Gravitino Dark Matter
& Collider Physics
in R-violating SUSY

M. Lola
MEXT-CT-2004-014297

Content

- R-violation: *Motivation & Generic Signatures*
- Bounds on R-violating couplings
- Dark Matter:

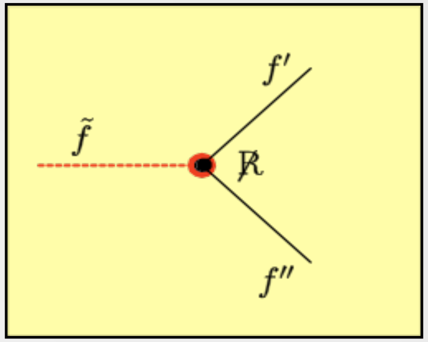
  Is observable R-violation compatible with SUSY DM?
- Experimental Signals *(Collider, low energy LFV, …)*
- Summary

Motivation for R-violating supersymmetry

In addition to couplings generating fermion masses,

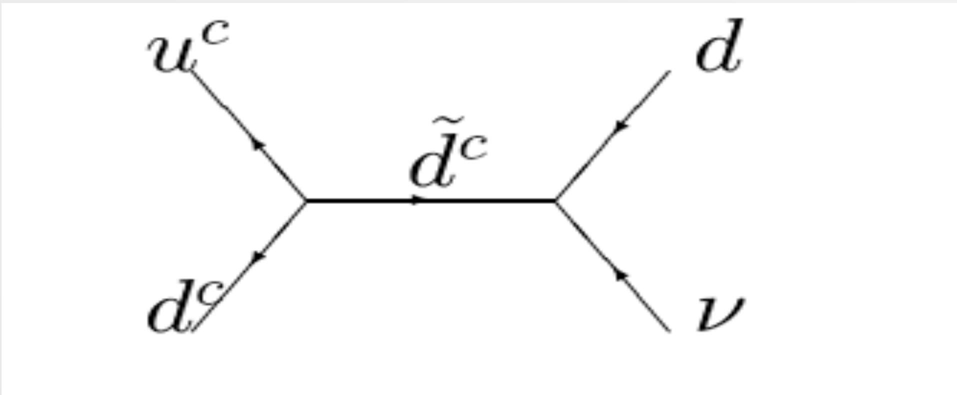
$$h_{ij} L_i H_1 \bar{E}_j \qquad h'_{ij} Q_i H_1 \bar{D}_j \qquad h''_{ij} Q_i H_2 \bar{U}_j$$

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



(in superfield notation: when passing to component fields, terms of the Fermion-Fermion-Scalar type)

- These *violate lepton (L) and baryon (B) number*
- If simultaneously present, <u>unacceptable</u> *p* decay



Ways out:

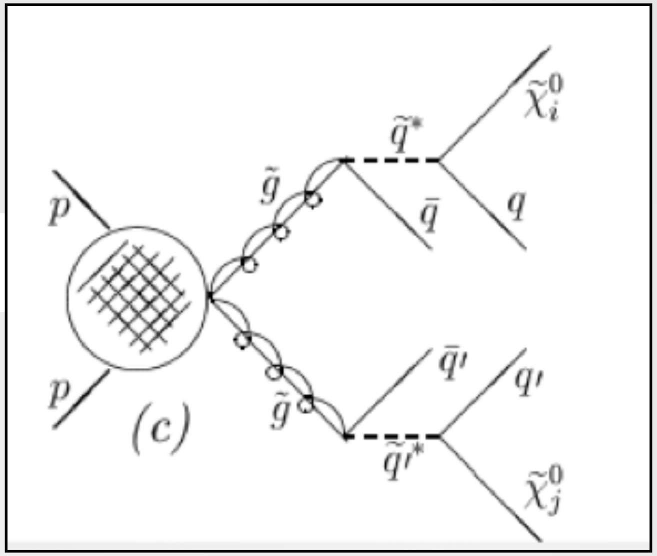
X Either kill all couplings via R-parity *(Fayet)*

(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



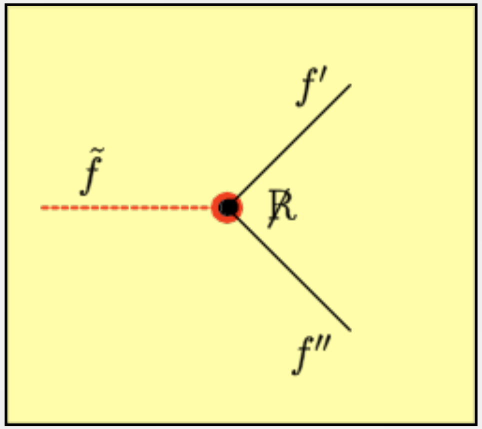
✓ Or allow subsets by baryon / lepton parities

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 the theoretical point of view

Viable models of Baryon and Lepton Parities have been constructed

ex. Baryon + Lepton Parities from
flavour-independent Discrete Z_N Symmetries *(Ibanez, Ross)*

- *Experimental bounds suggest large hierarchies between R-violating operators*

- *Similar hierarchies observed in fermion masses*

How are the two problems related?

Generation of masses AND R-violating couplings through flavour symmetries

$$LL\bar{E}\left(\frac{<\theta>}{M}\right)^n, LQ\bar{D}\left(\frac{<\theta>}{M}\right)^n, \bar{U}\bar{D}\bar{D}\left(\frac{<\theta>}{M}\right)^n$$

where n depends on flavour charges

(Ben-Hamo, Binetruy, Bhattacharyya,Dudas,Ellis, Irges,

Nir, Lavignac, SL, Ramond, Ross, Savoy …)

Some of the earliest refs on R-violation

F. Zwirner, Phys. Lett. B132 (1983) 103

L. Hall and M. Suzuki, Nucl. Phys. B231 (1984) 419

J. Ellis et al, Phys. Lett. B150 (1985) 142

G. Ross and J. Valle, Phys. Lett. B151 (1985) 375

S. Dawson, Nucl. Phys. B261 (1985) 297

R. Barbieri and A. Masiero, Nucl. Phys. B267 (1986) 679

S. Dimopoulos and L.J. Hall, Phys. Lett. B207 (1987) 210

V. Barger, G.F. Giudice, and T. Han, Phys. Rev. D40 (1989) 2987

For a Review, see Barbier et al., hep-ph/0406039 and Refs therein

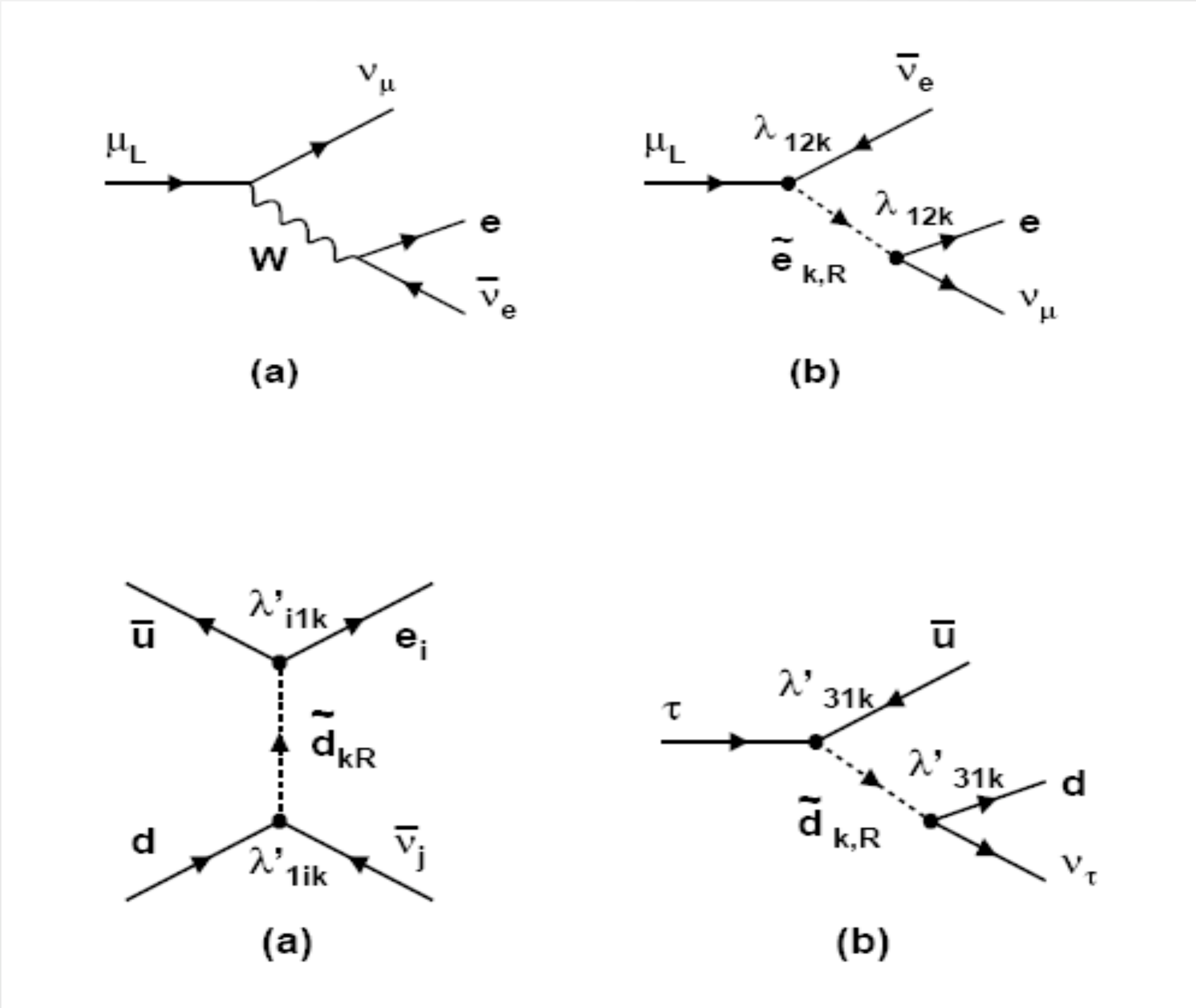
See also Allanach, Dedes & Dreiner, hep-ph/9906209

How large? Flavour-dependent Constraints from unacceptable modifications to SM predictions

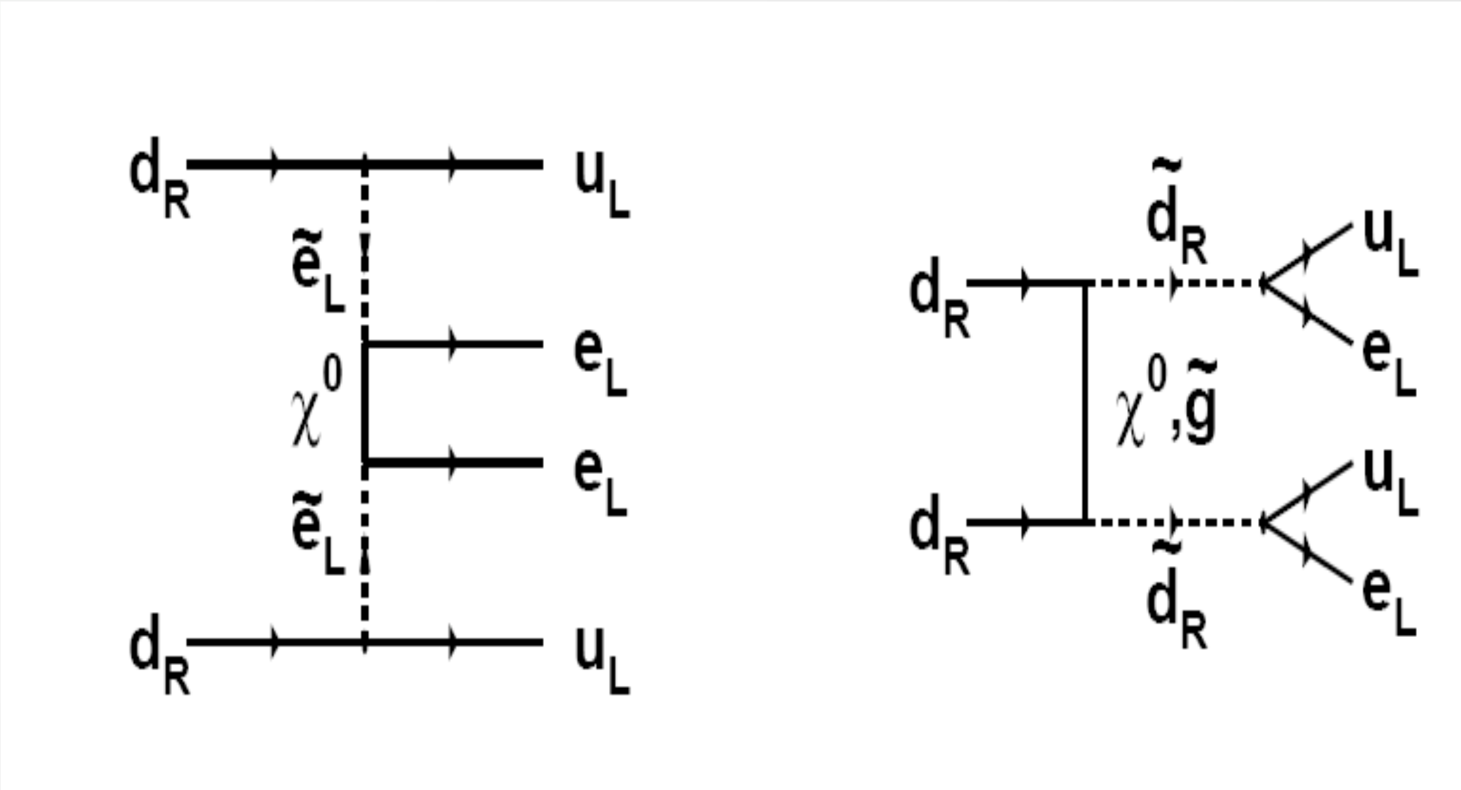
ijk	λ_{ijk}	Sources	ijk	λ''_{ijk}	Sources
121	0.05	CC univ.	112	10^{-6}	Double nucleon dec.
122	0.05	CC univ.	113	10^{-4}	n–$\bar{n}$ osc.
123	0.05	CC univ.	123	1.25	Perturb. unitar.
131	0.06	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$	212	1.25	Perturb. unitar.
132	0.06	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$	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



Neutrinoless Double Beta Decay



Neutrinos in R-violating SUSY

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

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

$$\lambda_{133} \leq 9.4 \times 10^{-4} \left(\frac{<m_\nu>}{0.35\ eV}\right)^{\frac{1}{2}} \left(\frac{\tilde{m}}{100\ GeV}\right)^{\frac{1}{2}}$$

$$\lambda'_{133} \leq 2.1 \times 10^{-4} \left(\frac{<m_\nu>}{0.35\ eV}\right)^{\frac{1}{2}} \left(\frac{4.5\ GeV}{m_b}\right) \left(\frac{\tilde{m}}{100\ GeV}\right)^{\frac{1}{2}}$$

Gravitino DM in R-violating supersymmetry?

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

-The lighter the gravitino, the longer the lifetime

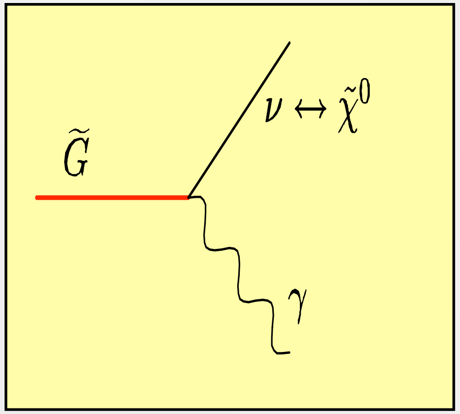
Question: *can gravitinos be DM even with broken R-parity?*

*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)

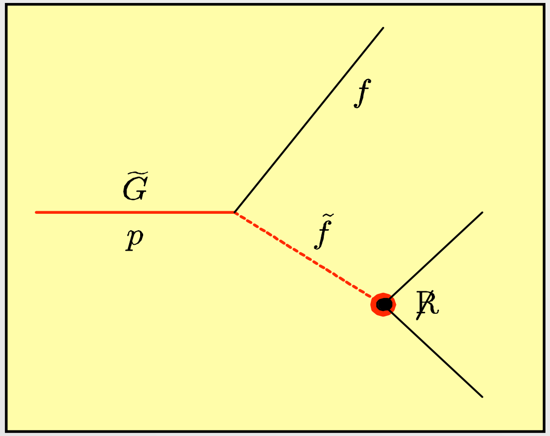


Suppressed by:

- Gravitino vertex (~1/Mp)

-Neutralino-neutrino mixing
 (model dependent)

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



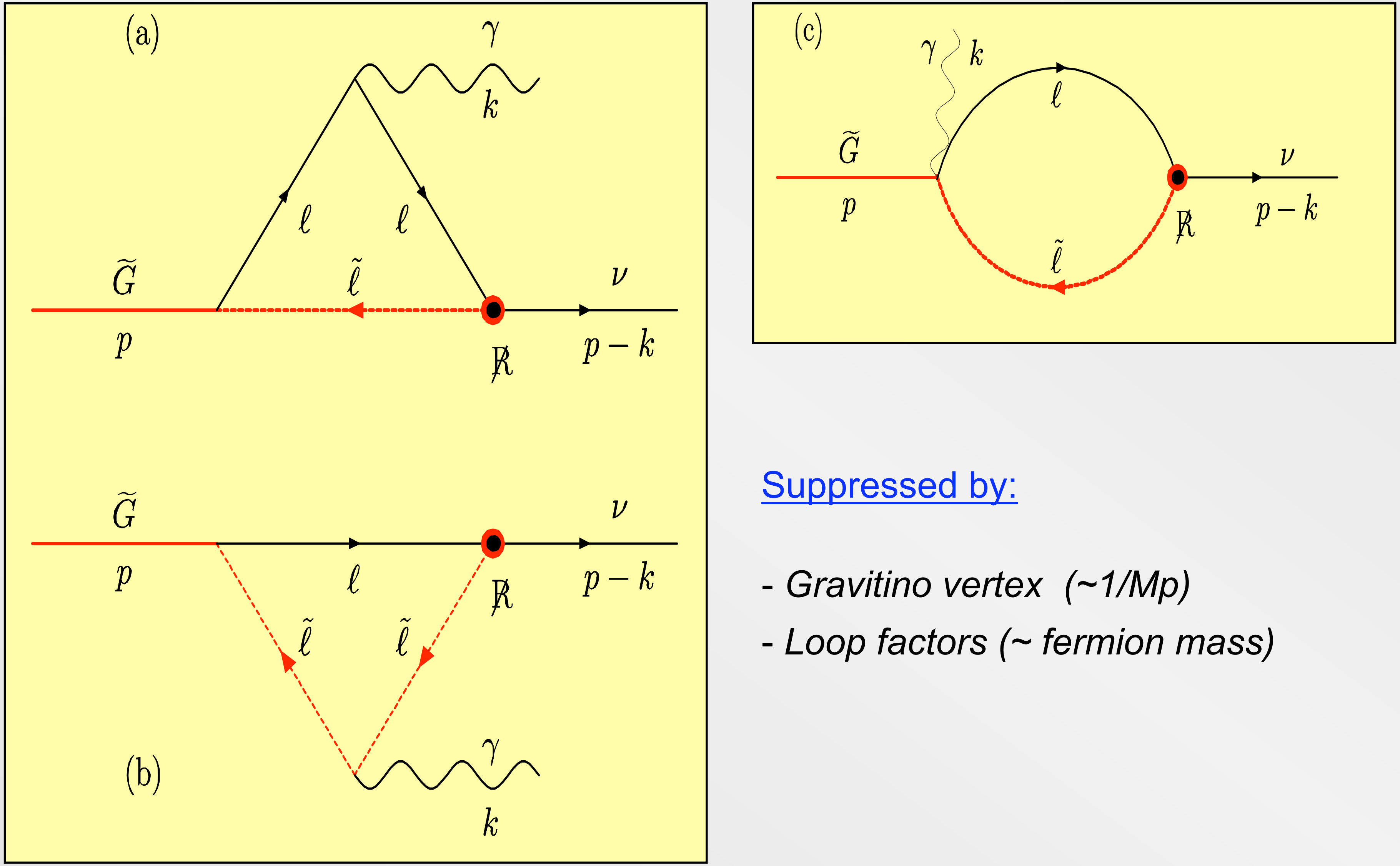
Suppressed by:

- Gravitino vertex (~1/Mp)

-Phase space / fermion masses
 (for light gravitino and heavy fermions)

Radiative 2-body trilinear R-violating decays

(SL, Osland, 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

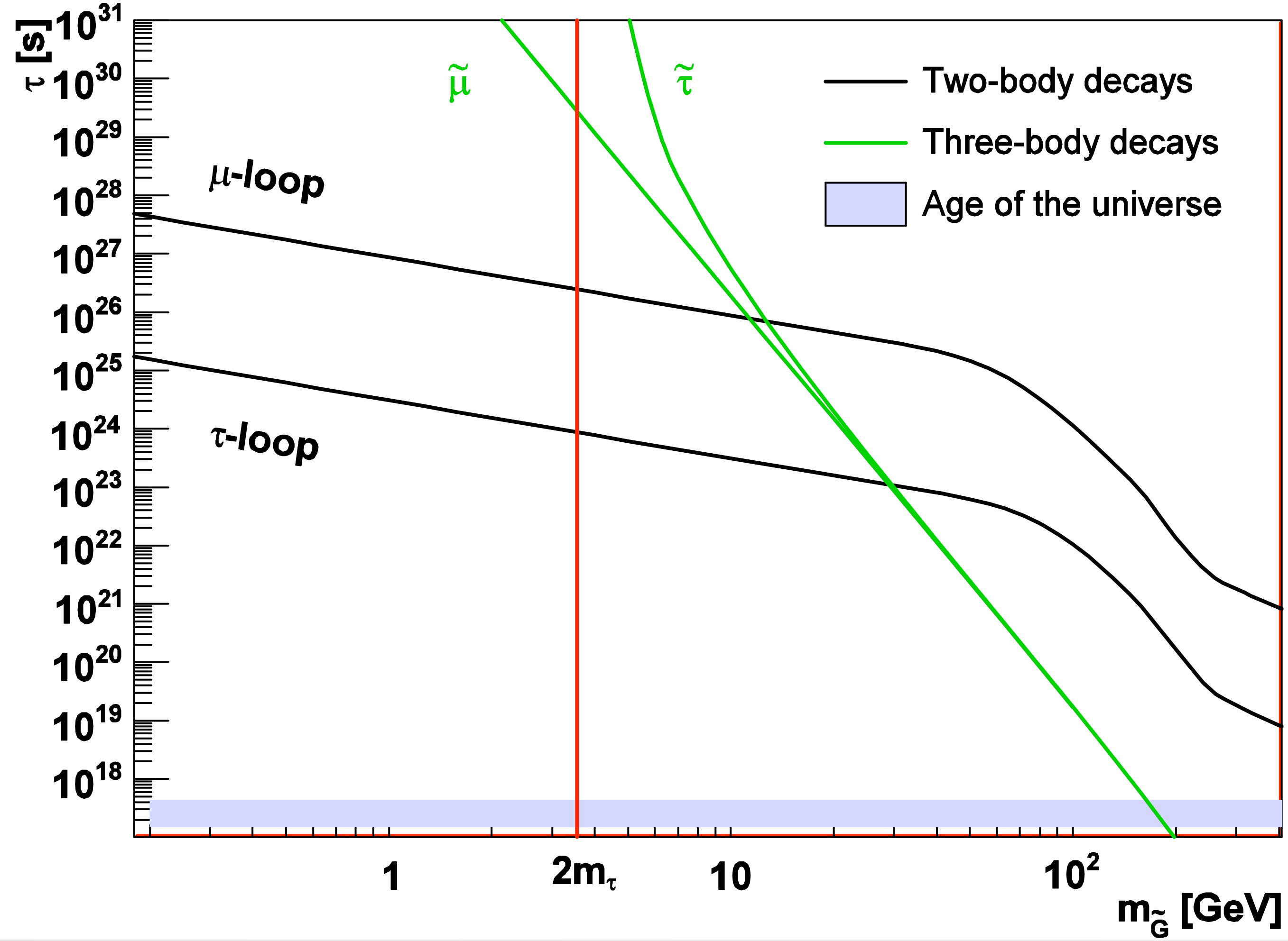
Large gravitino lifetime (can be DM), due to:

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

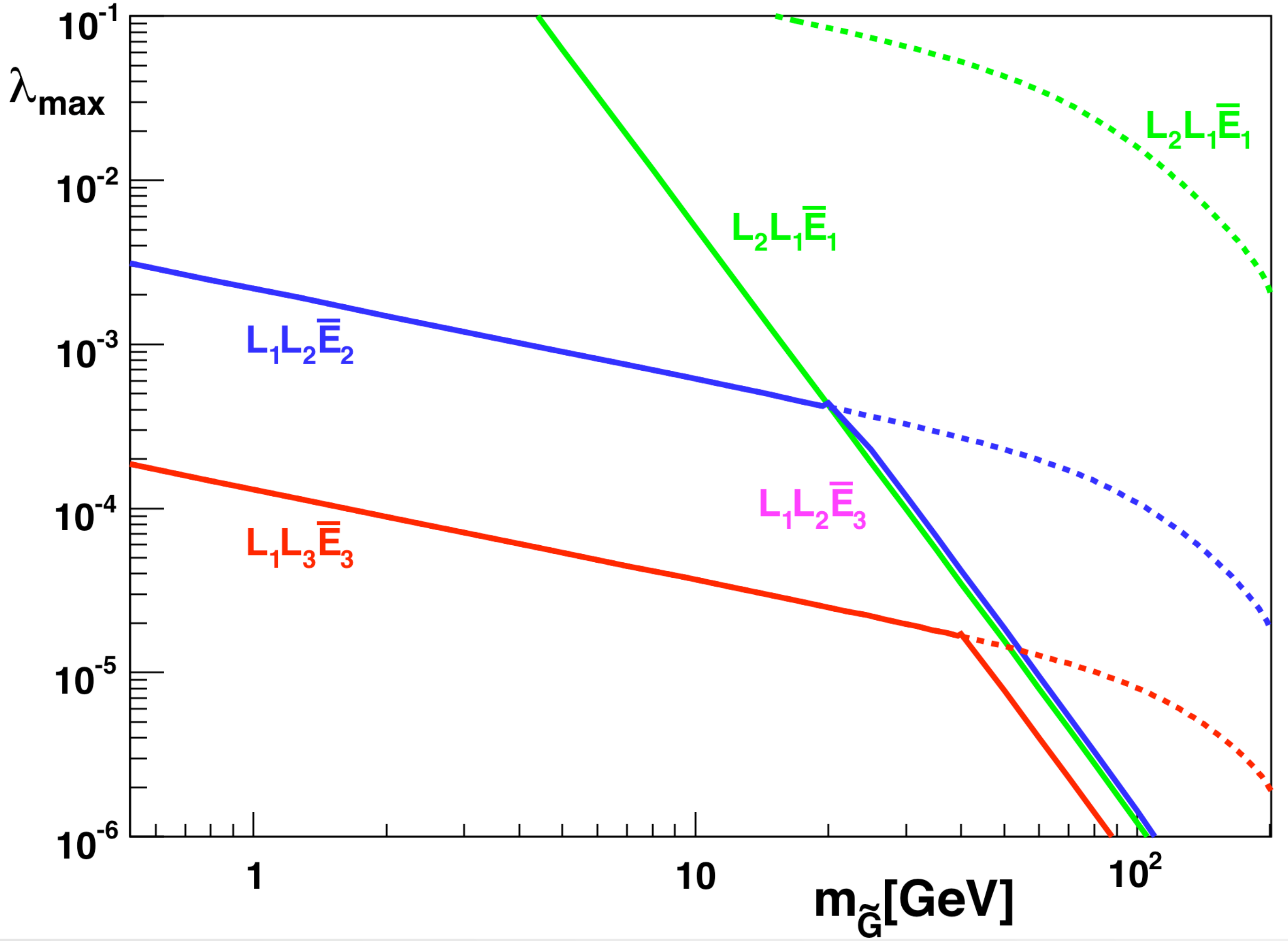
$$\bar{U}_3 \bar{D}_j \bar{D}_k$$

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

Radiative versus 3-body decays



Max allowed couplings from DM & Photon Spectra



Rapid 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

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 without missing Energy)

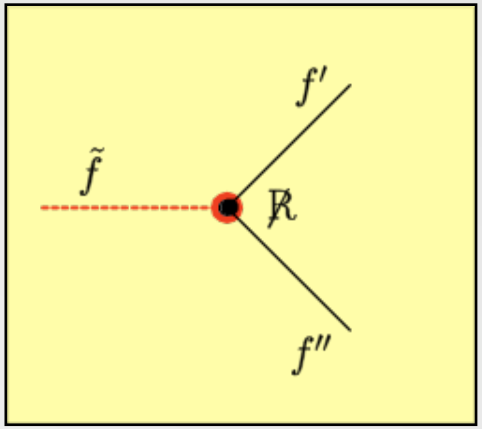
More detailed analysis (sophisticated jet clustering algorithms)

required for detecting ΔB operators

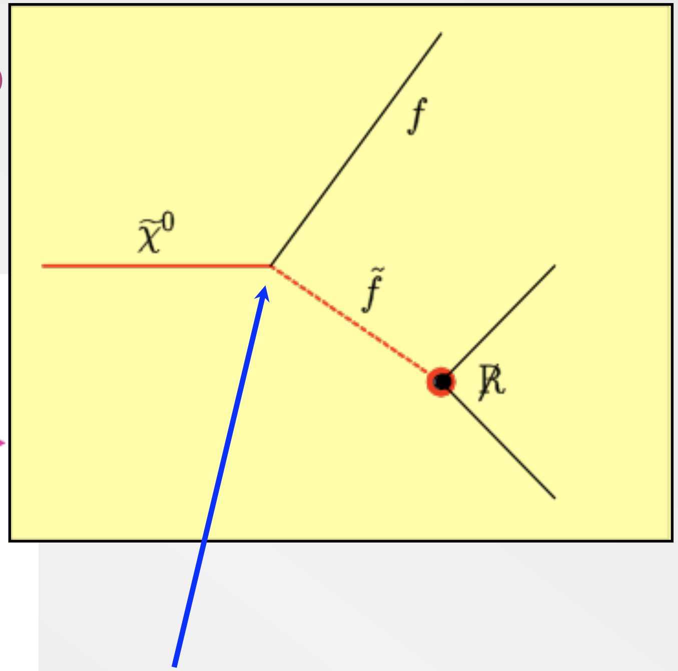
(Butterworth,Ellis, Raklev, Salam)

Possible Signals

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



- Single sparticle productions possible for large Rp
- Otherwise MSSM productions, and Rp decays



- (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

…keeping in mind the constraints

Fermion mixing $\Rightarrow$ mixing of different operators

$\Rightarrow$ Correlations of experimental bounds

that depend on flavour charges

…and even more constraints in given models

- Strong constraints on products of couplings ie:

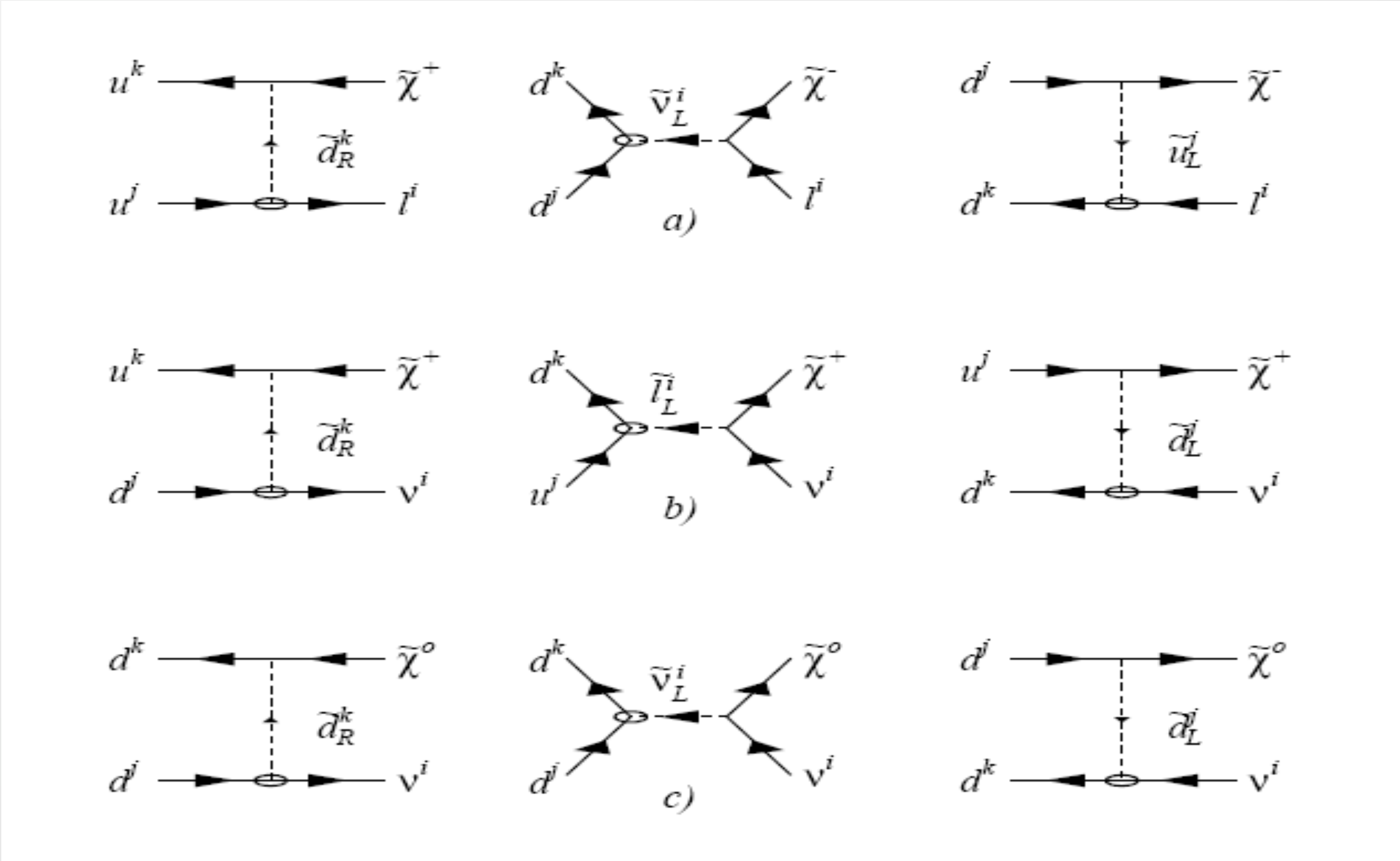
$$\lambda'_{i13}\lambda'_{i31} \leq 3.2 \cdot 10^{-7}$$
$$\lambda'_{i12}\lambda'_{i21} \leq 4 \cdot 10^{-9}$$

(+) Symmetric quark matrices $\Rightarrow$

$$\lambda'_{i13} \leq 6 \cdot 10^{-4}$$
$$\lambda'_{i12} \leq 6 \cdot 10^{-5}$$

(also for couplings with $j \leftrightarrow k$)

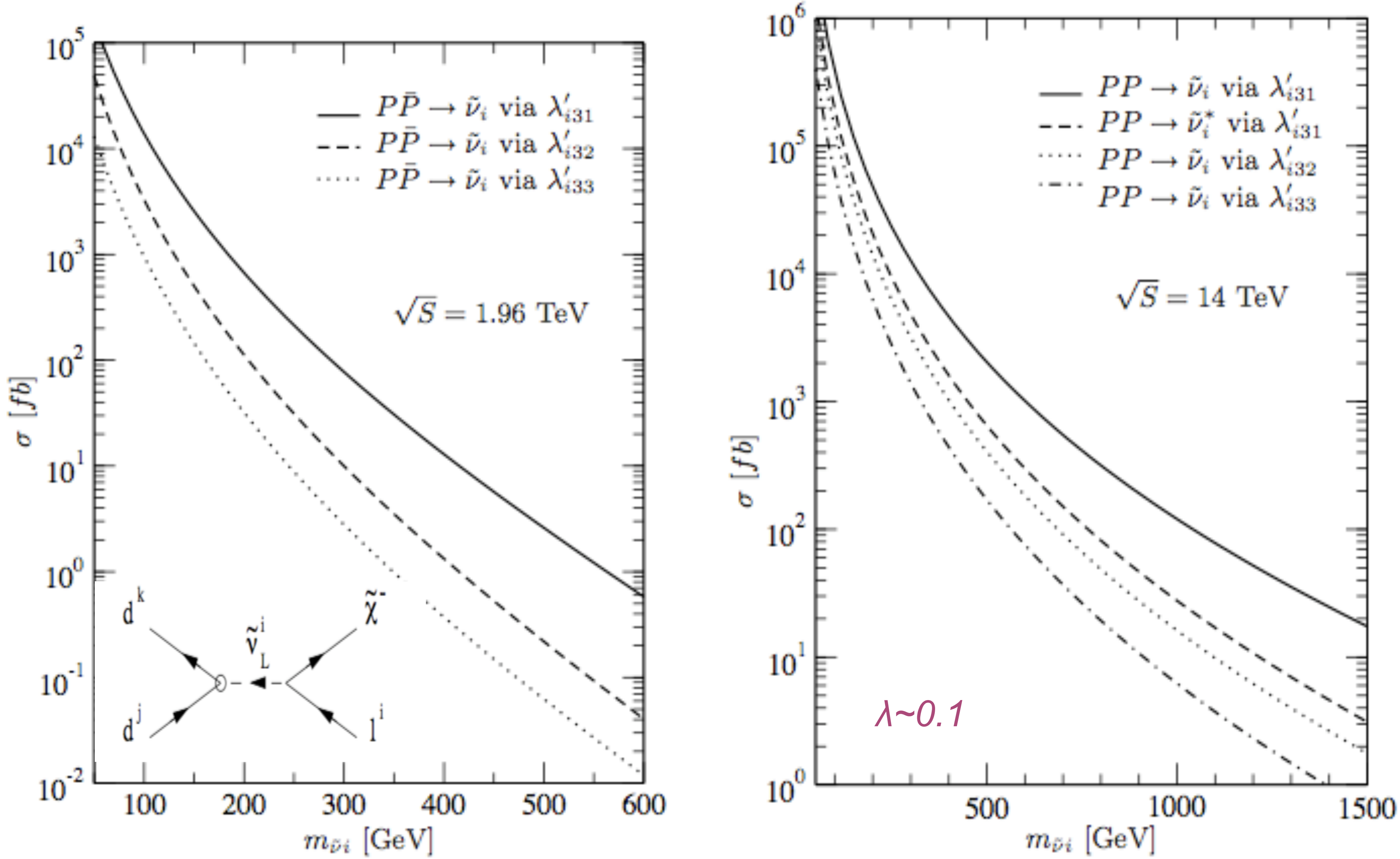
Single Superparticle Productions at Hadron Colliders



(Dimopoulos, Hall, Dreiner, Ross)

Resonant Single Charginos at Hadron Colliders

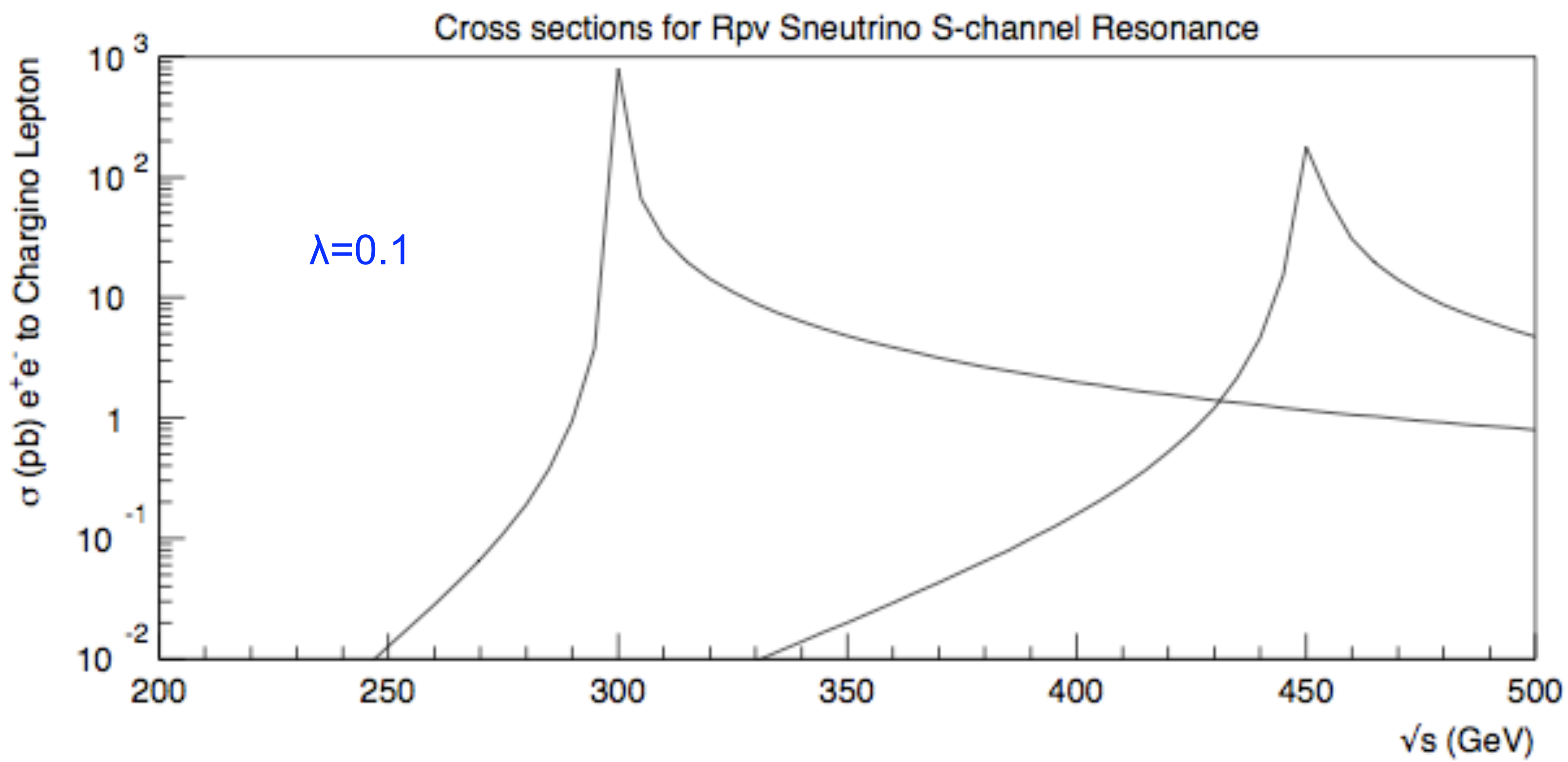
(Chemtob,Moreau,Deliot,Royon,Perez)



Single sleptons at e+e- Colliders (Dreiner,SL)

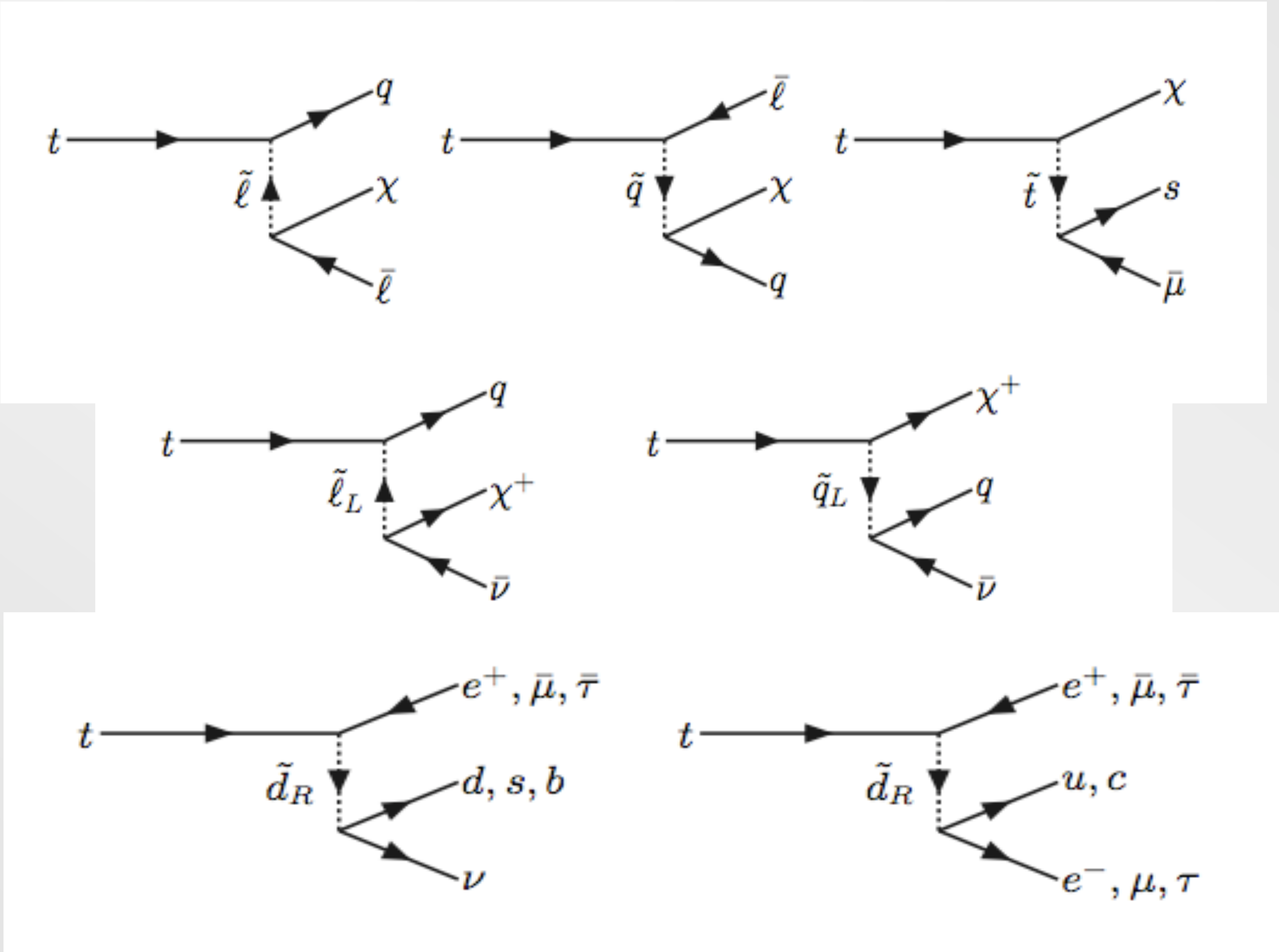
$$e^+e^- \to (\tilde{\nu})^* \to f\bar{f}' \quad \text{and} \quad e^+e^- \to (\tilde{\nu})^* \to \left\{ \begin{array}{l} \ell_i^\pm\, \tilde{\chi}^\mp \\ \nu_i\, \tilde{\chi}^0 \end{array} \right.$$

$$\to \quad \frac{8\pi}{m_{\tilde{\nu}}^2} B(\tilde{\nu} \to f\bar{f}) B(\tilde{\nu} \to \nu\tilde{\chi}^0)\ ,\ \text{as}\ s \to m_{\tilde{\nu}}^2$$

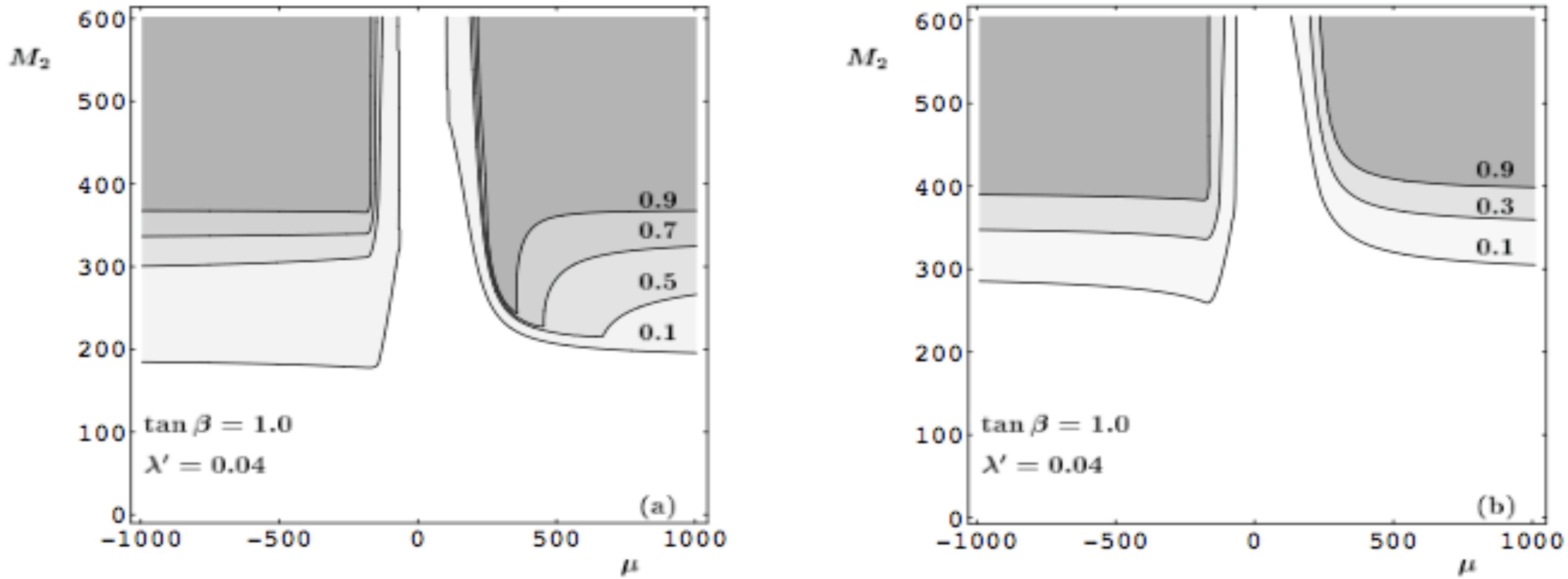


Rare Top Decays

(Belyaev, Ellis, SL)



Cancellation effects in LH - squark decays *(Altarelli,Ellis,Guidice,SL,Mangano)*



Due to cancellations,larger area where
Rp-violating decay of squarks to fermions dominates

$$\Gamma(\tilde{c}_L \to c\chi_i^0) = \frac{g^2}{32\pi}(A_i^2 + B_i^2)\, m_{\tilde{c}_L} \left(1 - \frac{m^2_{\chi_i^0}}{m^2_{\tilde{c}_L}}\right)^2$$

$$A_i = \frac{m_c N_{i4}}{M_W \sin\beta}, \quad B_i = N_{i2} + \frac{1}{3}\tan\theta_W N_{i1}\ .$$

$$\Gamma(\tilde{c}_L \to e^+ d) = \frac{1}{16\pi}(\lambda'_{121})^2 m_{\tilde{c}_L}$$

LFV IN RARE DECAYS AND CONVERSIONS

In SM extensions with $\Delta L_i \neq 0$, non-zero rates for processes such as:

$$\mu \longrightarrow e\gamma$$

$$\tau \longrightarrow \mu\gamma$$

$\mu - e$ conversion on nuclei

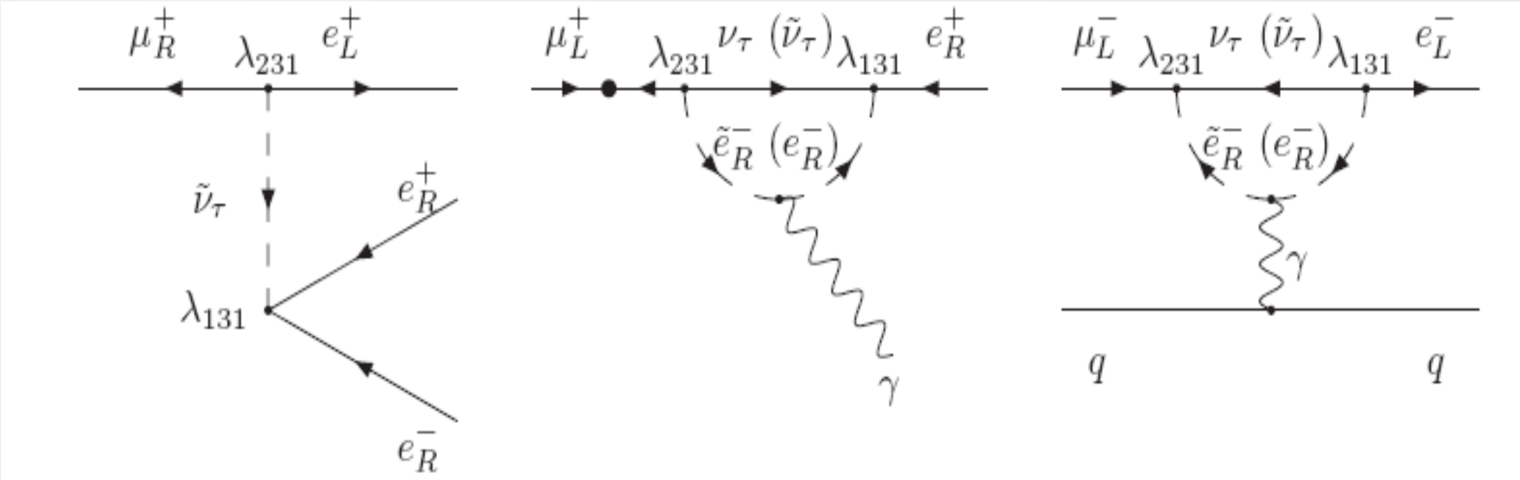
Very good expected future BR sensitivities:

$\mu \rightarrow e\gamma$	10^{-14}
$\mu^- Ti \rightarrow e^- Ti$	10^{-18}

Entirely different in MSSM & R-violation:

Correlated Rates depending on coupling combinations

(A. de Gouvea, S.L, K. Tobe)

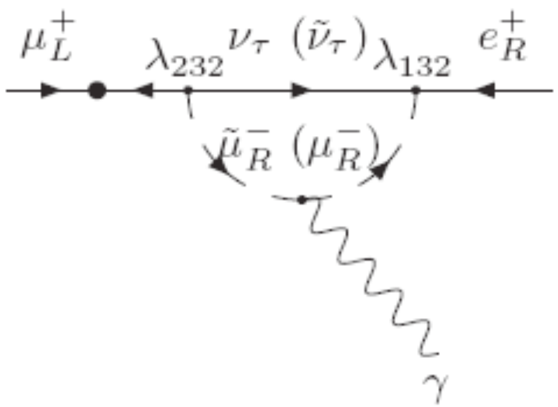


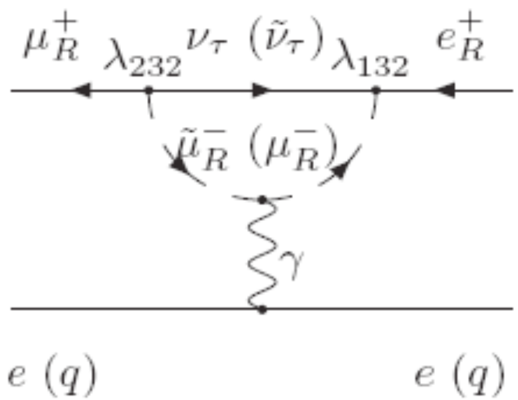
$$\frac{\mathrm{Br}(\mu^+ \to e^+\gamma)}{\mathrm{Br}(\mu^+ \to e^+e^-e^+)} = \frac{4 \times 10^{-4}\left(1 - \frac{m_{\tilde{\nu}_\tau}^2}{2m_{\tilde{e}_R}^2}\right)^2}{\beta} = 1 \times 10^{-4}$$

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

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

For all processes at loop level:

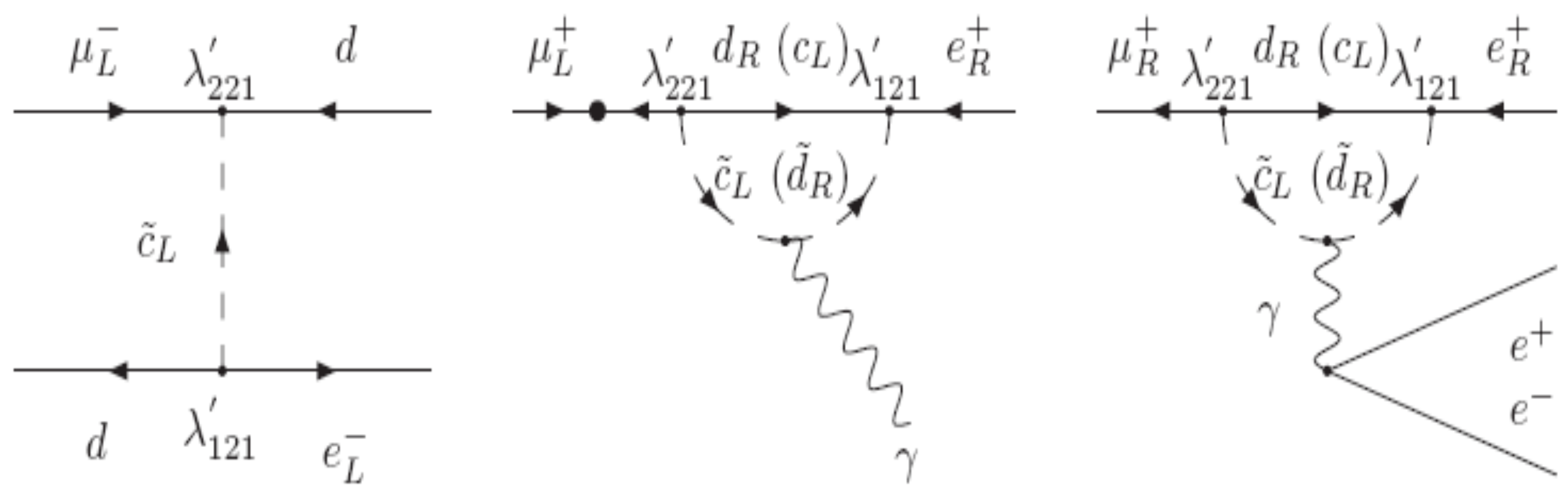




$$\frac{\mathrm{Br}(\mu^+ \to e^+\gamma)}{\mathrm{Br}(\mu^+ \to e^+e^-e^+)} = 1.2$$

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

For:



$$
\frac{\mathrm{Br}(\mu^+ \to e^+\gamma)}{\mathrm{Br}(\mu^+ \to e^+e^-e^+)} = 1.1,
$$

$$
\frac{\mathrm{R}(\mu^- \to e^- \text{ in Ti (Al)})}{\mathrm{Br}(\mu^+ \to e^+e^-e^+)} = 2\ (1) \times 10^5
$$

Distinct differences in LFV predictions between

(i) MSSM & R-violation

(ii) different combinations of (dominant) R-violating couplings

Conclusions

- ✓ R-violating SUSY equally motivated with MSSM
- ✓ Interesting Collider signals but also strong bounds
- ✓ Possible to have both gravitino DM **AND** observable R-violation in colliders
- ✓ Distinct differences in LFV predictions between MSSM & R-violation
- ✓ Results sensitive to flavour structure of R-violating operators

In SUSY searches, we have to make sure that we do not overlook any of its possible manifestations