Broken R-Parity in the Sky and at the LHC

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I.Broken R-Parity and Lepton Number

Theories with and without R-parity are on equal footing; in string compactifications R-parity (dis)favoured. Without R-parity lightest superparticle (LSP) no longer stable, in general no dark matter candidate.

Strong constraints on lepton number and R-parity violating interactions

$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk} l_i e^c_j l_k + \lambda'_{ijk} d^c_i q_j l_k$$

from baryogenesis (sphaleron processes); require baryon asymmetry not erased before electroweak transition, implies (Campbell et al., Fischler et al '91; Dreiner, Ross '93; Endo et al '10)

$$\lambda, \lambda' < 10^{-6} \ .$$

For small R-parity breaking, gravitino LSP has lifetime longer than age of the universe (Takayama, Yamaguchi '00). Reason: double suppression by inverse

Planck mass and R-parity breaking,

$$\tau_{3/2} \sim 10^{25}\ \mathrm{s} \left(\frac{\lambda}{10^{-6}}\right)^{-2} \left(\frac{m_{3/2}}{100\ \mathrm{GeV}}\right)^{-3} ,$$

consistent with gravitino dark matter.

Bound from thermal leptogenesis on reheating temperature: $T_R \gtrsim 10^9\ \mathrm{GeV}$; implies $m_{3/2} \gtrsim 5\ \mathrm{GeV}$ (gluino mass $m_{\tilde{g}} = 500\ \mathrm{GeV}$) to avoid overclosure of the universe. BBN: NLSP lifetime is sufficiently short for $\lambda, \lambda' > 10^{-13}$,

$$\tau_{\mathrm{NLSP}} \simeq 10\ \mathrm{s} \left(\frac{\lambda}{10^{-13}}\right)^{-2} \left(\frac{m_{\mathrm{NLSP}}}{100\ \mathrm{GeV}}\right)^{-1} .$$

Consistent cosmology (BBN, thermal leptogenesis, gravitino dark matter) for $10^{-13} < \lambda, \lambda' < 10^{-7}$ and $m_{3/2} \gtrsim 5\ \mathrm{GeV}$.

Spntaneous R-parity and B-L Breaking

Supersymmetric SM with $U(1)_{\mathrm{B-L}}$ and R-invariance,

$$W_\nu = h^\nu_{ij} l_i \nu^c_j H_u + \frac{1}{M_{\mathrm{P}}} h^n_{ij} \nu^c_i \nu^c_j N^2 \ ;$$

$\langle N \rangle$ generates Majorana masses for ν^c's; superpotential for B-L breaking:

$$W_{B-L} = X(NN^c - \Phi^2) \ ,$$

with spectator field Φ (R-charge -1); $\langle \Phi \rangle$ breaks B-L,

$$\langle N \rangle = \langle N^c \rangle = \langle \Phi \rangle = v_{B-L} \ ,$$

and also R-parity ! Transmitted to low-energies by higher-dimensional operators, leads to small bilinear R-parity breaking (Hall, Suzuki '83;...)

$$\Delta W = \mu_i H_u l_i \ , \quad \mu_i \sim m_{3/2}\Theta \ , \quad \Theta = \frac{v_{B-L}^2}{{M_{\rm P}}^2} \simeq \frac{M_3}{M_{\rm P}} \ .$$

Flavour dependence of R-parity breaking parameters (model with FN U(1) family symmetry, consistent with quark-lepton mass spectrum and leptogenesis):

$$h_{ij} \propto \eta^{Q_i+Q_j}, \quad \mu_i \propto \Theta\eta^{Q_i} \ , \quad \eta \ll 1 \ .$$

ψ_i	$\mathbf{10}_3$	$\mathbf{10}_2$	$\mathbf{10}_1$	$\mathbf{5}^*_3$	$\mathbf{5}^*_2$	$\mathbf{5}^*_1$	ν^c_3	ν^c_2	ν^c_1	H_u	H_d	Φ
Q_i	0	1	2	1	1	2	0	0	1	0	0	0

Table 1: *Chiral $U(1)$ charges.* $\mathbf{10}_i = (q_i, u^c_i, e^c_i)$, $\mathbf{5} = (d^c_i, l_i)$, $i = 1\ldots3$.

Seesaw mechanism for light neutrino masses determines scale of B-L and R-parity breaking:

$$v_{B-L} \simeq 10^{15}\ \mathrm{GeV}\ , \quad \Theta = \frac{v_{B-L}^2}{{M_{\mathrm{P}}}^2} \simeq 10^{-6}\ ,$$

hence Θ is small !!

Gravitino dark matter can be obtained by thermal gravitino production,

$$\Omega_{3/2}h^2 \simeq 0.5 \left(\frac{T_R}{10^{10}\mathrm{GeV}}\right)\left(\frac{100\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}(\mu)}{1\mathrm{TeV}}\right)$$

$\rightarrow \Omega_{DM}h^2$ for typical parameters of supergravity and leptogenesis (Bolz, WB, Plümacher '98)

II. Superparticle Mass Window

What are the constraints from leptogenesis and GDM on superparticle masses for unstable gravitinos, i.e., without BBN constraints? (different from stable gravitinos, $\rightarrow$ L. Covi) GDM: upper bound on gluino mass for given reheating temperature; low energy observables: lower bound on NLSP.

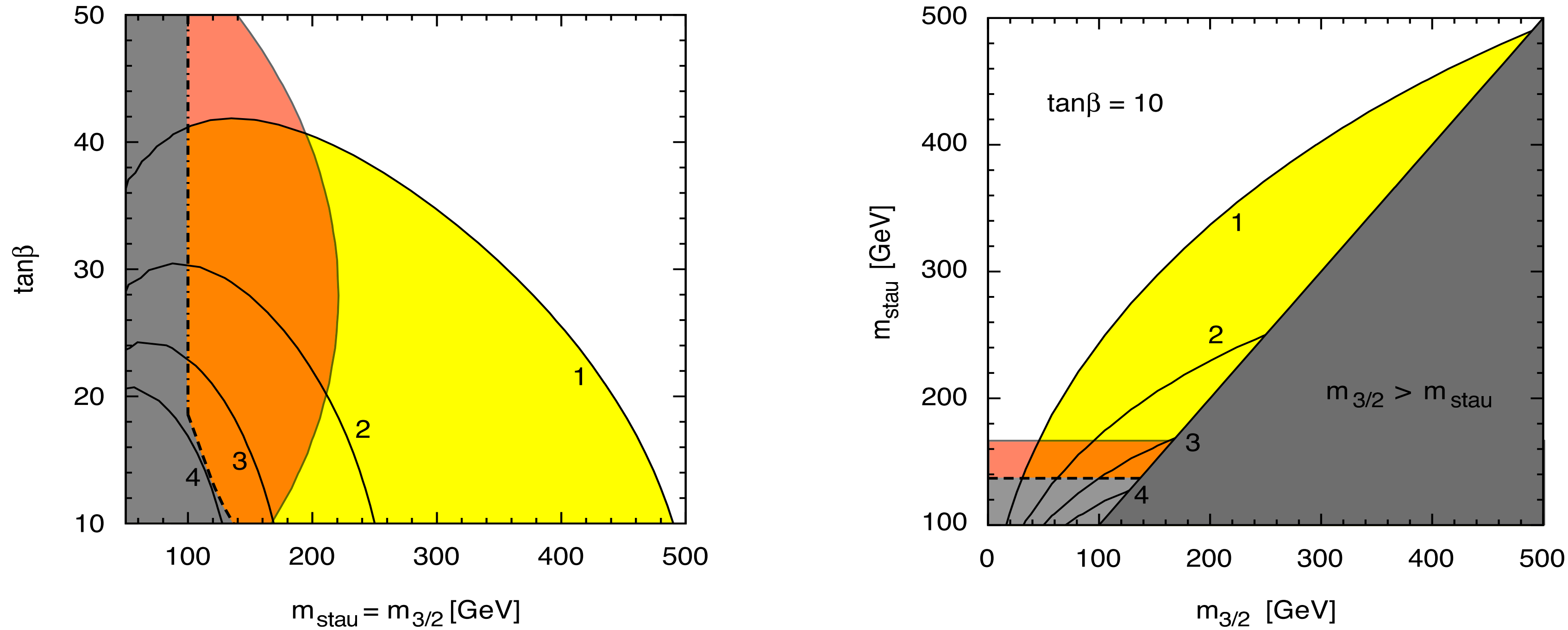
Connection is model dependent; assume gaugino mass unification ($m_{\rm gluino} \simeq 6 m_{\rm bino}$). Two typical examples (different ratios $m_{\rm NLSP}/m_{\rm gluino}$),

$$(A) \quad \chi \text{ NLSP}: \quad m_0 = m_{1/2}\,, \quad a_0 = 0\,, \quad \tan\beta\,;$$
$$(B) \quad \tilde{\tau} \text{ NLSP}: \quad m_0 = 0\,, \quad m_{1/2}\,, \quad a_0 = 0\,, \quad \tan\beta\,.$$

Low energy observables: $m_h > 114$ GeV, BR($B_d \rightarrow B_s\gamma$), $m_{\rm charged} > 100$ GeV. Possible hint for supersymmetry (Marciano, Sirlin '08),

$$a_\mu(\exp) - a_\mu(\mathrm{SM}) = 302(88) \times 10^{-11}\,.$$

Stau and gravitino masses



Left: (A) gravitino: $m_{3/2} < 490$ GeV. *Right:* (B) stau: $100 \text{ GeV} < m_{\text{stau}} < 490$ GeV. *Red:* mass range favoured by a_μ.

III. CR Signatures from Decaying Gravitinos

Gravitino decays: $\psi_{3/2} \rightarrow \gamma\nu; h\nu, Z\nu, W^{\pm}l^{\mp}$, leads to continuous gamma-ray and antimatter spectrum: $\psi_{3/2} \rightarrow \gamma X, \bar{p}X, e^{\pm}X$; qualitative features from operator analysis (assumed hierarchy: $m_{SM} < m_{3/2} < m_{\rm soft}$):

$$\mathcal{L}_{\rm eff} = \frac{i\kappa}{\sqrt{2}M_{\rm P}} \left\{ \bar{l}\gamma^{\lambda}\gamma^{\nu}D_{\nu}\phi\psi_{\lambda} + \frac{i}{2}\bar{l}\gamma^{\lambda}\left(\xi_1 g' Y B_{\mu\nu} + \xi_2 g W_{\mu\nu}\right)\sigma^{\mu\nu}\phi\psi_{\lambda} \right\} + \text{h.c.}$$

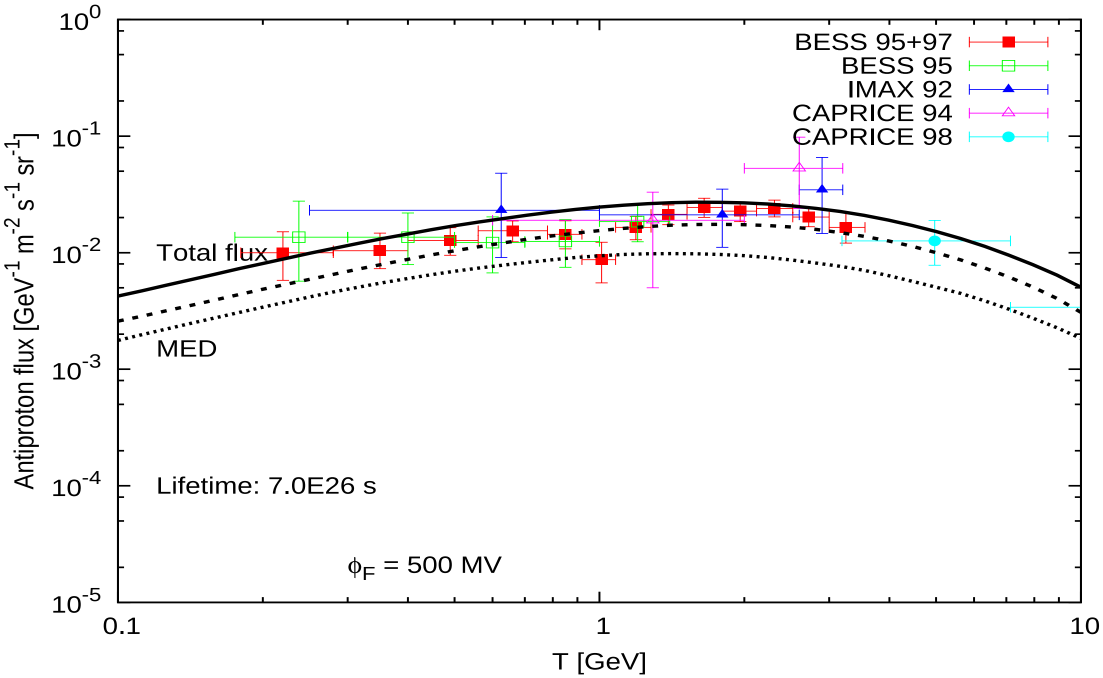
R-parity breaking: κ; further suppression: $\xi_{1.2} = \mathcal{O}(1/m_{3/2})$

$$\text{dim } 5: \ \psi_{3/2} \rightarrow h\nu, Z\nu, W^{\pm}l^{\mp}; \text{ continuous spectrum },$$

i.e., single term correlates antiproton flux, PAMELA and Fermi!

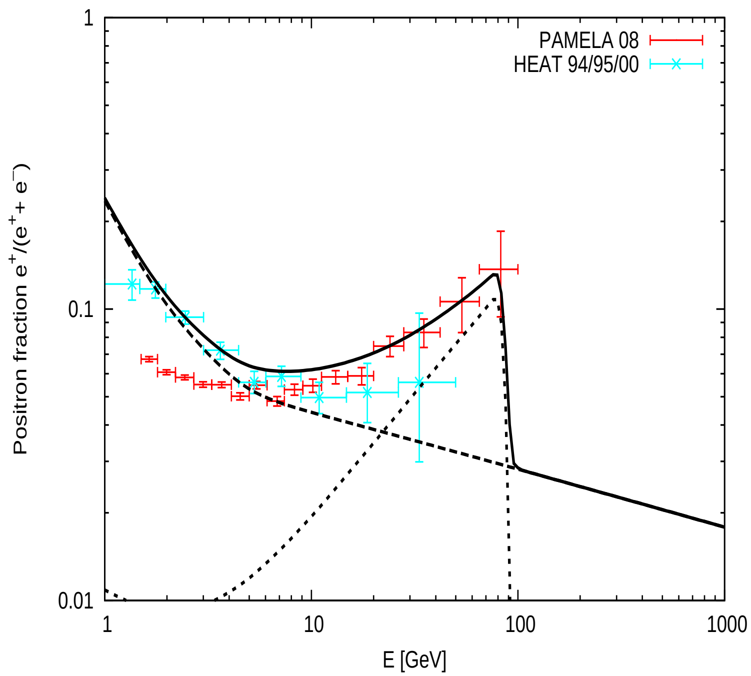
$$\text{dim } 6: \ \psi_{3/2} \rightarrow \gamma\nu; \text{ gamma line}$$

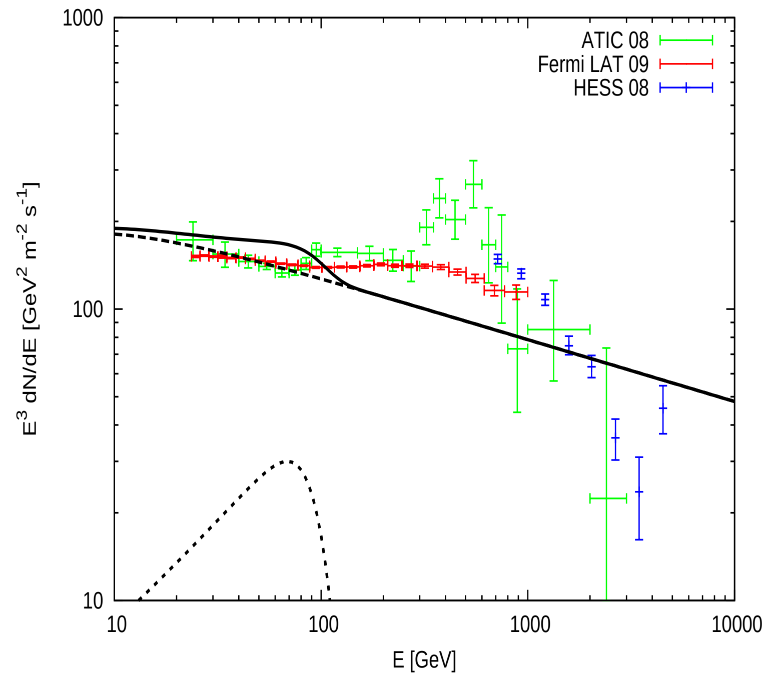
Minimal gravitino lifetime from antiproton flux



conservative propagation model (B/C ratio): MED model; require that total antiproton flux (including gravitino decays) lies below maximal flux from spallation (including astrophysical uncertainties) $\rightarrow$ minimal lifetime; for $m_{3/2} = 200$ GeV one finds $\tau_{3/2}^{\rm min}(200) = 7 \times 10^{26}$ s; close to lower bound from recent Fermi-LAT search for photon lines.

Comparison with PAMELA & Fermi-LAT





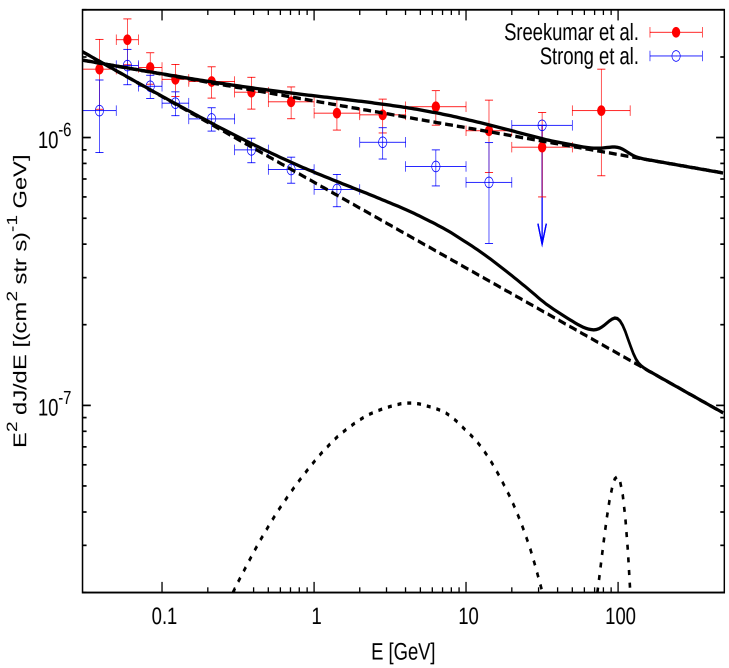
Input: $m_{3/2} = 200$ GeV, $\tau_{3/2} = 3.2 \times 10^{26}$ s, $\mathrm{BR}(\psi \to \mu^{\pm} W^{\mp}, \tau^{\pm} W^{\mp}) \ll \mathrm{BR}(\psi \to e^{\pm} W^{\mp})$ (why?); background: "Model 0" (Grasso et al, Fermi LAT '09)

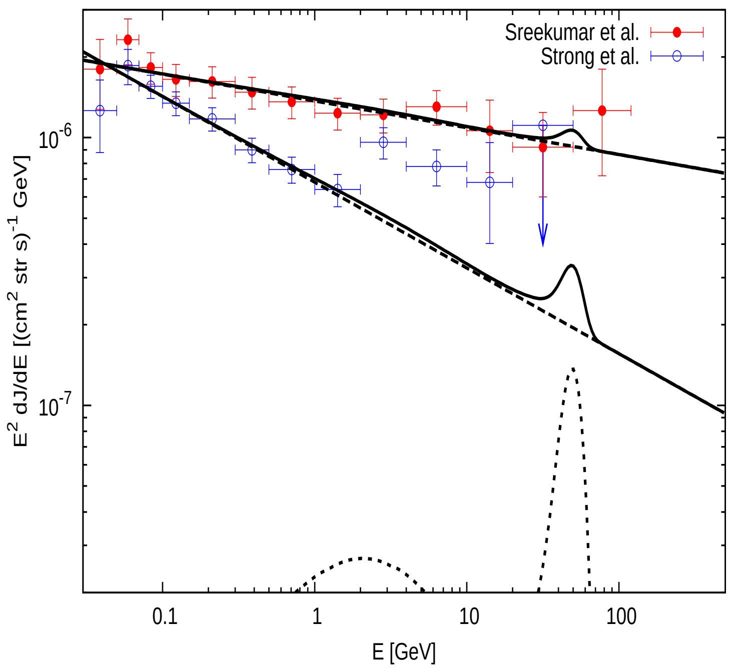
Conclusion: GALPROP & gravitino incompatible with PAMELA & Fermi !!

[Explanation of PAMELA & Fermi by dark matter UNLIKELY !!]

Predicted Gamma-Ray Spectrum

'Minimal' lifetime from antiproton flux gives maximal gamma-ray flux:





left: $m_{3/2} = 200$ GeV, $\tau_{3/2} = 7 \times 10^{26}$ s; *right:* $m_{3/2} = 100$ GeV, $\tau_{3/2} = 1 \times 10^{27}$ s; now strongest bound on lifetime from Fermi-Lat data !!

IV. Signatures at the LHC

General bilinear R-parity breaking, superpotential and scalar potential, is characterized by 9 parameters $(i = 1 \ldots 3)$ (cf. Allanach et al '04, Barbier et al '05,...),

$$\begin{aligned} \Delta W &= \mu_i H_u l_i \\ -\Delta \mathcal{L} &= B_i H_u \tilde{l}_i + m_{id}^2 \tilde{l}_i^\dagger H_d + \text{h.c.}\,; \end{aligned}$$

together with R-parity conserving superpotential and scalar mass terms,

$$\begin{aligned} W &= \mu H_u H_d + h_{ij}^u q_i u_j^c H_u + h_{ij}^d d_i^c q_j H_d + h_{ij}^e l_i e_j^c H_d \ , \\ -\mathcal{L}_{\mathrm{M}} &= m_u^2 H_u^\dagger H_u + m_d^2 H_d^\dagger H_d + (B H_u H_d + \text{h.c.}) \\ &\quad + \tilde{m}_{lij}^2 \tilde{l}_i^\dagger \tilde{l}_i + \tilde{m}_{eij}^2 \tilde{e}_i^{c\dagger} \tilde{e}_i^c + \tilde{m}_{qij}^2 \tilde{q}_i^\dagger \tilde{q}_i + \tilde{m}_{uij}^2 \tilde{u}_i^{c\dagger} \tilde{u}_i^c + \tilde{m}_{dij}^2 \tilde{d}_i^{c\dagger} \tilde{d}_i^c \ , \end{aligned}$$

this defines the considered extension of Standard Model.

Convenient basis of doublets: all R-parity breaking bilinear terms vanish; supersymmetric and non-supersymmetric field redefinitions:

$$H_d = H_d' - \epsilon_i l_i' \ , \quad l_i = l_i' + \epsilon_i H_d' \ ,$$
$$H_d' = H_d'' - \epsilon_i' \tilde{l}_i'' \ , \quad \varepsilon H_u^* = \varepsilon H_u^{'*} - \epsilon_i'' \tilde{l}_i'' \ , \quad \tilde{l}_i' = \tilde{l}_i'' + \epsilon_i' H_d' + \epsilon_i'' \varepsilon H_u^{'*} \ ,$$

generates new Yukawa couplings

$$\begin{aligned} -\Delta\mathcal{L} \quad \supset \quad & \frac{1}{2}\lambda_{ijk} l_i \tilde{e}_j^c l_k + \hat{\lambda}_{ijk} l_i e_j^c \tilde{l}_k + \lambda'_{ijk} d_i^c q_j \tilde{l}_k + \hat{\lambda}'_{ijk} q_i u_j^c \varepsilon \tilde{l}_k^* \\ & + h_{ij}^e (\epsilon_i' H_d + \epsilon_i'' \varepsilon H_u^*) e_j^c \tilde{H}_d \\ & - \frac{g'}{\sqrt{2}} (\epsilon_i' H_d^\dagger - \epsilon_i'' H_u^T \varepsilon) l_i \tilde{B} - \frac{g}{\sqrt{2}} (\epsilon_i' H_d^\dagger - \epsilon_i'' H_u^T \varepsilon) \tau^I l_i \tilde{W}^I + \mathrm{h.c.} \ , \\ & \lambda_{ikj} = -h_{ij}^e \epsilon_k - h_{kj}^e \epsilon_i \ , \ldots , \ \hat{\lambda}'_{ijk} = -h_{ij}^u \epsilon_k'' \ . \end{aligned}$$

Note: 108 R-parity breaking couplings in terms of 9 (1) parameters!

After electroweak breaking new mass mixings,

$$-\Delta\mathcal{L}_M \supset \; m^e_{ij}\frac{\zeta_i}{\cos\beta}e^c_j\tilde{H}_d - m_Z s_w \zeta_i^\dagger \nu_i \tilde{B} - m_Z c_w \zeta_i^\dagger \nu_i \tilde{W}^3 + \mathrm{h.c.}\ ,$$

with

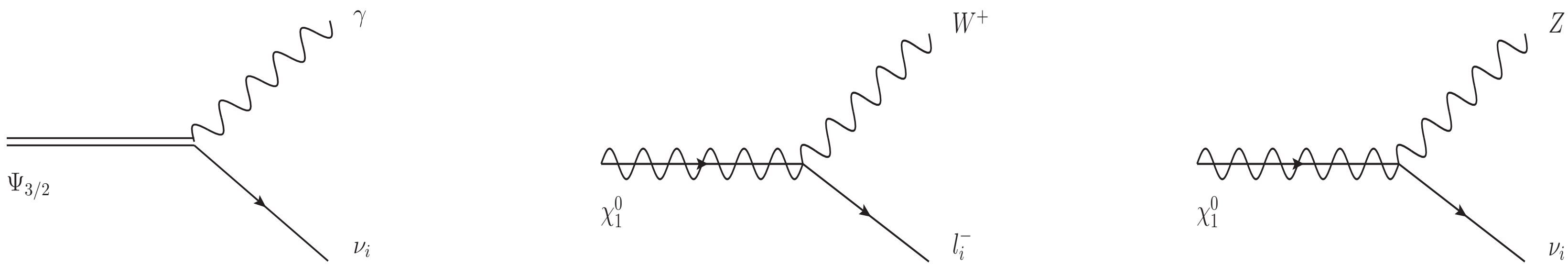
$$\zeta_i = \frac{\epsilon'_i v_d + \epsilon''_i v_u}{v}\ , \quad m^e_{ij} = h^e_{ij} v_d\ , \quad s_w = \frac{g'}{\sqrt{g^2+g'^2}}\ .$$

Convenient set of independent parameters (i=1,...,3):

$$\zeta_i\ , \quad \epsilon_i\ , \quad \epsilon''_i\ ,$$

Cosmic-ray data constrain (or determine!) these parameters, which leads to predictions for LHC.

Neutralino NLSP Decays



Matrix elements for gravitino decay, charged and neutral currents (7×7 neutralino mass matrix, 5×5 chargino mass matrix):

$$U_{\tilde{\gamma}\nu_i} = \zeta_i \frac{m_Z(M_2 - M_1)}{M_1 M_2} s_w c_w \left(1 + \mathcal{O}\left(\frac{m_Z}{\mu}\right)\right) ,$$

$$U_{\chi_1^0 \nu_i} = -\zeta_i \frac{m_Z}{M_1} s_w \left(1 + \mathcal{O}\left(\frac{m_Z}{\mu}\right)\right) , \quad U_{\chi_1^0 e_i} = \ldots$$

Lower bound on neutralino NLSP decay length

$$\tau_{\chi_1^0} = \frac{2c_w^2}{g_2^2}\left(\frac{M_1}{M_2 - M_1}\right)^2 \frac{m_{3/2}^3}{M_1 {M_{\rm P}}^2}\tau_{3/2}(\gamma\nu)\left(1 + \mathcal{O}\left(\frac{m_Z}{\mu}\right)\right)$$

The Fermi-LAT data, $\tau_{3/2}(\gamma\nu) \gtrsim 5 \times 10^{28}\ s,\ 30\ \mathrm{GeV} < E_\gamma < 200\ \mathrm{GeV}$, imply

$$c\tau_{\chi_1^0} \gtrsim 0.6\ \mathrm{km}\left(\frac{m_{\chi_1^0}}{100\ \mathrm{GeV}}\right)^{-1},$$

i.e., neutralino NLSP mostly decays outside detector!

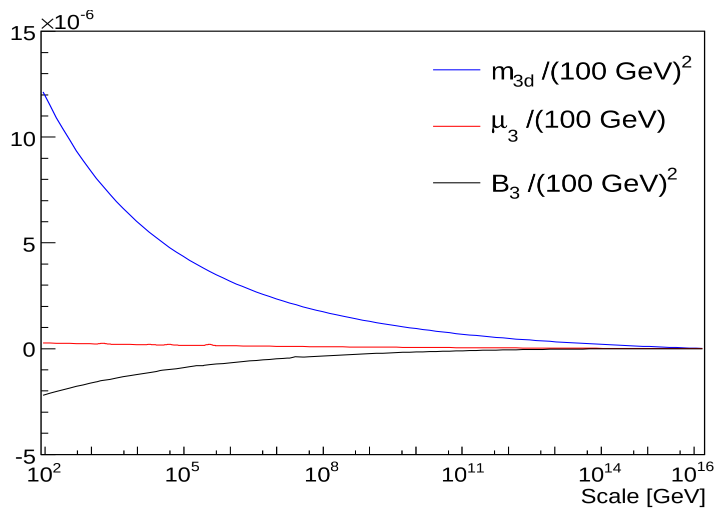
$\tilde{\tau}_1$-NLSP Decays

depend on flavour structure and pattern of supersymmetry breaking, e.g.:

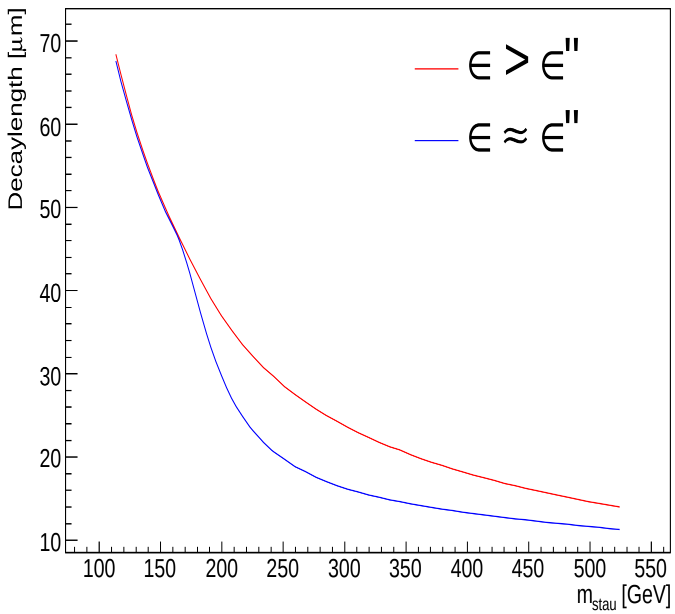
(a) universal breakings : $\mu_i \sim B_i \sim m^2_{id} \propto \Theta\eta^{Q_i}$

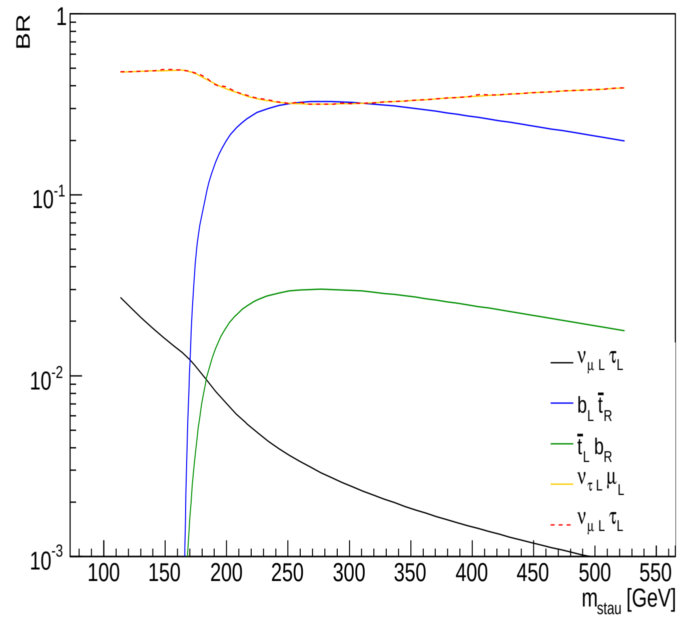
(b) soft breakings from RG running :

$$\epsilon_i \sim \Theta\eta^{Q_i} \; ; \quad \mu_i \sim B_i \sim m^2_{id} \propto \Theta\frac{\eta^2}{16\pi^2}\ln\frac{\Lambda_{\mathrm{GUT}}}{\Lambda_{\mathrm{EW}}}$$



Decay length $c\tau_{\tilde{\tau}_1} \gtrsim 20\ \mu\mathrm{m}$, for largest $\epsilon_3 \simeq 10^{-5}$ consistent with cosmological bound; in general competition between leptonic and 2jet decay modes:





$\tilde{\tau}_L$-$\tilde{\tau}_R$ mixing depends on $m_{\tilde{\tau}}$; characteristic branching ratios! For $\epsilon_3 \sim \ldots \sim \zeta^{\mathrm{max}}_{\mathrm{gravitino}} \sim 10^{-9}$, one has $c\tau_{\tilde{\tau}_1} = \mathcal{O}(\mathrm{km})$!

SUMMARY

- R-parity breaking theoretically well motivated
- Decaying gravitino DM viable possibility, naturally consistent with leptogenesis and BBN
- GALPROP & gravitino DM cannot explain PAMELA & Fermi-LAT data, astrophysical sources needed!
- Optimistic perspective: Fermi-LAT observes photon line $\rightarrow m_{3/2}$ & size of R-parity breaking; for NLSP, detailed predictions for LHC, hopefully decay in detector!