Broken R-Parity in the Sky and at the LHC

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I. R-Parity and B-L Breaking

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

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

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

$$\lambda\ , \lambda' < 10^{-7}\ .$$

NOTE: 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,

$$\tau_{3/2} \sim 10^{26}\text{s} \left(\frac{\lambda}{10^{-7}}\right)^{-2} \left(\frac{m_{3/2}}{10\ \text{GeV}}\right)^{-3} ,$$

consistent with gravitino dark matter !!

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

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

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

A Model for R-parity Breaking

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

$$W_M = h_{ij}^{(u)} \mathbf{10}_i \mathbf{10}_j H_u + h_{ij}^{(d)} \bar{\mathbf{5}}_i \mathbf{10}_j H_d + h_{ij}^{(\nu)} \bar{\mathbf{5}}_i \mathbf{1}_j H_d + \frac{1}{M_{\mathrm{P}}} h_{ij}^{(n)} \mathbf{1}_i \mathbf{1}_j N^2 \; ;$$

$\langle N \rangle$ generates Majorana masses for $\mathbf{1}$'s; superpotential for B-L breaking:

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

with spectator 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,

$$\delta W_1 = \mu_i \Theta \bar{\mathbf{5}}_i H_u \; , \quad \mu_i = \mathcal{O}(m_{3/2}) \; , \quad \Theta = \frac{v_{B-L}^2}{{M_{\mathrm{P}}}^2} \lesssim 10^{-6} \; .$$

Gravitino Virtue

Can one understand the amount of dark matter, $\Omega_{DM} \simeq 0.23$, with $\Omega_{DM} = \rho_{DM}/\rho_c$, if gravitinos are dominant component, i.e. $\Omega_{DM} \simeq \Omega_{3/2}$?

Production mechanisms: (i) 'Super-WIMP' mechanism,

$$\Omega_{3/2} = \frac{m_{3/2}}{m_{\rm NLSP}} \Omega_{\rm NLSP} \ ,$$

independent of initial temperature T_R (!), but inconsistent with BBN constraints; (ii) Thermal production, from $2 \rightarrow 2$ QCD processes,

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

$\rightarrow \Omega_{DM} h^2$ 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? GDM: upper bound on gluino mass for given reheating temperature; low energy observables: lower bound on NLSP.

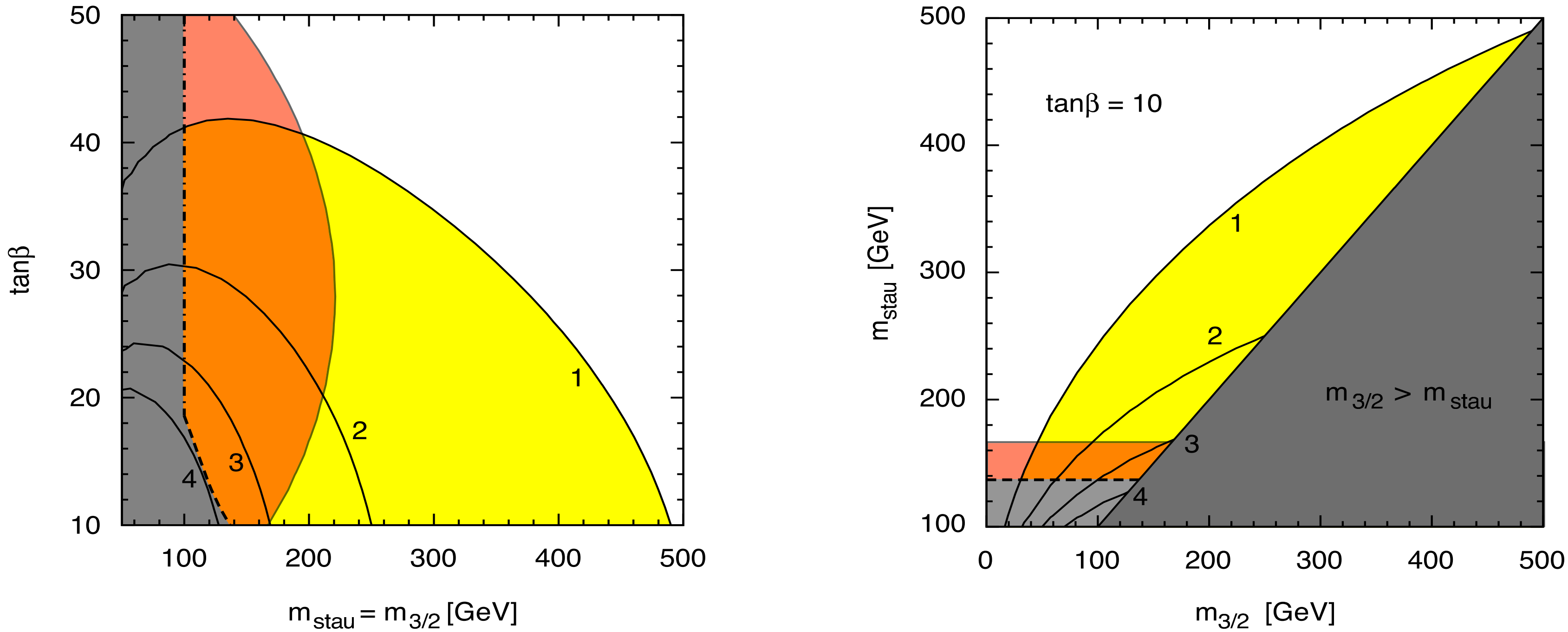
Connection is model dependent; assume gaugino mass unification ($m_{\text{gluino}} \simeq 6 m_{\text{bino}}$). Two typical examples (different ratios $m_{\text{NLSP}}/m_{\text{gluino}}$),

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

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

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

Stau and gravitino masses



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

III. CR Signatures from Decaying Gravitinos

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

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

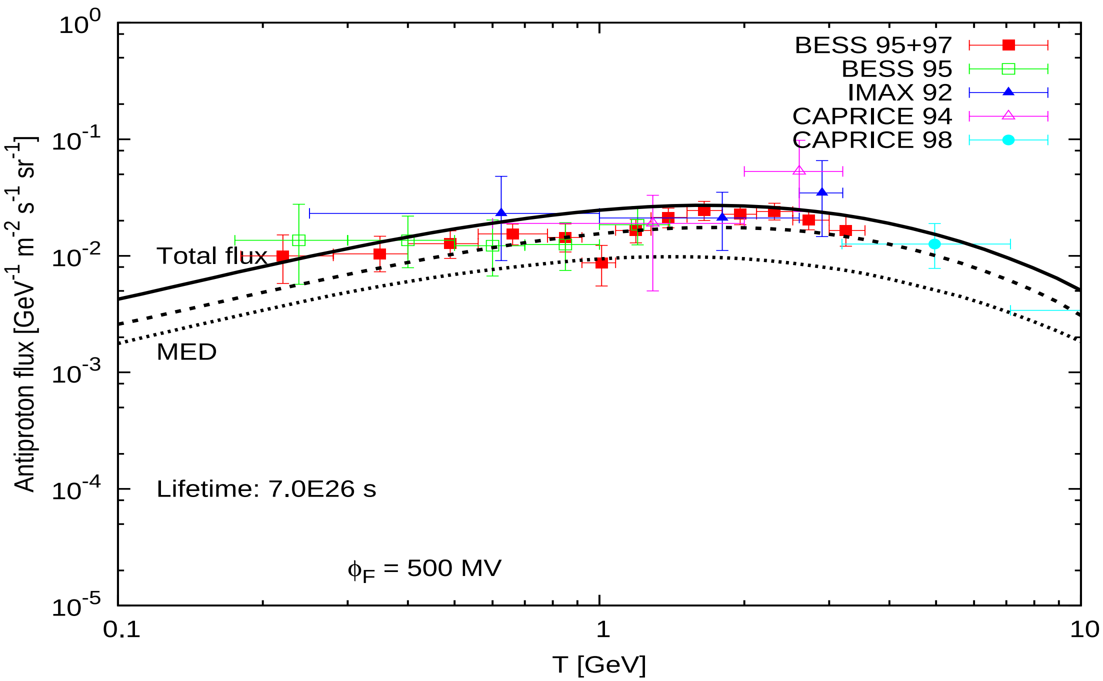
R-parity breaking: κ; further suppression: $\xi_{1.2} = \mathcal{O}(1/m_{3/2})$

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

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

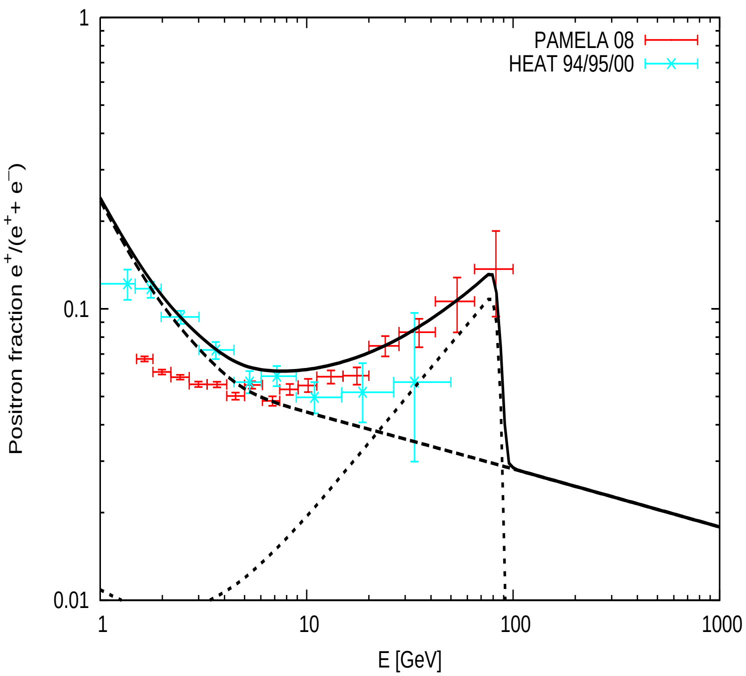
$$\text{dim } 6: \;\; \psi_{3/2} \to \gamma\nu; \text{ gamma line}$$

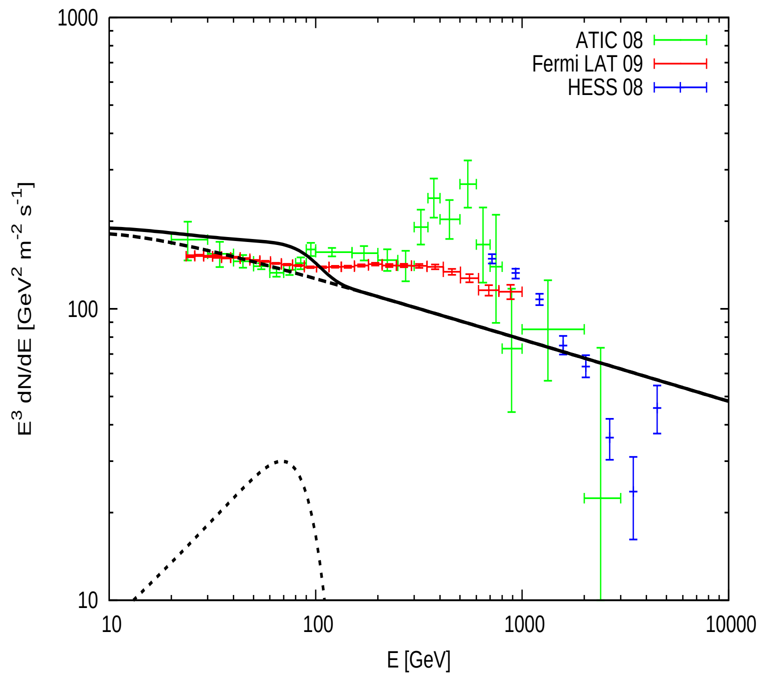
Minimal gravitino lifetime from antiproton flux



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) $\longrightarrow$ minimal lifetime; for $m_{3/2} = 200$ GeV one finds $\tau_{3/2}^{\min}(200) = 7 \times 10^{26}$ s.

PAMELA & Fermi vs 'electron dominance'



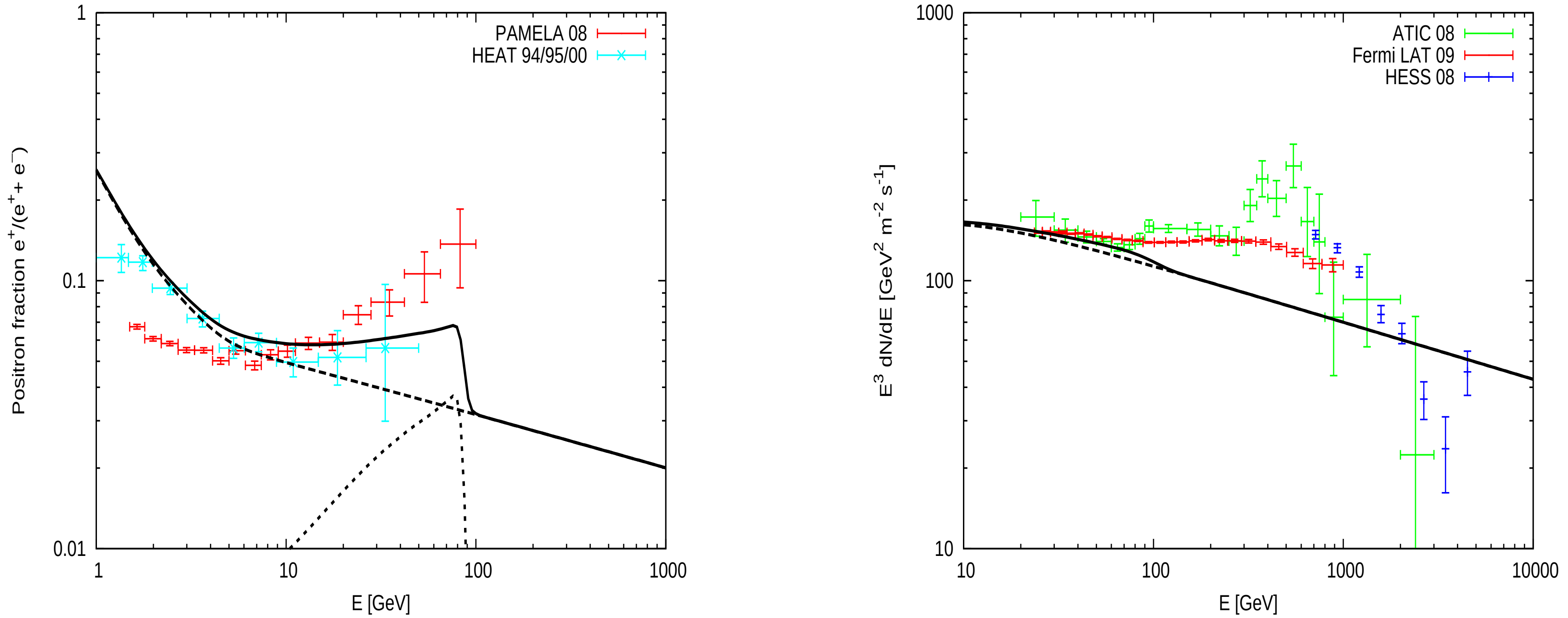


Input: $m_{3/2} = 200$ GeV, $\tau_{3/2} = 3.2 \times 10^{26}$ s, $\mathrm{BR}(\psi \to \mu^{\pm} W^{\mp}, \tau^{\pm} W^{\mp}) \ll \mathrm{BR}(\psi \to e^{\pm} W^{\mp})$ (why?); background: "Model 0" (Grasso et al, Fermi LAT '09)

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

[PAMELA & Fermi make CR signature for dark matter UNLIKELY !!]

PAMELA & Fermi vs ‘flavour democracy’



Input: $m_{3/2} = 200$ GeV, $\tau_{3/2} = 7 \times 10^{26}$ s, $\mathrm{BR}(\psi \to l_i^{\pm} W^{\mp})$ universal for $i = e, \mu, \tau$ (theoretical model exists), background: “Model 0”.

Conclusion: astrophysical sources needed to explain PAMELA & FERMI!!

Predictions for the Gamma-Ray Spectrum

Important contributions form extragalactic DM and DM in the Milky Way halo; typical branching ratio for gamma line (cf. operator analysis):

$$\mathrm{BR}(\psi_{3/2} \to \nu\gamma) \sim 0.02 \left(\frac{200\ \mathrm{GeV}}{m_{3/2}}\right)^2 \ ;$$

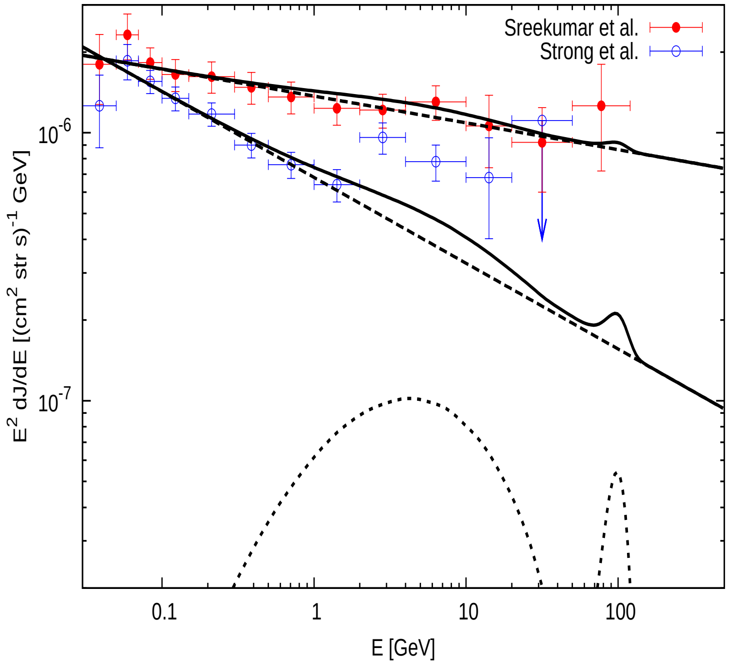
Gamma-ray background presently uncertain, two analyses of EGRET data; Sreekumar et al:

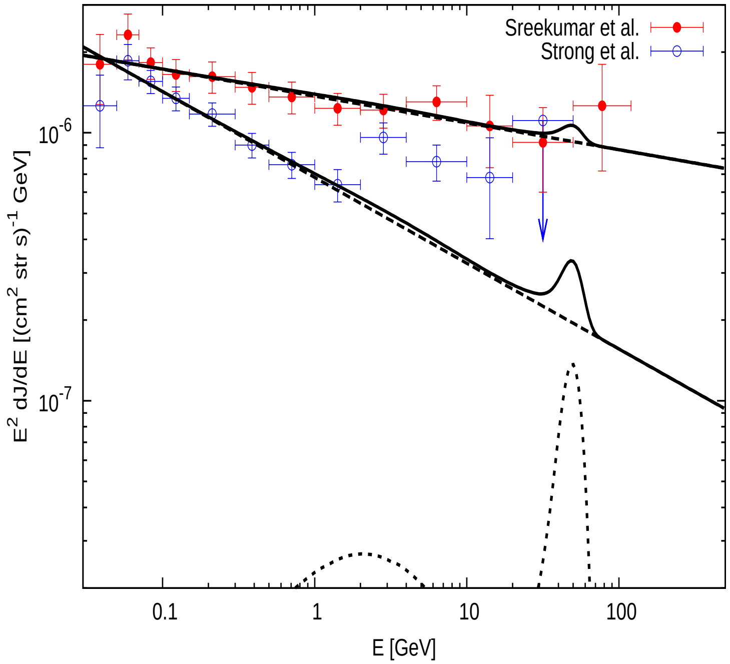
$$\left[E^2 \frac{dJ}{dE}\right]_{\mathrm{bg}} = 1.37 \times 10^{-6} \left(\frac{E}{\mathrm{GeV}}\right)^{-0.1} (\mathrm{cm}^2\ \mathrm{str\ s})^{-1}\ \mathrm{GeV}\ ,$$

and Moskalenko et al:

$$\left[E^2 \frac{dJ}{dE}\right]_{\mathrm{bg}} = 6.8 \times 10^{-7} \left(\frac{E}{\mathrm{GeV}}\right)^{-0.32} (\mathrm{cm}^2\ \mathrm{str\ s})^{-1}\ \mathrm{GeV}.$$

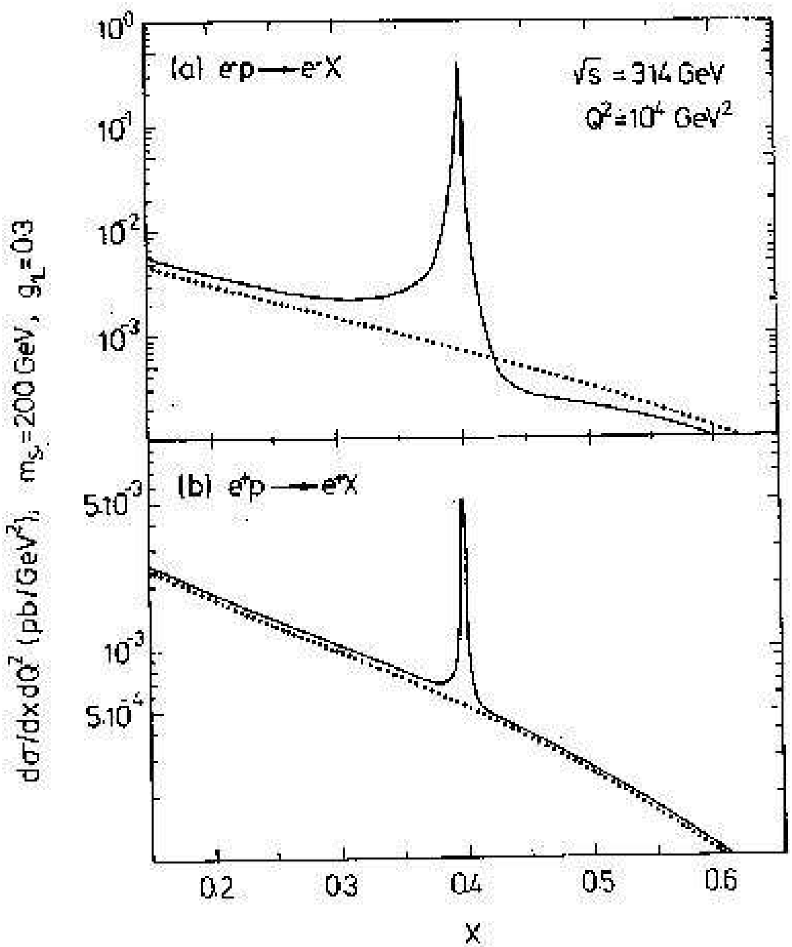
Height of gamma line depends on energy resolution (assumed: $\sigma(E)/E = 15\%$) and background; 'minimal' lifetime from antiproton flux constraint give maximal gamma-ray flux:





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; improvement of energy resolution?

Peaks are interesting ... cf. Wyler et al.



leptoquark peak predicted
for ep collisions at HERA

subtle choice of energy

with some significance
observed by H1 ...

decreasing significance
with increasing statistics...

IV. Hope for the LHC: $\tilde{\tau}$-decays

R-parity breaking leads to decays $\widetilde{\tau}_R \longrightarrow \tau\ \nu_\mu, \mu\ \nu_\tau$, $\widetilde{\tau}_L \longrightarrow b^c t$, ...; small breaking predicted from connection with B-L breaking,

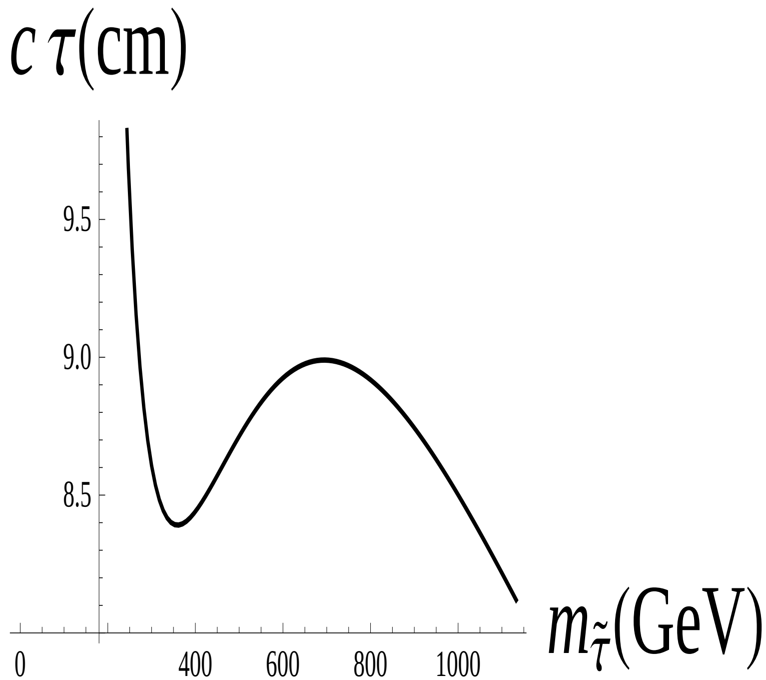
$$\lambda \sim h^{(e,d)}\Theta \lesssim 10^{-7}\,, \quad \Theta = \frac{v_{B-L}^2}{{M_\mathrm{P}}^2} \lesssim 10^{-6}\,.$$

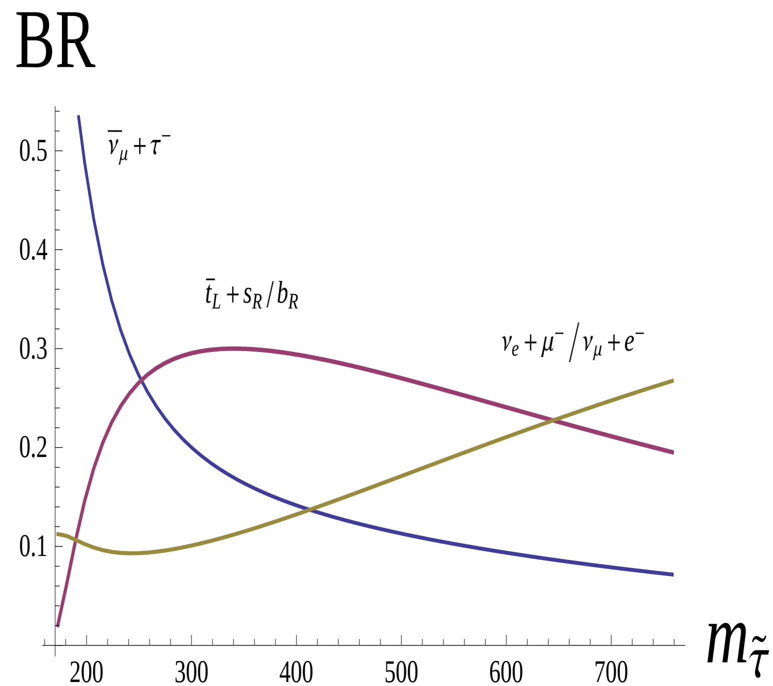
The NLSP lifetime becomes sufficiently short (decay before BBN),

$$c\tau_{\tilde{\tau}}^{lep} \sim 30\ \mathrm{cm}\left(\frac{m_{\tilde{\tau}}}{200\mathrm{GeV}}\right)^{-1}\left(\frac{\lambda}{10^{-7}}\right)^{-2}\,.$$

At LHC characteristic signals with strongly ionising macroscopic charged tracks, followed by muon track or jet and missing energy, corresponding to $\widetilde{\tau} \longrightarrow \mu\nu_\tau$ or $\widetilde{\tau} \longrightarrow \tau\nu_\mu$.

Specific predictions for SUGRA boundary conditions (cf. III); $\tilde{\tau}$ may decay in detector; its mass is obtained from $m_{\tilde{\tau}} = p_{\rm meas}/\beta\gamma_{\rm meas}$, slow $\tilde{\tau}$'s important! (background from muon tracks); example for $\Theta\mu_3/\mu = 10^{-7}$ (consistent with Fermi-LAT; PRELIMINARY):





$\tilde{\tau}_L$-$\tilde{\tau}_R$ mixing depends on $m_{\tilde{\tau}}$; characteristic branching ratios! Lower bounds on gravitino lifetime from Fermi-LAT imply lower limit on $\tilde{\tau}$ decay length!

SUMMARY

- R-parity breaking theoretically well motivated
- Favours gravitino DM; viable possibility!
- Decaying gravitino DM consistent with leptogenesis and BBN
- GALPROP & gravitino DM incompatible with PAMELA & Fermi, astrophysical sources needed !!
- Sizable excess in gamma-ray spectrum possible, in particular line at $E_\gamma \simeq m_{3/2}/2$. Wait for Fermi-LAT !!
- Specific predictions for LHC, connection to Fermi-LAT !!