R-Parity Violating Supersymmetry & Long-Lived Sparticles @ LHC

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What is R-Parity & Why We Should Care

The non-gauge interactions of the (chiral) (s)fermions and Higgs(inos) are governed by the superpotential:

$$W = W_{RPC} + W_{RPV}$$

whose structure is determined by gauge invariance and renormalizability requirements…

$$W_{RPC} = y_e H_d L E^c + y_d H_d Q D^c + y_u H_u Q U^c + \mu H_d H_u$$

is responsible for genenerating the SM fermion masses with the y_i being the familiar Yukawa couplings (Note: here I will suppress generational indices throughout)

However, the second term is also present and is potentially dangerous:

$$W_{RPV} = \lambda LLE^c + \lambda' LQD^c + \lambda'' UDD^c + \kappa H_u L$$

Here the first 2 trilinear terms and the bilinear term are ΔL=1 and the third term is ΔB=1, leading to rapid proton decay if all are present *simultaneously*… (Due to very strong constraints we will ignore the bilinear terms.)

$$\mathscr{L}_{L_iL_jE_k^c} = -\frac{1}{2}\lambda_{ijk}(\tilde{\nu}_{iL}\bar{l}_{kR}l_{jL} + \tilde{l}_{jL}\bar{l}_{kR}\nu_{iL} + \tilde{l}^*_{kR}\bar{\nu}^c_{iR}l_{jL} - (i \leftrightarrow j)) + \text{h.c.}\,,$$

$$\mathscr{L}_{L_iQ_jD_k^c} = -\lambda'_{ijk}(\tilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \tilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \tilde{d}^*_{kR}\bar{\nu}^c_{iR}d_{jL} - \tilde{l}_{iL}\bar{d}_{kR}u_{jL} - \tilde{u}_{jL}\bar{d}_{kR}l_{iL} - \tilde{d}^*_{kR}\bar{l}^c_{iR}u_{jL}) + \text{h.c.}\,,$$

etc.

In the usual MSSM, one imposes the familiar R-parity symmetry:

$$R = (-1)^{3B+L+2S} = (-1)^{3(B-L)+2S}$$

which removes these dangerous terms completely.

Note the obvious direct connection to B- and L-numbers as well as the particle's spin.

However…

It is important to note that it is *not* necessary to impose R-parity to remove these L- and B-violating terms.

For example, it was shown long ago that the existence of almost any additional (e.g., GUT-based) gauge symmetry, such as an extra U(1) or SU(2), will kill these couplings at tree-level and in many cases to all orders depending on model details.

We will not discuss this possibility here.

Under R-parity symmetry the SM fields are even while their spartners are odd…this implies the familiar results:

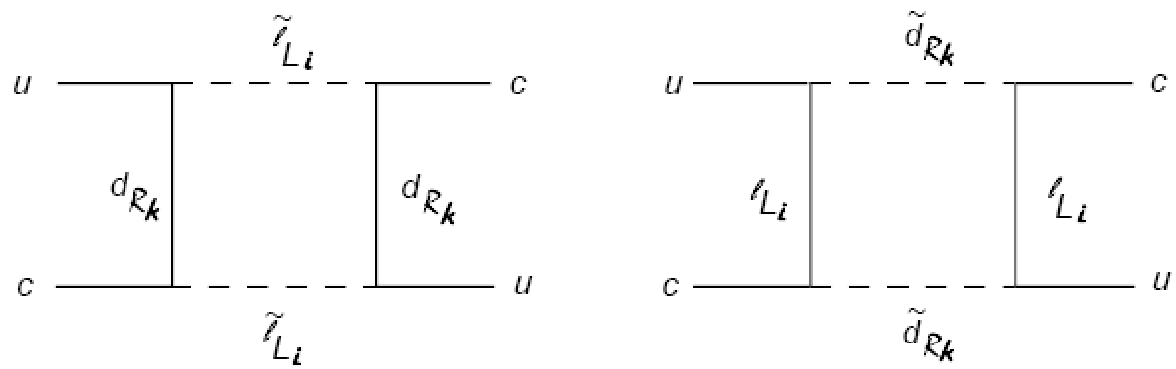
- SUSY particles can only be pair produced
- The LSP is stable and leads to MET final states
- The LSP can be a good DM candidate, e.g., the lightest neutralino in the MSSM

Of course this may be too strict and we can invent other parities that only remove the only the offending B- *or* the offending L-violating terms in the superpotential.

The phenomenology then depends upon the sizes of the various λ's… However, once these are > ~$O(10^{-22})$ there will be *no* MSSM DM! Furthermore, to avoid disruption of nucleosynthesis we need λ's > ~$O(10^{-13})$; of course even these numbers depend upon the identity of the (unstable) LSP.

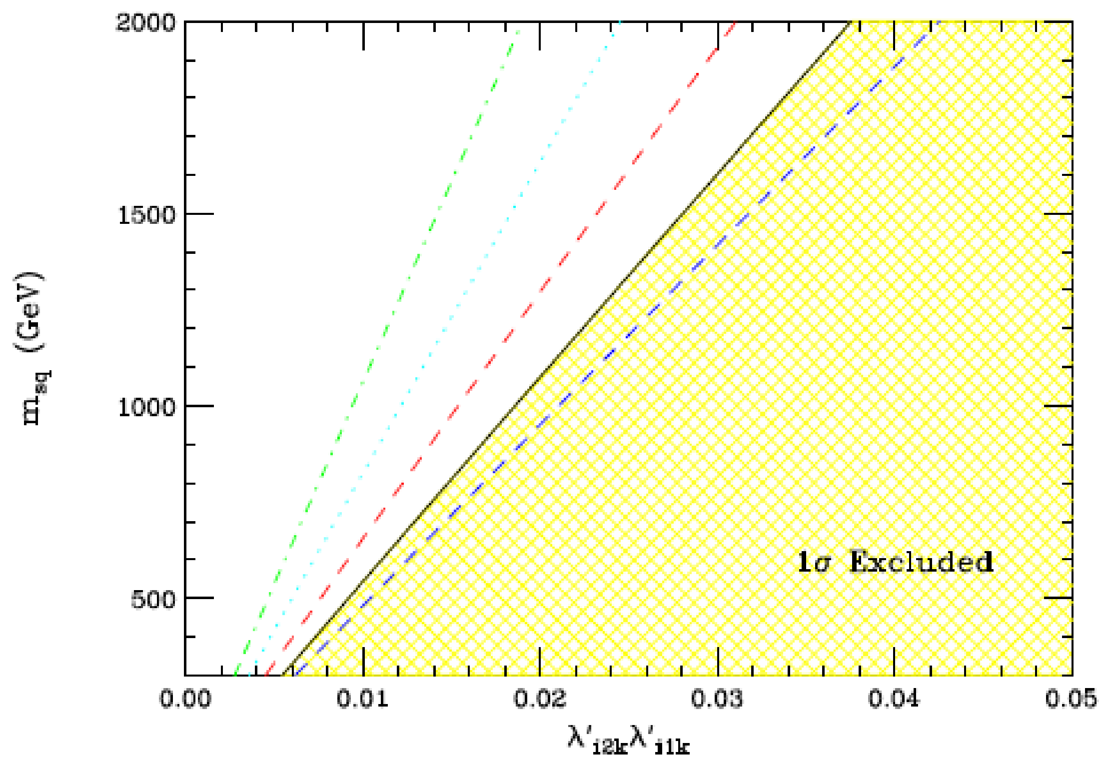
Remembering the generational indices, it is clear that the possible values of the λ's are restricted by, e.g., low energy data, usually under the assumption that only one or two of them are non-zero or dominant… *

As one example, consider D-Dbar mixing:



which can go through either λ' or λ'' couplings, and is now restricted by recent BaBar/BELLE data…

*Barbier etal, Phys Rep 420 1 2005



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Of course there are *many* other constraints. These are usually quoted assuming spartner masses of 100 GeV and scale as (100 GeV/m) for single couplings. They are all rather weak for heavier spartner masses and particularly so for couplings involving the third generation…

*** Golowich etal, arXiv:0705.3650**

CKM unitarity

τ universality

$b \to \tau$

	Charged current	Neutral current	Other processes
λ_{12k}	$0.05\ \tilde{e}_{kR}\ [V_{ud}]$ (6.25) $0.07\ \tilde{e}_{kR}[R_{\mu\pi}]$ (6.14)	$0.14\tilde{e}_{kR}\ [\nu_\mu e]$ (6.35) $0.13\tilde{e}_{k=1L}\ [\nu_\mu e]$ (6.35) $[0.37,\ 0.25,\ 0.11]\tilde{\nu}$ $k = 1, 2, 3\ [A_{FB}]$ (6.39) $0.05\ \tilde{e}_{kR}\ [Q_W(Cs)]$ (6.47) $0.13\ \tilde{e}_{kR}\ [\nu_\mu q]$(6.36)	
λ_{13k}	$0.07\ \tilde{e}_{kR}\ [R_\tau]$ (6.17)	$[0.37,\ 0.25,\ 0.11]\tilde{\nu}$ $k = 1, 2, 3\ [A_{FB}]$ (6.39)	
λ_{23k}	$0.07\ \tilde{e}_{kR}\ [R_\tau]$ (6.17) $0.07\ \tilde{e}_{kR}\ [R_{\tau\mu}]$ (6.17)	$0.11\ \tilde{\tau}_L\ [\nu_\mu e]$ (6.35) $k = 1$	
λ_{233}			$0.90\ [RG]$
λ_{i22}			$2.7 \times 10^{-2}\ \tilde{\mu}\tilde{m}^{-1/2}\ [m_\nu < 1\ eV]$ $(\tilde{m}^{e2}_{LR22} = \tilde{m} m_\mu)$ (5.11)
λ_{i33}			$1.6 \times 10^{-3}\ \tilde{\tau}\tilde{m}^{-1/2}\ [m_\nu < 1\ eV]$ $(\tilde{m}^{e\,2}_{LR33} = \tilde{m} m_\tau)$ (5.11)
λ'_{11k}	$0.02\ \tilde{d}_{kR}\ [V_{ud}]$ (6.25) $0.03\ \tilde{d}_{kR}\ [R_\pi]$ (6.19)	$[0.28, 0.18]\ \tilde{u}_L$ $k = 2, 3\ [A_{FB}]$ (6.39) $0.02\tilde{d}_{kR}\ [Q_W(Cs)]$(6.47)	
λ'_{111}			$3.3 \times 10^{-4}\ \tilde{q}^2 \tilde{g}^{1/2}\ [\beta\beta 0\nu]$ (6.106)
λ'_{12k}	$0.44\ \tilde{d}_{kR}[R_{D^+}]$ (6.27) $0.27\ \tilde{d}_{kR}[R_{D^0}]$ (6.27) $0.23\ \tilde{d}_{kR}[R^*_{D^+}]$ (6.27)	$0.21\ \tilde{d}_{kR}\ [A_{FB}]$ (6.39) $[0.28,\ 0.18]\ \tilde{c}_L$ $k = 2, 3\ [A_{FB}]$ (6.39)	
λ'_{13k}		$[0.28,\ 0.18]\ \tilde{t}_L$ $k = 2, 3\ [A_{FB}]$ (6.39) $0.47\ [R_e]$ (6.40) $(m(\tilde{d}_{kR}) = 100\ GeV)$	
λ'_{1j1}		$0.03\ \tilde{u}_{jL}\ [Q_W(Cs)]$ (6.47)	
λ'_{2j1}		$0.18\ \tilde{d}_{jL}\ [\nu_\mu q]$ (6.36)	
λ'_{21k}	$0.06\ \tilde{d}_{kR}\ [R_\pi]$ (6.19) $0.08\ \tilde{d}_{kR}\ [R_{\tau\pi}]$(6.21)	$0.15\ \tilde{d}_{kR}\ [\nu_\mu q]$ (6.36)	
λ'_{22k}	$0.61\ \tilde{d}_{kR}[R_{D^+}]$ (6.27) $0.38 d_{kR}\ [R^*_{D^+}]$ (6.27) $0.21\ \tilde{d}_{kR}\ [R_{D^0}]$ (6.27) $0.65\ \tilde{d}_{kR}[R_{D_s}(\tau\mu)]$ (6.30)		
λ'_{23k}		$0.45\ [R_\mu]$ (6.40) $(m_{\tilde{d}_{kR}} = 100\ GeV)$	
λ'_{31k}	$0.12\ \tilde{d}_{kR}\ [R_{\tau\pi}]$ (6.21)		
λ'_{32k}	$0.52\ \tilde{d}_{kR}\ [R_{D_s}(\tau\mu)]$ (6.30)		
λ'_{33k}		$0.58\ [R_\tau]$ (6.40) $(m_{\tilde{d}_{kR}} = 100\ GeV)$	
λ'_{333}	$0.32\ \tilde{b}_R\ [B \to \tau\nu X]$ (6.28)		$1.06\ [RG]$
λ'_{i11}			$0.2\ \tilde{d}\tilde{m}^{-1/2}\ [m_\nu < 1\ eV]$ $(\tilde{m}^{d\,2}_{LR11} = \tilde{m} m_d)$ (5.12)

These constraints arise from many places

	Charged current	Neutral current	Other processes
λ'_{122}			$10^{-2}\,\tilde{s}\tilde{m}^{-1/2}$ $[m_\nu < 1\ \mathrm{eV}]$ $(\tilde{m}^{d\,2}_{LR22} = \tilde{m} m_s)$ (5.12)
λ'_{133}			$4 \times 10^{-4}\,\tilde{b}\tilde{m}^{-1/2}$ $[m_\nu < 1\ \mathrm{eV}]$ $(\tilde{m}^{d\,2}_{LR33} = \tilde{m} m_b)$ (5.12)
λ''_{11k}			$(10^{-8}\text{–}10^{-7})(10^{8}\mathrm{s}/\tau_{osc})\tilde{m}^{5/2}$ $[n\bar{n}]$ (6.128)
λ''_{112}			10^{-6} $[NN]$ $(\tilde{m} = 300\ \mathrm{GeV})$ (6.131) $6 \times 10^{-17}\,\tilde{s}^2_R\,(m_{3/2}/1\ \mathrm{eV})$ $[p \to K^+\tilde{G}]$ (6.121) $8 \times 10^{-17}\,C_q^{-1}\,\tilde{s}^2_R\,(F_a/10^{10}\ \mathrm{GeV})$ $[p \to K^+\tilde{a}]$ (6.122)
λ''_{113}			10^{-3} $[NN]$ $(\tilde{m} = 300\ \mathrm{GeV})$ (6.131)
λ''_{123}			1.25 $[RG]$
λ''_{212}			1.25 $[RG]$
λ''_{213}			1.25 $[RG]$
λ''_{223}			1.25 $[RG]$
λ''_{312}		1.45 $[R_l]$ (6.41) $(\tilde{m} = 100\ \mathrm{GeV})$	1.28 $[RG]$
λ''_{313}		1.46 $[R_l]$ (6.41) $(\tilde{m} = 100\ \mathrm{GeV})$	2.1×10^{-3} $[n\bar{n}]$ (6.129) 1.12 $[RG]$
λ''_{323}		1.46 $[R_l]$ (6.41) $(\tilde{m} = 100\ \mathrm{GeV})$	2.6×10^{-3} $[n\bar{n}]$ (6.129) 1.12 $[RG]$
λ''_{ijk}			$(10^{-11}\,\tilde{m}^3\text{–}10^{-8}\,\tilde{m}^2)$ $\times (m_{3/2}/1\ \mathrm{eV})$ $[p \to K^+\tilde{G}]$(6.123) $\times (F_a/10^{10}\ \mathrm{GeV})$ $[p \to K^+\tilde{a}]$ (6.124)

RGE running

NN-bar oscillations

We use the notation V_{ij} for the CKM matrix, R_l, $R_{l\,\nu}$, R_D, R_l^Z for various branching fractions or ratios of branching fractions as defined in the text, Q_W for the weak charge, νq, νl for the neutrino elastic scattering on quarks and leptons, m_ν for the neutrino Majorana mass, RG for the renormalization group, A_{FB} for forward–backward asymmetry, $Q_W(\mathrm{Cs})$ for atomic physics parity violation, $n\bar{n}$ for neutron–antineutron oscillation and NN for two nucleon nuclear decay, $[K\bar{K}]$, for $K^0 - \bar{K}^0$ mixing . The generation indices denoted i, j, k run over the three generations while those denoted l, m, n run over the first two generations. The dependence on the superpartner mass follows the notational convention $\tilde{m}^p = (\frac{\tilde{m}}{100\ \mathrm{GeV}})^p$. Aside from a few cases associated with one-loop effects, we use the reference value $\tilde{m} = 100$ GeV. The quoted equation labels refer to equations in the text.

Quadratic coupling constant product bounds

	Lepton flavor	Hadron flavor	L and/or B violation
$\lvert\lambda^*_{ij2}\lambda_{ij1}\rvert$	$8.2 \times 10^{-5}(\tilde{\nu}^2_L, \tilde{l}^2_L)[\mu \to e\gamma]$ (6.95)		
$\lvert\lambda_{23k}\lambda^*_{13k}\rvert$	$2.3 \times 10^{-4}(\tilde{\nu}^2_L, \tilde{l}^2_R)[\mu \to e\gamma]$ (6.95)		
$\lvert\lambda_{312}\lambda^*_{321}\rvert$	$1.9 \times 10^{-3}\tilde{\nu}^2_L$ $[\mu^+ e^- \to \mu^- e^+]$ (6.103)		
$\lvert\lambda^*_{i12}\lambda_{i11}\rvert$	$6.6 \times 10^{-7}\tilde{\nu}^2_L$ $[\mu \to 3e]$ (6.97)		
$\lvert\lambda_{321}\lambda^*_{311}\rvert$	$6.6 \times 10^{-7}\tilde{\nu}^2_L$ $[\mu \to 3e]$ (6.97)		
$\lvert\lambda^*_{i23}\lambda_{i22}\rvert$	$2.2 \times 10^{-3}\tilde{\nu}^2_L$ $[\tau \to 3\mu]$ (6.97)		
$\lvert\lambda_{132}\lambda^*_{122}\rvert$	$2.2 \times 10^{-3}\tilde{\nu}^2_L$ $[\tau \to 3\mu]$ (6.97)		
$\lvert\lambda_{i12}\lambda_{j21}\rvert$			$0.15\tilde{l}^2\tilde{m}^{-1}$ $[m_\nu < 1\,\mathrm{eV}]$
$\lvert\lambda_{i13}\lambda_{j31}\rvert$			$8.7 \times 10^{-3}\tilde{l}^2\tilde{m}^{-1}[m_\nu < 1\,\mathrm{eV}]$
$\lvert\lambda_{i22}\lambda_{j22}\rvert$			$7 \times 10^{-4}\tilde{\mu}^2\tilde{m}^{-1}[m_\nu < 1\,\mathrm{eV}]$
$\lvert\lambda_{i23}\lambda_{j32}\rvert$			$4.2 \times 10^{-5}\tilde{l}^2\tilde{m}^{-1}[m_\nu < 1\,\mathrm{eV}]$
$\lvert\lambda_{i33}\lambda_{j33}\rvert$			$2.5 \times 10^{-6}\tilde{\tau}^2\tilde{m}^{-1}[m_\nu < 1\,\mathrm{eV}]$ $(\tilde{m}^{e\,2}_{LR} = \tilde{m}\,M^e)$(5.11)
$\lvert\lambda^*_{i12}\lambda'_{i11}\rvert$	$2.1 \times 10^{-8}\tilde{\nu}^2_L$ $[\mu \to e\ (\mathrm{Ti})]$ (6.99)		
$\lvert\lambda_{i21}\lambda'^*_{i11}\rvert$	$2.1 \times 10^{-8}\tilde{\nu}^2_L$ $[\mu \to e\ (\mathrm{Ti})]$ (6.99)		
$\lvert\lambda^*_{1j1}\lambda'_{j33}\rvert$	$\emptyset 6 \times 10^{-7}\tilde{\nu}^2_j$ $[d^\gamma_e]$ (6.60)		
$\lvert\lambda_{i31}\lambda'^*_{i11}\rvert$	$1.6 \times 10^{-3}\tilde{\nu}^2_{iL}$ $[\tau \to e\eta]$(6.104)		
$\lvert\lambda^*_{i13}\lambda'_{i11}\rvert$	$1.6 \times 10^{-3}\tilde{\nu}^2_{iL}$ $[\tau \to e\eta]$ (6.104)		
$\lvert\lambda_{i32}\lambda'^*_{i11}\rvert$	$1.7 \times 10^{-3}\tilde{\nu}^2_{iL}$ $[\tau \to \mu\eta]$ (6.104)		
$\lvert\lambda^*_{i23}\lambda'_{i11}\rvert$	$1.7 \times 10^{-3}\tilde{\nu}^2_{iL}$ $[\tau \to \mu\eta]$ (6.104)		

	Lepton flavor	Hadron flavor	L and/or B violation
$\lvert\lambda^{*}_{122}\lambda'_{112}\rvert$		$2.2 \times 10^{-7}\tilde{\nu}^2_L$ $[K_L \to \mu^+\mu^-]$ (6.76)	
$\lvert\lambda^{*}_{122}\lambda'_{121}\rvert$		$2.2 \times 10^{-7}\tilde{\nu}^2_L$ $[K_L \to \mu^+\mu^-]$ (6.76)	
$\lvert\lambda^{*}_{121}\lambda'_{212}\rvert$		$1.0 \times 10^{-8}\tilde{\nu}^2_L$ $[K_L \to e^+e^-]$ (6.76)	
$\lvert\lambda^{*}_{121}\lambda'_{221}\rvert$		$1.0 \times 10^{-8}\tilde{\nu}^2_L$ $[K_L \to e^+e^-]$ (6.76)	
$\lvert\lambda^{*}_{i12}\lambda'_{i12}\rvert$		$6 \times 10^{-9}\tilde{\nu}^2_L$ $[K_L \to e^{\pm}\mu^{\mp}]$ (6.78)	
$\lvert\lambda^{*}_{i12}\lambda'_{i21}\rvert$		$6 \times 10^{-9}\tilde{\nu}^2_L$ $[K_L \to e^{\pm}\mu^{\mp}]$ (6.78)	
$\lvert\lambda^{*}_{i21}\lambda'_{i12}\rvert$		$6 \times 10^{-9}\tilde{\nu}^2_L$ $[K_L \to e^{\pm}\mu^{\mp}]$(6.78)	
$\lvert\lambda^{*}_{i21}\lambda'_{i21}\rvert$		$6 \times 10^{-9}\tilde{\nu}^2_L$ $[K_L \to e^{\pm}\mu^{\mp}]$ (6.78)	
$\lvert\lambda_{i31}\lambda'^{*}_{i13}\rvert$		$6 \times 10^{-4}\tilde{l}^2_{iL}$ $[B^- \to e^-\bar{\nu}]$ (6.85)	
$\lvert\lambda_{i32}\lambda'^{*}_{i13}\rvert$		$7 \times 10^{-4}\tilde{l}^2_{iL}$ $[B^- \to \mu^-\bar{\nu}]$ (6.85)	
$\lvert\lambda_{233}\lambda'^{*}_{313}\rvert$		$2 \times 10^{-3}\tilde{l}^2_{3L}$ $[B^- \to \tau^-\bar{\nu}]$(6.85)	
$\lvert\lambda^{*}_{i11}\lambda'_{i13}\rvert$		$1.7 \times 10^{-5}\tilde{\nu}^2_L$ $[B^0_d \to e^+e^-]$ (6.79)	
$\lvert\lambda^{*}_{i11}\lambda'_{i31}\rvert$		$1.7 \times 10^{-5}\tilde{\nu}^2_L$ $[B^0_d \to e^+e^-]$ (6.79)	
$\lvert\lambda^{*}_{i22}\lambda'_{i13}\rvert$		$1.5 \times 10^{-5}\tilde{\nu}^2_L$ $[B^0_d \to \mu^+\mu^-]$ (6.79)	
$\lvert\lambda^{*}_{i22}\lambda'_{i31}\rvert$		$1.5 \times 10^{-5}\tilde{\nu}^2_L$ $[B^0_d \to \mu^+\mu^-]$(6.79)	
$\lvert\lambda^{*}_{i12}\lambda'_{i13}\rvert$		$2.3 \times 10^{-5}\tilde{\nu}^2_L$ $[B^0_d \to e^{\pm}\mu^{\mp}]$ (6.79)	
$\lvert\lambda^{*}_{i12}\lambda'_{i31}\rvert$		$2.3 \times 10^{-5}\tilde{\nu}^2_L$ $[B^0_d \to e^{\pm}\mu^{\mp}]$(6.79)	
$\lvert\lambda^{*}_{i21}\lambda'_{i13}\rvert$		$2.3 \times 10^{-5}\tilde{\nu}^2_L$ $[B^0_d \to e^{\pm}\mu^{\mp}]$(6.79)	
$\lvert\lambda^{*}_{i21}\lambda'_{i31}\rvert$		$2.3 \times 10^{-5}\tilde{\nu}^2_L$ $[B^0_d \to e^{\pm}\mu^{\mp}]$(6.79)	
$\lvert\lambda_{231}\lambda''^{*}_{112}\rvert$			10^{-16} $[p \to K^+e^{\pm}\mu^{\mp}\bar{\nu}]$
$\lvert\lambda_{132}\lambda''^{*}_{112}\rvert$			10^{-16} $[p \to K^+e^{\pm}\mu^{\mp}\bar{\nu}]$
$\lvert\lambda_{123}\lambda''^{*}_{112}\rvert$			10^{-14} $[p \to K^+\nu\bar{\nu}\bar{\nu}]$
$\lvert\lambda_{i11}\lambda''^{*}_{112}\rvert$			10^{-17} $[p \to K^+\bar{\nu}]$
$\lvert\lambda_{i22}\lambda''^{*}_{112}\rvert$			10^{-20} $[p \to K^+\bar{\nu}]$
$\lvert\lambda_{i33}\lambda''^{*}_{112}\rvert$			10^{-21} $[p \to K^+\bar{\nu}]$
			$(\tilde{m} = 1\,\text{TeV})$ (6.115)
$\lvert\lambda_{ijj}\lambda''^{*}_{i'j'k'}\rvert$			$(10^{-12}$–$10^{-6})$ $[p \to \pi^+(K^+)\bar{\nu}]$
			$(m_{\tilde{k}^+} = \tilde{m} = 1\,\text{TeV})$ (6.116)
$\lvert\lambda_{ijk}\lambda''_{113}\rvert$			10^{-13} $[p \to l^+\nu\nu]$ (6.117)
$\lvert\lambda_{ijk}\lambda''_{123}\rvert$			10^{-12} $[p \to l^+\nu\nu]$ (6.117)
$\lvert\lambda_{ijk}\lambda''_{212}\rvert$			10^{-13} $[p \to l^+\nu\nu]$ (6.117)
$\lvert\lambda_{ijk}\lambda''_{312}\rvert$			10^{-12} $[p \to l^+\nu\nu]$ (6.117)

	Lepton flavor	Hadron flavor	L and/or B violation
$\vert\lambda'^{*}_{i21}\lambda'_{i12}\vert$		$4.5 \times 10^{-9}\ \tilde{\nu}^2_{iL}\ [K\bar{K}]$	
$\vert\lambda'_{i31}\lambda'^{*}_{i22}\vert$		$1. \times 10^{-4}\ [K\bar{K}]\ (\tilde{m} = 100\ \text{GeV})$	
$\vert\lambda'^{*}_{i31}\lambda'_{i32}\vert$		$7.7 \times 10^{-4}\ [K\bar{K}]\ (\tilde{m} = 100\ \text{GeV})$	
$\vert\lambda'^{*}_{i2k}\lambda'_{i'1k}\vert$		$2.11 \times 10^{-5}\ \tilde{d}^2_{kR}\ [K^+ \to \pi^+ \nu\bar{\nu}]$ (6.87)	
$\vert\lambda'^{*}_{ij1}\lambda'_{i'j2}\vert$		$2.11 \times 10^{-5}\ \tilde{d}^2_{jL}\ [K^+ \to \pi^+ \nu\bar{\nu}]$ (6.87)	
$\vert\lambda'^{*}_{i31}\lambda'_{i13}\vert$		$3.3 \times 10^{-8} \tilde{\nu}^2_{iL}\ [B\bar{B}]$	
$\vert\lambda'_{i31}\lambda'^{*}_{i33}\vert$		$1.3 \times 10^{-3}\ [B\bar{B}]$	
$\vert\lambda'^{*}_{i3k}\lambda'_{i'2k}\vert$		$1.5 \times 10^{-3} \tilde{d}^2_{kR}\ [B \to X_s \nu\bar{\nu}]$ (6.88)	
$\vert\lambda'^{*}_{ij2}\lambda'_{i'j3}\vert$		$1.5 \times 10^{-3} \tilde{d}^2_{jL}\ [B \to X_s \nu\bar{\nu}]$ (6.88)	
$\vert\lambda'_{2mk}\lambda'^{*}_{1mk}\vert$	$7.6 \times 10^{-5} \tilde{d}^2_{kR}\ [\mu \to e\gamma]$(6.95)		
$\vert\lambda'_{23k}\lambda'^{*}_{13k}\vert$	$2.0 \times 10^{-3}\ [\mu \to e\gamma]$ (6.96)		
	$(m_{\tilde{d}_{kR}} = m_{\tilde{t}_L} = 300\ \text{GeV})$		
$\vert\lambda'^{*}_{1j1}\lambda'_{1j2}\vert$		$\mathscr{I}\ 8.1 \times 10^{-5} \tilde{u}^2_L\ [K_L \to e^+e^-]$ (6.77)	
$\vert\lambda'^{*}_{2j1}\lambda'_{2j2}\vert$		$\mathscr{I}\ 7.8 \times 10^{-6} \tilde{u}^2_L\ [K_L \to \mu^+\mu^-]$ (6.77)	
$\vert\lambda'^{*}_{1j1}\lambda'_{2j2}\vert$		$3 \times 10^{-7} \tilde{u}^2_L\ [K_L \to e^\pm\mu^\mp]$(6.78)	
$\vert\lambda'^{*}_{1j2}\lambda'_{2j1}\vert$		$3 \times 10^{-7} \tilde{u}^2_L\ [K_L \to e^\pm\mu^\mp]$ (6.78)	
$\vert\lambda'^{*}_{2j1}\lambda'_{2j3}\vert$		$2.1 \times 10^{-3} \tilde{u}^2_L\ [B^0_d \to \mu^+\mu^-]$ (6.80)	
$\vert\lambda'^{*}_{1j1}\lambda'_{2j3}\vert$		$4.7 \times 10^{-3} \tilde{u}^2_L\ [B^0_d \to e^\pm\mu^\mp]$ (6.80)	
$\vert\lambda'^{*}_{1j3}\lambda'_{2j1}\vert$		$4.7 \times 10^{-3} \tilde{u}^2_L\ [B^0_d \to e^\pm\mu^\mp]$ (6.80)	
$\vert\lambda'_{2j1}\lambda'^{*}_{1j1}\vert$	$4.3 \times 10^{-8} \tilde{u}^2_{jL}\ [\mu \to e\ (\text{Ti})]$ (6.99)		
$\vert\lambda'_{3j1}\lambda'^{*}_{1j1}\vert$	$2.4 \times 10^{-3} \tilde{u}^2_{jL}\ [\tau \to e\rho]$(6.105)		
$\vert\lambda'^{*}_{11k}\lambda'_{12k}\vert$		$5.3 \times 10^{-3} \tilde{d}^2_{kR}\ [\Lambda \to p l^- \bar{\nu}_l]$(6.31)	
$\vert\lambda'_{21k}\lambda'^{*}_{11k}\vert$	$4.5 \times 10^{-8} \tilde{d}^2_{kR}\ [\mu \to e\ (\text{Ti})]$ (6.99)		
$\vert\lambda'_{31k}\lambda'^{*}_{11k}\vert$	$2.4 \times 10^{-3} \tilde{d}^2_{kR}\ [\tau \to e\rho]$(6.105)		

	Lepton flavor	Hadron flavor	L and/or B violation
$\lvert\lambda'_{113}\lambda'_{131}\rvert$			3.8×10^{-8} [$\beta\beta 0\nu$] (6.107)
$\lvert\lambda'_{112}\lambda'_{121}\rvert$			1.1×10^{-6} [$\beta\beta 0\nu$] (6.107)
$\lvert\lambda'_{i3k}\lambda'^{*}_{i2k}\rvert$		$0.09\ (\tilde{\nu}^2_{iL}, \tilde{d}^2_{iR})$ [$B \to K\gamma$] (6.93)	
$\lvert\lambda'^{*}_{ij3}\lambda'_{ij2}\rvert$		$0.035\ (\tilde{e}^2_{iL}, \tilde{d}^2_{jL})$ [$B \to K\gamma$](6.93)	
$\lvert\lambda'_{i11}\lambda'_{j11}\rvert$			$5 \times 10^{-2}\tilde{d}^2\tilde{m}^{-1}$ [$m_\nu < 1$ eV]
$\lvert\lambda'_{i12}\lambda'_{j21}\rvert$			$3 \times 10^{-3}\tilde{q}^2\tilde{m}^{-1}$ [$m_\nu < 1$ eV]
$\lvert\lambda'_{i13}\lambda'_{j31}\rvert$			$8 \times 10^{-5}\tilde{q}^2\tilde{m}^{-1}$ [$m_\nu < 1$ eV]
$\lvert\lambda'_{i22}\lambda'_{j22}\rvert$			$2 \times 10^{-4}\tilde{s}^2\tilde{m}^{-1}$ [$m_\nu < 1$ eV]
$\lvert\lambda'_{i23}\lambda'_{j32}\rvert$			$5 \times 10^{-6}\tilde{q}^2\tilde{m}^{-1}$ [$m_\nu < 1$ eV]
$\lvert\lambda'_{i33}\lambda'_{j33}\rvert$			$10^{-7}\ \tilde{b}^2\tilde{m}^{-1}$ [$m_\nu < 1$ eV]
			$(\tilde{m}^{d2}_{LR} = \tilde{m} M^d)$ (5.12)
$\lvert\lambda'_{11k}\lambda''^{*}_{11k}\rvert$			$(2-3) \times 10^{-27}\tilde{d}^2_{kR}$ [$p \to \pi^0 l^+$] (6.110)
$\lvert\lambda'_{31k}\lambda''^{*}_{11k}\rvert$			$7 \times 10^{-27}\tilde{d}^2_{kR}$ [$n \to \pi^0\bar{\nu}$](6.110)
$\lvert\lambda'_{i2k}\lambda''^{*}_{11k}\rvert$			$3 \times 10^{-27}\tilde{d}^2_{kR}$ [$p \to K^+\bar{\nu}$] (6.110)
$\lvert\lambda'_{i1k}\lambda''^{*}_{12k}\rvert$			$(6-7) \times 10^{-27}\tilde{d}^2_{kR}$ [$p \to K^0 l^+$] (6.111)
$\lvert\lambda'_{ij1}\lambda''_{11j}\rvert$			$7 \times 10^{-26}\ \tilde{d}^2_{jL}(m^2_{\tilde{d}_{jR}}/(\tilde{m}^{d\,2}_{\mathrm{LR}})_{jj})$
$\lvert\lambda'_{ij2}\lambda''_{11j}\rvert$			$3 \times 10^{-27}\ \tilde{d}^2_{jL}(m^2_{\tilde{d}_{jR}}/(\tilde{m}^{d\,2}_{\mathrm{LR}})_{jj})$
$\lvert\lambda'_{i31}\lambda''_{123}\rvert$			$3 \times 10^{-27}\ \tilde{b}^2_L(m^2_{\tilde{b}_R}/(\tilde{m}^{d\,2}_{\mathrm{LR}})_{33})$
			[$n \to \pi^0\nu,\ p \to K^+\nu$] (6.112)
$\lvert\lambda'_{ij1}\lambda''_{j12}\rvert$			$10^{-26}\ \tilde{u}^2_{jL}(m^2_{\tilde{u}_{jR}}/(\tilde{m}^{u\,2}_{\mathrm{LR}})_{jj})$
			[$n \to K^+ l$] (6.113)
$\lvert\lambda'_{ijk}\lambda''^{*}_{i'j'k'}\rvert$			10^{-9} [$p \to X\bar{\nu}(X\nu)$]
			$(\tilde{m} = 1$ TeV$)$ (6.114)
$\lvert\lambda''^{*}_{232}\lambda''_{231}\rvert$		Min[$6. \times 10^{-4}\tilde{c},\ 2. \times 10^{-4}\tilde{c}^2$]	
		[$K\bar{K}$]	
$\lvert\lambda''^{*}_{332}\lambda''_{331}\rvert$		Min[$6. \times 10^{-4}\tilde{t},\ 3. \times 10^{-4}\tilde{t}^2$]	
		[$K\bar{K}$]	
$\lvert\lambda''_{i13}\lambda''^{*}_{i12}\rvert$		$6.4 \times 10^{-3}\tilde{u}^2_{iR}$ [$B^+ \to K^0\pi^+$] (6.89)	
$\lvert\lambda''^{*}_{i23}\lambda''_{i12}\rvert$		$6 \times 10^{-5}\tilde{u}^2_{iR}$ [$B^- \to \phi\pi^-$] (6.91)	
$\lvert\lambda''_{213}\lambda''^{*}_{232}\rvert$		$\mathscr{I}\ 10^{-2}\tilde{q}^2$ [d^γ_n] (6.58)	
$\lvert\lambda''_{312}\lambda''^{*}_{332}\rvert$		$\mathscr{I}\ 10^{-1}\tilde{q}^2$ [d^γ_n] (6.59)	
$\lvert\lambda''^{*}_{i3k}\lambda''_{i2k}\rvert$		$0.16\tilde{q}^2_R$ [$B \to K\gamma$] (6.93)	

Issues:

What ranges of the λ's are `interesting'? If we use the SM Yukawa couplings as a guide, since they have the same form in the superpotential (why not??), then we *might* expect (??) the various λ's most likely lie in the range $O(10^{-6}-1)$. Very little of this range is presently excluded by experiment as the above Tables show. However, in principle, we can't exclude values as low as $\sim 10^{-12}$ based solely on data.

Until we have a real theory of superpotential couplings, the window is *wide* open. For example, in a theory where the couplings are zero at tree-level and are calculable at higher order, very small values might be expected.

A *very* important point to remember is that

once the LSP is no longer DM, there is no reason to require it to be the lightest neutralino; within the MSSM context it can be one of many candidates: slepton, sneutrino, stau, stop, neutralino, chargino, gluino…

Clearly the phenomenology of this potentially long-lived state is sensitive to these choices. Broadly, we can divide these possibilities into two categories depending upon whether the LSP is either a sfermion or a gaugino. Additional special care is required if the LSP also carries color.

Let us consider these two possibilities in turn…

A scan of MSSM parameter space* : 5685 points

Who is the LSP???

neutralino: 1936

gluino: 85

sbottom: 208

RH-selectron: 588

stau: 1131

chargino: 33

squark: 128

stop: 195

sneutrino: 864

tau sneutrino: 517

*J. Gainer c/o SUSPECT2.34

The LSP is a Sfermion:

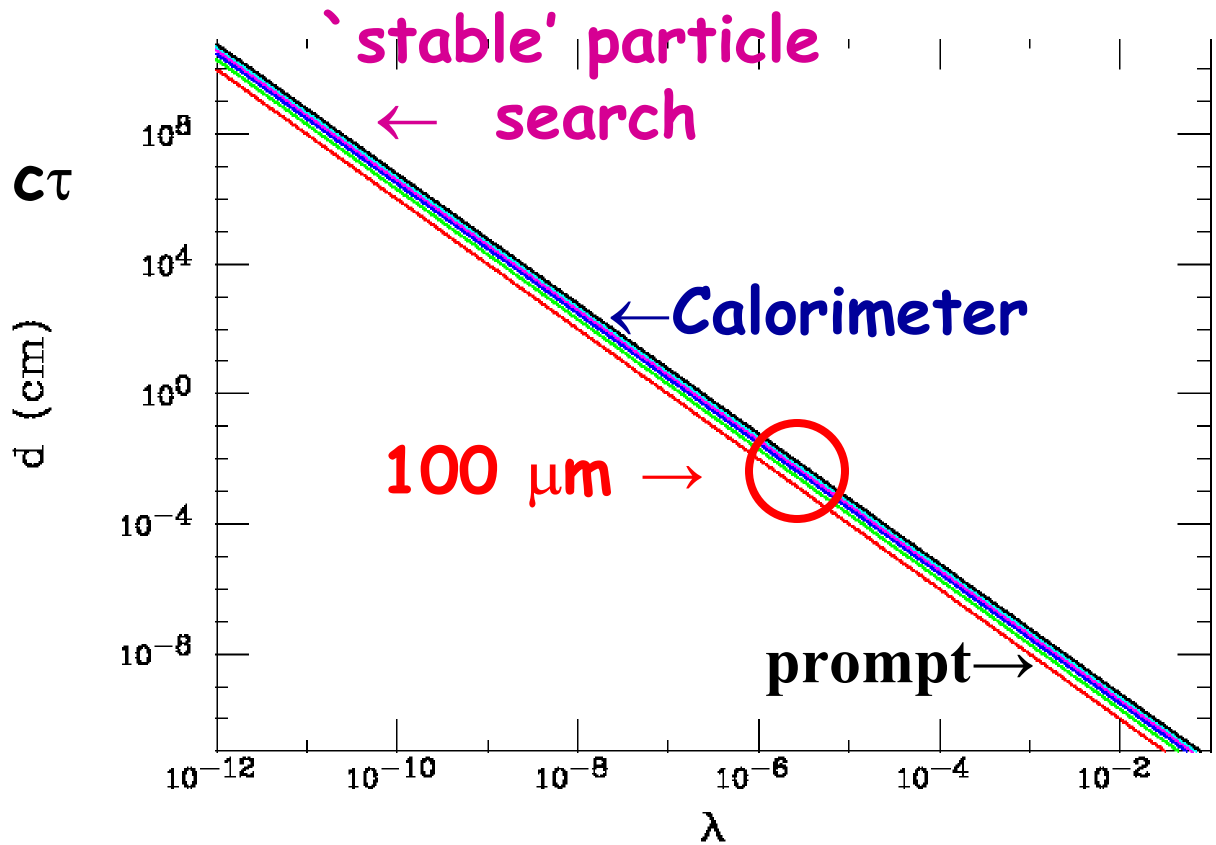
The decays are all 2-body modes directly through the RPV coupling and can be quite rapid. Of course, more than one final state may be allowed.

Direct decays of sleptons and squarks via trilinear $\not{R}_p$ operators $\lambda_{ijk} L_i L_j \bar{E}_k$, $\lambda'_{ijk} L_i Q_j \bar{D}_k$ and $\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$

Supersymmetric particles	Couplings λ_{ijk}	λ'_{ijk}	λ''_{ijk}
$\tilde{\nu}_{i,L}$	$\ell^+_{j,L} \ell^-_{k,R}$	$\bar{d}_{j,L} d_{k,R}$	
$\tilde{\ell}^-_{i,L}$	$\bar{\nu}_{j,L} \ell^-_{k,R}$	$\bar{u}_{j,L} d_{k,R}$	
$\tilde{\nu}_{j,L}$	$\ell^+_{i,L} \ell^-_{k,R}$		
$\tilde{\ell}^-_{j,L}$	$\bar{\nu}_{i,L} \ell^-_{k,R}$		
$\tilde{\ell}^-_{k,R}$	$\nu_{i,L} \ell^-_{j,L}$, $\ell^-_{i,L} \nu_{j,L}$		
$\tilde{u}_{i,R}$			$\bar{d}_{j,R} \bar{d}_{k,R}$
$\tilde{u}_{j,L}$		$\ell^+_{i,L} d_{k,R}$	
$\tilde{d}_{j,L}$		$\bar{\nu}_{i,L} d_{k,R}$	
$\tilde{d}_{j,R}$			$\bar{u}_{i,R} \bar{d}_{k,R}$
$\tilde{d}_{k,R}$		$\nu_{i,L} d_{j,L}$, $\ell^-_{i,L} u_{j,L}$	$\bar{u}_{i,R} \bar{d}_{j,R}$

$$L = 1\mu m\ (\beta\gamma)\ N_c^{-1}\ (100\ GeV/m)\ (10^{-5}/\lambda)^2\ F$$

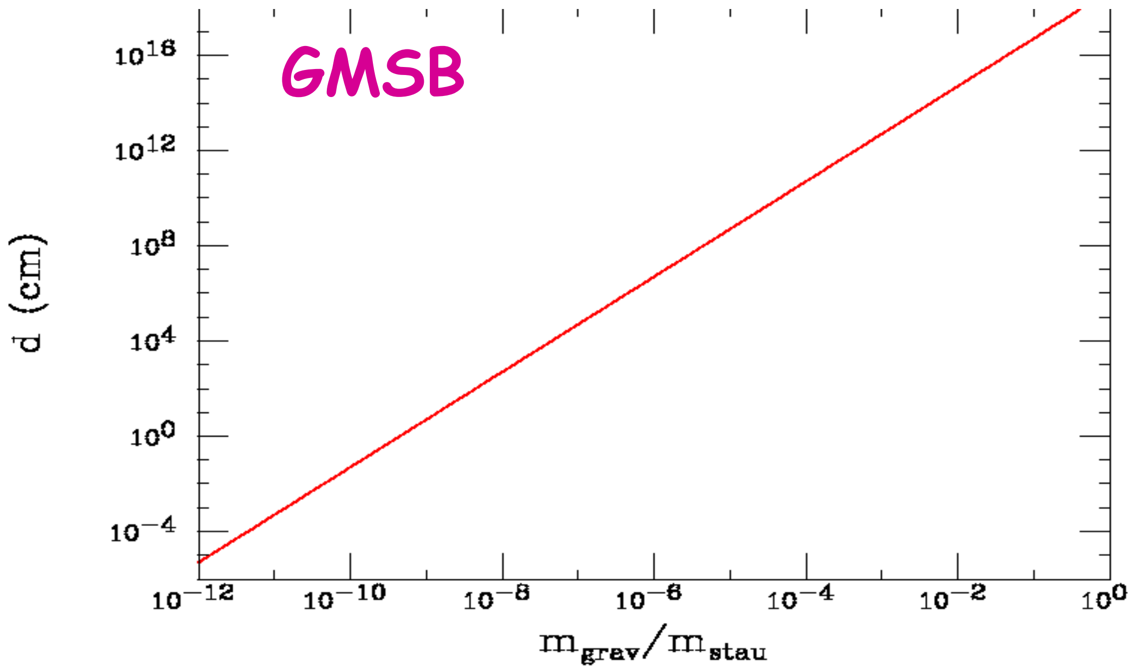
Since the decay is 2-body, it is harder to get (very) long-lived states in this case unless the coupling is quite small…



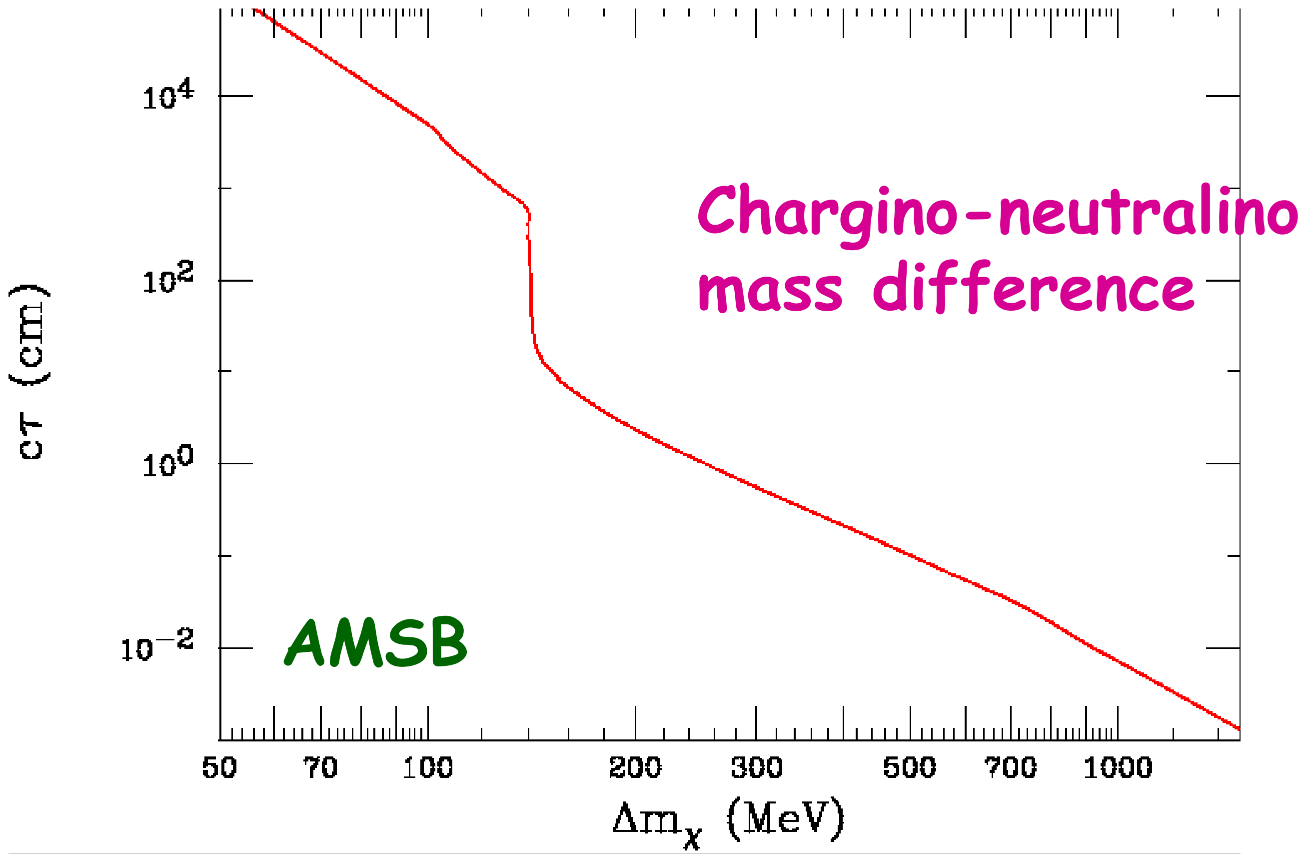
Sfermion decay length for various spartner masses

Given the a priori allowed range of λ a wide range of decay lengths is possible. *But* if we regard values below 10^{-6} as `unnatural' (?) then `interesting' values are rare… but we *can't* assume this.

This is somewhat similar to, e.g., gauge mediation where very long-lived stau NLSPs decaying into gravitinos are easily possible…



..or to the case of AMSB where very-long lived NLSP charginos are quite possible due to a symmetry…



Note that in the case of a stop LSP, over almost all of the parameter range, the stop will hadronize first before it decays

The allowed range of λ parameters is such that we must in general consider the entire range from prompt decays, to those taking place anywhere in the detector, to essentially stable particles.

The `stable' case has recently been reviewed by Bressler (arXiv:0710.2113) for both ATLAS & CMS

The `prompt' case is the most difficult & has gotten the most attention by both experimenters and theorists, e.g., Allanach etal (arXiv:0710.2034). CDF/D0 searches have mainly concentrated on this as well as the `stable' cases.

The intermediate case is more of interest to us here…

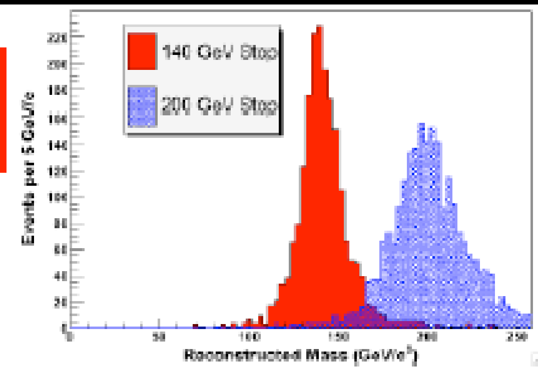
CHAMPS: Charged Massive Stable Particles

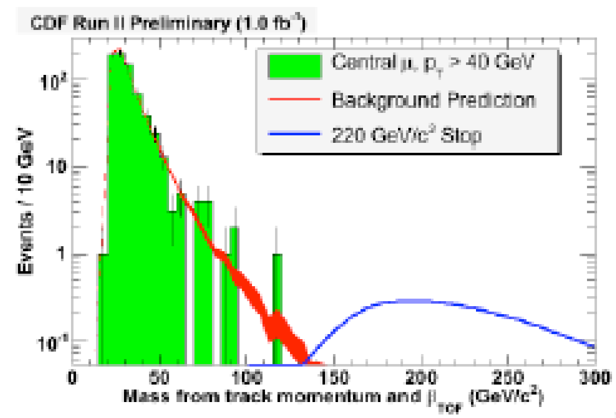
- Scenario:
  - Escape detector completely

$$m = p\sqrt{1/\beta^2 - 1}$$

- Experimentally:
  - Search for "muons" that travel at $\beta << 1$
    - CDF: Time-Of-Flight detector and drift chamber
    - D0: muon system
  - Reconstruct mass from p and β
- Cross Section Limits

  (for $p_T > 40$ GeV and $|\eta| < 1$, $0.4 < \beta < 0.9$)
  - Weakly interacting ($\tilde{\tau}$, $\tilde{\chi}_1^\pm$):
    - $\sigma < 10$ fb at 95% CL
  - Strongly interacting (stop):
    - $\sigma < 48$ fb at 95% CL
    - Assumes stop stays charged up to muon system with P=43±7%





CDF: $m(\tilde{t}) > 250$ GeV

DØ: $m(\tilde{\chi}_1^\pm) > 140\text{-}170$ GeV

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In the gaugino case, the decays are 3-body through an intermediate sfermion:*

Direct decays of neutralinos and charginos with trilinear $\not{R}_p$ operators $\lambda_{ijk} L_i L_j \bar{E}_k$, $\lambda'_{ijk} L_i Q_j \bar{D}_k$ and $\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$

Supersymmetric	Couplings		
particles	λ_{ijk}	λ'_{ijk}	λ''_{ijk}
$\tilde{\chi}^0$	$\ell_i^+ \bar{\nu}_j \ell_k^-$, $\ell_i^- \nu_j \ell_k^+$, $\bar{\nu}_i \ell_j^+ \ell_k^-$, $\nu_i \ell_j^- \ell_k^+$	$\ell_i^+ \bar{u}_j d_k$, $\ell_i^- u_j \bar{d}_k$, $\bar{\nu}_i \bar{d}_j d_k$, $\nu_i d_j \bar{d}_k$	$\bar{u}_i \bar{d}_j \bar{d}_k$, $u_i d_j d_k$
$\tilde{\chi}^+$	$\ell_i^+ \ell_j^+ \ell_k^-$, $\ell_i^+ \bar{\nu}_j \nu_k$, $\bar{\nu}_i \ell_j^+ \nu_k$, $\nu_i \nu_j \ell_k^+$	$\ell_i^+ \bar{d}_j d_k$, $\ell_i^+ \bar{u}_j u_k$, $\bar{\nu}_i \bar{d}_j u_k$, $\nu_i u_j \bar{d}_k$	$u_i d_j u_k$, $u_i u_j d_k$, $\bar{d}_i \bar{d}_j \bar{d}_k$

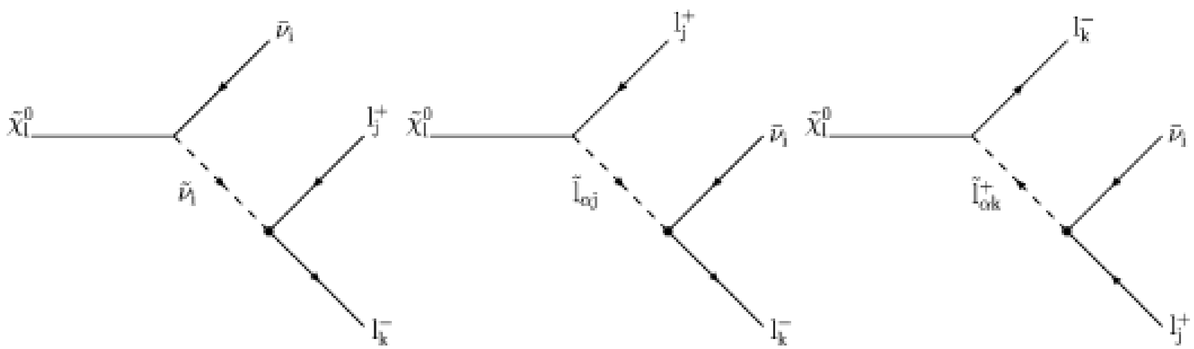


Fig. 7.1. Diagrams for the direct decays of the neutralino $\tilde{\chi}_l^0$ via the coupling λ_{ijk} of the $\not{R}_p$ trilinear $L_i L_j E_k^c$ interaction. The index $l = 1 \ldots 4$ determines the mass eigenstate of the neutralino. The indices $i, j, k = 1, 2, 3$ correspond to the generation. Gauge invariance forbids $i = j$. The index $\alpha = 1, 2$ gives the slepton mass eigenstate (i.e. the chirality of the Standard Model lepton partner in absence of mixing).

which can lead to somewhat longer lifetimes…

* S. Dawson '85

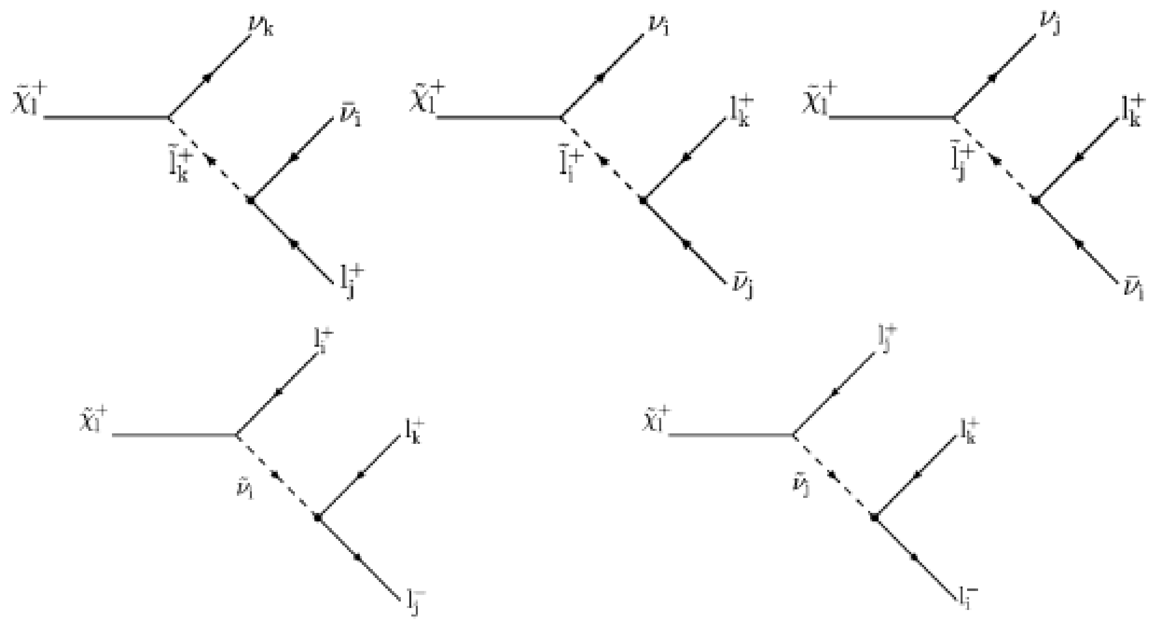
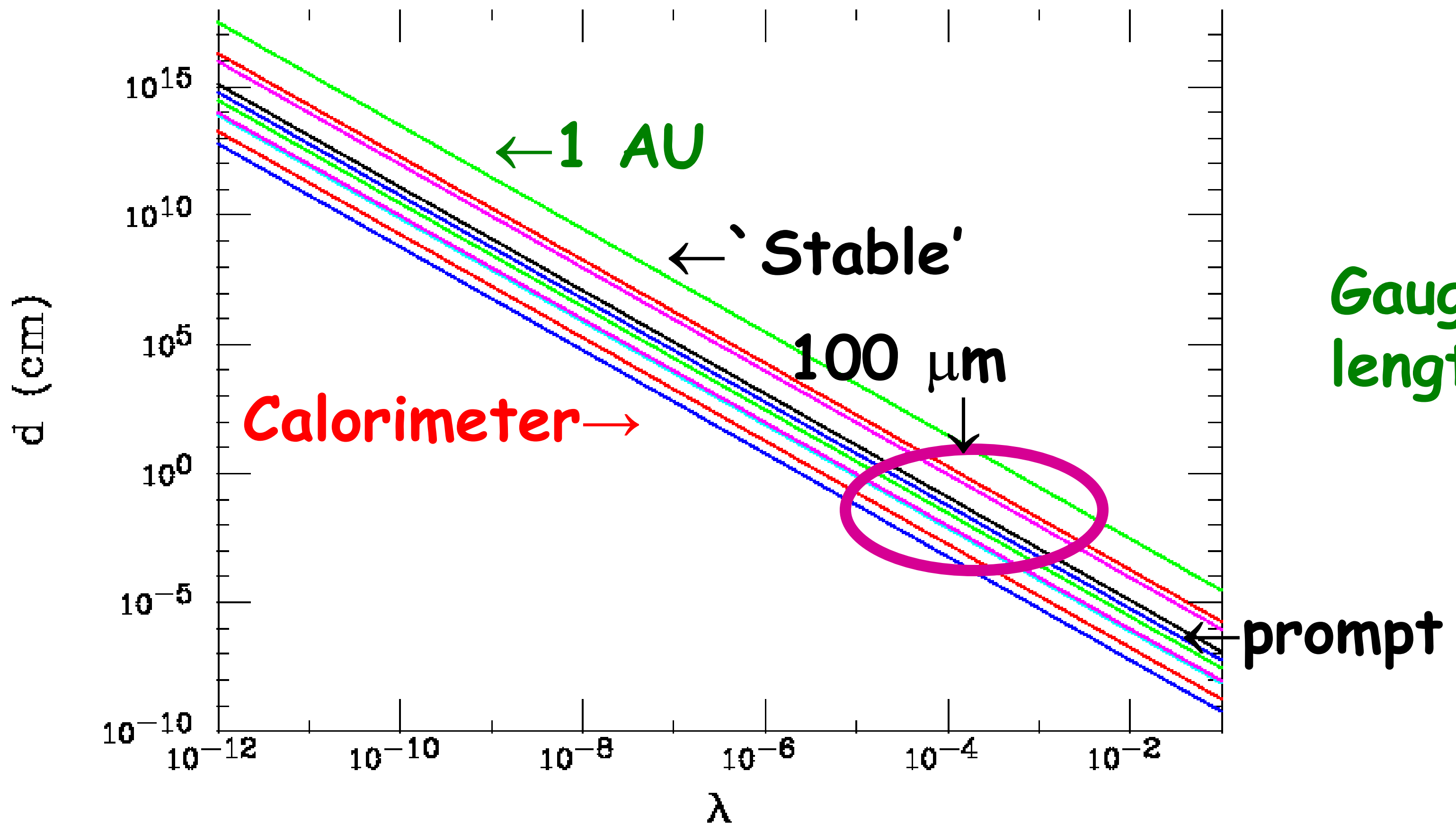


Fig. 7.2. Diagrams for the direct decays of the chargino $\tilde{\chi}_l^+$ via the coupling λ_{ijk} of the $\not{R}_p$ trilinear $L_i L_j E_k^c$ interaction. The index $l = 1 \ldots 4$ determines the mass eigenstate of the neutralino. The indices $i, j, k = 1, 2, 3$ correspond to the generation. Gauge invariance forbids $i = j$. The index $\alpha = 1, 2$ gives the slepton mass eigenstate (i.e. the chirality of the Standard Model lepton partner in absence of mixing).

$$L = 190\ \mu\text{m}\ (\beta\gamma)\ (m_f/500\ \text{GeV})^4\ (100\ \text{GeV}/m_X)^5\ F$$

$$\times\ (10^{-3}/\lambda)^2\ N_c^{\ -1}$$

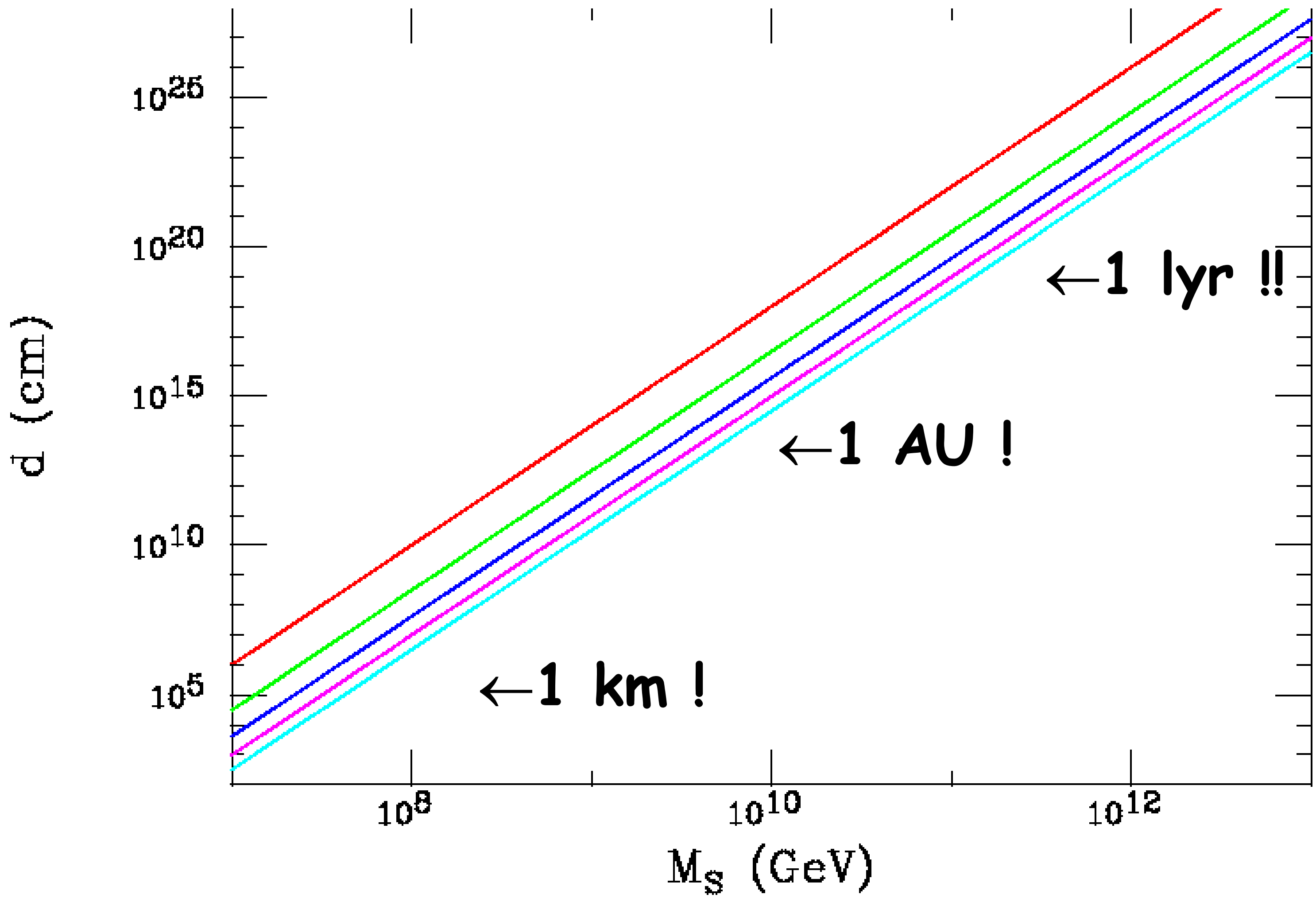


Gaugino decay lengths

The variation is greater than for sfermions due to the presence of an addition parameter

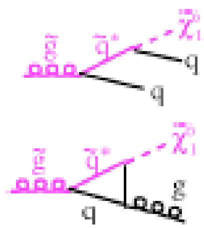
The case of a gluino LSP is again somewhat different as it too likely hadronizes, forming R-hadrons, before decaying…

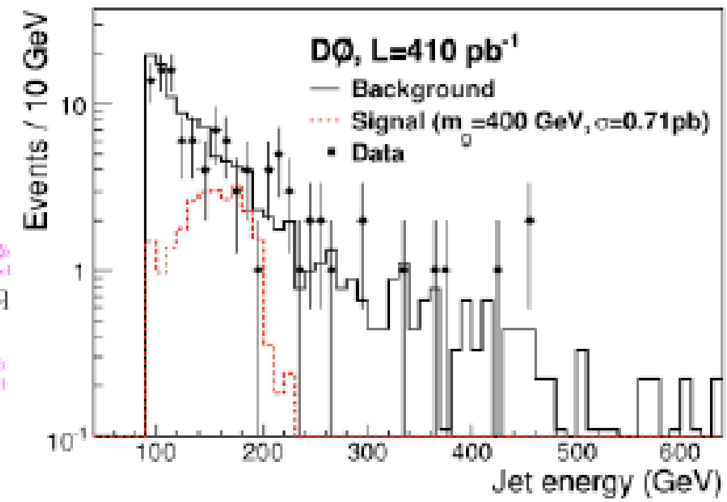
This is quite different from split-SUSY where the gluino generally has a **very** long lifetime…



Stable particles: "stopped Gluinos"

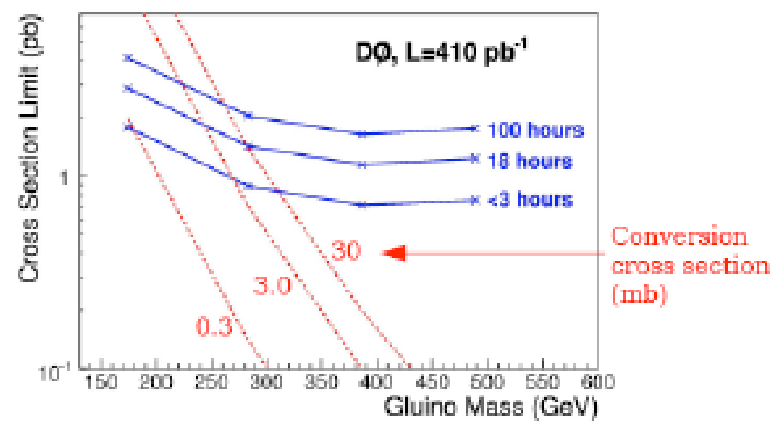
- Particles can be rather stable:
  - Lifetime ~hours
    - Interact in calorimeter and decay at some later time
  - Split-SUSY:
    - $m(\tilde{q})>10^2$ TeV, $m(\tilde{g})$~TeV
    - Gluino long-lived





- Trigger on events with
  - "no interaction" but jet activity
- Main background:
  - Cosmic ray and beam-halo muons
- Result: **$m(\tilde{g})$>270 GeV** @95%CL

for $\tau(\tilde{g})$<3h, $\sigma(R_m \rightarrow R_b)$=3mb,
$BR(\tilde{g} \rightarrow g\tilde{\chi}_1^0)$=100%, $m(\tilde{\chi}_1^0)$=50 GeV



[A. Arvanitaki et al.: hep-ph/0506242]

CMS proposal for additional `stopper' detectors to capture long-lived particles*

`stoppers'

`coarse-grained' iron

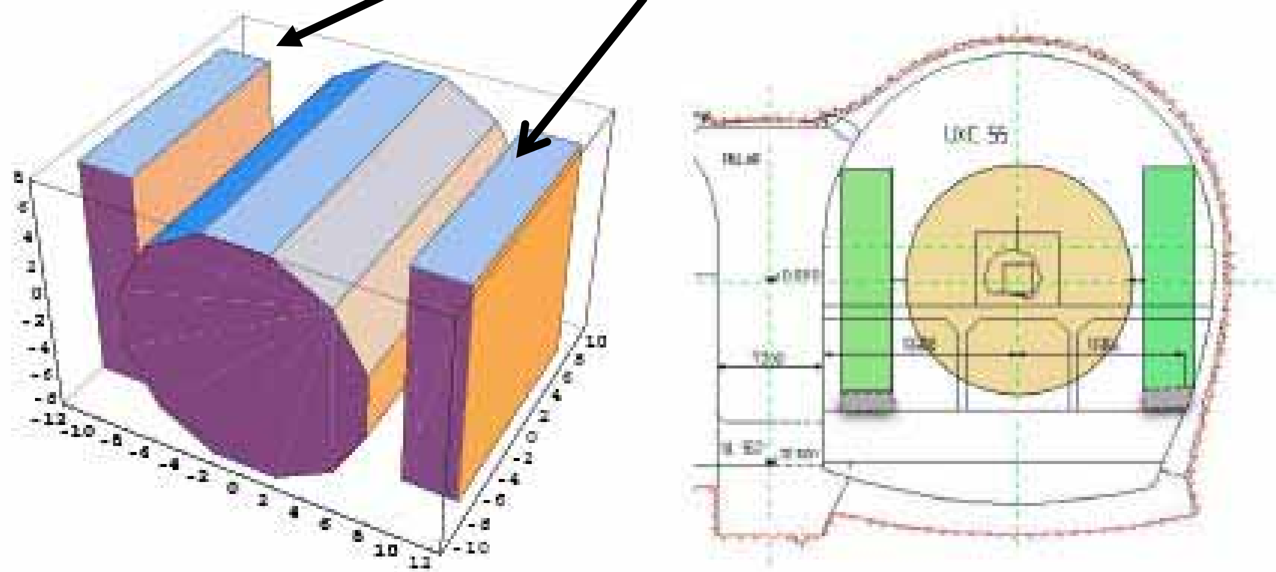


FIG. 1: Left: a schematic figure of the CMS detector and two stoppers. The numbers are in units of meters, and (0,0,0) is the collision point. Right: two stopper–detectors and a circle about the size of CMS detector are superimposed on the cross section of CMS cavern UXC 55, drawing taken from Ref. [9].

*Hamaguchi etal, hep-ph/0612060

For an ATLAS study of long lived sleptons & R-hadrons, see CSC SUSY Note-8

Draft version 0.0

ATLAS NOTE

ATL-PHYS-xxx-yyy-zzz

January 8, 2008

Studies of the SUSY signatures with photonic, long-lived heavy particles in ATLAS

The list of contributors

...

The ATLAS Collaboration

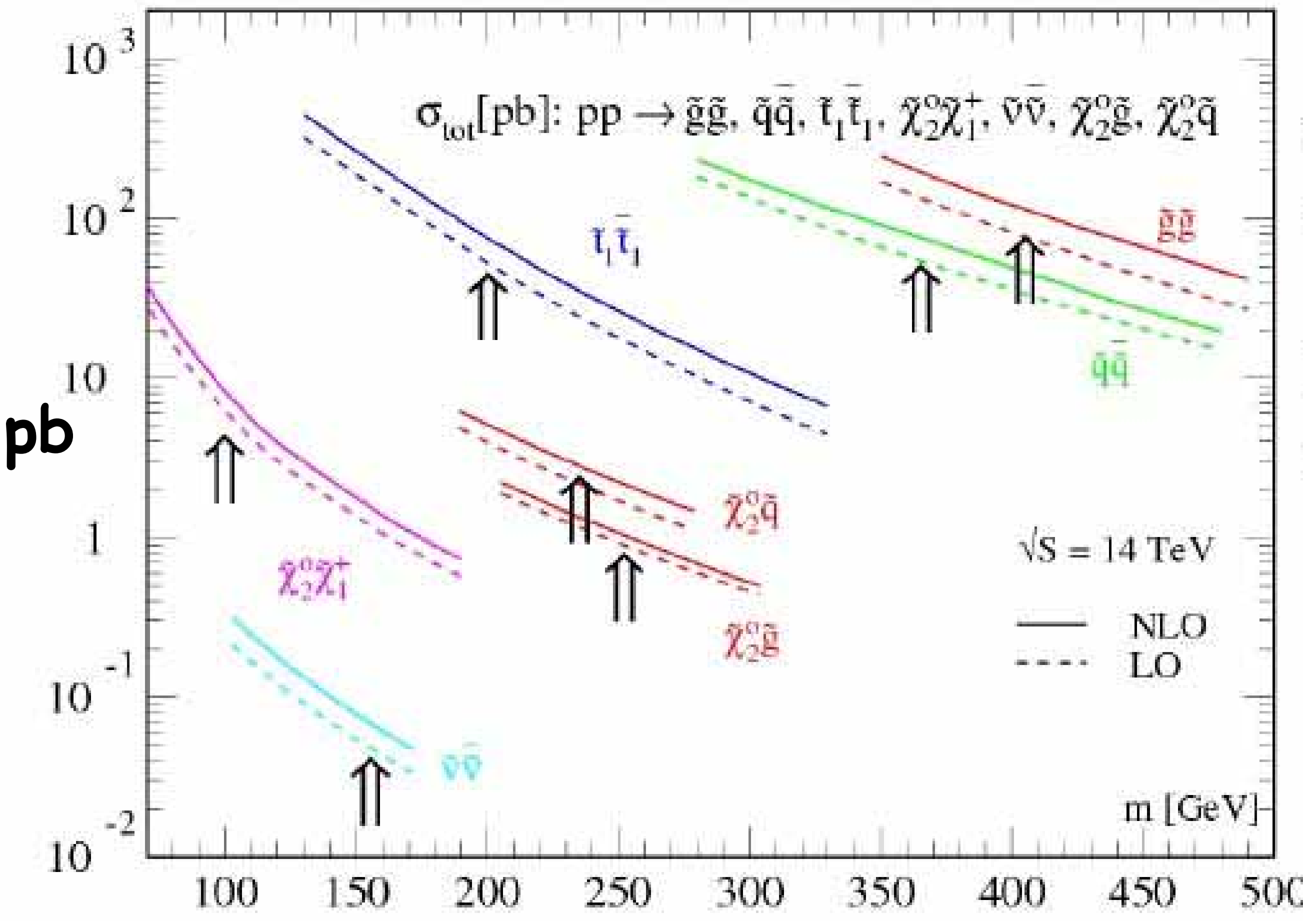
Once we choose the identity of the long-lived LSP to examine we need to decide the best way to produce/study it at LHC.

Remember:

For λ's < 10^{-2} or so, sparticles will still be dominantly pair-produced as in the ordinary RPC MSSM

Thus long-lived stops and gluinos will be made in pairs in the usual fashion from gg and qq-bar annihilation with quite large cross sections… For our parameter range they hadronize before decaying.

SUSY: Rates

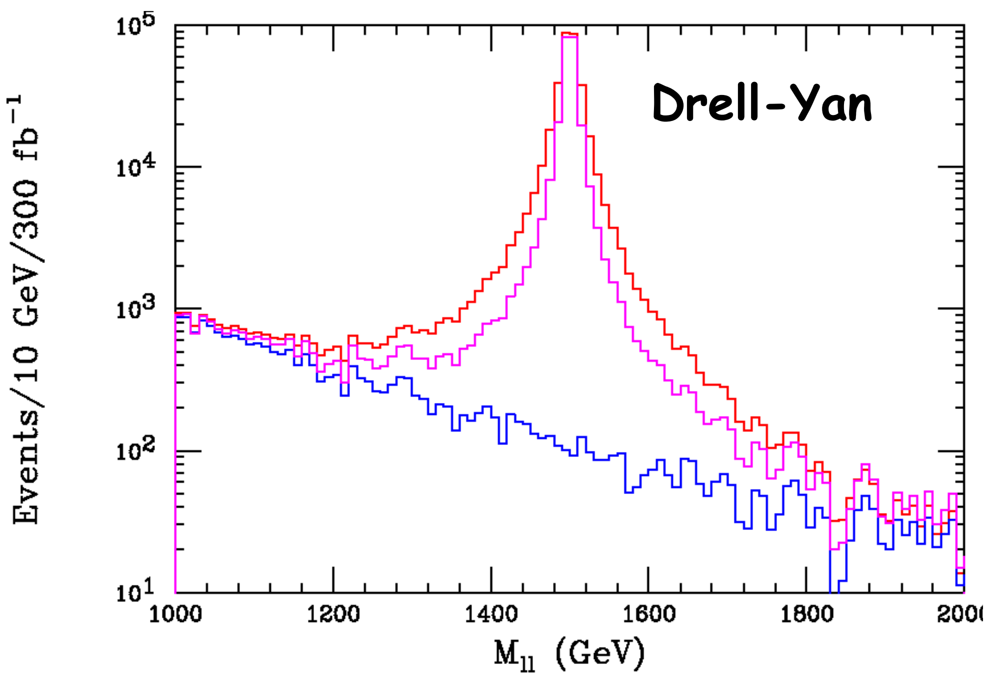


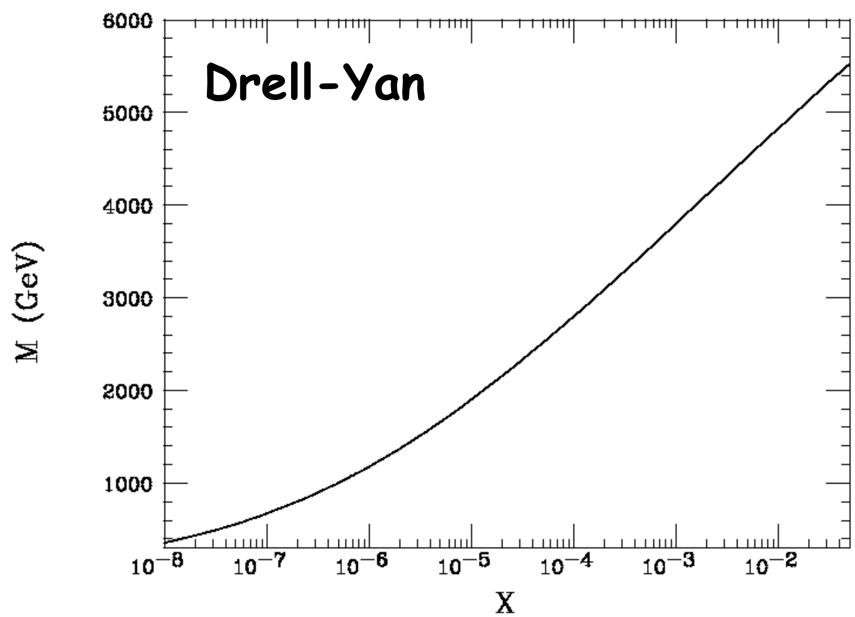
LHC produces mostly the heavier states

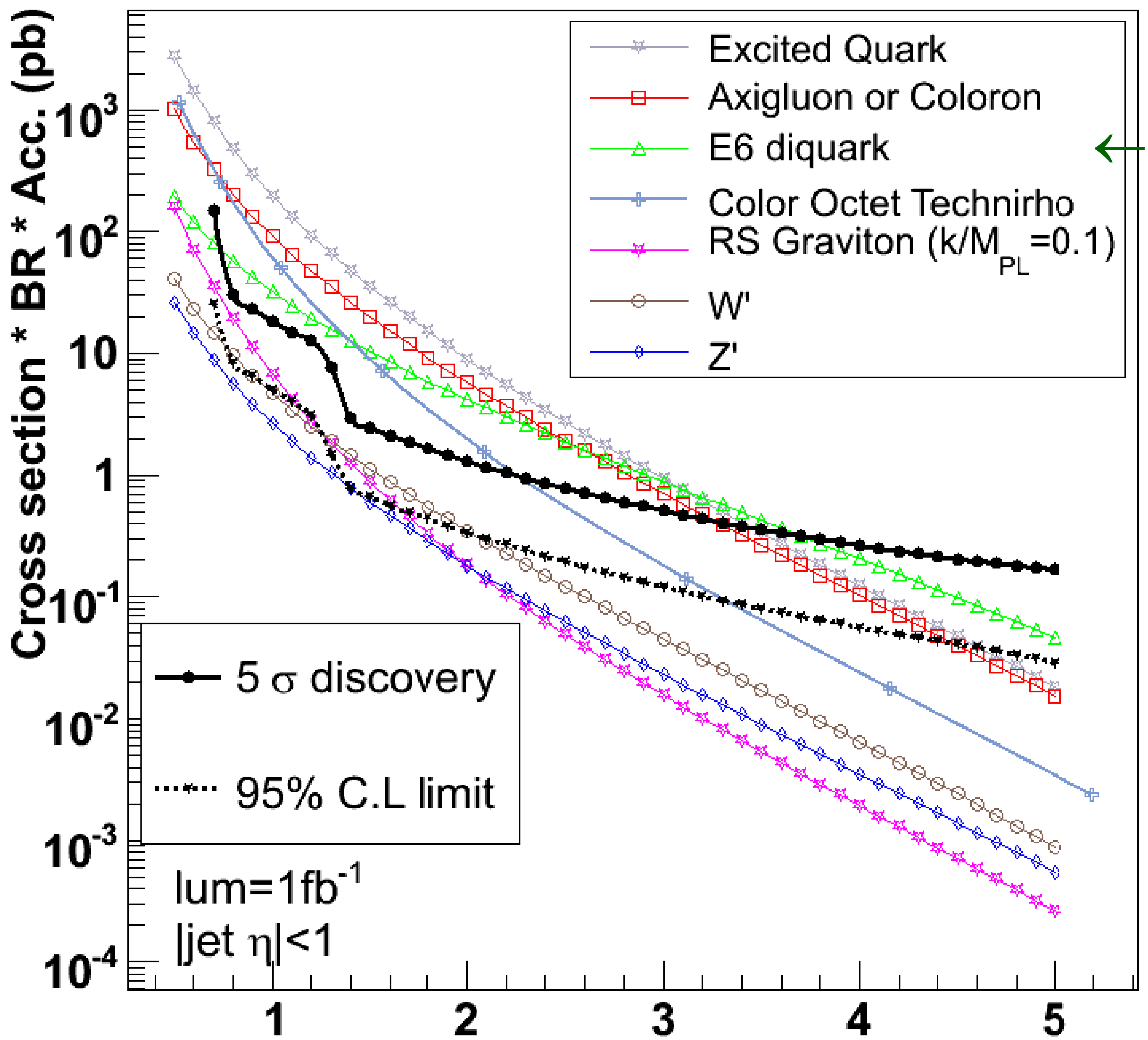
Then we get a cascade

Aside:

If the λ's become of order $10^{-(2-3)}$, the production of a single resonant spartner becomes possible and benefits from smaller phase space suppression, e.g. qq-bar -> sneutrino -> l^+l^-, jj. Many other processes are possible.







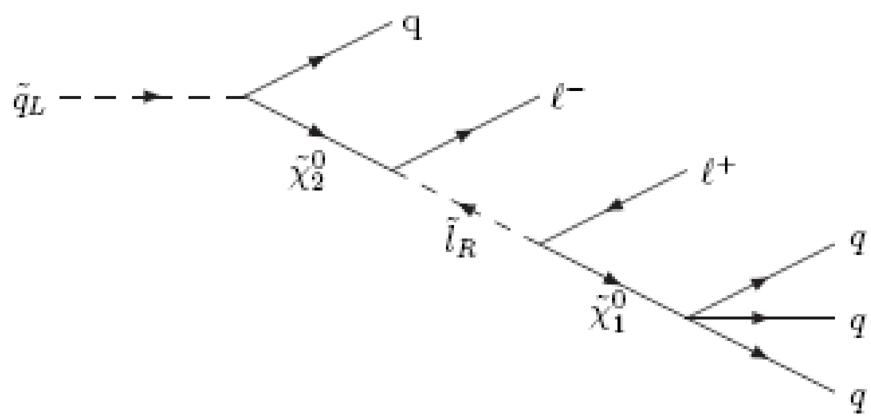
←RPV

Dijet Resonance Search

K. Gumus etal, CMS-NOTE-2006-070

In the case where the LSP is *not* strongly interacting there are two possibilities:

- The LSP will be the last SUSY particle in the decay chain initiated by a strongly interacting spartner which yields large rates, e.g.,



In this `worst' case scenario there are no additional leptons only jets (short-lived case studied by Allanach et al, ATLAS-COM-PHYS-2001-003)

In the long-lived case, one can select events with several high p_t jets and multi-leptons with large M_{eff} without the MET requirement. Then there are two sub-cases depending upon whether the LSP is charged or neutral.

In the charged case, one also observes a single pair of charged tracks each leading to a secondary vertex

In the neutral case, a pair of secondary vertices appear `from nowhere' as part of the event

The secondary vertex can be the source of leptons, jets or both depending on the type of R-parity violating coupling.

• However, unlike in the RPC case, here we might want to consider the *direct* production of weakly interacting LSP's, e.g., sleptons or charginos, if they are not too heavy. Ordinarily, this production mechanism is not given much attention due to large LHC backgrounds and small rates. With RPV these events may be quite clean.

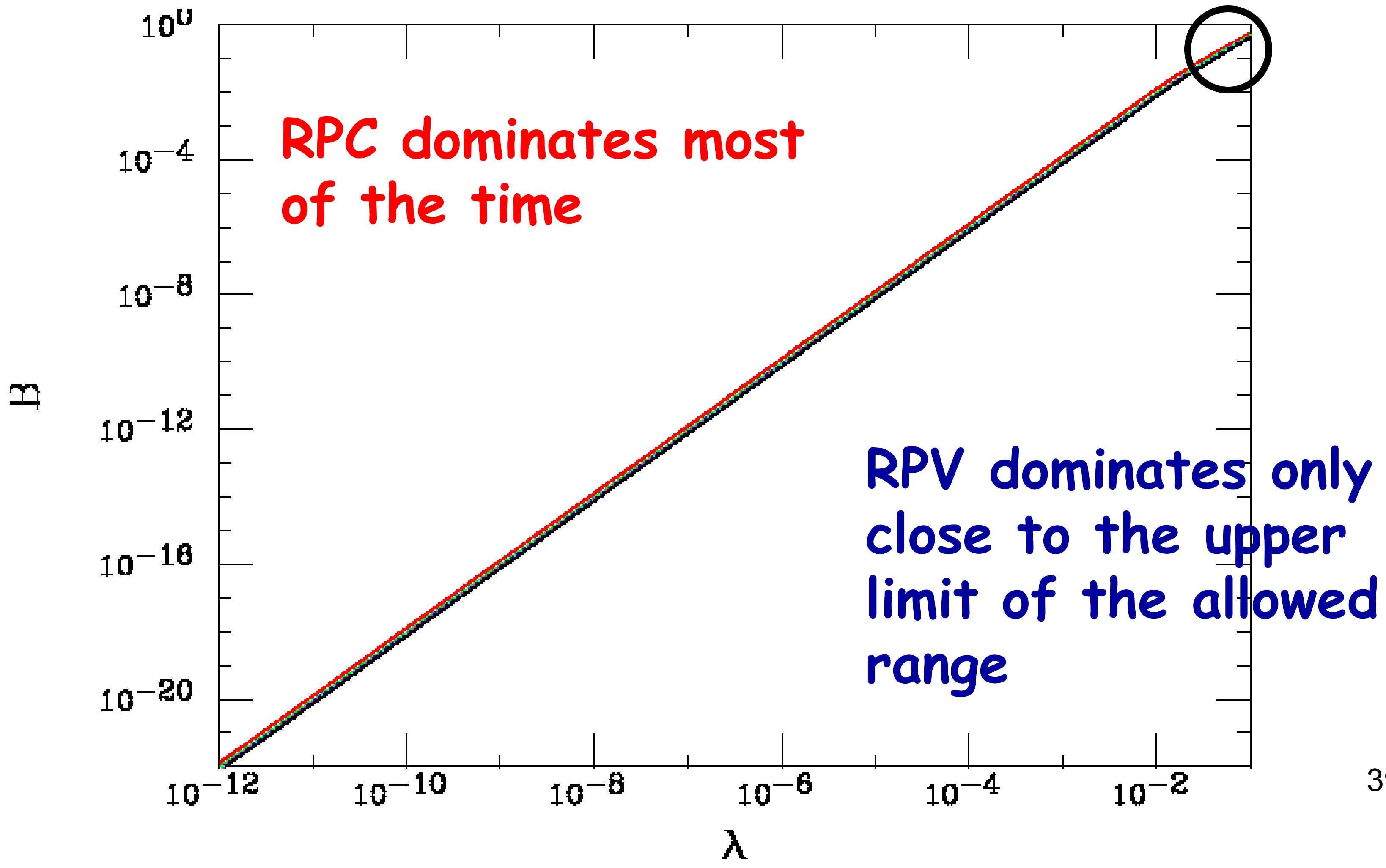
For example, if the lightest slepton is the LSP with a 0.5 cm decay length and a cross section of ~200 fb, we don't need to worry too much about backgrounds.

A variety of final states resulting from the secondary vertices are possible…

Gauginos	Decay mode	$LL\bar{E}$	$LQ\bar{D}$	$\bar{U}\bar{D}\bar{D}$
$\tilde{\chi}_1^0\,\tilde{\chi}_1^0$	Direct	$4\ell + \not{E}$	$1\ell + 4j + \not{E}$	$6j$
			$2\ell + 4j$	
			$4j + \not{E}$	
$\tilde{\chi}_1^+\,\tilde{\chi}_1^-$	Direct	$2\ell + \not{E}$	$1\ell + 4j + \not{E}$	$6j$
		$4\ell + \not{E}$	$2\ell + 4j$	
		6ℓ	$4j + \not{E}$	
$\tilde{\chi}_2^0\,\tilde{\chi}_1^0$	Indirect	$4\ell + \not{E}$	$1\ell + 4j + \not{E}$	$8j$
		$4\ell + 2j + \not{E}$	$1\ell + 6j + \not{E}$	$6j + 2\ell$
		$6\ell + \not{E}$	$2\ell + 4j + \not{E}$	$6j + \not{E}$
			$2\ell + 6j$	
			$3\ell + 4j + \not{E}$	
			$4\ell + 4j$	
			$6\ell + \not{E}$	
$\tilde{\chi}_1^+\,\tilde{\chi}_1^-$	Indirect	$4\ell + 4j + \not{E}$	$1\ell + 6j + \not{E}$	$10j$
		$5\ell + 2j + \not{E}$	$1\ell + 8j + \not{E}$	$8j + 1\ell + \not{E}$
		$6\ell + \not{E}$	$2\ell + 4j + \not{E}$	$6j + 2\ell + \not{E}$
			$2\ell + 6j + \not{E}$	
			$2\ell + 8j$	
			$3\ell + 4j + \not{E}$	
			$3\ell + 6j + \not{E}$	
			$4\ell + 4j + \not{E}$	
			$8j + \not{E}$	

The notations l, $\not{E}$ and j correspond, respectively, to charged lepton, missing energy from at least one neutrino and jet final states.

Finally, RPV decays may compete with RPC ones if the couplings are sufficiently large. Consider the decay $q_R \rightarrow q$+ bino vs $q_R \rightarrow lu$ via RPC. What is the RPV branching fraction???



Summary

- RPV can take many forms and can lead to significant changes in SUSY expectations, e.g., no MET signals and/or single spartner production
- The a priori allowed range of the potential B- or L-violating couplings is in general rather wide.
- The identity of the LSP is wide open and no longer need be the lightest neutralino as in the MSSM
- The LSP may be `almost stable' or can decay anywhere inside the detector

BACKUP SLIDES