Testing supersymmetric neutrino mass models at the LHC

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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

$$Y_\nu \, H \, \bar{\nu}_L \, \nu_R \rightarrow Y_\nu \, v \, \bar{\nu}_L \, \nu_R = m_\nu \, \bar{\nu}_L \, \nu_R$$

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

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

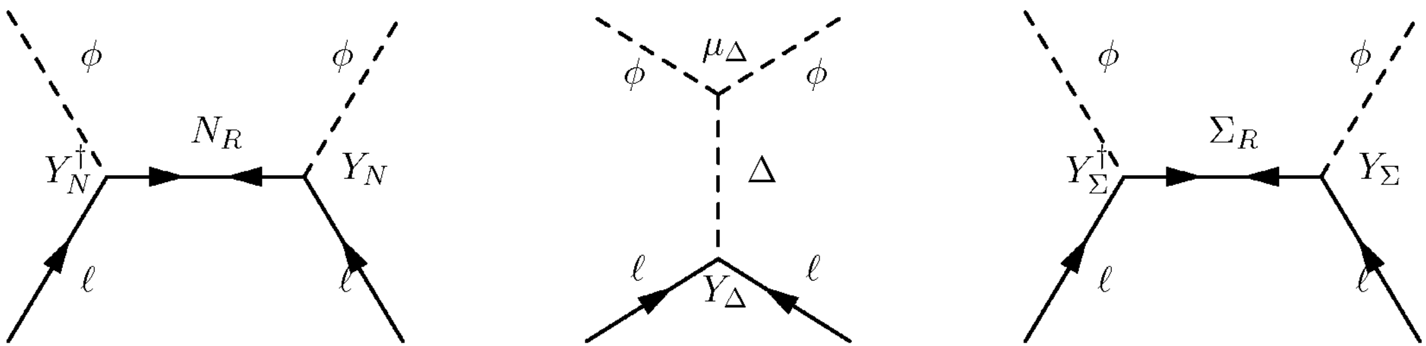
$m_{\tilde{\nu}_R} \simeq 0$ in GMSB

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

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

RGE running

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

Seesaw I

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

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

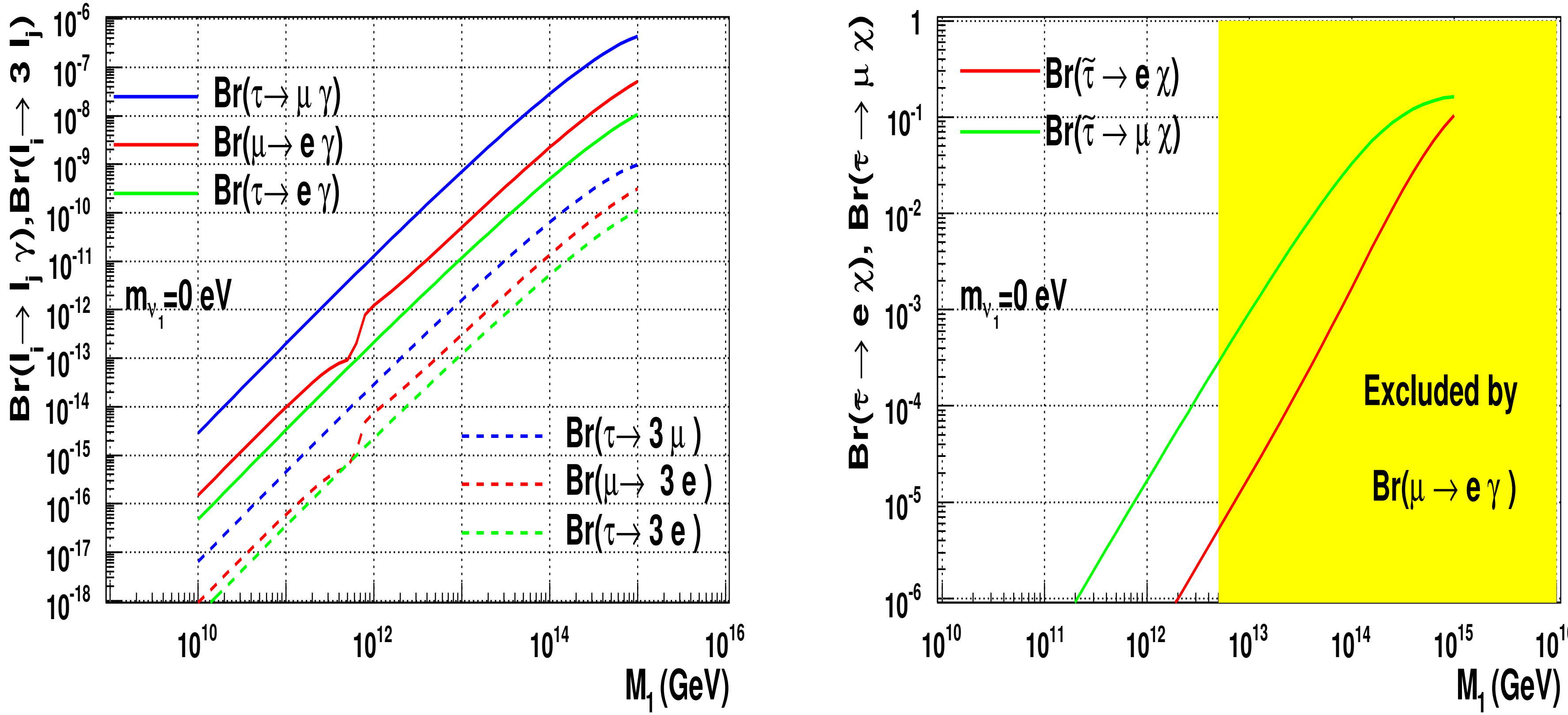
Neglecting L-R mixing:

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

Moreover, in most of the parameter space

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

Seesaw I

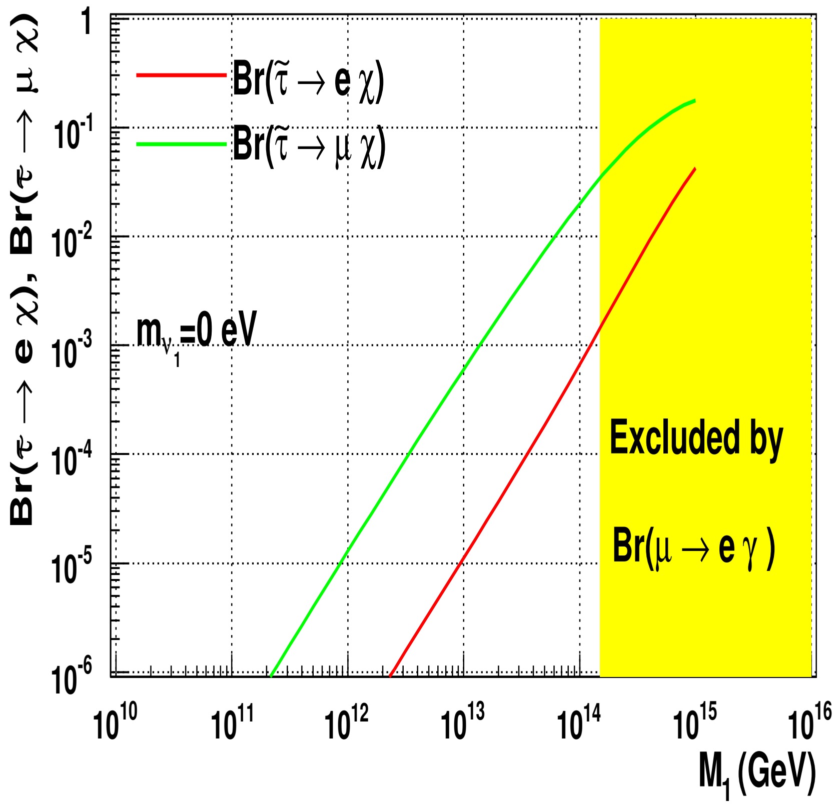


degenerate ν_R

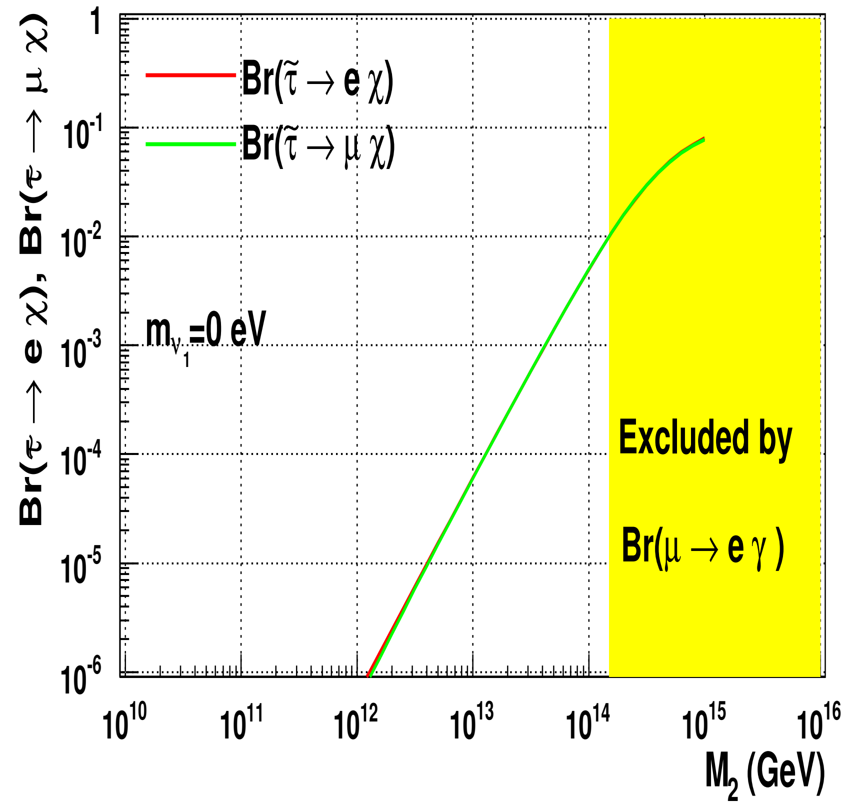
SPS1a' ($M_0 = 70$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, $\mu > 0$)

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 II

include $SU(2)$ Triplet Higgs

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

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

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

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

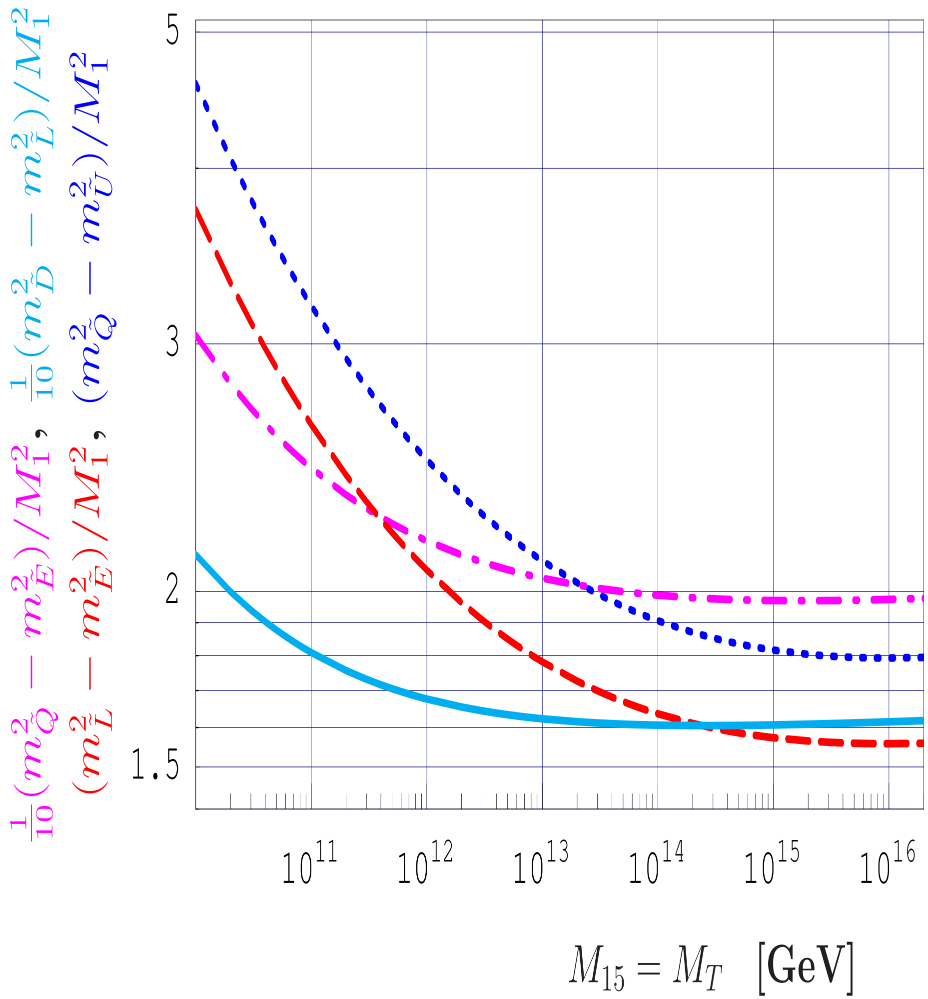
$$\mathbf{15} = S + T + Z$$

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

$$W \subset \frac{1}{\sqrt{2}}(Y_T\hat{L}\hat{T}_1\hat{L} + \hat{Y}_S D^c\hat{S}\hat{D}^c) + Y_Z\hat{D}^c\hat{Z}\hat{L} + Y_d\hat{D}^c\hat{Q}\hat{H}_d + \hat{Y}_u\hat{U}^c\hat{Q}\hat{H}_u + Y_e\hat{E}^c\hat{L}\hat{H}_d$$

$$+ \frac{1}{\sqrt{2}}(\lambda_1\hat{H}_d\hat{T}_1\hat{H}_d + \lambda_2\hat{H}_u\hat{T}_2\hat{H}_u) + M_T\hat{T}_1\hat{T}_2 + M_Z\hat{Z}_1\hat{Z}_2 + M_S\hat{S}_1\hat{S}_2 + \mu\hat{H}_d\hat{H}_u$$

Seesaw II with 15-plets



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

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

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

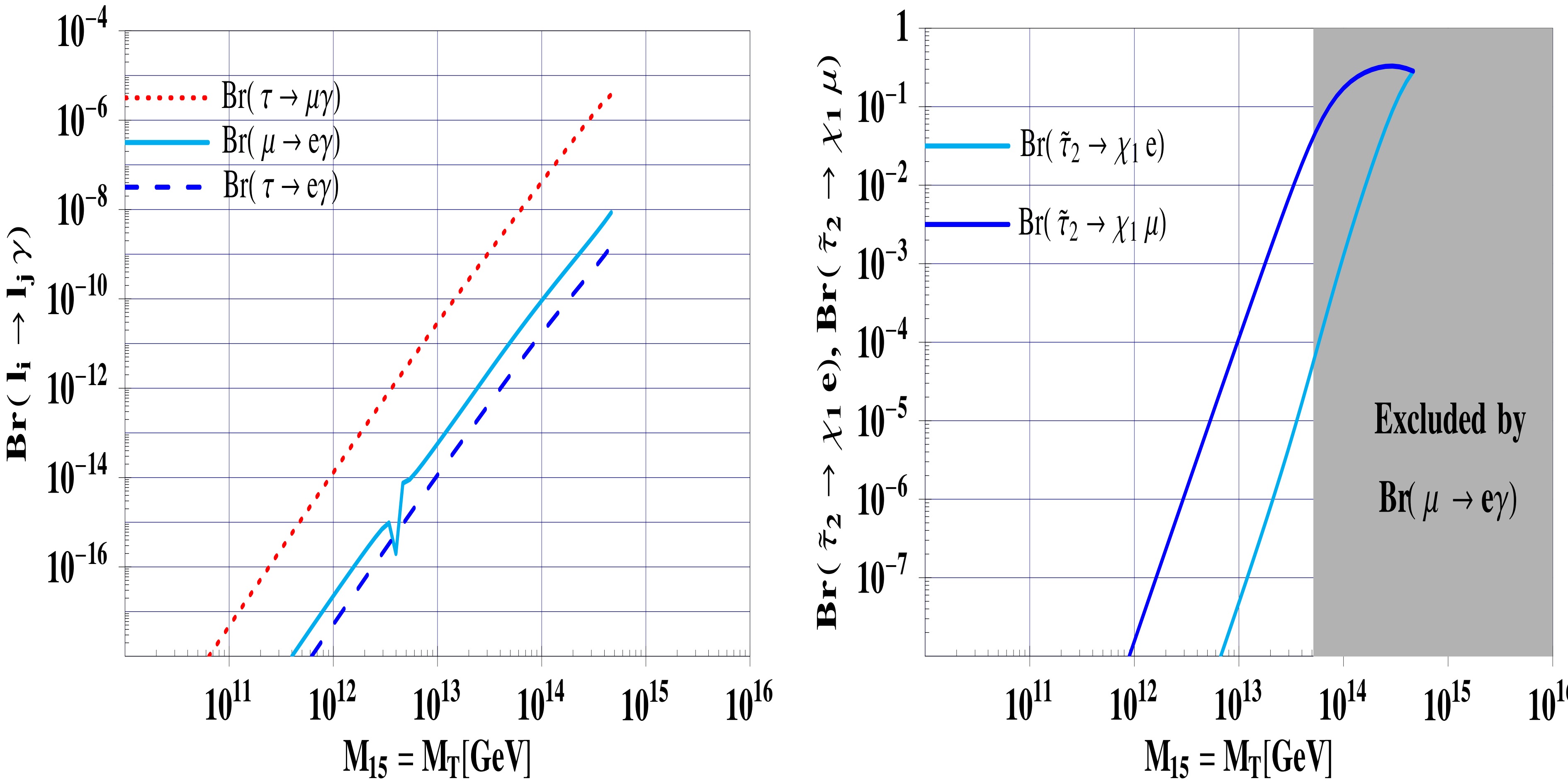
Seesaw I ($\simeq$ MSSM)

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

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

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

Seesaw II with 15-plets



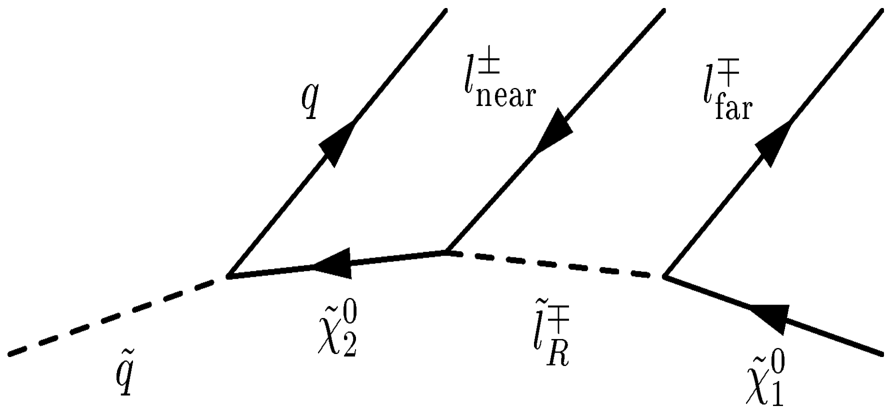
$\lambda_1 = \lambda_2 = 0.5$

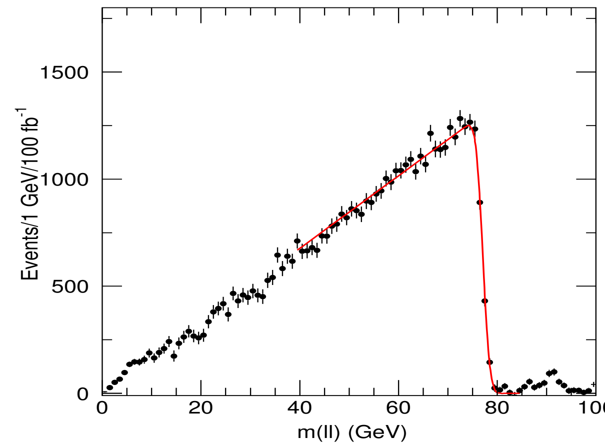
SPS3 ($M_0 = 90$ GeV, $M_{1/2} = 400$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, $\mu > 0$)

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

Masses at LHC

G. Polesello





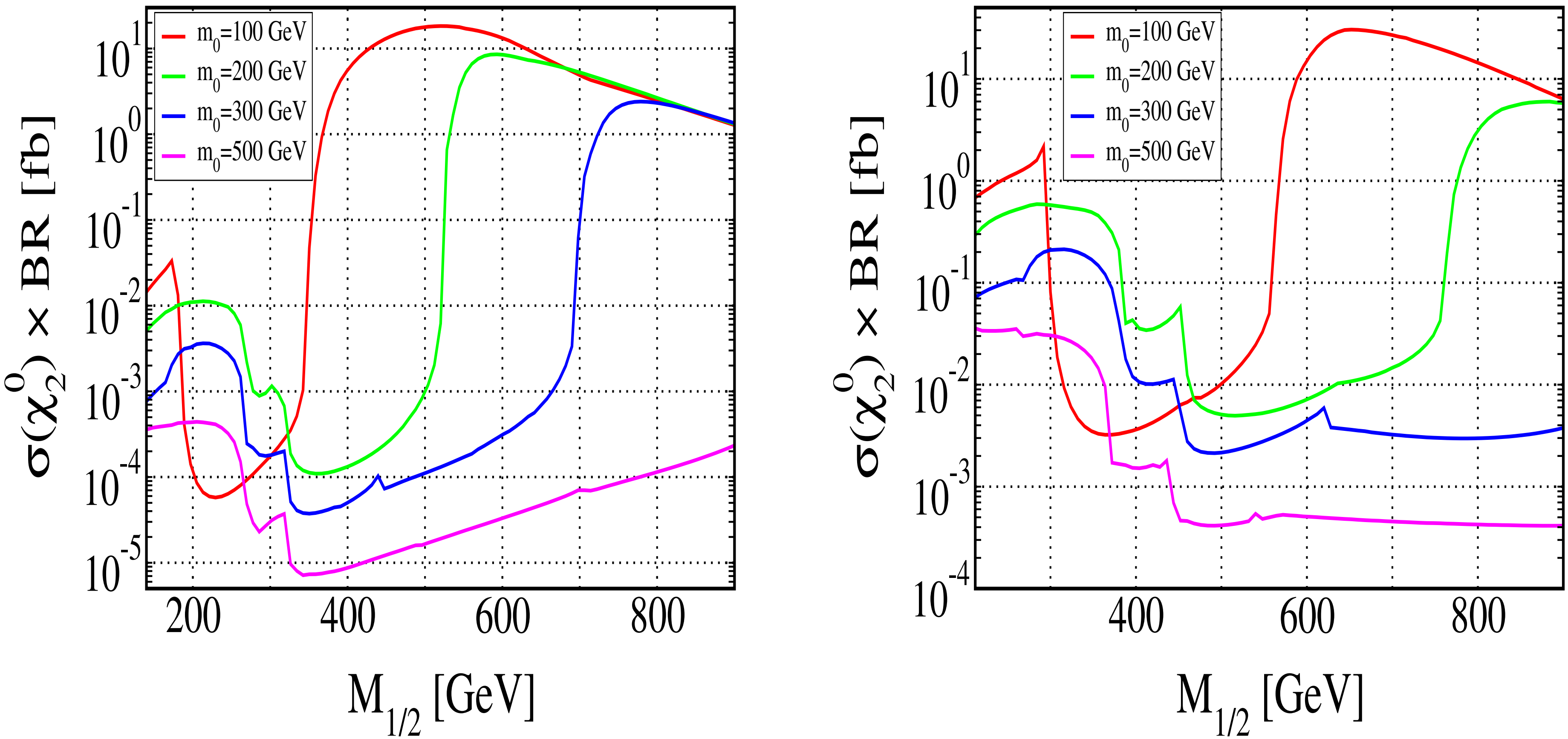
5 kinematical observables depending on 4 SUSY masses

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

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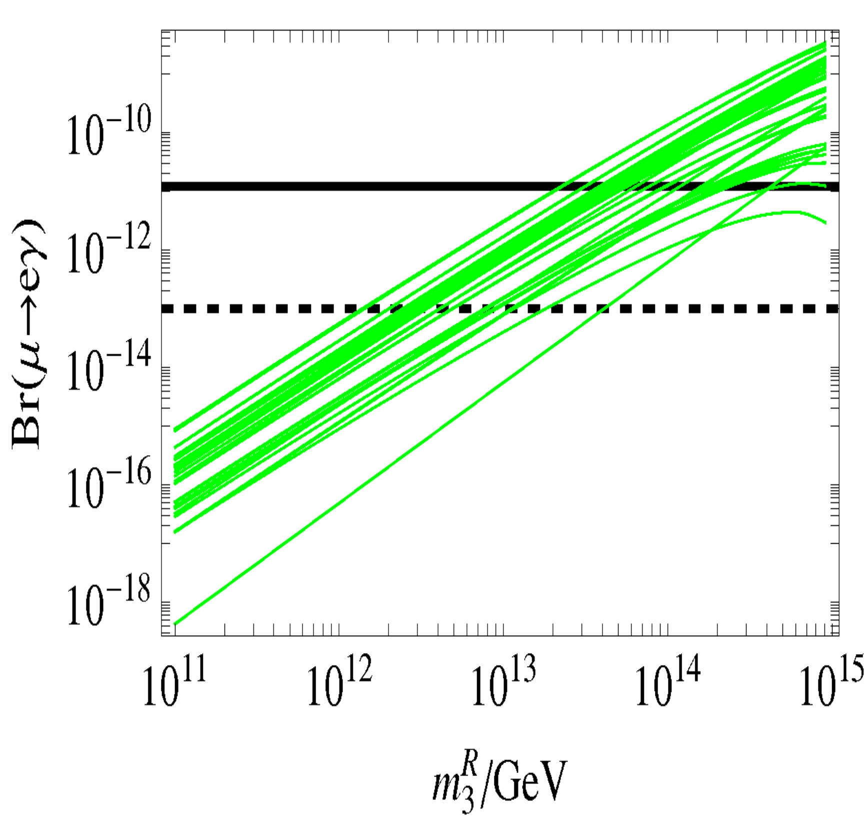
Conclusions

- 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
  - difficult to test at LHC, signals of O(10 fb) or below
  - in case of seesaw II: different mass ratios

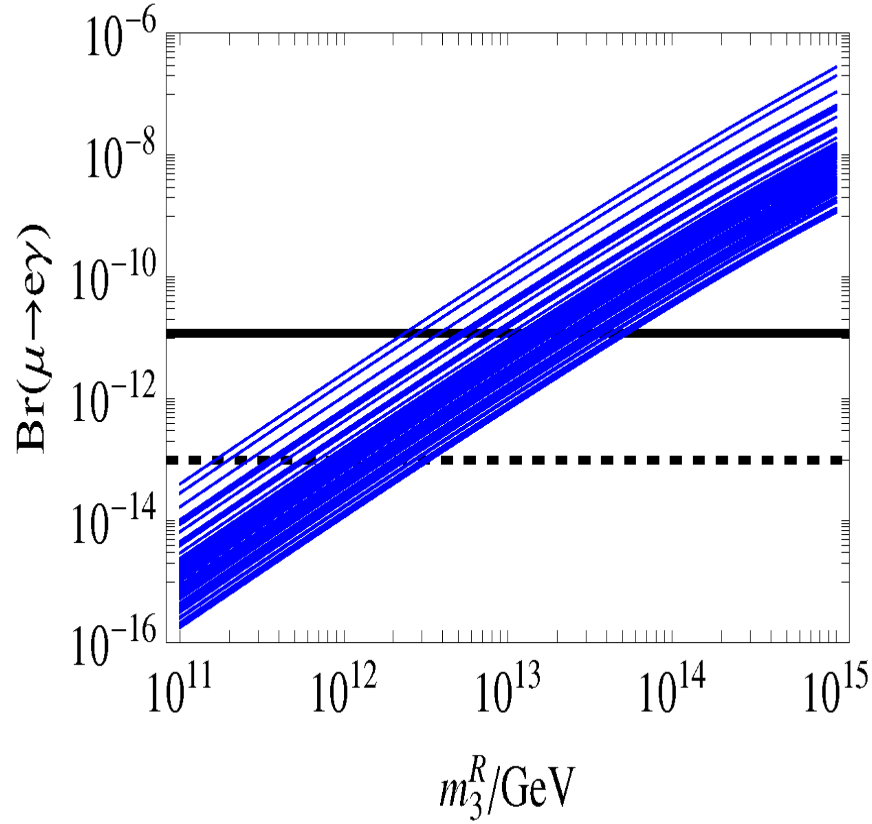
Seesaw I

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

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
$m(ll)^{\rm edge}$	77.077	77.024	0.08	0.05
$m(qll)^{\rm edge}$	431.1	431.3	4.3	2.4
$m(ql)^{\rm edge}_{\rm min}$	302.1	300.8	3.0	1.5
$m(ql)^{\rm edge}_{\rm max}$	380.3	379.4	3.8	1.8
$m(qll)^{\rm thres}$	203.0	204.6	2.0	2.8

Mass reconstruction

5 endpoints measurements, 4 unknown masses

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

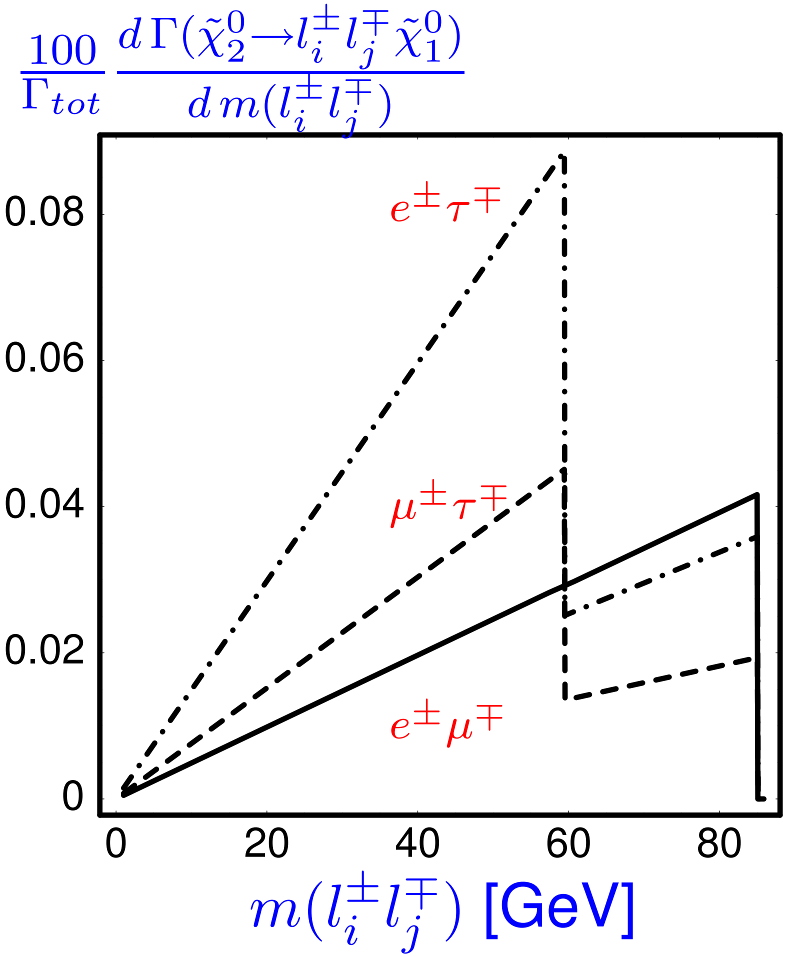
$$E_j^i = E_j^{\rm nom} + a_j^i \sigma_j^{\rm fit} + b^i \sigma_j^{Escale}$$

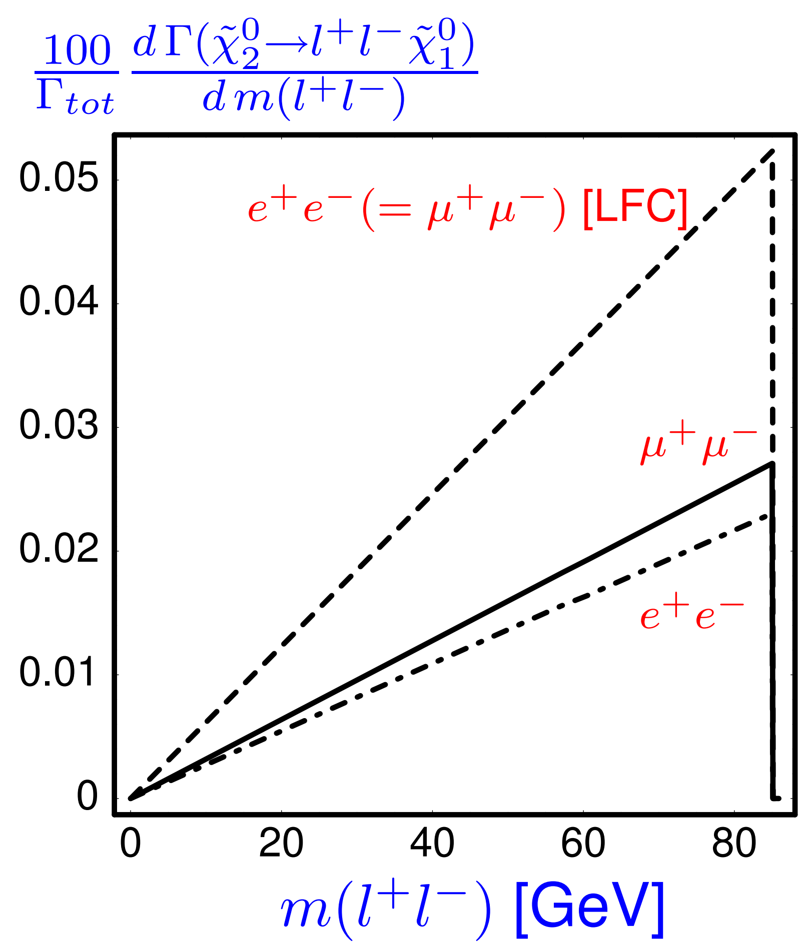
$m(\chi_1^0) =$ 96 GeV
$m(l_R) =$ 143 GeV
$m(\chi_2^0) =$ 177 GeV
$m(q_L) =$ 540 GeV

$\Delta m(\chi_1^0) = 4.8$ 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

Flavour mixing and edge variables





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