,u,ij} = 0.06$

$\sigma(pp \to \tilde{g}\tilde{g}) \simeq 2$ pb

$m_{\tilde{g}} = 1300$ GeV, $m_{\tilde{u}_1} = 470$ GeV, $m_{\tilde{u}_j} \gtrsim 1$ TeV

$\delta_{LL,ij} = 0.17, , \delta_{RR,u,ij} = 0.61$

$\sigma(pp \to \tilde{g}\tilde{g}) \simeq 40$ fb

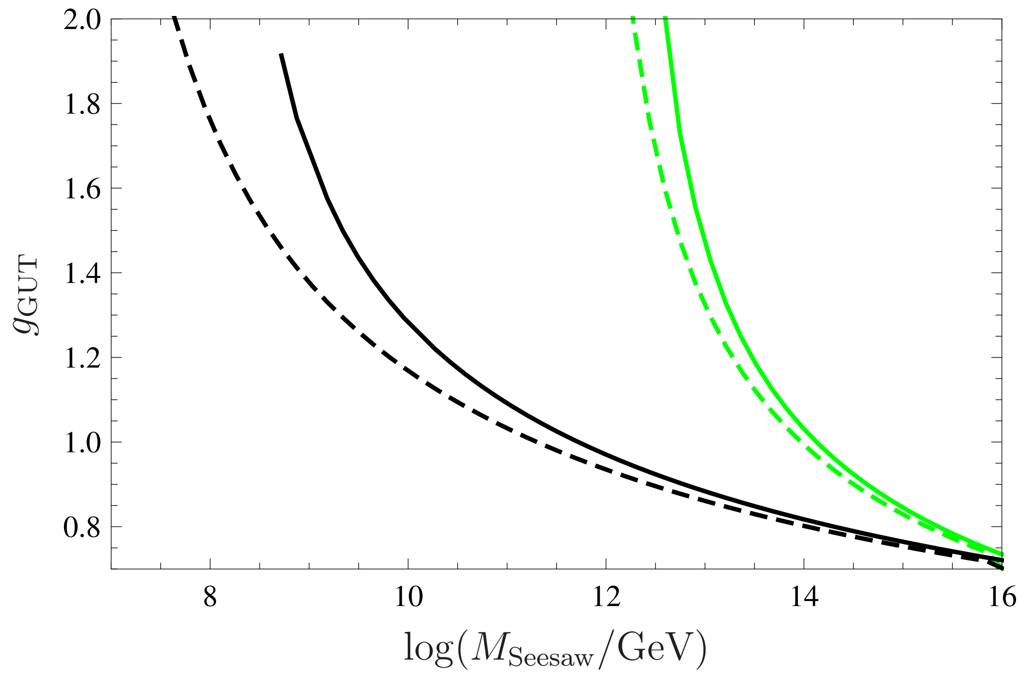
A. Bartl et al., PLB **679** (2009) 260, PLB **698** (2011) 380

Conclusions

MSSM extensions in view of neutrino physics

- SUSY flavour problem orginates in the SM flavour problem
- Dirac neutrinos: displaced vertices if $\tilde{\nu}_R$ LSP, e.g. $\tilde{t}_1 \to lb\tilde{\nu}_R$ (but NMSSM: $\tilde{t}_1 \to lb\nu\tilde{\chi}_1^0$)
- Seesaw models:
  - most promising: $\tilde{\tau}_2$ decays
  - difficult to test at LHC, signals of O(10 fb) or below
  - in case of seesaw II or III: different mass ratios
- NMSSM
  - potenitally larger LFV signals due to lower seesaw scale
  - modified Higgs/neutralino sector
  - modified phenomenology; $h_1^0 \to a_1 a_1$ and/or displace vertices
- Squarks: similar techniques for flavour violating signals as for sleptons but technically more challanging
- general MSSM larger effects; require special parameter combinations
  $\Rightarrow$ hint of hidden symmetries ?

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

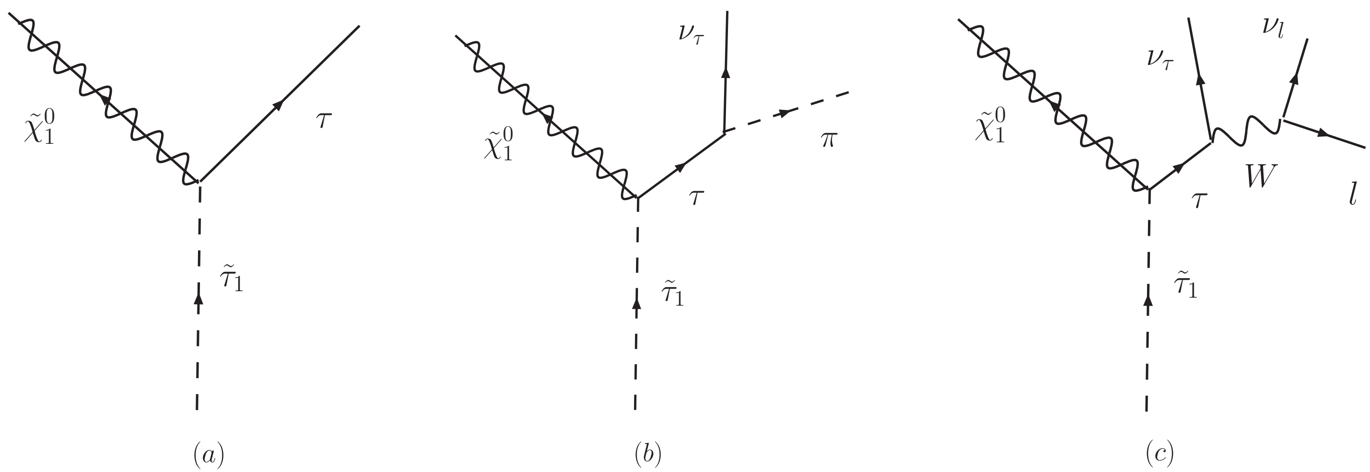
black lines . . . seesaw type-II

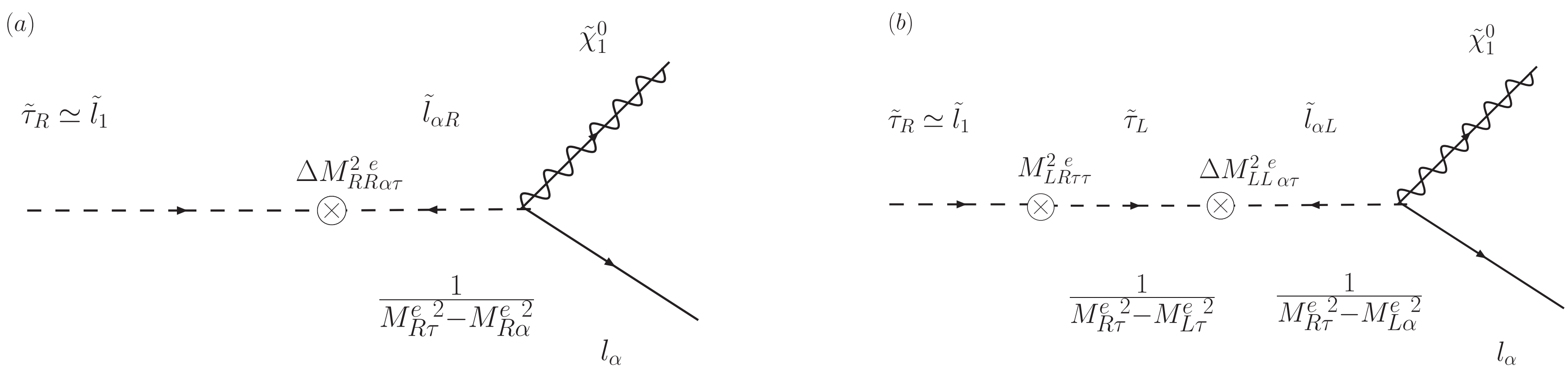
green lines . . . seesaw type-III with three **24**-plets with degenerate mass spectrum

full (dashed) lines . . . 2-loop (1-loop) results

Seesaw, special kinematics†

mSugra: stau co-annihilation for DM, in particular $m_{\tilde{\tau}_1} - m_{\tilde{\chi}^0_1} \lesssim m_\tau$





$\tilde{\tau}_1$ life times up to 10^4 sec

† S. Kaneko et al., Phys. Rev. D **78** (2008) 116013