Gravitino Dark Matter and LHC searches in R-violating SUSY

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Based on:
- *N. E. Bomark, SL, P. Osland, A. Raklev,* PLB 2009 & PLB 2010
- *N.E.Bomark, D.Choudhuri,SL, P. Osland in preparation*
- *SL, P. Osland, A. Raklev,* PLB 2007

Content

- R-violation: *Motivation, Generic Signals, Bounds*
- Dark Matter:

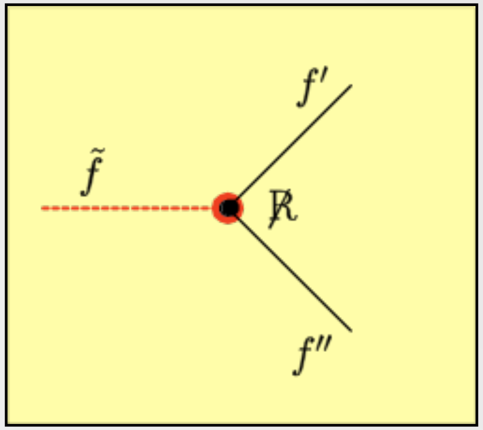
  Is observable R-violation compatible with SUSY DM?
- Experimental signals: (Collider, low energy LFV)

  Flavour structure of R-violating neutralino decays
- Conclusions

Motivation for R-violating supersymmetry

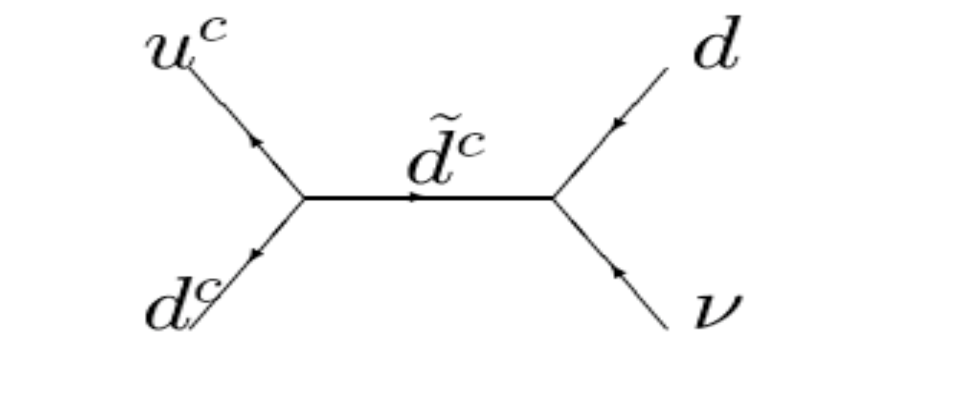
In addition to couplings generating fermion masses,

$$h_{ij} L_i H_1 \bar{E}_j \qquad h'_{ij} Q_i H_1 \bar{D}_j \qquad h''_{ij} Q_i H_2 \bar{U}_j$$



also $$\lambda_{ijk} L_i L_j \bar{E}_k \qquad \lambda'_{ijk} L_i Q_j \bar{D}_k \qquad \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

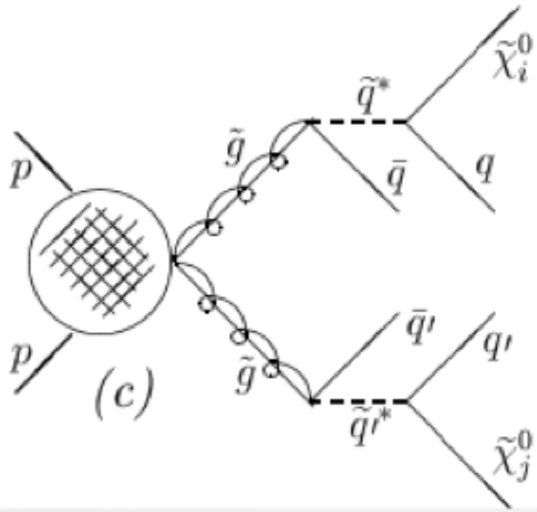
- These *violate lepton and baryon number*
- If simultaneously present, unacceptable *p* decay



Ways out:

X Either kill all couplings via R-parity *(Fayet)*
(SM: +1 , SUSY: -1)

forbids all terms with $\Delta L \neq 0$ and $\Delta B \neq 0$

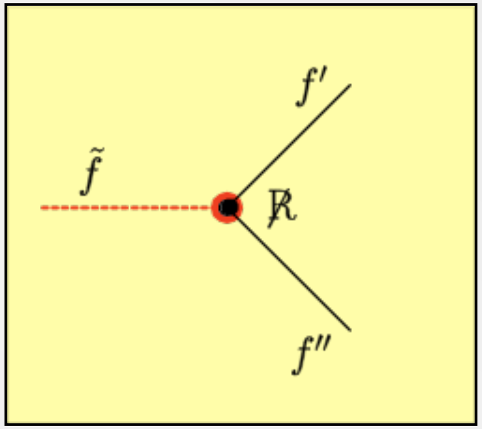


***LSP: stable**, dark matter candidate*
Colliders: Missing energy

✓ Or allow subsets by baryon / lepton parities

Only $\Delta B \neq 0$ or $\Delta L \neq 0$

(p-decay needs both types of terms)



***LSP: unstable** – lose (?) a dark matter candidate*
Colliders: Multi-lepton/jet events

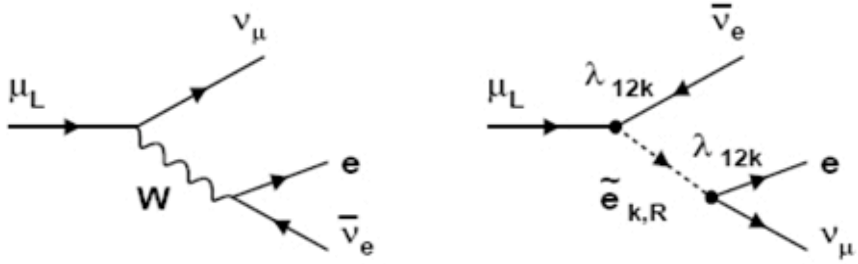
Both possibilities open from theoretical point of view
(several viable models have been constructed)

Very rich flavour structure! Flavour-dependent constraints from unacceptable SM modifications

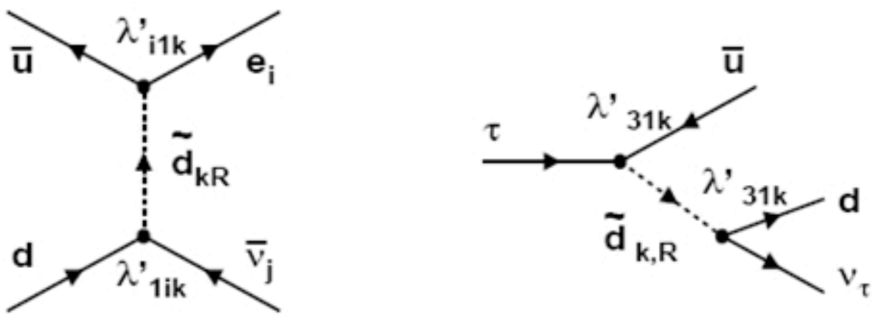
ijk	λ_{ijk}	Sources	ijk	λ''_{ijk}	Sources
121	0.05	CC univ.	112	10^{-6}	Double nucleon dec.
122	0.05	CC univ.	113	10^{-4}	n–$\bar{n}$ osc.
123	0.05	CC univ.	123	1.25	Perturb. unitar.
131	0.06	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$	212	1.25	Perturb. unitar.
132	0.06	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$	213	1.25	Perturb. unitar.
133	0.003	ν_e- mass	223	1.25	Perturb. unitar.
231	0.06	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$	312	0.50	R_l (LEP1)
232	0.06	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$	313	0.50	R_l (LEP1)
233	0.06	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$	323	0.50	R_l (LEP1)

Upper limits on λ- and λ''-couplings for $\tilde{m} = 100$ GeV.

i.e. Charged Current Universality



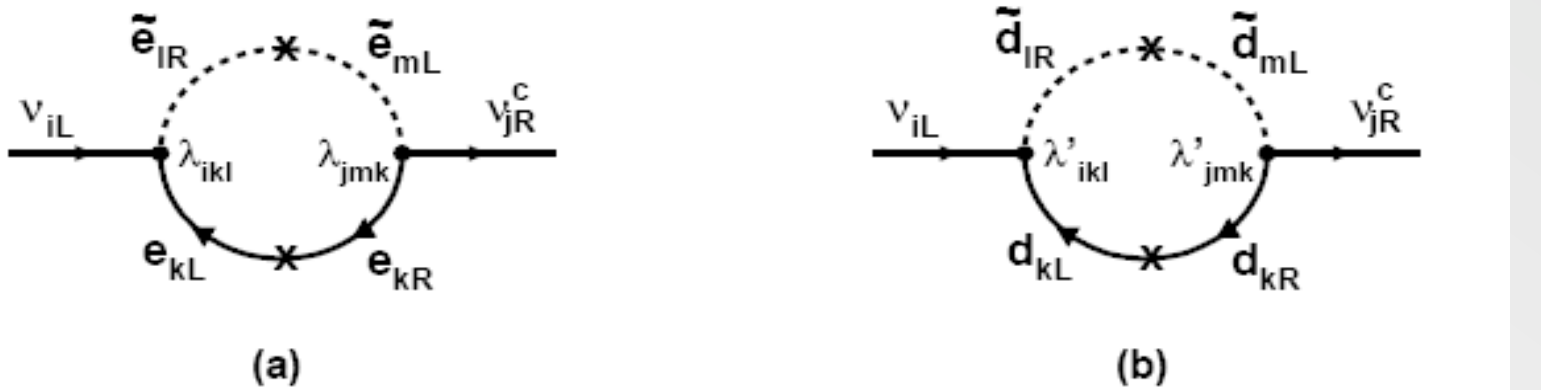
(a) (b)



(a) (b)

Neutrinos in R-violating SUSY

1-loop neutrino mass contributions:



$$M^{\nu}_{ij}|_{\lambda} = \frac{1}{16\pi^2}\sum_{k,l,m}\lambda_{ikl}\lambda_{jmk}\, m_{e_k}\frac{(\tilde{m}^{e\,2}_{LR})_{ml}}{m^2_{\tilde{e}_{Rl}} - m^2_{\tilde{e}_{Lm}}}\ln\left(\frac{m^2_{\tilde{e}_{Rl}}}{m^2_{\tilde{e}_{Lm}}}\right) + (i \leftrightarrow j)$$

$$M^{\nu}_{ij}|_{\lambda'} = \frac{3}{16\pi^2}\sum_{k,l,m}\lambda'_{ikl}\lambda'_{jmk}\, m_{d_k}\frac{(\tilde{m}^{d\,2}_{LR})_{ml}}{m^2_{\tilde{d}_{Rl}} - m^2_{\tilde{d}_{Lm}}}\ln\left(\frac{m^2_{\tilde{d}_{Rl}}}{m^2_{\tilde{d}_{Lm}}}\right) + (i \leftrightarrow j)$$

Gravitino DM in R-violating supersymmetry?

-If LSP a gravitino, its decays very suppressed by Mp

-The lighter the gravitino, the longer the lifetime

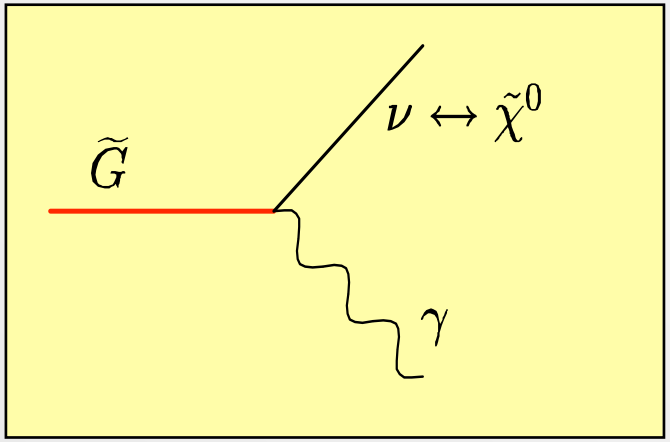
Questions: *can gravitinos be DM even with broken R-parity?*
*Can we hope for **BOTH** DM **AND** R-violation in colliders?*

Answer: *depends on how gravitinos decay under R-violation*

2-body bi-linear R-violating decays

Takayama, Yamaguchi, Buchmuler, Covi,Hamaguchi, Ibarra, Yanagida

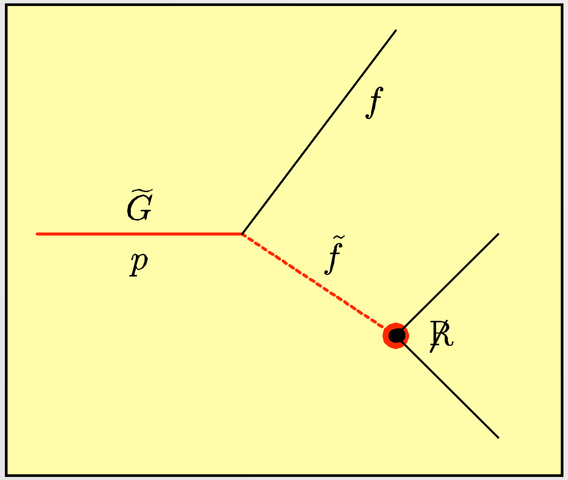
μνSSM: Choi, Lopez-Fogliani,Munoz, de Austri



Suppressed by:

- Gravitino vertex (~1/Mp)
- Neutralino-neutrino mixing (model dependent)

3-body trilinear R-violating decays (Chemtob, Moreau)

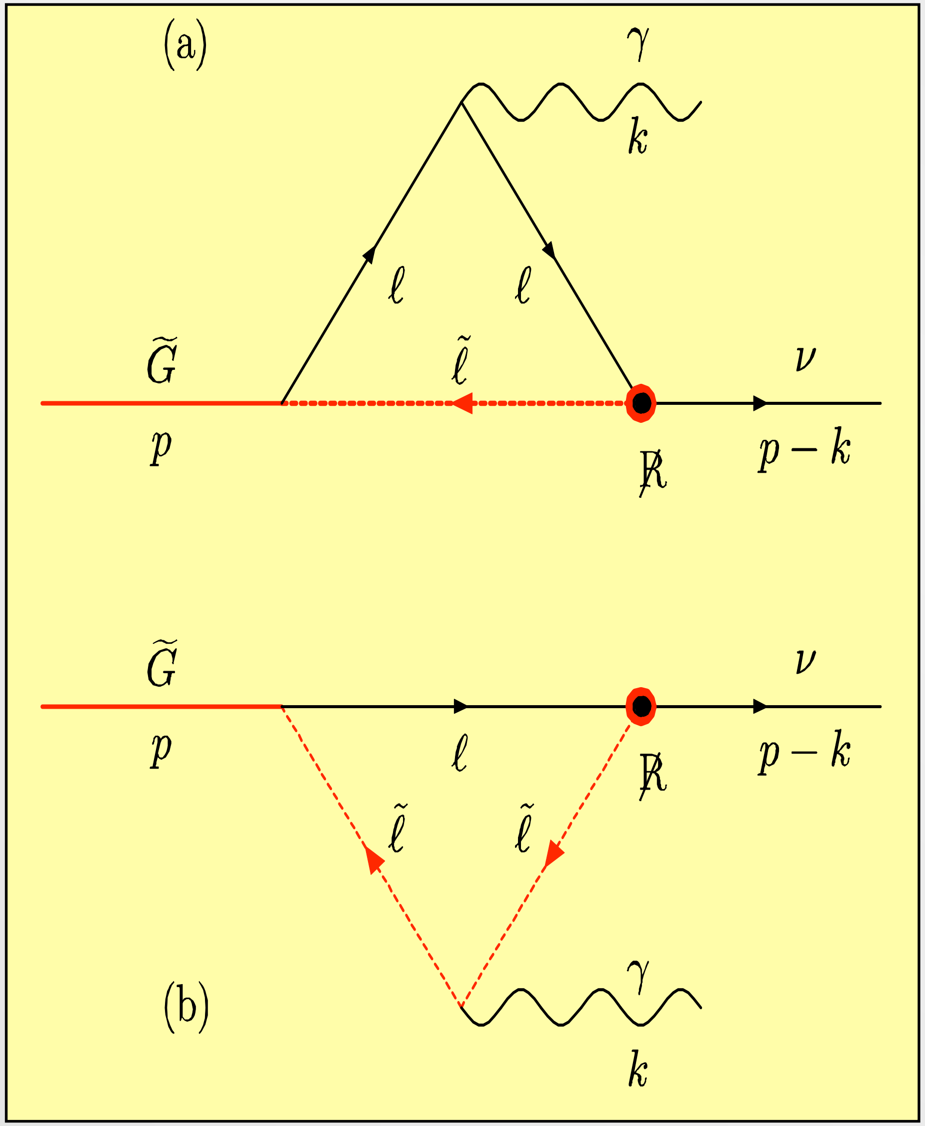


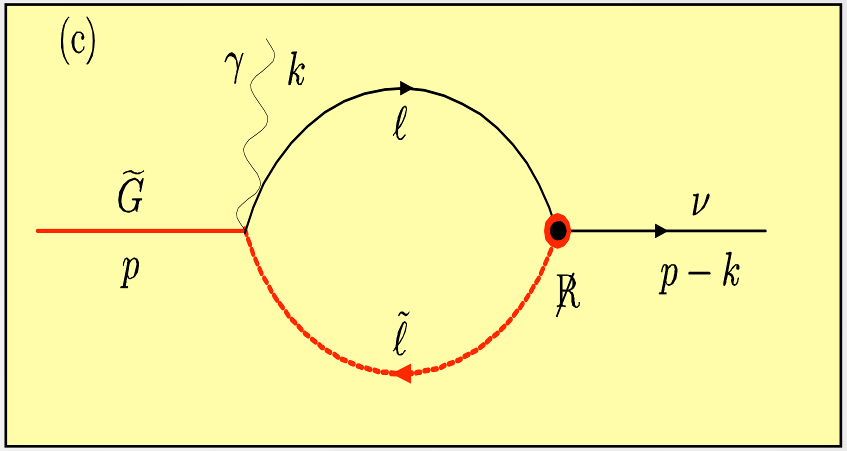
Suppressed by:

- Gravitino vertex (~1/Mp)
- Phase space / fermion masses (for light gravitino and heavy fermions)

Radiative 2-body trilinear R-violating decays

SL, P. Osland, A. Raklev





Suppressed by:

- *Gravitino vertex (~1/Mp)*
- *Loop factors (~ fermion mass)*

Radiative decays dominate for:

- Smaller gravitino masses
- R and L violation via operators of the 3rd generation
- Small neutrino-neutralino mixing

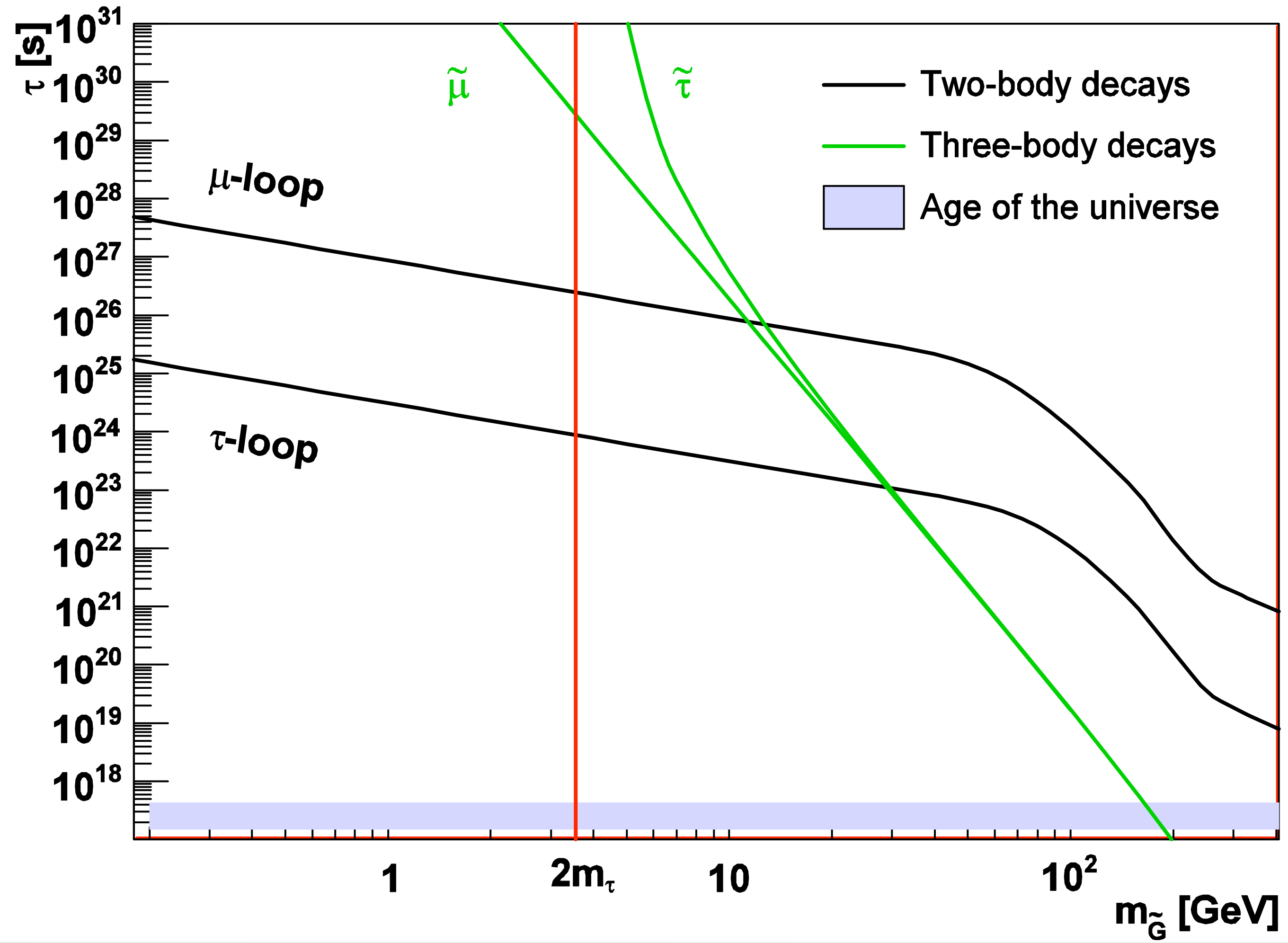
Large gravitino lifetime (can be DM), due to:

- Gravitational suppression of its couplings
- Smallness of R-violating vertices
- Loop, phase space, or mixing effects

$\bar{U}_3 \bar{D}_j \bar{D}_k$

Maximum stability
(neither radiative nor tree-level decays
-modulo mixing effects)!

Radiative versus 3-body decays



NLSP decays

NLSP	$LL\bar{E}$	$LQ\bar{D}$	$\bar{U}\bar{D}\bar{D}$
χ^0	$\ell_i^\pm \ell_j^\mp \nu$	$q_j \bar{q}_k \ell^\pm (q_j \bar{q}_k \nu)$	$q_i q_j q_k (\bar{q}_i \bar{q}_j \bar{q}_k)$
$\tilde{\nu}$	$\ell_i^\pm \ell_j^\mp$ $\ell_i^\pm \ell_j^\mp \nu\nu$	$q_j \bar{q}_k$ $q_j \bar{q}_k \ell^\pm \nu (q_j \bar{q}_k \nu\nu)$	$\nu q_i q_j q_k (\nu \bar{q}_i \bar{q}_j \bar{q}_k)$
$\tilde{\tau}_R$	$\ell_i \nu$ $\ell_i^\pm \ell_j^\mp \nu\tau$	$q_j \bar{q}_k$ $q_j \bar{q}_k \ell^\pm \tau (q_j \bar{q}_k \nu\tau)$	$\tau q_i q_j q_k (\tau \bar{q}_i \bar{q}_j \bar{q}_k)$

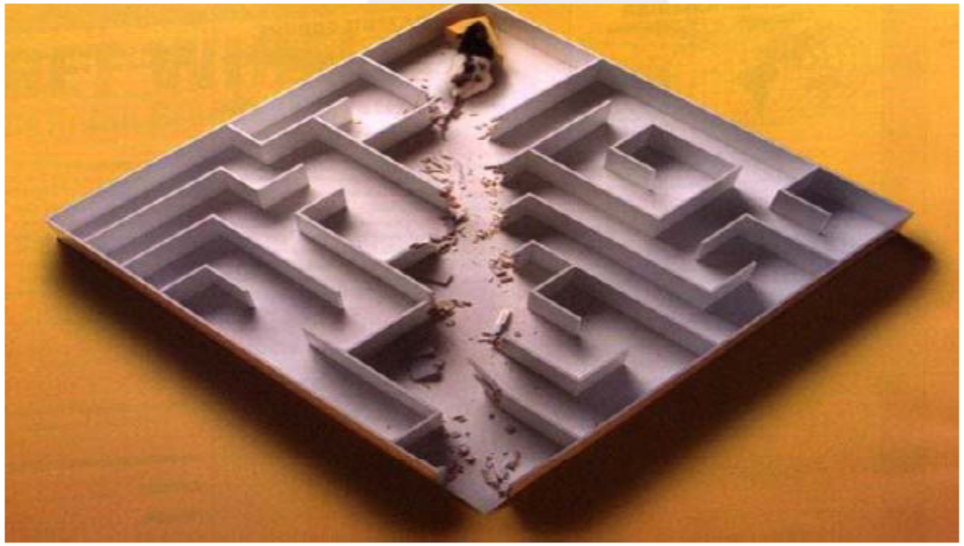
- No source of suppression other than R-violating couplings

-Decay well before BBN compatible with gravitino DM

(without fine-tuning of the SUSY parameter space)

Alternative way to avoid BBN bounds:

(No Rules!)



Collider Search Strategies:

For **ΔL** look for:

Modifications to SM Processes or Exotic Events

(like ΔLi, novel final state topologies,

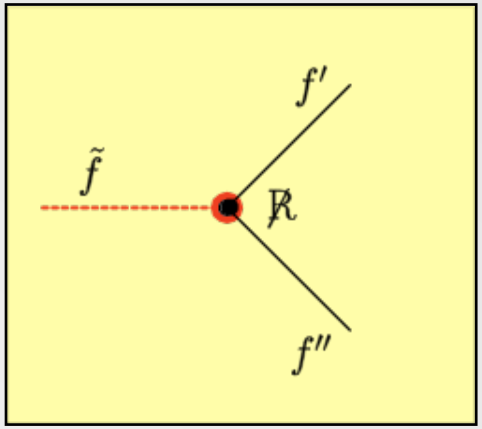
Isolated leptons in jet backgrounds with limited missing energy)

For **ΔB** need more detailed analysis

sophisticated jet clustering algorithms

Possible Signals

- Pair sparticle productions and R-violating decays
- Single superparticle productions
- Virtual processes



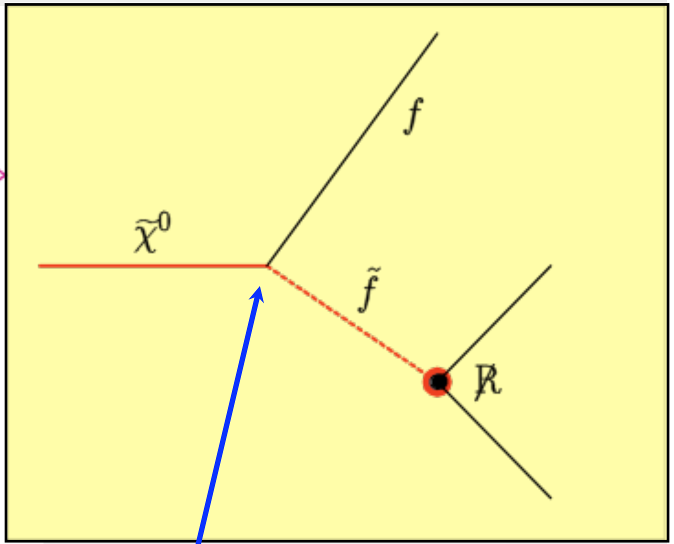
- (neutral/charged) LSP decay to SM particles

  for any $\lambda, \lambda', \lambda'' \geq 10^{-6}$, decay inside apparatus $\Rightarrow$

- Missing energy $\rightarrow$ multi-lepton/jet signals

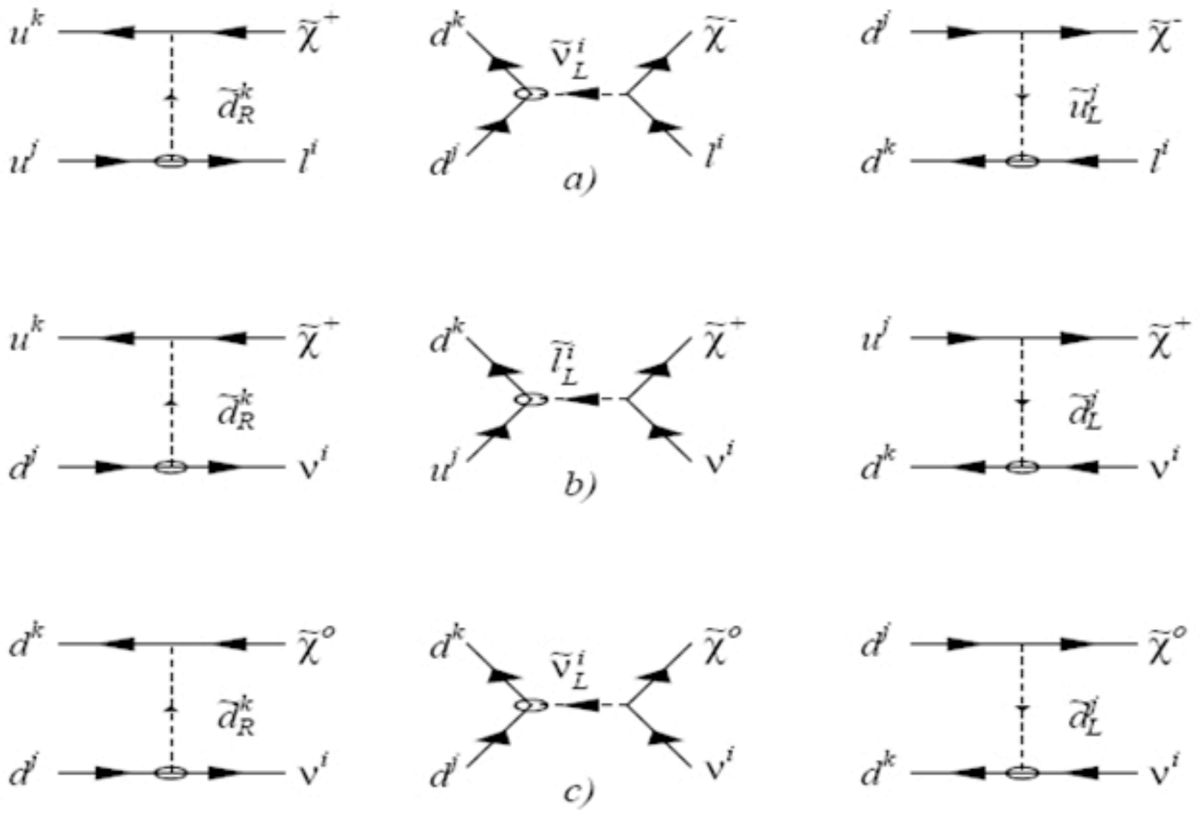
  otherwise: Standard missing energy signature

  $[h_{top} \approx O(1), h_{up} \approx O(10^{-5})]$



Ordinary MSSM neutralino coupling
Neutr. Decays to 3 SM particles

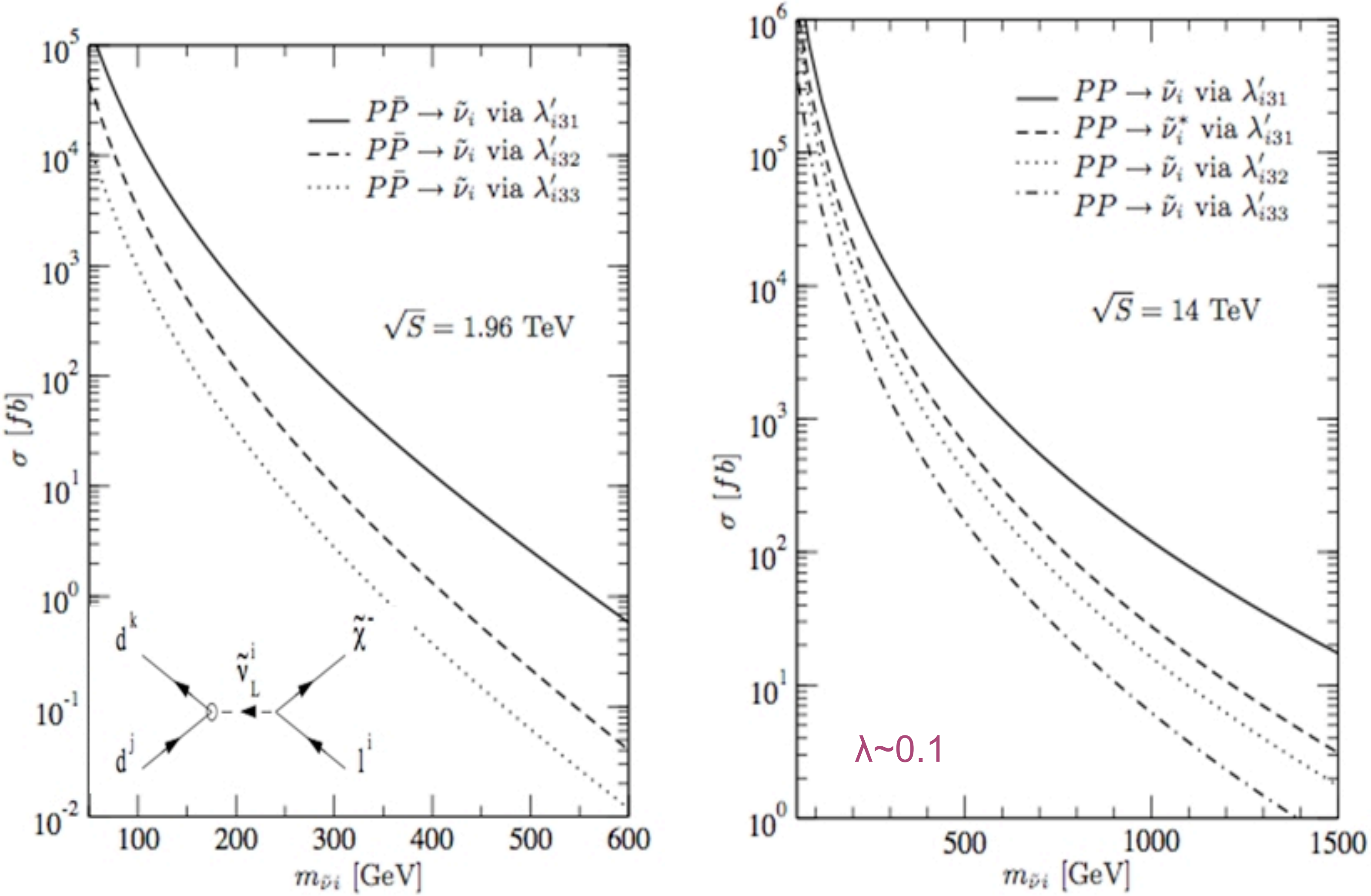
Single Superparticle Productions at Hadron Colliders



(Dimopoulos, Hall, Dreiner, Ross)

Resonant Single Charginos at Hadron Colliders

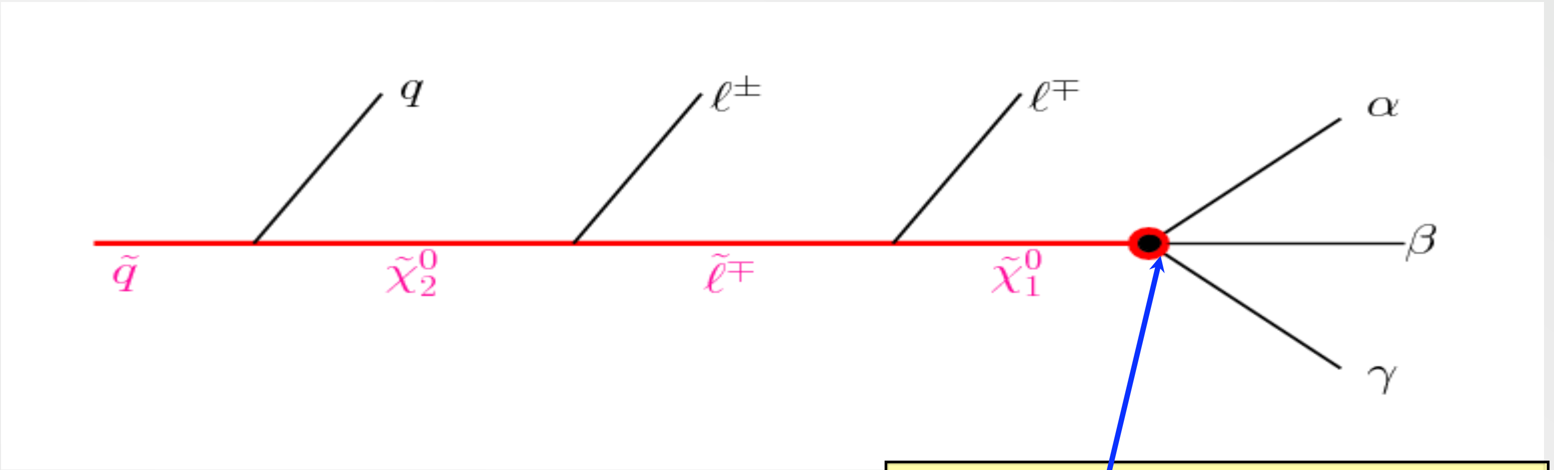
(Chemtob,Moreau,Deliot,Royon,Perez)



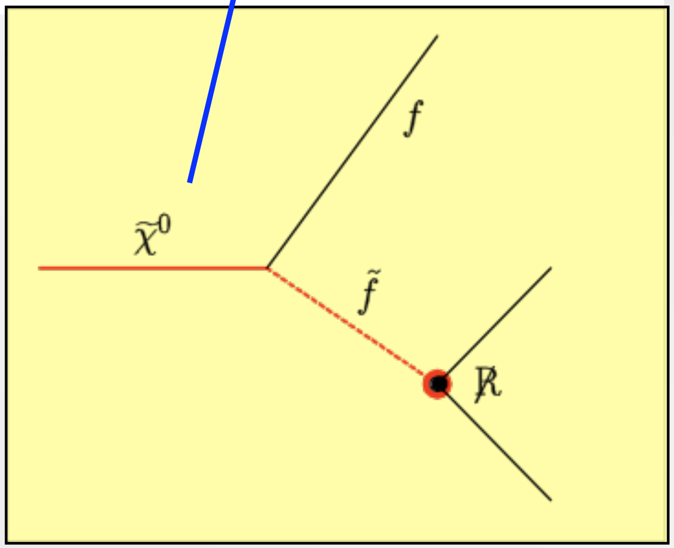
For smaller couplings, Cascade Decays

-Neutralinos couple of ALL (s)fermions

-Simultaneous study of ALL operators in neutralino decays



- Neutralino NLSP
- (Gravitino LSP – for Dark Matter)
- Pair production of squarks and gluinos
- Cascade decay down to neutralino
- Three-body decay of neutralino
- Try to determine operator hierarchies



LLĒ: Final State Structure

- Lots of leptons → easy detection
- Some p_T^{miss} due to neutrinos
- Taus (depends on coupling)

Interesting questions:

- Which couplings dominate?
- What is the Neutralino mass?

Can we determine operator hierarchies?

model	$P_{e^-e^+}$	$P_{e\mu}$	$P_{\mu^-\mu^+}$
LLE231sps1a	0.153	0.827	0.01
LLE231sps1b	0.176	0.804	0.012
LLE231sps6	0.16	0.818	0.0209
LLE121sps1a	0.485	0.504	0.00987
LLE122sps1a	0.00959	0.488	0.503
LLE122sps1b	0.00813	0.494	0.499
LLE123sps1a	0.255	0.45	0.251
LLE123sps1b	0.248	0.512	0.246
LLE131sps1b	0.797	0.181	0.0087
LLE131sps1a	0.829	0.154	0
LLE132sps1a	0.0222	0.835	0.16
LLE133sps1a	0.474	0.419	0.105
LLE133sps1b	0.41	0.469	0.0775
LLE232sps1a	0	0.13	0.835
LLE232sps1b	0	0.165	0.805
LLE233sps1a	0.0959	0.437	0.458
LLE233sps1b	0.0657	0.485	0.421

Bomark, Choudhuri, SL, Osland

$LQ\bar{D}$: Final State Structure

Neutralino $\rightarrow$ lepton + 2 jets, neutrino + 2 jets

Neutralino boosted $\Rightarrow$ jets are close in the detector

- $L_{1,2}Q_{1,2}\bar{D}_3 \Rightarrow$ lepton + b-jet + light jet
- taus $\Rightarrow$ loss of information (momentum) through neutrinos
- $Q_3 \Rightarrow$ only neutrino + 2 jets (at least one b-jet)

ŪĎĎ: Final State Structure

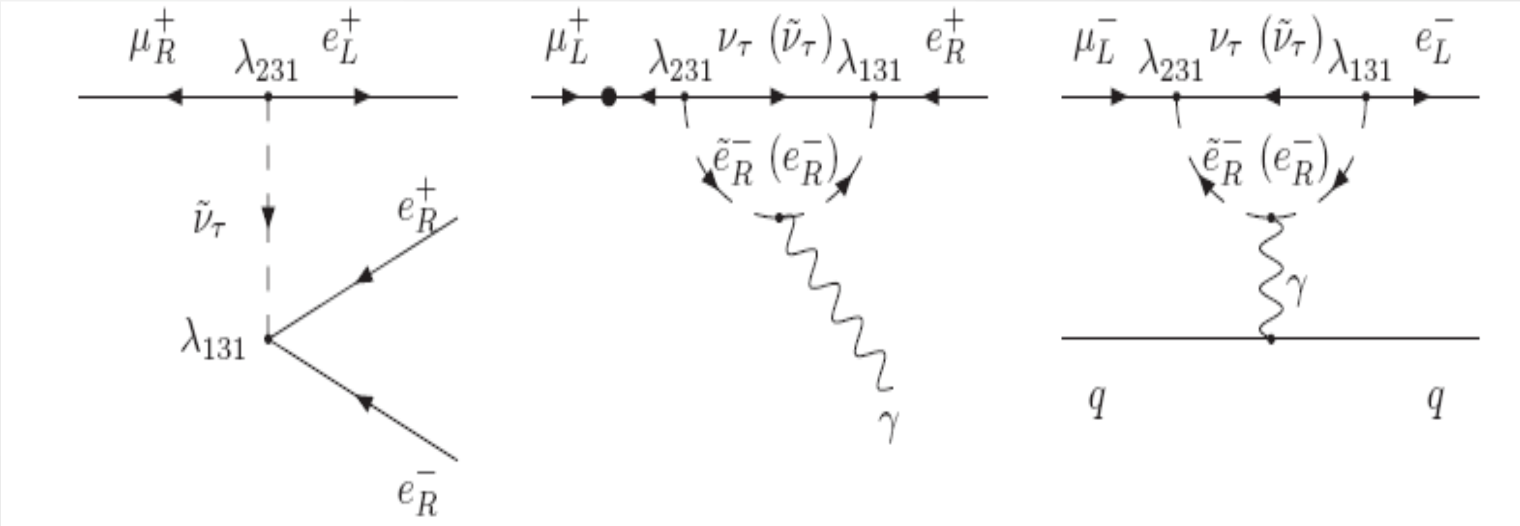
Difficult!

Butterworth, Ellis, Raklev and Salam [hep-ph:0906.0728]:
Jet structure can do the job

b-tagging for studying flavour structure.

$$\text{Exception: } \bar{U}_3 \Rightarrow \begin{cases} M_{\chi_1^0} < M_{top} & \Rightarrow \quad \chi_1^0 \ \textit{escapes} \\ M_{\chi_1^0} > M_{top} & \Rightarrow \quad \chi_1^0 \to t(\bar{t}) + 2\ (\textit{soft})\ \textit{jets} \end{cases}$$

Low Emergy LFV: Correlated Rates depending on coupling combinations (A. de Gouvea, S.L, K. Tobe)

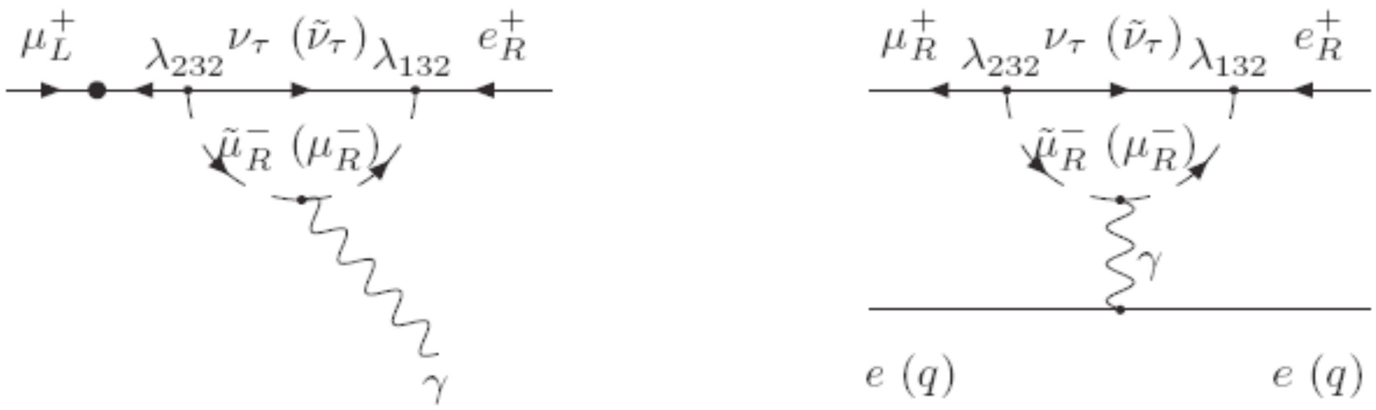


$$\frac{\mathrm{Br}(\mu^+ \to e^+\gamma)}{\mathrm{Br}(\mu^+ \to e^+e^-e^+)} = \frac{4\times 10^{-4}\left(1-\frac{m^2_{\tilde{\nu}_\tau}}{2m^2_{\tilde{e}_R}}\right)^2}{\beta} = 1\times 10^{-4}$$

$$\frac{\mathrm{R}(\mu^- \to e^- \text{ in Ti (Al)})}{\mathrm{Br}(\mu^+ \to e^+e^-e^+)} = 2\ (1) \times 10^{-3}$$

To be compared with ***160*** *and* ***0.92*** *in MSSM*
(where on shell photon penguin dominates)

For all processes at loop level:



$$\frac{\mathrm{Br}(\mu^+ \longrightarrow e^+\gamma)}{\mathrm{Br}(\mu^+ \longrightarrow e^+e^-e^+)} = 1.2$$

$$\frac{\mathrm{R}(\mu^- \longrightarrow e^- \ \text{ in Ti (Al)})}{\mathrm{Br}(\mu^+ \longrightarrow e^+e^-e^+)} = 18$$

PAMELA and Fermi LAT Anomalies

(Bomark,SL,Osland,Raklev)

Coupling	$m_{\tilde{G}}$ [TeV]	λ at best fit	τ [10^{26} s]
λ_{123}	$1.8^{+0.1}_{-0.2}$	7.3×10^{-9}	2.0
λ_{132}	$1.8^{+0.1}_{-0.1}$	6.9×10^{-9}	2.3
λ_{133}	$1.8^{+0.1}_{-0.3}$	8.0×10^{-9}	1.7
λ_{232}	$2.8^{+0.4}_{-0.2}$	1.7×10^{-9}	1.5
λ_{233}	$3.6^{+0.6}_{-0.3}$	8.7×10^{-10}	0.9

X *If the gravitino mass is large enough to account for the anomalies,*

the couplings are too small for detecting R-violation at the LHC

? *If the couplings are indeed tiny,*

particle spectra may provide the only way to probe them

Conclusions

- Possible to reconcile gravitino Dark Matter &

  observable R-violation in colliders
- Interesting Possibilities but also Strong Bounds
- Very distinct signatures (at high AND low energies)
- Results very sensitive to flavour structure of R-violating operators

  3-body neutralino decays enable simultaneous study

  of ALL 45 R-violating couplings

  -LLĒ: precise measurements of flavour structure

  -LQĎ: well-measured for light leptons – τaus more difficult

  -ŪĎĎ: Difficult / b-tagging? / $\bar{U}_3$ an open question

In searching for SUSY and DM

we have to keep an open mind,

making sure we do not overlook

any of their possible manifestations