# Testing supersymmetric neutrino mass models at LHC (and beyond)

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# Overview

- Introduction
- Flavour violating decays of SUSY particles
  - Dirac neutrinos
  - Majorana neutrinos
  - Neutrino masses via R-parity violation
- ”Reconstruction of supersymmetric models” or
  ”Can we access heavy right-handed neutrinos”
- Conclusions

# Introduction: Why supersymmetry

- local SUSY implies gravity
- gauge coupling unification
- provides dark matter candidates
- solves hierarchy problem
- might help to explain observed baryon asymmetry

# 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

$BR(\mu \to e\gamma) \lesssim 1.2 \cdot 10^{-11}$ $\quad BR(\mu^- \to e^- e^+ e^-) \lesssim 10^{-12}$

$BR(\tau \to e\gamma) \lesssim 1.1 \cdot 10^{-7}$ $\quad BR(\tau \to \mu\gamma) \lesssim 6.8 \cdot 10^{-8}$

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

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

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

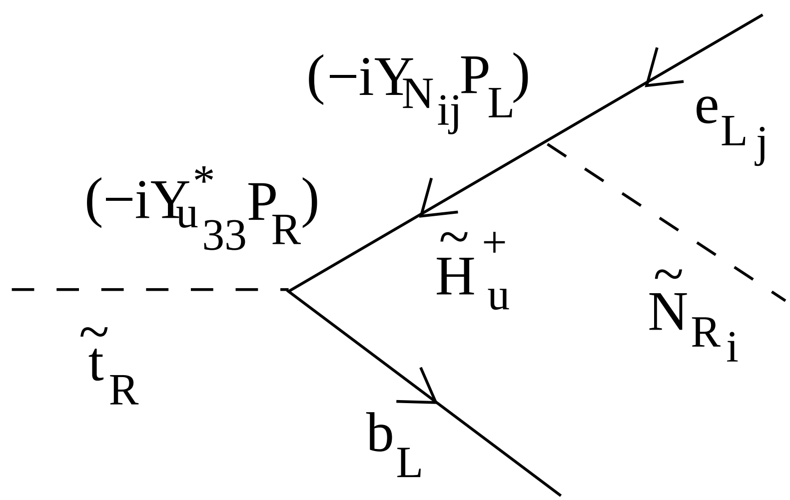
$$Y_\nu\, H\, \bar\nu_L\, \nu_R \to Y_\nu\, v\, \bar\nu_L\, \nu_R = m_\nu\, \bar\nu_L\, \nu_R$$

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




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

# Dirac neutrinos

| NLSP | decay modes | comments |
| --- | --- | --- |
| $\tilde{\chi}_1^0$ | $\nu\tilde{\nu}_R$ | invisble |
| $\tilde{\chi}_1^+$ | $l^+\tilde{\nu}_R$ | mainly inside detector |
| | | but finite decay length |
| $\tilde{f}$ | $f\nu\tilde{\nu}_R$, $f'l\tilde{\nu}_R$ | inside/outside detector |
| $\tilde{g}$ | $q\bar{q}\nu\tilde{\nu}_R$, $q'\bar{q}l\tilde{\nu}_R$ | mainly outside detector |

in mSUGRA: $m_{\tilde{\nu}_R} = m_0$

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

# Majorana neutrinos: Seesaw mechanism*

Assume the existence of very heavy $\nu_R$:

$$\Rightarrow \begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} 0 & Y_\nu v \\ Y_\nu v & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

$Y_\nu v$ in the range 1 MeV - 100 GeV.

$$\begin{aligned} m_1 &\simeq -\frac{h_\nu^2 v^2}{M_R} \\ m_2 &\simeq M_R \end{aligned}$$

expect: $10^7$ GeV $\lesssim M_R \lesssim 10^{14}$ GeV.
3 generations:

$$m_\nu \simeq -(Y_\nu^T v) M_R^{-1} (Y_\nu v)$$

much more parameters than observables

* 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

# Impact on SUSY breaking parameters

$Y_\nu$ contributes to RGEs :

$$
\begin{aligned}
16\pi^2 \dot{A}_e &= \cdots + 2 Y_\nu A_\nu \\
16\pi^2 \dot{M}_L^2 &= \cdots + M_L^2 Y_\nu^\dagger Y_\nu + Y_\nu^\dagger Y_\nu M_L^2
\end{aligned}
$$

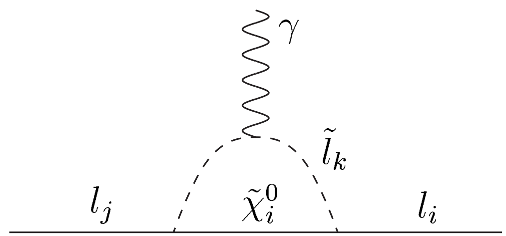
Off-diagonal elements

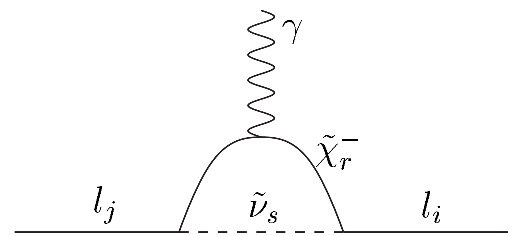
- rare lepton decays
- flavour violating SUSY decays

Change diagonal elements $\Rightarrow$ ratio of masses change

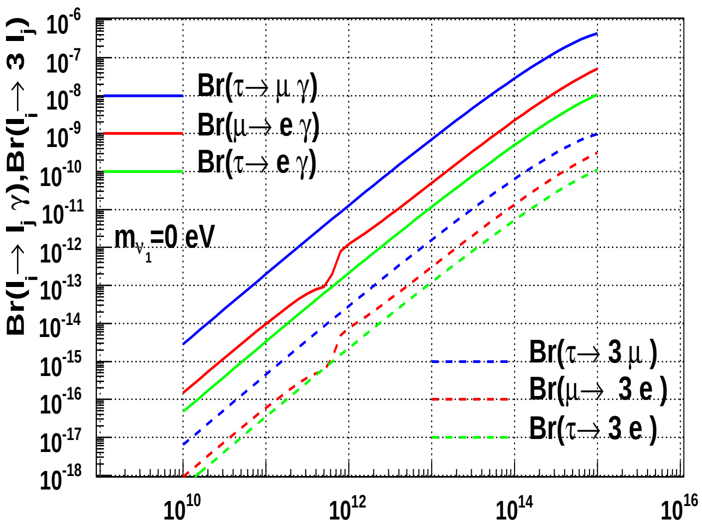
# Low energy observables

$$\tilde{\chi}_i^0 = (\tilde{\gamma}, \tilde{z}^0, \tilde{h}_d^0, \tilde{h}_d^0) \qquad \tilde{\chi}_i^- = (\tilde{w}^-, \tilde{h}^-)$$

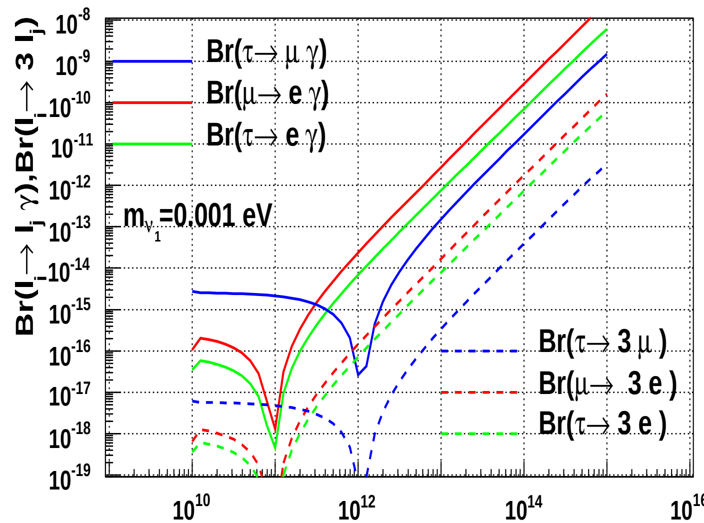



$\Rightarrow$ anomalous magnetic moments, electric dipole moments, rare lepton decays




degenerate $\nu_R$




hierarchical $\nu_R$
$M_{\nu_2} = M_{\nu_3} = 10^{10}$ GeV

M. Hirsch et al., arXiv:0804.4072

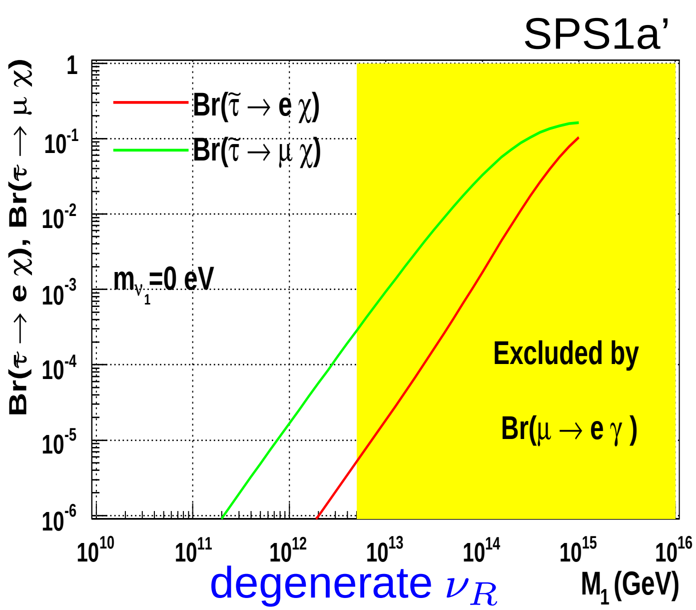
# Stau decays

$$(\Delta M^2_{\tilde{L}})_{ij} = -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(Y_\nu^\dagger L Y_\nu)_{ij} \ , \ (\Delta A_l)_{ij} = -\frac{3}{8\pi^2} A_0 Y_{l_i} (Y_\nu^\dagger L Y_\nu)_{ij} \ ,$$

$$L_{kl} = \log\left(\frac{M_{GUT}}{M_k}\right)\delta_{kl}$$

$$\frac{BR(\tilde{\tau}_2 \to e + \chi_1^0)}{BR(\tilde{\tau}_2 \to \mu + \chi_1^0)} \simeq \left(\frac{\theta_{13}}{\theta_{23}}\right)^2 \simeq \left(\frac{(\Delta M^2_{\tilde{L}})_{13}}{(\Delta M^2_{\tilde{L}})_{23}}\right)^2,$$

(neglecting $L$-$R$ mixing)

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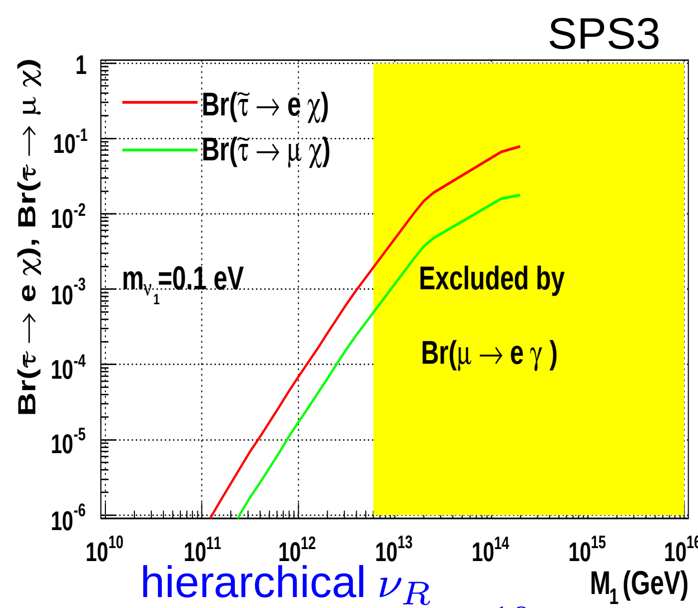


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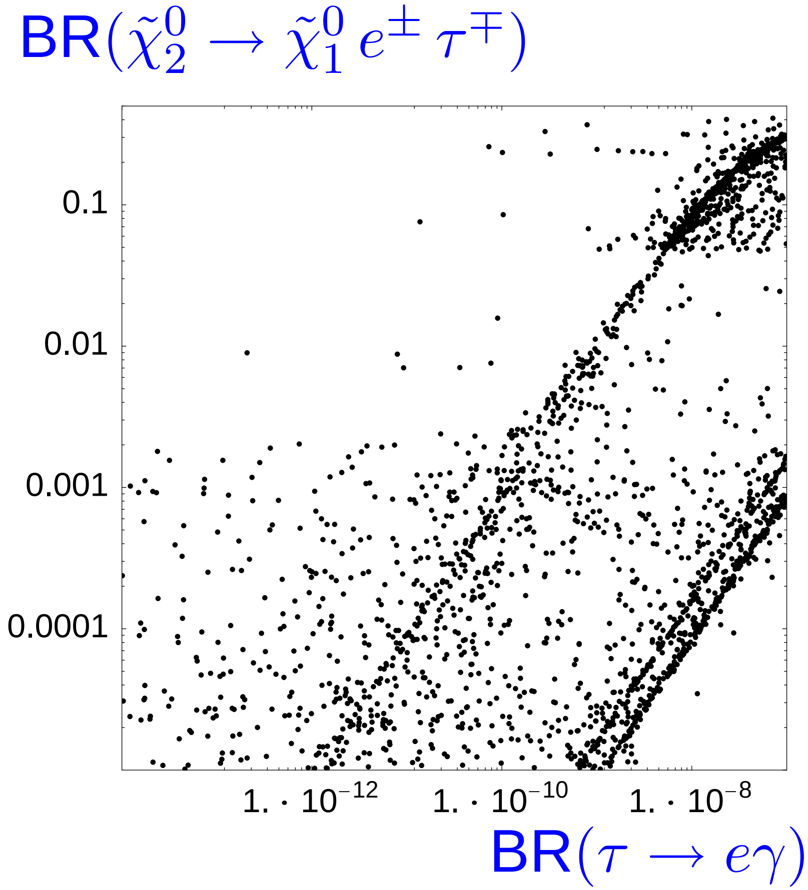
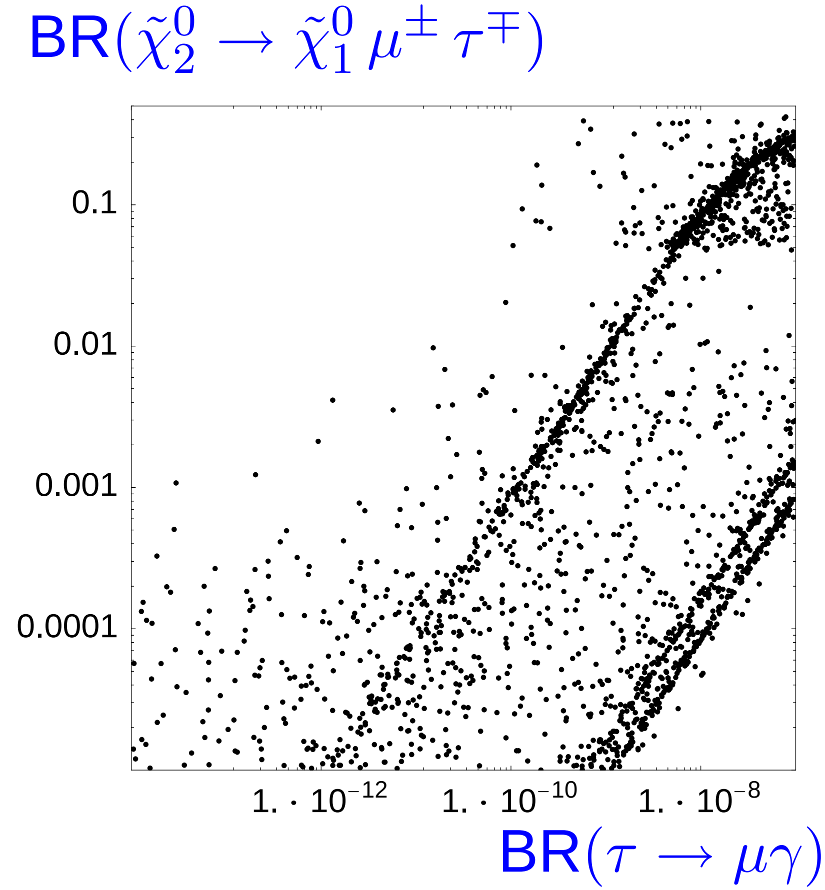
# MSSM Phenomenology: $\tilde{\chi}_2^0 \to \tilde{l}_i l_j \to l_k l_j \tilde{\chi}_1^0$

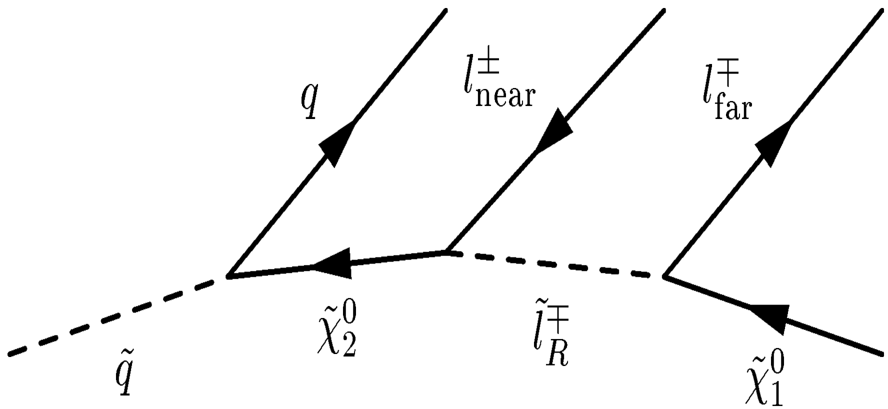


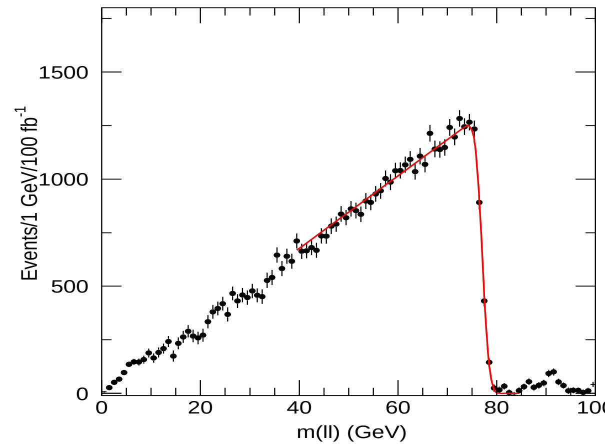

Variations around SPS1a

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

# SUSY phenomenology: implications for 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%

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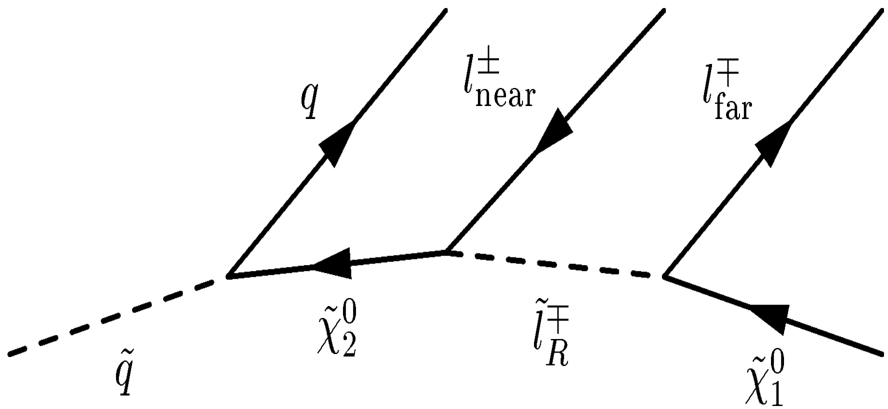


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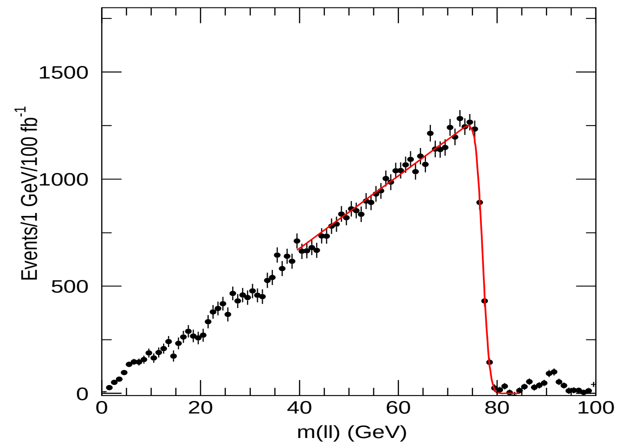


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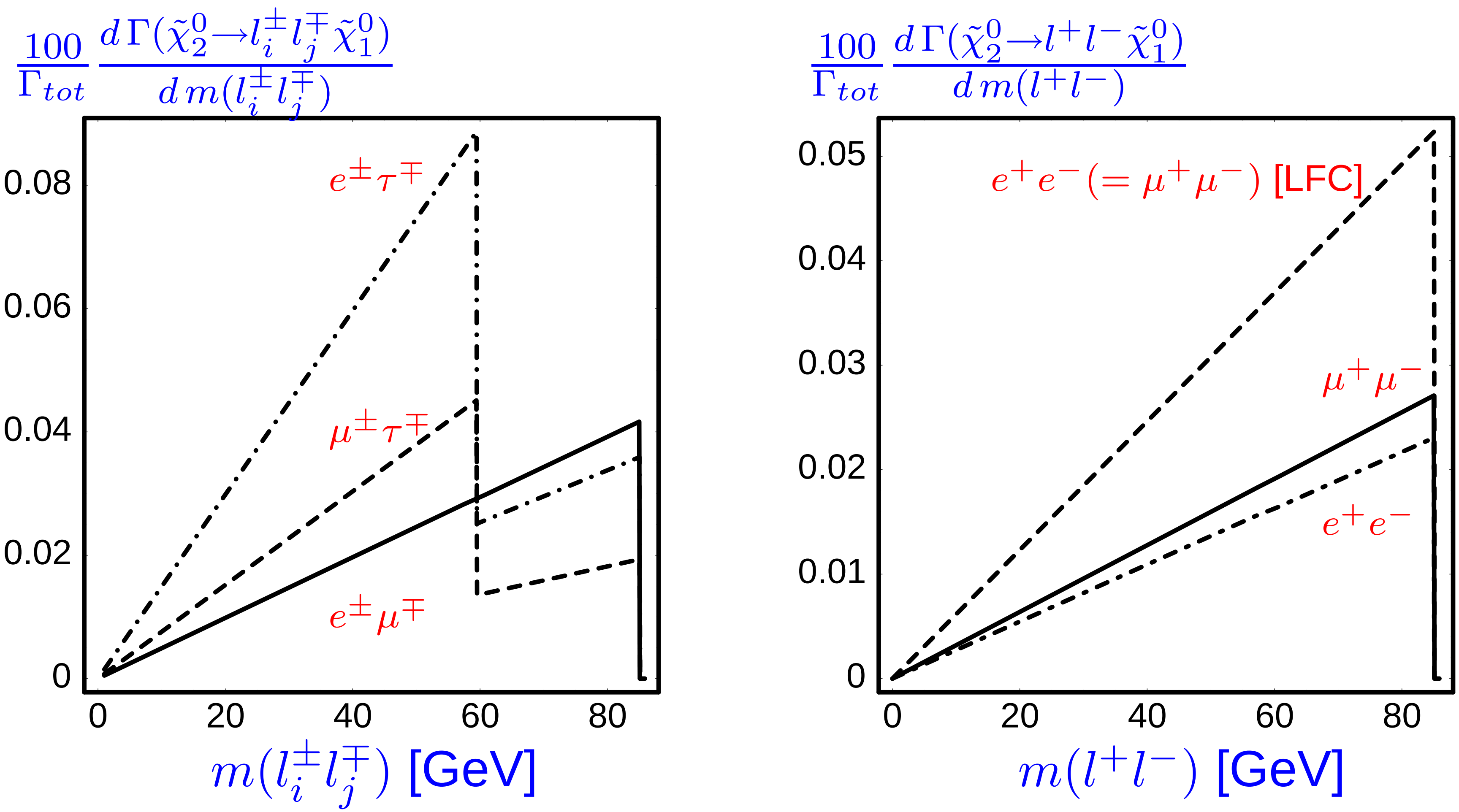
For background suppression

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

assumptions: — no flavour violation

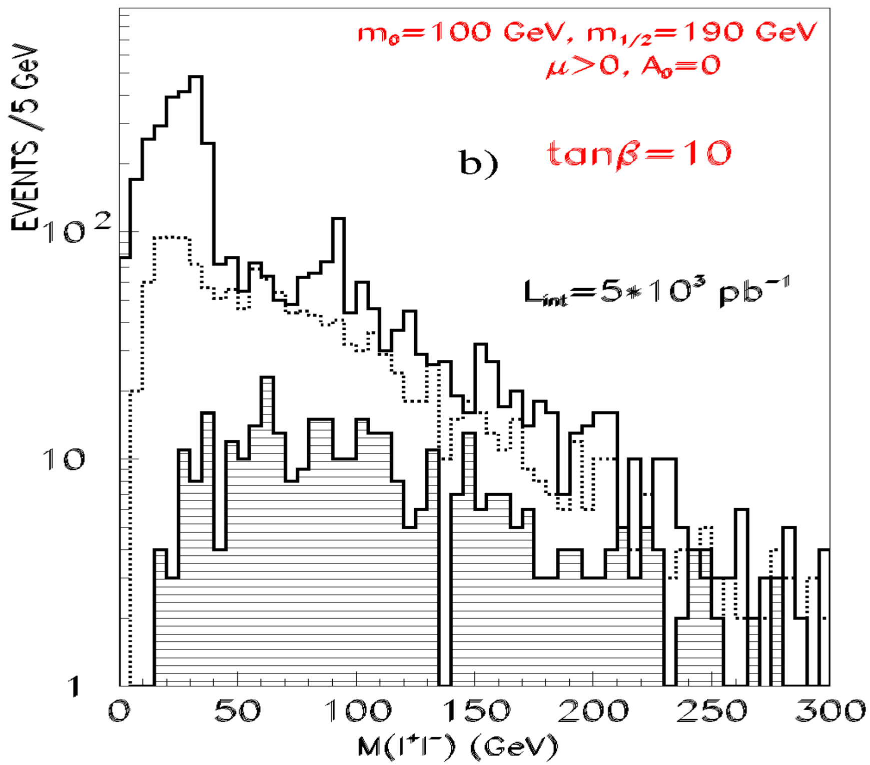
— BR$(\tilde{\chi}^0_2 \to \tilde{e}_R e)$ = BR$(\tilde{\chi}^0_2 \to \tilde{\mu}_R \mu)$

# SUSY phenomenology: implications for LHC




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

# SUSY phenomenology: implications for LHC




D. Denegri, W. Majerotto und L. Rurua

PRD **60** (1999) 035008

increase of experimental uncertainty

on the edges by an order of magnitude

see also I. Hinchliffe and F. E. Paige, PRD **63** (2001) 115006;

J. Hisano, R. Kitano and M. M. Nojiri, PRD **65** (2002) 116002

# SUSY phenomenology: broken R-parity

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)

# SUSY phenomenology: broken R-parity

## Neutrino physics*:

- neutrino masses via $\nu$-$\tilde{\chi}_i^0$ mixing
- neutrino mixing angles in terms of R-parity violating couplings

* M. Hirsch, et al. Phys. Rev. D **62**, 113008 (2000)

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## Neutralino decays:

- dominant R-parity violating decays: $\tilde{\chi}_1^0 \to W^\pm l_i^\mp$, $\tilde{\chi}_1^0 \to Z\nu_i$, $\tilde{\chi}_1^0 \to \nu\tau^+ l_i^-$
- R-parity conserving decay: $\Gamma(\tilde{\chi}_1^0 \to \tilde{G}\gamma) \propto \left(\frac{m_{\tilde{\chi}_1^0}}{100 \quad \text{GeV}}\right)^5 \left(\frac{100 \quad \text{eV}}{m_{3/2}}\right)^2$
- $\Gamma(\tilde{\chi}_1^0) \simeq (10^{-4}$–$10^{-2})$ eV $\Rightarrow$ decay length of O(10 $\mu$m) – O(1 mm)

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- $\Gamma(\tilde{\chi}^0_1) \simeq (10^{-4}\text{–}10^{-2})$ eV $\Rightarrow$ decay length of O(10 $\mu$m) – O(1 mm)

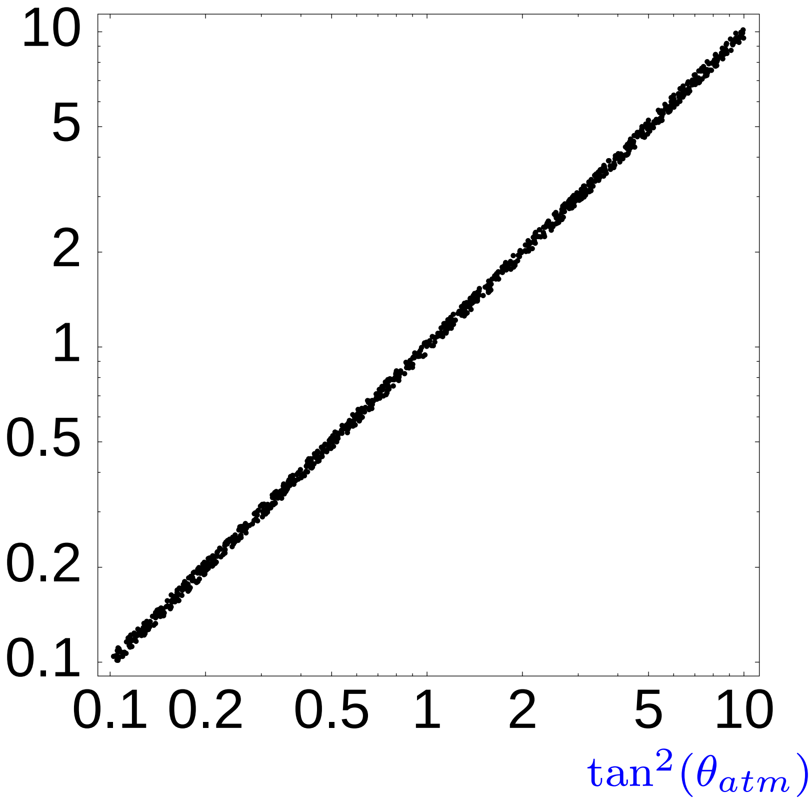
## Gravitino:

- $\tilde{G}$ eventually decays into $\nu\gamma$
  but: $\tau(\tilde{G}) \sim O(10^{30})\cdot$ life time of the universe

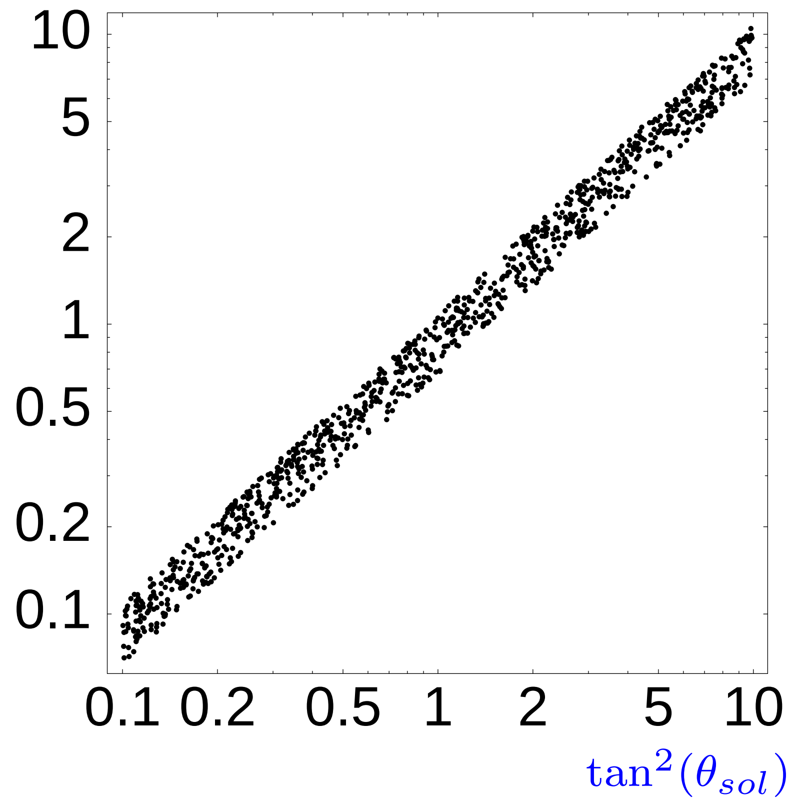
* M. Hirsch, et al. Phys. Rev. D **62**, 113008 (2000)

## Correlations

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



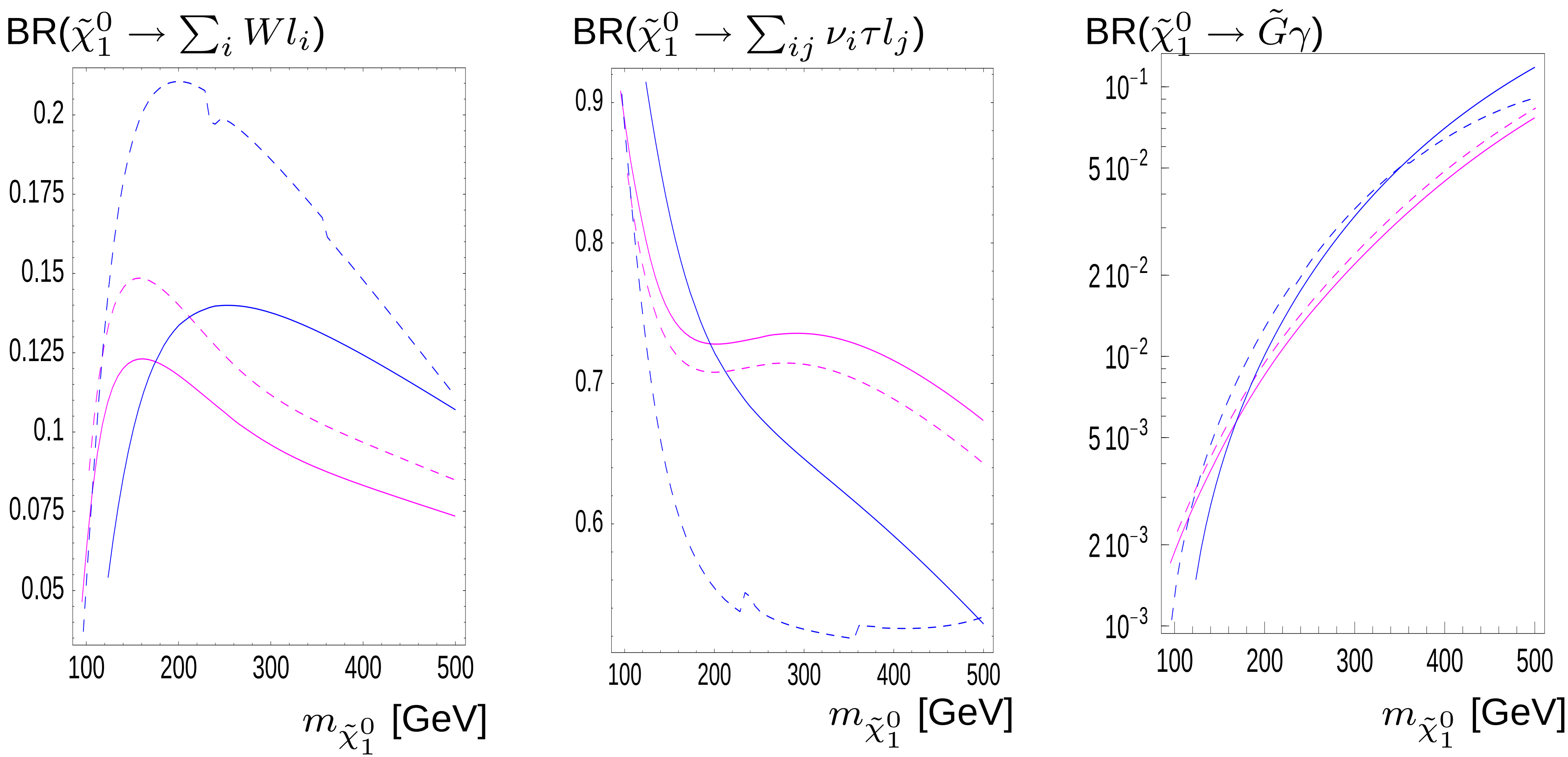

$\mathrm{BR}(\tilde{\chi}^0_1 \to \nu e\tau)$ /$\mathrm{BR}(\tilde{\chi}^0_1 \to \nu\mu\tau)$




W. P. et al., Phys. Rev. D **63**, 115004 (2001)

Julius-Maximilians-UNIVERSITÄT WÜRZBURG

# SUSY Phenomenology: broken R-parity




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

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

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

## Comments

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

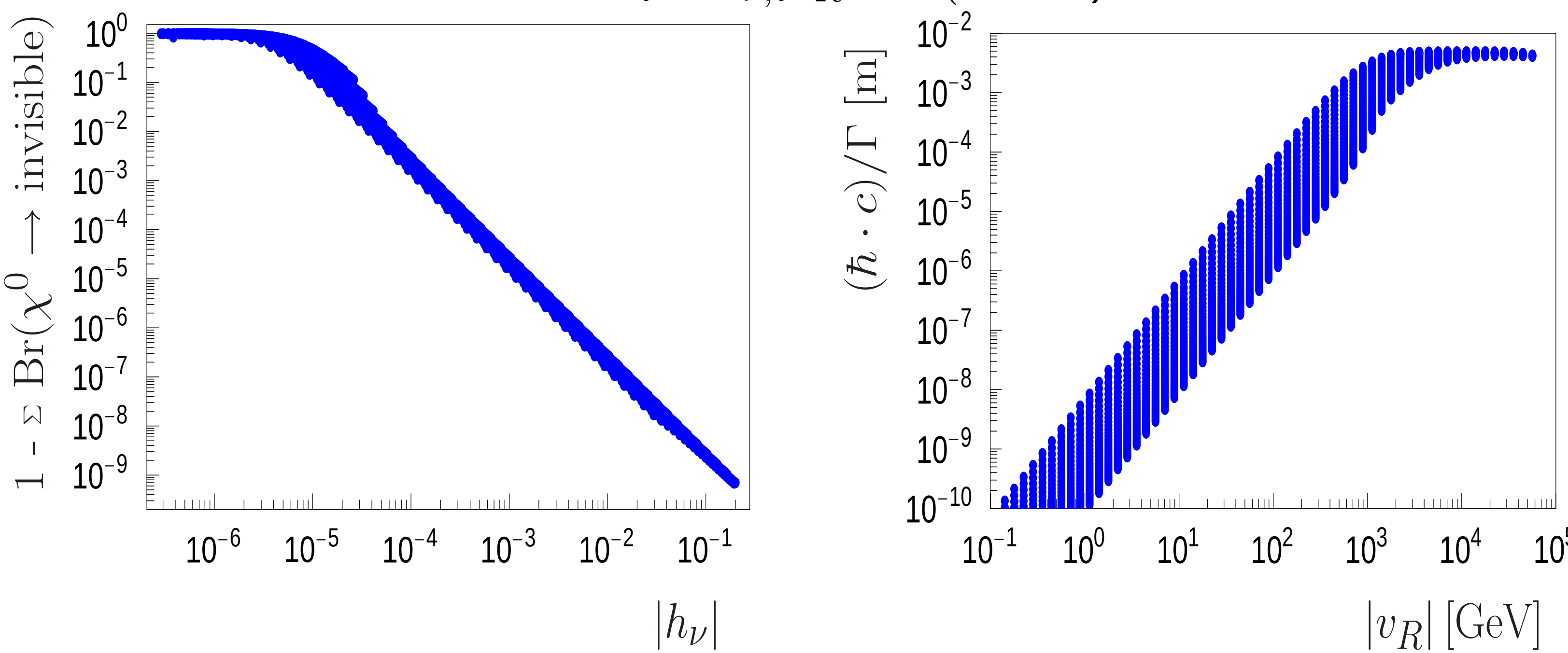
  $\Rightarrow$ for $n_5 \geq 3$ hardly points with $\tilde{\chi}_1^0$ NLSP
- $\tilde{l}_R$ NLSPs: BR($l\nu$) $>$ BR($l\tilde{G}$)
- $n_5 = 2$: BR($\tilde{G}\gamma$) reduced by a factor 2-3

# SUSY Phenomenology: broken R-parity

Spontaneous R-Parity violation:

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

SPS1a', $\epsilon_i = h_{\nu,i} v_R = O($ 1 GeV)




M. Hirsch, W.P., PRD74 (2006) 055003

# Reconstruction of supersymmetric models

Two-scale picture of nature:

| elektroweak<br>$< H > \simeq 10^2$ GeV | $\Leftarrow$ | SUSY | $\Rightarrow$ | GUT/string/Planck scale<br>$10^{16-19}$ GeV |
|---|---|---|---|---|

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|---|---|---|---|---|

program to explore the high scale†:

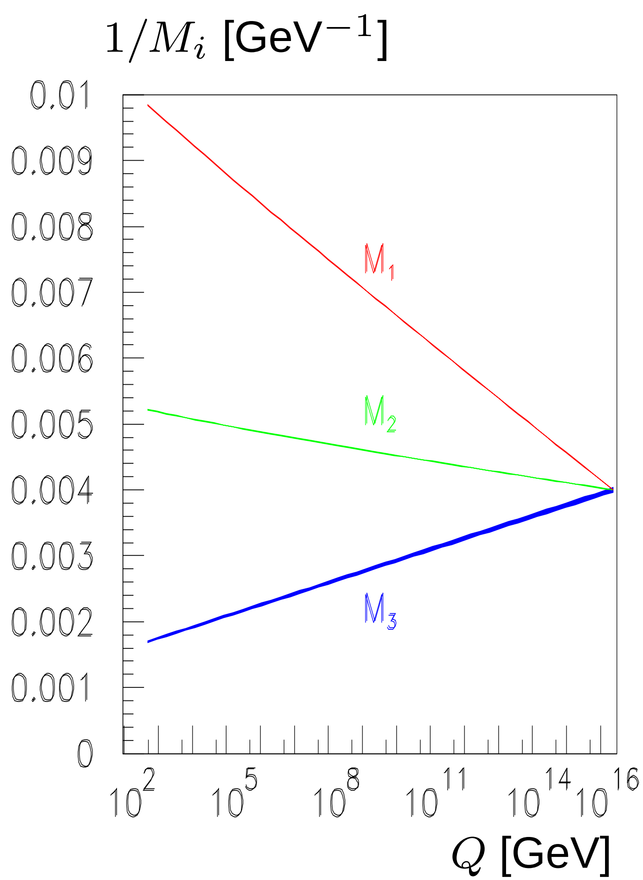
- LHC, ILC: masses, mixings, couplings . . .
  $\oplus$ low energy observables: $b \to s\gamma$, $(g-2)_\mu$, . . .
- extract SUSY Lagrange parameters
- extrapolation to GUT/Planck scale*

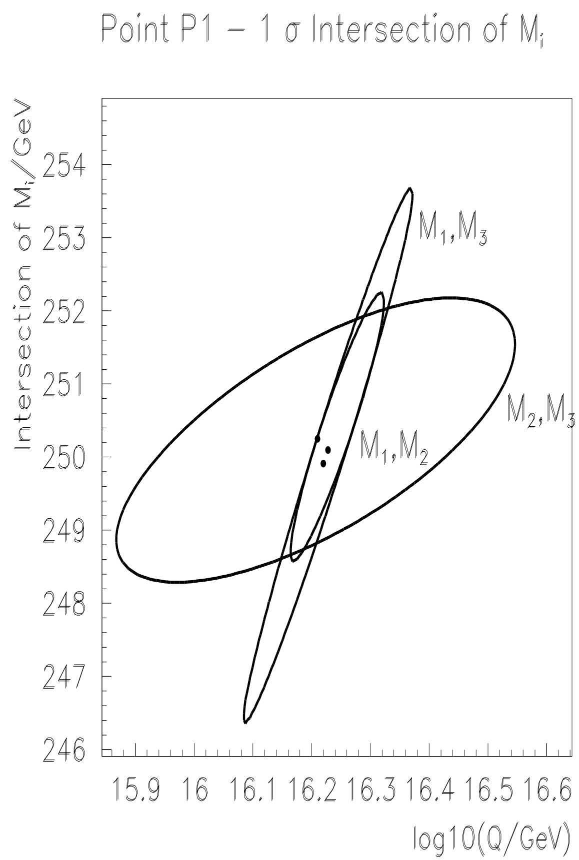
† „Supersymmetry Parameter Analysis" project

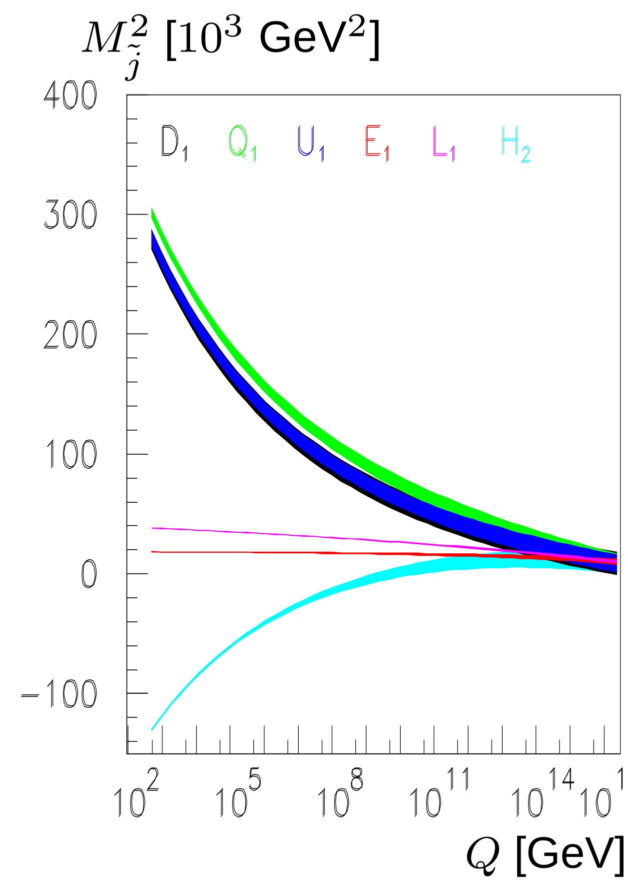
* G. Blair, W. P., P. Zerwas, Phys. Rev. D **63**, 017703 (2001); Eur. Phys. J. C **27**, 263 (2003)

# Reconstruction of supersymmetric models

## Extrapolation of gaugino- and scalar mass parameters




1 $\sigma$ error bands

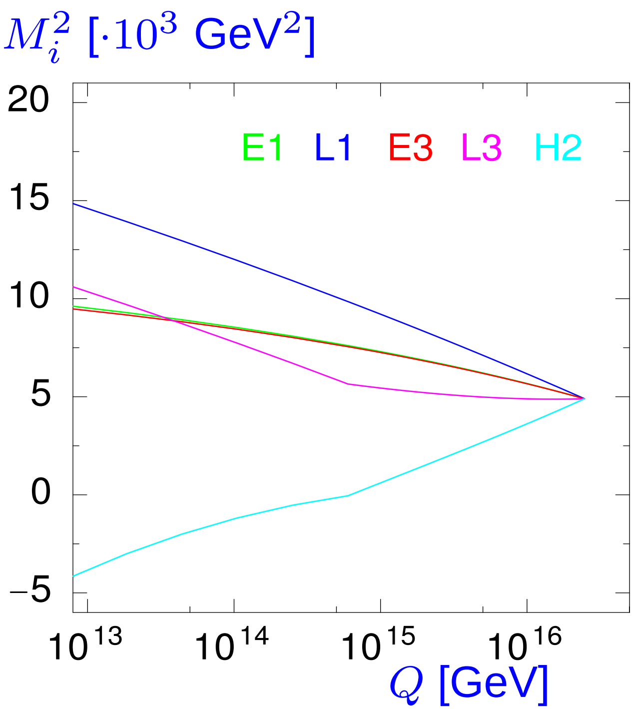
SPA: $M_{1/2}$ =250 GeV, $M_0 = 70$ GeV, $A_0 = -300$ GeV, $\tan\beta = 10$, sign($\mu$)=+

# Reconstruction of supersymmetric models

$m_\nu \neq 0$ neutrino masses via seesaw mechanism

$\Rightarrow$ Seesaw scale $M[\nu_R] \sim 10^{10}/10^{14}$ GeV in SO(10)

$\Rightarrow$ affects evolution of 3rd generation parameters $\Rightarrow$ kink




A. Freitas, W. P. and P. M. Zerwas, Phys. Rev. D **72** (2005) 115002

A. Freitas, F. Deppisch, W. P. and P. M. Zerwas, arXiv:0712.0361

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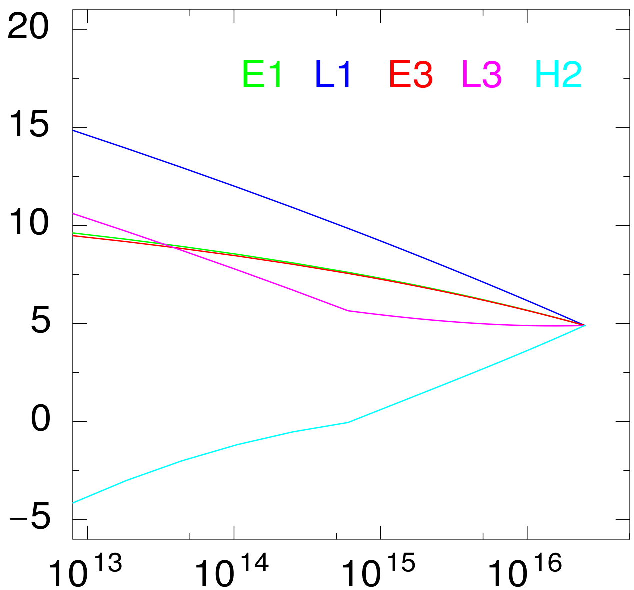
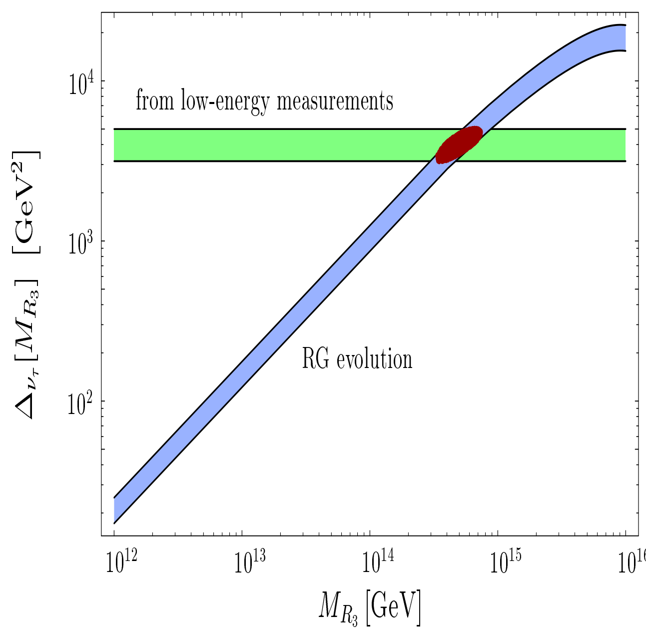
$M_i^2$ [$\cdot 10^3$ GeV$^2$]




$Q$ [GeV]

$\oplus\, M_\nu \Rightarrow M[\nu_{R3}] \sim 10^{14}$ GeV [30%]




A. Freitas, W. P. and P. M. Zerwas, Phys. Rev. D **72** (2005) 115002

A. Freitas, F. Deppisch, W. P. and P. M. Zerwas, arXiv:0712.0361

# Conclusions

- Neutrino physics requires extension of the Standard Model
- Supersymmetry is a very promising and well motivated extension
- $\Rightarrow$ in general lepton flavour violating decays of SUSY particles
- can be measured at the LHC
  but things might turn out to be more complicated

# SUSY phenomenology: implications for 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 |
|---|---|---|---|---|
| $m(ll)^{\text{edge}}$ | 77.077 | 77.024 | 0.08 | 0.05 |
| $m(qll)^{\text{edge}}$ | 431.1 | 431.3 | 4.3 | 2.4 |
| $m(ql)^{\text{edge}}_{\text{min}}$ | 302.1 | 300.8 | 3.0 | 1.5 |
| $m(ql)^{\text{edge}}_{\text{max}}$ | 380.3 | 379.4 | 3.8 | 1.8 |
| $m(qll)^{\text{thres}}$ | 203.0 | 204.6 | 2.0 | 2.8 |

## Mass reconstruction

5 endpoints measurements, 4 unknown masses

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

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

$m(\chi_1^0)$ = 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

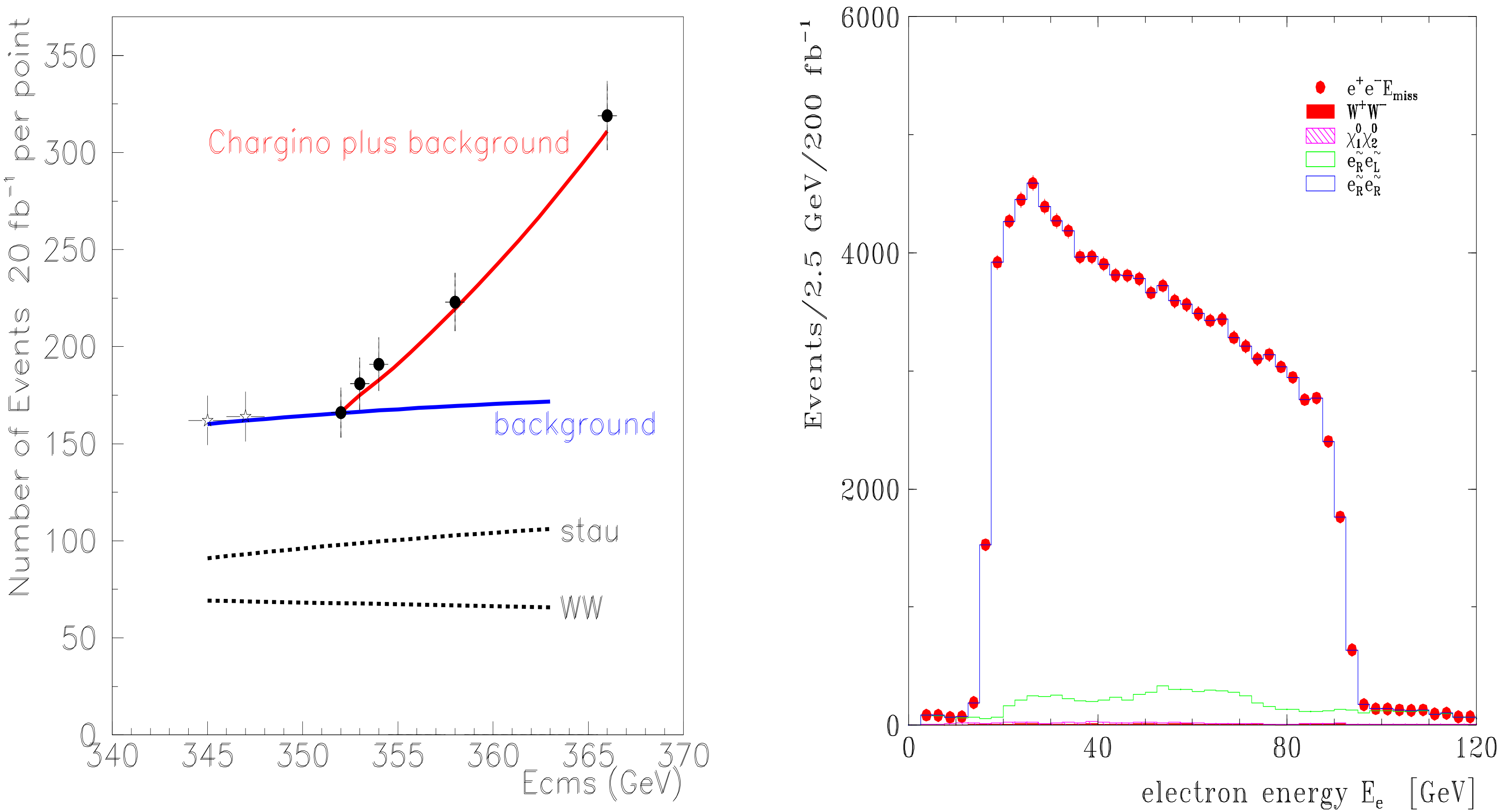
**Gjelsten, Lytken, Miller, Osland, Polesello, ATL-PHYS-2004-007**

# 1-loop solutions to RGEs

$$
\begin{aligned}
m^2_{\tilde{e}_R} &= M_0^2 + D_{\mathcal{U}} + \alpha_R M^2_{1/2} - \tfrac{6}{5} S' - 2 s^2_W D_{EW} \\
m^2_{\tilde{e}_L} &= M_0^2 - 3 D_{\mathcal{U}} + \alpha_L M^2_{1/2} + \tfrac{3}{5} S' - c_{2W} D_{EW} \\
m^2_{\tilde{\nu}_{eL}} &= M_0^2 - 3 D_{\mathcal{U}} + \alpha_L M^2_{1/2} + \tfrac{3}{5} S' + D_{EW} \\
\alpha_L &= \tfrac{3}{10} f_1 + \tfrac{3}{2} f_2 \,, \qquad \alpha_R = \tfrac{6}{5} f_1 \\
f_i &= \frac{1}{b_i} \left( 1 - \left[ 1 + \frac{\alpha_{\mathcal{U}}}{4\pi} b_i \log \frac{\Lambda^2_{\mathcal{U}}}{\tilde{M}^2} \right]^{-2} \right) \quad \text{with} \quad (b_1, b_2) = (\tfrac{33}{5}, 1) \\
m^2_{\tilde{\tau}_R} - m^2_{\tilde{e}_R} &= m^2_\tau - 2\Delta_\tau \\
m^2_{\tilde{\tau}_L} - m^2_{\tilde{e}_L} &= m^2_\tau - \Delta_\tau - \Delta_{\nu_\tau} \\
m^2_{\tilde{\nu}_{\tau L}} - m^2_{\tilde{\nu}_{eL}} &= -\Delta_\tau - \Delta_{\nu_\tau} \\
\Delta_\tau &\approx \frac{m^2_\tau(\Lambda_{\mathcal{U}})}{8\pi^2 v_d^2} \left(3M_0^2 + A_0^2\right) \log \frac{\Lambda^2_{\mathcal{U}}}{\tilde{M}^2} \\
\Delta_{\nu_\tau} &\approx \frac{m^2_t(\Lambda_{\mathcal{U}})}{8\pi^2 v_u^2} \left(3M_0^2 + A_0^2\right) \log \frac{\Lambda^2_{\mathcal{U}}}{M^2_{\nu_{R3}}}
\end{aligned}
$$

# Mass measurements, ILC

$$e^+_R e^-_L \to \tilde{\chi}^+_1 \tilde{\chi}^-_1 \qquad e^+_L e^-_R \to \tilde{e}^+_R \tilde{e}^-_R \to e^+ \tilde{\chi}^0_1 \, e^- \tilde{\chi}^0_1$$

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# Expected experimental accuracies

| | Mass, ideal | "LHC" | "LC" | "LHC+LC" |
|---|---|---|---|---|
| $h^0$ | 116.0 | 0.25 | 0.05 | 0.05 |
| $H^0$ | 425.0 | | 1.5 | 1.5 |
| $\tilde{\chi}_1^0$ | 97.7 | 4.8 | 0.05 | 0.05 |
| $\tilde{\chi}_2^0$ | 183.9 | 4.7 | 1.2 | 0.08 |
| $\tilde{\chi}_4^0$ | 413.9 | 5.1 | 3-5 | 2.5 |
| $\tilde{\chi}_1^\pm$ | 183.7 | | 0.55 | 0.55 |
| $\tilde{e}_R$ | 125.3 | 4.8 | 0.05 | 0.05 |
| $\tilde{e}_L$ | 189.9 | 5.0 | 0.18 | 0.18 |
| $\tilde{\tau}_1$ | 107.9 | 5-8 | 0.24 | 0.24 |
| $\tilde{q}_R$ | 547.2 | 7-12 | - | 5-11 |
| $\tilde{q}_L$ | 564.7 | 8.7 | - | 4.9 |
| $\tilde{t}_1$ | 366.5 | | 1.9 | 1.9 |
| $\tilde{b}_1$ | 506.3 | 7.5 | - | 5.7 |
| $\tilde{g}$ | 607.1 | 8.0 | - | 6.5 |

$m_0 = 70$ GeV

$m_{1/2} = 250$ GeV

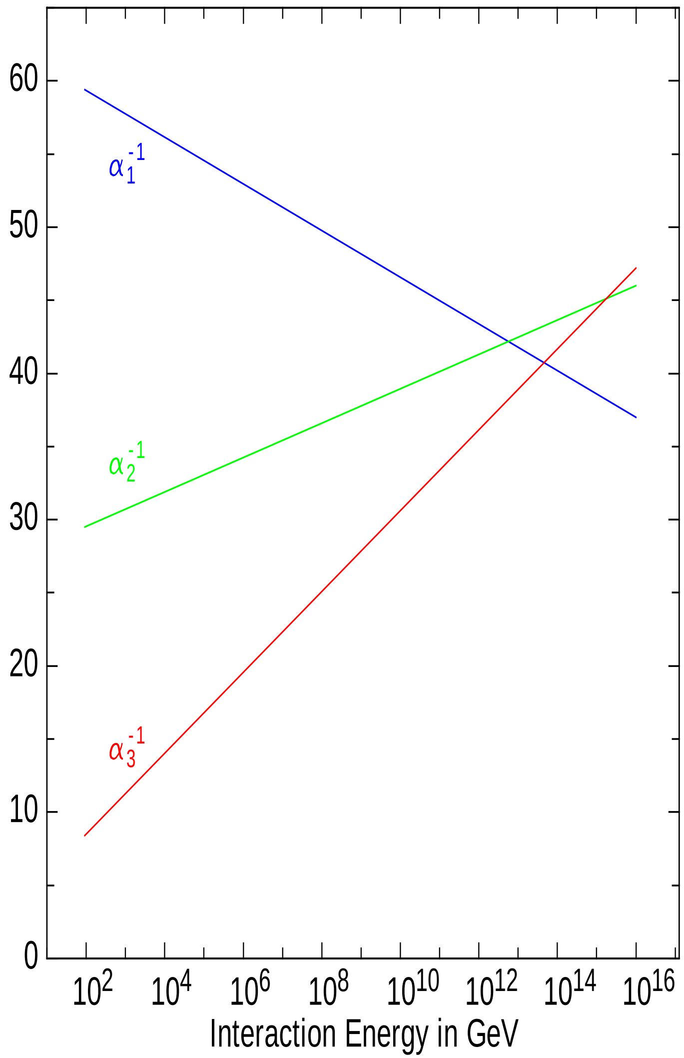
$A_0 = -300$ GeV

$\tan\beta = 10$

sign$(\mu) = +$

# Evolution of gauge couplings: SM versus SUSY

## SM




## MSSM