Tests of R-parity violation*

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* for more details see hep-ph/0406039 (Phys. Rep. in press)

Introduction

R-parity is associated with a Z_2 subgroup of the group of continuous $U(1)$ R-symmetry transformations acting on the gauge and chiral superfields (it acts chirally on the anticommuting Grassmann coordinate θ appearing in the definition of superfields)

$$R_p \;=\; (-1)^R \;=\; \begin{cases} +1 & \text{for ordinary particles,} \\ -1 & \text{for their superpartners.} \end{cases}$$

Connection between R-parity and B and L conservation laws is

$$R\text{-parity} \;=\; (-1)^{2S}\,(-1)^{3B+L}$$

$\boldsymbol{R}$-Parity-Violating Couplings

Assuming R-parity invariance, the MSSM superpotential couplings are:

$$W_{R_p} \equiv W_{MSSM} = \mu H_u H_d + \lambda^e_{ij} H_d L_i E^c_j + \lambda^d_{ij} H_d Q_i D^c_j - \lambda^u_{ij} H_u Q_i U^c_j \,.$$

In the absence of R-parity, however, R-parity odd terms allowed by renormalizability and gauge invariance (48 param.)

$$W_{\not R_p} = \mu_i H_u L_i + \frac{1}{2} \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2} \lambda''_{ijk} U^c_i D^c_j D^c_k$$

The ones that violate lepton-number conservation can be easily found by noting that the lepton superfields L_i and the Higgs superfield H_d have exactly the same gauge quantum numbers. Gauge invariance enforces antisymmetry

$$\lambda_{ijk} = -\lambda_{jik} \,, \qquad \lambda''_{ijk} = -\lambda''_{ikj} \,.$$

In the absence of R-parity, one must also consider the soft terms associated with $W_{\not R_p}$ (51 param.):

$$
\begin{aligned}
V_{\not R_p}^{soft} &= \frac{1}{2} A_{ijk}\, \tilde{L}_i \tilde{L}_j \tilde{l}^c_k \;+\; A'_{ijk}\, \tilde{L}_i \tilde{Q}_j \tilde{d}^c_k + \;\frac{1}{2} A''_{ijk}\, \tilde{u}^c_i \tilde{d}^c_j \tilde{d}^c_k \\
&\quad + B_i\, h_u \tilde{L}_i \;+\; \widetilde{m}^2_{di}\, h^\dagger_d\, \tilde{L}_i \;+\; \text{h.c. .}
\end{aligned}
$$

Note that one can freely rotate the weak eigenstate basis by a unitary transformation

$$
\begin{pmatrix} H_d \\ L_i \end{pmatrix} \rightarrow \begin{pmatrix} H'_d \\ L'_i \end{pmatrix} = U \begin{pmatrix} H_d \\ L_i \end{pmatrix} ,
$$

where U is an $SU(4)$ matrix. It is clear that the values of the lepton-number-violating couplings are basis-dependent. 3 among the 9 bilinear $\not R_p$ parameters μ_i, B_i and $\widetilde{m}^2_{di}$ can be rotated away leaving $48 + 51 - 3 = 96$ parameters.

Renormalization group

The superpotential including RpV in a compact notation

$$W \;=\; \mu_\alpha H_u \hat{L}_\alpha \;+\; \frac{1}{2}\lambda^e_{\alpha\beta k}\,\hat{L}_\alpha \hat{L}_\beta E^c_k + \lambda^d_{\alpha jk}\,\hat{L}_\alpha Q_j D^c_k \;+ \lambda'' \text{ and } \lambda^u_{ij} \text{ terms},$$

where $\alpha \equiv (0,i) = (0,1,2,3)$, $\beta \equiv (0,j) = (0,1,2,3)$ and :

$$H_d \equiv \hat{L}_0\,, \qquad \mu \equiv \mu_0\,,$$

$$\lambda^e_{0jk} \equiv \lambda^e_{jk}\,, \qquad \lambda^d_{0jk} \equiv \lambda^d_{jk}\,.$$

The RGEs for the bilinear μ terms are:

$$\frac{d}{dt}\mu_\alpha = \mu_\alpha\,\Gamma_{uu} + \mu_\beta\,\Gamma_{\alpha\beta},$$

where $t = \log q^2$ and Γ are the anomalous dimensions. If we start with all $\mu_i = 0$, non-zero μ_i will be generated through the RGEs via a non-zero μ_0 and vice-versa.

The RGEs for the Yukawa couplings are

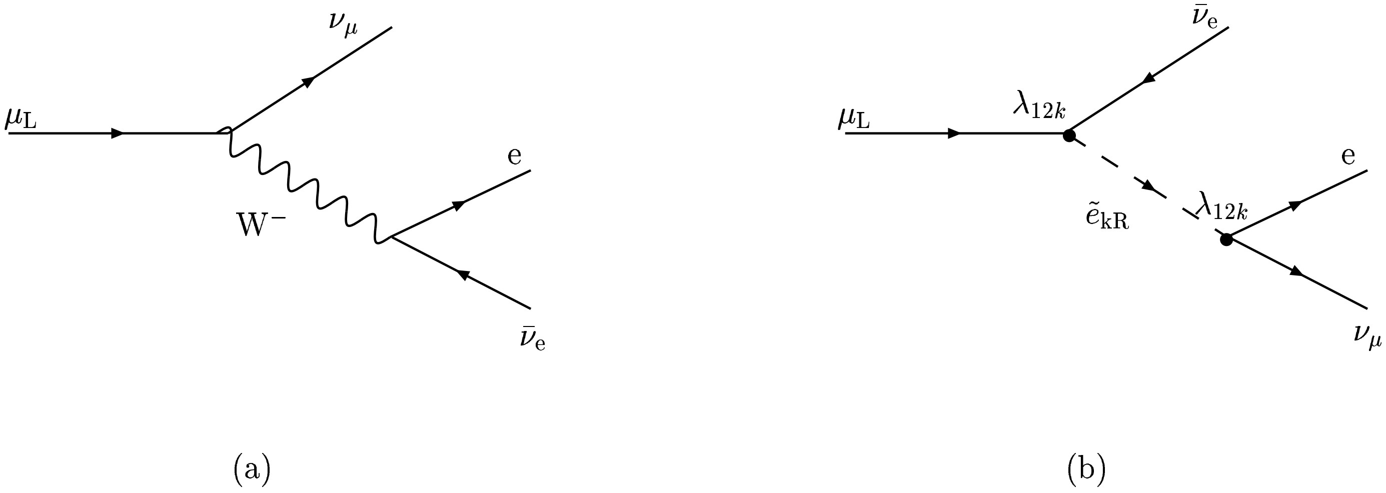
$$\begin{aligned}
\frac{d}{dt}\lambda^e_{\alpha\beta k} &= \lambda^e_{\alpha\beta l}\,\Gamma_{E_l\,E_k} + \lambda^e_{\alpha\delta k}\,\Gamma_{\delta\beta} + \lambda^e_{\gamma\beta k}\,\Gamma_{\gamma\alpha}\ , \\
\frac{d}{dt}\lambda^d_{\alpha jk} &= \lambda^d_{\alpha jl}\,\Gamma_{D_l\,D_k} + \lambda^d_{\alpha lk}\,\Gamma_{Q_l\,Q_j} + \lambda^d_{\gamma jk}\,\Gamma_{\gamma\alpha}\ ,
\end{aligned}$$

$$\begin{aligned}
\frac{d}{dt}\lambda^u_{ij} &= \lambda^u_{ik}\,\Gamma_{U_j\,U_k} + \lambda^u_{ij}\,\Gamma_{uu} + \lambda^u_{kj}\,\Gamma_{Q_i\;Q_k}\ , \\
\frac{d}{dt}\lambda''_{ijk} &= \lambda''_{ilk}\,\Gamma_{D_j\;D_l} + \lambda''_{ljk}\,\Gamma_{U_i\,U_l} + \lambda''_{ijl}\,\Gamma_{D_k\;D_l}.
\end{aligned}$$

RGEs for the Yukawa couplings preserve $\lambda''{}_{ijk} = 0$. The same is true if lepton parity is imposed at some scale for λ^e_{ijk} and λ^d_{ijk}. If however one imposes only one coupling to be non-zero at some scale, this remains in general not true at all scales.

Charged current interactions

$L_1 L_2 E^c_k$ additional contribution to the muon decay



The uncertainty in M_W dominates. $\lambda_{12k} < 0.07\,\tilde{e}_{kR}$. From τ leptonic decays

$$\lambda_{13k} < 0.07\,\tilde{e}_{kR}\,[R_\tau]; \quad \lambda_{23k} < 0.07\,\tilde{e}_{kR}\,[R_\tau]; \quad \lambda_{23k} < 0.07\,\tilde{e}_{kR}\,[R_{\tau\mu}].$$

$$R_\tau = \Gamma(\tau \to e\bar{\nu}_e\nu_\tau)/\Gamma(\tau \to \mu\bar{\nu}_\mu\nu_\tau) \qquad R_{\tau\mu} = \Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu})$$

Leptonic decays of the π as well as $\tau^- \to \pi^- \nu_\tau$ can be mediated at the tree level by RpV interactions giving

$$\lambda'_{21k} < 0.059\, \tilde{d}_{kR},\ \lambda'_{11k} < 0.026\, \tilde{d}_{kR},\ \lambda'_{31k} < 0.12\, \tilde{d}_{kR}\ .$$

In the quark sector, the presence of a $LQ\bar{D}$ operator leads to additional contributions to quark semileptonic decays.

$$\lambda_{12k} < 0.05\, \tilde{e}_{kR}, \quad \lambda'_{11k} < 0.02\, \tilde{d}_{kR},$$
$$(\lambda'^{\star}_{11k}\lambda'_{12k})^{1/2} < 0.04\, \tilde{d}_{kR}, \quad (\lambda'^{\star}_{11k}\lambda'_{13k})^{1/2} < 0.37\, \tilde{d}_{kR}.$$

For more bounds from meson decays see hep-ph/0301079.

Neutral current interactions

$R\!\!\!/_p$ interactions lead to corrections to fermion pair production. Example 2σ bounds from A_{FB}:

$$\lambda_{ijk} < 0.37\ \tilde{\nu}_{jL} \quad ; \quad (ijk) = (121), (131) \quad [A^e_{FB}]$$
$$\lambda_{ijk} < 0.25\ \tilde{\nu}_{jL} \quad ; \quad (ijk) = (122), (132), (211), (231) \quad [A^\mu_{FB}]$$
$$\lambda_{ijk} < 0.11\ \tilde{\nu}_{jL} \quad ; \quad (ijk) = (123), (133), (311), (321) \quad [A^\tau_{FB}]$$
$$\lambda'_{12k} < 0.21\ \tilde{d}_{kR} \quad [A^c_{FB}]$$
$$\lambda'_{1j2} < 0.28\ \tilde{u}_{jL} \quad [A^s_{FB}]$$
$$\lambda'_{1j3} < 0.18\ \tilde{u}_{jL} \quad [A^b_{FB}]$$

Low energy precision experiment can also be used to set bounds. APV from $^{133}_{55}$Cs gives in the single coupling dominance hypothesis the $2-\sigma$ bounds:

$$|\lambda_{12k}| < 0.05\ \tilde{e}_{kR},\ |\lambda'_{11k}| < 0.02\ \tilde{d}_{kR},\ |\lambda'_{1j1}| < 0.03\ \tilde{u}_{jL} \quad .$$

Collider phenomenology

Even for weak RpV interaction strengths, LSP decay will lead to event topologies departing considerably from the characteristic ”missing momentum” of R_p conserving theories.

Weakest RpV couplings likely to be felt through the decay of sparticles otherwise pair produced via gauge couplings. Strongest RpV coupling contribute to single sparticle production.

- In practice assume a strong hierarchy among the trilinear couplings to make predictions.
- Hierarchy by analogy with Yukawa couplings structure in the SM ?
- Bilinears often neglected in collider analyses (strong constraints from the neutrino sector)
- Complementarity of bounds from sigly produced sparticle, displaced vertices and low energy constraints.

Resonant Production of Sfermions at Colliders (lowest-order processes)				
Collider	Coupling	Sfermion Type	Elementary Process	
e^+e^-	λ_{1j1}	$\tilde{\nu}_\mu, \tilde{\nu}_\tau$	$l_i^+ l_k^- \rightarrow \tilde{\nu}_j$	$i = k = 1\,,\ j = 2, 3$
pp, $p\bar{p}$	λ'_{ijk}	$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$	$d_k \bar{d}_j \rightarrow\ \tilde{\nu}_i$	$i, j, k = 1, \ldots, 3$
		$\tilde{e}, \tilde{\mu}, \tilde{\tau}$	$u_j \bar{d}_k \rightarrow\ \tilde{l}_{iL}$	$i, k = 1, \ldots, 3\,,\ j = 1, \ldots, 2$
	λ''_{ijk}	$\tilde{d}, \tilde{s}, \tilde{b}$	$\bar{u}_i \bar{d}_j \rightarrow\ \tilde{d}_k$	$i, j, k = 1, \ldots, 3\,,\ j \neq k$
		$\tilde{u}, \tilde{c}, \tilde{t}$	$\bar{d}_j \bar{d}_k \rightarrow\ \tilde{u}_i$	$i, j, k = 1, \ldots, 3\,,\ j \neq k$
ep	λ'_{1jk}	$\tilde{d}_R, \tilde{s}_R, \tilde{b}_R$	$l_1^- u_j \rightarrow \tilde{d}_{kR}$	$j = 1, 2$
	λ'_{1jk}	$\tilde{u}_L, \tilde{c}_L, \tilde{t}_L$	$l_1^+ d_k \rightarrow \tilde{u}_{jL}$	$i, j, k = 1, \ldots, 3$

Table 1: *Sfermions s-channel resonant production at colliders. Charge conjugate processes are also possible.*

Tevatron searches Run II

$\tilde{\chi}_1^0$ pair production

2 electrons plus taus final state in the weak RpV scenario (RpV coupling much smaller than the gauge couplings and only affect LSP decay)

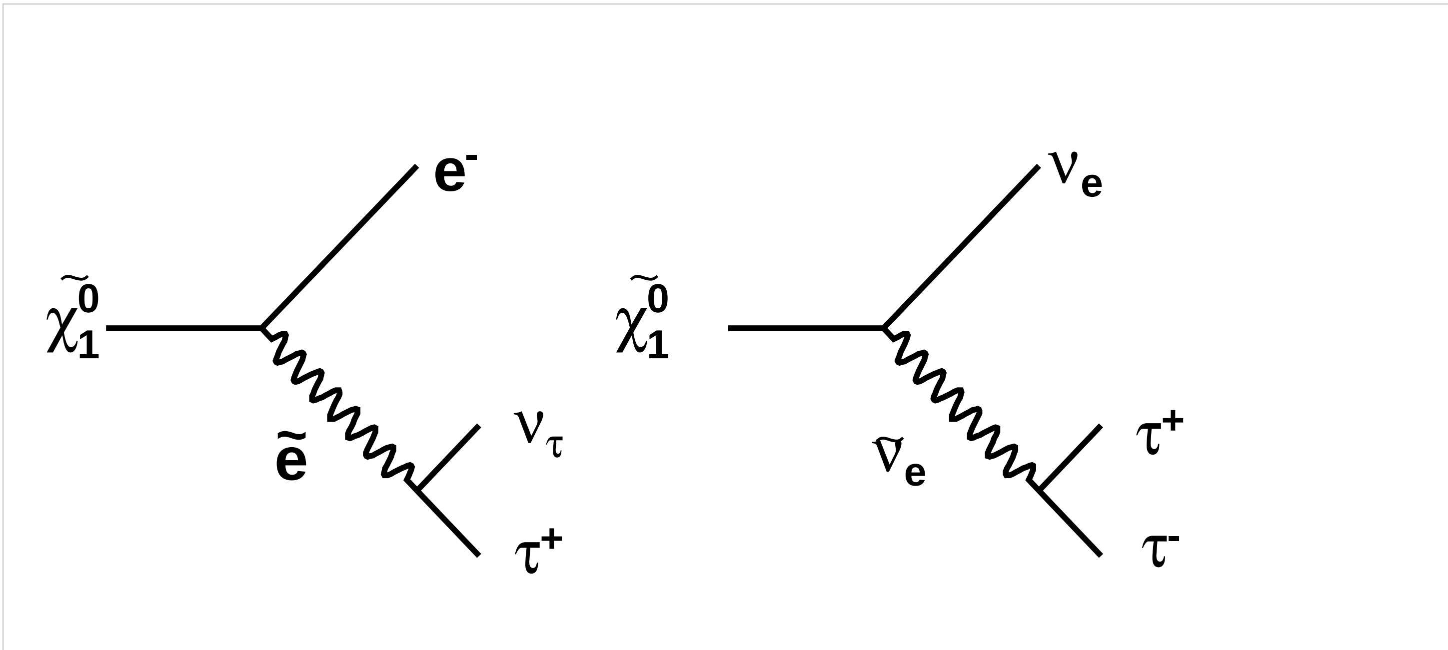


Figure 1: $\tilde{\chi}_1^0$ *RpV decay with* λ_{133} *coupling*

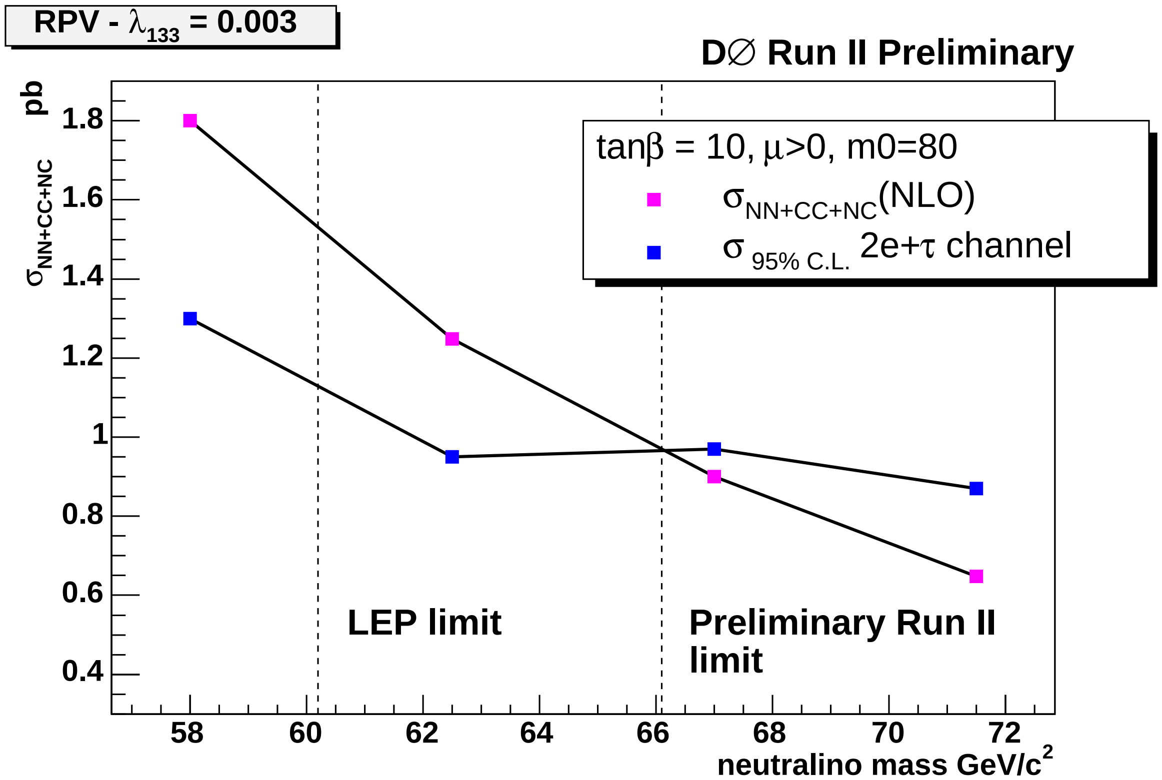


Figure 2: *D0 search for 2 electrons plus taus with missing transverse energy. Integrated luminosity of* 198.7 ± 12.9 *pb*$^{-1}$. *95% C.L. upper limit on the cross-section compared to the theoretical one. Note D0-4595*

Smuon production

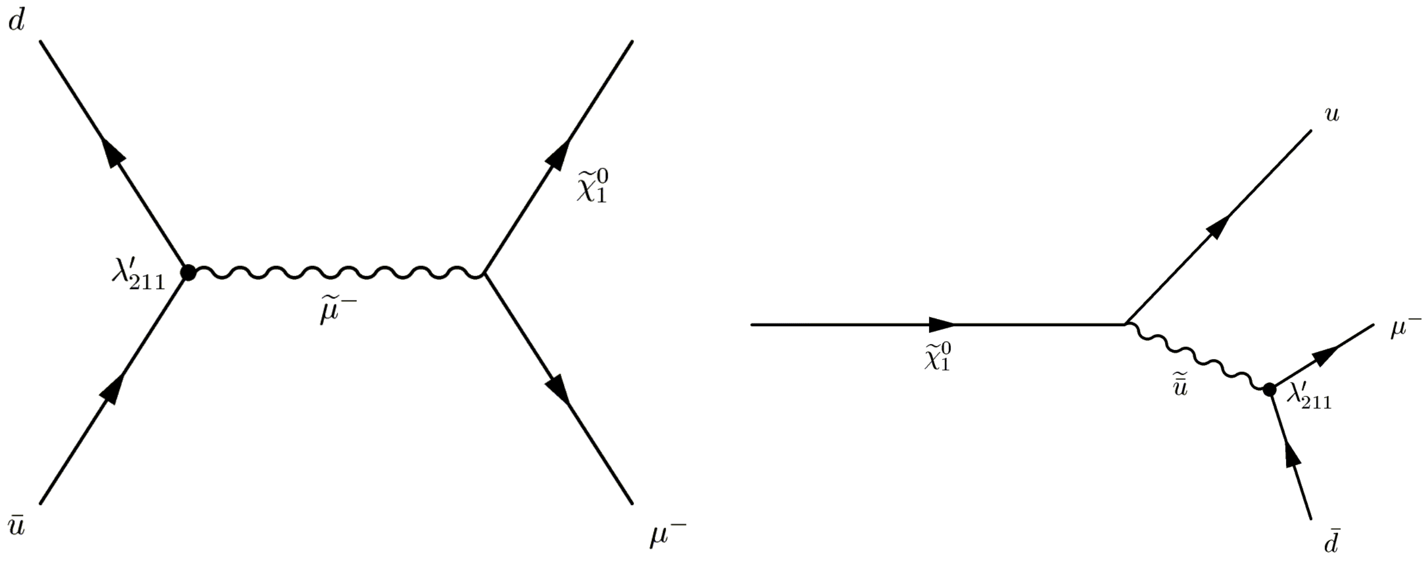


Figure 3: *Resonant smuon production and neutralino decay via* λ'_{211}

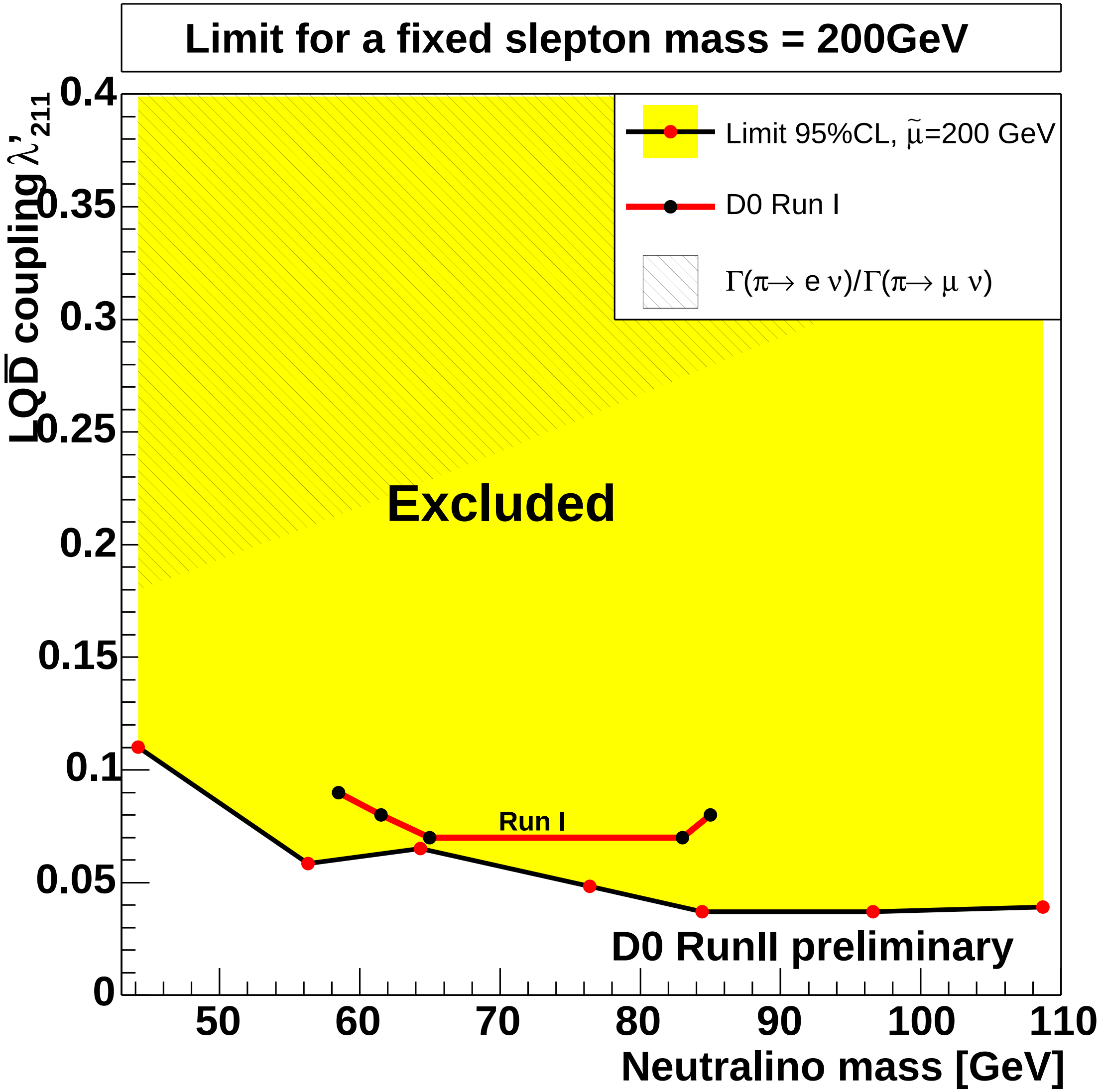


Figure 4: *D0 95% C.L. limit on* λ'_{211} *for a slepton mass of 200 GeV. Integrated luminosity of* 153.8 *pb*$^{-1}$*. Note D0-4535*

Stop pair production

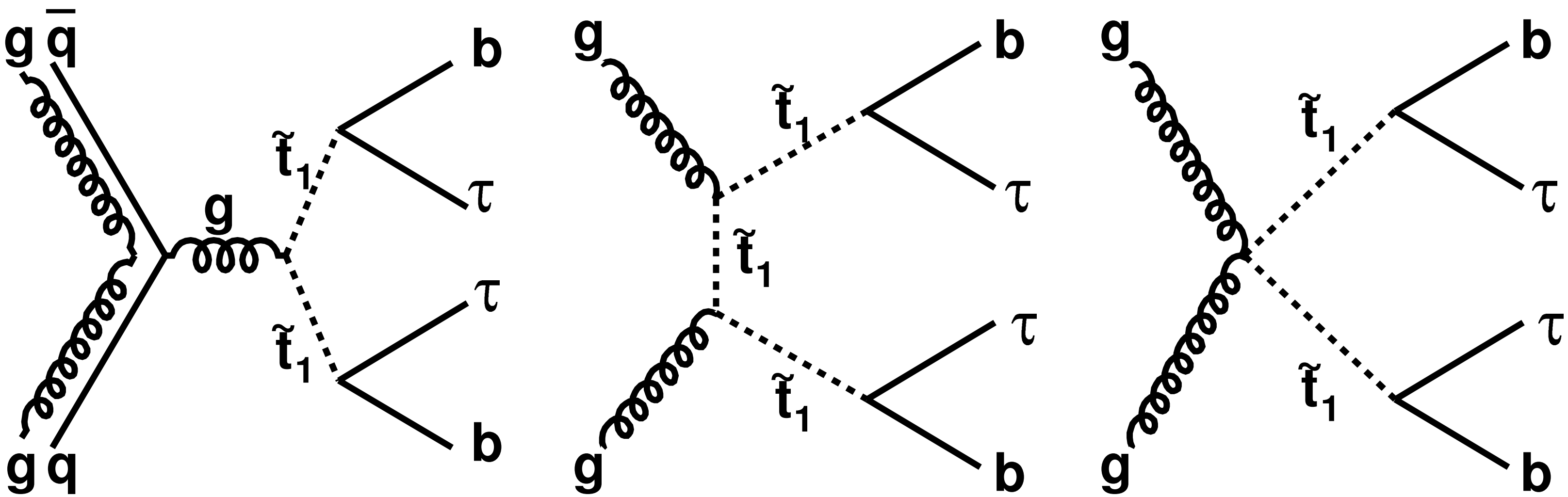


Figure 5: *Feynman diagrams for stop pair production.*

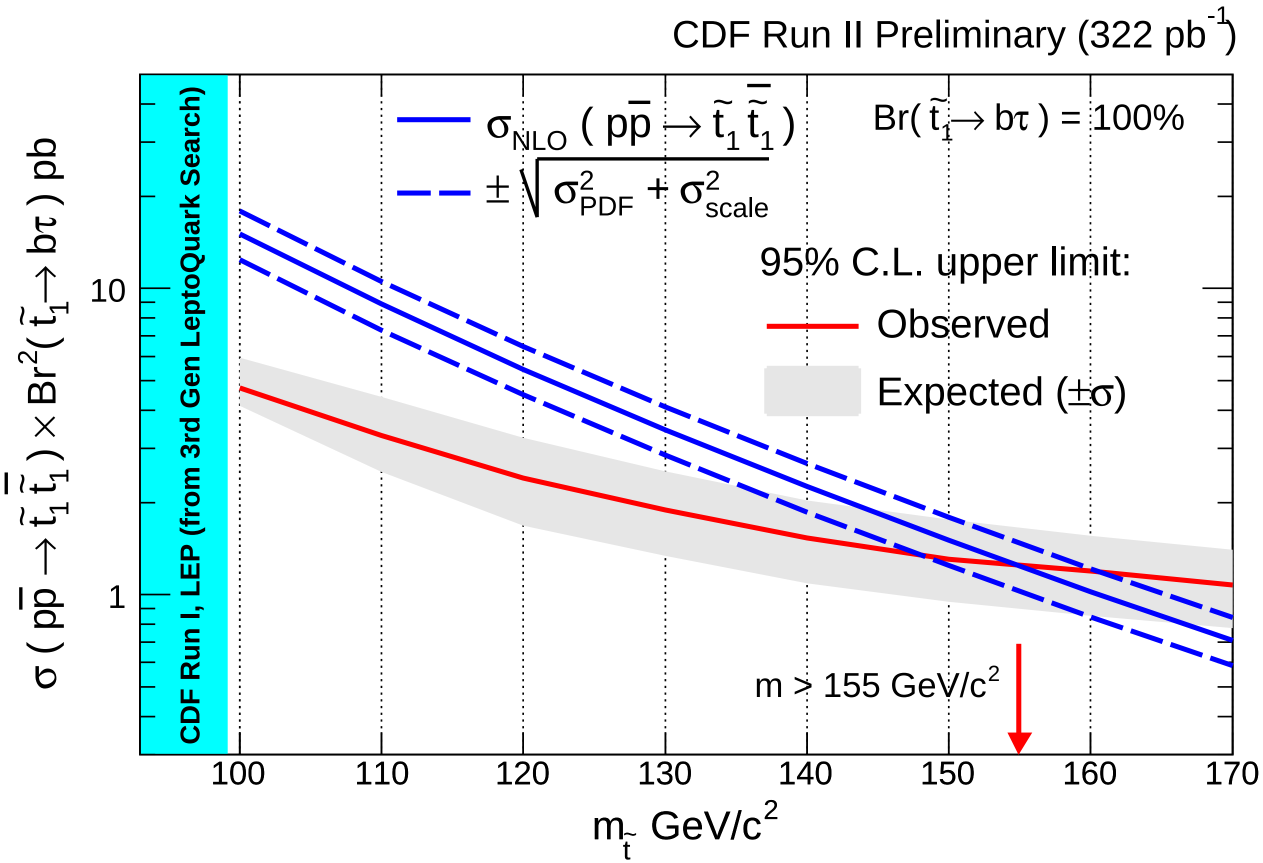


Figure 6: *Exclusion limit in the plane of the cross section of stop pair production vs. stop mass. Observed limit is shown as a red line; expected limit is shown as a band and corresponds to 68% probability; theoretical cross-section (solid blue line) and its uncertainty (dashed blue lines); earlier limit from CDF and LEP. CDF note 7835*

Sneutrino production and decay

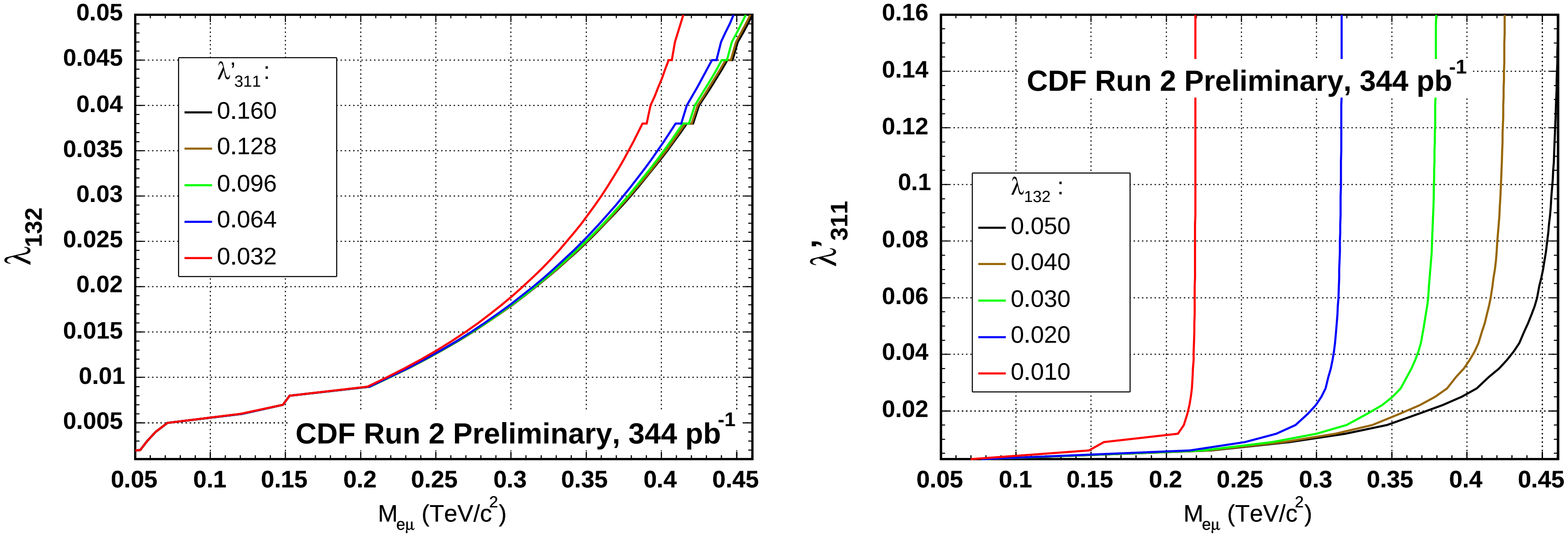


Figure 7: *Excluded values for the RpV couplings for production and decay of the tau sneutrino. The exclusion curves for each coupling are drawn for several values of the alternate coupling. CDF note 7616*

Hera searches

With an initial e^+ beam the sensitivity is highest to couplings λ'_{1j1} ($j = 1, 2, 3$), where mainly $\widetilde{u}_L^j$ squarks are produced. In contrast, with an initial e^- beam HERA is most sensitive to couplings λ'_{11k} ($k = 1, 2, 3$) and can mainly produce $\widetilde{d}_R^k$ squarks.

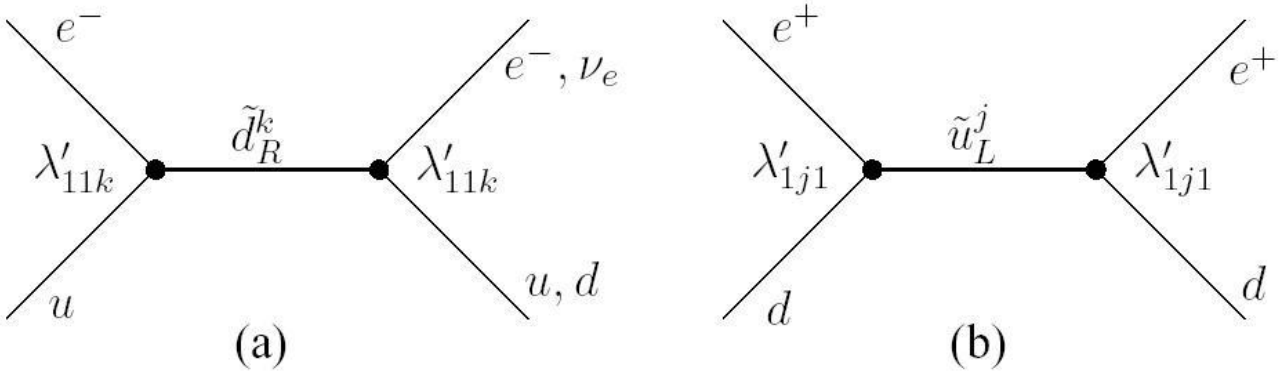


Figure 8: *Lowest order s-channel diagrams for RpV squark production via the Yukawa coupling λ' in (a) e^-p and (b) e^+p interactions, followed by RpV squark decays.*

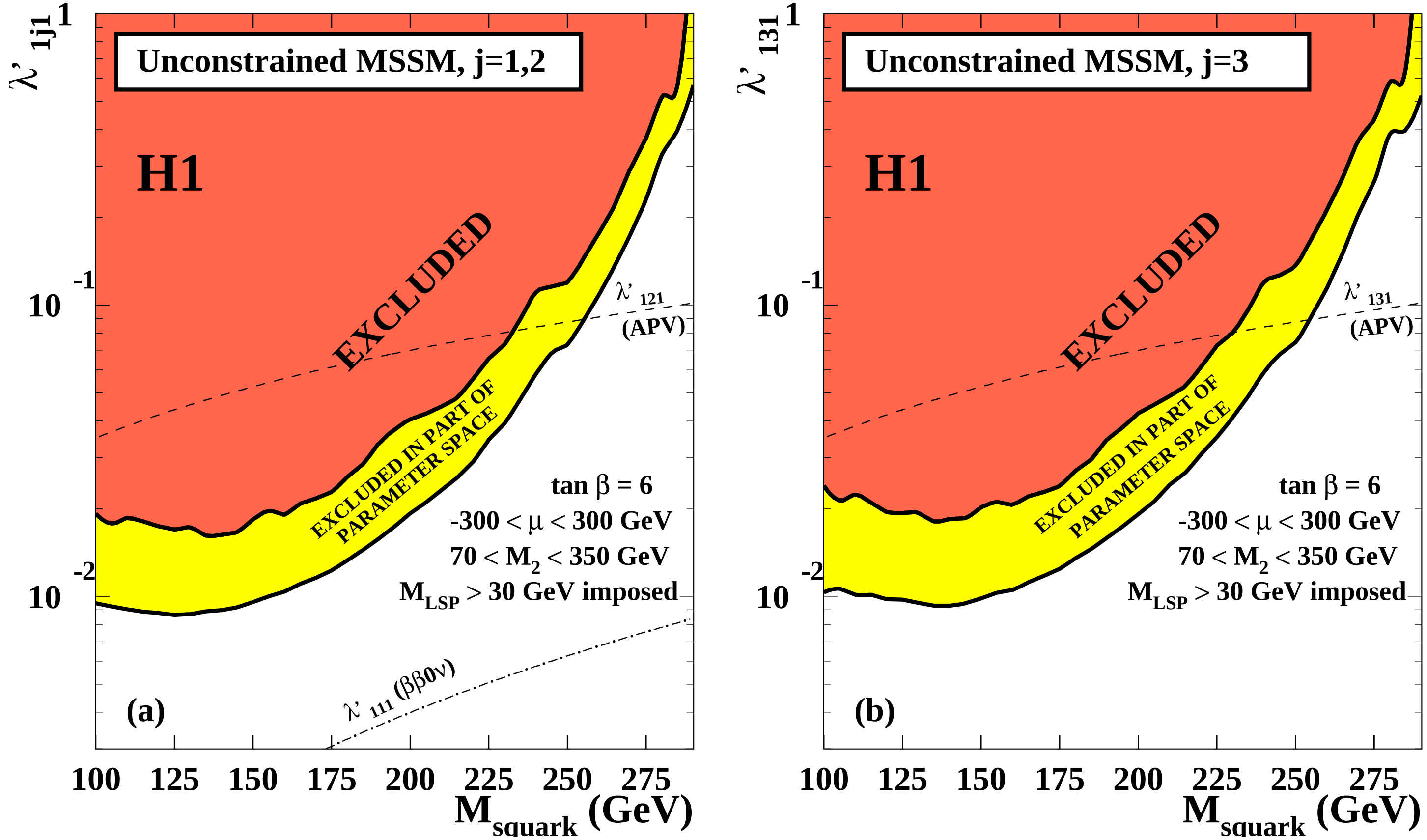


Figure 9: *Exclusion limits ($95\,\%$ CL) on λ'_{1j1} for (a) $j = 1, 2$ and (b) $j = 3$ as a function of the squark mass. The two full curves indicate the strongest and the weakest limits on λ' in the parameter space investigated. From hep-ex/0403027.*

LHC searches

Single top production indicate that the LHC is better at probing the B-violating couplings λ'' whereas the Tevatron and the LHC have a similar sensitivity to λ' couplings.

$m_{\tilde{s}}$ (GeV)	300		600	
Γ_R (GeV)	0.5	20	0.5	20
N_s	6300	250	703	69
N_b	4920	5640	558	1056
Limits on $\lambda'' \times \lambda''$	2.36$\times 10^{-3}$	1.21$\times 10^{-2}$	4.10$\times 10^{-3}$	1.51 $\times 10^{-2}$

Table 2: *Limits for the values of the $\lambda''_{132}\lambda''_{332}$ Yukawa couplings from $ud \to \tilde{s} \to tb \to Wbb$ for an integrated luminosity of 30 fb^{-1}. Current limit is 6.25$\times 10^{-1}$. hep-ph/9910483*

$t\bar{t}$ pair production followed by RpV decay of one of the top quarks

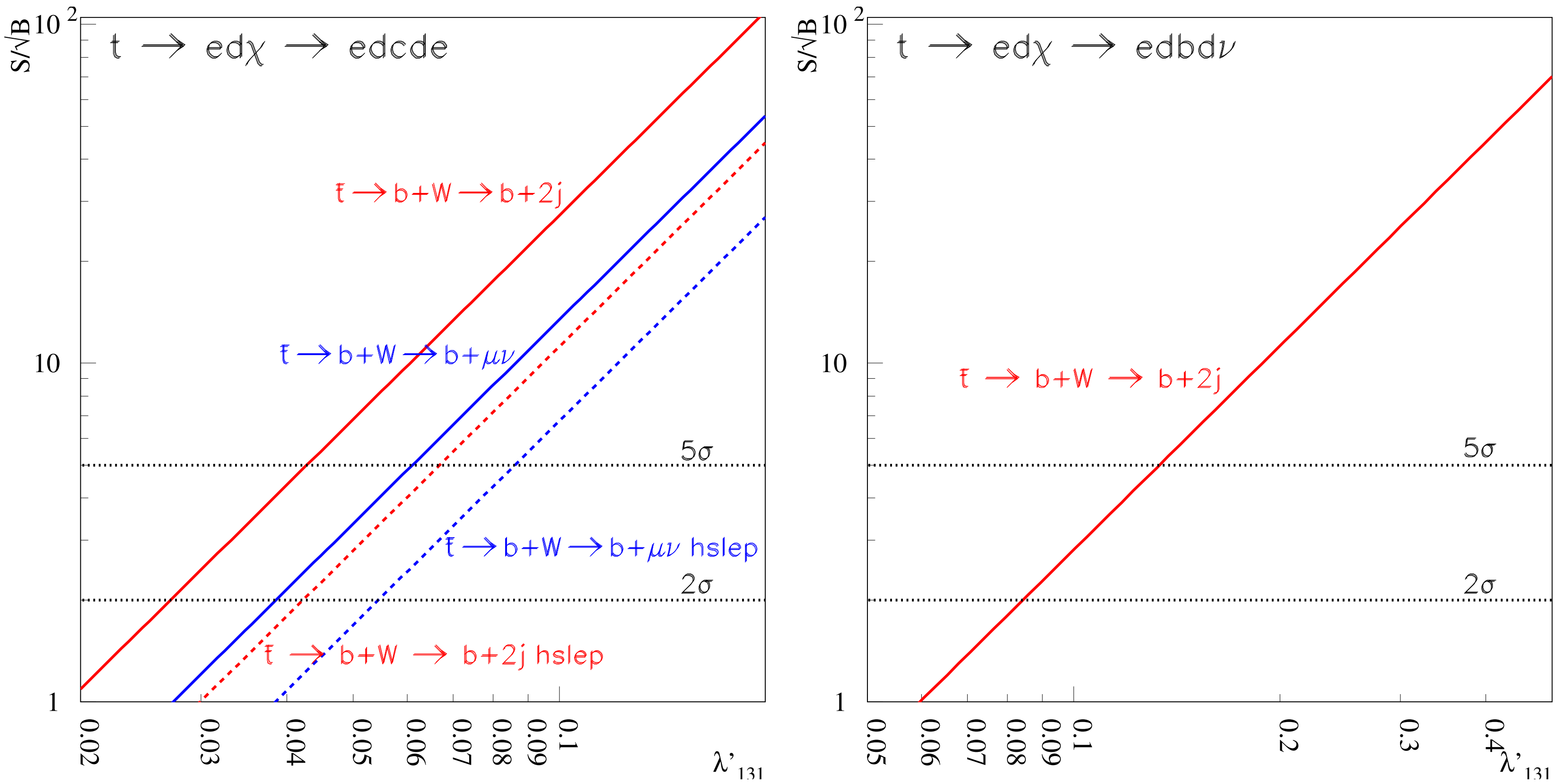


Figure 10: $S/\sqrt{B}$ *vs* λ' *for* $\tilde{\chi}^0 \to cde$*(left) and* $\tilde{\chi}^0 \to bd\nu$*(right) channels. For* $W \to \mu\nu$ *decay channel* $m_{\tilde{\ell}} = 150$ *GeV (solid line) and* $m_{\tilde{\ell}} = 200$ *GeV (dashed line). From hep-ph/0401065*

Resonant production of sneutrinos

Test R-parity violating couplings $\lambda'_{ijk} L_i Q_j D^c_k$ through its three-leptons signature

$$\begin{array}{lll}\tilde{\nu}_\mu & \rightarrow & \tilde{\chi}^+_1 \; \mu^- \\ & & \;\; \hookrightarrow \tilde{\chi}^0_1 \;\; W^+ \rightarrow e^+(\mu^+)\nu \\ & & \qquad\quad \hookrightarrow \mu^\pm \; q \; \bar{q}' \end{array} \quad (1)$$

λ'_{211}	λ'_{212}	λ'_{213}	λ'_{221}	λ'_{222}	λ'_{223}	λ'_{231}	λ'_{232}	λ'_{233}
0.01	0.02	0.02	0.02	0.03	0.05	0.03	0.06	0.09

Table 3: *Sensitivities on the* λ'_{2jk} *coupling constants deduced from the sensitivity on* λ'_{211} *for* $\tan\beta$*=1.5,* $M_1 = 100$ *GeV,* $M_2 = 200$ *GeV,* $\mu = -500$ *GeV,* $m_{\tilde{q}} = m_{\tilde{l}} = 300$ *GeV and* $m_{\tilde{\nu}} = 400$ *GeV. hep-ph/0003012*

Dimuon production

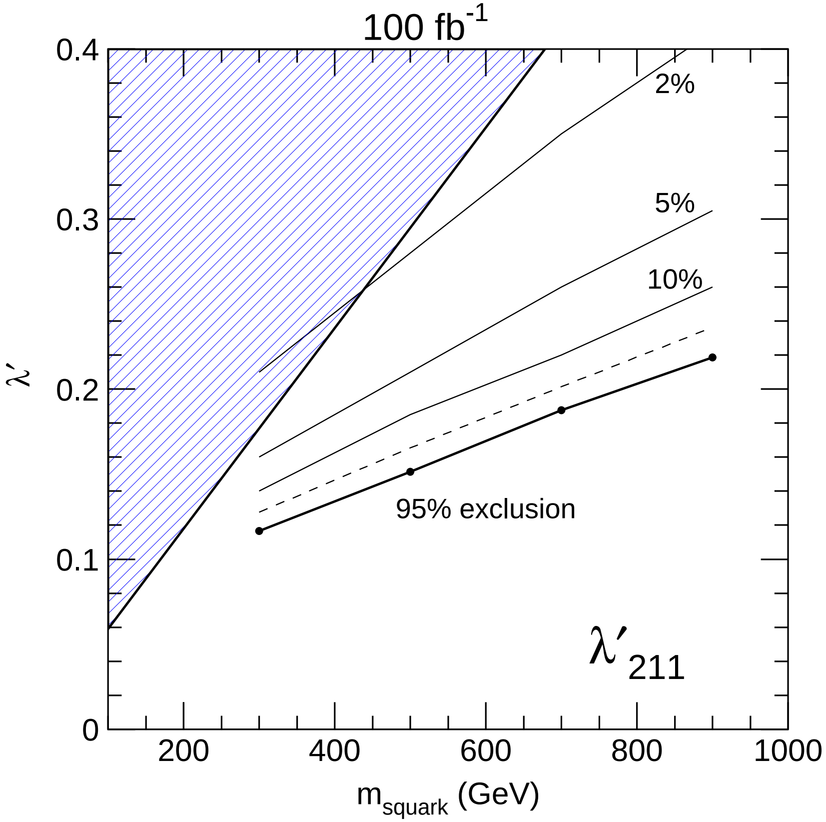


Figure 11: *95% sensitivity in the $m_{\tilde{q}}$–λ' plane for 100 pb^{-1}. Contours correspond to uncertainty on λ' of 2, 5 and 10% . Shaded region excluded by low energy measurements. From hep-ph/0207248.*

Conclusions

- RpV leads to event topologies departing considerably from the characteristic ”missing momentum” of R_p conserving theories.
- Couplings of the order of 10^{-1}-10^{-2}, could lead to observable effects at high energy colliders
- Knowledge about conservation or possible violations of R-parity is expected to be essential for the understanding of the general flavour problem