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Single top quark production as a probe of R-parity-violating SUSY at pp and $p\bar{p}$ colliders

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ABSTRACT

We investigate the ability of single top quark production via $qq' \to$ squark $\to tb$ and $q\bar{q}' \to$ slepton $\to t\bar{b}$ at the LHC and Tevatron to probe the strength of R-parity violating couplings in the minimal supersymmetric model. We found that given the existing bounds on R-parity violating couplings, single top quark production may be greatly enhanced over that predicted by the standard model, and that both colliders can either discover R-parity violating SUSY or set strong constraints on the relevant R-parity violating couplings. We further found that the LHC is much more powerful than the Tevatron in probing the squark couplings, but the two colliders have comparable sensitivity for the slepton couplings.

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1. Introduction

The HERA data showed excess events in deep-inelastic positron-proton scattering at high-Q^2 and high x, which are in apparent conflict with the Standard Model expectation [1]. The excess events have been interpreted as evidence of R-parity breaking supersymmetry[2]. Hence detailed examination of effects of R-parity breaking supersymmetry in other processes is in order. Some of the phenomenological implications of R-parity violating couplings at e^+e^- colliders have been investigated in Ref.[3]. Constraints on the R-parity violating couplings have also been obtained from perturbative unitarity [4,5], $n-\bar{n}$ oscillation [5,6], ν_e-Majorana mass [7], neutrino-less double β decay [8], charged current universality [9], $e-\mu-\tau$ universality [9], $\nu_\mu - e$ scattering [9], atomic parity violation [9], ν_μ deep-inelastic scattering [9], double nucleon decay [10], K decay [11,12], τ decay [13], D decay [13], B decay [14-16] and Z decay at LEPI [17,18]. Another important effect of R-parity violating couplings is that they may enhance the flavor changing top quark decays to the observable level of the upgraded Tevatron and LHC [19].

As is shown in Refs.[20-24], single top quark production is very interesting to study at the Tevatron and the LHC since, in contrast to the QCD process of $t\bar{t}$ pair production, it can be used to probe the electroweak theory. Single top production processes have been used to study the new physics effects involving the third-family quarks in a model independent approach [25] and in specific models [26,27]. More recently, motivated by the evidence of R-parity breaking supersymmetry [28,29] from the anomalous events at HERA [1], single top quark production $q\bar{q}' \to t\bar{b}$ at the Tevatron induced by baryon-number violating (BV) couplings λ'' (via the exchange of a squark in the t-channel) and by lepton-number violating (LV) couplings λ' (via the exchange of a slepton in the s-channel) has been studied [30] in minimal supersymmetric model (MSSM). It was found [30] that the upgraded Tevatron can probe the relevant BV couplings efficiently, while the probe for the relevant LV couplings is very limited.

In addition to the process $q\bar{q}' \to t\bar{b}$ mentioned above, which can be effectively studied at the Tevatron, the R-parity BV coupling can lead to the reaction $qq' \to tb$ via an s-channel squark contribution which is suppressed at the Tevatron. This process is suitable for study at the LHC and it probes a different set of BV couplings. In this paper we make a detailed study of the s-channel BV effect. For completeness we study the effect at both the LHC and the upgraded Tevatron. We also study the s-channel slepton contribution to $q\bar{q}' \to t\bar{b}$ at the LHC which we compare to the result obtained for the upgraded Tevatron [30].

This paper is organized as follows. In Sec.2 we present the Lagrangian for R-parity violating couplings and squared matrix elements for the processes $qq' \to$ squark $\to tb$ and $q\bar{q}' \to$ slepton $\to t\bar{b}$. In Sec.3 we evaluate the signal for these processes and the SM background, and give the probing potential of the LHC in comparison to the upgraded Tevatron.

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2. tb and $t\bar{b}$ production in R-parity violating MSSM

2.1 Lagrangian of R-parity violating couplings

The R-parity violating part of the superpotential of the MSSM is given by

$$\mathcal{W}_{\not R} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c + \mu_i L_i H_2. \tag{1}$$

Here $L_i(Q_i)$ and $E_i(U_i, D_i)$ are the left-handed lepton (quark) doublet and right-handed lepton (quark) singlet chiral superfields, i, j, k are generation indices, and c denotes charge conjugation. $H_{1,2}$ are the chiral superfields representing the two Higgs doublets. The λ and λ' couplings violate lepton-number conservation, while the λ'' couplings violate baryon-number conservation. The coefficient λ_{ijk} is antisymmetric in the first two indices and λ''_{ijk} is antisymmetric in the last two indices. In terms of the four-component Dirac notation, the Lagrangians for the λ' and λ'' couplings that affect single top production at the Tevatron and the LHC are given by

$$\begin{aligned}\mathcal{L}_{\lambda'} &= -\lambda'_{ijk}\Big[\tilde{\nu}_L^i \bar{d}_R^k d_L^j + \tilde{d}_L^j \bar{d}_R^k \nu_L^i + (\tilde{d}_R^k)^* (\bar{\nu}_L^i)^c d_L^j \\ &\qquad -\tilde{e}_L^i \bar{d}_R^k u_L^j - \tilde{u}_L^j \bar{d}_R^k e_L^i - (\tilde{d}_R^k)^* (\bar{e}_L^i)^c u_L^j\Big] + h.c., \end{aligned} \tag{2}$$

$$\mathcal{L}_{\lambda''} = -\lambda''_{ijk}\Big[\tilde{d}_R^k (\bar{u}_L^i)^c d_L^j + \tilde{d}_R^j (\bar{d}_L^k)^c u_L^i + \tilde{u}_R^i (\bar{d}_L^j)^c d_L^k\Big] + h.c.. \tag{3}$$

The terms proportional to λ are not relevant to our present discussion and will not be considered here. Note that while it is theoretically possible to have both BV and LV terms in the Lagrangian, the non-observation of proton decay imposes very stringent conditions on their simultaneous presence[31]. We, therefore, assume the existence of either LV couplings or BV couplings, and investigate their separate effects in single top quark production.

2.2 $qq' \to$ squark $\to tb$

Production of tb via an s-channel diagram $u^i d^j \to \tilde{d}^k_R \to tb$ can be induced by the BV couplings λ''. The matrix element squared is given by

$$\overline{\sum}|M^{ij}_{\lambda''}|^2 = \frac{32}{3}\left|\sum_k \frac{\lambda''_{ijk}\lambda''_{33k}}{\hat{s} - M^2_{\tilde{d}^k} + iM_{\tilde{d}^k}\Gamma_{\tilde{d}^k_R}}\right|^2 (p_1 \cdot p_2)\,[p_3 \cdot p_4 - M_t(s_t \cdot p_4)]\,, \tag{4}$$

where p_1 and p_2 denote the momenta of the incoming quarks u^i and d^j, p_3 and p_4 of the outgoing t and b quarks. The center-of-mass energy of the parton is given by $\hat{s}$ and s_t denotes the spin of top quark which is given by

$$s_t = \frac{h}{M_t}\,(|\vec{p}_3|, E_t\hat{p}_3)\,, \tag{5}$$

where $h = \pm 1$ denotes the two helicity states, and $\hat{p}_3$ is the unit three-vector in the momentum direction of top quark.

Neglecting the contribution of third-family sea quark in the initial states, we obtain

$$\overline{\sum}|M_{\lambda''}(ud \to tb)|^2 = \frac{32}{3}\frac{(\lambda''_{112}\lambda''_{332})^2}{(\hat{s} - M^2_{\tilde{s}})^2 + (M_{\tilde{s}}\Gamma_{\tilde{s}_R})^2}(p_1 \cdot p_2)\,[p_3 \cdot p_4 - M_t(s_t \cdot p_4)]\,, \tag{6}$$

$$\overline{\sum}|M_{\lambda''}(us \to tb)|^2 = \frac{32}{3}\frac{(\lambda''_{112}\lambda''_{331})^2}{(\hat{s} - M^2_{\tilde{d}})^2 + (M_{\tilde{d}}\Gamma_{\tilde{d}_R})^2}(p_1 \cdot p_2)\,[p_3 \cdot p_4 - M_t(s_t \cdot p_4)]\,, \tag{7}$$

$$\overline{\sum}|M_{\lambda''}(cd \to tb)|^2 = \frac{32}{3}\frac{(\lambda''_{212}\lambda''_{332})^2}{(\hat{s} - M^2_{\tilde{s}})^2 + (M_{\tilde{s}}\Gamma_{\tilde{s}_R})^2}(p_1 \cdot p_2)\,[p_3 \cdot p_4 - M_t(s_t \cdot p_4)]\,, \tag{8}$$

$$\overline{\sum}|M_{\lambda''}(cs \to tb)|^2 = \frac{32}{3}\frac{(\lambda''_{212}\lambda''_{331})^2}{(\hat{s} - M^2_{\tilde{d}})^2 + (M_{\tilde{d}}\Gamma_{\tilde{d}_R})^2}(p_1 \cdot p_2)\,[p_3 \cdot p_4 - M_t(s_t \cdot p_4)]\,. \tag{9}$$

In the R-parity conserving MSSM, the down-type squark $\tilde{d}^k_R$ can decay into charginos and neutralinos via the processes $\tilde{d}^k_R \to u^k + \overline{\tilde{\chi}^+_j}$ $(j = 1, 2)$ and $\tilde{d}^k_R \to d^k + \tilde{\chi}^0_j$ $(j = 1, 2, 3, 4)$, where $\tilde{\chi}^+_j$ and $\tilde{\chi}^0_j$ represent a chargino and neutralino, respectively [32]. Of course, it can also decay into gluino plus quark if kinematically allowed. In the R-parity violating MSSM, the down-type squark $\tilde{d}^k_R$ can also decay into quark pairs $\tilde{d}^k \to \bar{d}^j + \bar{u}^i$ via the λ'' couplings. Since some of

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the relevant λ'' couplings may be quite large, the width of a heavy down-type squark $\tilde{d}_R^k$ can be large even if we do not consider the decay involving the gluino. We found that within the allowed parameter space (λ'', chargino and neutralino sector) its width $\Gamma_{\tilde{d}_R}$ can be as large as $M_{\tilde{d}_R}/3$.

2.3 $q\bar{q}' \to$ slepton $\to t\bar{b}$

Production of $t\bar{b}$ via an s-channel slepton $u^i\bar{d}^j \to \tilde{e}_L^k \to t\bar{b}$ can be induced by the LV couplings λ'. The matrix element squared is given by

$$\overline{\sum}|M_{\lambda'}^{ij}|^2 = \frac{1}{2}\frac{\left(\lambda'_{1ij}\lambda'_{133}+\lambda'_{2ij}\lambda'_{233}+\lambda'_{3ij}\lambda'_{333}\right)^2}{(\hat{s}-M_{\tilde{e}_L}^2)^2+(M_{\tilde{e}_L}\Gamma_{\tilde{e}_L})^2}(p_1\cdot p_2)\,[p_3\cdot p_4 - M_t(s_t\cdot p_4)]\,, \tag{10}$$

where we assumed mass degeneracy for sleptons of different flavors.

In the R-parity conserving MSSM, the charged sleptons $\tilde{e}_L$ will decay into charginos and neutralinos via the processes $\tilde{e}_L \to \nu_e + \overline{\tilde{\chi}_j^+}$ ($j=1,2$) and $\tilde{e}_L \to e + \tilde{\chi}_j^0$ ($j=1,2,3,4$) [32]. However, in the R-parity violating MSSM, the slepton can also decay into quark pairs via the λ' couplings $\tilde{e}_L^i \to \bar{u}_L^j + d_R^k$. Since the allowed λ' couplings are quite small, the dominant decays are the chargino and neutralino modes. The partial widths are given by

$$\Gamma(\tilde{e}_L \to \nu_e + \overline{\tilde{\chi}_j^+}) = \frac{g^2}{16\pi M_{\tilde{e}}^3}|U_{j1}|^2\left(M_{\tilde{e}}^2 - M_{\tilde{\chi}_j^+}^2\right)^2, \tag{11}$$

$$\Gamma(\tilde{e}_L \to e + \tilde{\chi}_j^0) = \frac{g^2}{8\pi M_{\tilde{e}}^3}\left|s_W N'_{j1} + \frac{1}{c_W}(\frac{1}{2}-s_W^2)N'_{j2}\right|^2\left(M_{\tilde{e}}^2 - M_{\tilde{\chi}_j^0}^2\right)^2, \tag{12}$$

where $s_W \equiv \sin\theta_W, c_W \equiv \cos\theta_W$ and the masses of the lepton and down-type quarks are neglected. The masses of charginos and neutralinos, and the matrix elements U_{ij} and N'_{ij} which respectively diagonalize the mass matrix of chargino and neutralino, depend on the SUSY parameters M_2, M_1, μ, and $\tan\beta$ [29]. Here, M_2 and M_1 are the masses of gauginos corresponding to $SU(2)$ and $U(1)$, respectively, μ is the coefficient of the H_1H_2 mixing term in the superpotential, and $\tan\beta = v_2/v_1$ is the ratio of the vacuum expectation values of the two Higgs doublets.

3. Numerical calculation and results

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