Testing supersymmetric neutrino mass models at the LHC

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Overview

- ”Why supersymmetry” or
  ”Why do we want to extend the Standard Model”
- Neutrinos & lepton flavour violation
- Signals in models with
  - Dirac neutrinos
  - Majorana neutrinos
  - Neutrino masses via R-parity violation
- Conclusions

Why supersymmetry

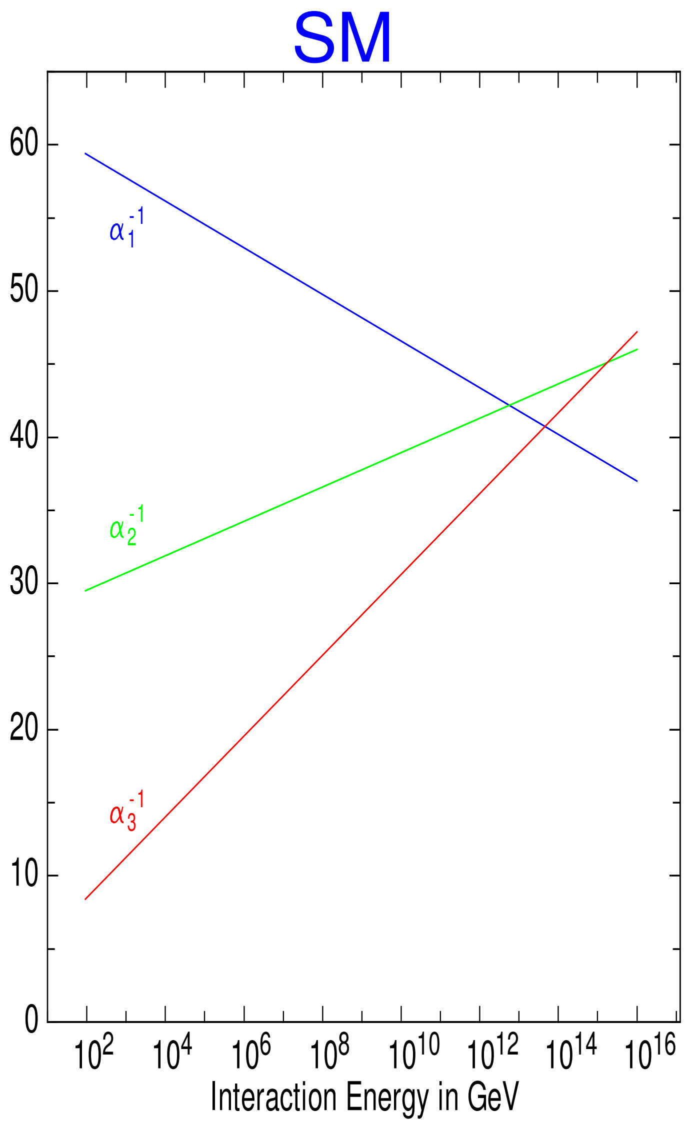
- How to combine gravity with the SM?

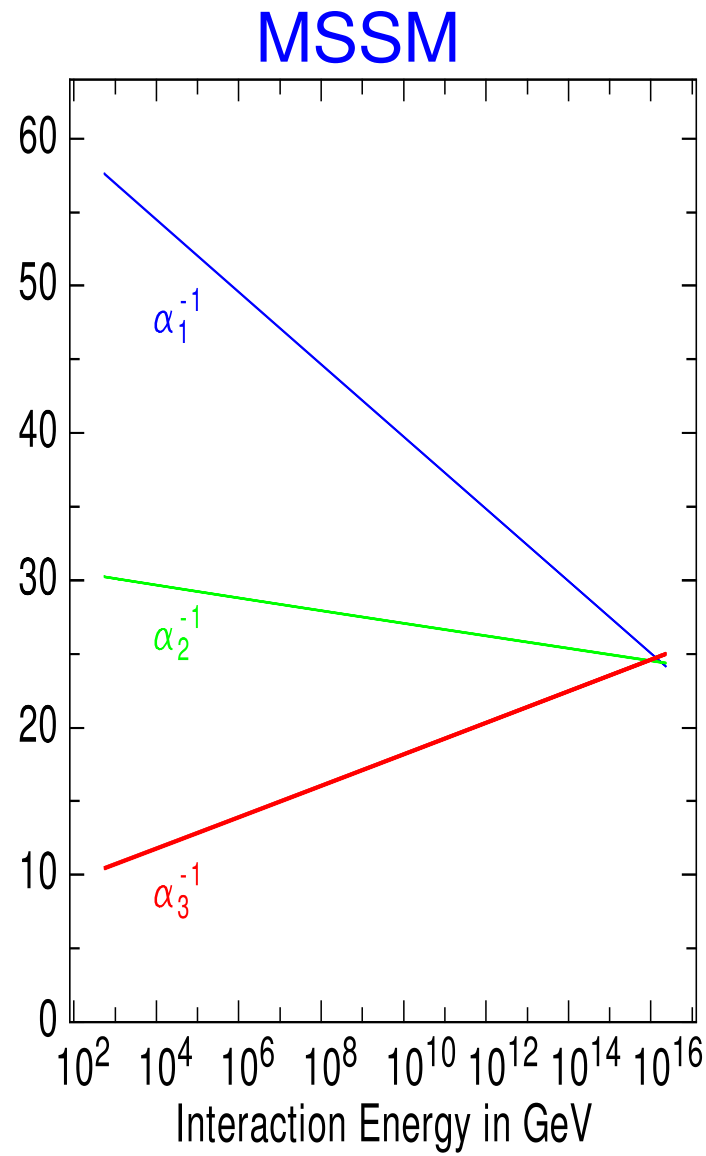
  $\Rightarrow$ local Supersymmetry (SUSY) implies gravity

- SM particles can be put in multiplets of larger gauge groups
  - in $SU(5)$: $1 = \nu_R^c$, $5 = (d^c_{\alpha,R}, \nu_{l,L}, l_L)$, $10 = (u_{\alpha,L}, u^c_{\alpha,R}, d_{\alpha,L}, l_R)$
  - in $SO(10)$: $16 = (u_{\alpha,L}, u^c_{\alpha,R}, d_{\alpha,L}, d^c_{\alpha,R}, l_L, l_R, \nu_{l,L}, \nu_R^c)$

  However there are two problems in the SM but not in SUSY:
  - proton decay (also in SUSY $SU(5)$ a problem)
  - gauge coupling unification

Evolution of gauge couplings: SM versus SUSY





Why supersymmetry

- What is the nature of dark matter ?
- What is the origin of the observed baryon asymmetry?
- Why three generations ?

  Why do have neutrinos so tiny masses?
- ”Why does electroweak symmetry break?” or

  ”Why is $\mu^2 < 0$ in the SM?”
- Hierarchy problem

Supersymmetry, MSSM

	Standard Model		MSSM
matter:	e d d d ν_e u u u	$\Leftrightarrow$	$\tilde{e}$ $\tilde{d}$ $\tilde{d}$ $\tilde{d}$ $\tilde{\nu}_e$ $\tilde{u}$ $\tilde{u}$ $\tilde{u}$
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 for the moment conserved R-Parity: $(-1)^{(3(B-L)+2s)}$

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

Experimental information

- Mass bounds from LEP/Tevatron:
  - Higgs: $\gtrsim$ 100 GeV
  - charginos/sleptons $\gtrsim$ 100 GeV
  - squarks (except $\tilde{t}, \tilde{b}$), gluinos: $\gtrsim$ 300 GeV
- rare decays:
  bounds on flavour violation beyond CKM
- Cold dark matter: $\Omega h^2 \lesssim 0.12$
- high precision measurments of gauge couplings
  $\Rightarrow$ unification if SUSY is present

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. $\tilde{t}_1 \to l^+ b \tilde{\nu}_R$

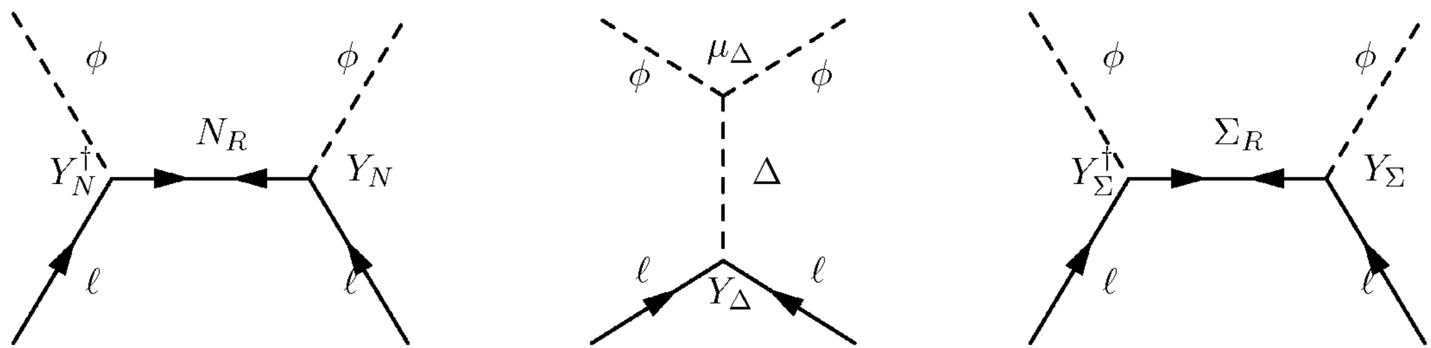
Remark: $m_{\tilde{\nu}_R}$ hardly runs $\Rightarrow$ e.g. $m_{\tilde{\nu}_R} \simeq m_0$ in mSUGRA
$m_{\tilde{\nu}_R} \simeq 0$ in GMSB

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

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

†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

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

Seesaw I

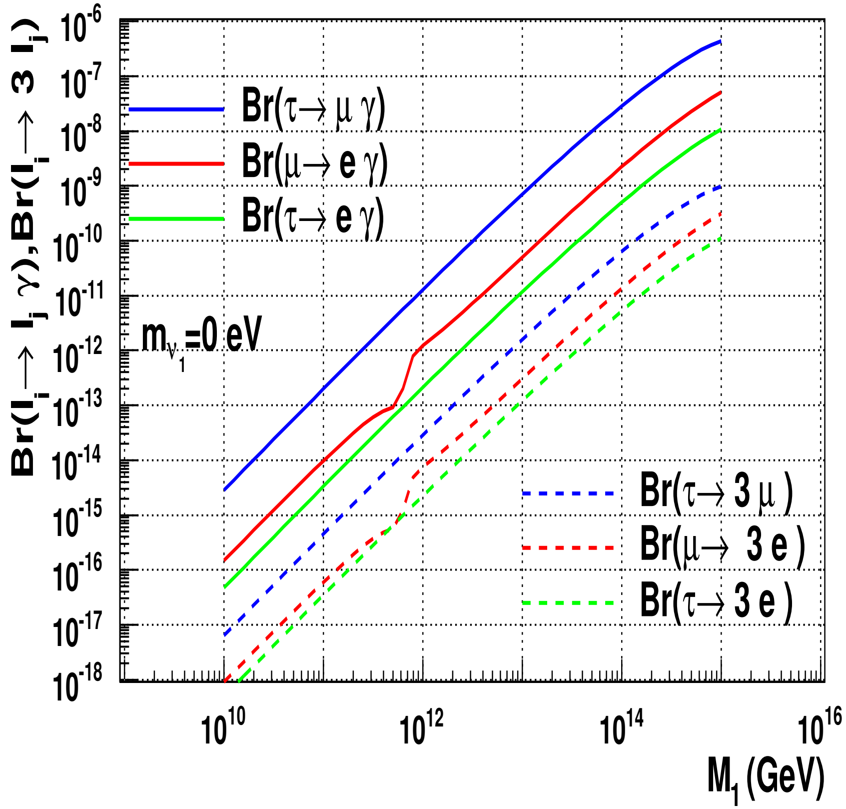
take all parameters real

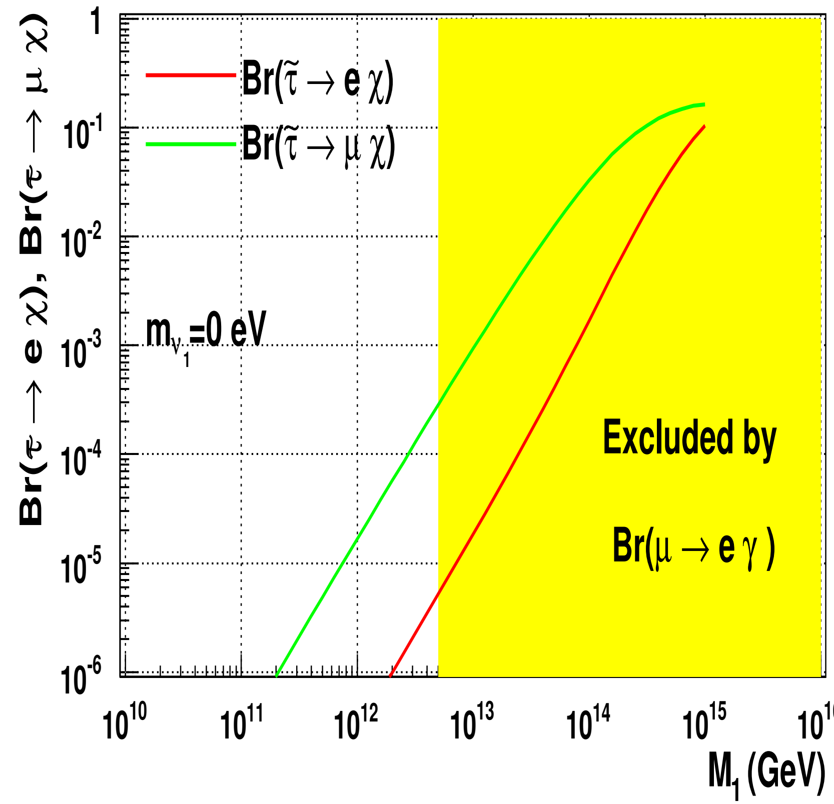
$$U = U_{\text{TBM}} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

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

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

Seesaw I



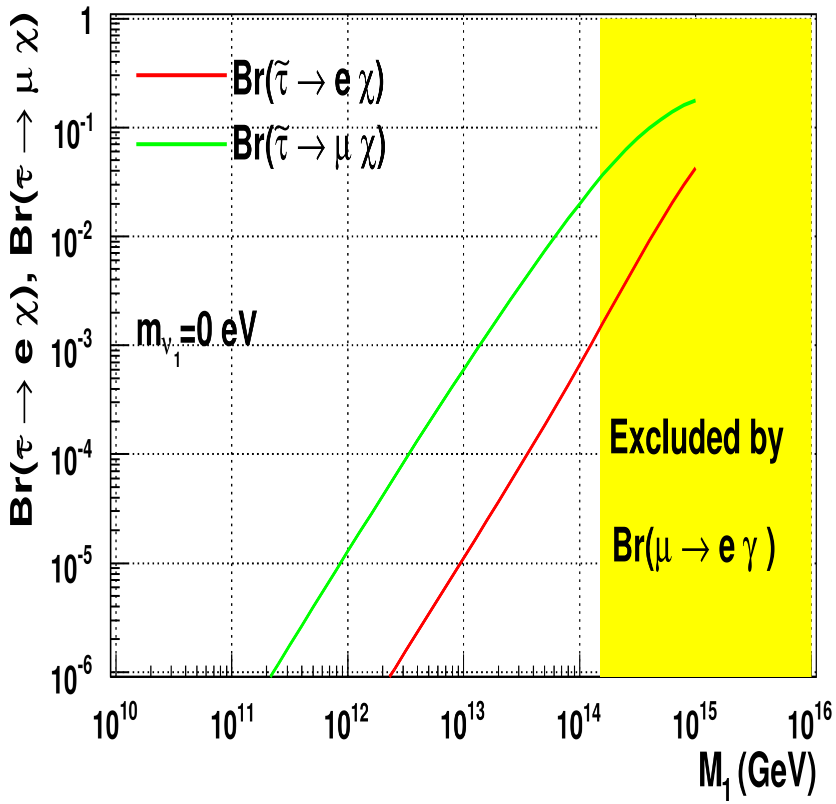


degenerate ν_R

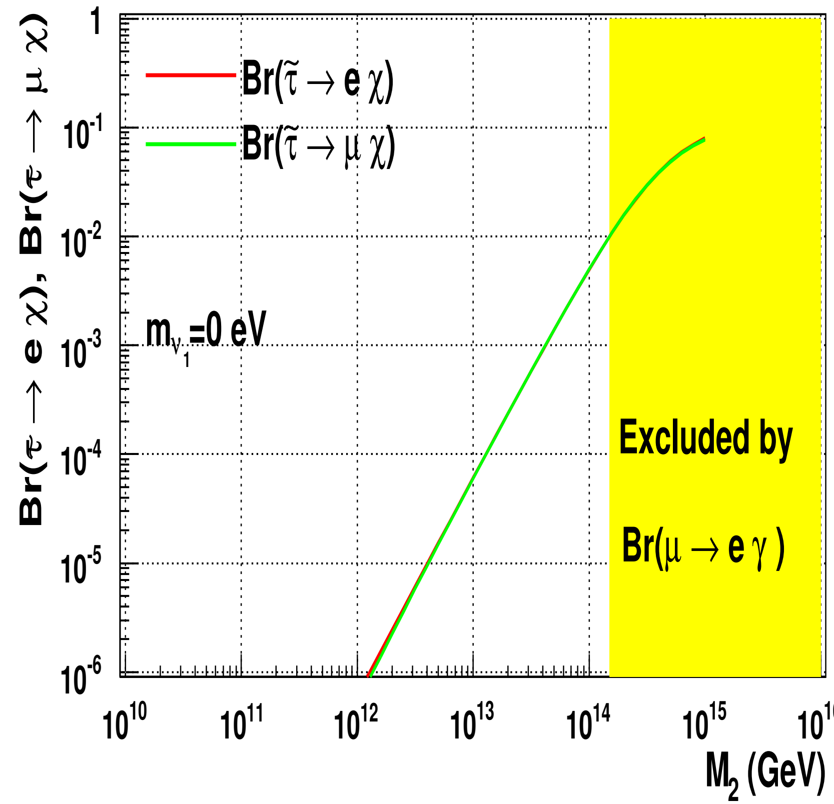
SPS1a' ($M_0 = 70$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, $\mu > 0$)

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, $\tan\beta = 10$, $\mu > 0$)

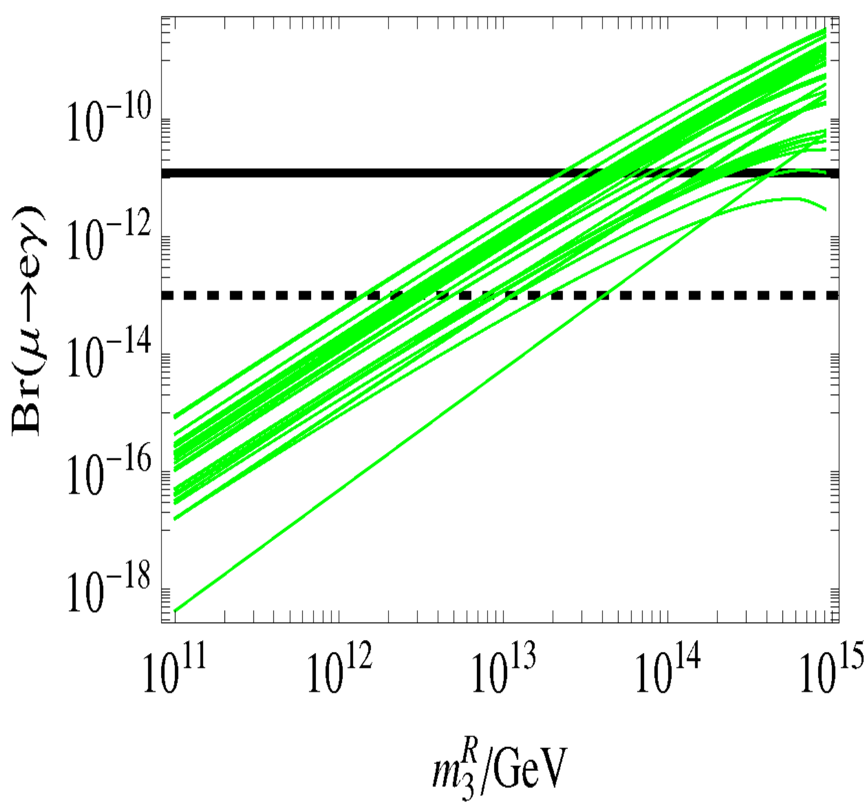
M. Hirsch et al. Phys. Rev. D **78** (2008) 013006

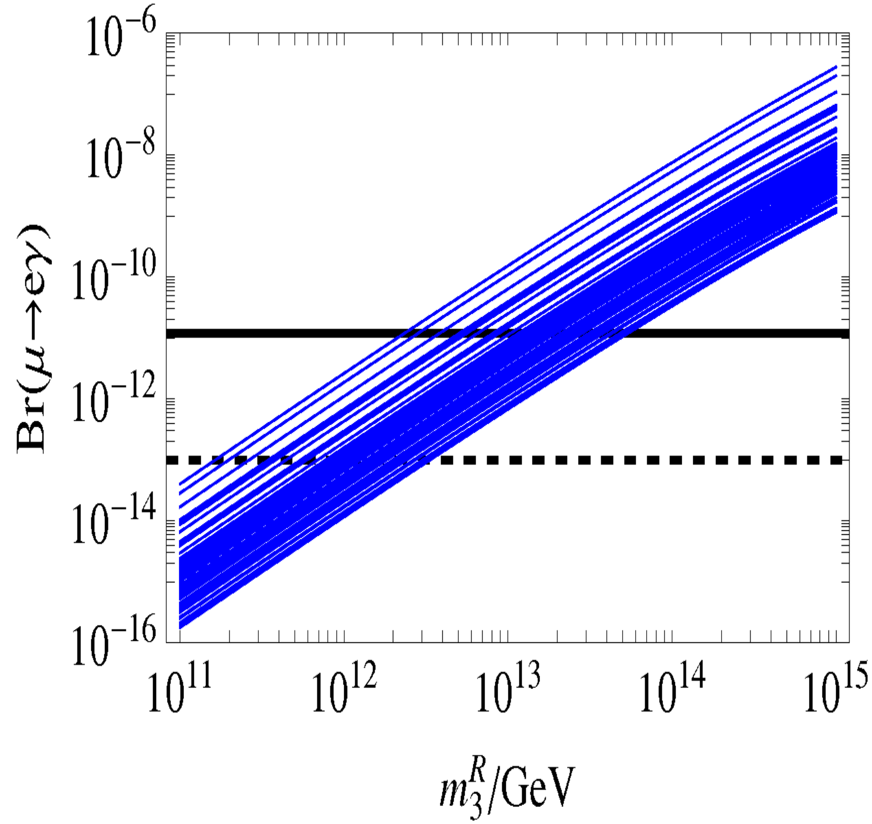
Seesaw I

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

Seesaw II

include $SU(2)$ Triplet Higgs

$$W = W_{\rm MSSM} + \frac{1}{\sqrt{2}}\left(Y_T^{ij}\hat{L}_i\hat{T}_1\hat{L}_j + \lambda_1\hat{H}_d\hat{T}_1\hat{H}_d + \lambda_2\hat{H}_u\hat{T}_2\hat{H}_u\right) + M_T\hat{T}_1\hat{T}_2$$

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

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

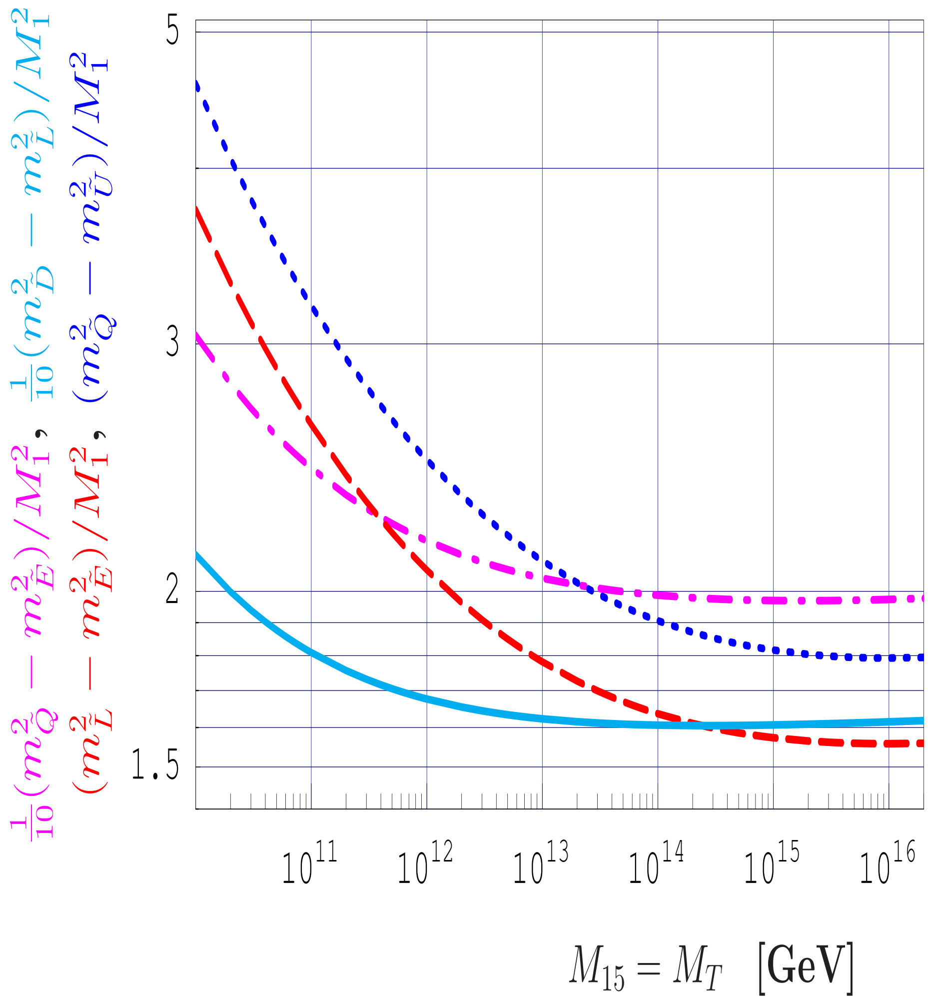
Gauge coupling unification $\Rightarrow$ use $\mathbf{15}$

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

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

$$W \supset \frac{1}{\sqrt{2}}(Y_T\hat{L}\hat{T}_1\hat{L} + \hat{Y}_S D^c\hat{S}\hat{D}^c) + Y_Z\hat{D}^c\hat{Z}\hat{L} + Y_d\hat{D}^c\hat{Q}\hat{H}_d + \hat{Y}_u\hat{U}^c\hat{Q}\hat{H}_u + Y_e\hat{E}^c\hat{L}\hat{H}_d$$
$$+ \frac{1}{\sqrt{2}}(\lambda_1\hat{H}_d\hat{T}_1\hat{H}_d + \lambda_2\hat{H}_u\hat{T}_2\hat{H}_u) + M_T\hat{T}_1\hat{T}_2 + M_Z\hat{Z}_1\hat{Z}_2 + M_S\hat{S}_1\hat{S}_2 + \mu\hat{H}_d\hat{H}_u$$

Seesaw II with 15-plets



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

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

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

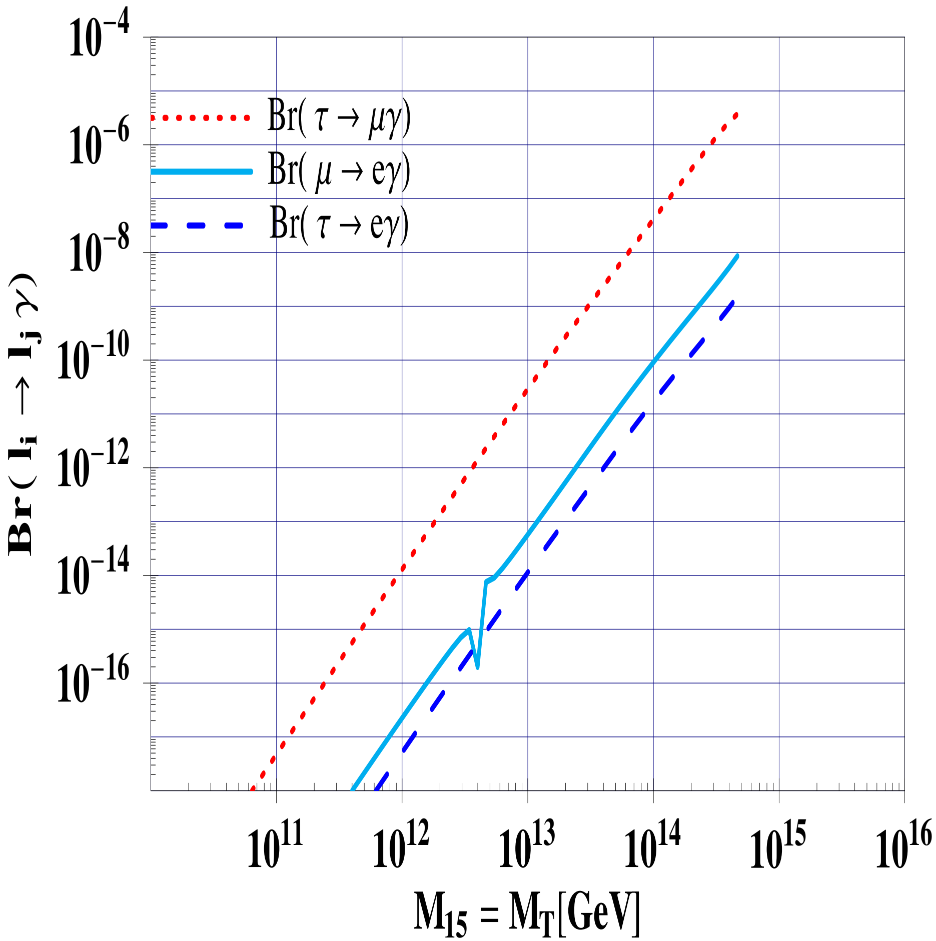
Seesaw I ($\simeq$ MSSM)

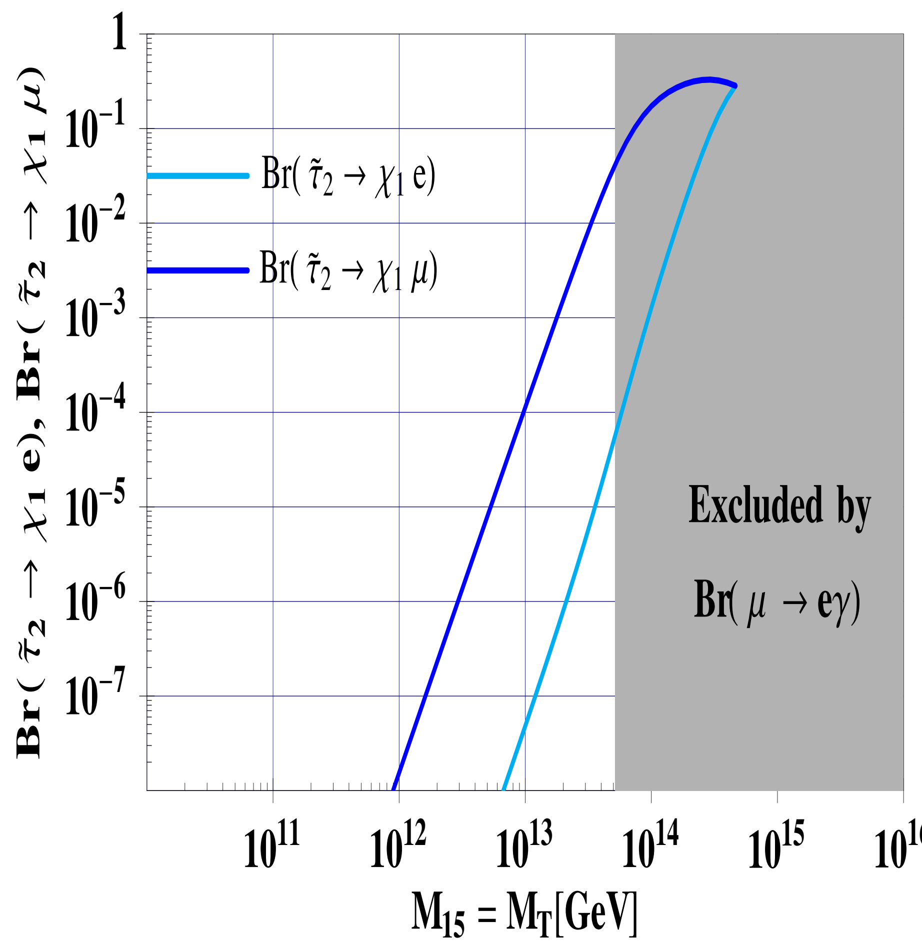
$$\frac{m_Q^2 - m_E^2}{M_1^2} \simeq 20, \quad \frac{m_D^2 - m_L^2}{M_1^2} \simeq 18$$

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

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

Seesaw II with 15-plets



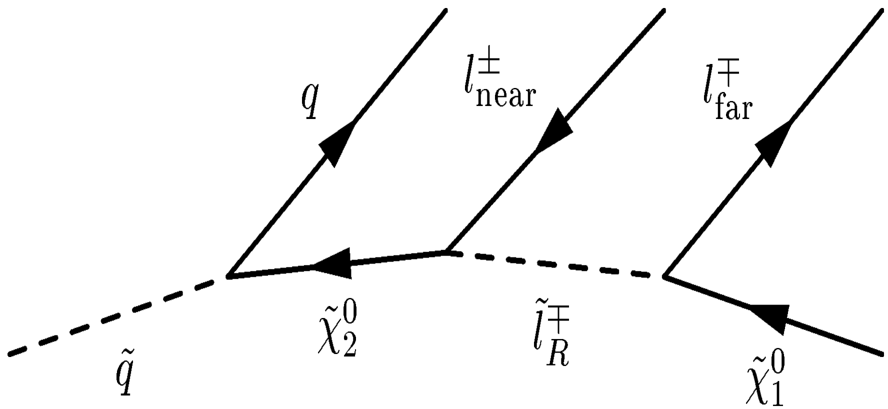


$\lambda_1 = \lambda_2 = 0.5$

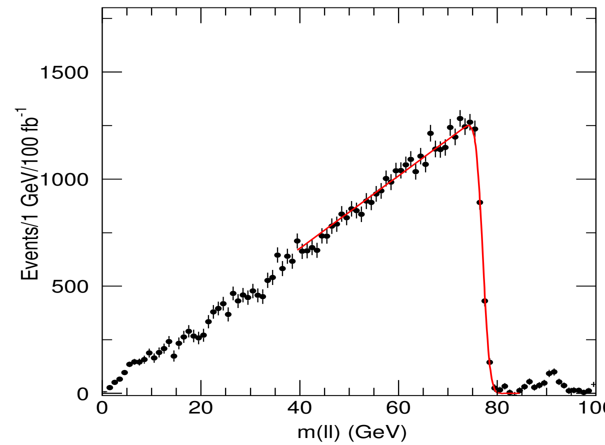
SPS3 ($M_0 = 90$ GeV, $M_{1/2} = 400$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, $\mu > 0$)

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

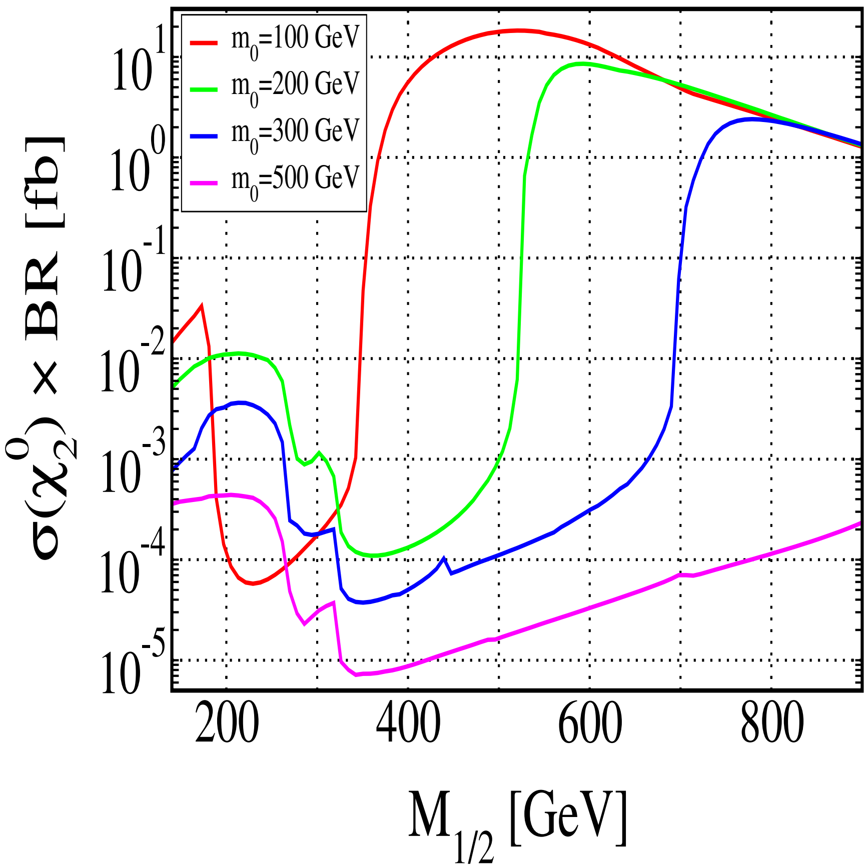
e.g.: $m(ll) = 77.02 \pm 0.05 \pm 0.08$

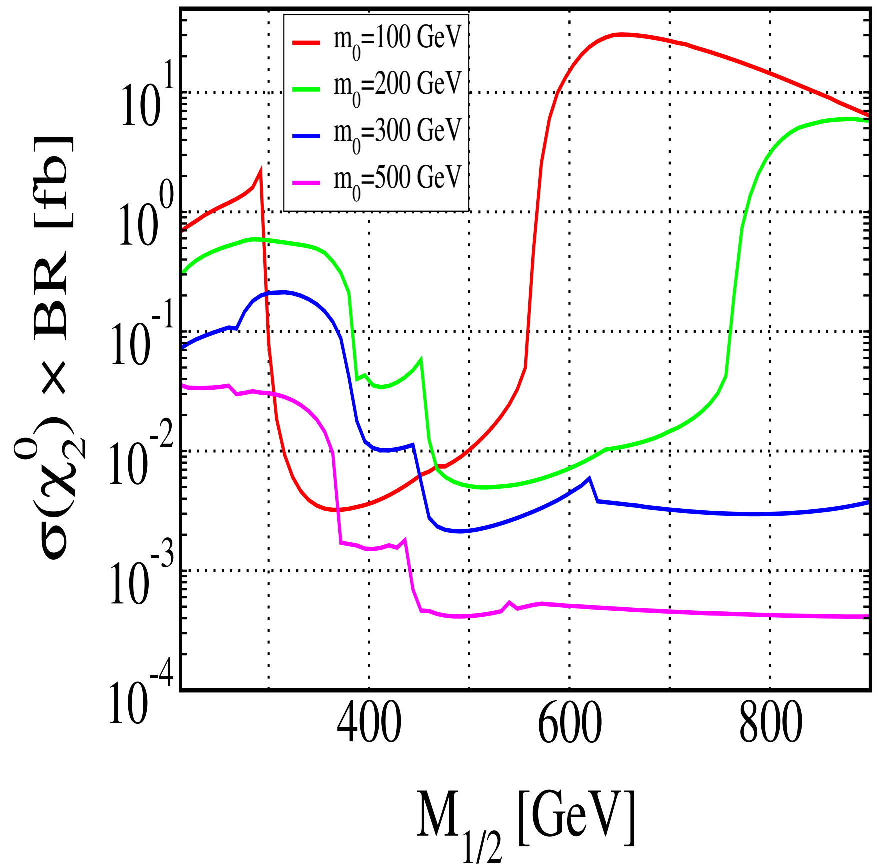
$\Rightarrow$ mass determination within 2-5%

For background suppression

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

Seesaw I + II, signal at LHC





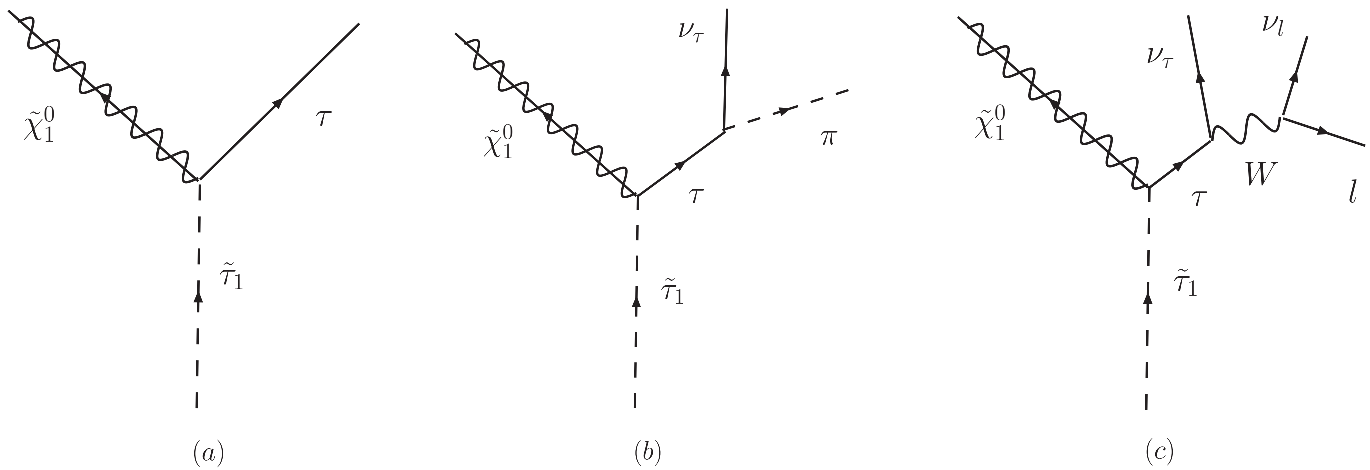
$\sigma(pp \to \tilde{\chi}_2^0) \times BR(\chi_2^0 \to \sum_{i,j} \tilde{l}_i l_j \to \mu^\pm \tau^\mp \tilde{\chi}_1^0)$

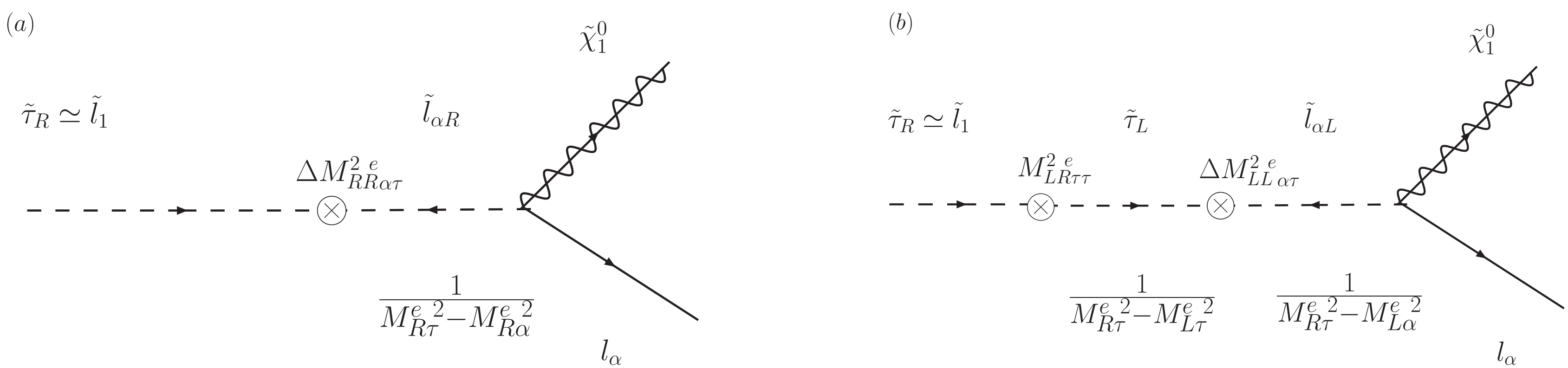
$A_0 = 0$, $\tan\beta = 10$, $\mu > 0$ (Seesaw II: $\lambda_1 = 0.02$, $\lambda_2 = 0.5$)

J.N. Esteves et al., 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

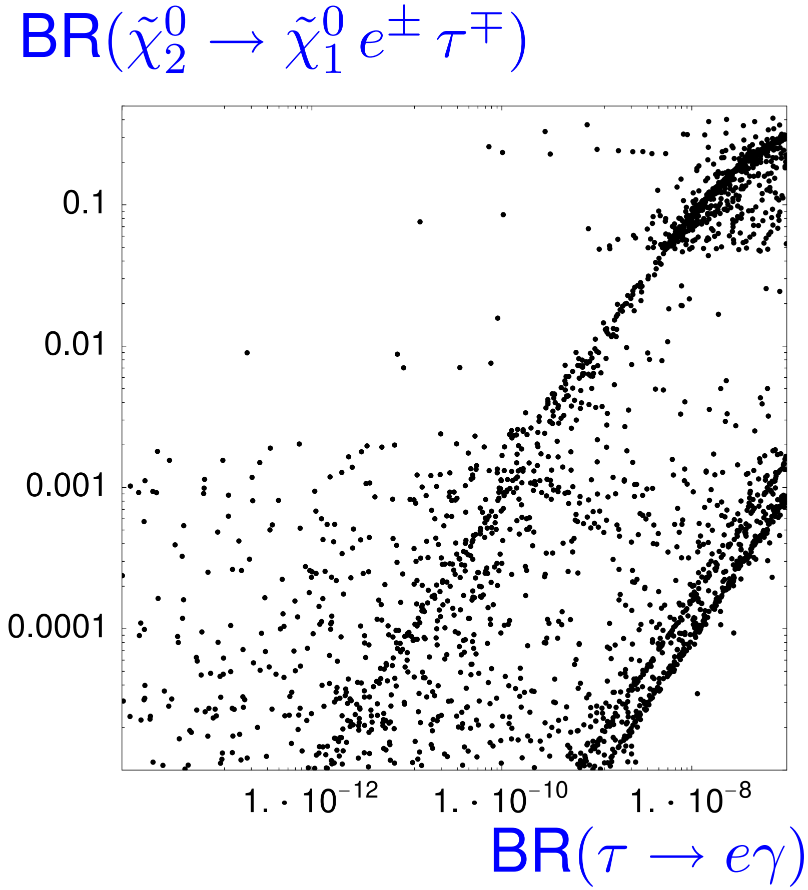
forbid dim-5 operator, e.g. Z_3 + NMSSM†

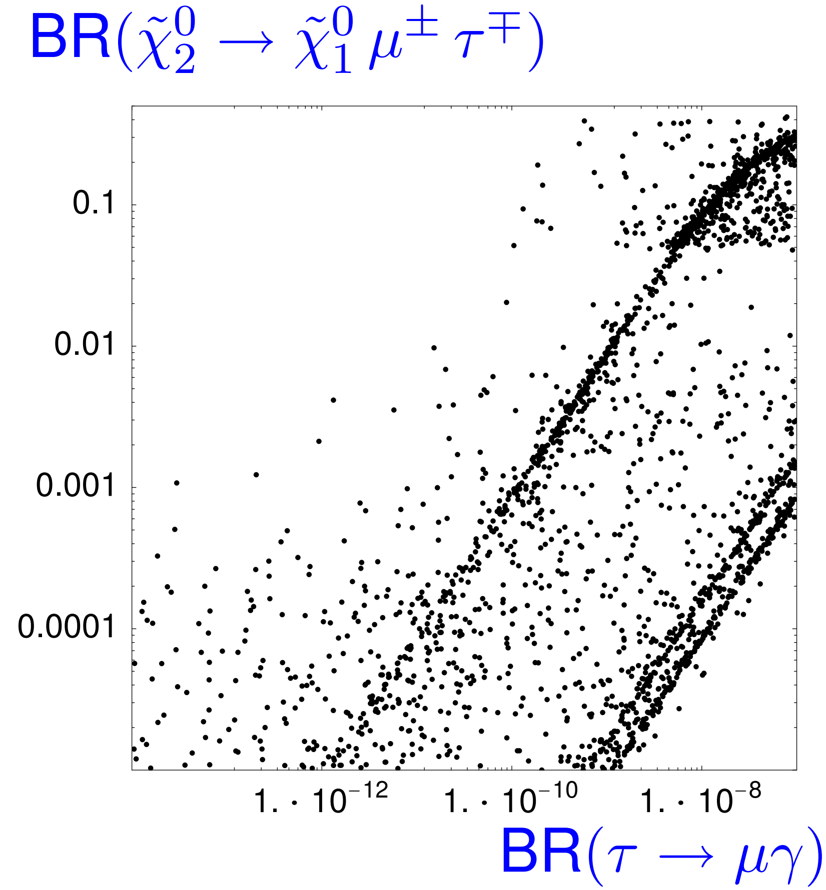
$$\frac{(LH_u)^2 S}{M_6^2} \quad , \quad \frac{(LH_u)^2 S^2}{M_7^3}$$

solves at the same time the μ-problem

† I. Gogoladze, N. Okada, Q. Shafi, Phys. Lett. B **672** (2009) 235

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

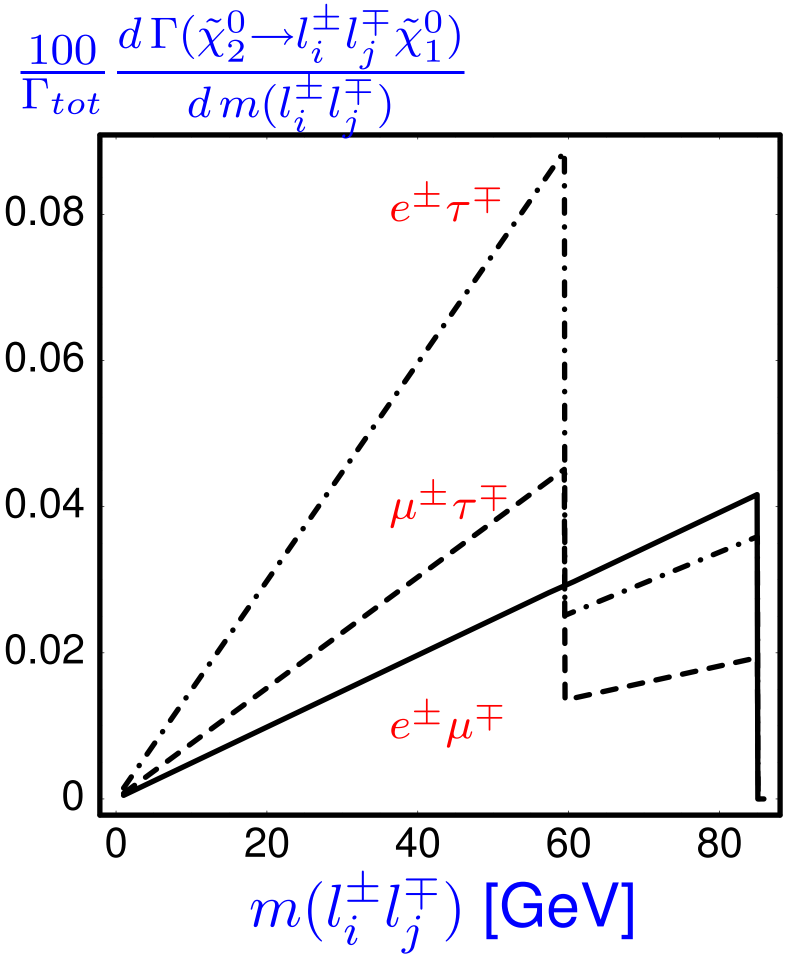


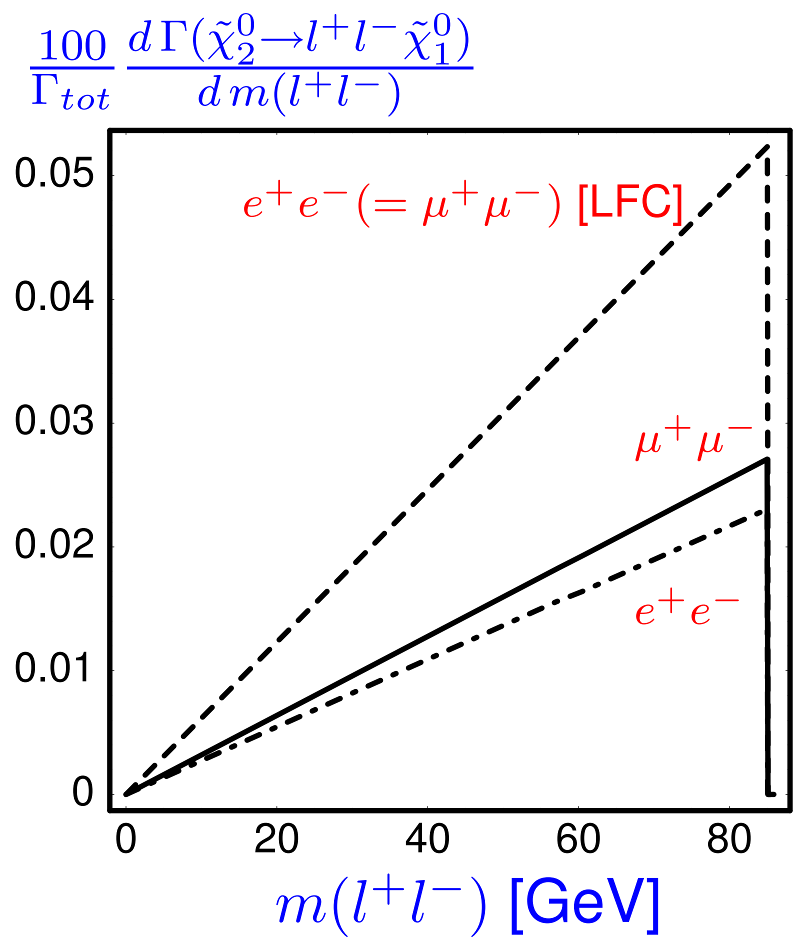


Variations around SPS1a

($M_0 = 100$ 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

Introduction to explicit R-parity violation

The most general superpotential allowed by $SU(3) \times SU(2) \times U(1)$:

$$W = W_{R_P} + W_{R\!\!\!/_p}$$

$\Rightarrow$ MSSM part:

$$W_{R_P} = Y_e^{ij} \hat{H}_d \hat{L}_i \hat{E}_j^C + Y_d^{ij} \hat{H}_d \hat{Q}_i \hat{D}_j^C + Y_u^{ij} \hat{H}_u \hat{Q}_i \hat{U}_j^C - \mu \hat{H}_d \hat{H}_u$$

$\Rightarrow$ R-parity violating part:

$$W_{R\!\!\!/_p} = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^C + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k^C + \lambda''_{ijk} \hat{U}_i^C \hat{D}_j^C \hat{D}_k^C + \epsilon_i \hat{L}_i \hat{H}_u$$

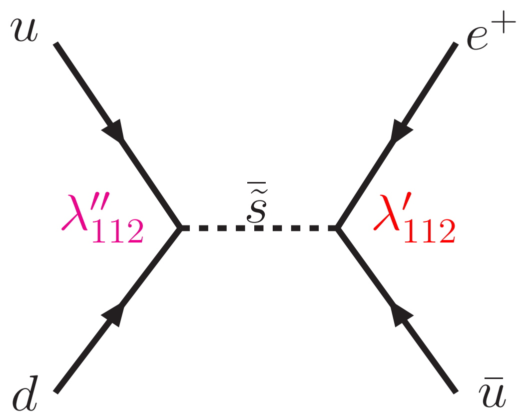
$\Rightarrow$ λ_{ijk}, λ'_{ijk} and ϵ_i violate lepton number

$\Rightarrow$ λ''_{ijk} violate baryon number

$\Rightarrow$ lepton number and baryon number violation shouldn't be present at the same time, because...

Proton decay

⇒ Consider, for example:



Estimated decay width:

$$\Gamma(P \to e^+\pi^0) \approx \frac{(\lambda'_{11k})^2(\lambda''_{11k})^2}{16\pi^2\tilde{m}^4_{dk}} M^5_{proton}$$

Given that $\tau(P \to e\pi) > 10^{32}\, yr$:

$$\lambda'_{11k} \cdot \lambda''_{11k} \lesssim 2 \cdot 10^{-27} \left(\frac{\tilde{m}_{dk}}{100\mathrm{GeV}}\right)^2 .$$

⇒ For this reason the MSSM assumes R-parity:

$$R_P = (-1)^{3(B-L)+2S}$$

Alternatives to R_P

⇒ An alternative is matter parity (all λ, λ', λ'' and ϵ forbidden):

$$(L_i, \bar{E}_i, Q_i, \bar{U}_i, \bar{D}_i) \quad \to \quad -(L_i, \bar{E}_i, Q_i, \bar{U}_i, \bar{D}_i), \quad (H_d, H_u) \to (H_d, H_u).$$

⇒ Sufficient to forbid baryon number violation, for example via baryon-parity†
(all λ'' forbidden):

$$(Q_i, \bar{U}_i, \bar{D}_i) \quad \to \quad -(Q_i, \bar{U}_i, \bar{D}_i), \quad (L_i, \bar{E}_i, H_d, H_u) \to (L_i, \bar{E}_i, H_d, H_u).$$

⇒ Spontaneous R-parity violation (all λ, λ' and λ'' forbidden):

$$W = W_{MSSM} + Y_i^{\nu} \widehat{L}_i \widehat{H}_u \widehat{N}^c + \cdots$$

⇒ If $\langle \tilde{\nu}^c \rangle \neq 0$ explicit bilinear RPV terms are generated effectively:

$$\epsilon_i = Y_{\nu}^{ij} \langle \tilde{\nu}^c_j \rangle$$

† complete list of possible discrete symmetries by H. Dreiner et al.

Gauge Mediated SUSY Breaking (GMSB)

Basis idea: transfer of SUSY breaking from hidden sector via messenger fields using gauge interactions

Messenger scale: $M_i(M_M) \sim g(x)\alpha_i \Lambda_G$

$$M_j^2(M_M) \sim f(x) \sum C_i \alpha_i^2 \Lambda_G^2$$

$$x = \Lambda_G / M_M,\ f(x), g(x) = (n_5 + 3n_{10}) O(1)$$

Generic prediction: light gravitino being the LSP

NLSP: $\tilde\chi_1^0$ or $\tilde l_R$ ($l = e, \mu, \tau$)

add bilinear R-parity violating terms:

$$W = W_{MSSM} + \epsilon_i \widehat{L}_i \widehat{H}_u, \qquad V_{\rm soft} = V_{\rm soft}^{MSSM} + B_i \epsilon_i \tilde{L}_i H_u.$$

$\Rightarrow$ sneutrino vevs v_i

in the following: take v_i as free parameters instead B_i

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

$$m_\nu^{1\text{lp}} \simeq \frac{1}{16\pi^2}\left(3h_b^2\sin(2\theta_{\tilde b})m_b\log\frac{m^2_{\tilde b_2}}{m^2_{\tilde b_1}} + h_\tau^2\sin(2\theta_{\tilde\tau})m_\tau\log\frac{m^2_{\tilde\tau_2}}{m^2_{\tilde\tau_1}}\right)\frac{(\tilde\epsilon_1^2+\tilde\epsilon_2^2)}{\mu^2}$$

$$\tilde\epsilon_i = V^\nu_{ji}\epsilon_j$$

mixing angles

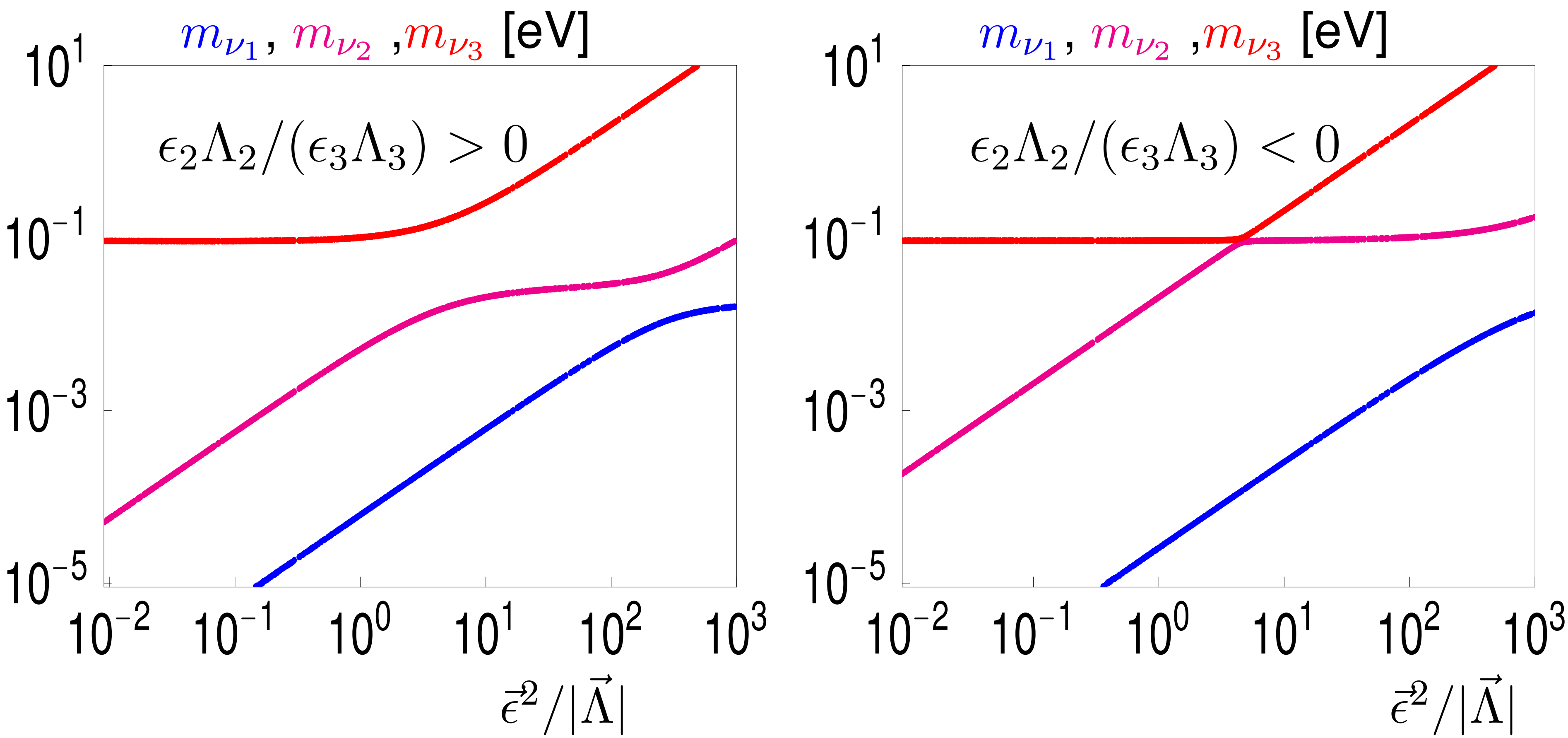
$$\tan^2\theta_{atm} \simeq \left(\frac{\Lambda_2}{\Lambda_3}\right)^2, \; U^2_{e3} \simeq \frac{|\Lambda_1|}{\sqrt{\Lambda_2^2+\Lambda_3^2}}, \; \tan^2\theta_{sol} \simeq \left(\frac{\tilde\epsilon_1}{\tilde\epsilon_2}\right)^2$$

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

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

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

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

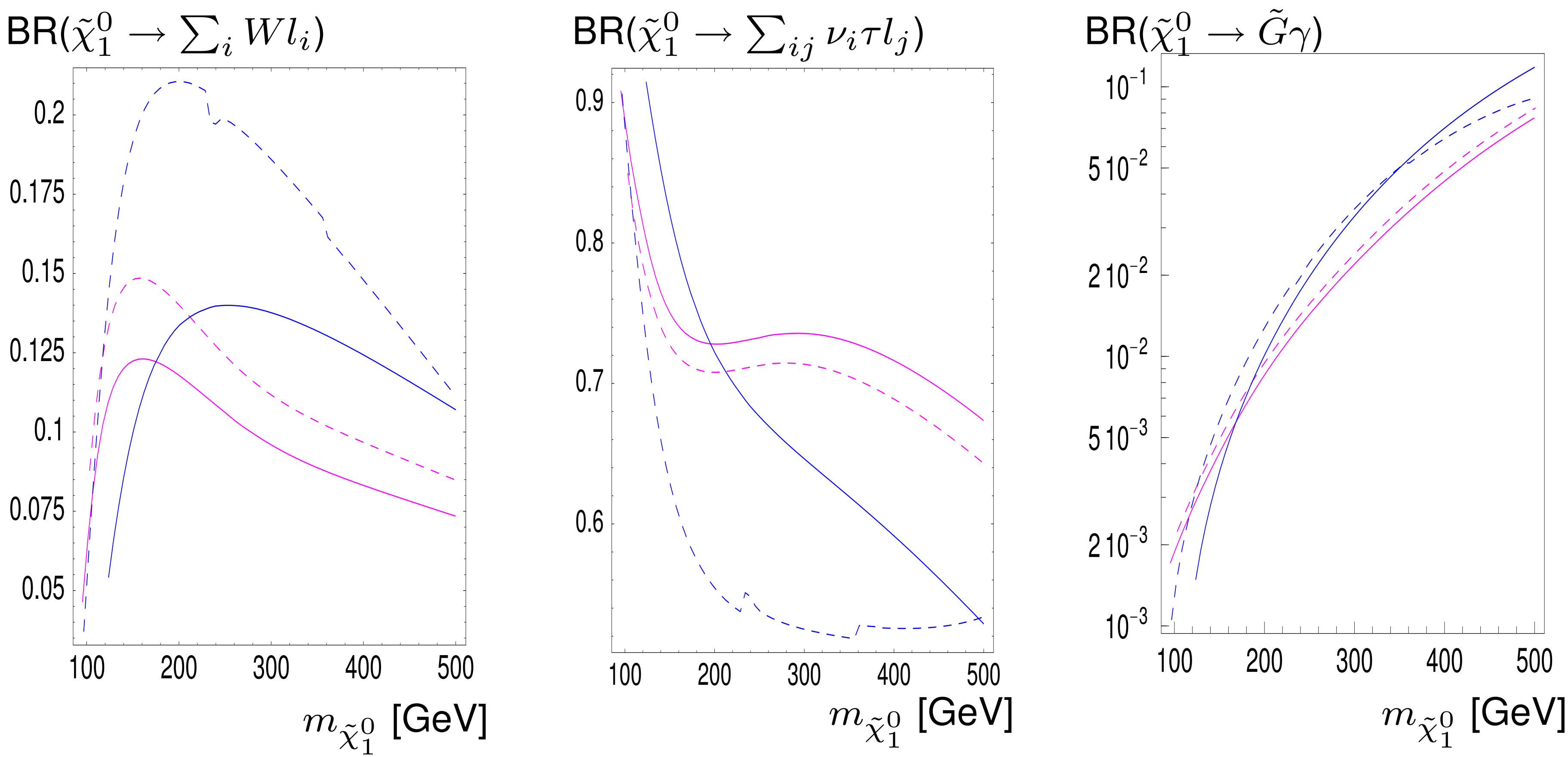
R-parity conserving mode

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

total width

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

Neutralino decays



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

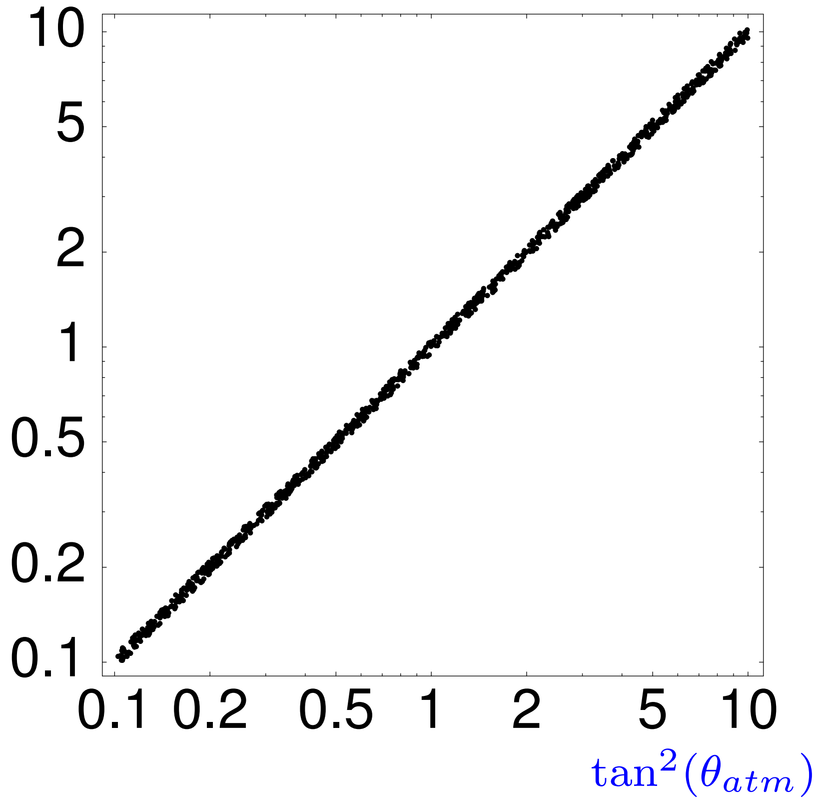
$m_{3/2} = 100$ eV, $n_5 = 1$

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

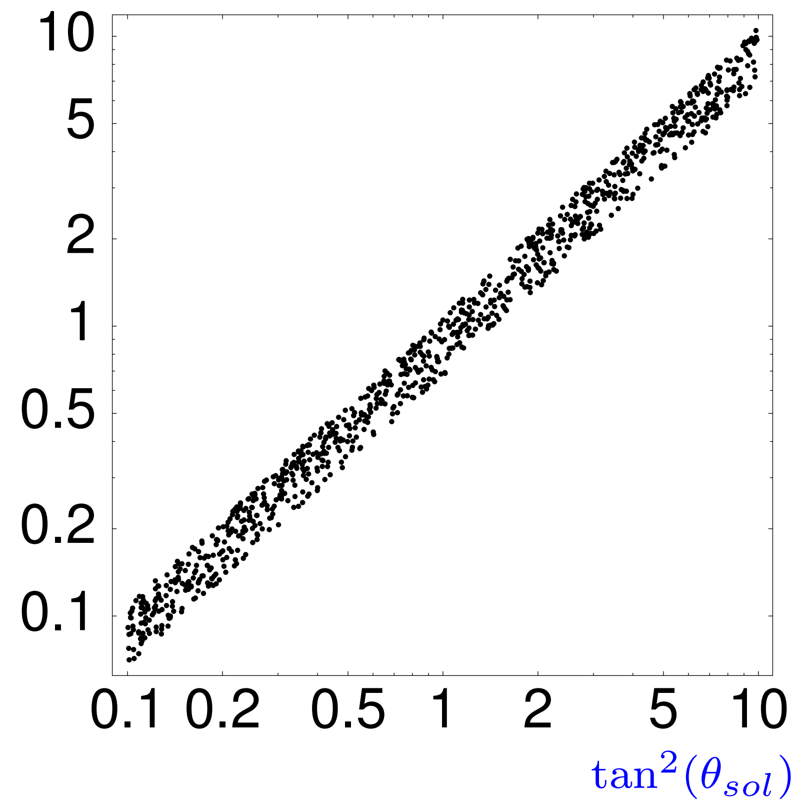
Neutralino decays, correlations

Correlations

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



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



Comments

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

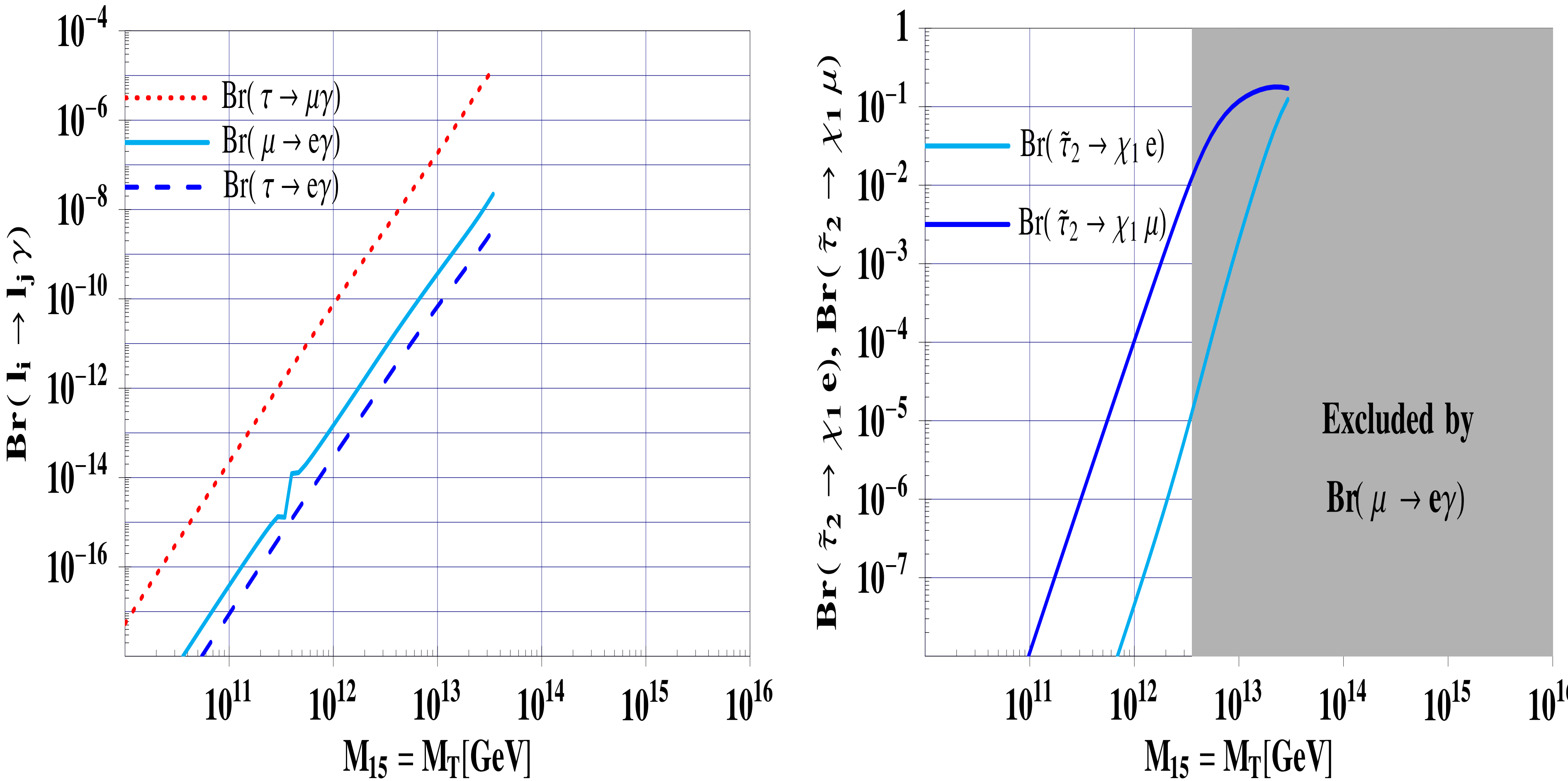
  $\Rightarrow$ for $n_5 \geq 3$ hardly points with $\tilde{\chi}^0_1$ LSP
- $\tilde{l}_R$ NLSPs: BR($l\nu$) $\gg$ BR($l\tilde{G}$)
- $n_5 = 2$: BR($\tilde{G}\gamma$) reduced by a factor 2-3
- $\tilde{G}$ decays via R-parity violating couplings, however:

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

Conclusions

- Dirac neutrinos: displaced vertices if $\tilde{\nu}_R$ LSP, e.g. $\tilde{t}_1 \to lb\tilde{\nu}_R$ (but NMSSM: $\tilde{t}_1 \to lb\nu\tilde{\chi}^0_1$)
- Seesaw models:
  - most promosing: $\tilde{\tau}_2$ decays
  - very difficult to test at LHC, signals of O(10 fb) or below
  - in case of Seesaw II: different mass ratios
- R-parity violation
  - interesting correlations between ν-physics and LSP decays, testable at LHC
  - displaced vertices
  - Can the model be pinned down?

Seesaw II with 15-plets

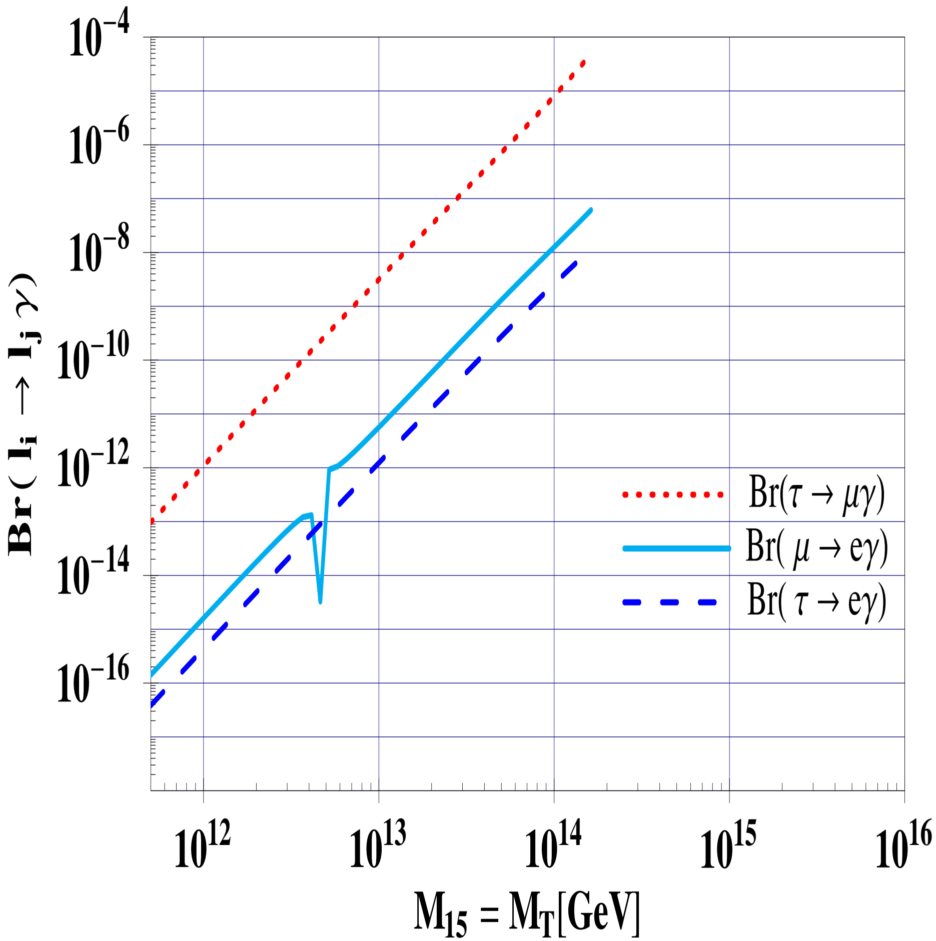


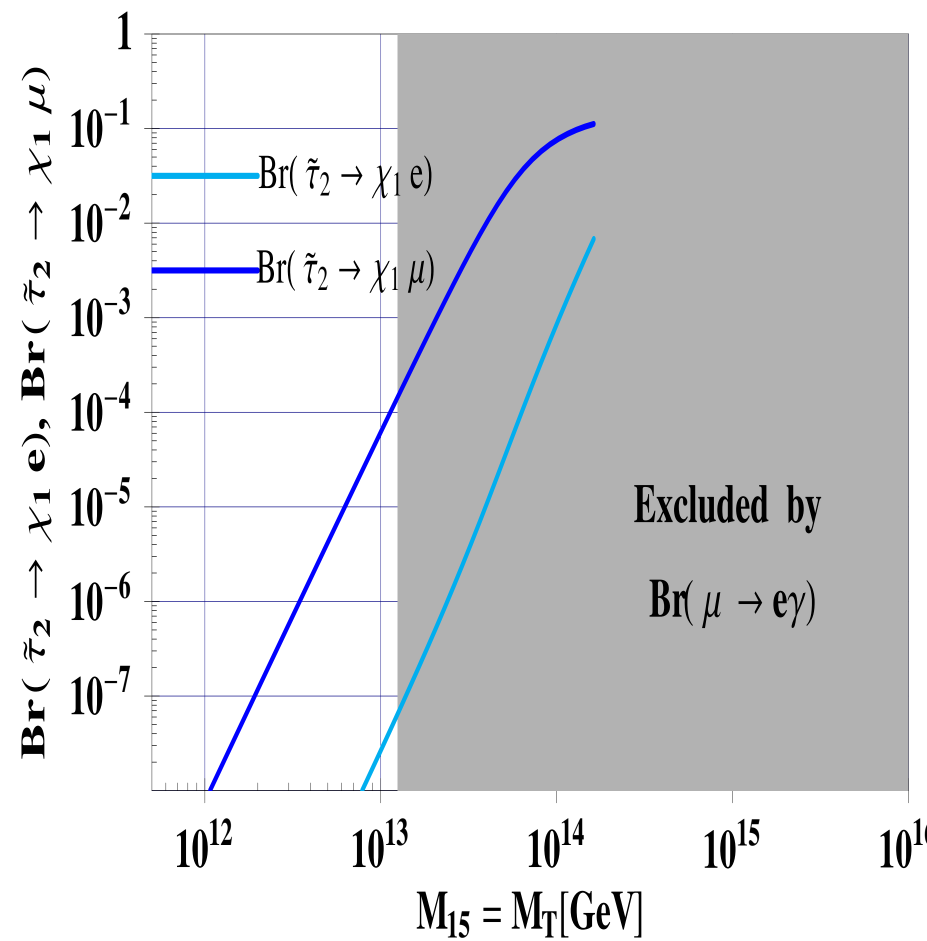
$\lambda_1 = \lambda_2 = 0.05$

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 II with 15-plets



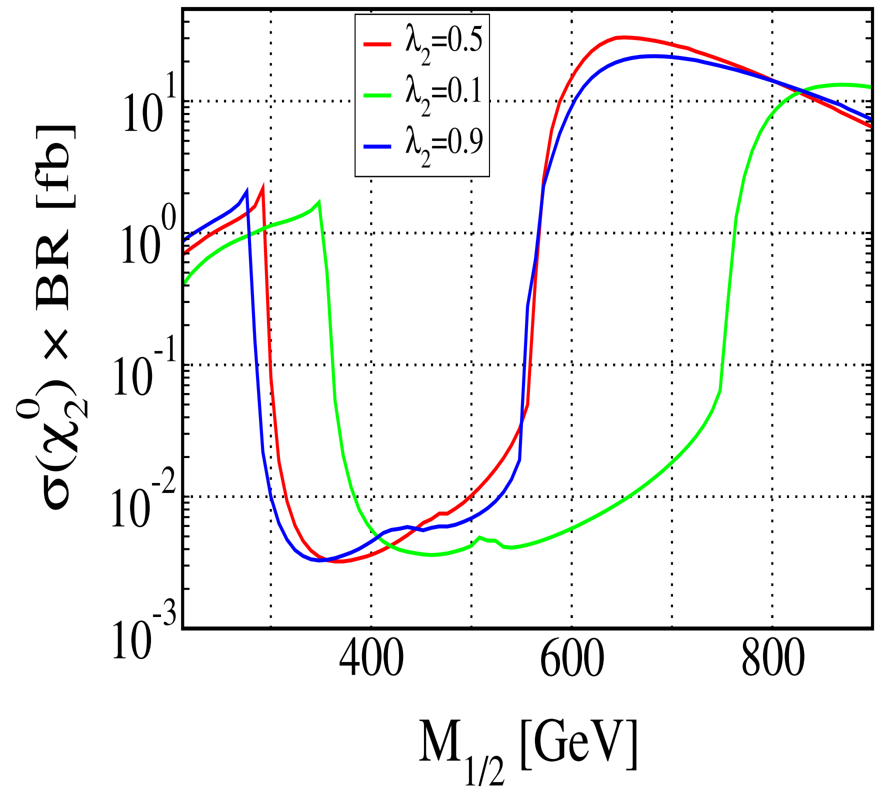


$\lambda_1 = \lambda_2 = 0.5$

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, 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

Bilinear R-parity breaking extension of the MSSM

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:

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

and

$$\lambda_{121} = h_e\frac{\epsilon_2}{\mu}, \quad \lambda_{122} = h_\mu\frac{\epsilon_1}{\mu}, \quad \lambda_{123} = 0$$

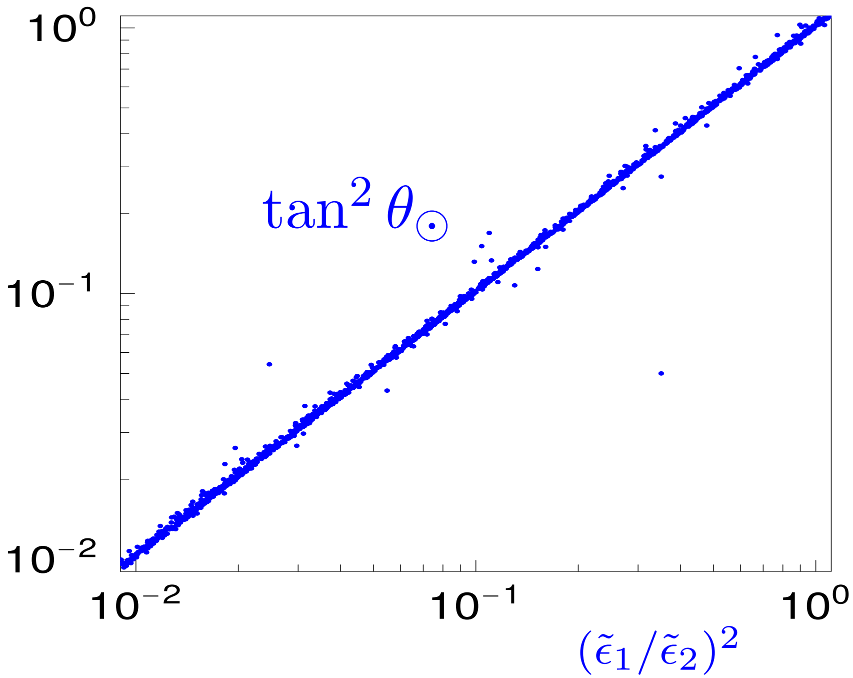
$$\lambda_{131} = h_e\frac{\epsilon_3}{\mu}, \quad \lambda_{132} = 0, \quad \lambda_{133} = h_\tau\frac{\epsilon_1}{\mu}$$

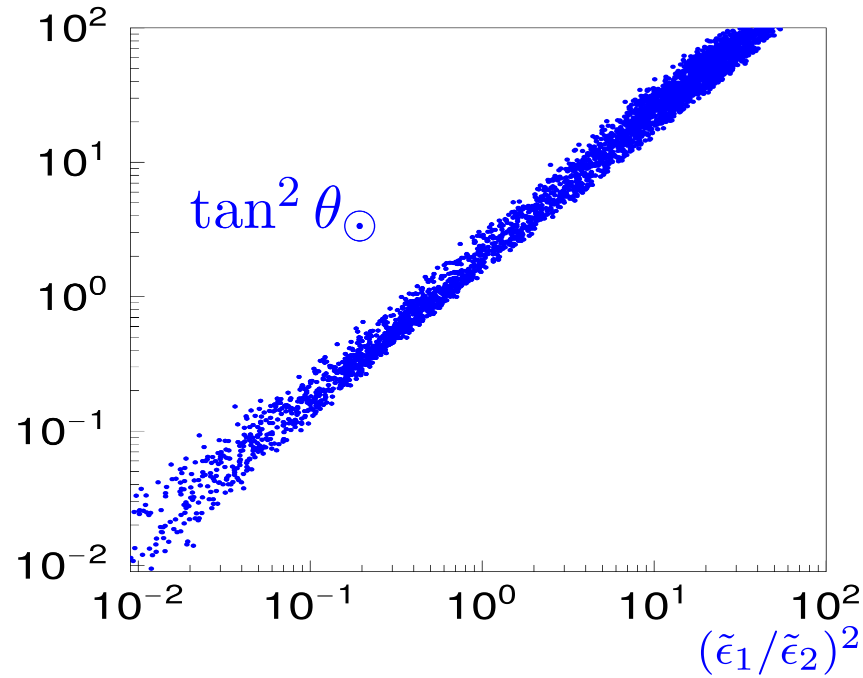
$$\lambda_{231} = 0, \quad \lambda_{232} = h_\mu\frac{\epsilon_3}{\mu}, \quad \lambda_{233} = h_\tau\frac{\epsilon_2}{\mu}$$

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

Solar angle

$$\text{Approximation formula gives : } \tan^2\theta_\odot \simeq \left(\frac{\tilde{\epsilon}_1}{\tilde{\epsilon}_2}\right)^2$$





⇒ Left figure: Neutralino LSP, b–$\tilde{b}_i$ loop usually dominant

⇒ Right figure: Stau LSP, both, b–$\tilde{b}_i$ and $S_j^\pm$–$\tilde{\chi}_k^\mp$ ($j = 1, .., 7$, $k = 1, .., 5$), equally important

Gravitino Dark Matter

Standard thermal history of the universe:

$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{m_{3/2}}{100\,\mathrm{eV}}\right)\left(\frac{100}{g_*}\right) \qquad (g_* \simeq 90 - 140)$$

Current data:

$$\Omega_{CDM}h^2 \simeq 0.105 \pm 0.008$$

$\Rightarrow m_{3/2} \simeq 100$ eV if DM candidate, warm dark matter

constraints from Lyman-α forest: $m_{WDM} \gtrsim 550$ eV

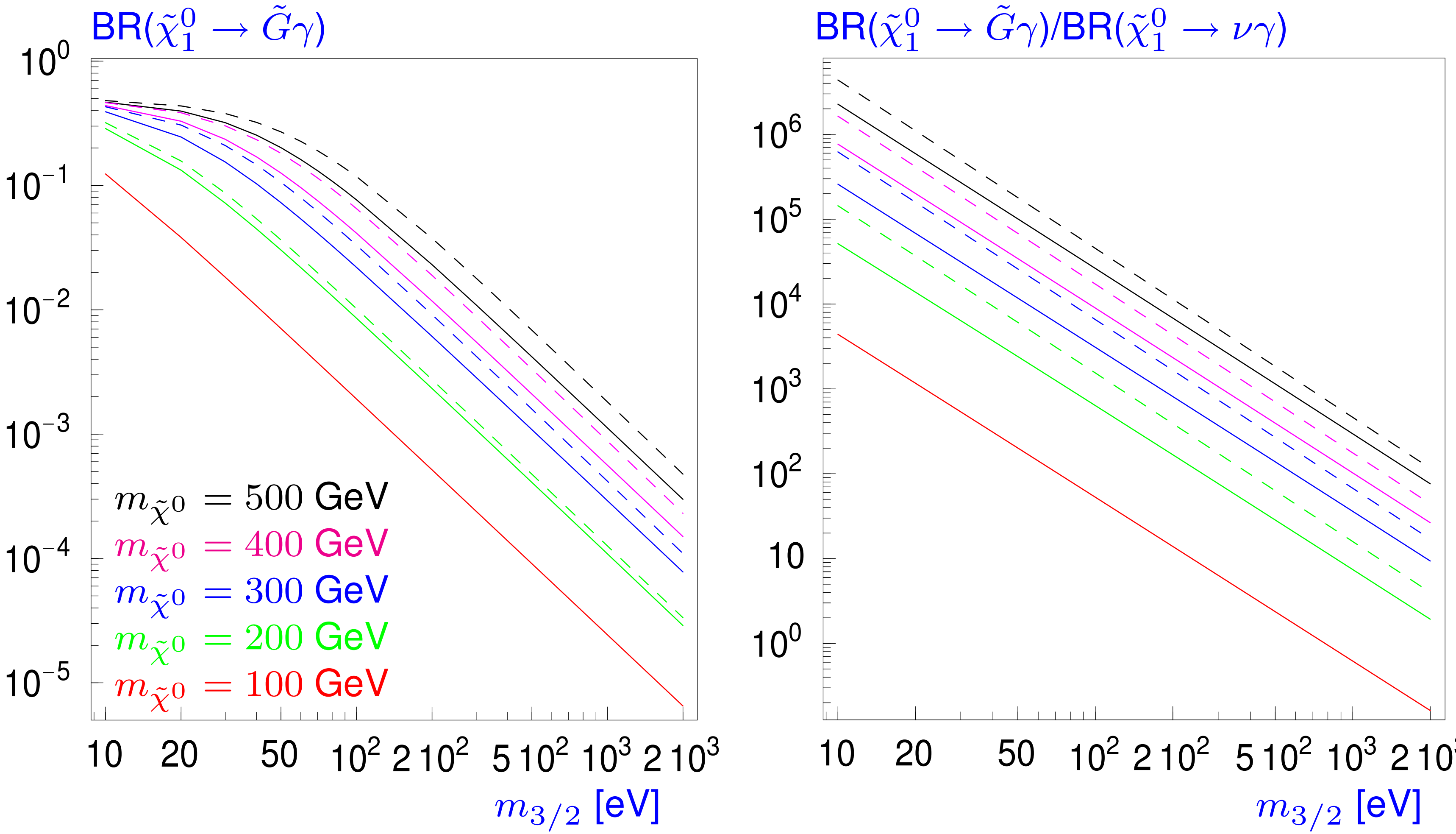
(M. Viel et al., arXiv:astro-ph/0501562)

$\Rightarrow$ assume additional entropy production, e.g. non-standard decays of messenger particles

(E. Baltz, H. Murayama, astro-ph/0108172; M. Fujii and T. Yanagida hep-ph/0208191)

does not work in practice: F. Staub, W. P., J. Niemeyer, arXiv:0907.0530

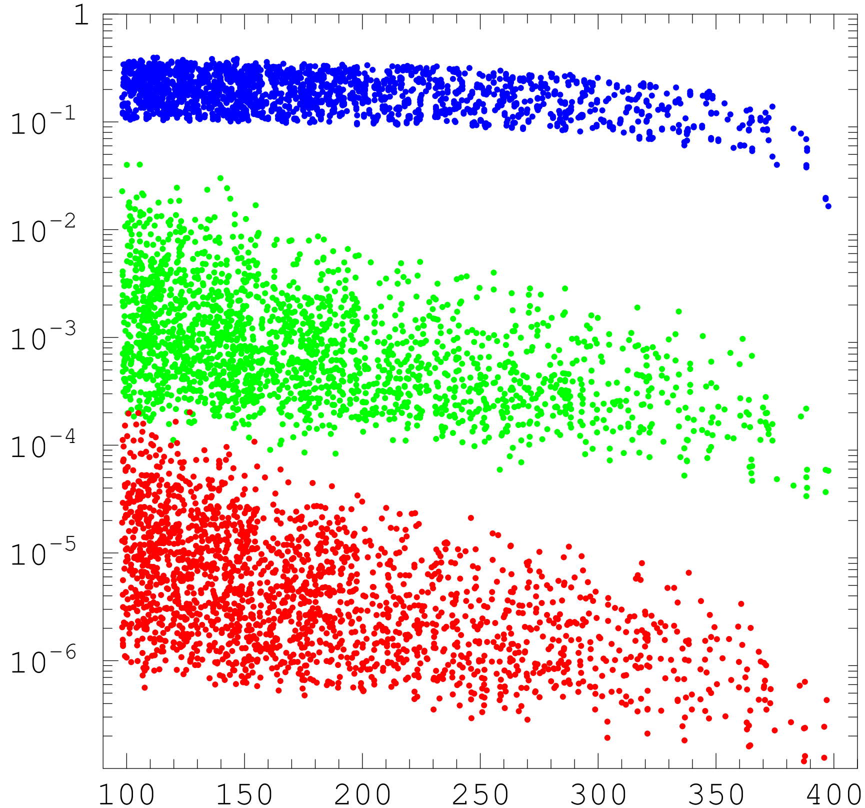
GMSB signals



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

Charged Scalar LSP

Decay length ($\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$) [cm]



$m_{\tilde{l}}$ [GeV]

$\Rightarrow$ $\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$ can be separated in this model.

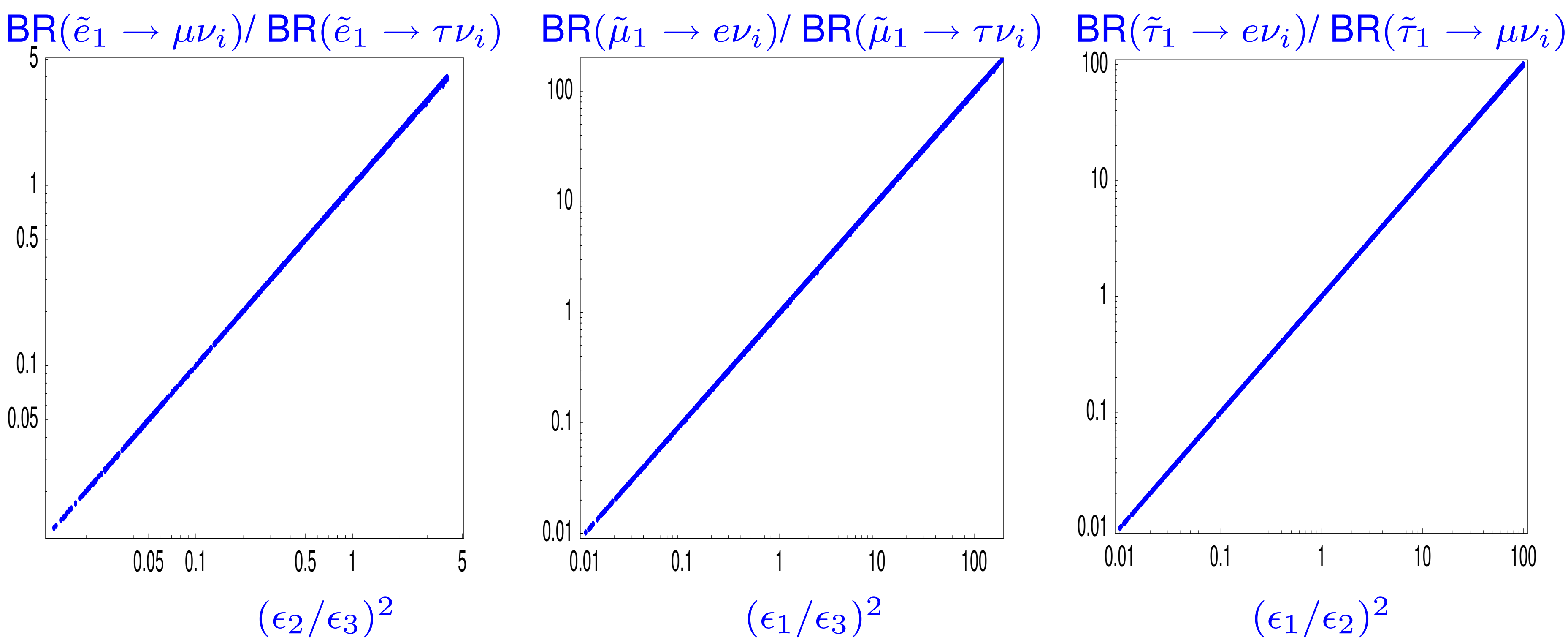
Moreover

$$\frac{\Gamma(\tilde{\tau})}{\Gamma(\tilde{\mu})} \simeq \left(\frac{Y_\tau}{Y_\mu}\right)^2 \frac{m_{\tilde{\tau}}}{m_{\tilde{\mu}}}$$

$$\tilde{l}_j \to l_i \sum_k \nu_k \ , \ qq'$$

M. Hirsch, W. Porod, J. C. Romão and J. W. F. Valle, Phys. Rev. **D66** (2002) 095006.

Charged Scalar LSP

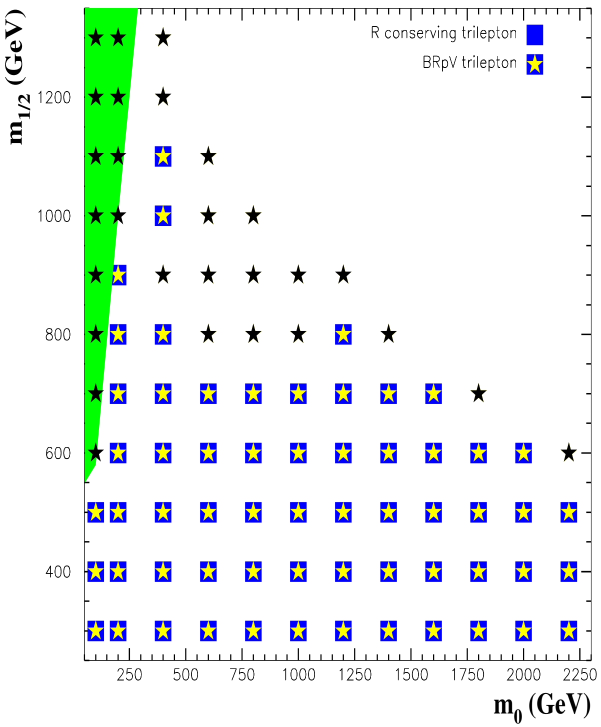


Cross check possible: $(\epsilon_1/\epsilon_3)^2/(\epsilon_1/\epsilon_2)^2 \equiv (\epsilon_2/\epsilon_3)^2$

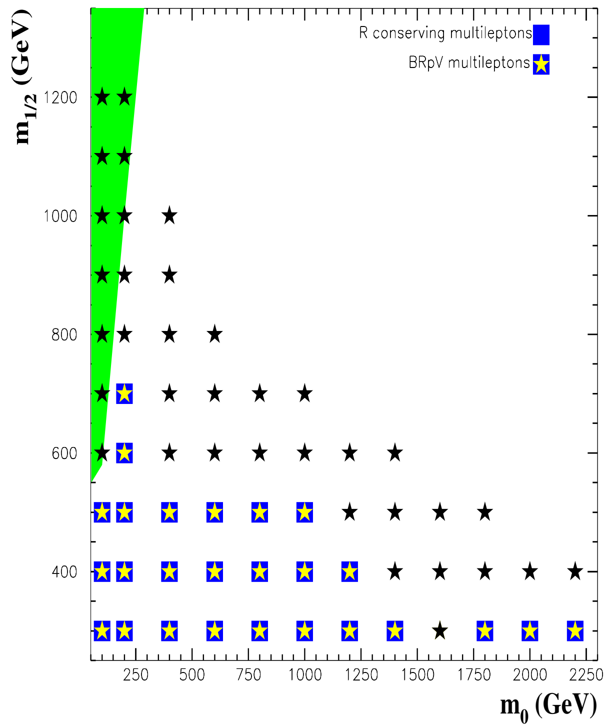
$\Rightarrow$ Measure 2 ratios, 3rd is fixed.

bilinear R-parity violation, reach in mSUGRA

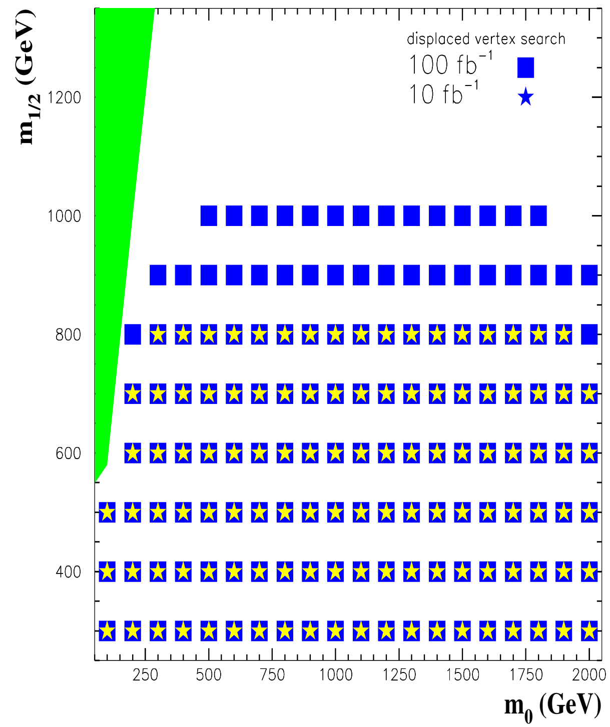
3-lepton channel



multi-lepton channel



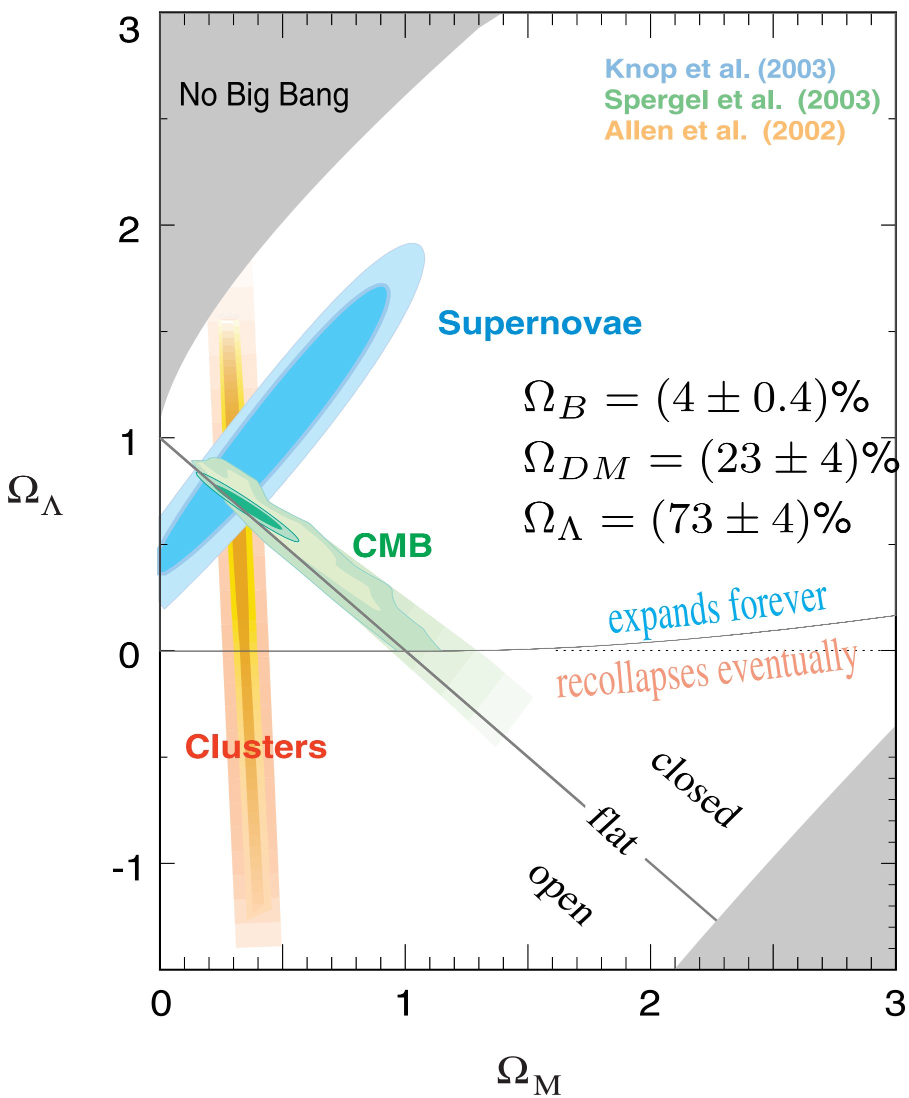
displaced vertex



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

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

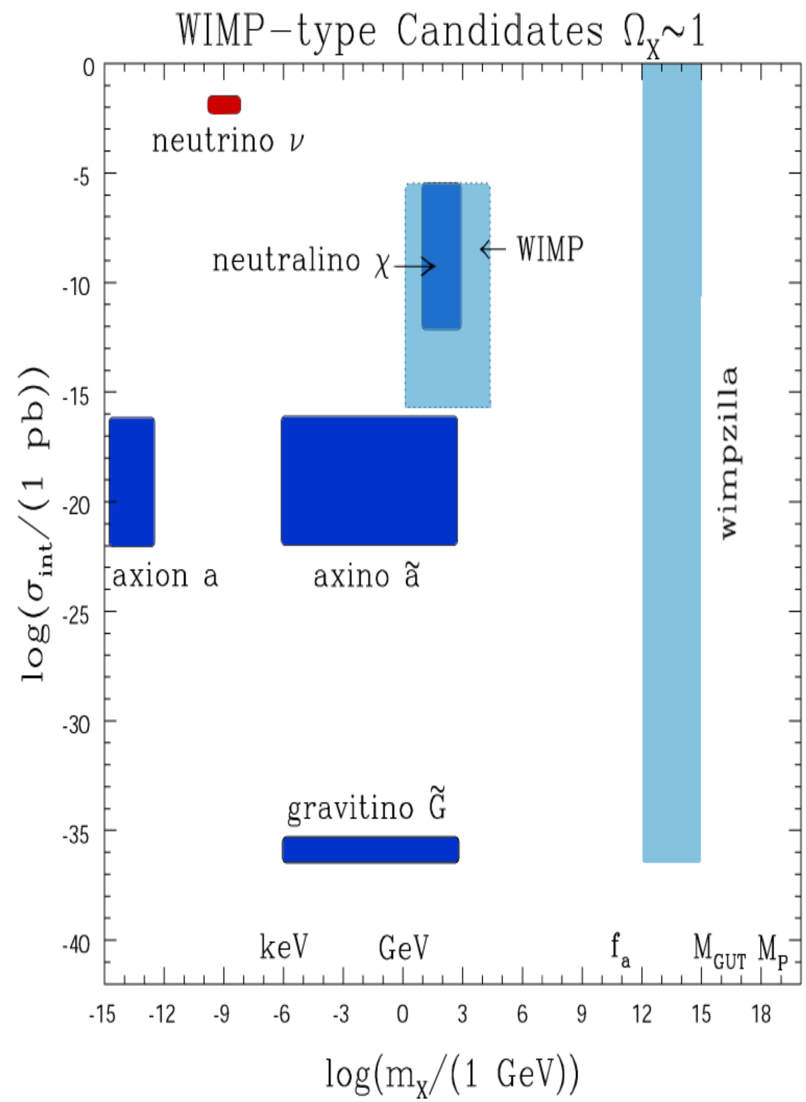
Cosmology



$\Omega_B = (4 \pm 0.4)\%$

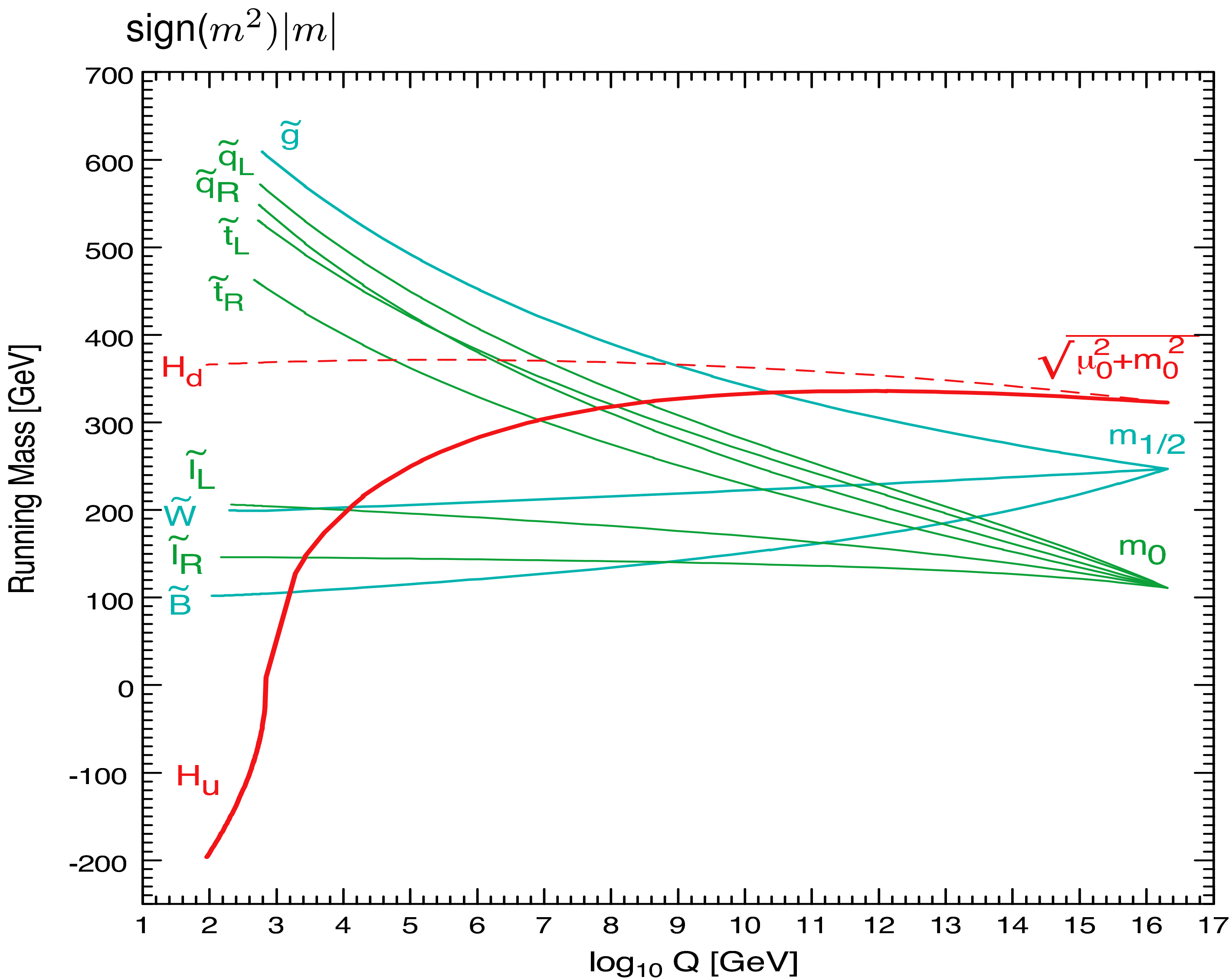
$\Omega_{DM} = (23 \pm 4)\%$

$\Omega_\Lambda = (73 \pm 4)\%$



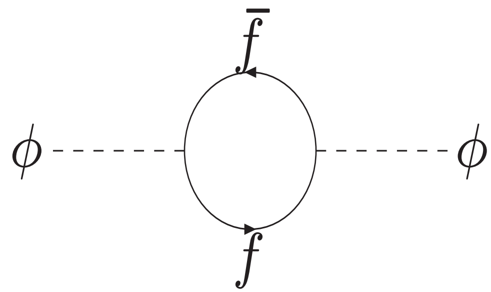
R.A. Knopp et al., Astrophys. J. **598** (2003) 102 L. Roszkowski, astro-ph/0404052

Running SUSY masses

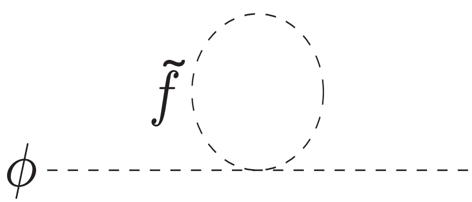


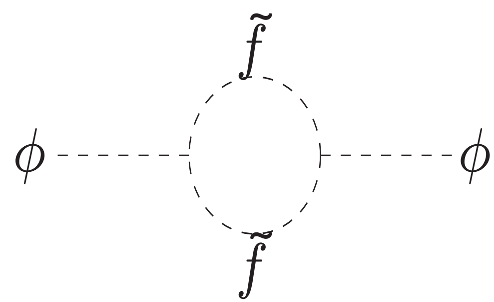
G. Kane, C. Kolda, L. Roszkowski, J. Wells, PRD 1994

Hierarchy problem



$$\delta m^2 = -N(f)\frac{\lambda_f^2}{8\pi^2}\Lambda^2 + \ldots$$





$$\delta m^2 = N(f)\frac{\lambda_f^2}{8\pi^2}\Lambda^2 - \ldots$$

exacte SUSY: $\delta m^2 = 0$

softly broken SUSY: $\delta m^2 \propto (m_{\tilde{f}}^2 - m_f^2)\log(m_{\tilde{f}}^2/m_f^2)$

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

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

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

$m(\chi_1^0) =$ 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