Bounds from $t\bar{t}$ production on $R$-parity violating models of supersymmetry

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ABSTRACT

We study $t\bar{t}$ production in $R$-parity violating supersymmetry. The annihilation channel $q\bar{q} \rightarrow t\bar{t}$ gets new contributions from $t$-channel exchange of squarks or sleptons. With the data from Tevatron on $t\bar{t}$ production, we find that the squark- or slepton-exchange processes constrain the $B$-violating $\lambda''$ couplings or the $L$-violating $\lambda'$ couplings, respectively. Our bounds are already comparable to the few existing constraints on third-generation $R$-parity violating couplings, and will improve when more precise measurements of the $t\bar{t}$ production cross-section become available. We also discuss the effects of these couplings for top production at the LHC.
Supersymmetry is considered to be one of the most promising candidates for physics beyond the Standard Model (SM) and, consequently, a significant amount of effort has been devoted to looking for signals of supersymmetry in experiments. The minimal supersymmetric extension of the Standard Model (MSSM) \[1\] contains, in addition to the usual particles of the Standard Model, their superpartners and two Higgs doublets. While the gauge structure of the MSSM essentially replicates that of the Standard Model, the Yukawa sector of the MSSM is somewhat more complicated. In addition to the usual Yukawa couplings of the fermions to the Higgs (responsible for the fermion masses), other interactions involving squarks or sleptons are possible.

The relevant part of the superpotential containing the Yukawa interactions involving squarks or sleptons in the MSSM is given in terms of the chiral superfields by

\[
W = \lambda_{ijk} \epsilon_{\alpha\beta} L_i^\alpha L_j^\beta E_k^c + \lambda'_{ijk} \epsilon_{\alpha\beta} L_i^\alpha Q_j^\beta D_k^c + \epsilon_{\alpha\beta} \mu_i L_i^\alpha H_2^\beta + \lambda''_{ijk} \epsilon^{abd} U_i^a D_j^b D_k^d \tag{1}
\]

where the \(L_i\) and \(Q_i\) are \(SU(2)\)-doublet lepton and quark superfields and the \(E_i, U_i, D_i\) are singlet superfields, \(H_2\) is a Higgs superfield, \(c\) denotes conjugation, \(i, j, k\) are generation indices, \(\alpha, \beta\) are \(SU(2)\) indices and \(a, b, d\) are \(SU(3)\) indices. The couplings \(\lambda, \lambda'\) and \(\mu_i\) violate lepton (\(L\)) number, whereas the \(\lambda''\) coupling violates baryon (\(B\)) number. The \(B\)-and \(L\)-violating couplings cannot be present simultaneously, because that would lead to very rapid proton decay. The term \(\epsilon_{\alpha\beta} \mu_i L_i^\alpha H_2^\beta\) is not usually included, because it can be rotated away from the superpotential by a redefinition of the Higgs \(H_1\) and the leptonic \(L_i\) superfields \[2\]. We will not consider this term any further. It is possible to forbid the existence of all the interactions in Eq. (1) by imposing a discrete symmetry – \(R\)-parity. This discrete symmetry may be represented by \(R = (-1)^{3B+L+2S}\), where \(S\) is the spin of the particle, so that the usual particles of the SM have \(R = 1\), while their superpartners have \(R = -1\).

The requirement that the MSSM Lagrangian be invariant under \(R\)-parity is sufficient to exclude each of the interactions in Eq. (1). However, \(R\)-parity conservation is too strong a requirement to ensure proton stability \[4\] – the latter can simply be ensured by assuming that either the \(L\)-violating or the \(B\)-violating couplings in Eq. (1) are present, but not both. Relaxing the requirement of \(R\)-parity conservation has important implications for supersymmetric particle searches at colliders: a superparticle can decay into standard particles \textit{via} the \(R\)-parity violating couplings in Eq. (1), and, hence, the lightest supersymmetric particle will no longer be stable or escape detection. Thus bounds on MSSM parameters derived from missing energy and momentum signals are no longer valid in \(R\)-parity violating scenarios.

In this letter, we will not be concerned with the \(L\)-violating \(\lambda\) couplings, since we will be interested in the effects of \(R\)-parity violation at hadronic colliders. Consequently, we

\[^1\text{We remark that this redefinition does not leave the full Lagrangian (i.e. including the soft supersymmetry-breaking terms) invariant and can be achieved only at the expense of generating two additional complex parameters in the soft supersymmetry-breaking sector of the Lagrangian \[\mathcal{L}\]. This complication is of no consequence to our analysis.}\]
focus on $\lambda'$ and $\lambda''$ couplings and we begin by presenting a quick review of the existing bounds on the $\lambda'$ and $\lambda''$ couplings. Direct searches for the squarks coupling to quarks and leptons via the $L$-violating interaction induced by the $\lambda'$ coupling, by the CDF \cite{CDF} and the D0 experiments \cite{D0} at the Tevatron yield bounds \cite{7} on the first generation squark which are of the order of 100 GeV (almost irrespective of the size of the Yukawa couplings). At HERA, the H1 collaboration has excluded \cite{H1} first-generation squarks up to masses of 240 GeV for a $\lambda' \sim \sqrt{4\pi\alpha_{em}}$. There are also reasonably stringent indirect limits on first- and second-generation $\lambda'$ couplings. For instance, the upper limit on the $\nu_e$ majorana mass \cite{9} or the non-observation of neutrinoless double beta decay \cite{10} give $\lambda' < 10^{-2}$ for a squark mass of 100 GeV. Bounds of the order of $10^{-2} - 10^{-1}$ on $\lambda'$ from a variety of low-energy observables have been obtained \cite{11}. In contrast, there are weaker bounds on the third-generation couplings and the most stringent limits are of the order of 0.5 which are obtained by considering radiative corrections induced by $\lambda'$ couplings to the partial widths of the $Z$ \cite{12}.

For $\lambda'$ couplings involving the first-generation, the non-observation of $n\bar{n}$-oscillations \cite{13} and double nucleon decays into kaons of identical strangeness \cite{14} place very strong constraints on the $\lambda''$ couplings. Data on neutral meson mixing or that on $CP$-violation in the $K$-sector can also be used to put stringent bounds on certain products of the $\lambda''$ couplings. Again, as for $\lambda'$, the $\lambda''$ couplings involving third-generation quarks are not very strongly constrained – the best bounds \cite{15} are of the order of 1.25 for a squark mass of 100 GeV, obtained from computing the contribution to $R_t = \Gamma_t/\Gamma_h$ from one-loop diagrams involving squarks and top-quarks. Similar bounds on $R$-violating couplings involving third-generation quarks also follow from the assumption of perturbative unification \cite{16}. Cosmological considerations seem to place very strong constraints – for example, the requirement that GUT-scale baryogenesis does not get washed out gives $\lambda'' \ll 10^{-7}$ generically \cite{17}, though these bounds are model dependent and can be evaded \cite{18}.

Given that the constraints on $\lambda'$ and $\lambda''$ couplings involving third-generation fields are not very stringent, it is important to study $L$- and $B$-violating processes that involve third-generation particles. In this letter, we study $t\bar{t}$ production at the Tevatron with precisely this objective in mind. In addition, to the usual QCD sub-processes that contribute to $t\bar{t}$ production, we have the distinctive $t$-channel slepton/squark exchange subprocess also contributing, when the corresponding $R$-violating coupling is non-zero. The measured values of the cross-section from the CDF and the D0 experiments at the Tevatron allows us to put constraints on the third-generation $R$-violating coupling as a function of the slepton or squark mass.

Since we are only interested in the interactions generated by the $\lambda'$ and $\lambda''$ couplings, we write this part of the interaction in Eq. \cite{1} in terms of the component fields. In four-component Dirac notation, the part of the Lagrangian with $\lambda'$ couplings is given by

$$
\mathcal{L}_{\lambda'} = -\lambda'_{ijk} \left[ \bar{\nu}_L^i \tilde{d}_R^k \tilde{d}_L^j + \bar{d}_L^i \tilde{d}_R^j \nu_L^k + \bar{d}_R^i (\bar{\nu}_L^j) (\tilde{d}_L^k)^c d_L^j - \bar{e}_L^i \tilde{d}_R^k u_L^j - \bar{u}_L^i \tilde{d}_R^j e_L^j - (\bar{d}_R^k)^c (\tilde{e}_L^j)^c u_L^j \right] + \text{h.c.};
$$

(2)
and the corresponding expression for the $\nu'$ coupling:

$$\mathcal{L}_{\nu'} = -\lambda'_{ijk} \left[ \bar{d}^k_R (\bar{u}^i_L)^* d^j_L + \bar{d}^k_R (\bar{d}^i_L)^* u^j_L + \bar{u}^i_R (\bar{d}^j_L)^* d^k_L \right] + \text{h.c.} \quad (3)$$

Because of the existence of these couplings, we have new $q\bar{q}$ annihilation processes contributing to $tt$ production, in addition to the usual QCD mechanisms. These new processes involve $t$-channel squark or slepton exchange and, as is evident from Eqs. (3) and (4), only $d$-quark-initiated subprocesses contribute in these production channels. It is important to emphasise that proton-decay non-observation constrains us to consider only one of either $\nu'$ or $\nu''$ couplings to be non-zero. In what follows, we will present a general discussion which can be easily specialised to either of the two cases: this is, in fact, possible because the only difference in the two cases is that for the $L$-violating case a slepton is exchanged and for the $B$-violating case a squark is exchanged. In both cases, it is only the $d\bar{d}$ initial state which gives a $tt$ final state. Consequently, except for an overall colour factor, there is no difference in the expressions for the cross-sections for these two cases.

It is straightforward to compute the expression for the full cross-section at leading order. The expressions for the cross-sections at leading order in QCD for both the $q\bar{q}$- and the $gg$-initiated subprocesses are well-known. Since the $R$-parity violating contribution is only via the $q\bar{q}$ initial state, the $gg$ part of the cross-section coming from QCD is unaffected by this new contribution. The $q\bar{q}$ contribution from both production mechanisms will interfere: in fact, as explained above, even here only the $d\bar{d}$-initiated contribution will be affected. We write down explicitly the expressions for the $q\bar{q}$ part of the cross-section. We use the notation $\Lambda$ to denote the generic coupling, with $\Lambda$ being understood to be $\nu'$ or $\nu''$, depending on the case under consideration.

$$\frac{d\hat{\sigma}_{uu}}{dt} = T_{11}^{uu}, \quad \frac{d\hat{\sigma}_{dd}}{dt} = T_{11}^{dd} + T_{22}^{dd} + T_{12}^{dd}, \quad (4)$$

where

$$T_{11}^{uu} = T_{11}^{dd} = \frac{16\pi\alpha_s^2}{3s^4}C_{11}[2m_t^2s + (\hat{t} - m_t^2)^2 + (\hat{u} - m_t^2)^2],$$

$$T_{22}^{dd} = \frac{\Lambda^4_{31}}{8\pi s^2}C_{22}(\hat{t} - m_t^2)^2,$$

$$T_{12}^{dd} = -\frac{\alpha_s\Lambda^2_{31}}{2s^3(\hat{t} - m_t^2)^2}C_{12}[m_t^2s + (\hat{t} - m_t^2)^2], \quad (5)$$

and

$$C_{11} = \frac{1}{12}, \quad C_{22} = \frac{2}{3}, \quad C_{12} = -\frac{4}{9}, \quad \text{for } \nu'' (\nu') \text{couplings.} \quad (6)$$

The hadronic cross-sections are obtained by folding these sub-process cross-sections with the parton luminosities, as follows:

$$\sigma_{qq} = \int dx_1dx_2dt[f_{p/q}(x_1)f_{\bar{p}/q}(x_2) + f_{p/q}(x_1)f_{\bar{p}/q}(x_2)]\frac{d\hat{\sigma}_{qq}}{dt}, \quad (7)$$
where \( f_{h/i} \) denotes the probability of finding a parton \( i \) inside a hadron \( h \). The gluon-gluon fusion part of the cross-section is unaffected by the \( R \)-violating interactions.

Just as the presence of the \( R \)-violating couplings affects the \( t\bar{t} \) production vertex, their presence will be also felt at the decay vertices. As opposed to the two-body decay of the top in the standard model, the \( R \)-violating channel will necessarily involve a three-body final state when the squark or the slepton is heavier than the top quark (\( m_t \sim 169 - 176 \text{ GeV} \)). This is because, for the case of \( \lambda''(\lambda') \) couplings, the top will decay into a virtual squark (slepton) and a \( d \)-type quark and the virtual squark (slepton) will further decay into two other particles. This three-body decay is expected to be negligibly small as compared to the Standard Model decay, so that the branching ratio into the Standard Model decay channel will still be close to 100%. This will, however, no longer be true when the squark (slepton) mass is smaller than the mass of the top, in which case the decay of the top quark into a \( d \)-type quark and a real \( d \)-type squark (slepton) becomes possible. This decay mode will compete with the usual \( t \rightarrow bW \) decay mode of the Standard Model. The ratio of these two decay-widths turns out to be

\[
R \equiv \frac{\Gamma(t \rightarrow d_j\bar{d}_jR(\tilde{e}_jL))}{\Gamma(t \rightarrow bW)} = \frac{2s^2_W\Lambda^2_{ji}C_R}{\pi\alpha} \frac{\lambda(m_t^2, m_i^2, \tilde{m}_j^2)}{\lambda(m_t^2, m_W^2, m_b^2)} \frac{m_t^2 + m_i^2 - \tilde{m}_j^2}{m_t^2 - 2m_W^2 + m_b^2 + \frac{(m_t^2 - m_W^2)^2}{m_W^4}},
\]

where

\[
C_R = 2(1), \quad \text{for } \lambda''(\lambda') \text{ couplings},
\]

and \( \lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz \). The branching ratio for the decay into the \( Wb \) channel then gets multiplied by a factor \( B = (1 + R)^{-1} \), when the squark (slepton) mass is lesser than the top mass.

With the above expressions at hand, we are now able to compute the cross-section for \( t\bar{t} \) production in the \( R \)-parity violating scenario. Before we discuss the results of our computation, a few remarks about the significance of higher-order corrections are in order. The cross-sections presented above are at the lowest order in perturbation theory. In the QCD case, significant progress has been made in computing higher-order corrections to heavy quark production. Not only have the next-to-leading order corrections been calculated a long time ago [19], but the resummation of soft gluons and its effect on the total cross-section have been recently computed [20]. In principle, a reliable estimate of the cross-section for the \( R \)-parity violating case under consideration, can also be made only when we have (at least) the corrections to these processes at next-to-leading order. But for want of such a calculation, the best we can do is to use the leading order QCD and the resummed QCD cross-sections [20] in the \( q\bar{q} \) annihilation channel to extract a ‘\( K \)-factor’ for the annihilation channel. We then work with the approximation that the \( R \)-violating cross-section will also be affected by QCD corrections in a similar fashion so that we can fold in our cross-sections for the \( R \)-violating case by the same \( K \)-factor. Clearly, more work is needed in this direction but we do not expect that our results will be qualitatively changed by higher order QCD corrections.
In Fig. 1, we have presented the $t \bar{t}$ production cross-section for the $B$-violating $\lambda'' \neq 0$ scenario. The case of a non-vanishing $\lambda'$ yields very similar results and we do not present the results for the cross-section in that case separately. We have plotted the $t \bar{t}$ production cross-section as a function of the $\lambda''$ coupling for different values of the mass of the right $d$-squark. The cross-section is computed for both the Tevatron ($\sqrt{s} = 1.8$ TeV) and for the LHC energy ($\sqrt{s} = 14$ TeV). These are shown by solid and dashed lines respectively, in Fig. 1. For the input parton distributions, have used the CTEQ-3M distributions [21]. This choice is motivated by the fact that our $K$-factor is extracted from the higher order QCD calculations presented in Ref. [20] which use this set of distribution functions. Our parton distributions were taken from the package PDFLIB [22]. The 95% confidence-level band from the D0 experiment [23] is indicated by the dotted lines in Fig. 1. This is shown for the two cases when the squark mass (100 GeV) is lighter than the top mass and for the case when it is heavier (marked). For a squark mass of 100 GeV a band is disallowed for $\lambda''$, whereas for values of squark mass higher than $m_t$, we get an upper bound.

For the results shown for the LHC energy, we have not folded in the cross-sections with a $K$-factor since the expectation is that at these energies higher-order QCD corrections will be very small. For this computation, we have used the MRSD'- parton distribution functions [24]. Since the effect we are studying comes from a $q \bar{q}$ annihilation process, we would naively expect that the effect at the LHC energy is very small since we would expect that the gluon-initiated processes swamp the $q \bar{q}$-initiated process completely. While the gluon-initiated contribution is much larger because of the steep gluon distributions at low-$x$, the usual annihilation process in QCD is further suppressed because it is an $s$-channel process. The $t$-channel subprocess in the $R$-parity violating case does not suffer this suppression and hence the effects at the LHC energy, while smaller than the corresponding effects at the Tevatron, are still sizeable.

Our results for the cross-sections can be easily translated into bounds on the values of the squark/slepton masses and the corresponding $\lambda''$ or $\lambda'$ couplings. In Fig. 2, we have shown the allowed regions in the $\lambda'' - m_{\tilde{d}_R}$ plane allowed at 95% confidence level by the D0 and the CDF data [23] on $t \bar{t}$ production cross-section. The bounds resulting from the CDF data are shown by solid lines and those from the D0 data are shown by dashed lines. For squark masses lesser than the top mass, the bounds are weakened considerably because the decay channel $t \rightarrow d \tilde{d}_R$ opens up, and this tends to dilute the branching into the Standard Model decay mode $t \rightarrow bW$.

In Fig. 3, we have shown the allowed regions in the $\lambda' - m_{\tilde{\ell}_L}$ plane. We would like to point out again at this stage that the part of the $L$-violating interaction that the $t \bar{t}$ production process selects out involves only left-handed charged sleptons and does not involve sneutrinos. As in Fig. 2, the solid and dashed lines are the 95% bounds resulting from the CDF and the D0 data respectively. These bounds are stronger than those in Fig. 2 because of the larger colour factor that appears in the $t \bar{t}$ production through $\lambda'$ couplings. Simultaneously, the opening up of the decay channel $t \rightarrow d \tilde{\ell}_L$ for light sleptons does not affect the bounds quite as much as in Fig. 2 because the relevant $R$-violating
branching ratio is suppressed by a smaller colour factor.

In summary, we have studied the constraints coming from $t\bar{t}$ production at the Tevatron on $\lambda'$ and $\lambda''$ couplings in $R$-parity violating models of supersymmetry. These direct bounds that we obtain constrain the third-generation couplings – and are comparable to the indirect bounds on third-generation couplings obtained from electroweak precision data from LEP. We stress that our aim in this paper is to illustrate the kind of bounds that can be obtained by considering this process. The actual bounds can be improved when the cross-section for the production of $t\bar{t}$ is determined more accurately, and the present discrepancy between the CDF and D0 values for the top cross-section is resolved. It is also important to consider QCD corrections to the $R$-violating processes before we can have a true quantitative estimate of the bounds. Nevertheless, the bounds on both couplings, and especially that obtained for $\lambda'$, are interesting and deserve more attention. Our results for the LHC are also rather encouraging.

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Figure 1: The $t\bar{t}$ production cross-section in a baryon-number violating scenario as a function of the $\lambda''$ coupling for different values of the mass of the right $d$-squark. Solid (dashed) lines show the cross-section at the Tevatron (LHC), with the squark masses in GeV marked next to the former. Dotted lines show the D0 2-$\sigma$ results for the two cases when $m_{\tilde{d}_R} < m_t$ (100 GeV) and when $m_{\tilde{d}_R} > m_t$ (marked).
Figure 2: Allowed regions in the plane of $\lambda''$ and the mass of the right $d$-squark in a baryon number-violating scenario. Solid (dashed) lines correspond to the 2-$\sigma$ bounds from the CDF (D0) collaborations.
Figure 3: Allowed regions in the plane of $\lambda'$ and the mass of the left slepton in a lepton number-violating scenario. Solid (dashed) lines correspond to the 2-$\sigma$ bounds from the CDF (D0) collaborations.