Predictions of neutrino mass models with R-parity violation for future collider experiment

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Overview

- ”Why supersymmetry” or
  ”Why do we want to extend the Standard Model”
- Neutrinos
- R-parity and dark matter
- LSP decays
- Conclusions

Why supersymmetry

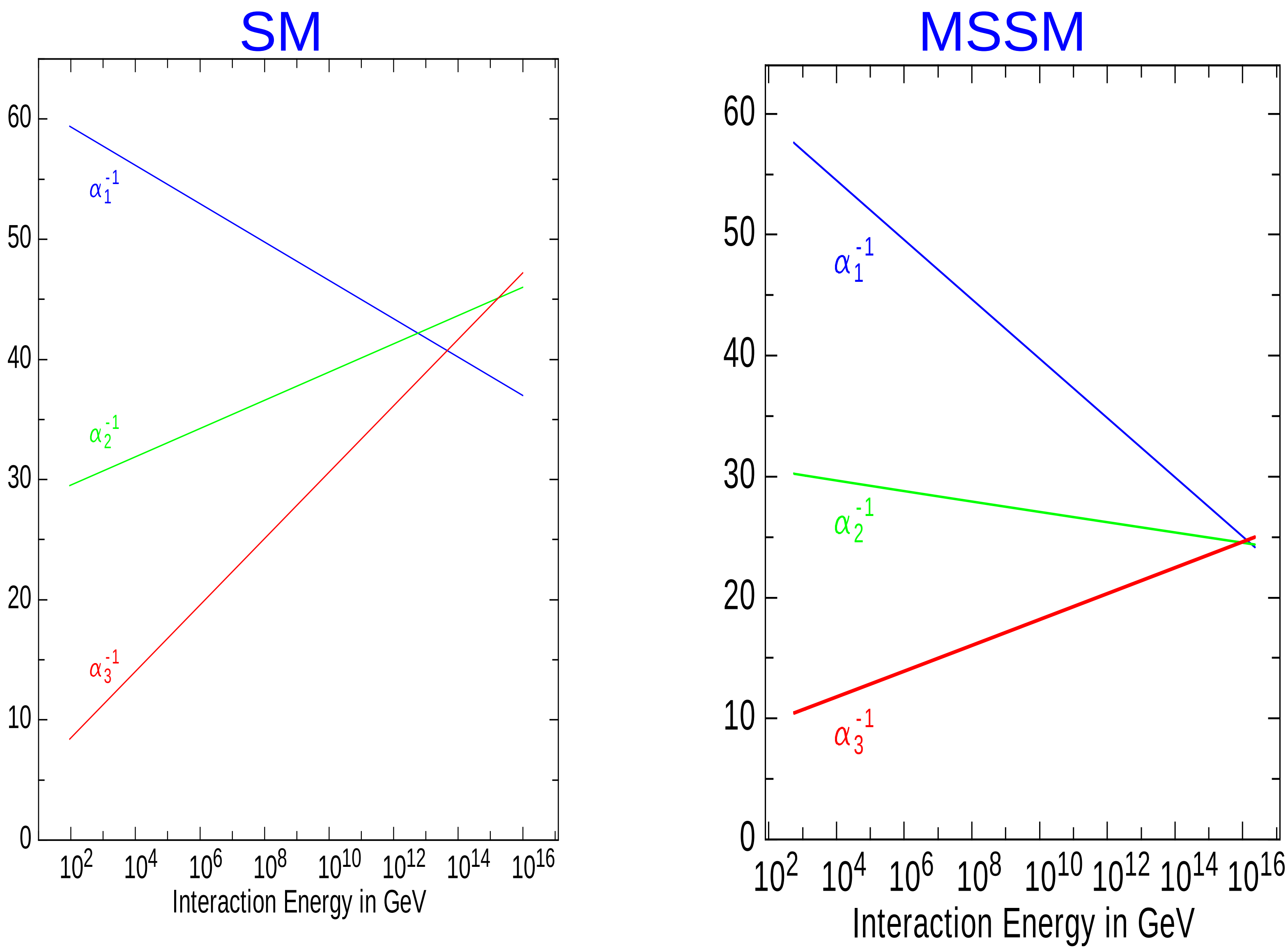
- How to combine gravity with the SM?

  $\Rightarrow$ local Supersymmetry (SUSY) implies gravity

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

  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



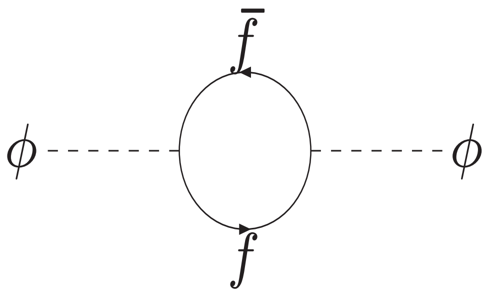
Why supersymmetry

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

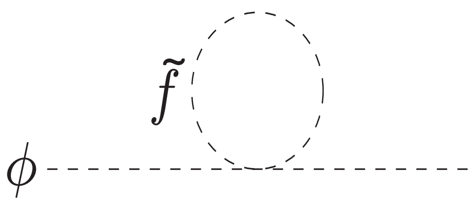
  Why do have neutrinos so tiny masses?
- ”Why does electroweak symmetry break?” or

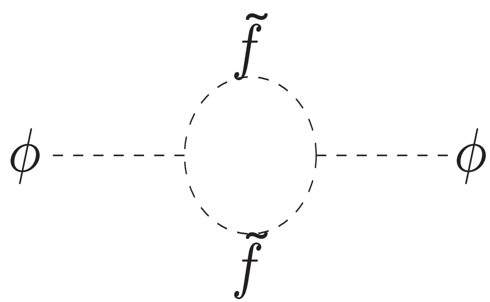
  ”Why is $\mu^2 < 0$ in the SM?”
- Hierarchy problem

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: $\delta m^2 \propto (m^2_{\tilde{f}} - m^2_f)\log(m^2_{\tilde{f}}/m^2_f)$

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 $H^\pm$	$\Leftrightarrow$	$\tilde{h}^0_d$ $\tilde{h}^0_u$ $\tilde{h}^\pm$

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

Introduction to explicit R-parity violation

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

$$W = W_{R_P} + W_{\not R_p}$$

$\Rightarrow$ MSSM part:

$$W_{R_P} \quad = \quad h_e^{ij} \hat{H}_d \hat{L}_i \hat{E}_j^C + h_d^{ij} \hat{H}_d \hat{Q}_i \hat{D}_j^C + h_u^{ij} \hat{H}_u \hat{Q}_i \hat{U}_j^C - \mu \hat{H}_d \hat{H}_u$$

$\Rightarrow$ R-parity violating part:

$$W_{\not R_p} \quad = \quad \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^C + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k^C + \lambda''_{ijk} \hat{U}_i^C \hat{D}_j^C \hat{D}_k^C + \epsilon_i \hat{L}_i \hat{H}_u$$

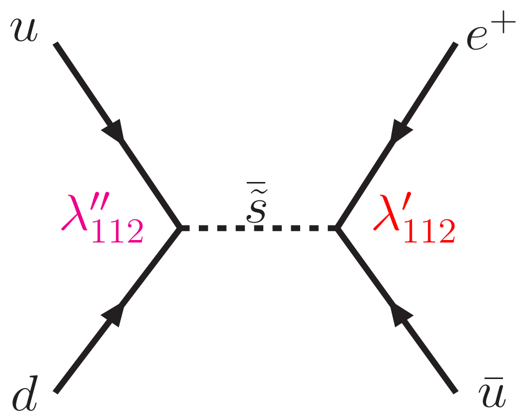
$\Rightarrow$ λ_{ijk}, λ'_{ijk} and ϵ_i violate lepton number

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

$\Rightarrow$ lepton number and baryon number violation can not be present at the same time, because...

Proton decay

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

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

$\Rightarrow$ 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):

$$(L_i, \bar{E}_i, Q_i, \bar{U}_i, \bar{D}_i) \quad \rightarrow \quad -(L_i, \bar{E}_i, Q_i, \bar{U}_i, \bar{D}_i), \quad (H_1, H_2) \rightarrow (H_1, H_2).$$

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

$$(Q_i, \bar{U}_i, \bar{D}_i) \quad \rightarrow \quad -(Q_i, \bar{U}_i, \bar{D}_i), \quad (L_i, \bar{E}_i, H_1, H_2) \rightarrow (L_i, \bar{E}_i, H_1, H_2).$$

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

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

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

$$\epsilon_i = h_i \langle \tilde{\nu}^c \rangle = h_i v_R$$

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

Bilinear R-parity breaking extension of the MSSM

Take the Minimal Supersymmetric extension of the Standard Model (MSSM), add to the superpotential:

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

and to the soft supersymmetry breaking terms:

$$V^{soft} = V^{soft}_{MSSM} + B_i \epsilon_i \tilde{L}_i H_u$$

$\Rightarrow$ Note that unless $B_{MSSM} \equiv B_i$ *and* $m^2_{H_d} \equiv m^2_{L_i}$ the bilinear terms can not be eliminated simultaneously from V^{soft} *and* W.

$\Rightarrow$ Presence of $B_i \epsilon_i \tilde{L}_i H_u \Rightarrow$ Sneutrino fields acquire VEV

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

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

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

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

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

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

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

mixing angles

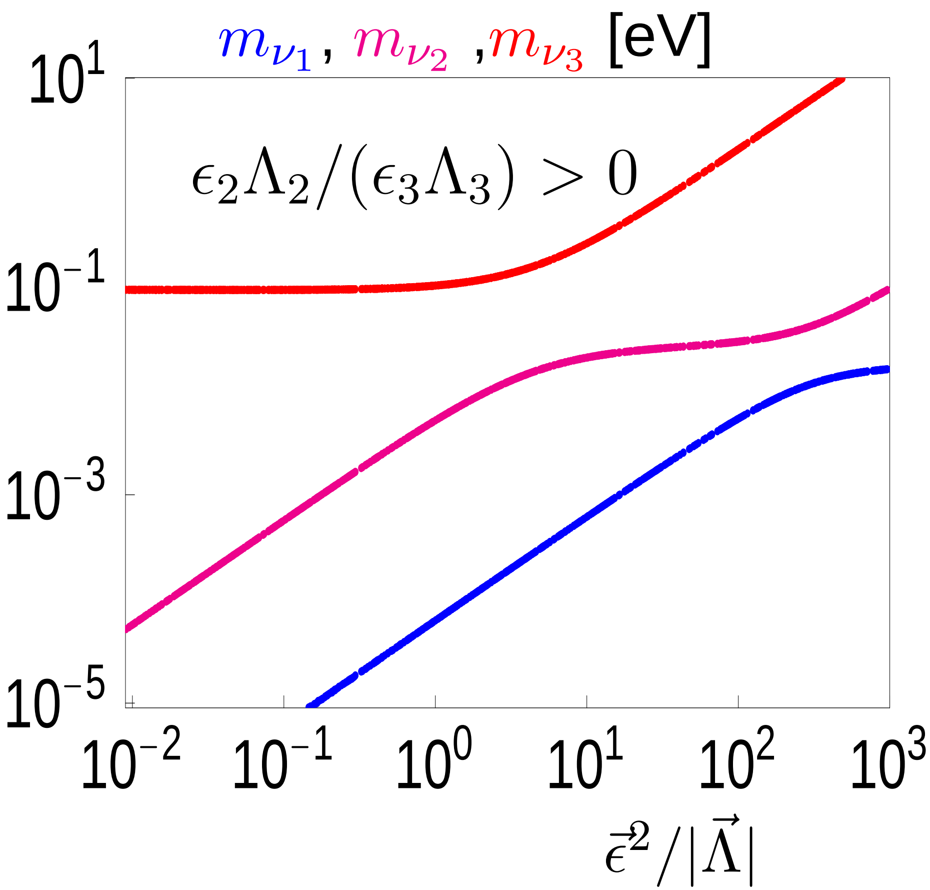
$$
\tan^2\theta_{atm} \simeq \left(\frac{\Lambda_2}{\Lambda_3}\right)^2, \; U^2_{e3} \simeq \frac{|\Lambda_1|}{\sqrt{\Lambda_2^2+\Lambda_3^2}}, \; \tan^2\theta_{sol} \simeq \left(\frac{\tilde{\epsilon}_1}{\tilde{\epsilon}_2}\right)^2
$$

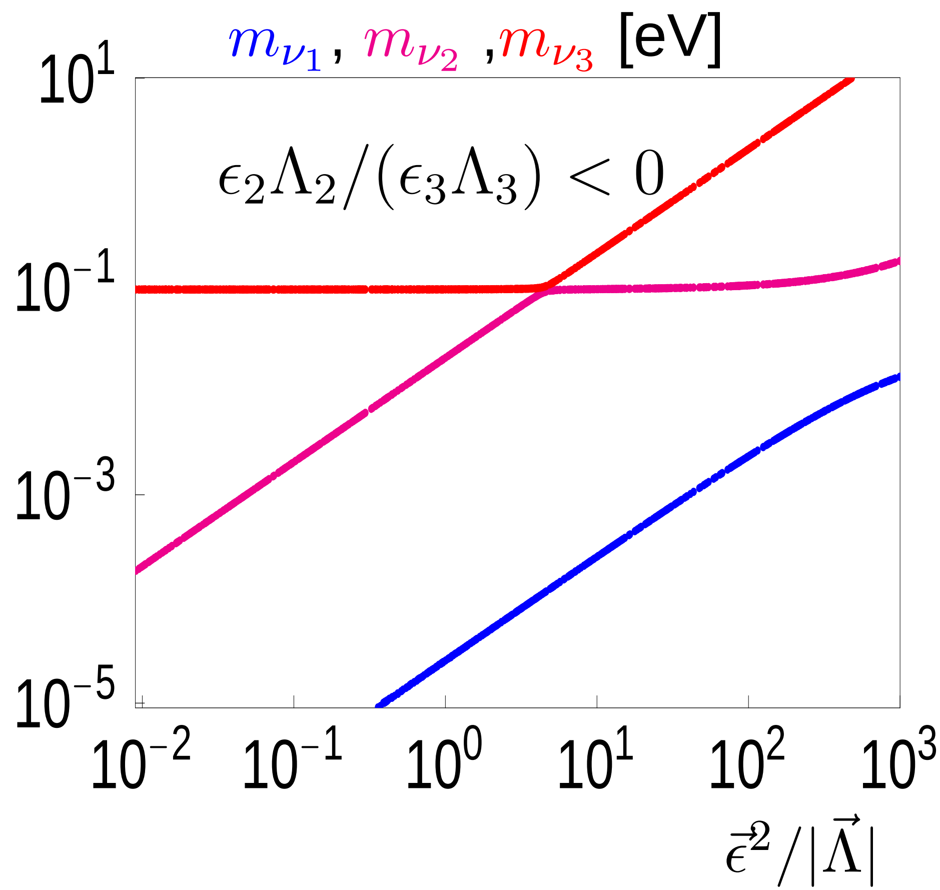
experimental data require:

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

Neutrino masses

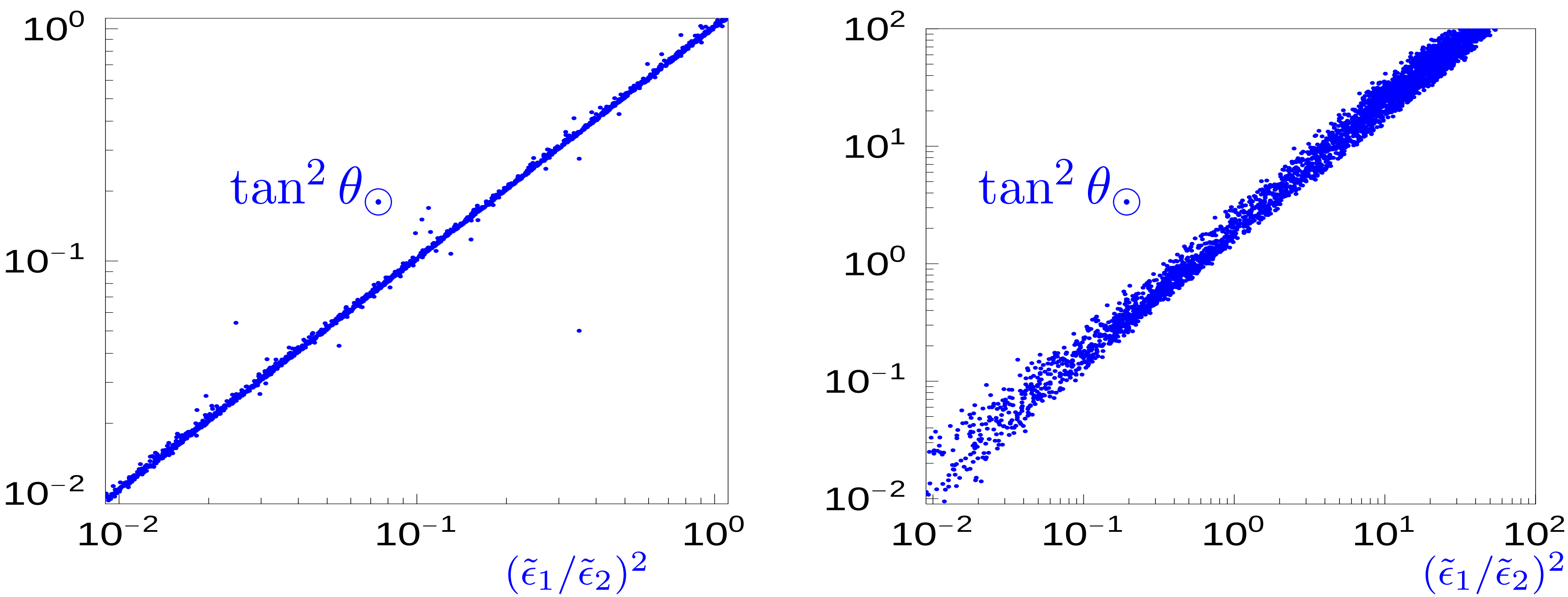
Two examples of neutrino masses as function of $\vec{\epsilon}^2/|\vec{\Lambda}|$ (other parameters fixed):





Solar angle

$$\text{Approximation formula gives}: \quad \tan^2\theta_\odot \simeq \left(\frac{\tilde\epsilon_1}{\tilde\epsilon_2}\right)^2$$



$\Rightarrow$ Left figure: Neutralino LSP, b–$\tilde b_i$ loop usually dominant

$\Rightarrow$ Right figure: Scalar Tau LSP, both, b–$\tilde b_i$ and $S^\pm_j$–$\tilde\chi^\mp_k$ ($j = 1, .., 7$, $k = 1, .., 5$), equally important

Decay of the Lightest Supersymmetric Particle

If R-parity is violated, the LSP is unstable.

Any SUSY particle can therefore be the LSP!

Consider all possibilities:

$\Rightarrow$ Neutralino: Final states: $\nu_i\nu_j\nu_k$, $\nu_i q\bar{q}$, $\nu_i l_j^+ l_k^-$, $l_i^\pm q\bar{q}'$

$\Rightarrow$ Chargino: Final states: $l_i \sum_{j,k} \nu_j\nu_k$, $l_i q\bar{q}$, $3l_i$, $l_i l_j l_k$, $qq' \sum_j \nu_j$

$\Rightarrow$ Gluino: Final states: $q\bar{q} \sum_j \nu_j$, $l_i q q'$

$\Rightarrow$ Charged scalar ($\tilde{\tau}$, $\tilde{\mu}$, $\tilde{e}$): Final states: $l_i \sum_j \nu_j$, qq'

$\Rightarrow$ Sneutrinos ($\tilde{\nu}_\tau$, $\tilde{\nu}_\mu$, $\tilde{\nu}_e$): Final states: $l_i l_j$, $\sum_{i,j} \nu_i\nu_j$, $q\bar{q}$

$\Rightarrow$ Squarks: Final states: $l_i q'$, $l_i b$ *or* $l_i t$, $q \sum \nu_i$

What about dark matter?

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:

$$\Omega_{CDM}h^2 \simeq 0.113 \pm 0.008$$

$\Rightarrow m_{3/2} \simeq 100$ 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)

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:

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

$\Rightarrow$ sneutrino vevs v_i

in the following: take v_i as free parameters instead B_i

Neutralino decays

dominant modes R-parity violating modes

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

$$\Gamma(\tilde{\chi}^0_1 \to \sum_i Z \nu_i)$$

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

R-parity conserving mode

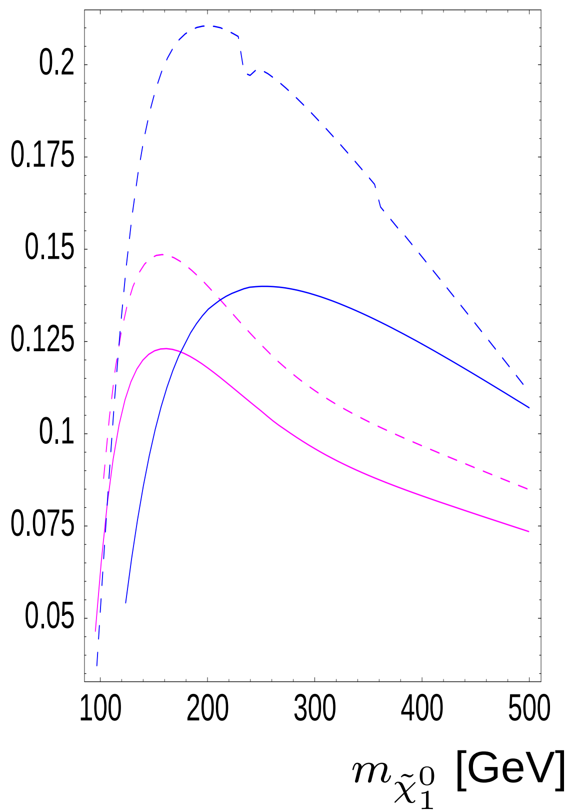
$$\Gamma(\tilde{\chi}^0_1 \to \tilde{G}\gamma) \quad \simeq \quad 1.2 \times 10^{-6} \kappa_\gamma^2 \Big(\frac{m_{\tilde{\chi}^0_1}}{100 \;\; \mathrm{GeV}}\Big)^5 \Big(\frac{100 \;\; \mathrm{eV}}{m_{3/2}}\Big)^2 \, \mathrm{eV}$$

total width

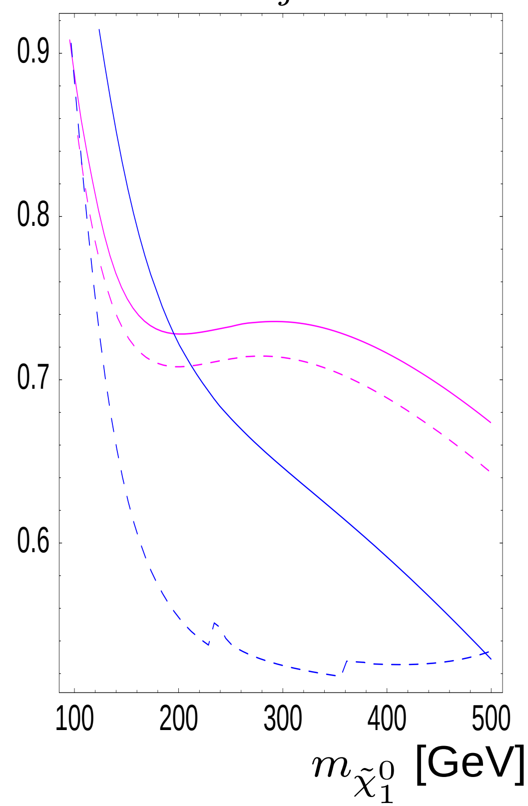
$$\Gamma \simeq (10^{-4} - 10^{-2}) \, \mathrm{eV}$$

Neutralino decays

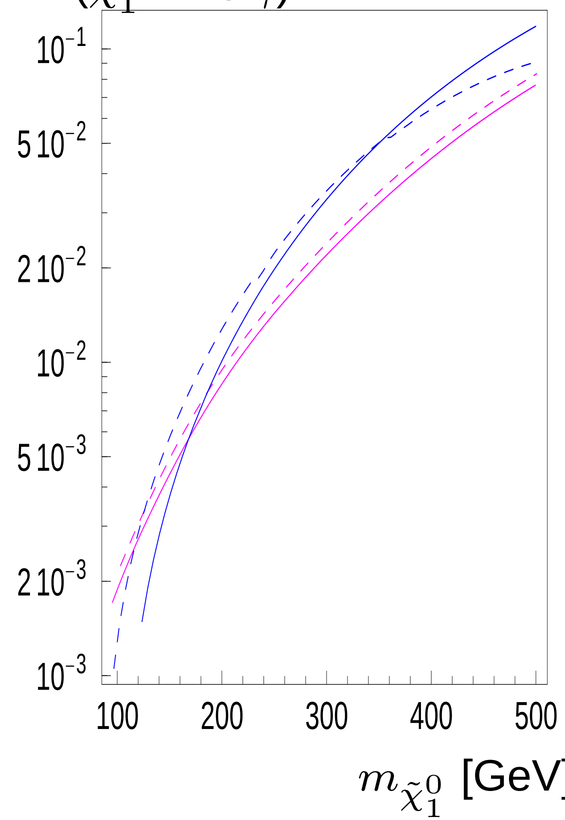
BR($\tilde{\chi}_1^0 \to \sum_i W l_i$)



BR($\tilde{\chi}_1^0 \to \sum_{ij} \nu_i \tau l_j$)



BR($\tilde{\chi}_1^0 \to \tilde{G}\gamma$)



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

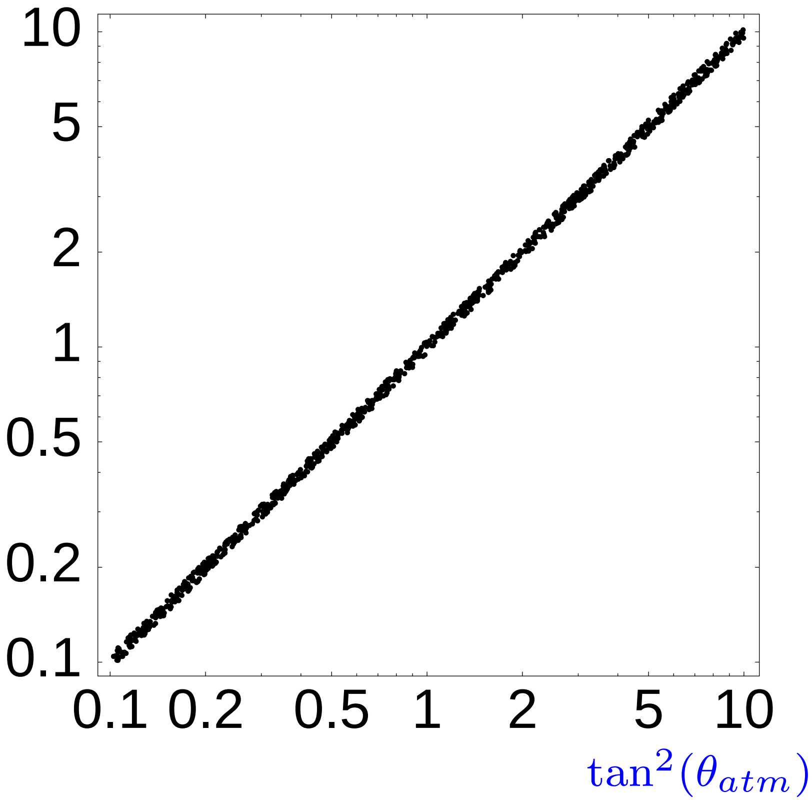
$m_{3/2} = 100$ eV, $n_5 = 1$

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

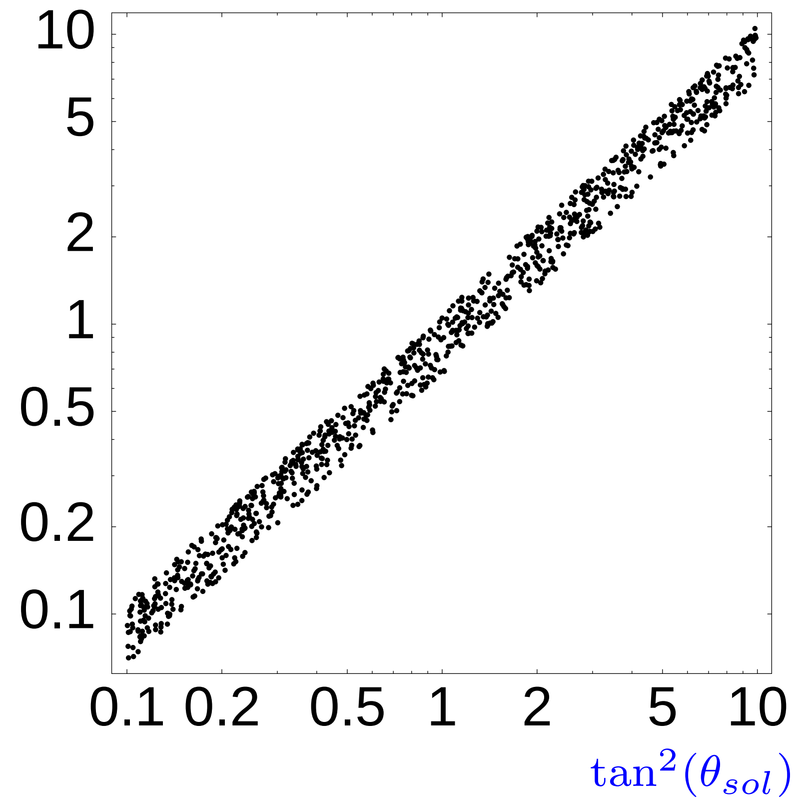
Neutralino decays, correlations

Correlations

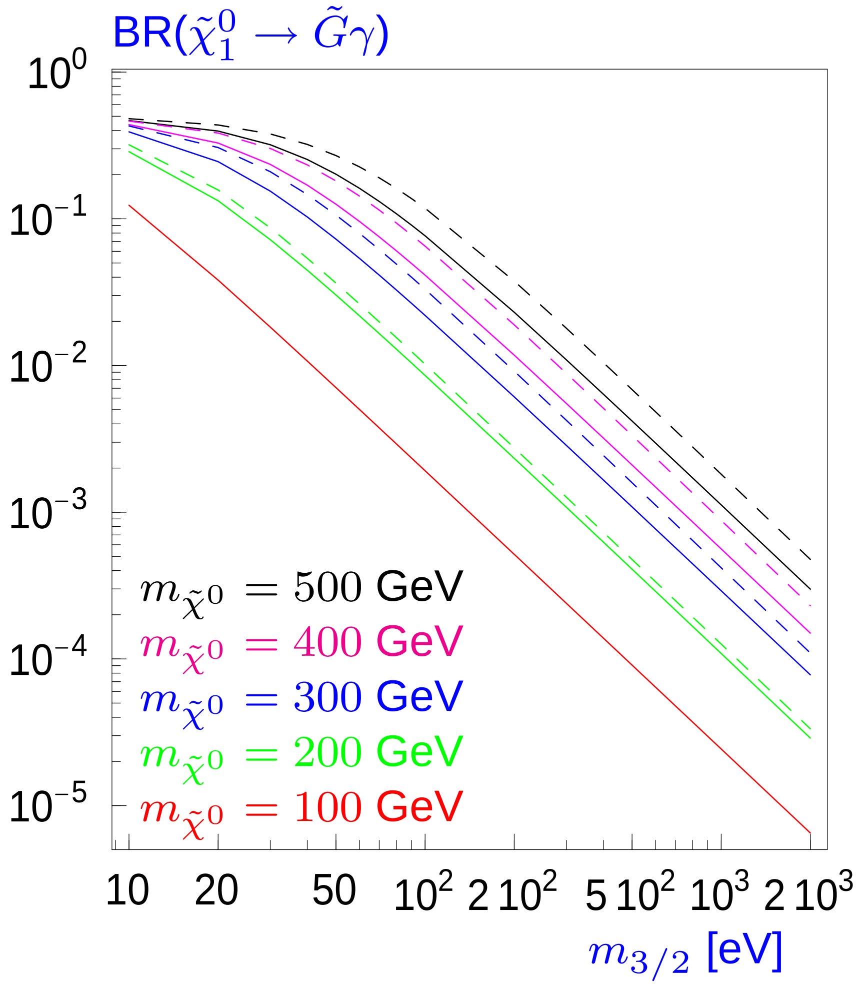
BR($\tilde{\chi}_1^0 \to W\mu$) / BR($\tilde{\chi}_1^0 \to W\tau$)

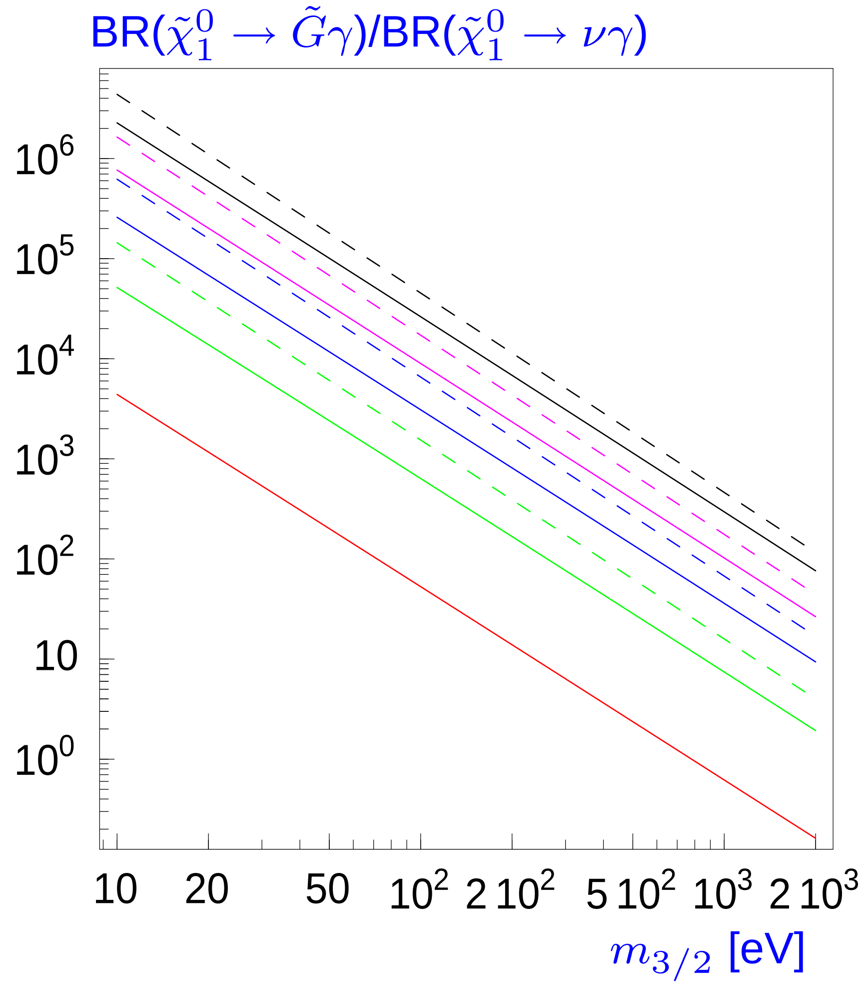


BR($\tilde{\chi}_1^0 \to \nu e\tau$) /BR($\tilde{\chi}_1^0 \to \nu\mu\tau$)



GMSB signals





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

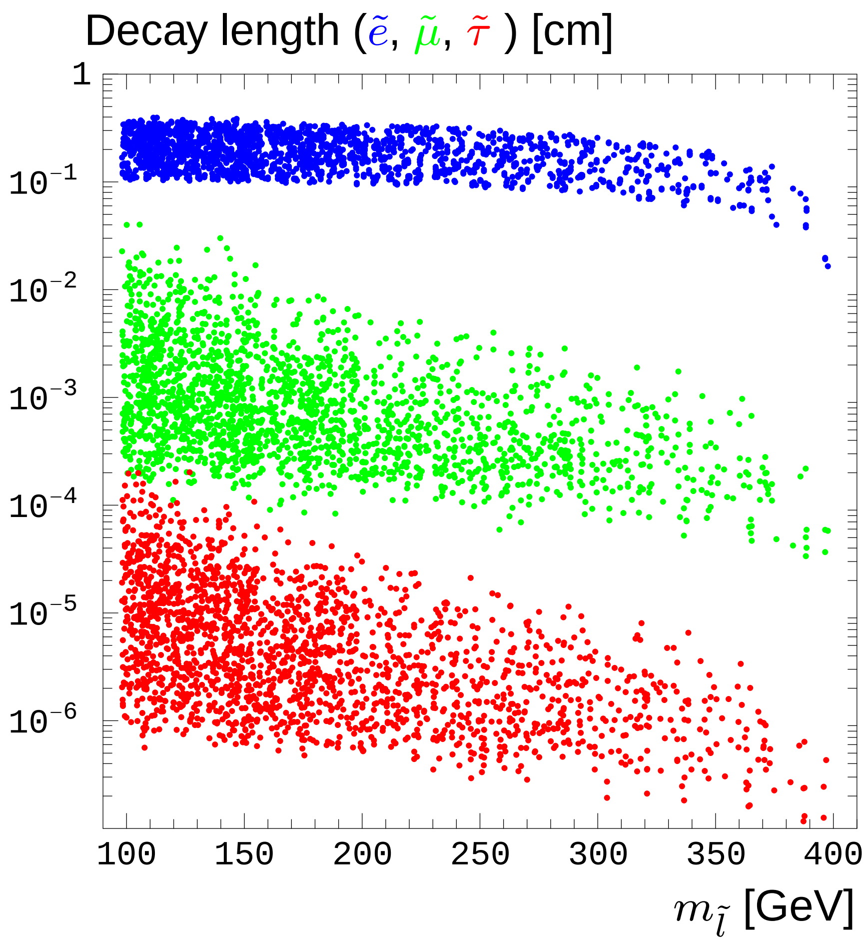
Comments

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

  $\Rightarrow$ for $n_5 \geq 3$ hardly points with $\tilde{\chi}^0_1$
- $\tilde{l}_R$ 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:

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

Charged Scalar LSP



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

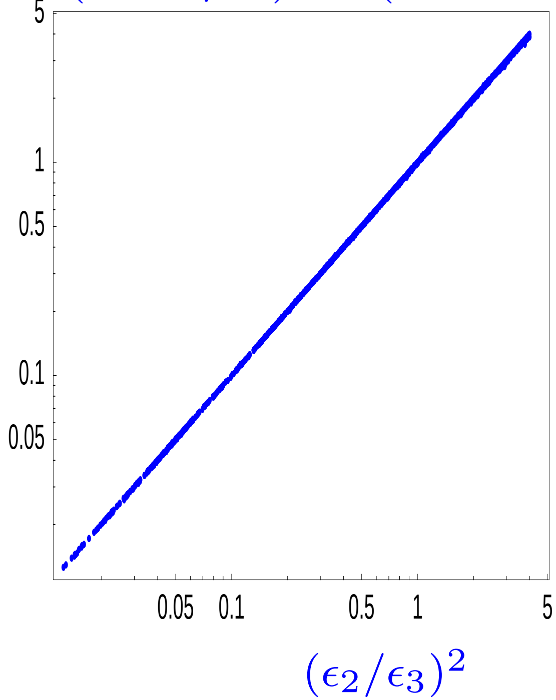
Moreover

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

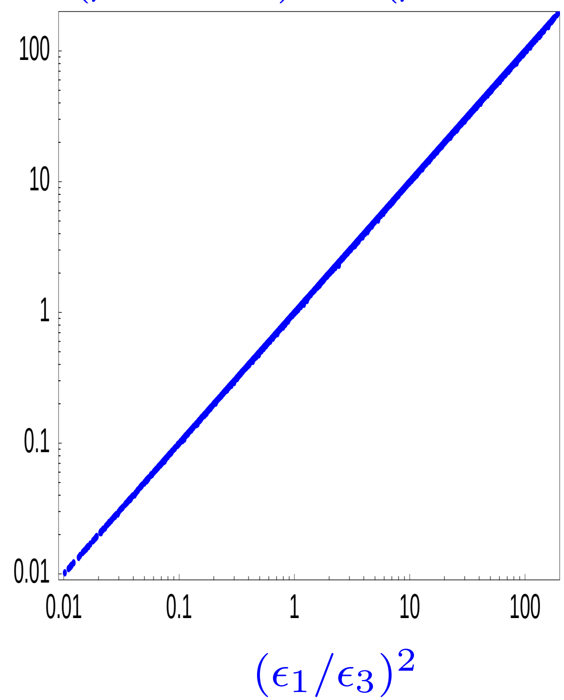
$$\tilde{l}_j \to l_i \sum_k \nu_k \ , \ q q'$$

Charged Scalar LSP

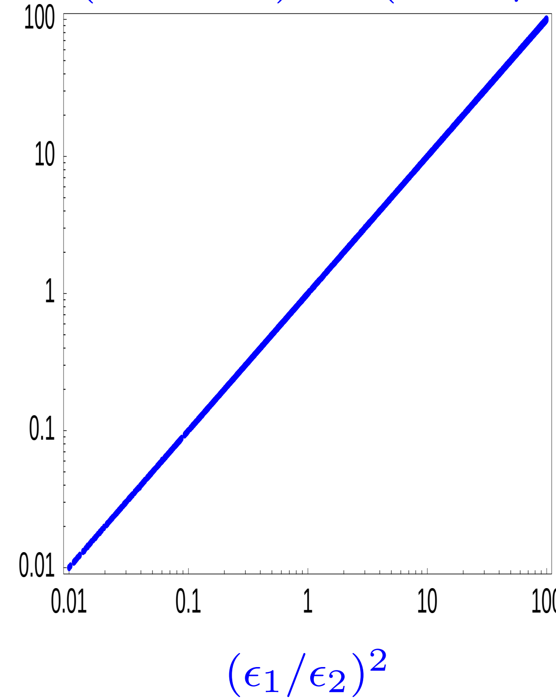
BR($\tilde{e}_1 \to \mu\nu_i$)/ BR($\tilde{e}_1 \to \tau\nu_i$)



BR($\tilde{\mu}_1 \to e\nu_i$)/ BR($\tilde{\mu}_1 \to \tau\nu_i$)



BR($\tilde{\tau}_1 \to e\nu_i$)/ BR($\tilde{\tau}_1 \to \mu\nu_i$)

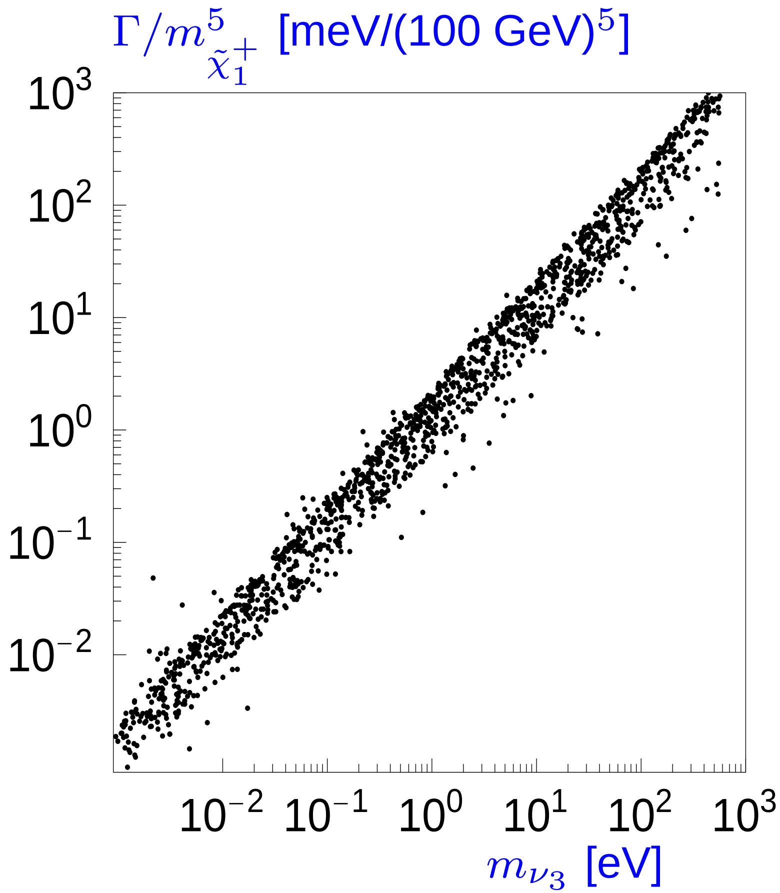


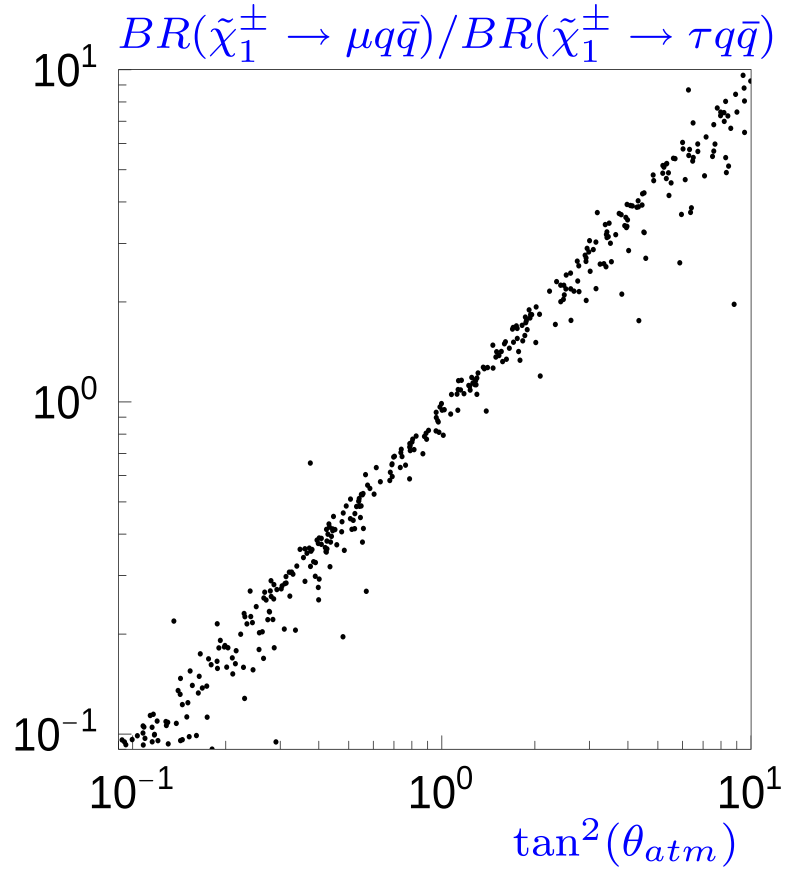
Cross check possible: $(\epsilon_1/\epsilon_3)^2/(\epsilon_1/\epsilon_2)^2 \equiv (\epsilon_2/\epsilon_3)^2$

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

Chargino LSPs

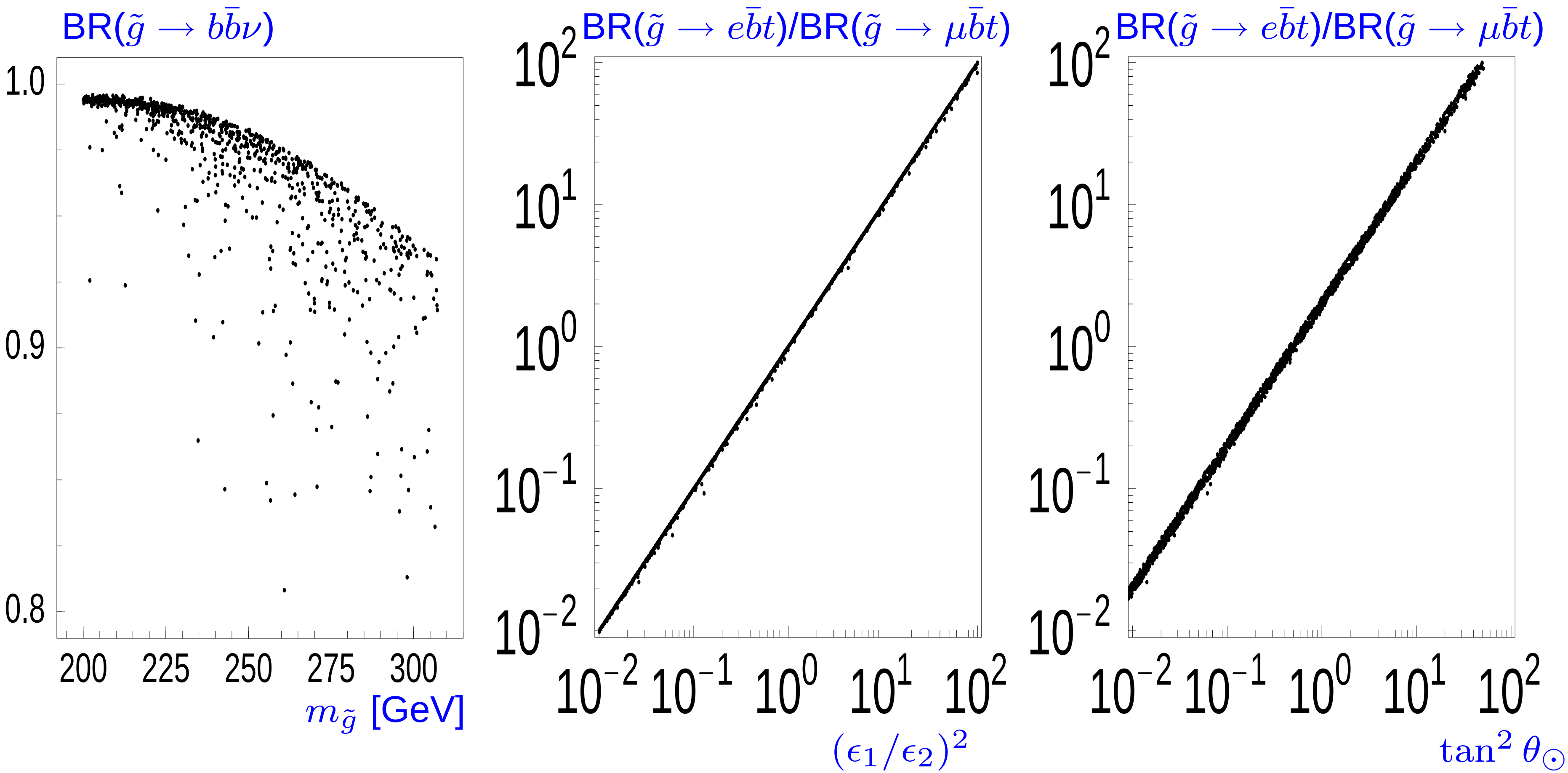
motivated by AMSB scenarios, nearly degenerate neutralinos/charginos



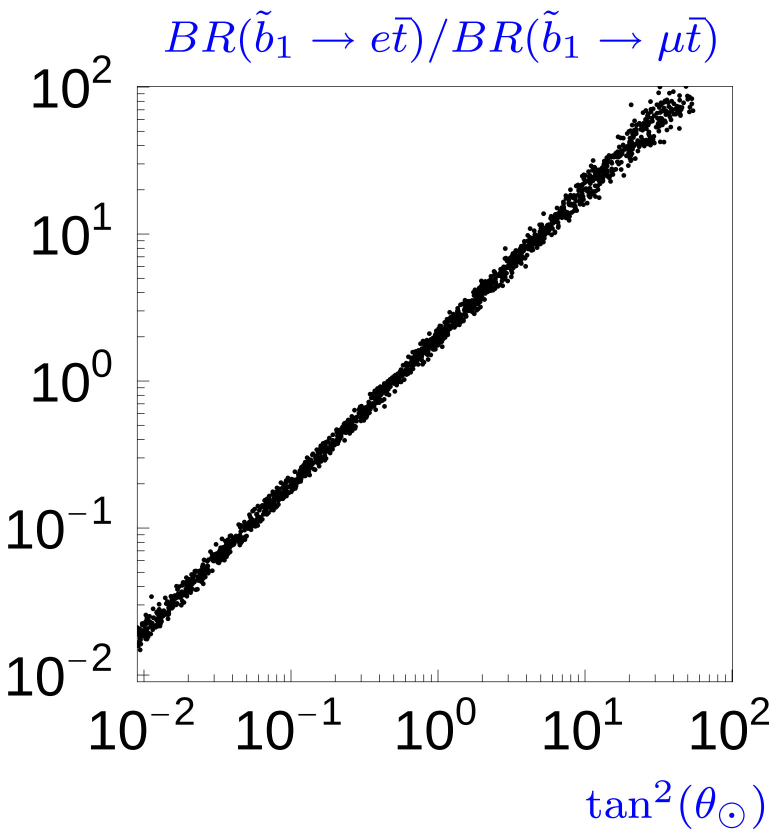


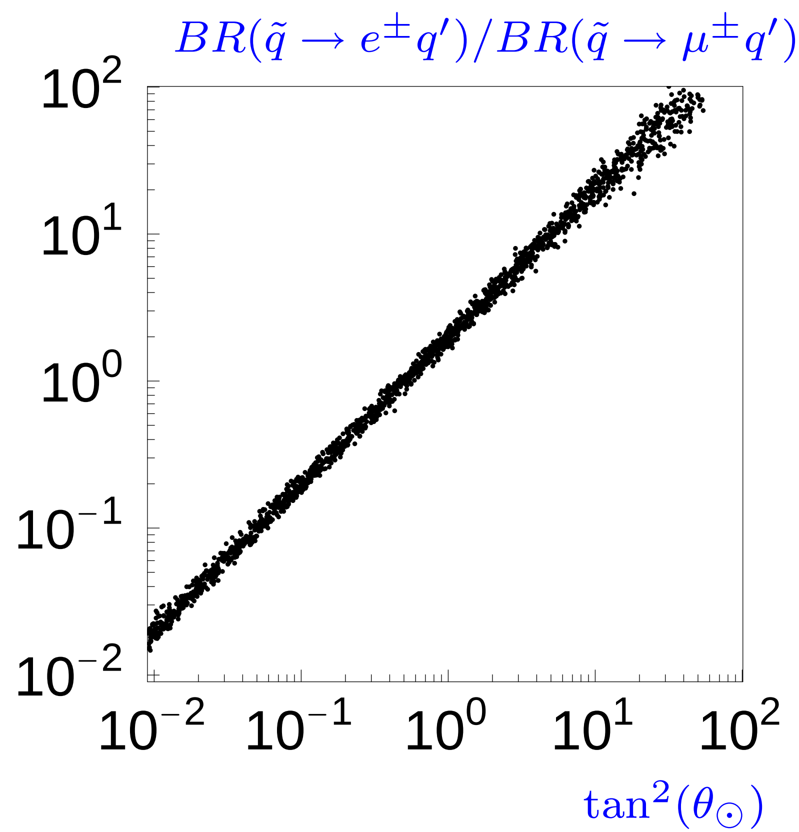
$\Rightarrow$ Prediction much sharper, if i) atmospheric neutrino mass more accurately measured and ii) some information on MSSM parameters available

Gluino LSPs


BR($\tilde{g} \to b\bar{b}\nu$)
1.0
0.9
0.8
200
225
250
275
300
$m_{\tilde{g}}$ [GeV]
BR($\tilde{g} \to e\bar{b}t$)/BR($\tilde{g} \to \mu\bar{b}t$)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
$(\epsilon_1/\epsilon_2)^2$
BR($\tilde{g} \to e\bar{b}t$)/BR($\tilde{g} \to \mu\bar{b}t$)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
$\tan^2\theta_\odot$

Squark LSPs





$\Rightarrow$ similar as left figure for $t \leftrightarrow b$

$\Rightarrow$ in right figure summing over first two generations

Sneutrino LSPs

$$\tilde{\nu}_i \quad \rightarrow \quad q_j\,\bar{q}_k\,,\; l_j^+\,l_k^-\,,\; \nu_j\,\nu_k$$

Complicated, separation of $\tilde{\nu}$ with „different flavour" is difficult, maybe in chargino decays via :

$$\begin{aligned} \tilde{q}_L &\rightarrow q'\,\tilde{\chi}_1^+ \rightarrow q'\,l_i^+\,\tilde{\nu}_i^* \rightarrow q'\,l_i^+\,l_r^+\,l_s^- \\ \tilde{q}_L &\rightarrow q\tilde{\chi}_2^0 \rightarrow q\nu_i\tilde{\nu}_i^* \rightarrow q'\,\nu_i\bar{b}b \end{aligned}$$

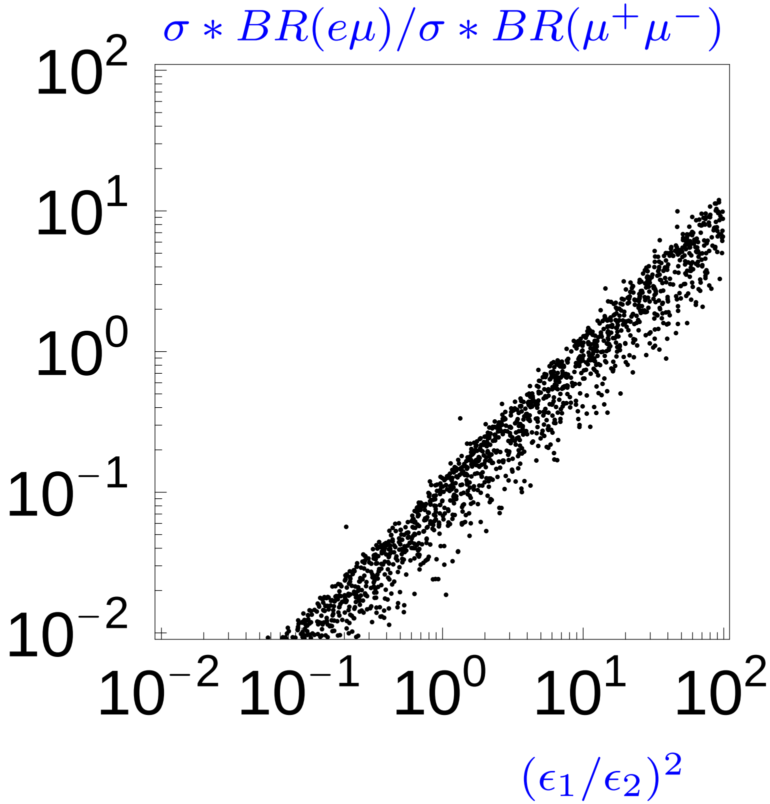
In rest frame of $\tilde{\chi}_1^+$ confusion of l_i^+ and l_r^+ is only possible for one kinematical situation:

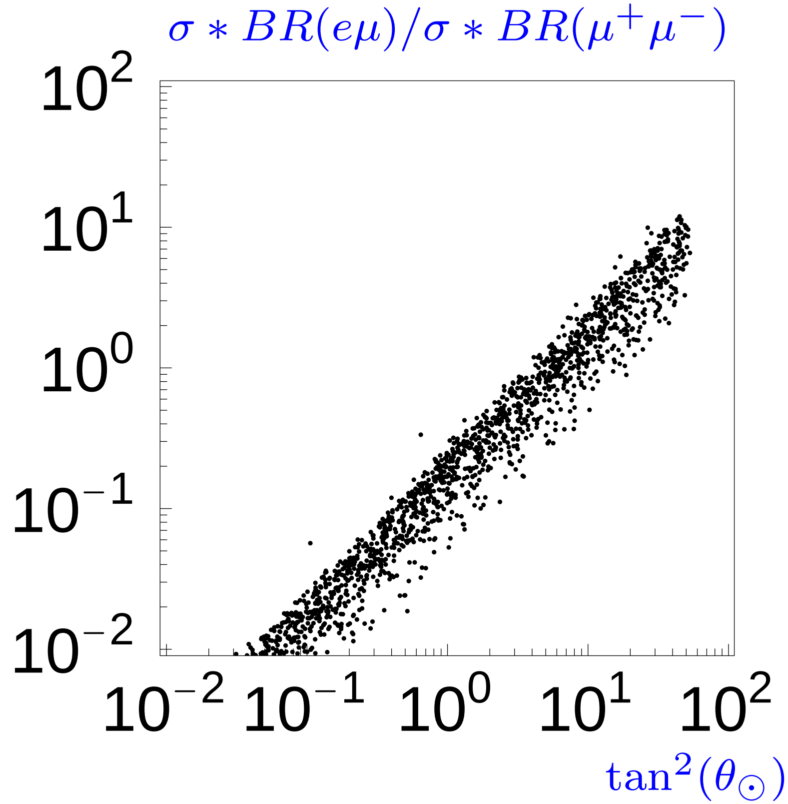
$$\cos\theta \quad = \quad \frac{1-2\beta}{\beta}\;,\;\beta = \frac{m^2_{\tilde{\chi}_1^+} - m^2_{\tilde{\nu}_l}}{m^2_{\tilde{\chi}_1^+} + m^2_{\tilde{\nu}_l}}\;.$$

The condition $|\cos\theta| \le 1$ requires $m_{\tilde{\nu}_l}/m_{\tilde{\chi}_1^+} \lesssim 0.755$

Scenario I: bilinear terms only

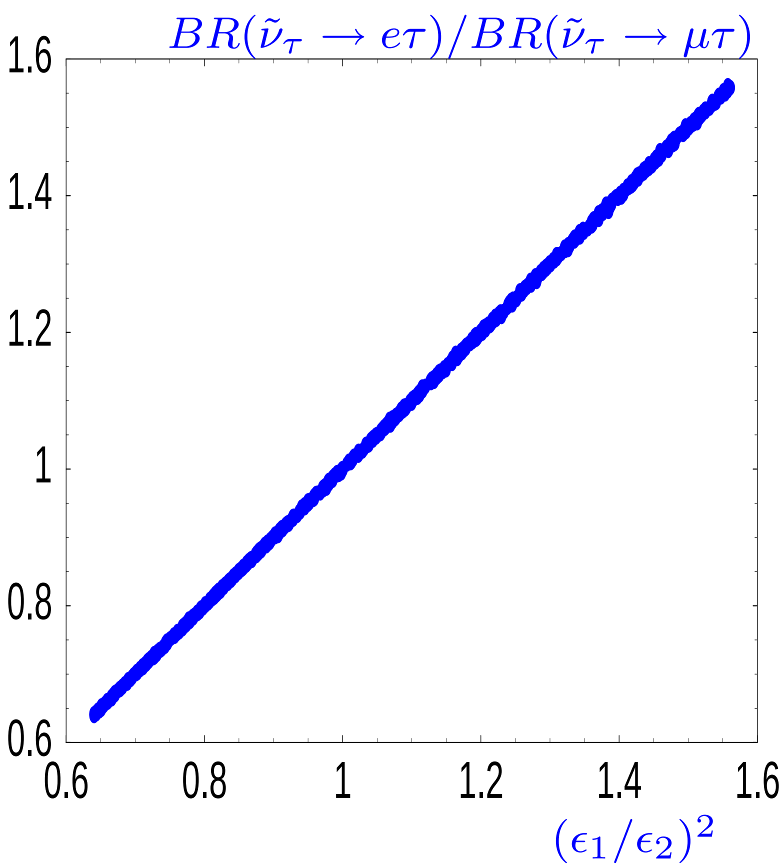
If „flavour separation" is impossible:

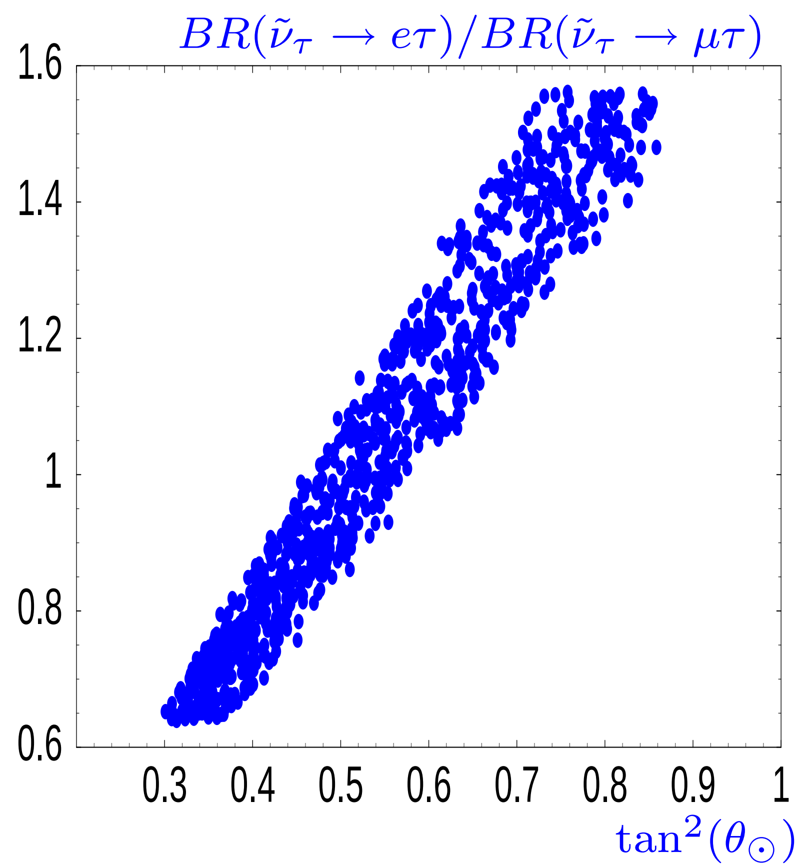




Scenario I: bilinear terms only

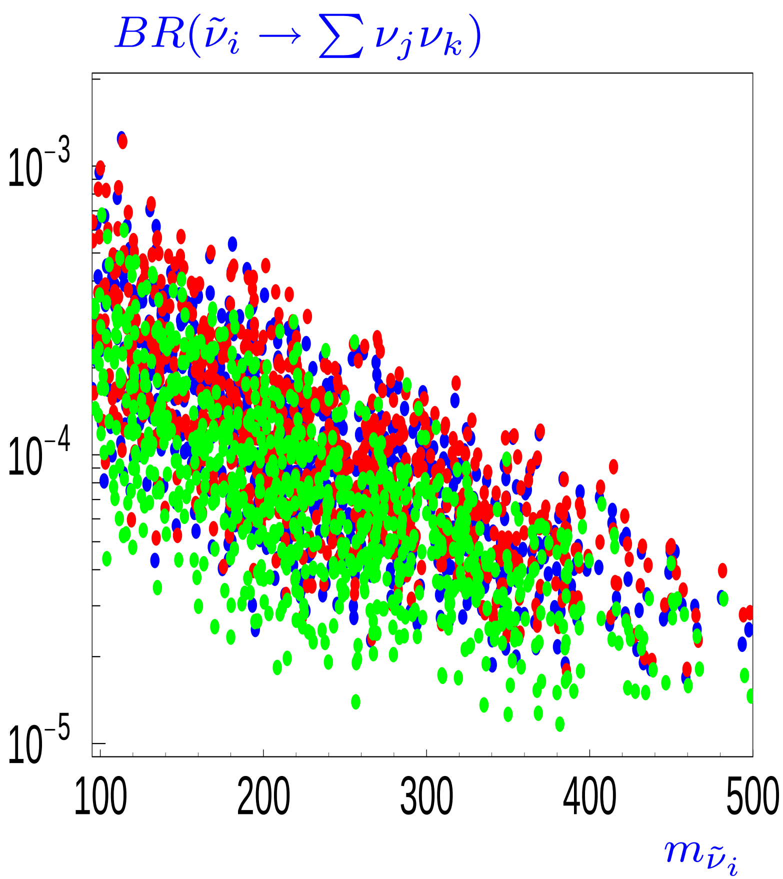
If „flavour separation" is possible:

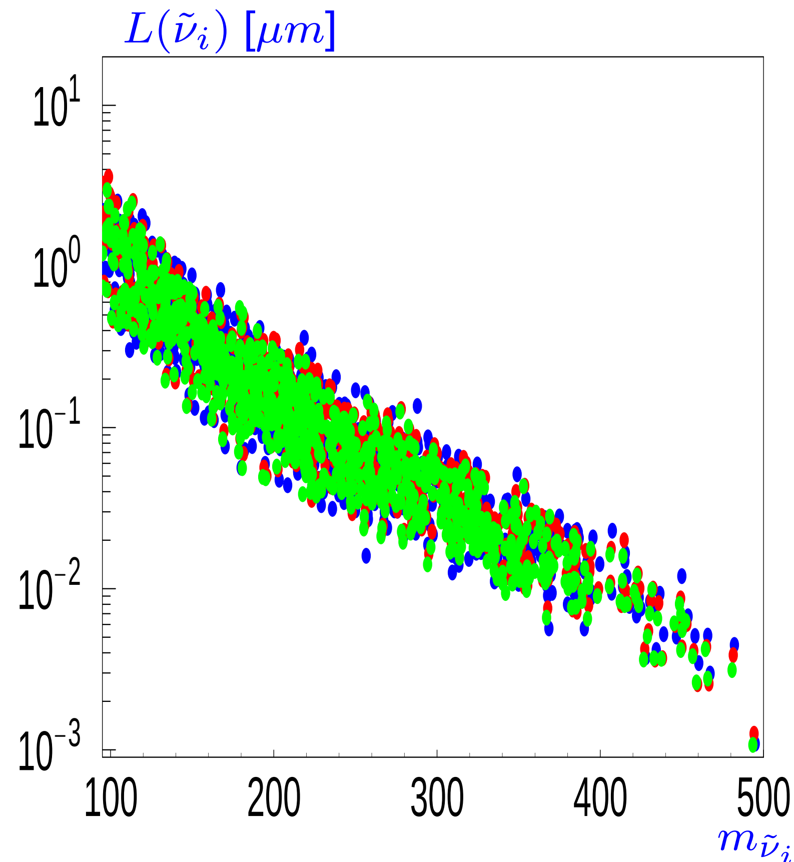




Scenario I: bilinear terms only

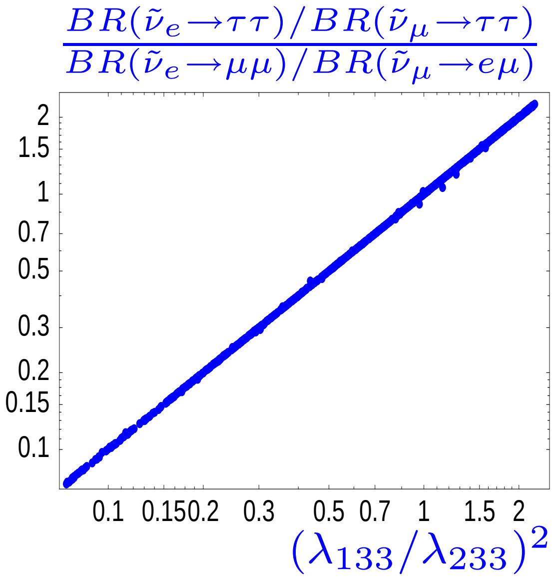
additional features of this scenario

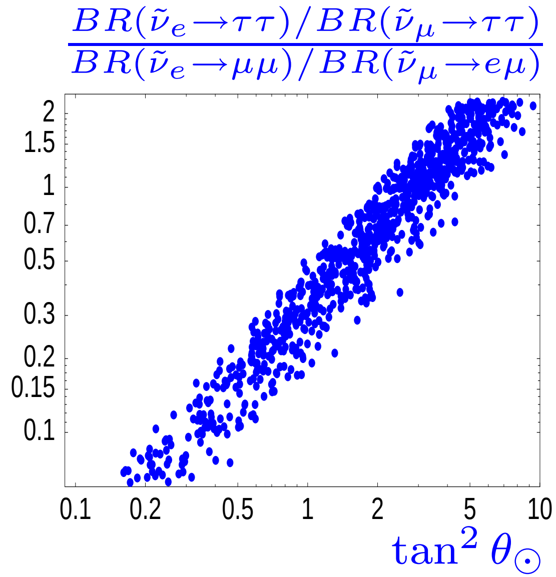




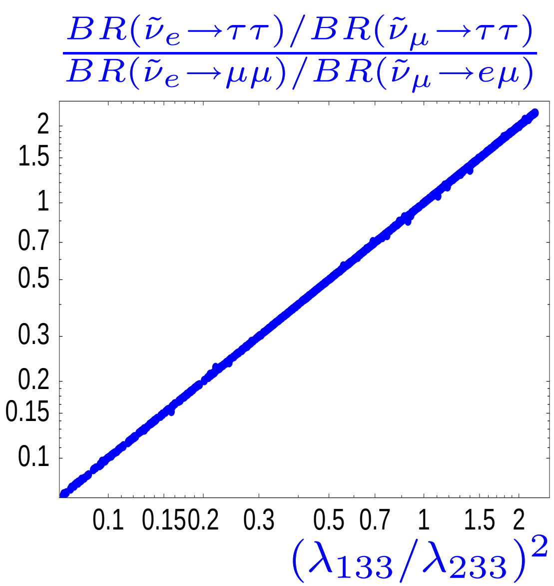
In the following scenarios the branching ratio for the invisible decays as well as the decay length are considerable smaller.

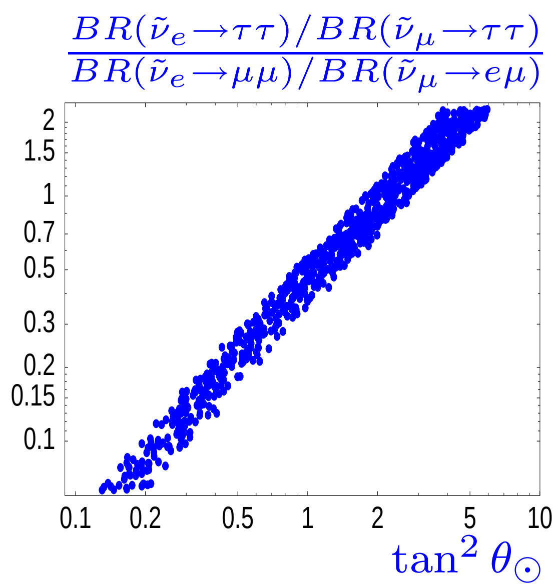
Scenario II: $\lambda'_{ijk} \simeq 0$





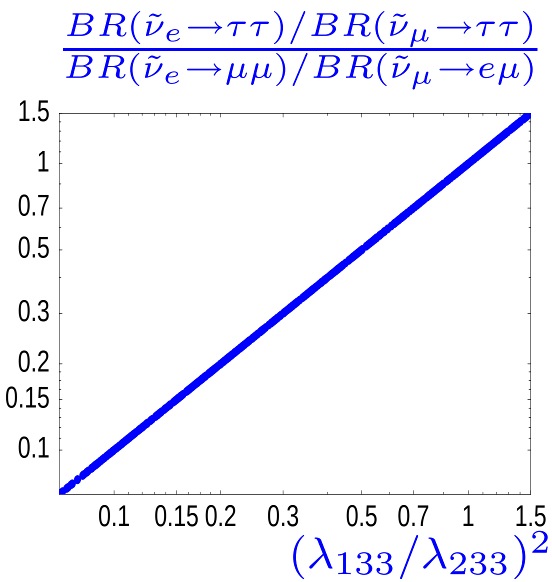
in rotated basis:
all λ_{ijk} are of similar size

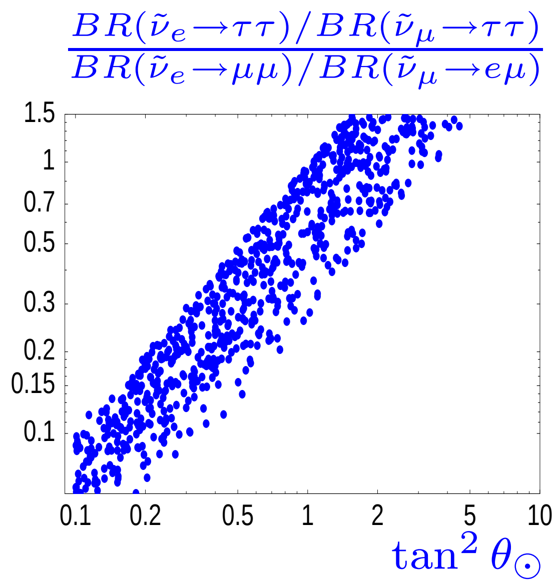




all λ_{i33} are a factor few
larger than other λ_{ijk}

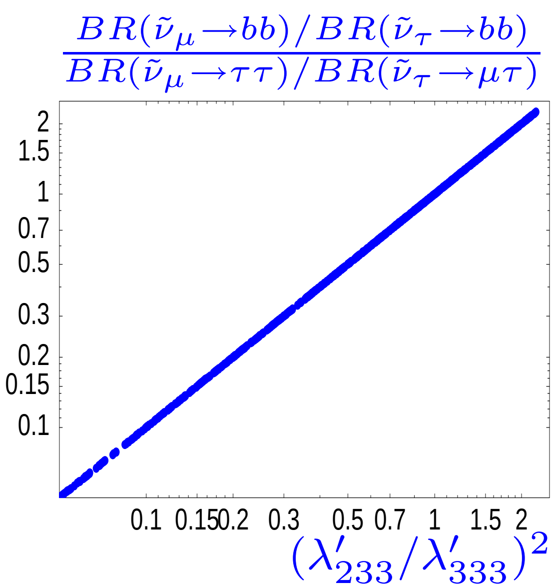
Scenario III: $v_i \simeq 0$

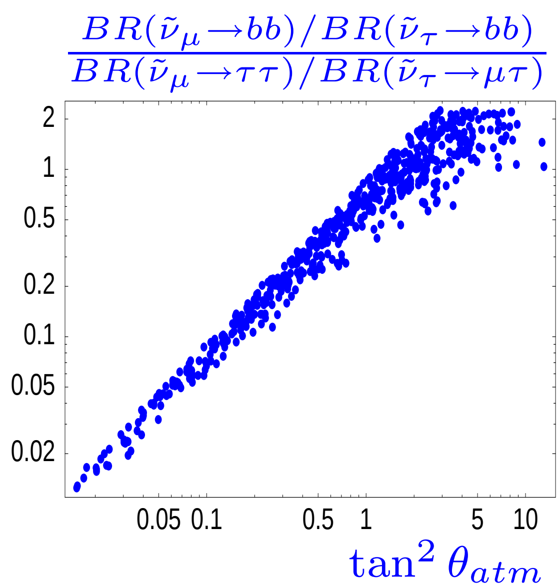




in rotated basis

all λ_{ijk}, λ'_{ijk} are of similar size





all λ_{i33} (λ'_{i33}) are a factor few larger than other λ_{ijk} (λ'_{ijk})

Summary

- R-parity violation via lepton number violation: explains neutrino data
- GMSB + RP-violation: $\tilde{G}$ is natural DM candidate
- BR($\tilde{\chi}_1^0 \to \tilde{G}\,\gamma$) sufficiently large in the cosmologically interesting region to get $m_{3/2}$
- independent of scenario: correlations between LSP decay modes and neutrino mixing angles in case of bilinear R-parity violation
- first studies of adding trilinear couplings: there are still correlations but situation is much more involved

Lepton flavour violation, experimental data

Neutrinos: tiny masses

$$\Delta m^2_{atm} \simeq 3 \cdot 10^{-3}\ \text{eV}^2$$
$$\Delta m^2_{sol} \simeq 7 \cdot 10^{-5}\ \text{eV}^2$$
^{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

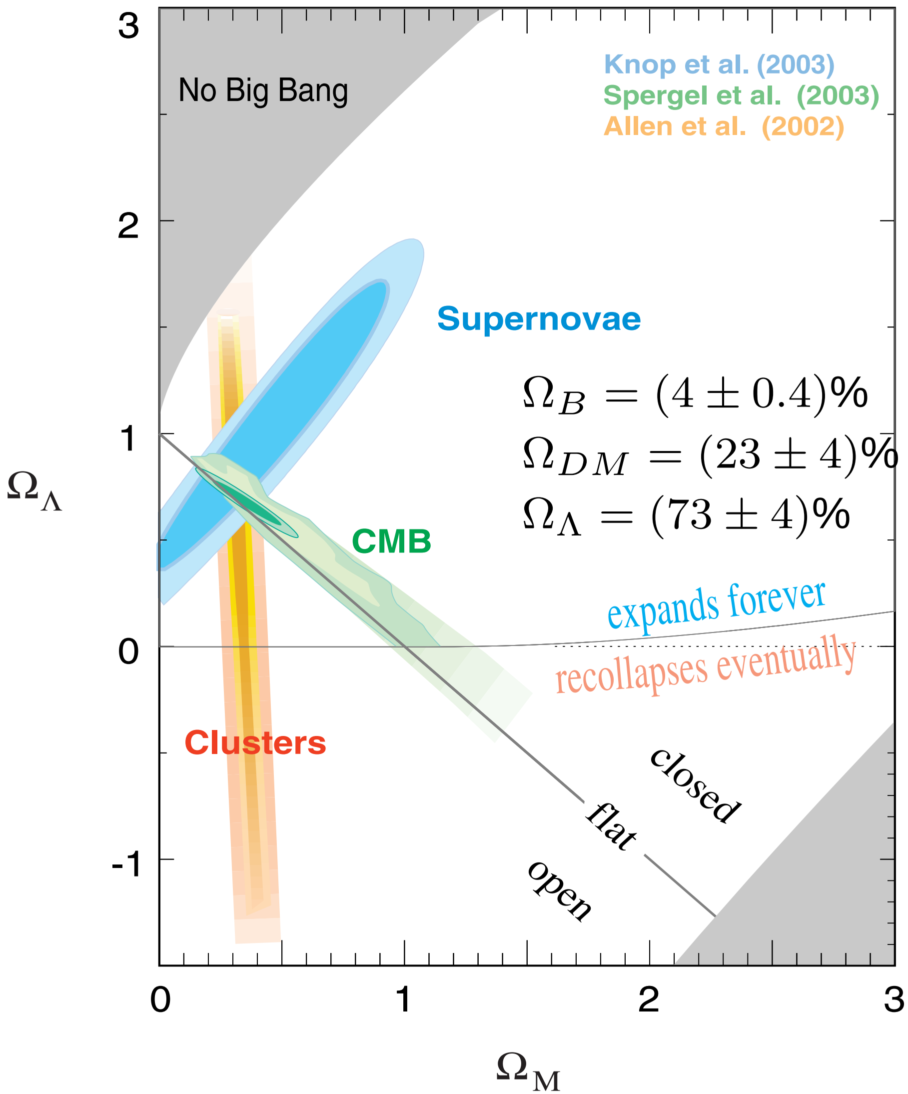
$$BR(\mu \to e\gamma) \lesssim 1.2 \cdot 10^{-11} \qquad BR(\mu^- \to e^- e^+ e^-) \lesssim 10^{-12}$$
$$BR(\tau \to e\gamma) \lesssim 1.1 \cdot 10^{-7} \qquad BR(\tau \to \mu\gamma) \lesssim 6.8 \cdot 10^{-8}$$
$$BR(\tau \to l l l') \lesssim O(10^{-8})\ (l, l' = e, \mu)$$

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

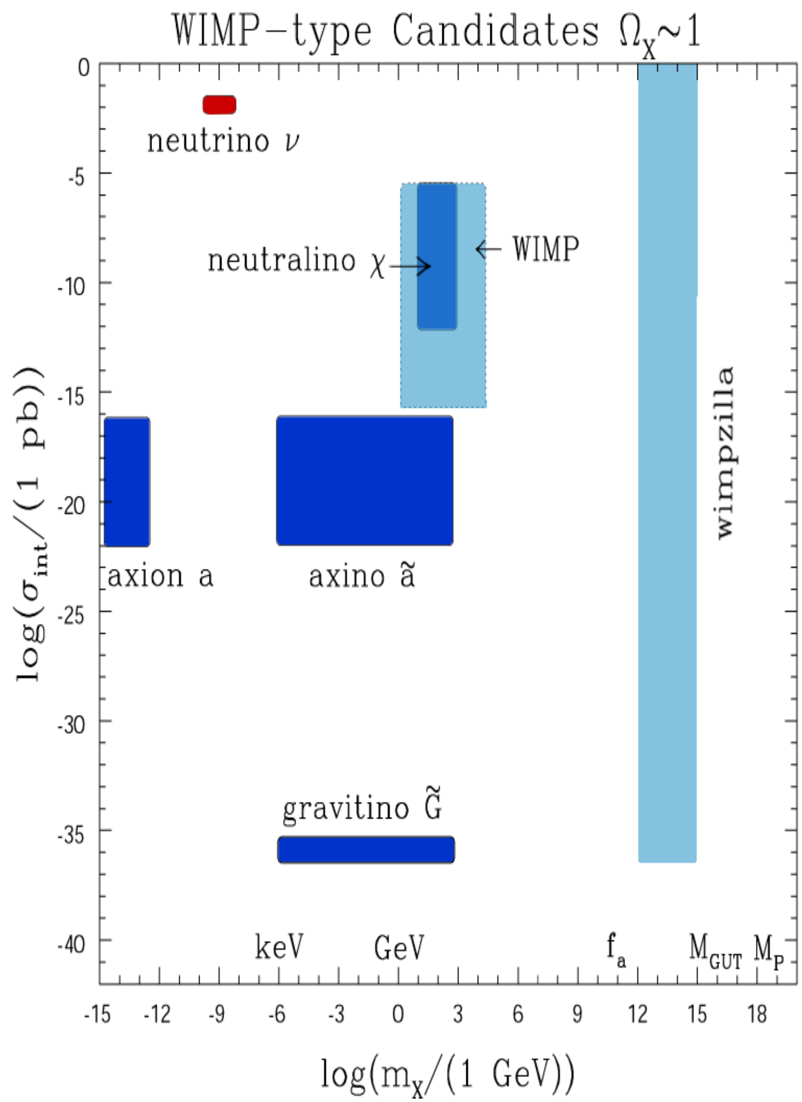
SUSY contributions to anomalous magnetic moments

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

Cosmology



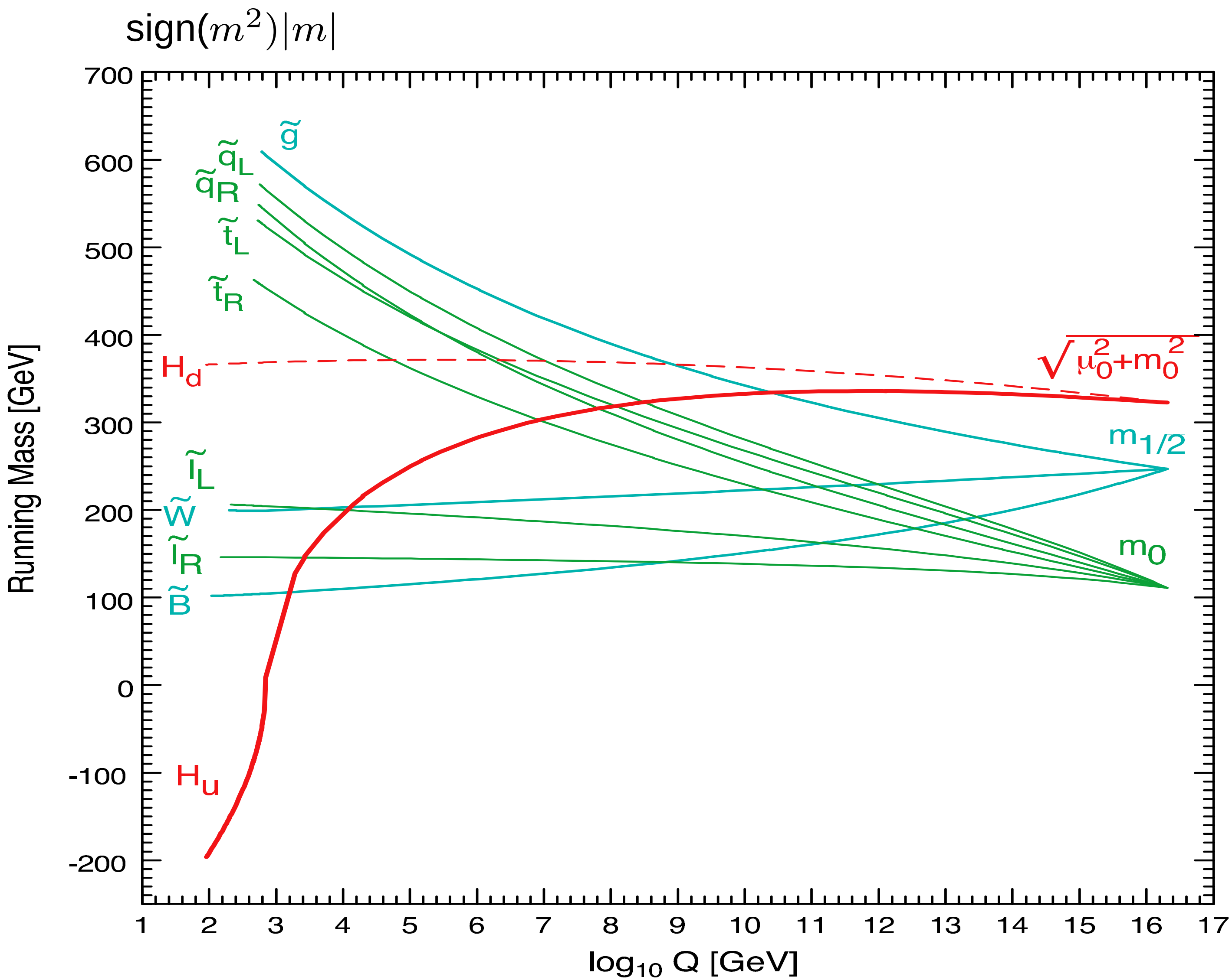
$$\Omega_B = (4 \pm 0.4)\%$$
$$\Omega_{DM} = (23 \pm 4)\%$$
$$\Omega_\Lambda = (73 \pm 4)\%$$



R.A. Knopp et al., Astrophys. J. **598** (2003) 102

L. Roszkowski, astro-ph/0404052

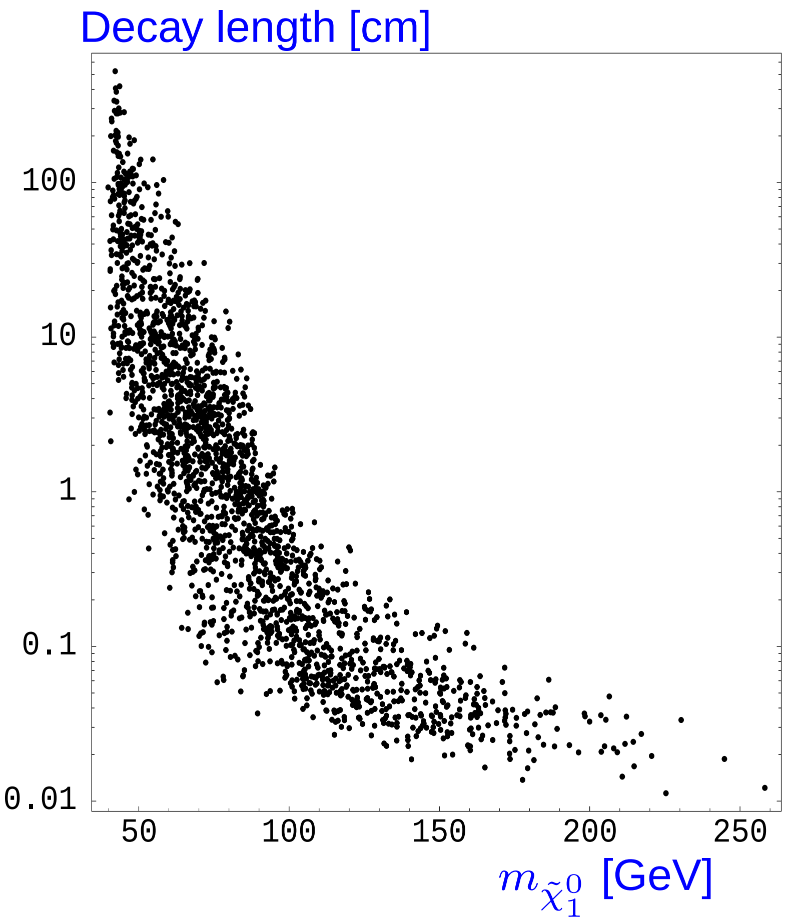
Running SUSY masses

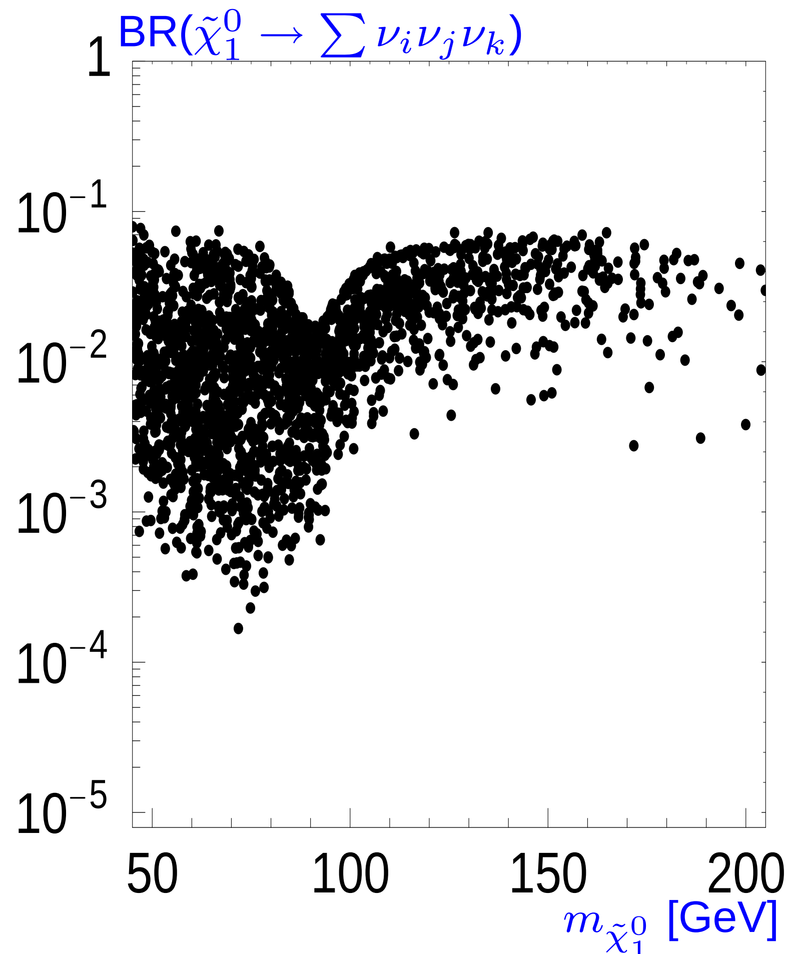


G. Kane, C. Kolda, L. Roszkowski, J. Wells, PRD 1994

Neutralino decays, general case

$\Rightarrow$ Take points which fulfill requirements by neutrino data.

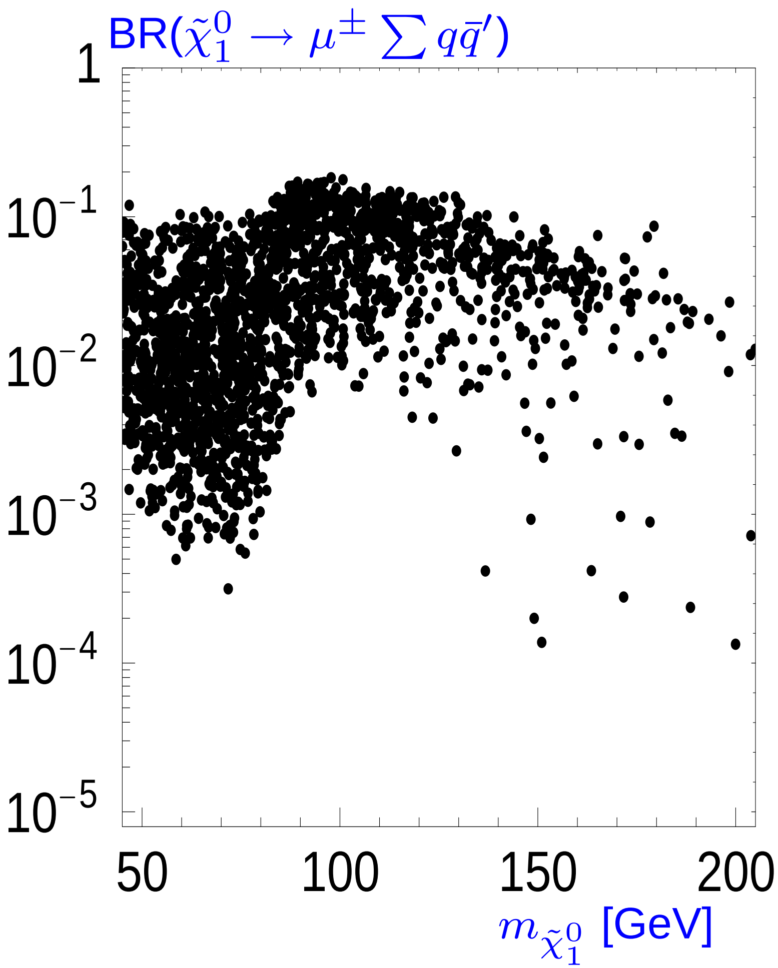


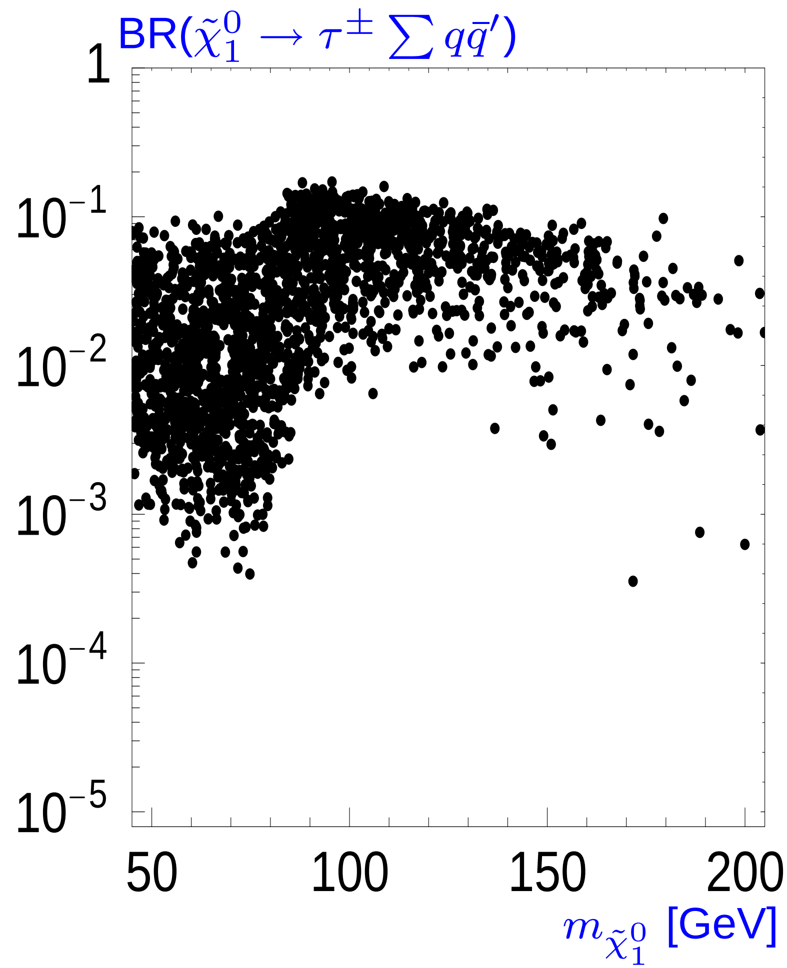


Neutralino decays - inside detector!

Sum over all invisible modes < 10 % !

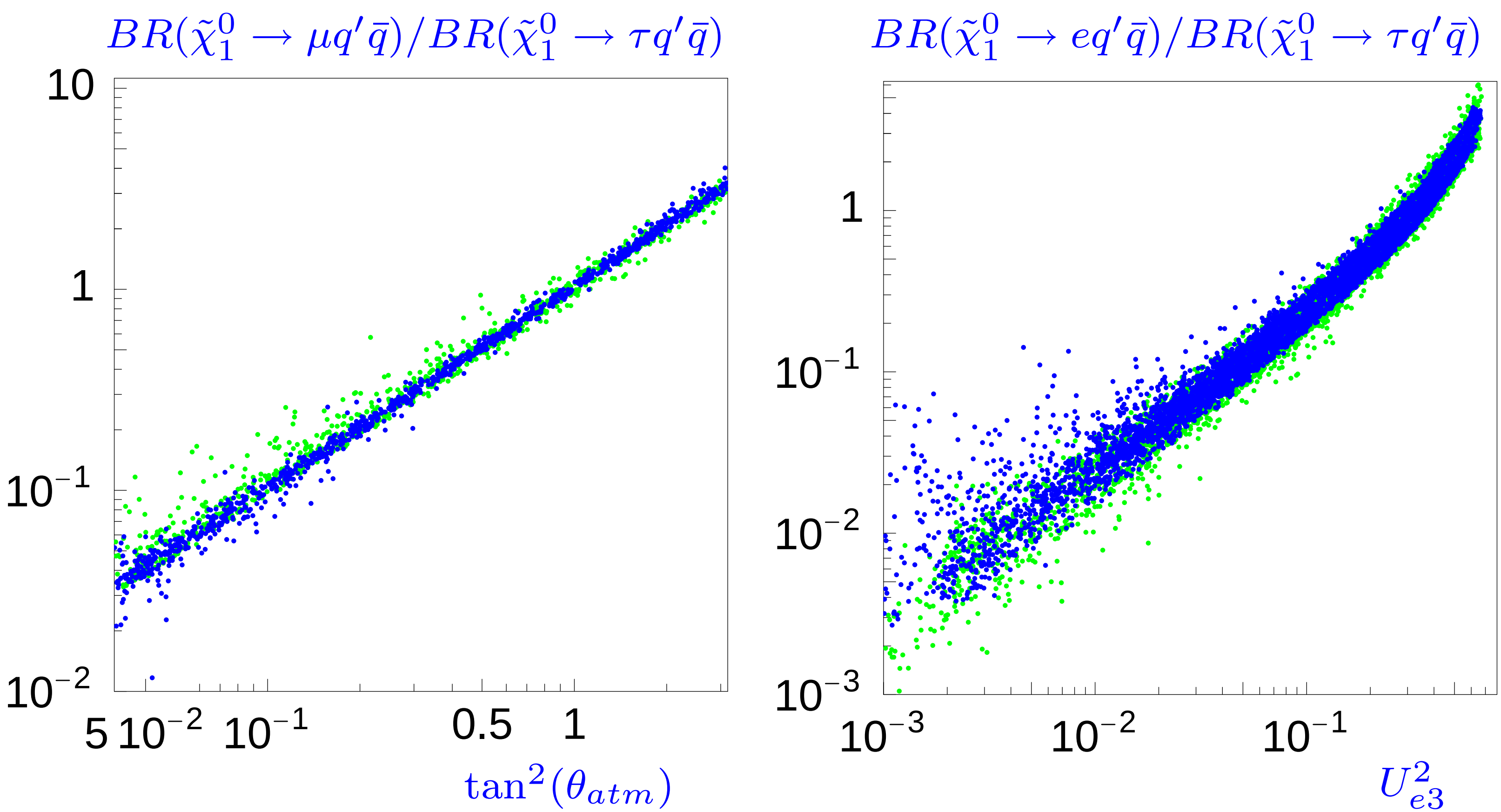
Neutralino decays, general case





$\Rightarrow$ Large scatter as function of $m_{\tilde{\chi}^0_1}$, but ...

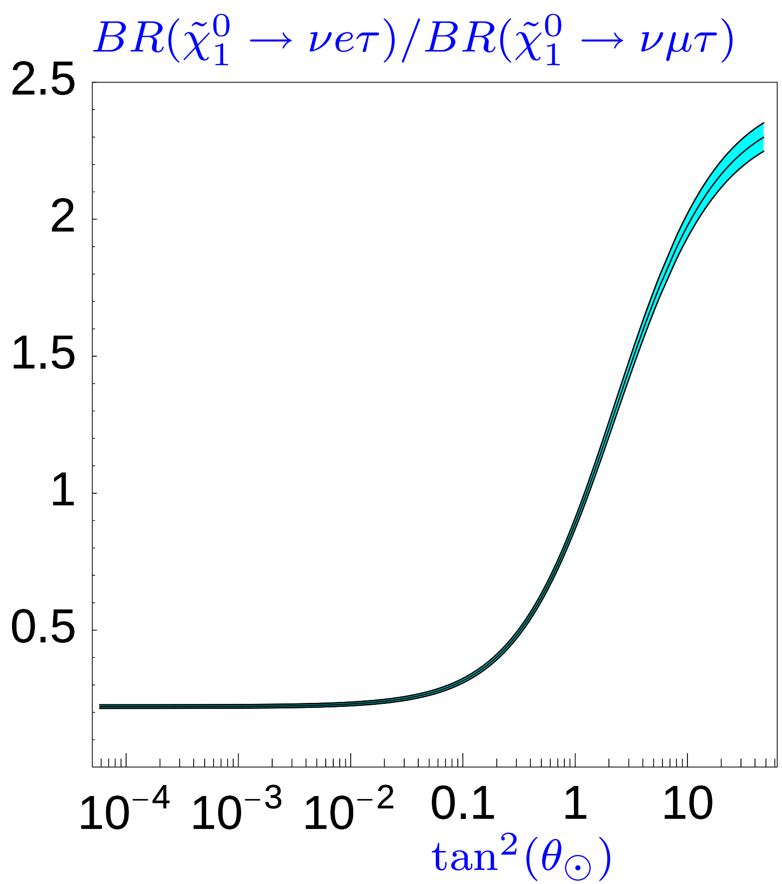
Correlations for semileptonic neutralino decays

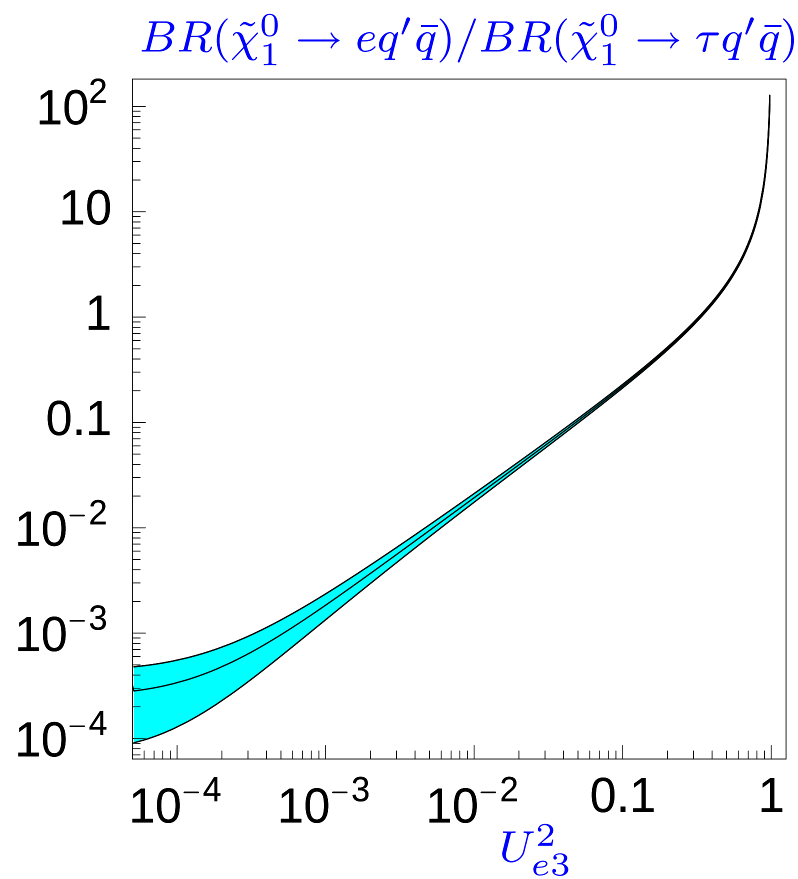


$\Rightarrow$ Note, for small U_{e3}^2 scatter due to random variation of MSSM parameters quite large

Precision measurements

Assume SUSY has been found and MSSM parameters have been measured to 1 % accuracy (arbitrary set of MSSM parameters):





$\Rightarrow$ "Scatter" ($\equiv$ uncertainty) nearly completely disappears, once information about the SUSY spectrum is available, i.e. SUSY has been found