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Top Quark Three-Body Decays in R-Violating MSSM

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Abstract

In the Minimal Supersymmetric Standard Model, R-parity violating interactions can trigger various exotic three-body decays for the top quark, which may be accessible at the LHC. In this work we examine the R-violating decays $t \to cX_1X_2$, which include the tree-level processes $t \to c\ell_i^-\ell_j^+$ ($\ell_i = e, \mu, \tau$) and $t \to cd_i\bar{d}_j$ ($d_i = d, s, b$), as well as the loop-induced processes $t \to cgX$ ($X = g, \gamma, Z, h$). We find that the heretofore weakly constrained R-violating couplings can render the decay branching ratios quite sizable, some of which already reach the sensitivity of the Tevatron collider and can be explored at the LHC with better sensitivity.

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I. INTRODUCTION

The top quark stands as one of the foremost topics in high-energy physics. As the heaviest known elementary particle, it is speculated to provide a window into TeV-scale physics. The properties of the top quark have been measured at the Tevatron collider, and thus far the Tevatron data are in agreement with Standard Model (SM) predictions. However, due to limited statistics at the Tevatron, the precision of current measurements of top quark properties remains modest, leaving considerable room for new physics in the top quark sector. The CERN Large Hadron Collider (LHC) will serve as a top quark factory and enable detailed scrutiny of the top quark' s nature. Precise measurements of top quark properties at the LHC may provide clues to physics beyond the Standard Model.

Owing to the large number of top pair samples anticipated at the LHC, various exotic decays of the top quark could be explored with high sensitivity. In the SM, the top quark dominantly decays into a W boson plus a bottom quark. However, in new physics models, various exotic decays can open up and may reach detectable levels. For example, the flavor-changing neutral current (FCNC) two-body decays $t \to cX$ $(X = g, \gamma, Z, h)$, which are extremely suppressed in the SM [**?**], could be enhanced to observable levels in the Minimal Supersymmetric Standard Model (MSSM) [**?**, **?**] and in technicolor models [**?**]. Additionally, new decay modes may emerge in new physics models, such as those involving supersymmetric particles in the MSSM [**?**]. Given the stringent lower bounds on the masses of new particles from current experiments, such two-body new decay modes are becoming kinematically suppressed or forbidden. In this work we focus on kinematically allowed three-body decays where all final states are Standard Model particles.

It is well known that in the MSSM, R-parity, defined by $R = (-1)^{2S+3B+L}$ with spin S, baryon number B, and lepton number L, is often imposed on the Lagrangian to maintain separate conservation of B and L. However, this conservation requirement is not dictated by any fundamental principle such as gauge invariance or renormalizability. Consequently, the phenomenology of R-parity violation has attracted considerable attention. Regarding the effects of R-violating interactions in the top quark sector, large FCNC two-body decays $t \to cX$ $(X = g, \gamma, Z, h)$ and exotic top production mechanisms at the LHC may arise [**?**]. Notably, R-violating couplings can also induce various three-body decays of the top quark. In this work we examine three-body decays where all final states are SM particles, including the tree-level processes $t \to c\ell_i^- \ell_j^+$ $(\ell_i = e, \mu, \tau)$ and $t \to c d_i \bar{d}_j$ $(d_i = d, s, b)$, as well as the loop-induced processes $t \to cgX$ $(X = g, \gamma, Z, h)$. Although these three-body decays may be quite rare, they merit investigation because top decays will soon be scrutinized at the LHC. As our study demonstrates, the heretofore weakly constrained R-violating couplings can yield sizable branching ratios, some of which marginally reach the sensitivity of the Tevatron collider.

We note that top quark three-body decays with one or two new (heavy) particles in the final states have been studied in the MSSM with and without R-parity [?, ?, ?] and in the general two-Higgs-doublet model [?]. In Ref. [?], the lepton-number-violating decay $t \to c\ell_i^- \ell_j^+$ was also studied; we include it here for completeness.

This work is structured as follows. In Sec. II, we recapitulate the R-parity violating couplings and present calculations for top three-body decays. In Sec. III, we show numerical results for the branching ratios of these decays. In Sec. IV we present our conclusions. Analytic expressions from the loop calculations are provided in the Appendix.

II. CALCULATION

The R-parity violating superpotential of the MSSM is given by [?]:

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

where $L_i(Q_i)$ and E_i^c (U_i^c, D_i^c) are respectively the doublet and singlet lepton (quark) chiral superfields, and i, j, k are generation indices. The λ and λ' terms violate lepton number while the λ'' terms violate baryon number. The non-observation of proton decay imposes very strong constraints on the product of L-violating and B-violating couplings [?]. Thus in our numerical calculations we assume that only one type of these interactions (either L- or B-violating) exists. Since only λ' or λ'' couplings can induce three-body top quark decays, we drop the λ couplings in what follows.

In terms of four-component Dirac notation, the Lagrangian for the λ' and λ'' couplings is given by:

$$\mathcal{L}_{\lambda'} = -\lambda'_{ijk} \left[\tilde{d}_{kR}^* \bar{\nu}_{iL} \ell_{jL} + \tilde{\ell}_{jL} \bar{\nu}_{iL} d_{kR} + \tilde{\nu}_{iL}^* \bar{d}_{kR} \ell_{jL} \right] + \text{h.c.}$$

$$\mathcal{L}_{\lambda''} = -\lambda''_{ijk} \left[\tilde{d}_{jR}^* \bar{u}_{iR} d_{kR}^c + \tilde{d}_{kR}^* \bar{u}_{iR} d_{jR}^c + \tilde{u}_{iR}^* \bar{d}_{jR}^c d_{kR} \right] + \text{h.c.}$$

The three-body decays $t \to c\ell_i^- \ell_j^+$ can be induced at tree-level by the L-violating $\lambda'_{i3k}\lambda'_{j2k}$ couplings, as shown in Fig. 1(a); while $t \to c\ell_i^- \ell_j^+$ can also be induced at loop-level by the B-violating λ''_{3jk} couplings, as shown in Fig. 1(b) where the effective vertices $tc\gamma$ and tcZ are similar to the effective vertex tcg defined in Fig. 3. The decays $t \to cd_i\bar{d}_j$ can be induced at tree-level either by the L-violating $\lambda'_{k3i}\lambda'_{k2j}$ or by the B-violating $\lambda''_{2ik}\lambda''_{3jk}$ couplings, as shown in Figs. 1(c) and 1(d), respectively. The decay $t \to cgg$ can be induced at loop-level by the L-violating $\lambda'_{i2k}\lambda'_{i3k}$ or the B-violating $\lambda''_{2jk}\lambda''_{3jk}$ couplings, as shown in Fig. 2 with the effective vertex tcg defined in Fig. 3. The Feynman diagrams for $t \to cg\gamma$, cgZ, and cgh are similar to $t \to cgg$ and are not plotted here. The analytic expressions for the amplitudes of the loop-induced processes are lengthy and tedious. As an example, we list the expressions for the L-violating loop contributions to the effective vertex tcV in Appendix A. The corresponding B-violating contributions can be found in the third paper of Ref. [**?**].

[Figure 1: see original paper] shows the Feynman diagrams: (a) $t \to c\ell_i^- \ell_j^+$ induced at tree-level by $\lambda'_{i3k}\lambda'_{j2k}$; (b) $t \to c\ell_i^- \ell_j^+$ induced at loop-level by λ''_{3jk} where the effective vertices $tc\gamma$ and tcZ are similar to the effective vertex tcg defined in Fig. 3; (c-d) $t \to cd_i\bar{d}_j$ induced at tree-level by $\lambda'_{k3i}\lambda'_{k2j}$ and $\lambda''_{2ik}\lambda''_{3jk}$, respectively. In (a) the charged lepton ℓ_i and the charm quark can be replaced respectively by a neutrino ν_i and a strange quark to give the process $t \to s\nu_i\ell_j^+$.

The current upper bounds for all R-parity violating couplings are summarized in Ref. [**?**]. Table I lists the current limits for those couplings relevant to our study, taken from Ref. [**?**]. We see that the constraints are quite weak for the couplings λ''_{3jk}, which induce the tree-level decays shown in Fig. 1(d).

III. NUMERICAL RESULTS AND DISCUSSIONS

In our calculation the top quark mass is taken as the new CDF value $m_t = 172$ GeV [**?**]. Other SM parameters are taken as [**?**]: $m_Z = 91.19$ GeV, $m_W = 80.4$ GeV, $\sin^2\theta_W = 0.2228$, $\alpha_s(m_t) = 0.1095$ and $\alpha = 1/128$. The SUSY parameters involved in our calculations are the masses of squarks and sleptons as well as the R-parity violating couplings λ'_{i2k}, λ'_{i3k}, and λ''_{3jk}, whose upper bounds are listed in Table I. The strongest bound on squark mass comes from the Tevatron experiment. For example, from the search for inclusive production of squarks and gluinos in R-conserving minimal supergravity models with $A_0 = 0$, $\mu < 0$ and $\tan\beta = 5$, CDF gives a bound of 392 GeV at 95% C.L. [**?**] for degenerate gluinos and squarks. However, this bound may not be applicable to the R-violating scenario because the SUSY signal in the case of R-violation is very different from the R-conserving case. The most robust bounds on sparticle masses come from LEP results, which give a bound of about 100 GeV on squark or slepton mass [**?**]. In our numerical calculations we assume the presence of the minimal number of R-violating couplings, i.e., for each process only the two relevant couplings (not summed over family indices) are assumed to be present.

[TABLE:I] shows the current upper limits on the R-parity violating couplings relevant to our study, taken from Ref. [**?**].

In Fig. 4 we show the branching ratios of the three-body decays as a function of squark or slepton mass. In this figure the product of the two λ'' (λ') couplings involved in each decay is fixed as 1.2 (0.1), which are approximately the maximal values shown in Table I for squark or slepton mass of 100 GeV.

Among the B-violating decay modes shown in the left frame of Fig. 4, $t \to cd_i\bar{d}_j$ has the largest branching ratio because it is a tree-level process, as shown in

Fig. 1(d); while other decay modes are all induced at loop-level, among which $t \to cgg$ has the largest branching ratio.

Among the L-violating decay modes shown in the right frame of Fig. 4, $t \to cd_i\bar{d}_j$ also has the largest branching ratio because it is a tree-level process, as shown in Fig. 1(c). The decay $t \to c\ell_i^- \ell_j^+$ also occurs at tree-level, as shown in Fig. 1(a); but its branching ratio is always below that of $t \to cd_i\bar{d}_j$ for a common value of slepton and squark mass because $t \to cd_i\bar{d}_j$ is relatively enhanced by a color factor. Other decay modes are all induced at loop-level, among which $t \to cgg$ has the largest branching ratio.

We also calculated the channels $t \to c\gamma X$ $(X = \gamma, Z, h)$ and found that their branching ratios are below 10^{-9}, which is far below the detectable level at the LHC and thus are not plotted in the figures.

From Fig. 4 we see that for squark or slepton masses below 200 GeV, the decay $t \to cd_i\bar{d}_j$ can be quite sizable and could even compete with the SM decay $t \to W^+b$. Such a large branching ratio could be readily constrained by available Tevatron data. For example, the decay $t \to cd_i\bar{d}_j$ is "exotic" for dileptonic $t\bar{t}$ event counting because the final states of $t\bar{t}$ followed by $t \to cd_i\bar{d}_j$ and/or $\bar{t} \to \bar{c}\bar{d}_i d_j$ do not produce enough leptons to be included in the dileptonic event samples. In other words, only the normal decay modes of t and $\bar{t}$ (i.e., $t \to W^+b$ and $\bar{t} \to W^-\bar{b}$) can be counted in the dileptonic event samples. By comparing the CDF data [?] $\sigma[t\bar{t}]_{\text{exp}} = 6.7 \pm 0.8(\text{stat}) \pm 0.4(\text{syst}) \pm 0.4(\text{lumi})$ pb measured from dileptonic channels with $\sigma[t\bar{t}]_{\text{QCD}}[1 - \text{Br}(t \to cd_i\bar{d}_j)]^2$, we find the upper bound on $\text{Br}(t \to cd_i\bar{d}_j)$ to be:

$$\text{Br}(t \to cd_i\bar{d}_j) \leq \begin{cases} 0.12 & \text{at } 1\sigma \\ 0.19 & \text{at } 2\sigma \end{cases}$$

where we used $\sigma[t\bar{t}]_{\text{QCD}} = 7.39^{+0.57}_{-0.52}$ pb [?] and neglected SUSY effects on the production rate [?]. This upper bound is plotted as horizontal lines in Fig. 4. If we project the bound onto the plane of λ''_{k3i} versus squark mass or λ'_{k2j} versus slepton mass, we obtain Fig. 5, where we also show the bounds from $B \to K\gamma$ and Z-decays [?]. We see that the Tevatron has better sensitivity for light squarks or sleptons.

Since the statistical uncertainty of the top production rate will be greatly reduced at the LHC, the LHC will have better sensitivity to these exotic three-body decays. Of course, the sensitivity will differ for different decay channels. To determine the sensitivity for each channel requires detector-dependent full Monte Carlo simulations. A preliminary fast detector simulation showed [?] that the LHC may achieve high sensitivity (about 10^{-6}) to R-violating top decays if the decay products contain two leptons plus some jets.

IV. CONCLUSION

In the Minimal Supersymmetric Standard Model, R-parity violating interactions can induce various exotic three-body decays for the top quark, which might be accessible at the LHC. We have collectively examined these decays, including the tree-level processes $t \to c\ell_i^-\ell_j^+$ ($\ell_i = e, \mu, \tau$) and $t \to c d_i \bar{d}_j$ ($d_i = d, s, b$), as well as the loop-induced processes $t \to cgX$ ($X = g, \gamma, Z, h$). We find that the weakly constrained R-violating couplings can make the decay branching ratios quite sizable, some of which marginally reach the sensitivity of the Tevatron collider and can be explored at the LHC with better sensitivity.

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Appendix A: Expressions of Loop-Induced Effective Vertices

Here we list the expressions for the L-violating contributions to the effective vertex tcg in Fig. 2. We also present results for the effective vertices $tc\gamma$, tcZ, and tch, whose Feynman diagrams are similar to Fig. 2. Their expressions are given by:

$$\Gamma^\mu_{tcg} = \Gamma^\mu_{tcg}(\tilde{\ell}^i_L) + \Gamma^\mu_{tcg}(\tilde{d}^k_R)$$

$$\Gamma^\mu_{tc\gamma} = \Gamma^\mu_{tc\gamma}(\tilde{\ell}^i_L) + \Gamma^\mu_{tc\gamma}(\tilde{d}^k_R)$$

$$\Gamma^\mu_{tcZ} = \Gamma^\mu_{tcZ}(\tilde{\ell}^i_L) + \Gamma^\mu_{tcZ}(\tilde{d}^k_R)$$

$$\Gamma^\mu_{tch} = \Gamma^\mu_{tch}(\tilde{\ell}^i_L) + \Gamma^\mu_{tch}(\tilde{d}^k_R)$$

where $\tilde{\ell}^i_L$ and $\tilde{d}^k_R$ denote the L-violating loop contributions from exchanging slepton $\tilde{\ell}^i_L$ and squark $\tilde{d}^k_R$, respectively, given by:

$$\Gamma^\mu_{tcg}(\tilde{\ell}^i_L) = a g_s \left[C_1^{\alpha\beta}\gamma_\alpha\gamma^\mu\gamma_\beta P_L - C_1^\alpha(p_t - p_c)\gamma^\mu\gamma_\alpha P_L + \gamma^\mu p_t \gamma_\alpha B_1^\alpha + (\gamma_\alpha p_c \gamma^\mu P_L + m_t \gamma_\alpha \gamma^\mu P_R) B_2^\alpha\right]$$

$$\Gamma^\mu_{tcg}(\tilde{d}^k_R) = a g_s \left[-2C_4^{\alpha\mu}\gamma_\alpha P_L + C_4^\alpha(p_t + p_c)^\mu\gamma_\alpha P_L + (\gamma_\alpha p_c \gamma^\mu P_L + m_t \gamma_\alpha \gamma^\mu P_R) B_4^\alpha + \gamma^\mu p_t \gamma_\alpha B_3^\alpha\right]$$

$$\Gamma^\mu_{tc\gamma}(\tilde{\ell}^i_L) = a e \left[C_1^{\alpha\beta}\gamma_\alpha\gamma^\mu\gamma_\beta - C_1^\alpha(p_t - p_c)\gamma^\mu\gamma_\alpha\right] P_L$$

$$\Gamma^{\mu}_{tc\gamma}(\tilde{d}^{k}_{R}) = ae\left[-2C^{\alpha\mu}_{3}\gamma_{\alpha} + C^{\alpha}_{3}(p_t + p_c)^{\mu}\gamma_{\alpha}\right]P_L$$

$$\Gamma^{\mu}_{tcZ}(\tilde{\ell}^{i}_{L}) = \frac{ae}{2s_W c_W}\left[C^{\alpha\beta}_{1}\gamma_{\alpha}\gamma^{\mu}\gamma_{\beta} - C^{\alpha}_{1}(p_t - p_c)\gamma^{\mu}\gamma_{\alpha}\right]P_L - \frac{ae}{2s_W c_W}\left[2C^{\alpha\mu}_{2}\gamma_{\alpha} - C^{\alpha}_{2}(p_t + p_c)^{\mu}\gamma_{\alpha}\right]P_L + \frac{ae}{2s_W c_W}\,[(1$$

$$\Gamma^{\mu}_{tcZ}(\tilde{d}^{k}_{R}) = \frac{ae}{2s_W c_W}\left[-2C^{\alpha\mu}_{4}\gamma_{\alpha} + C^{\alpha}_{4}(p_t + p_c)^{\mu}\gamma_{\alpha}\right]P_L + \frac{ae}{2s_W c_W}\left[(1 - \frac{4}{3}s^2_W)\gamma_{\alpha}p_c\gamma^{\mu}P_L - \frac{4}{3}s^2_W m_t\gamma_{\alpha}\gamma^{\mu}P_R\right]B^{\alpha}_{4}$$

$$\Gamma^{\mu}_{tch}(\tilde{\ell}^{i}_{L}) = ae\left[-m_{d_k}Y_d\left(2C^{\alpha}_{1}\gamma_{\alpha} - C^{0}_{1}(p_t - p_c)\right)P_L - \frac{m_Z\sin(\alpha+\beta)}{2s_W c_W}C^{\alpha}_{2}\gamma_{\alpha}P_L + \left[\gamma_{\alpha}p_c P_R + m_t\gamma_{\alpha}P_L\right]B^{\alpha}_{2}\right]$$

$$\Gamma^{\mu}_{tch}(\tilde{d}^{k}_{R}) = ae\left[-m_{\ell_i}Y_{\ell}\left(2C^{\alpha}_{3}\gamma_{\alpha} - C^{0}_{3}(p_t - p_c)\right)P_L + \frac{m_Z\sin(\alpha+\beta)}{2s_W c_W}C^{\alpha}_{2}\gamma_{\alpha}P_L + \left[\gamma_{\alpha}p_c P_R + m_t\gamma_{\alpha}P_L\right]B^{\alpha}_{4}\right]$$

with $a = i\lambda'_{i3k}\lambda'_{i2k}/(16\pi^2)$, $s_W = \sin\theta_W$, $c_W = \cos\theta_W$, and p_t and p_c denoting respectively the momenta of the top and charm quarks. The Yukawa couplings are given by:

$$Y_d = \frac{m_d\sin\alpha}{\sqrt{2}m_W\cos\beta}, \quad Y_{\ell} = \frac{m_{\ell}\sin\alpha}{\sqrt{2}m_W\cos\beta}, \quad Y_t = \frac{m_t\cos\alpha}{\sqrt{2}m_W\sin\beta}$$

For the loop functions B and C in Eqs. (A1-A8), we adopt the definitions in Ref. [?] and use LoopTools [?] in the calculations. The loop functions' dependence is given by:

$$C_1 = C(-p_t, p_c, m^2_{\tilde{\ell}^i_L}, m^2_{d_k}, m^2_{\tilde{\ell}^i_L}), \quad C_2 = C(-p_t, p_t - p_c, m^2_{\tilde{\ell}^i_L}, m^2_{d_k}, m^2_{\tilde{\ell}^i_L})$$

$$C_3 = C(-p_t, p_c, m^2_{\tilde{d}^k_R}, m^2_{\ell_i}, m^2_{\tilde{d}^k_R}), \quad C_4 = C(-p_t, p_t - p_c, m^2_{\tilde{d}^k_R}, m^2_{\ell_i}, m^2_{\tilde{d}^k_R})$$

$$B_1 = B(-p_t, m^2_{\tilde{\ell}^i_L}, m^2_{d_k}), \quad B_2 = B(-p_c, m^2_{\tilde{\ell}^i_L}, m^2_{d_k})$$

$$B_3 = B(-p_t, m^2_{\tilde{d}^k_R}, m^2_{\ell_i}), \quad B_4 = B(-p_c, m^2_{\tilde{d}^k_R}, m^2_{\ell_i})$$

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Note: Figure translations are in progress. See original paper for figures.