

# Probing $R$ -parity violating interactions from top-quark polarization at LHC

Peiyong Li<sup>1</sup>, Gongru Lu<sup>1</sup>, Jin Min Yang<sup>2,3,a</sup>, Huanjun Zhang<sup>1,3</sup>

<sup>1</sup> Department of Physics, Henan Normal University, Xinxiang 453007, P.R. China

<sup>2</sup> CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, P.R. China

<sup>3</sup> Institute of Theoretical Physics, Academia Sinica, P.O. Box 2735, Beijing 100080, P.R. China

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**Abstract.** In the minimal supersymmetric standard model the  $R$ -parity violating interactions can induce anomalous top pair productions at the LHC through the  $t$ -channel process  $d_R \bar{d}_R \rightarrow t_L \bar{t}_L$  by exchanging a slepton or by the  $u$ -channel process  $d_R \bar{d}_R \rightarrow t_R \bar{t}_R$  exchanging a squark. Such top pair productions with a certain chirality cause top-quark polarization in the top pair events. We found that at the LHC, due to the large statistics, the statistical significance of the polarization observable, and thus the probing ability for the corresponding  $R$ -parity violating couplings, is much higher than at the Tevatron upgrade.

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## 1 Introduction

It has long been speculated that, as the heaviest fermion in the standard model (SM), the top quark may have a close connection to new physics (for some reviews on top-quark physics, see, e.g., [1–5]). So far, there remains plenty of room for new physics in the top-quark sector due to the small statistics of the events entailing the top quark at the Fermilab Tevatron collider. Since the LHC will produce top quarks copiously and allow for a precision test of the nature of the top quark, it will either uncover or stringently constrain the new physics related to the top quark (for model-independent studies of new physics in top-quark physics, see, e.g., [6–8]).

As a popular candidate for new physics, TeV-scale supersymmetry can sizably alter some of the top-quark properties. For example, the minimal supersymmetric standard model (MSSM) can significantly enhance the top-quark flavor-changing neutral-current (FCNC) interactions [9–20] and may thus make the top-quark FCNC processes observable at the LHC.

It is well known that, in the MSSM, the discrete multiplicative symmetry of  $R$ -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 the separate conservation of  $B$  and  $L$ . Since such a conservation requirement is not dictated by any fundamental principle such as gauge invariance or renormalizability, the phenomenology of  $R$ -parity violation has attracted much attention (for some reviews, see [21–24]). So far as top-

quark physics at the LHC is concerned,  $R$ -parity violation can cause some exotic top-quark processes, like  $s$ -channel single top production and decays via exchanging a squark or slepton [25–29].

Note that  $R$ -parity violating interactions can also induce new mechanisms for top pair productions at the LHC through the  $t$ -channel process  $d_R \bar{d}_R \rightarrow t_L \bar{t}_L$  by exchanging a slepton or in the  $u$ -channel process  $d_R \bar{d}_R \rightarrow t_R \bar{t}_R$  by exchanging a squark. Although their contribution to the total  $t\bar{t}$  cross section is unobservable – as small as a few percent [30] – they may induce a sizable asymmetry between the left- and right-handed polarized top quarks due to the chiral nature of these couplings. In [31] such an induced polarization in top pair events is studied for the Tevatron collider and turns out to be a sensitive probe for these couplings due to the fact that both the SM and  $R$ -conserving MSSM contributions to the polarization are unobservably small [32–35]. Since the upcoming LHC will overwhelmingly outclass the Tevatron for the study of top-quark physics, in this work we extend the analysis of [31] to the LHC.

This work is organized as follows. In Sect. 2 we briefly describe our calculations. In Sect. 3 we present some numerical results and give some discussions. Finally, in Sect. 4 we give our conclusions.

## 2 Calculations

The  $R$ -parity violating interactions in the superpotential of the MSSM are given by

<sup>a</sup> e-mail: jmyang@itp.ac.cn

$$\begin{aligned} \mathcal{W}_{\mathcal{R}} = & \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} \delta^{\alpha\beta} L_i Q_{j\alpha} D_{k\beta}^c \\ & + \frac{1}{2} \lambda''_{ijk} \epsilon^{\alpha\beta\gamma} U_{i\alpha}^c D_{j\beta}^c D_{k\gamma}^c + \mu_i L_i H_2, \end{aligned} \quad (1)$$

where  $H_{1,2}$  are the Higgs chiral superfields, and  $L_i$  ( $Q_i$ ) and  $E_i$  ( $U_i$ ,  $D_i$ ) are the left-handed lepton (quark) doublet and singlet chiral superfields. The indices  $i, j, k$  denote the generations, and  $\alpha, \beta$  and  $\gamma$  are color indices. For top pair productions at hadron colliders, the lepton number violating couplings  $\lambda'_{i31}$  can induce the  $t$ -channel process  $d_R \bar{d}_R \rightarrow t_L \bar{t}_L$  by exchanging a slepton, while the baryon number violating couplings  $\lambda''_{31j}$  can induce the  $u$ -channel process  $d_R \bar{d}_R \rightarrow t_R \bar{t}_R$  by exchanging a squark, as shown in Fig. 1. The forms of these amplitudes are discussed in some detail in the appendix of [31].

It is clear that due to the chiral nature of these couplings, the processes they induced in Fig. 1 will cause top-quark polarization in the  $t\bar{t}$  events, i.e., an asymmetry between  $N_+$  (the number of  $t\bar{t}$  events with positive helicity of  $t$ ) and  $N_-$  (the number of  $t\bar{t}$  events with negative helicity of  $t$ ). The observables we will examine are the three polarizations:  $P_t$  for all  $t\bar{t}$  events and  $P_t^F$  ( $P_t^B$ ) for the  $t\bar{t}$  events with  $t$  in the forward (backward) hemisphere in the  $t\bar{t}$  c.m. frame, defined by [31]

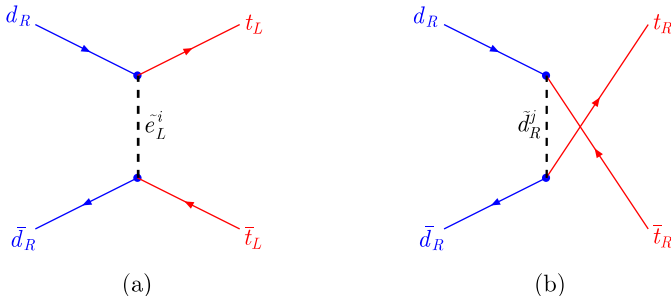
$$P_t = \frac{N_+ - N_-}{N_+ + N_-} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \quad (2)$$

$$P_t^F = \frac{N_+ - N_-}{N_+ + N_-} \Big|_{\cos\theta^* > 0} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \Big|_{\cos\theta^* > 0}, \quad (3)$$

$$P_t^B = \frac{N_+ - N_-}{N_+ + N_-} \Big|_{\cos\theta^* < 0} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \Big|_{\cos\theta^* < 0}. \quad (4)$$

Here  $\theta^*$  is the top scattering angle in the  $t\bar{t}$  c.m. frame, and  $\sigma_+$  ( $\sigma_-$ ) is the  $t\bar{t}$  hadronic cross section with positive (negative) helicity of  $t$ , which is obtained by convoluting the parton cross section  $\hat{\sigma}_+$  ( $\hat{\sigma}_-$ ) with the parton distribution functions [36, 37] (in our calculations we assume both the renormalization and factorization scales to be  $\mu = m_t$ ).

Note that it may seem naive to define the polarization asymmetry simply as  $(N_+ - N_-)/(N_+ + N_-)$ , since it would be sizable even when  $N_+$  and  $N_-$  are very small (say below unity). However, since  $N_+$  ( $N_-$ ) is the total number of  $t\bar{t}$  events with positive (negative) helicity and



**Fig. 1.** Feynman diagrams for top pair productions induced by  $\lambda'_{i31}$  and  $\lambda''_{31j}$ , respectively

not the number contributed by new physics alone (the  $R$ -parity violating contribution will become very small for small  $R$ -parity violating couplings and heavy sfermions involved),  $N_+$  and  $N_-$  are very large numbers at the LHC due to the large QCD  $t\bar{t}$  production cross section and the high luminosity of the LHC. Of course, as it will be discussed when we consider the statistical sensitivity in next section,  $N_+$  and  $N_-$  will be suppressed by the detection efficiency. But even so,  $N_+$  and  $N_-$  are very large, since the LHC can produce  $t\bar{t}$  copiously and can serve as a top-quark factory. Also, as it will be discussed at the end of this section, although  $N_+$  and  $N_-$  are very large numbers, the asymmetry  $(N_+ - N_-)/(N_+ + N_-)$  is very small in the SM, because the SM  $t\bar{t}$  production is dominated by QCD processes that predict  $N_+ = N_-$ . For this reason, this asymmetry will be a sensitive probe for any new physics that can predict a sizable difference between  $N_+$  and  $N_-$ .

The parton cross section  $\hat{\sigma}$  contains the SM contribution  $\hat{\sigma}^{\text{SM}}$  and the  $R$ -parity violating contribution  $\hat{\sigma}^{\text{new}}$ :

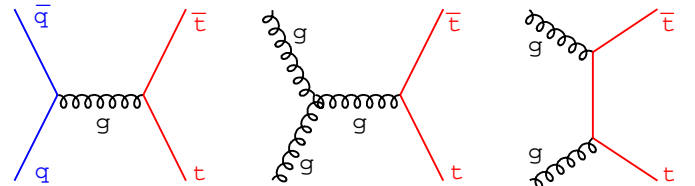
$$\hat{\sigma} = \hat{\sigma}^{\text{SM}} + \hat{\sigma}^{\text{new}}. \quad (5)$$

For  $\hat{\sigma}^{\text{SM}}$  the dominant contributions are from the QCD processes shown in Fig. 2. It is well known that at the LHC (Tevatron) the gluon-gluon fusion process  $gg \rightarrow t\bar{t}$  and the quark-antiquark annihilation process  $q\bar{q} \rightarrow t\bar{t}$  contribute about 90% (10%) and 10% (90%), respectively. We assume that the QCD correction factors ( $K$ -factor) to  $\hat{\sigma}^{\text{new}}$  and  $\hat{\sigma}^0$  take the same value, and thus the QCD correction effects cancel in the polarizations defined above. Note that due to the separate  $C$ - and  $P$ -invariance of QCD, the QCD cross section  $\hat{\sigma}_+^0$  equals  $\hat{\sigma}_-^0$ ; they are given by

$$\begin{aligned} \frac{d\hat{\sigma}_+^0}{d\cos\theta^*} &= \frac{d\hat{\sigma}_-^0}{d\cos\theta^*} \\ &= \frac{\pi\alpha_s^2\beta}{18\hat{s}} (1 + \cos^2\theta^*) + \frac{2\pi\alpha_s^2\beta m_t^2}{9\hat{s}^2} \sin^2\theta^* \end{aligned} \quad (6)$$

for  $q\bar{q} \rightarrow t\bar{t}$ , and

$$\begin{aligned} \frac{d\hat{\sigma}_+^0}{d\cos\theta^*} &= \frac{d\hat{\sigma}_-^0}{d\cos\theta^*} \\ &= \frac{\pi\beta\alpha_s^2}{32\hat{s}} \left[ 12 \frac{(\hat{t} - m_t^2)(\hat{u} - m_t^2)}{\hat{s}^2} \right. \\ &\quad \left. - \frac{2}{3} \frac{m_t^2(\hat{s} - 4m_t^2)}{(\hat{t} - m_t^2)(\hat{u} - m_t^2)} \right] \end{aligned}$$



**Fig. 2.** Feynman diagrams for top pair productions in the standard model

$$\begin{aligned}
& + \frac{8}{3} \frac{(\hat{t} - m_t^2)(\hat{u} - m_t^2) - 2m_t^2(\hat{t} + m_t^2)}{(\hat{t} - m_t^2)^2} \\
& + \frac{8}{3} \frac{(\hat{t} - m_t^2)(\hat{u} - m_t^2) - 2m_t^2(\hat{u} + m_t^2)}{(\hat{u} - m_t^2)^2} \\
& + 6 \frac{(\hat{t} - m_t^2)(\hat{u} - m_t^2) - m_t^2(\hat{t} - \hat{u})}{\hat{s}(\hat{t} - m_t^2)} \\
& + 6 \frac{(\hat{t} - m_t^2)(\hat{u} - m_t^2) + m_t^2(\hat{t} - \hat{u})}{\hat{s}(\hat{u} - m_t^2)} \Big], \quad (7)
\end{aligned}$$

for  $g\bar{g} \rightarrow t\bar{t}$ . Here  $\beta = \sqrt{1 - 4m_t^2/\hat{s}}$ ,  $\hat{t} = m_t^2 - \hat{s}(1 - \beta \cos \theta^*)/2$  and  $\hat{u} = m_t^2 - \hat{s}(1 + \beta \cos \theta^*)/2$ .

The  $R$ -parity violating contribution  $\hat{\sigma}^{\text{new}}$  comes from the interference of the diagrams in Fig. 1 with the corresponding quark–antiquark annihilation QCD diagram in Fig. 2. Due to the chiral nature of these  $R$ -parity violating couplings, the cross section with positive helicity of the top quark ( $\hat{\sigma}_+^{\text{new}}$ ) is not equal to that with negative helicity ( $\hat{\sigma}_-^{\text{new}}$ ). The detailed expressions for  $d\hat{\sigma}_+^{\text{new}}/d\cos\theta^*$  and  $d\hat{\sigma}_-^{\text{new}}/d\cos\theta^*$  can be found in [31].

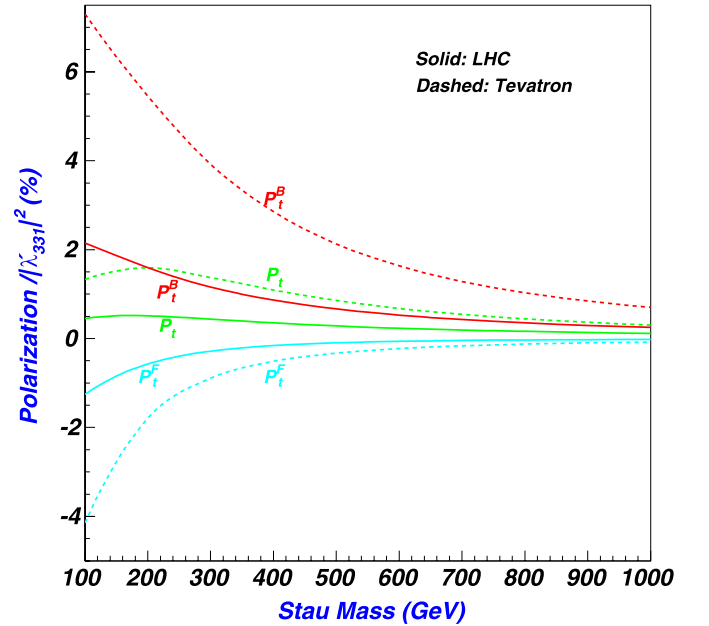
Finally, we stress the reasons to consider the polarization asymmetry in (2) rather than the *total*  $t\bar{t}$  cross section in probing the  $R$ -parity violating couplings.

- (i) This polarization asymmetry will be a sensitive probe for new physics due to the fact that the SM contribution to this polarization asymmetry is very small (below 1%) [32–35]. The  $t\bar{t}$  productions at the LHC are dominated by the QCD processes shown in Fig. 2. Of course, if we only consider the QCD interactions in the  $t\bar{t}$  productions, the polarization asymmetry in (2) is zero due to the separate  $C$ - and  $P$ -invariance of QCD. The SM electroweak process  $q\bar{q} \rightarrow Z^* \rightarrow t\bar{t}$  can cause a non-zero polarization asymmetry. But the polarization caused by this process is very small [32–35], since it does not interfere with the QCD amplitude because of the orthogonal color structure. Furthermore, the polarization caused by the SM electroweak loop corrections to the QCD  $t\bar{t}$  production processes is also very small [32–35]. Therefore, the observation of a sizable polarization asymmetry (say  $P_t > 1\%$ ) will serve as robust evidence for new physics.
- (ii) The  $R$ -conserving supersymmetric contribution to this polarization asymmetry is also very small [32–35]. So, if supersymmetry is the true story, only the  $R$ -parity violating couplings can cause a sizable value for the polarization asymmetry, which makes it a unique probe for  $R$ -parity violating couplings.
- (iii) Although the  $R$ -parity violating couplings can contribute to the *total*  $t\bar{t}$  cross section by a few percent [30], such correction effects of a few percent are hard to disentangle from the measurement of the  $t\bar{t}$  cross section, because of the uncertainties in the SM predictions of the  $t\bar{t}$  production cross section and the possible loop contributions from the  $R$ -conserving MSSM interactions [38–45].

### 3 Results and discussions

In our numerical calculations the top-quark mass is  $m_t = 175$  GeV, and the center-of-mass energy for the LHC (Tevatron) is  $\sqrt{s} = 14$  TeV (2 TeV). We assume that only one of the  $R$ -parity violating couplings involved dominates. For the  $L$ -violating couplings  $\lambda'_{i31}$ , we consider the existence of  $\lambda'_{331}$ , in which case the stau is exchanged in the process, since  $\lambda'_{131}$  and  $\lambda'_{231}$  are already strongly constrained by atomic parity violation and  $\nu_\mu$  deep-inelastic scattering [46]. For the  $B$ -violating interactions, the  $\lambda''_{31j}$ , none have been constrained well by other processes. So we may interpret our result as one holding on any of the  $\lambda''_{31j}$ , in which case the squark  $\tilde{d}^j$  is exchanged in the process.

In Fig. 3 we show the polarizations  $P_t$ ,  $P_t^F$  and  $P_t^B$  normalized to  $|\lambda'_{331}|^2$  versus the stau mass. This figure can be also read as  $-P_t$ ,  $-P_t^F$  and  $-P_t^B$  normalized to  $|\lambda''_{31j}|^2$  versus the mass of the squark  $\tilde{d}^j$  with  $P_t^F$  and  $P_t^B$  interchanged. The total polarization is smaller than the hemisphere polarizations, because of the cancellation between the two hemispheres. For the coupling  $\lambda'_{331}$  ( $\lambda''_{31j}$ ), the backward (forward) polarization has the largest magnitude of the three. Comparing the LHC results with the Tevatron results, we see that the polarizations at the LHC are smaller. This can be understood as follows: compared with the Tevatron, at the LHC both the difference  $\sigma_+ - \sigma_-$  ( $= \sigma_+^{\text{new}} - \sigma_-^{\text{new}}$ ) and the total cross section  $\sigma_+ + \sigma_-$  increase, but the total cross section increases more significantly, since it is dominated by the gluon–gluon fusion process.



**Fig. 3.** Top quark polarizations  $P_t$ ,  $P_t^F$  and  $P_t^B$  normalized to  $|\lambda'_{331}|^2$  at the LHC ( $\sqrt{s} = 14$  TeV) and the Tevatron upgrade ( $\sqrt{s} = 2$  TeV) versus the exchanged stau mass. The figure can be also read as  $-P_t$ ,  $-P_t^F$  and  $-P_t^B$  normalized to  $|\lambda''_{31j}|^2$  versus the exchanged squark mass with  $P_t^F$  and  $P_t^B$  interchanged

Now we estimate the statistical sensitivity. The statistical error for the top polarization asymmetry defined in (2) is given by

$$\delta P_t = \frac{[2(N_+^2 + N_-^2)]^{1/2}}{(N_+ + N_-)^{3/2}} \simeq \frac{1}{\sqrt{N_+ + N_-}} = \frac{1}{\sqrt{N}}, \quad (8)$$

while  $\delta P_t^F$  ( $\delta P_t^B$ ) is obtained by replacing the above events numbers with those in the forward (backward) hemisphere. For the number of  $t\bar{t}$  events, in estimating the statistical error we make the assumption

$$N = \epsilon [N^{\text{SM}} + N^{\text{new}}] \simeq \epsilon N^{\text{SM}} = \epsilon \mathcal{L} \sigma_{t\bar{t}}^{\text{SM}}, \quad (9)$$

with  $\sigma_{t\bar{t}}^{\text{SM}} = 873$  pb (6.77 pb) for the LHC (Tevatron upgrade), see, e.g., [53, 54],  $\mathcal{L}$  being the integrated luminosity and  $\epsilon$  being the efficiency factor in the event counting. The efficiency factor  $\epsilon$  can be written as

$$\epsilon = \epsilon_1 \epsilon_2 \epsilon_3 \quad (10)$$

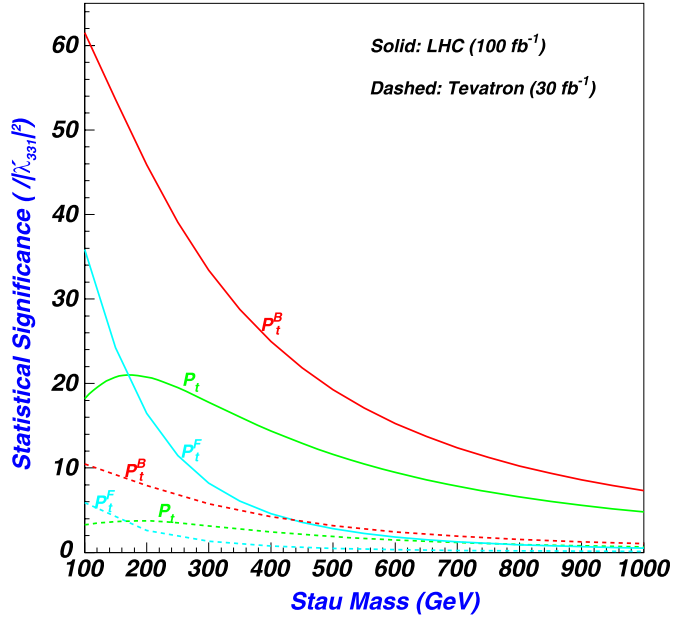
with  $\epsilon_{1,2,3}$  coming respectively from three aspects.

- (1) Firstly, as discussed in many previous works [47–51], the helicity states of the top quark may have to be determined from the kinematic distribution of its decay particles  $t \rightarrow W^+ b \rightarrow \ell^+ \nu_\ell b$  ( $\ell = e$  or  $\mu$ ) after reconstructing the top and anti-top quarks in the signal events. This will immediately lead to a suppression factor of  $\epsilon_1 = 2/9$ .
- (2) Secondly, as it is well known, considering both the detector acceptance and the suppression of the QCD background, some kinematic cuts on the top and anti-top decay particles as well as  $b$ -tagging are necessary. Depending on the detailed kinematic cuts and the  $b$ -tagging efficiency, the events number is further suppressed by an efficiency factor  $\epsilon_2$ . For example, if we impose the kinematic selection cuts  $p_T^\ell, \text{with } p_T^{\text{jet}} \geq 20$  GeV,  $\eta_{\text{jet}}, \eta_\ell \leq 3.0$ ,  $p_T^{\text{miss}} \geq 30$  GeV and  $\Delta R_{jj}, \Delta R_{j\ell} \geq 0.4$ , where  $p_T$  denotes the transverse momentum,  $\eta$  is the pseudo-rapidity, and  $\Delta R$  is the separation in the azimuthal angle–pseudo-rapidity plane ( $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ ) between a jet and a lepton or between two jets, then the efficiency from such kinematic cuts is about 30% (see, e.g., [58–60]). Combined with the  $b$ -tagging efficiency of about 50%, the efficiency factor  $\epsilon_2 \simeq 15\%$ . (Currently at Tevatron CDF, the efficiency for tagging at least one  $b$ -jet in a  $t\bar{t}$  event is  $(53 \pm 4)\%$  (see, e.g., [61]). At the LHC we expect an efficiency of better than 50% for tagging at least one  $b$ -jet in a  $t\bar{t}$  event.) Note that in theoretical analyses we usually impose  $\Delta R_{jj}, \Delta R_{j\ell} \geq 0.4$  [58–60]. But for the separation of jets at the LHC,  $\Delta R_{jj} \geq 0.4$  may be over-optimistic, and the realistic cut may be  $\Delta R_{jj} \geq 0.7$ . As a result of such a stronger cut, the efficiency factor  $\epsilon_2$  may drop below 10%. Further, in theoretical analyses we usually imposed  $\eta \leq 3$  [58–60] and did not consider the difference of the detector efficiencies in the different regions of  $\eta \leq 3$ . In practice, the detector efficiency will certainly be quite different in the barrel  $\eta < 1$  and endcap  $1 < \eta < 3$  regions.

Therefore, the realistic value of  $\epsilon_2$  can only be obtained from a detector-dependent full Monte Carlo simulation.

- (3) Thirdly, from analysing the distribution of the leptonic decays of a top quark, in practice we can only know its helicity with some probability  $\epsilon_3$ . A recent analysis [50] gives  $\epsilon_3 \simeq 75\%$ . But this figure may be over-optimistic, since the analysis [50] is a theoretical work making rather optimistic assumptions. As pointed in [51], the principal difficulty in measuring top-quark polarization comes from the ambiguities in reconstructing its momentum from the decay products, when both top and anti-top decay semileptonically. The realistic value of  $\epsilon_3$  may also have to be obtained from a detector-dependent full Monte Carlo simulation. For the ATLAS detector an analysis was given in [52] based on leading-order Monte Carlo generators and on a fast simulation of the detector.

Since the  $\epsilon_{2,3}$  are detector-dependent, and realistic values for them can only be obtained from detector-dependent full Monte Carlo simulations, in our numerical calculations for the statistical significance and statistical limits we only incorporate the suppression factor  $\epsilon_1$ , while we leave  $\epsilon_{2,3}$  as variables. Of course, it is straightforward to reinterpret our results once  $\epsilon_{2,3}$  are determined. We will explicitly point out how to reinterpret our results once the  $\epsilon_{2,3}$  are known. The statistical significances  $P_t/\delta P_t$ ,  $P_t^F/\delta P_t^F$  and  $P_t^B/\delta P_t^B$  normalized to  $|\lambda'_{331}|^2$  versus the stau mass are shown in Fig. 4. The figure can also be read as the statistical significances normal-



**Fig. 4.** Statistical significance at the LHC ( $\sqrt{s} = 14$  TeV) and the Tevatron upgrade ( $\sqrt{s} = 2$  TeV), normalized to  $|\lambda'_{331}|^2$  (or to  $|\lambda'_{331}|^2 \sqrt{\epsilon_2 \epsilon_3}$  if we consider the efficiency factors  $\epsilon_{2,3}$ ). The figure can also be read as the statistical significance normalized to  $|\lambda''_{31j}|^2$  versus the exchanged squark mass with  $P_t^F$  and  $P_t^B$  interchanged



ized to  $|\lambda''_{31j}|^2$  versus the exchanged squark mass with  $P_t^F$  and  $P_t^B$  interchanged. We see that in the case of  $\lambda'_{331}$  ( $\lambda''_{31j}$ ) the sensitivity of the backward (forward) polarization is best. Comparing Fig. 3 with Fig. 4, we see that, although the polarizations at the LHC are smaller than at the Tevatron upgrade, the LHC gives much larger statistical significances due to its much larger  $t\bar{t}$  sample. The statistical limits for  $\lambda'_{331}$  ( $\lambda''_{31j}$ ) versus stau (squark) mass are shown in Fig. 5. Here for the LHC we show the limits at  $5\sigma$  (discovery),  $3\sigma$  (evidence) and  $2\sigma$  (exclusion). The current  $2\sigma$  exclusion limits from  $Z$  decay at LEP [55–57] are also shown for comparison. We see that the LHC may be quite powerful in probing these  $R$ -parity violating couplings.

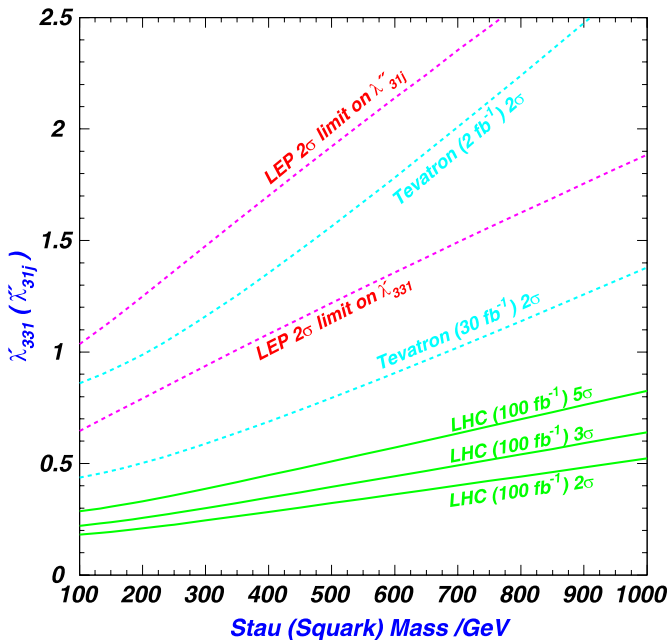
Finally, we stress that our above analyses are almost solely theoretical. We have only demonstrated the statistical sensitivity and statistical limits. As it is well known, in experiments some systematic errors are inevitable. Such systematic errors are detector-dependent and will certainly worsen the probing limits for the  $R$ -parity violating couplings. For example, as an artifact of the measurement problems, an apparent polarization asymmetry may arise. The analysis for the ATLAS detector showed [52] that the systematic uncertainties will dominate over the statistical errors after one LHC year at low luminosity ( $10 \text{ fb}^{-1}$ ). The analysis in [52] gives a quite encouraging result; it shows that a percent-level precision on the measurement of the polarization asymmetry between like-spin versus unlike-spin  $t\bar{t}$  events is possible even with  $10 \text{ fb}^{-1}$ . Of course, a higher luminosity (say  $100 \text{ fb}^{-1}$ ) will further enhance the precision of the measurement. Although the analy-

sis in [52] did not show the possible measurement precision on our polarization asymmetry  $(N_+ - N_-)/(N_+ + N_-)$ , we can expect a similar or even better precision, because here we sum over the helicities of the  $\bar{t}$  and consider an integrated asymmetry in the numbers of  $t_+$  and  $t_-$  produced.

## 4 Conclusions

In summary, the  $R$ -parity violating interactions of the top quark, which have not been constrained well by current experiments, can induce anomalous top pair productions at hadron colliders. Although such induced processes only contribute to the total  $t\bar{t}$  cross section at the percent level, they can cause top-quark polarization in the top pair events due to the chiral nature of these interactions. The polarization may be a useful observable for probing these interactions at the LHC and the upgraded Fermilab Tevatron collider, because the polarization is expected to be very small in the standard model. We found that at the LHC, due to the large statistics, the statistical significance of the polarization observable, and thus the probing ability for the corresponding  $R$ -parity violating couplings, is much higher than at the Tevatron upgrade.

Finally, we stress that for the purpose of probing these  $R$ -parity violating couplings, there may exist other processes, which are complementary to our analyses. For example, the  $\lambda''_{3ij}$  couplings can induce  $s$ -channel top-squark productions at the LHC and Tevatron and, as studied in [62, 63], such productions can be used to probe the parameter space of  $\lambda''_{3ij}$  versus the top-squark mass.



**Fig. 5.** The statistical limits for  $\lambda'_{331}$  (or for  $\lambda'_{331}(\epsilon_2\epsilon_3)^{1/4}$  if we consider the efficiency factors  $\epsilon_{2,3}$ ) versus stau mass. The figure can be also read as the statistical limits for  $\lambda''_{31j}$  versus squark mass

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