Supersymmetric LFV

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Overview

- Lepton flavour violation
- Signals in models with
  - Dirac neutrinos
  - Majorana neutrinos
  - Neutrino masses via R-parity violation
- Conclusions

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

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

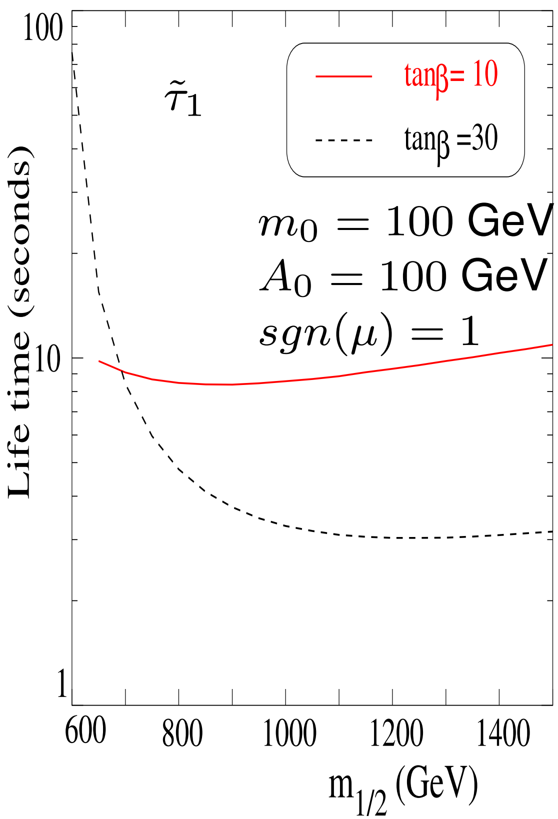
Exception: $\tilde{\nu}_R$ is LSP and thus a candidate for dark matter
$\Rightarrow$ long lived NLSP, e.g. $\tilde{t}_1 \to l^+ b \tilde{\nu}_R$

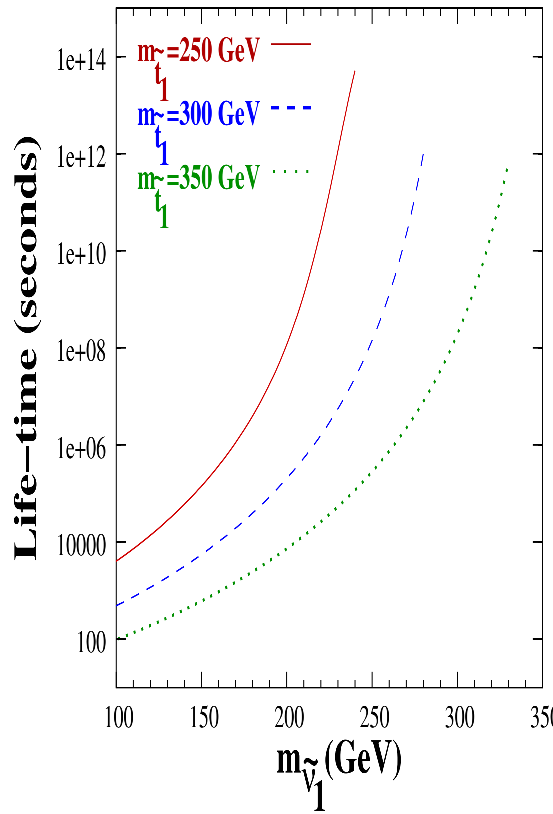
$$\frac{dm^2_{\tilde{\nu}_R}}{dt} = \frac{1}{8\pi^2} (Y_\nu A_\nu)^2$$

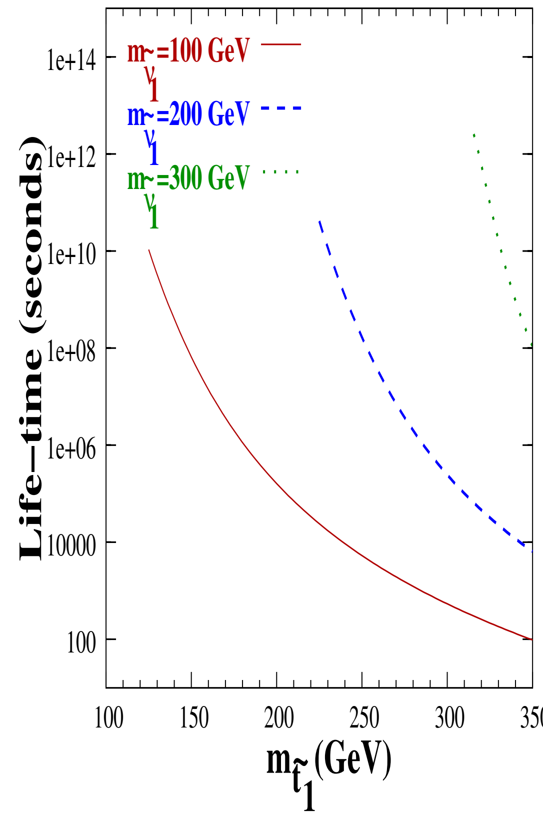
$\Rightarrow$ e.g. $m_{\tilde{\nu}_R} \simeq m_0$ in mSUGRA, $m_{\tilde{\nu}_R} \simeq 0$ in GMSB

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

Dirac neutrinos, NLSP life times







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

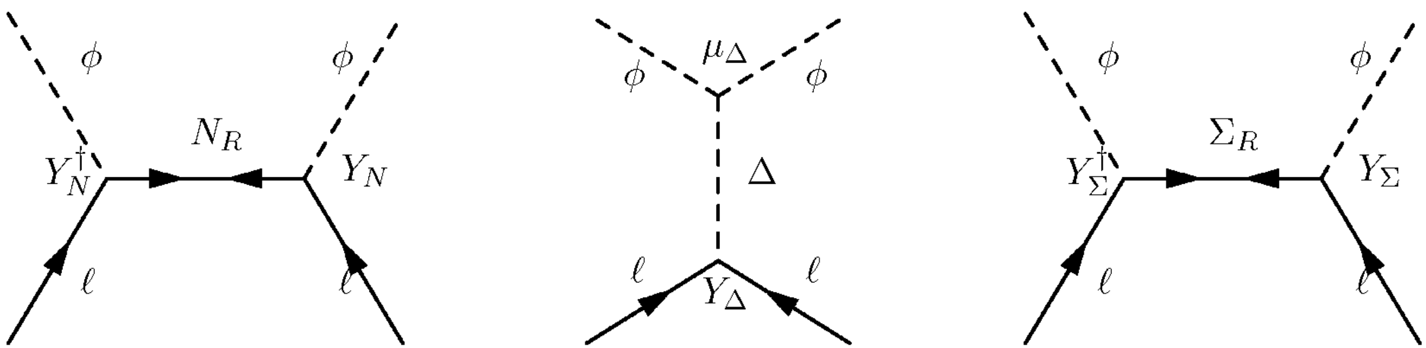
S. K. Gupta, B. Mukhopadhyaya, S. K. Rai, PRD **75** (2007) 075007

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.

Seesaw I

Supersymmetry

$$W = Y_e^{ji} \widehat{L}_i \widehat{H}_d \widehat{E}_j^c + Y_\nu^{ji} \widehat{L}_i \widehat{H}_u \widehat{N}_j^c + M_{R_i} \widehat{N}_i^c \widehat{N}_i^c$$

neutrino masses

$$m_\nu \simeq -(Y_\nu^T v) M_R^{-1} (Y_\nu v) \quad \Rightarrow \quad \hat{m}_\nu = U^T \cdot m_\nu \cdot U$$

convenient parameterization†:

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

RGE running

$$\begin{aligned} (\Delta M^2_{\tilde{L}})_{ij} &= -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(Y_\nu^\dagger L Y_\nu)_{ij} \\ (\Delta A_l)_{ij} &= -\frac{3}{8\pi^2} A_0 Y_{l_i} (Y_\nu^\dagger L Y_\nu)_{ij} \\ (\Delta M^2_{\tilde{E}})_{ij} &= 0 \\ L_{kl} &= \log\left(\frac{M_X}{M_k}\right)\delta_{kl} \end{aligned}$$

† J. A. Casas and A. Ibarra, Nucl. Phys. **B618**, 171 (2001), [hep-ph/0103065].

Seesaw 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:

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

Moreover, in most of the parameter space

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

Seesaw I

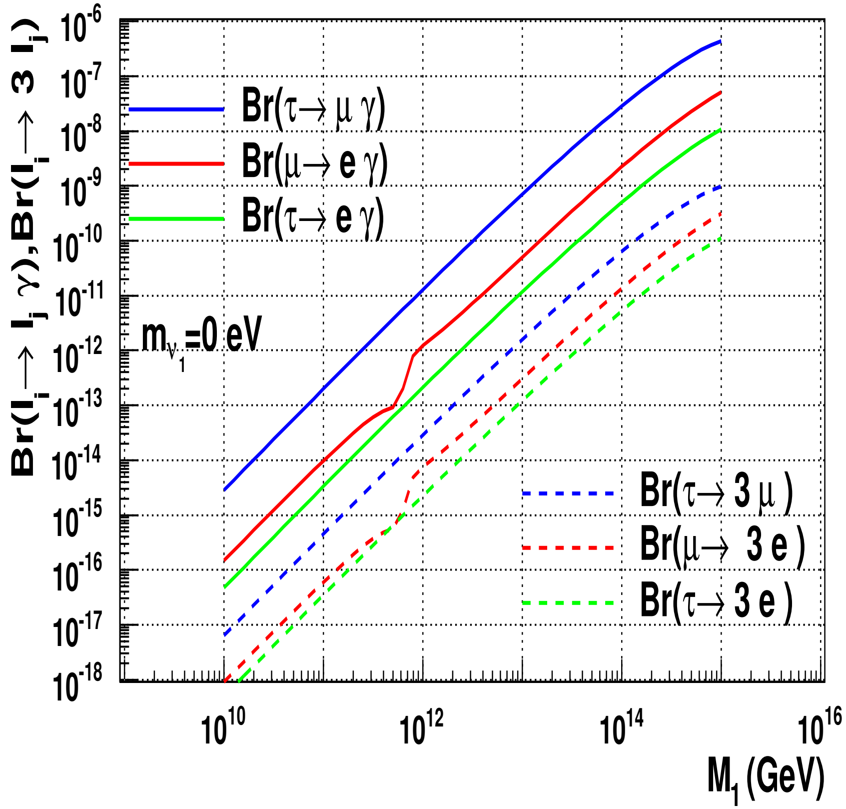
take all parameters real

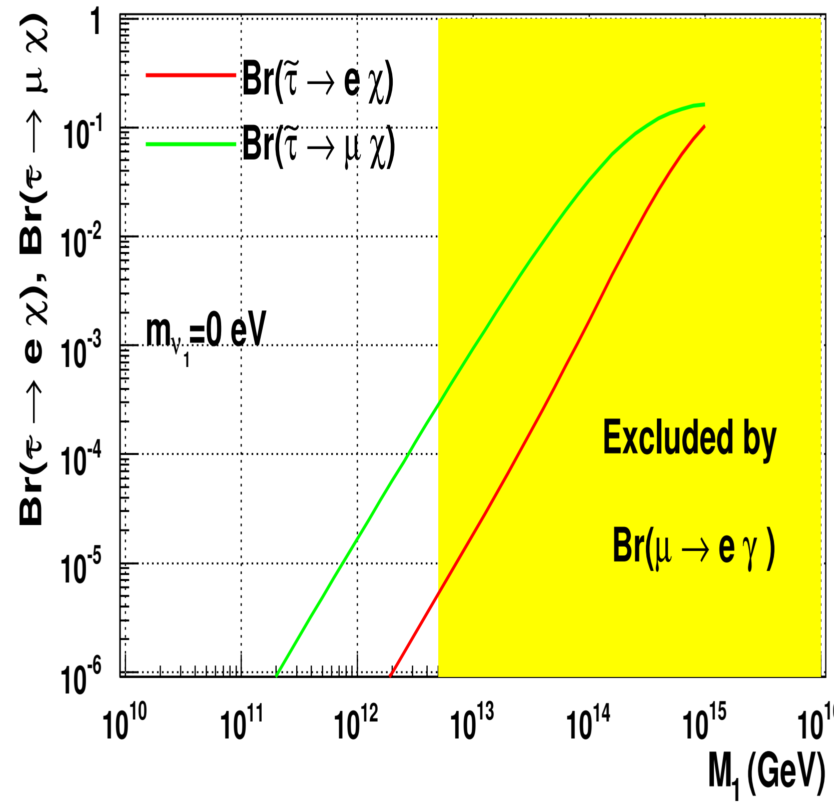
$$U = U_{\mathsf{TBM}} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

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

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

Seesaw I



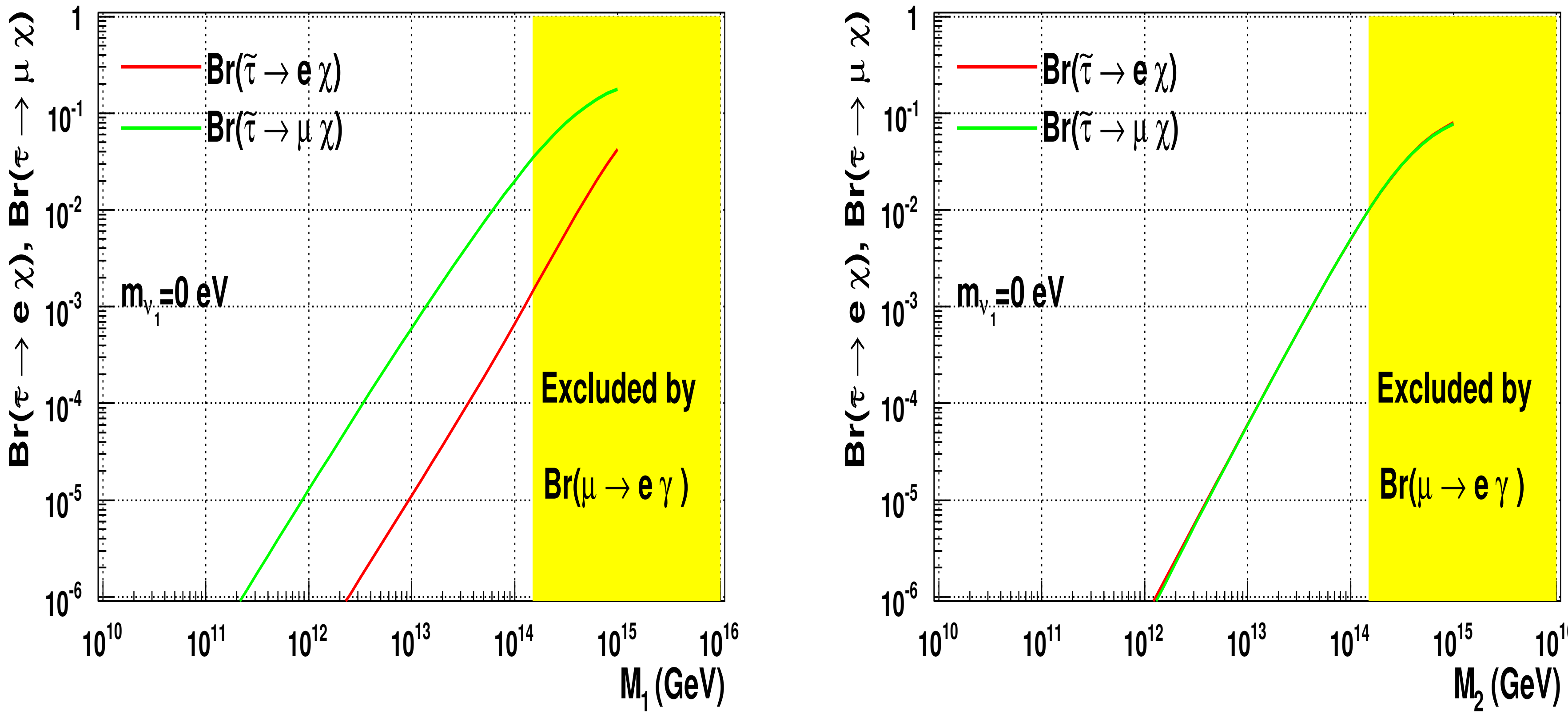


degenerate ν_R

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)

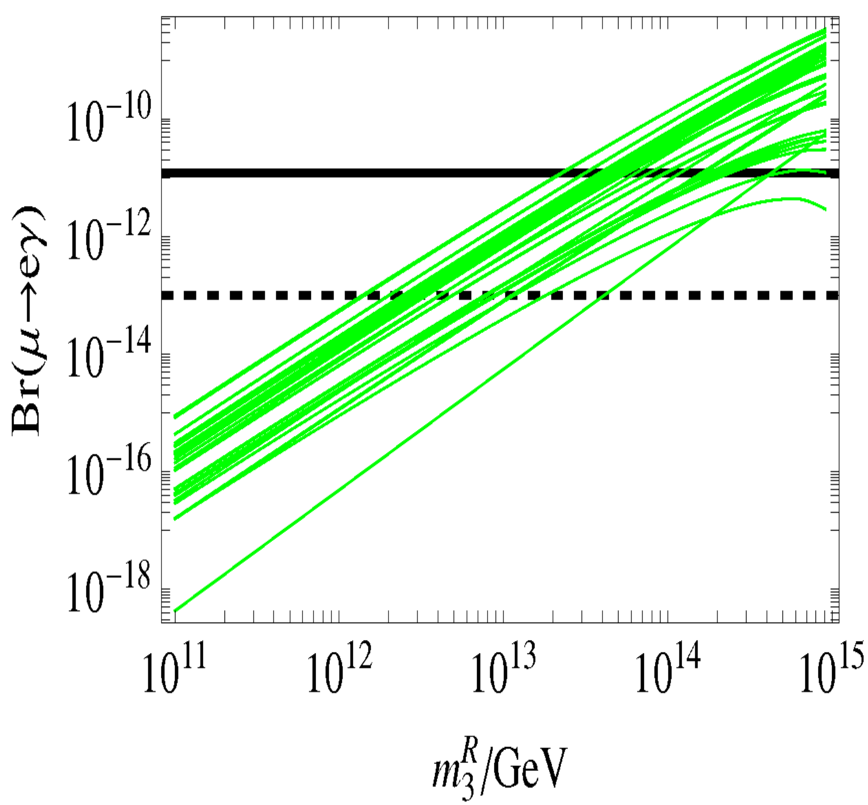
SPS3 ($M_0 = 90$ GeV, $M_{1/2} = 400$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, $\mu > 0$)

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

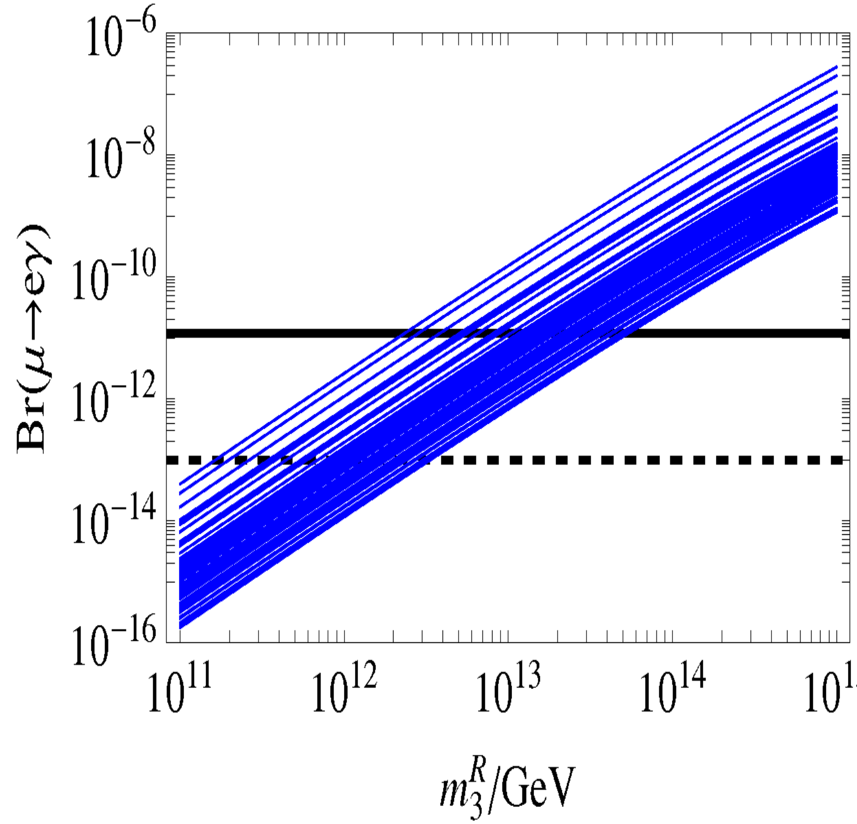
Seesaw I

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, W. P., R. Rückl, G. Seidl, in preparation

Seesaw II

include $SU(2)$ Triplet Higgs

$$W = W_{\rm MSSM} + \frac{1}{\sqrt{2}}\Big(Y_T^{ij} L_i T_1 L_j + \lambda_1 H_1 T_1 H_1 + \lambda_2 H_2 T_2 H_2\Big) + M_T T_1 T_2$$

$$m_\nu = \frac{v_2^2}{2}\frac{\lambda_2}{M_T} Y_T$$

$$\frac{M_T}{\lambda_2} \simeq 10^{15}{\rm GeV}\ \left(\frac{0.05\ {\rm eV}}{m_\nu}\right)$$

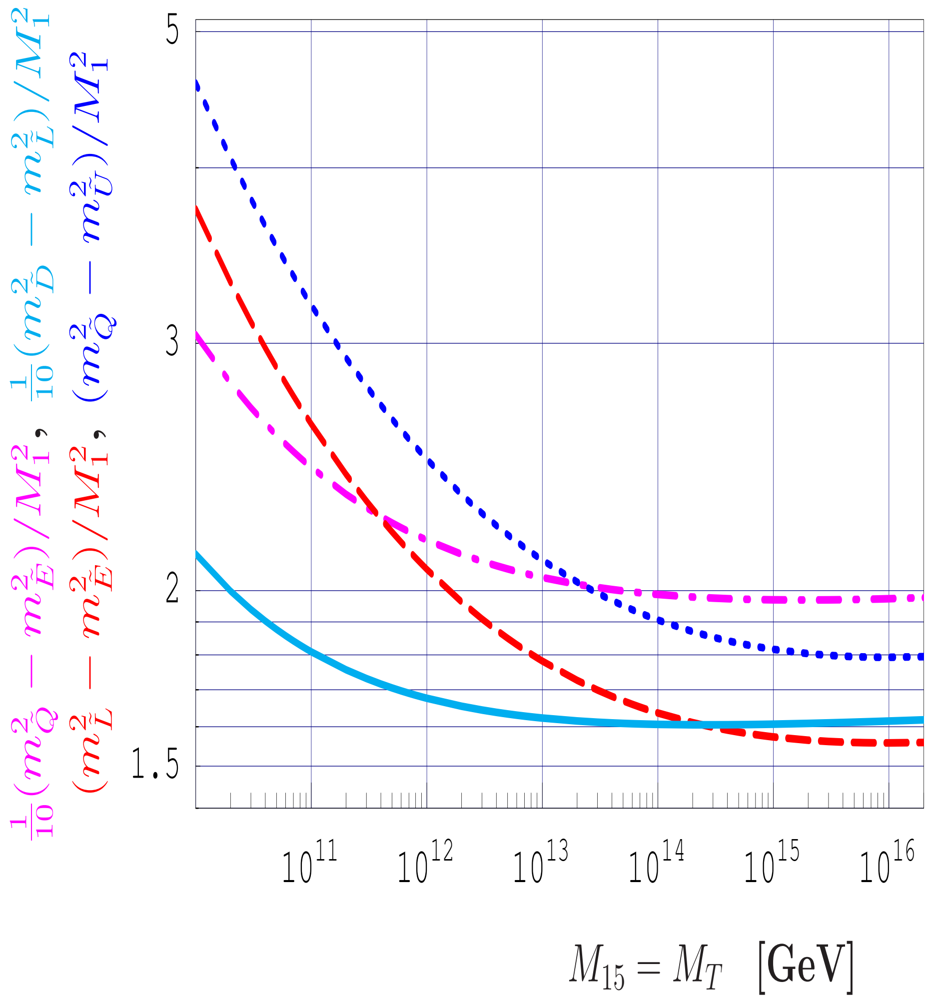
Gauge coupling unification $\Rightarrow$ use $\mathbf{15}$

$$\mathbf{15} = S + T + Z$$

$$S \sim (6,1,-\frac{2}{3}), \qquad T \sim (1,3,1), \qquad Z \sim (3,2,\frac{1}{6})$$

$$W \subset \frac{1}{\sqrt{2}}(Y_T L T_1 L + Y_S d^c S d^c) + Y_Z d^c Z L + Y_d d^c Q H_1 + Y_u u^c Q H_2 + Y_e e^c L H_1$$
$$+ \frac{1}{\sqrt{2}}(\lambda_1 H_1 T_1 H_1 + \lambda_2 H_2 T_2 H_2) + M_T T_1 T_2 + M_Z Z_1 Z_2 + M_S S_1 S_2 + \mu H_1 H_2$$

Seesaw II with 15-plets



$$(b_1, b_2, b_3)^{MSSM} = (\tfrac{33}{5}, 1, -3)$$

$$(b_1, b_2, b_3)^{T_1+T_2} = (\tfrac{18}{5}, 4, 0)$$

$$(b_1, b_2, b_3)^{\overline{15}+15} = (7, 7, 7)$$

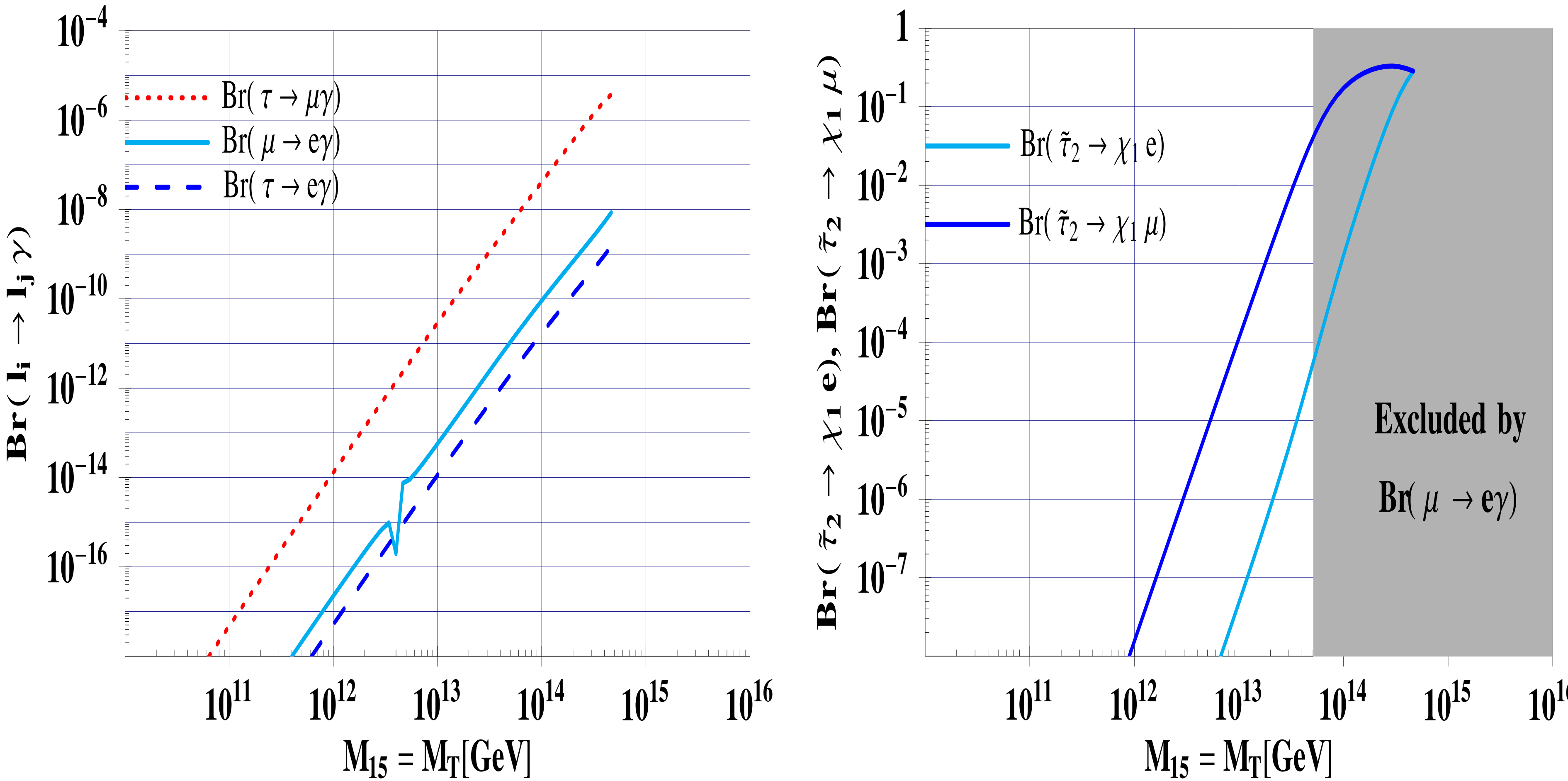
Seesaw I ($\simeq$ MSSM)

$$\frac{m^2_Q - m^2_E}{M_1^2} \simeq 20, \quad \frac{m^2_D - m^2_L}{M_1^2} \simeq 18$$

$$\frac{m^2_L - m^2_E}{M_1^2} \simeq 1.6, \quad \frac{m^2_Q - m^2_U}{M_1^2} \simeq 1.55$$

M. R. Buckley, H. Murayama, PRL **97** (2006) 231801; M. Hirsch, S. Kaneko, W. P., PRD **78** (2008) 093004.

Seesaw II with 15-plets

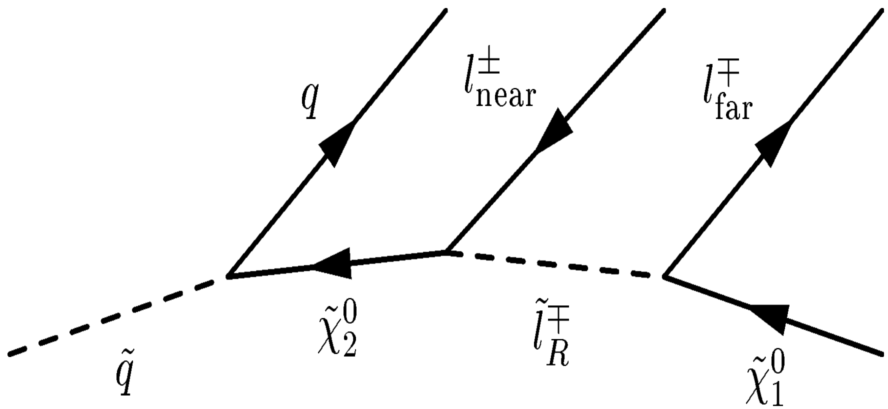


$\lambda_1 = \lambda_2 = 0.5$

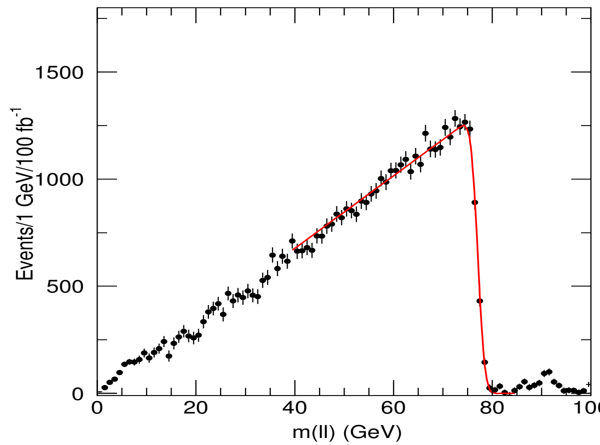
SPS3 ($M_0 = 90$ GeV, $M_{1/2} = 400$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, $\mu > 0$)

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

Masses at LHC



G. Polesello



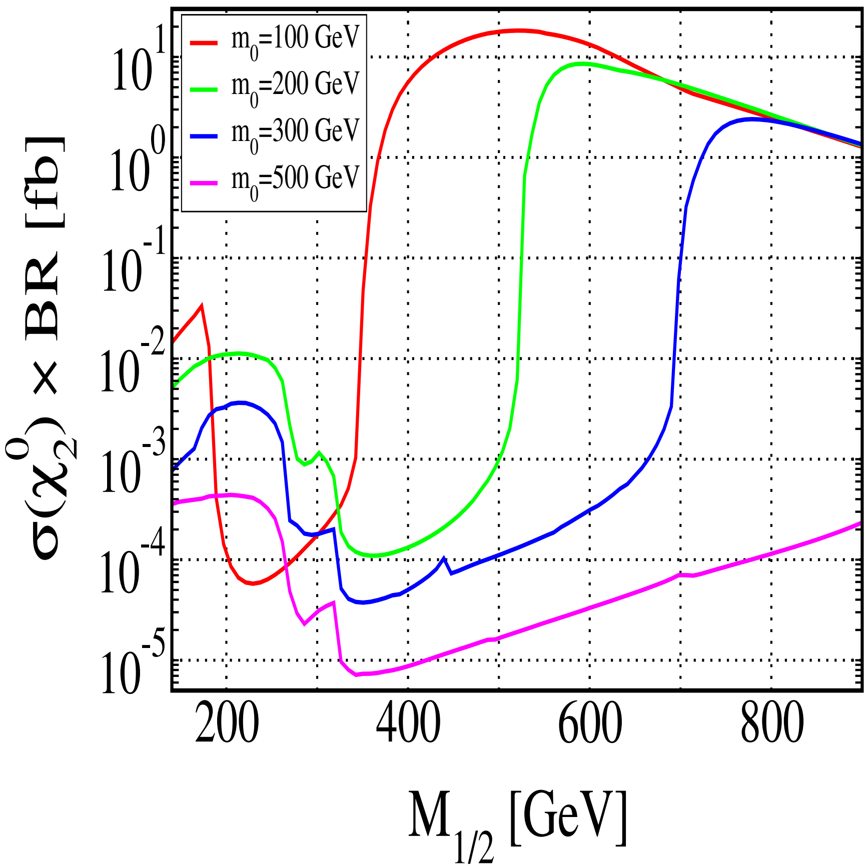
5 kinematical observables depending on 4 SUSY masses

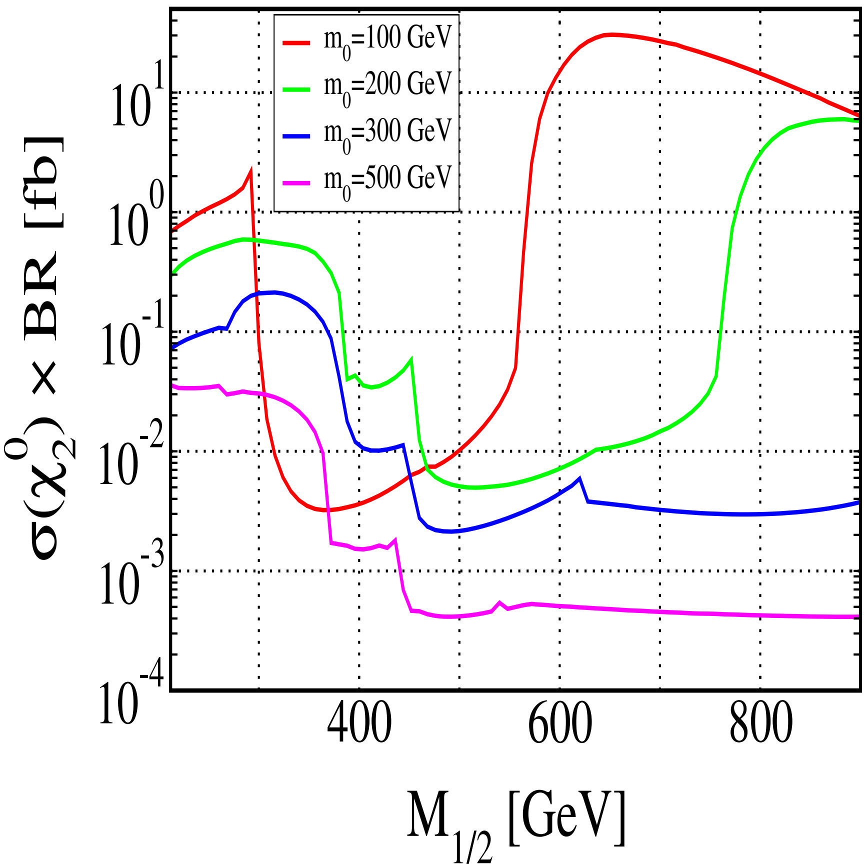
e.g.: $m(ll) = 77.02 \pm 0.05 \pm 0.08$
$\Rightarrow$ mass determination within 2-5%

For background suppression

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

Seesaw I + II, signal at LHC





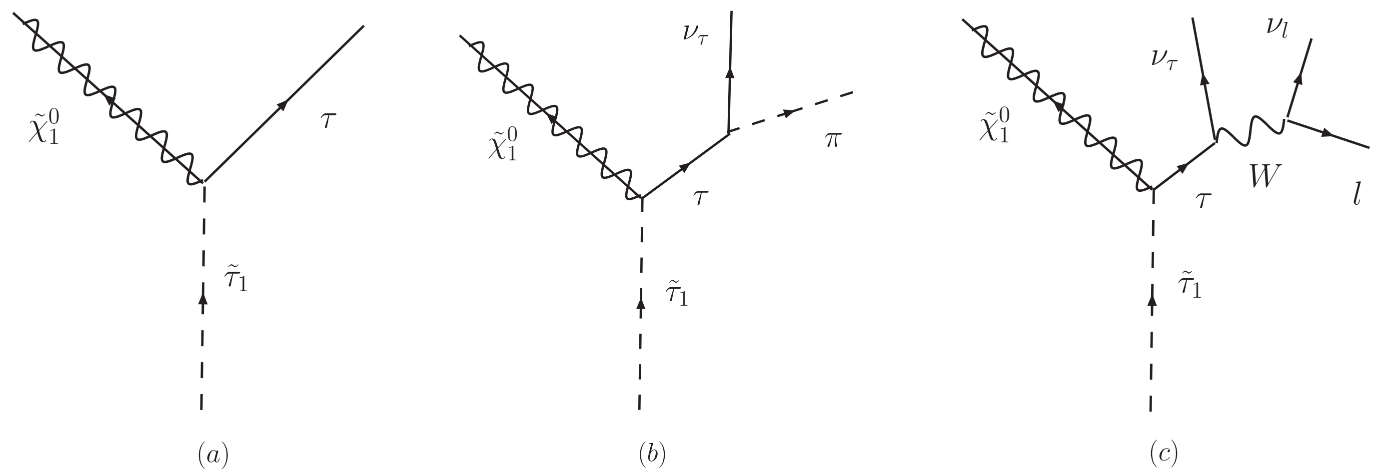
$\sigma(pp \to \tilde{\chi}^0_2) \times BR(\chi^0_2 \to \sum_{i,j} \tilde{l}_i l_j \to \mu^\pm \tau^\mp \tilde{\chi}^0_1)$

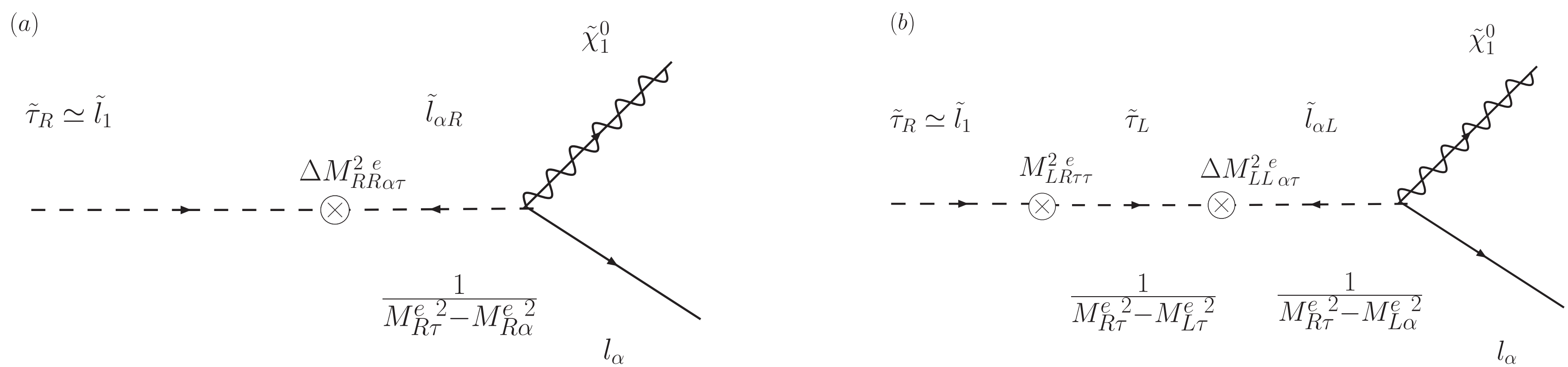
$A_0 = 0$, $\tan\beta = 10$, $\mu > 0$ (Seesaw II: $\lambda_1 = 0.02$, $\lambda_2 = 0.5$)

J.N. Esteves et al., arXiv:0903.1408

Seesaw, special kinematics†

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





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

† S. Kaneko et al., arXiv:0811.0703 (hep-ph)

NMSSM + Seesaw

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

forbid dim-5 operator, e.g. Z_3 + NMSSM†

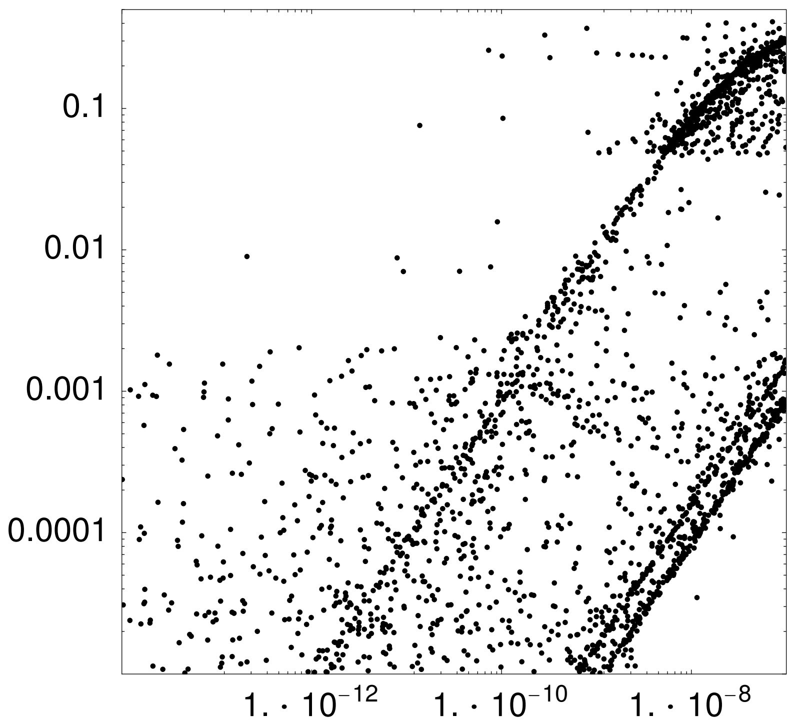
$$\frac{(LH_u)^2 S}{M_6^2} \quad , \quad \frac{(LH_u)^2 S^2}{M_7^3}$$

solves at the same time the μ-problem

† I. Gogoladze, N. Okada, Q. Shafi, arXiv:0809.0703 (hep-ph)

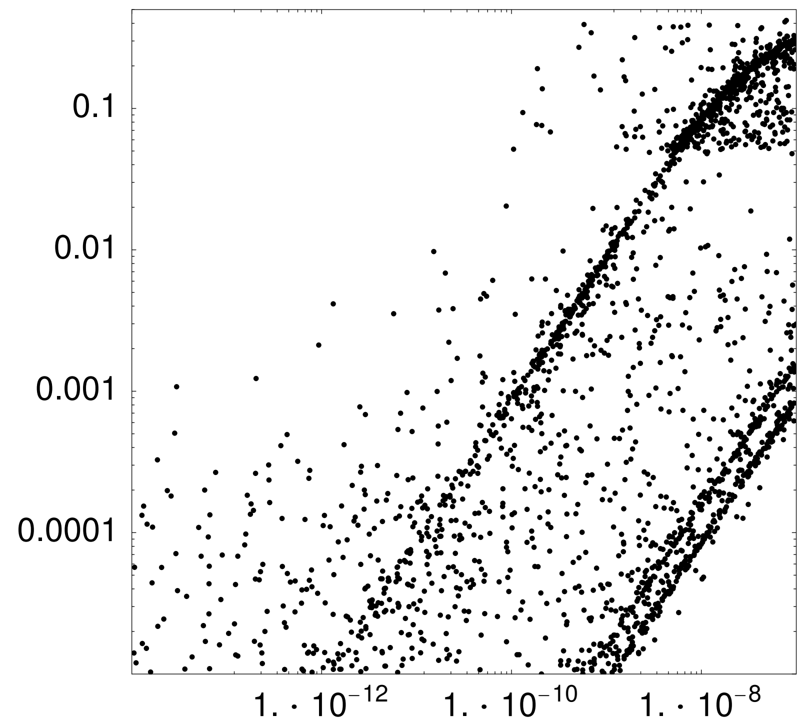
arbitrary $M^2_{E,ij}$, $M^2_{L,ij}$, $A_{l,ij}$: $\tilde{\chi}^0_2 \to \tilde{l}_i l_j \to l_k l_j \tilde{\chi}^0_1$

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



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

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

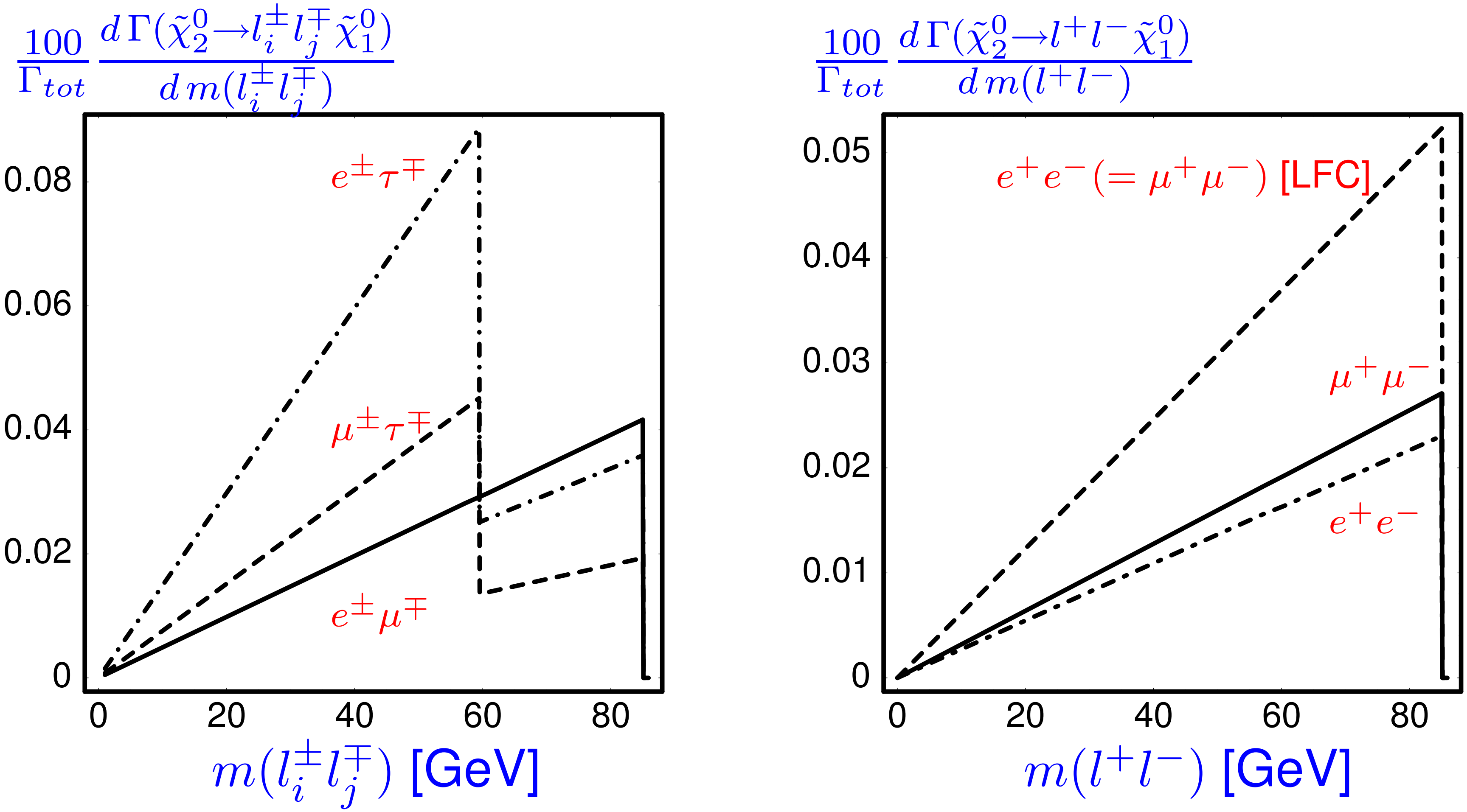


BR$(\tau \to \mu\gamma)$

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

bilinear R-parity violation

R-parity: $(-1)^{3(B-L)+2S}$

bilinear R-parity violation:

$$W = W_{MSSM} + \epsilon_i \widehat{L}_i \widehat{H}_u$$

$\Rightarrow$ mixings between SM and SUSY particles

Gravitino as dark matter*

generic prediction of GMSB : light Gravitino LSP

relic density requires: 100 eV $\lesssim m_{3/2} \lesssim$ 1000 eV

NLSP: $\tilde{\chi}_1^0$ oder $\tilde{l}_R$ ($l = e, \mu, \tau$)

*S. Borgani, A. Masiero, M. Yamaguchi, PLB**386** (1996) 189

F. Takayama and M. Yamaguchi, PLB **485** (2000) 388
M. Hirsch, W. P., D. Restrepo, JHEP **0503**, 062 (2005)

R-parity violation and neutrino masses/mixings

basis $\psi^{0T} = (-i\lambda', -i\lambda^3, \widetilde{H}_d^1, \widetilde{H}_u^2, \nu_e, \nu_\mu, \nu_\tau)$ we get:

$$M_N = \begin{bmatrix} \mathcal{M}_{\chi^0} & m^T \\ m & 0 \end{bmatrix}$$

$$\mathcal{M}_{\chi^0} = \begin{bmatrix} M_1 & 0 & -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u \\ 0 & M_2 & \frac{1}{2}gv_d & -\frac{1}{2}gv_u \\ -\frac{1}{2}g'v_d & \frac{1}{2}gv_d & 0 & -\mu \\ \frac{1}{2}g'v_u & -\frac{1}{2}gv_u & -\mu & 0 \end{bmatrix}, \quad m = \begin{bmatrix} -\frac{1}{2}g'v_1 & \frac{1}{2}gv_1 & 0 & \epsilon_1 \\ -\frac{1}{2}g'v_2 & \frac{1}{2}gv_2 & 0 & \epsilon_2 \\ -\frac{1}{2}g'v_3 & \frac{1}{2}gv_3 & 0 & \epsilon_3 \end{bmatrix}$$

Approximate diagonalization as in usual seesaw mechanism gives

$$m_{\nu,eff} = \frac{M_1 g^2 + M_2 {g'}^2}{4\,det(\mathcal{M}_{\chi^0})} \begin{pmatrix} \Lambda_1^2 & \Lambda_1\Lambda_2 & \Lambda_1\Lambda_3 \\ \Lambda_1\Lambda_2 & \Lambda_2^2 & \Lambda_2\Lambda_3 \\ \Lambda_1\Lambda_3 & \Lambda_2\Lambda_3 & \Lambda_3^2 \end{pmatrix}, \qquad \Lambda_i = \mu v_i + v_d \epsilon_i$$

R-parity violation and neutrino masses/mixings

second ν mass via loops

$$
\begin{aligned}
m_\nu^{1\mathrm{lp}} &\simeq \frac{1}{16\pi^2}\left(3h_b^2 \sin(2\theta_{\tilde{b}}) m_b \log\frac{m^2_{\tilde{b}_2}}{m^2_{\tilde{b}_1}} + h_\tau^2 \sin(2\theta_{\tilde{\tau}}) m_\tau \log\frac{m^2_{\tilde{\tau}_2}}{m^2_{\tilde{\tau}_1}}\right)\frac{(\tilde{\epsilon}_1^2+\tilde{\epsilon}_2^2)}{\mu^2} \\
\tilde{\epsilon}_i &= V^\nu_{ji}\epsilon_j
\end{aligned}
$$

mixing angles

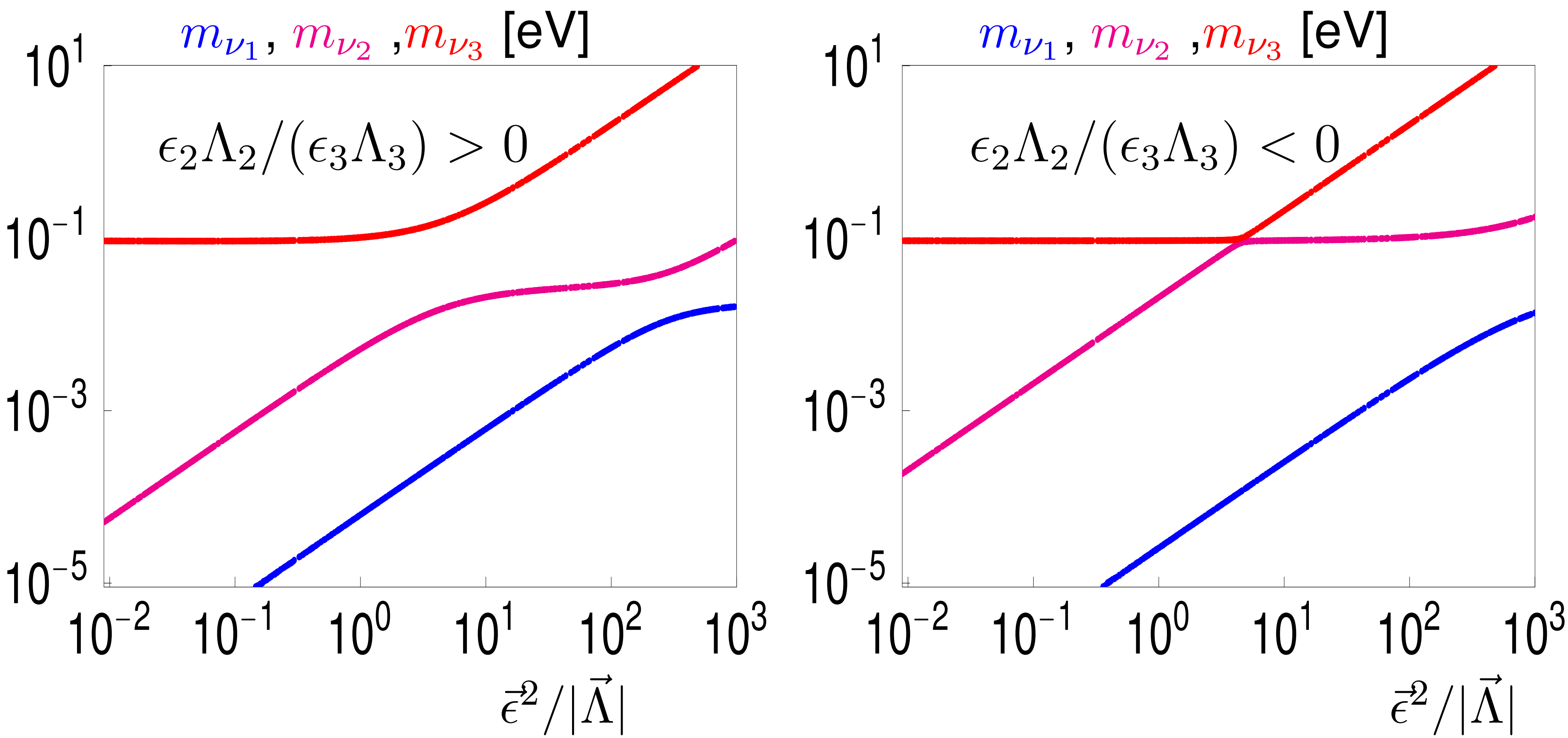
$$
\tan^2\theta_{atm} \simeq \left(\frac{\Lambda_2}{\Lambda_3}\right)^2, \; U^2_{e3} \simeq \frac{|\Lambda_1|}{\sqrt{\Lambda_2^2+\Lambda_3^2}}, \; \tan^2\theta_{sol} \simeq \left(\frac{\tilde{\epsilon}_1}{\tilde{\epsilon}_2}\right)^2
$$

experimental data require:

$$
\frac{|\vec{\Lambda}|}{\sqrt{\det\mathcal{M}_{\tilde{\chi}^0}}} \sim O(10^{-6}), \qquad \frac{|\vec{\epsilon}|}{\mu} \sim O(10^{-4})
$$

Neutrino masses

Two examples of neutrino masses as function of $\vec{\epsilon}^2/|\vec{\Lambda}|$
(other parameters fixed):



Neutralino decays

dominant modes R-parity violating modes

$$\Gamma(\tilde{\chi}^0_1 \to W^\pm l_i^\mp) \quad \propto \quad \frac{\Lambda_i^2}{\det \mathcal{M}_{\tilde{\chi}^0}}$$

$$\Gamma(\tilde{\chi}^0_1 \to \sum_i Z \nu_i) \quad \simeq \quad \frac{1}{2} \sum_i \Gamma(\tilde{\chi}^0_1 \to W^\pm l_i^\mp)$$

$$\Gamma(\tilde{\chi}^0_1 \to \nu \tau^+ l_i^-) \quad \propto \quad \frac{\epsilon_i^2}{\mu^2}$$

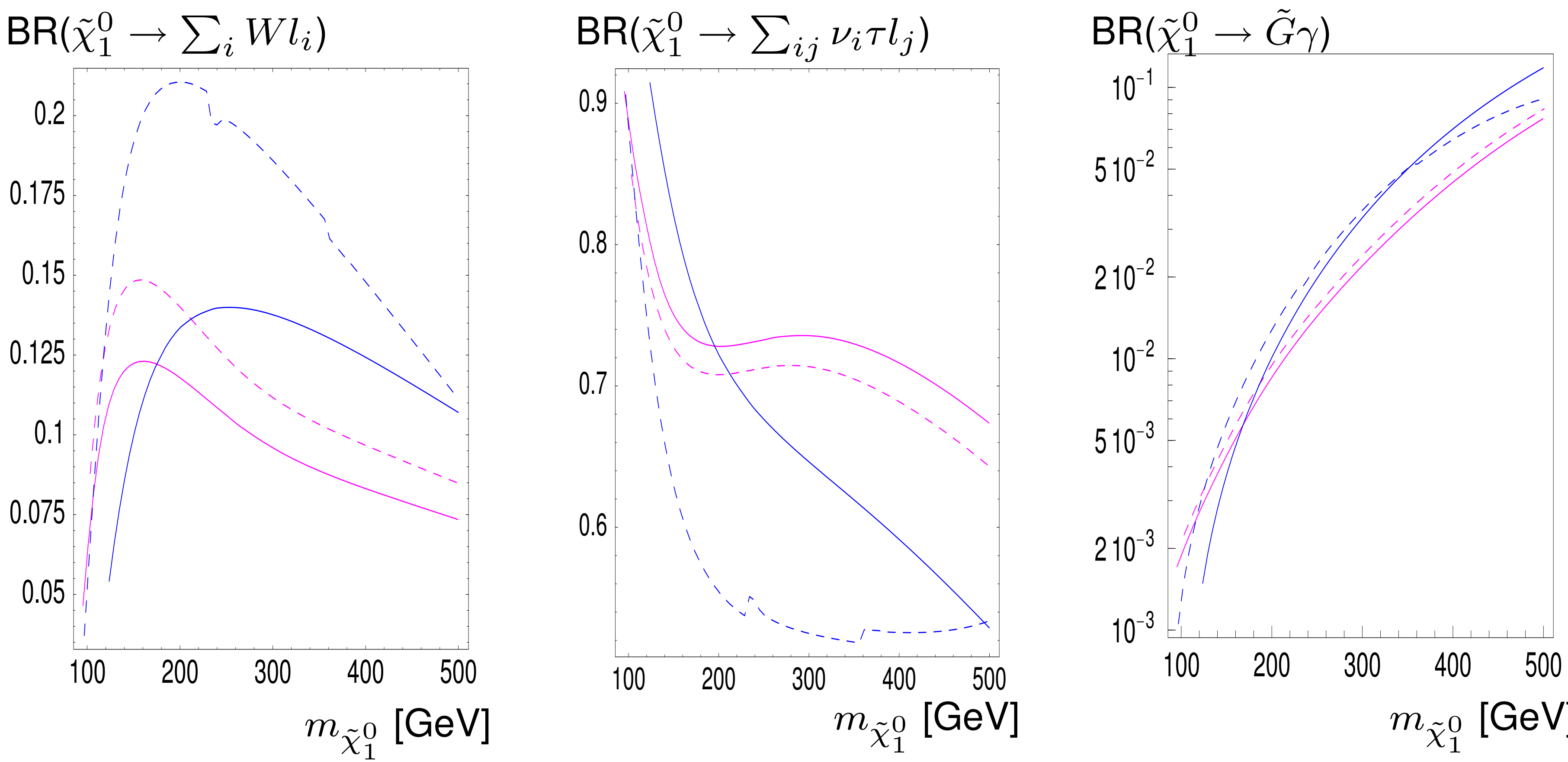
R-parity conserving mode

$$\Gamma(\tilde{\chi}^0_1 \to \tilde{G}\gamma) \quad \simeq \quad 1.2 \times 10^{-6} \kappa_\gamma^2 \left(\frac{m_{\tilde{\chi}^0_1}}{100 \;\; \mathrm{GeV}}\right)^5 \left(\frac{100 \;\; \mathrm{eV}}{m_{3/2}}\right)^2 \mathrm{eV}$$

total width

$$\Gamma \simeq (10^{-4} - 10^{-2})\,\mathrm{eV}$$

Neutralino decays



— $\tan\beta = 10,\ \mu > 0$, - - $\tan\beta = 10,\ \mu < 0$, — $\tan\beta = 35,\ \mu > 0$, - - $\tan\beta = 35,\ \mu < 0$

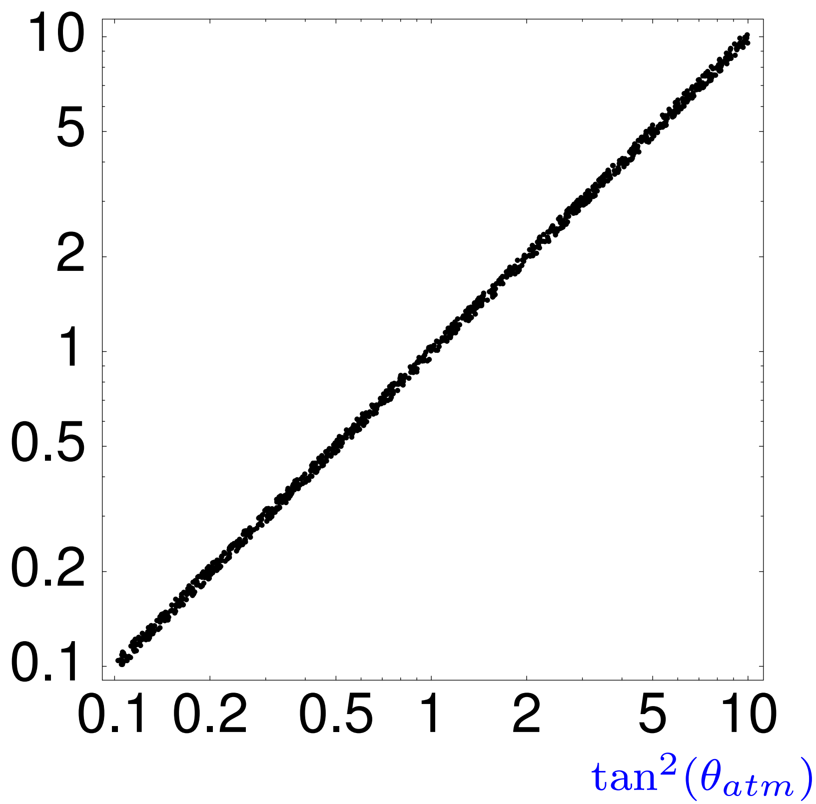
$m_{3/2} = 100$ eV, $n_5 = 1$

M. Hirsch, W. P. und D. Restrepo, JHEP **0503**, 062 (2005)

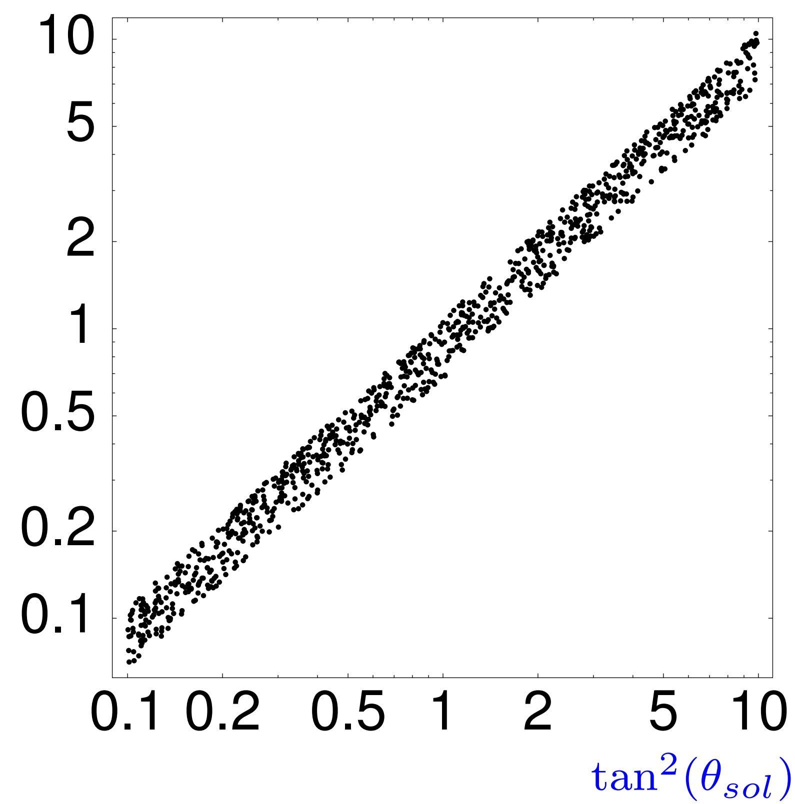
Neutralino decays, correlations

Correlations

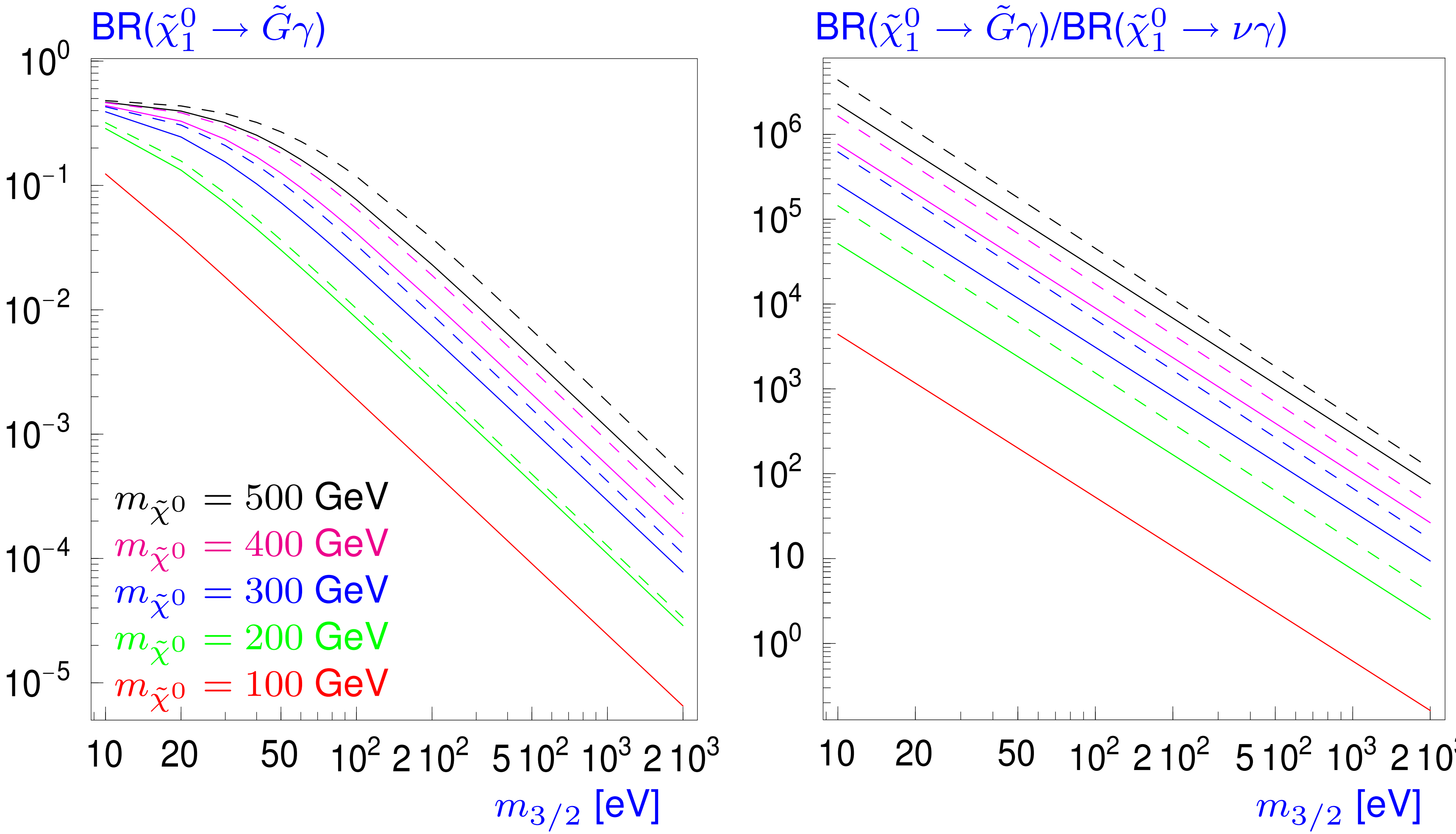
BR($\tilde{\chi}_1^0 \to W\mu$) / BR($\tilde{\chi}_1^0 \to W\tau$)



BR($\tilde{\chi}_1^0 \to \nu e\tau$) /BR($\tilde{\chi}_1^0 \to \nu\mu\tau$)



GMSB signals



$$n_5 = 1, \tan\beta = 10$$

Comments

- $$\frac{m_{\tilde{\tau}_1}}{m_{\tilde{\chi}_1^0}} \propto \frac{1}{\sqrt{n_5}}$$

  $\Rightarrow$ for $n_5 \geq 3$ hardly points with $\tilde{\chi}_1^0$ LSP
- $\tilde{l}_R$ NLSPs: BR($l\nu$) $\gg$ BR($l\tilde{G}$)
- $n_5 = 2$: BR($\tilde{G}\gamma$) reduced by a factor 2-3
- $\tilde{G}$ decays via R-parity violating couplings, however:

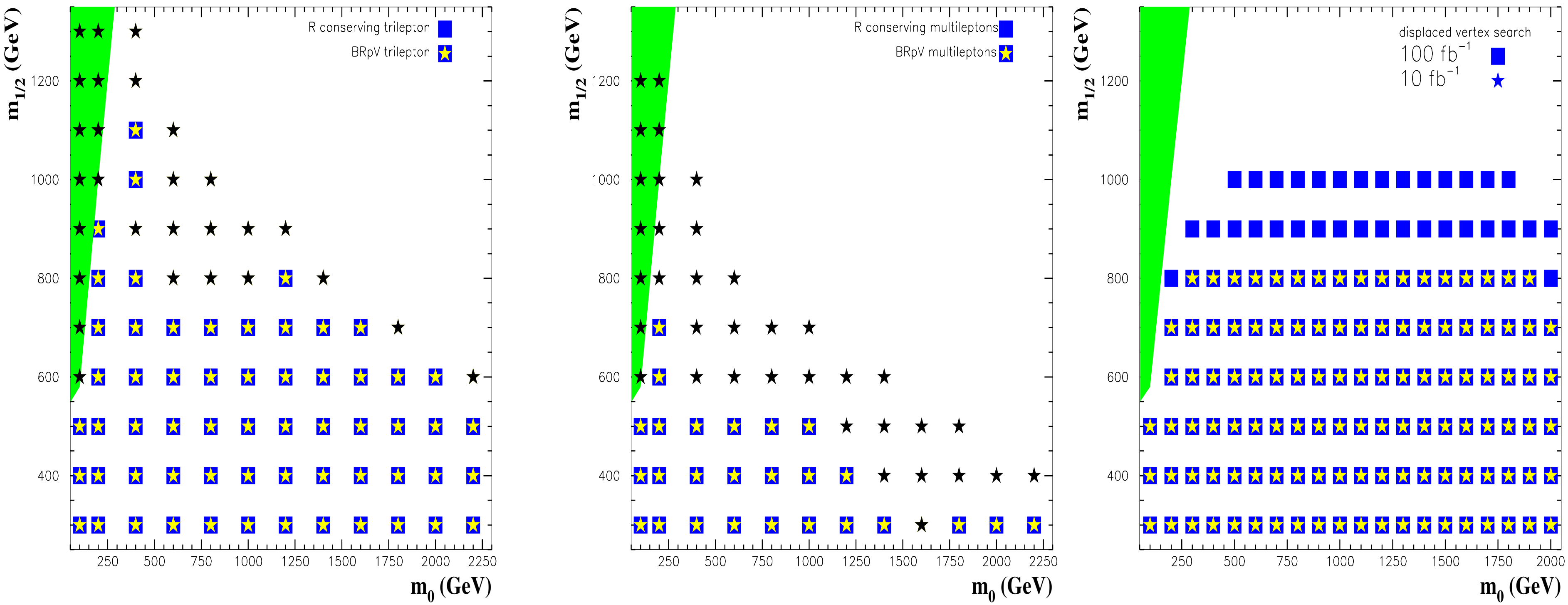
$$\Gamma(\tilde{G}) \simeq 3.5 \cdot 10^{-16} \frac{m_\nu[\mathrm{eV}]}{0.05\mathrm{eV}} \frac{m_{3/2}^3}{M_{Pl}^2} \quad \Rightarrow \tau(\tilde{G}) \sim O(10^{31})\mathrm{Hubbletimes}$$

bilinear R-parity violation, reach in mSUGRA

3-lepton channel

multi-lepton channel

displaced vertex

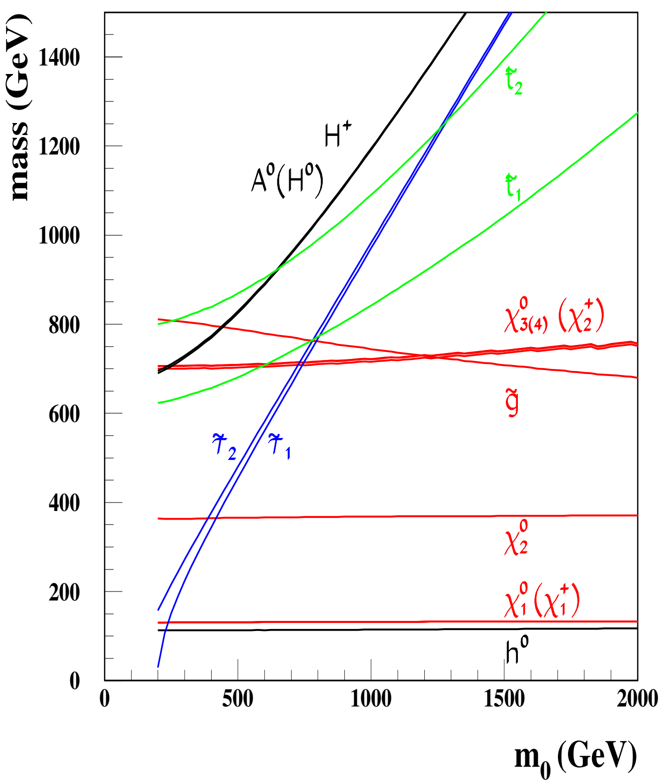


$L = 100$ fb^{-1}, $A_0 = -100$ GeV, $\tan\beta = 10$, $\mu > 0$

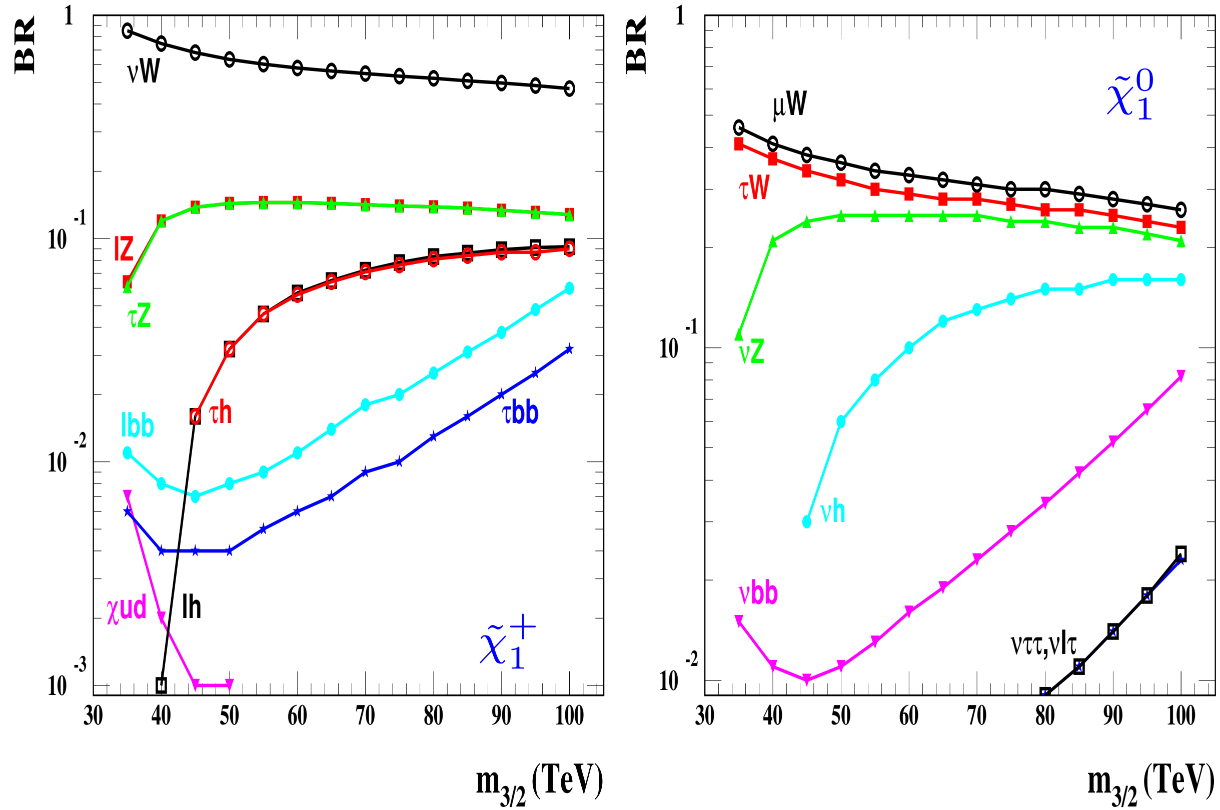
F. de Campos et al., JHEP **0805**, 048 (2008)

bilinear R-parity + AMSB

$\tan\beta = 10$, $\mu > 0$
$m_{3/2} = 40$ TeV



$\tan\beta = 10$, $\mu > 0$, $m_0 = 800$ GeV



F. de Campos et al., arXiv:0803.4405 (hep-ph)

Spontaneously broken R-parity

add singlet $\widehat{S}$ with lepton number

$$\begin{aligned}\mathcal{W} &= h_U^{ij}\widehat{Q}_i\widehat{U}_j\widehat{H}_u + h_D^{ij}\widehat{Q}_i\widehat{D}_j\widehat{H}_d + h_E^{ij}\widehat{L}_i\widehat{E}_j\widehat{H}_d \\ &+ h_\nu^i\widehat{L}_i\widehat{\nu}^c\widehat{H}_u - h_0\widehat{H}_d\widehat{H}_u\widehat{\Phi} + h\widehat{\Phi}\widehat{\nu}^c\widehat{S} + \frac{\lambda}{3!}\widehat{\Phi}^3\end{aligned}$$

electroweak symmetry breaking $\Rightarrow \langle\widehat{\nu}^c\rangle = v_R/\sqrt{2}$

$$h_\nu^i\widehat{L}_i\widehat{\nu}^c\widehat{H}_u \Rightarrow \frac{v_R h_\nu^i}{\sqrt{2}}$$

broken lepton number $\Rightarrow$ Goldstone boson called majoron J

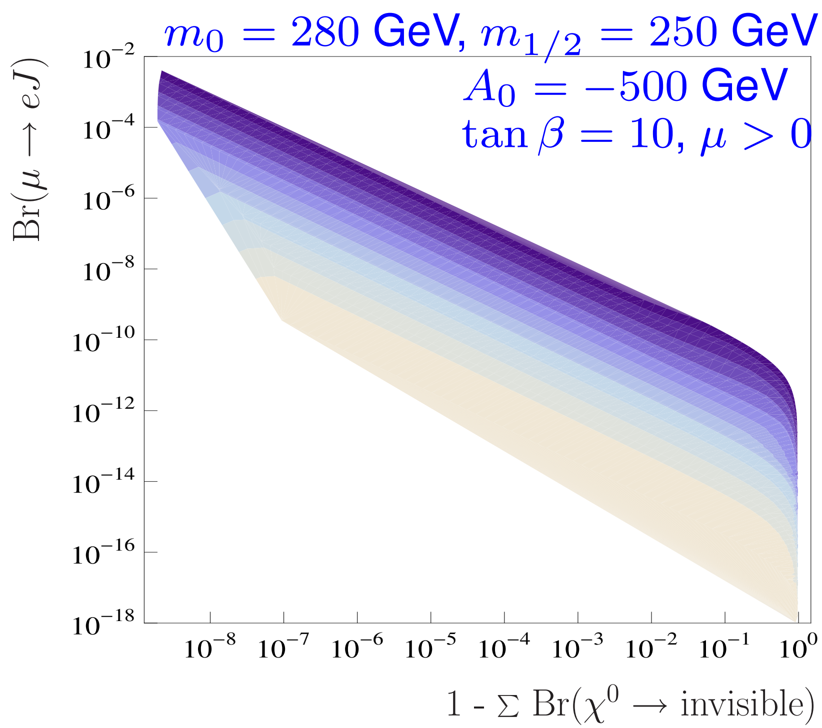
$$h^0 \to JJ$$

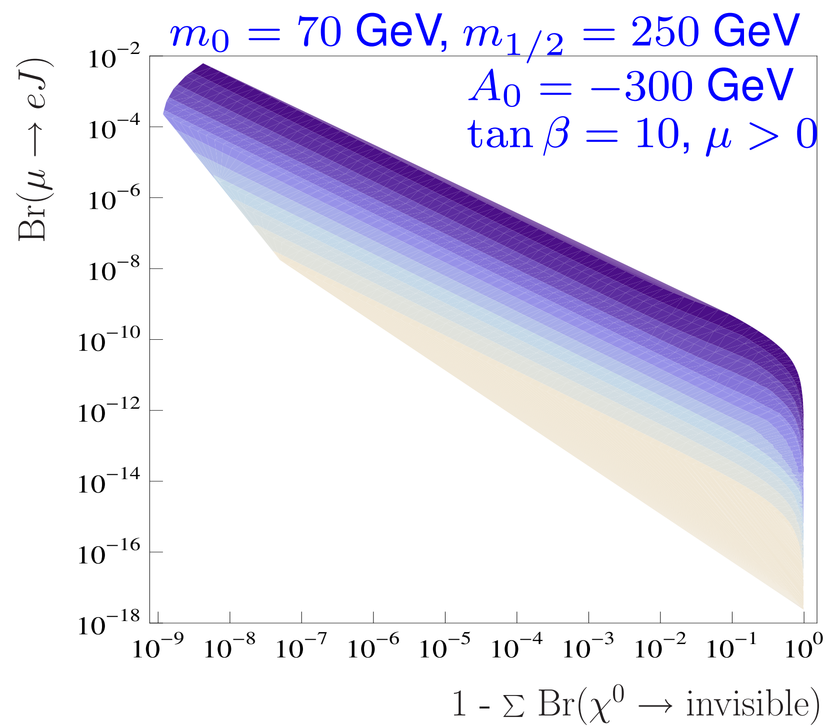
M. Hirsch, J. C. Romão, J. W. F. Valle and A. Villanova del Moral, PRD **70**, 073012 (2004), PRD **73**, 055007 (2006)

Spontaneously broken R-parity

induce also

$$\tilde{\chi}_1^0 \to \nu J \quad , \quad \mu \to eJ$$





M. Hirsch, W. P., PRD **74** (2006) 055003;

M. Hirsch, A. Vicente, J. Meyer, W. P., PRD **79** (2009) 055023.

Spontaneous R-parity via gauge interactions

no majoron J but heavy gauge bosons

extra $U(1)$: additional Z', $\tilde{Z}'$
(L. L. Everett, P. Fileviez Perez, S. Spinner PRD **80** (2009) 055007; P. Fileviez Perez, S. Spinner, PD **80** (2009) 015004)

extra $U(1)$ + SUGRA: additional Z', $\tilde{Z}'$ + exotic states with masses in the TeV range
(R. S. Hundi, S. Pakvasa and X. Tata, PRD **79** (2009) 095011)

Left-right symmetric models: triplet Higgs bosons + higgsinos, W_R, Z_R, $\tilde{W}_R$, $\tilde{Z}_R$
K. Huitu and J. Maalampi, *Phys. Lett.* **B344** (1995) 217

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Trilinear R-parity breaking

Connection to trilinear R-parity violation: rotate $(\hat{H}_d, \hat{L}_i)$ such, that $\epsilon_i' = 0$; gives in leading order of ϵ_i/μ:

$$\lambda'_{ijk} = \frac{\epsilon_i}{\mu} \delta_{jk} Y_{d_k}$$

and

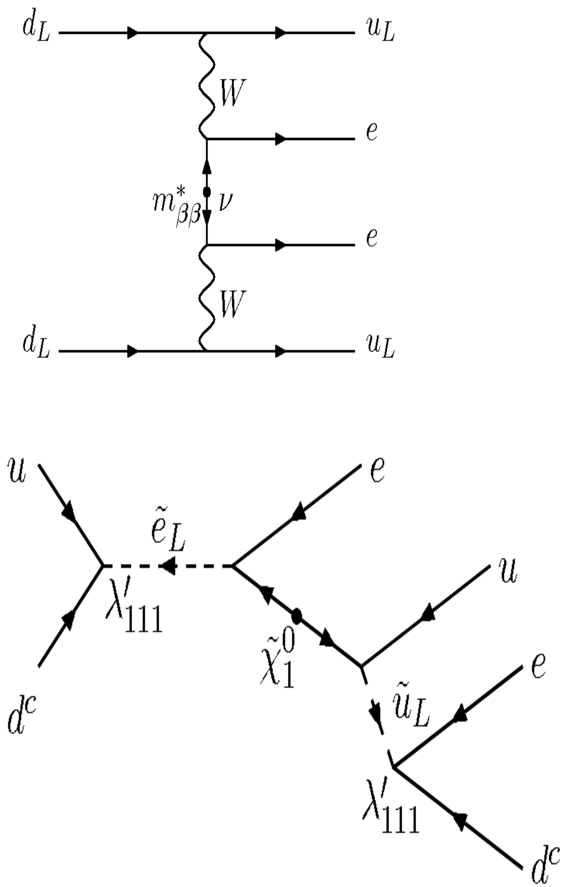
$$\lambda_{121} = Y_e \tfrac{\epsilon_2}{\mu}, \quad \lambda_{122} = Y_\mu \tfrac{\epsilon_1}{\mu}, \quad \lambda_{123} = 0$$

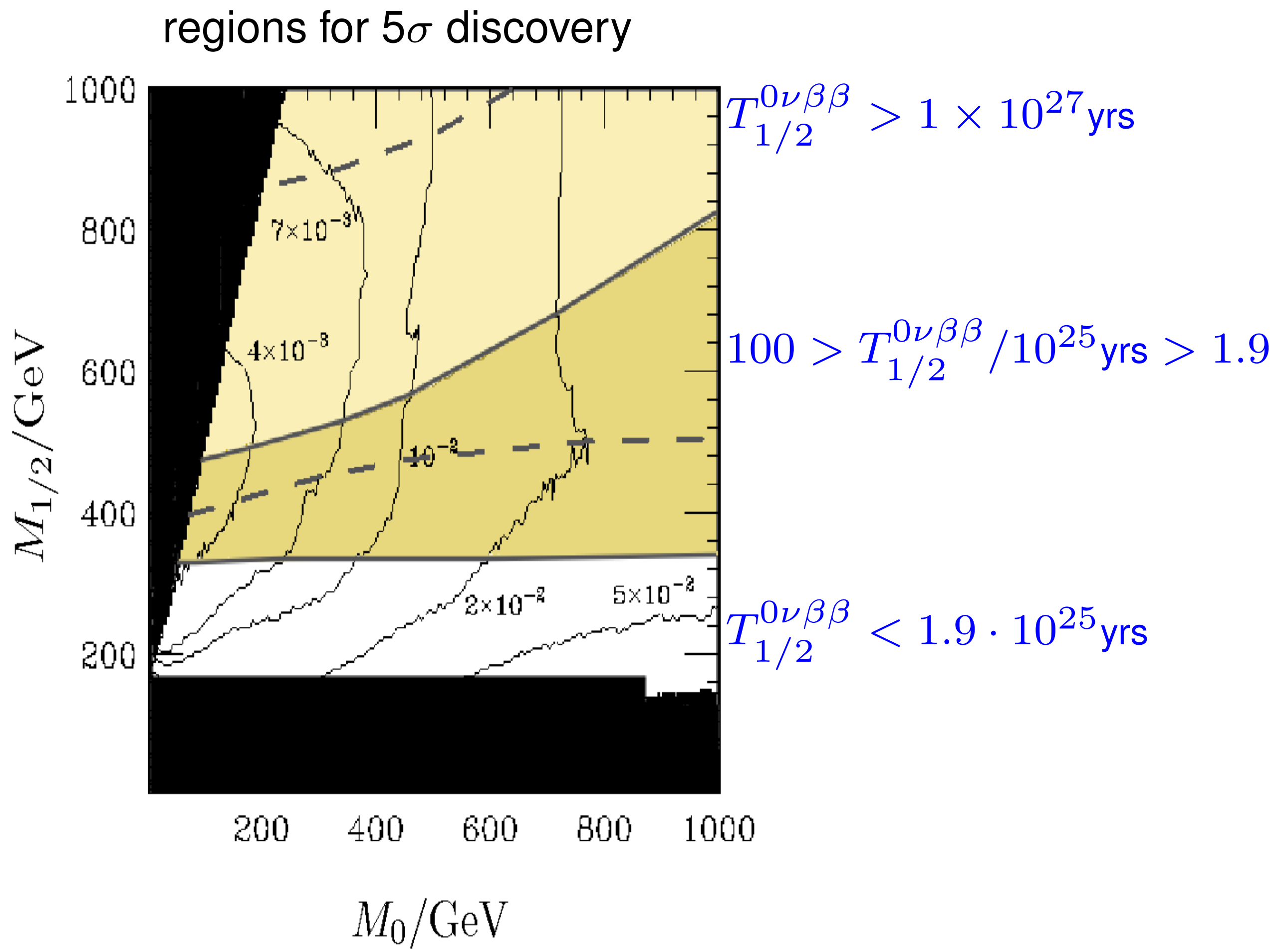
$$\lambda_{131} = Y_e \tfrac{\epsilon_3}{\mu}, \quad \lambda_{132} = 0, \quad \lambda_{133} = Y_\tau \tfrac{\epsilon_1}{\mu}$$

$$\lambda_{231} = 0, \quad \lambda_{232} = Y_\mu \tfrac{\epsilon_3}{\mu}, \quad \lambda_{233} = Y_\tau \tfrac{\epsilon_2}{\mu}$$

$$\lambda_{ijk} = -\lambda_{jik}$$

R-parity, $0\nu\beta\beta$, single slepton production





$L = 10$ fb^{-1} at 14 TeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$

B. C. Allanach, C. H. Kom, H. Päs, HEP **0910** (2009) 026

related work: H. K. Dreiner, P. Richardson, M. H. Seymour, JHEP 0004 (2000) 008

Conclusions

- Dirac neutrinos: displaced vertices if $\tilde{\nu}_R$ LSP, e.g. $\tilde{t}_1 \to l b \tilde{\nu}_R$ (but NMSSM: $\tilde{t}_1 \to l b \nu \tilde{\chi}^0_1$)
- Seesaw models:
  - most promosing: $\tilde{\tau}_2$ decays
  - very difficult to test at LHC, signals of O(10 fb) or below
  - exceptions: either special kinematics or additional symmetries + NMSSM
  - in case of Seesaw II: different mass ratios

Conclusions

- R-parity violation
  - interesting correlations between ν-physics and LSP decays, testable at LHC
  - displaced vertices
  - Can the model be pinned down?

SUSY masses at LHC

talk by I. Borjanovic at 'Flavour in the era of LHC', Nov.'05, CERN

L=**100 fb**$^{-1}$

Fit results

Edge	Nominal Value	Fit Value	Syst. Error Energy Scale	Statistical Error
$m(ll)^{edge}$	77.077	77.024	0.08	0.05
$m(qll)^{edge}$	431.1	431.3	4.3	2.4
$m(ql)^{edge}_{min}$	302.1	300.8	3.0	1.5
$m(ql)^{edge}_{max}$	380.3	379.4	3.8	1.8
$m(qll)^{thres}$	203.0	204.6	2.0	2.8

Mass reconstruction

5 endpoints measurements, 4 unknown masses

$$\chi^2 = \sum \chi_j^2 = \sum \left[\frac{E_j^{theory}(\vec{m}) - E_j^{exp}}{\sigma_i^{exp}} \right]^2$$

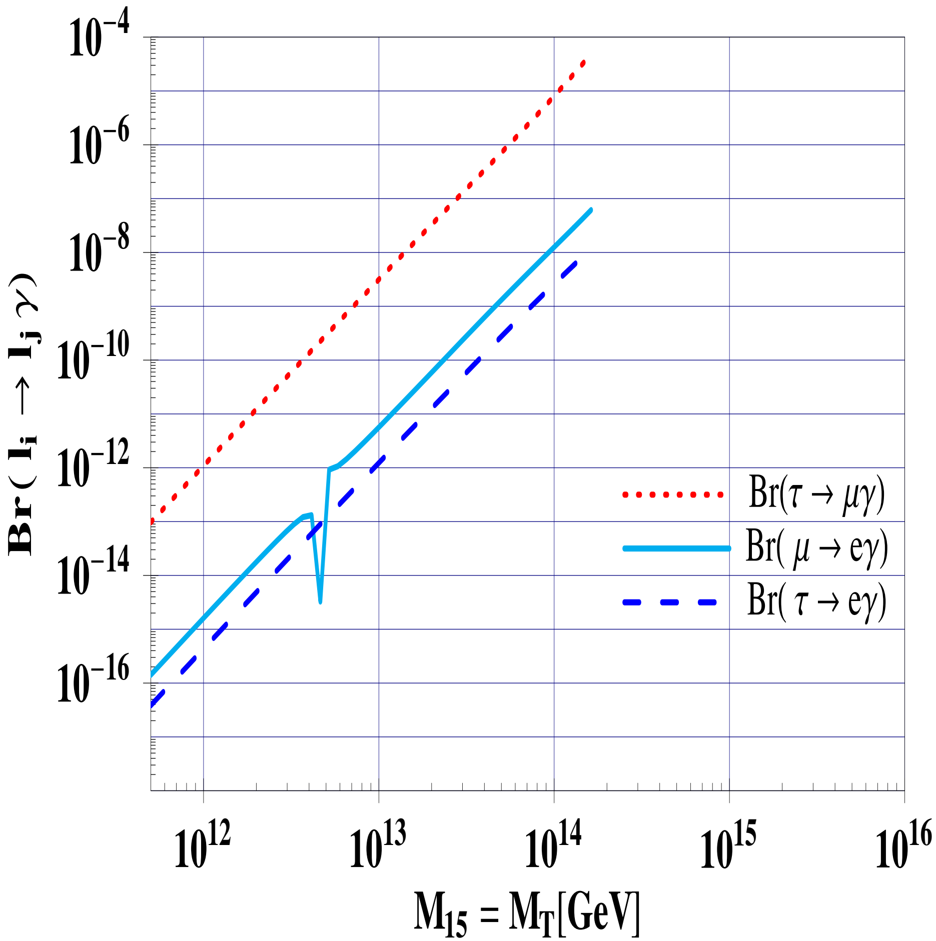
$$E_j^i = E_j^{nom} + a_j^i \sigma_j^{fit} + b^i \sigma_j^{Escale}$$

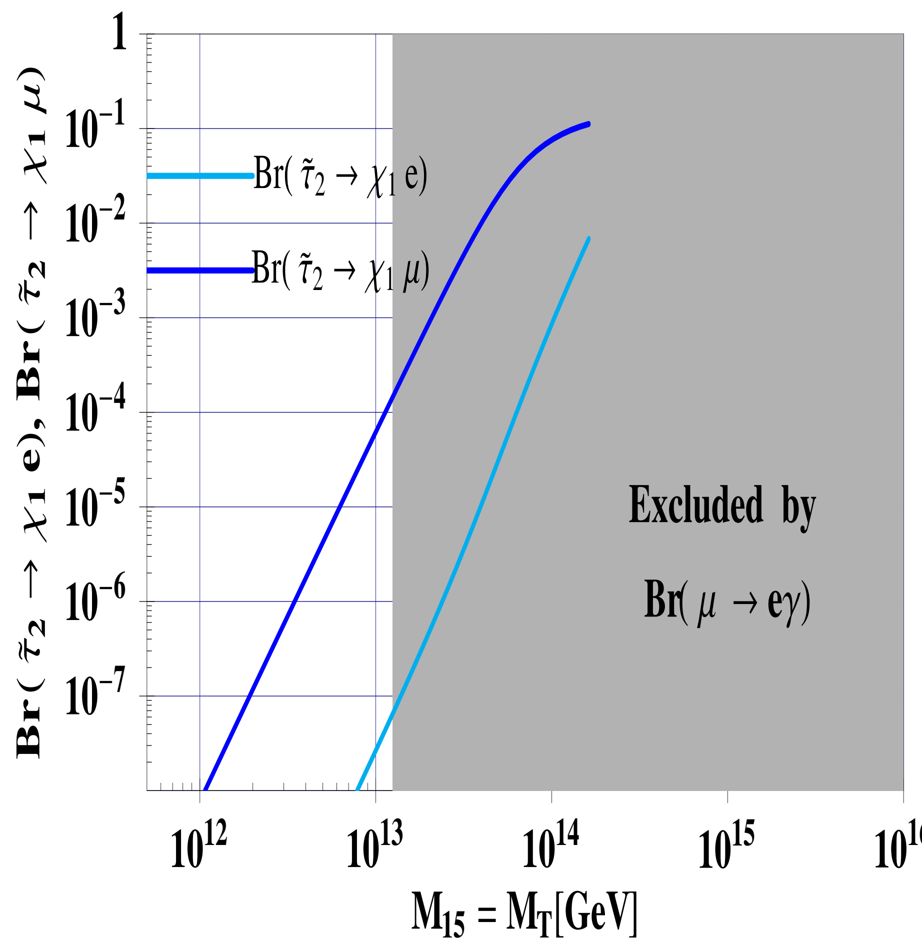
$m(\chi_1^0) = 96$ GeV
$m(l_R) = 143$ GeV
$m(\chi_2^0) = 177$ GeV
$m(q_L) = 540$ GeV

$\Delta m(\chi_1^0) = 4.8$ GeV, $\Delta m(\chi_2^0) = 4.7$ GeV,
$\Delta m(l_R) = 4.8$ GeV, $\Delta m(q_L) = 8.7$ GeV

Gjelsten, Lytken, Miller, Osland, Polesello, ATL-PHYS-2004-007

Seesaw II with 15-plets



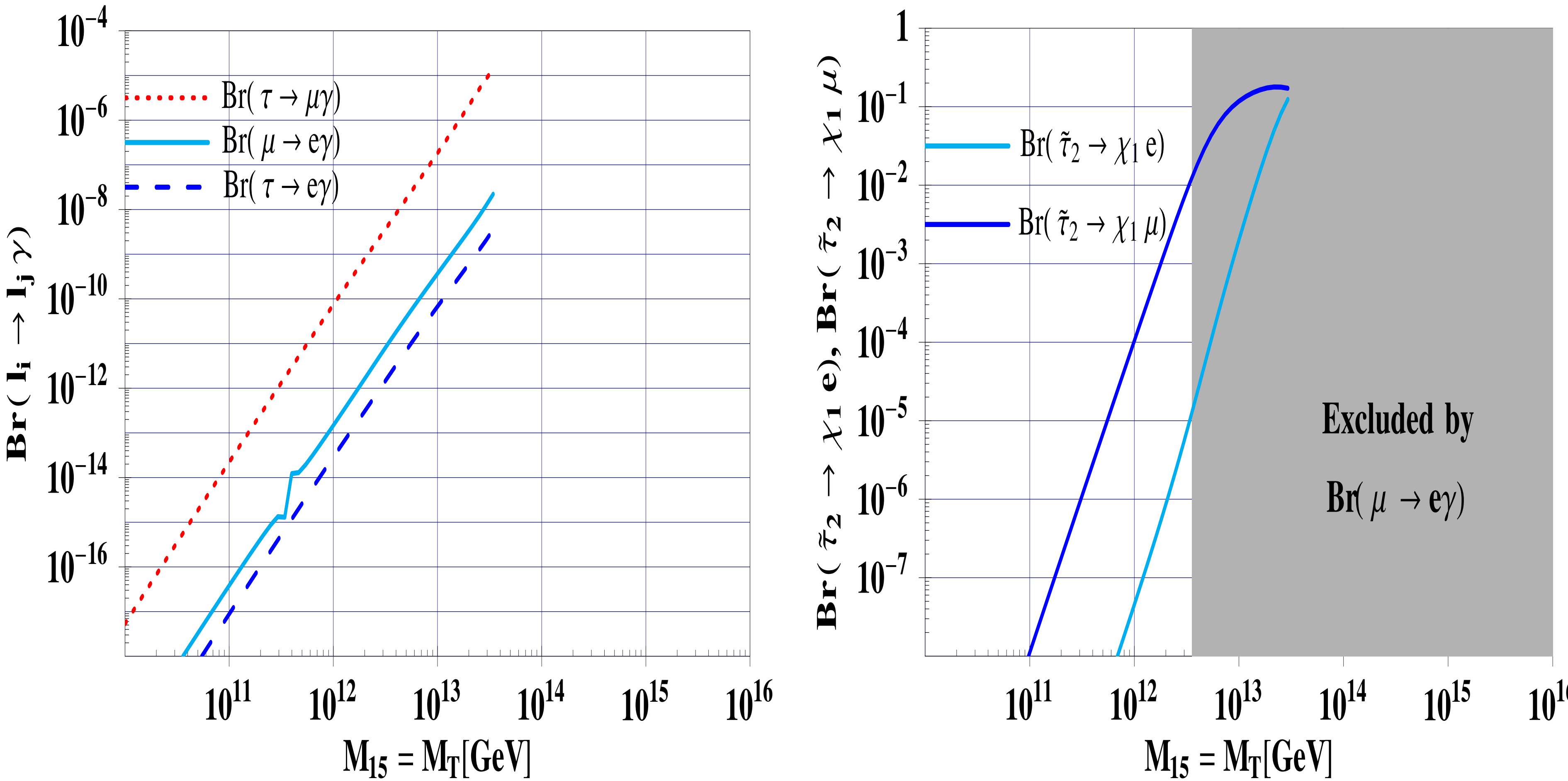


$\lambda_1 = \lambda_2 = 0.5$

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

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

Seesaw II with 15-plets

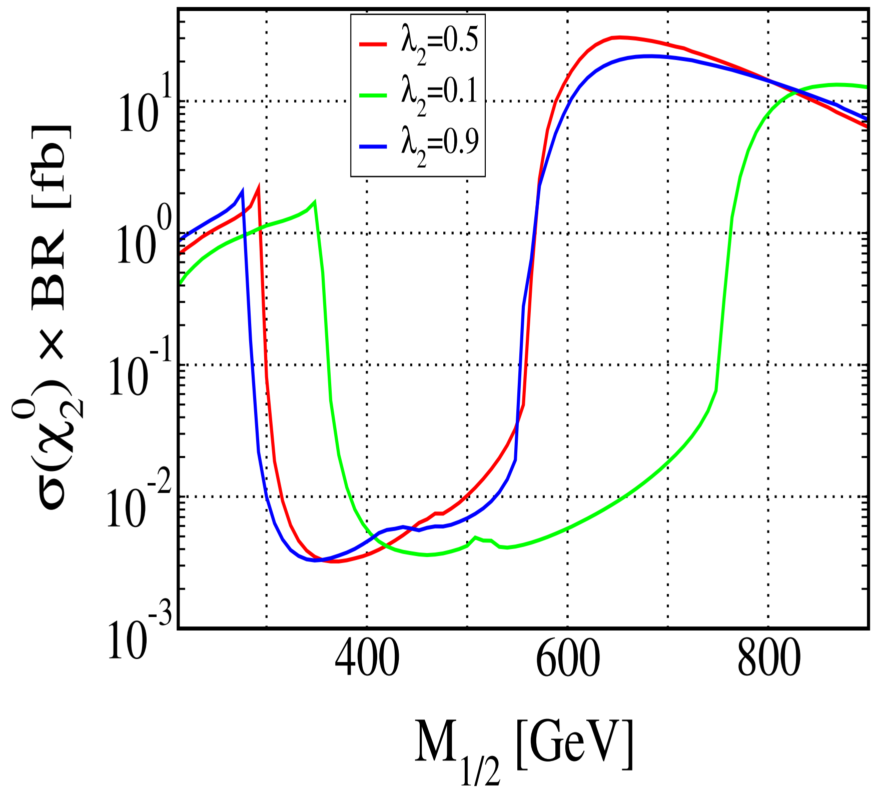


$\lambda_1 = \lambda_2 = 0.05$

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 I + II, signal at LHC



$\sigma(pp \to \tilde\chi_2^0) \times BR(\chi_2^0 \to \sum_{i,j} \tilde l_i l_j \to \mu^\pm \tau^\mp \tilde\chi_1^0)$

$m_0 = 100$ GeV $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$, $\lambda_1 = 0.02$

J.N. Esteves et al., arXiv:0903.1408