

# Probing R-violating top quark decays at hadron colliders

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## ABSTRACT

We examine the possibility of observing exotic top quark decays via R-violating SUSY interactions at the Fermilab Tevatron and CERN LHC. We present cross-sections for  $t\bar{t}$  production followed by the subsequent decay of either  $t$  or  $\bar{t}$  via the R-violating interaction while the other undergoes the SM decay. With suitable kinematic cuts, we find that the exotic decays can possibly be detected over standard model backgrounds at the future runs of the Tevatron and LHC, but not at Run 1 of the Tevatron due to limited statistics. Discovery limits for R-Violating couplings in the top sector are presented.

# 1 Introduction

The top quark, with a mass of the order of the electroweak symmetry breaking scale, is naturally considered to be related to new physics. Run 1 of the Fermilab Tevatron has small statistics on top quark events and thus leaves plenty of room for new physics to be discovered at the upgraded Tevatron [1] in the near future. Due to higher statistics, the  $t\bar{t}$  events at the upgraded Tevatron are expected to provide sensitive probes for new physics [2]. The most popular model for new physics is the Minimal Supersymmetric Model (MSSM) [3]. In this model,  $R$ -parity [4], 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  $L$ . As a consequence the sparticle number is conserved. Since instanton effects induce miniscule violations of baryon and lepton number [5],  $R$ -parity conservation is not dictated by any known fundamental principle such as gauge invariance or renormalizability. If  $R$ -parity is strictly conserved, it is conceivable that the conservation comes from some hitherto unidentified fundamental principle. Hence  $R$ -parity violation should be vigorously searched for.

The most general superpotential of the MSSM, consistent with the  $SU(3) \times SU(2) \times U(1)$  symmetry, supersymmetry, and renormalizability also contains  $R$ -violating interactions which are given by

$$\mathcal{W}_R = \frac{1}{2}\lambda_{ijk}L_iL_jE_k^c + \lambda'_{ijk}\delta^{\alpha\beta}L_iQ_{j\alpha}D_{k\beta}^c + \frac{1}{2}\lambda''_{ijk}\epsilon^{\alpha\beta\gamma}U_{i\alpha}^cD_{j\beta}^cD_{k\gamma}^c + \mu_iL_iH_2, \quad (1)$$

where  $L_i(Q_i)$  and  $E_i(U_i, D_i)$  are the left-handed lepton (quark) doublet and right-handed lepton (quark) singlet chiral superfields. The indices  $i, j, k$  are generation indices,  $\alpha, \beta$  and  $\gamma$  are the color indices,  $c$  denotes charge conjugation, and  $\epsilon^{\alpha\beta\gamma}$  is the total antisymmetric tensor in three-dimension.  $H_{1,2}$  are the Higgs-doublets chiral superfields. The coefficients  $\lambda$  and  $\lambda'$  are the coupling strengths of the  $L$ -violating interactions and  $\lambda''$  those of the  $B$ -violating interactions. The lower bound of the proton lifetime imposes very strong conditions on the simultaneous presence of both  $L$ -violating and  $B$ -violating interactions [6] and hence the strength of the couplings. However, the existence of either  $L$ -violating or  $B$ -violating couplings, but not both at the same time, does not induce nucleon decays and therefore the  $R$ -parity violating couplings are less constrained. This separate  $L$  and  $B$  violation is usually assumed in phenomenological analyses.

The study of the phenomenology of  $R$ -violating supersymmetry was started many years ago [7]. Some constraints on the  $R$ -parity violating couplings have been obtained from various analyses, such as perturbative unitarity [8],  $n-\bar{n}$  oscillation [9],  $\nu_e$ -Majorana

mass [10], neutrino-less double  $\beta$  decay [11], charged current universality [12],  $e - \mu - \tau$  universality [12],  $\nu_\mu - e$  scattering [12], atomic parity violation [12],  $\nu_\mu$  deep-inelastic scattering [12],  $\mu - e$  conversion [13],  $K$ -decay [16],  $\tau$ -decay [15],  $D$ -decay [15],  $B$ -decay [16] and  $Z$ -decay at LEP I [17]. As reviewed in Ref. [18], although many such couplings have been severely constrained, the bounds on the top quark couplings are generally quite weak. This is the motivation for the phenomenological study of  $R$ -violation in processes involving the top quark.

The production mechanisms of top pairs and single top in  $R$ -violating SUSY at the upgraded Tevatron have been examined in [19] and [20], respectively. In addition, the  $R$ -violating couplings can induce exotic decays for top quark at an observable level. For example, the top quark FCNC decays induced by  $R$ -violating couplings [21] can be significantly larger than those in the MSSM with  $R$ -parity conservation [22]. If we allow the co-existence of two  $\lambda'$  couplings, we have the new decay modes, such as  $t \rightarrow \ell \tilde{d} \rightarrow \ell^+ \ell^- u$  [23]. The bilinear term  $\mu_i L_i H_2$  can also induce some new decays for the top quark, as studied in [24].

In this work, we focus on the explicit trilinear couplings and assume only one trilinear coupling exists at one time. Then the possible exotic top decay modes are

$$t \rightarrow \tilde{d}_i \bar{d}_j, \tilde{d}_j \bar{d}_i \rightarrow \bar{d}_i \bar{d}_j \tilde{\chi}_1^0 \quad (2)$$

induced by the  $B$ -violating  $\lambda''_{3ij}$ , and

$$t \rightarrow e_i^+ \tilde{d}_j \tilde{e}_i d_j \rightarrow e_i^+ d_j \tilde{\chi}_1^0 \quad (3)$$

induced by the  $L$ -violating  $\lambda'_{ij}$ . Here the subscripts  $i, j$  are family indices and  $\tilde{\chi}_1^0$  is the lightest neutralino which, in our analysis, is assumed to be the lightest super particle (LSP) as favored in the MSSM where the SUSY breaking is propagated to the matter sector by gravity<sup>1</sup>. The sfermions involved in these decays can be on-shell or virtual, depending on the masses of the particles involved.

Among the exotic decays in (2) and (3), the relatively easy-to-detect modes are those induced by  $\lambda''_{33j}$  ( $j = 1, 2$ )<sup>2</sup> and  $\lambda'_{i33}$  ( $i = 1, 2, 3$ ) because their final states contain a  $b$ -quark which can be tagged. One of the  $L$ -violating channels, i.e.,  $t \rightarrow \tilde{\tau} b$  (or  $\tau \tilde{b}$ ) induced by  $\lambda'_{333}$  has been studied in [25]. So in our analysis we focus on the cases of  $\lambda'_{133}$  and  $\lambda'_{233}$  for  $L$ -violating couplings, and  $\lambda''_{331}$  and  $\lambda''_{332}$  for  $B$ -violating couplings. Since the decay induced by  $\lambda'_{133}$  has the similar final states to that induced by  $\lambda'_{233}$ , we take the

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<sup>1</sup>If the SUSY breaking is mediated by gauge interactions, the LSP is expected to be the gravitino.

<sup>2</sup> $\lambda''_{333}$  does not exist since  $\lambda''_{ijk}$  is antisymmetric in the last two indices.

presence of  $\lambda'_{233}$  as an example. For the same reason, we take the presence of  $\lambda''_{331}$  as an example in  $B$ -violating case. The Feynman diagrams for these two decays induced by  $\lambda''_{331}$  and  $\lambda'_{233}$  are shown in Figs. 1 and 2, respectively.

In our analysis we consider  $t\bar{t}$  events where one ( $t$  or  $\bar{t}$ ) decays via R-violating coupling while the other decays by the SM interaction. The SM decay will serve as the tag of the  $t\bar{t}$  event. Furthermore, the penalty of the suppressed  $R$ -violation coupling is paid only once. Top spin correlations are taken into account in our calculation.

Note that the LSP ( $\tilde{\chi}_1^0$ ) is no longer stable when R-parity is violated. In case just one R-violating top quark coupling does not vanish, the lifetime of the LSP will be very long, depending the coupling and the masses of squarks involved in the LSP decay chain (cf. the last paper of [18]). Thus it is generally assumed that the LSP decays outside the detector [26]. We will make this assumption in our analysis. This paper is organized as follows. In Sec. 2, we investigate the potential of observing the  $B$ -violating top quark decay at the Tevatron and LHC, and present numerical results. In Sec. 3 we present similar results for  $L$ -violating decay. Finally in Sec. 4 we present a summary and discussion.

## 2 Searching for $B$ -violating decay

### 2.1 Signal and background

To probe the decay  $t \rightarrow \bar{b}\tilde{\chi}_1^0$  in Fig. 1, we consider the final states given by  $t\bar{t}$  production where one (say  $t$ ) decays via the coupling  $\lambda''_{331}$  while the other (say  $\bar{t}$ ) has the SM decays to serve as the tag of the  $t\bar{t}$  event. Due to the large QCD background at hadron colliders, we do not search for the all-jets channel despite of its higher rate. Instead, we search for the signal given by  $t\bar{t}$  events followed by  $t \rightarrow \bar{b}\tilde{\chi}_1^0$  and  $\bar{t} \rightarrow W^- \bar{b} \rightarrow \ell \bar{\nu} \bar{b}$  ( $\ell = e, \mu$ ). Then the signature is a lepton, three jets containing two  $b$ -jets or two  $\bar{b}$ -jets, and missing energy ( $\ell + 3j/2b + \cancel{E}_T$ ). We require that two  $b$ -jets are tagged in the signal. The efficiency for double  $b$ -tagging is assumed to be 42% [1].

Note that the present events have the unique signal of the two same sign  $b$ -quarks. In our analysis, to be conservative, we assume that the tagging can not distinguish a  $b$ -quark jet from  $\bar{b}$ -quark jet. Then the SM backgrounds are mainly from

- (1)  $t\bar{t} \rightarrow W^- W^+ b\bar{b}$  followed by  $W^- \rightarrow \ell \bar{\nu}$  ( $\ell = e, \mu$ ) and  $W^+ \rightarrow \tau^+ \nu$  with the  $\tau$  decaying into a jet plus a neutrino;

- (2)  $t\bar{t} \rightarrow W^-W^+b\bar{b}$  followed by  $W^- \rightarrow \ell\nu$  ( $\ell = e, \mu$ ) and  $W^+ \rightarrow q\bar{q}'$ . This process contains an extra quark jet and can only mimic our signal if the quark misses detection by going into the beam pipe. We assume this can only happen when the light quark jet has the pseudo-rapidity greater than about 3 or the transverse momentum less than about 10 GeV.
- (3)  $Wb\bar{b}j$  which includes single top quark production via the quark-gluon process  $qg \rightarrow q't\bar{b}$  as well as non-top processes [27].

## 2.2 Numerical calculation and results

We calculated the signal and background cross sections with the CTEQ5L structure functions [28]. We assume  $M_t = 175$  GeV and take  $\sqrt{s} = 2$  TeV for the upgraded Tevatron and  $\sqrt{s} = 14$  TeV for the LHC.

As shown in Fig. 1, there are two contributing graphs. Since among the down-type squarks the sbottom is most likely to be lighter than other squarks (we will elaborate on this later), we assume the first graph in Fig.1 gives the dominant contribution. (If the  $\tilde{d}$  is as light as the sbottom, the second diagram in Fig.1 has to be taken into account. Then our results for the signal rate should be quadrupled. To be conservative, we do not consider this case.)

For the total width of the sbottom involved in our calculation, we note that since only a light sbottom is meaningful to our analysis (as will be shown in our results), its dominant (or maybe the only) decay mode is  $\tilde{b} \rightarrow b\tilde{\chi}_1^0$ . The charged current decay mode  $\tilde{b} \rightarrow t\tilde{\chi}_1^+$  is kinematically forbidden for a light sbottom in our analysis. We do not consider the strong decay mode  $\tilde{b} \rightarrow b\tilde{g}$  since the gluino  $\tilde{g}$  is likely to be heavy [29].

The signal cross section is proportional to  $|\lambda''_{331}|^2$ . We will present the signal results normalized to  $|\lambda''_{331}|^2$ . The signal cross section is very sensitive to the sbottom mass. We will vary it to see how heavy it can be for the signal to be observable. Other SUSY parameters involved are the lightest neutralino mass and its coupling to sbottom, which are determined by the parameters  $M, M', \mu$  and  $\tan\beta$ .  $M$  is the  $SU(2)$  gaugino mass and  $M'$  is the hypercharge  $U(1)$  gaugino mass.  $\mu$  is the Higgs mixing term ( $\mu H_1 H_2$ ) in the superpotential.  $\tan\beta = v_2/v_1$  is the ratio of the vacuum expectation values of the two Higgs doublets. We work in the framework of the general MSSM. But we assume the grand unification of the gaugino masses, which gives the relation  $M' = \frac{5}{3}M \tan^2\theta_W \simeq 0.5M$ . Then for the three independent parameters  $M, \mu$  and  $\tan\beta$ , we

choose a representative set of values

$$M = 100 \text{ GeV}, \mu = -200 \text{ GeV}, \tan \beta = 1. \quad (4)$$

They yield the lightest chargino and neutralino masses as  $m_{\tilde{\chi}_1^+} = 120 \text{ GeV}$ ,  $m_{\tilde{\chi}_1^0} = 55 \text{ GeV}$ . Thus this set of values are allowed by the current experimental bounds on the chargino and neutralino masses, which are about 90 GeV and 45 GeV, respectively [30].

We simulate detector effects by assuming Gaussian smearing of the energy of the charged final state particles, given by:

$$\Delta E/E = 30\%/\sqrt{E} \oplus 1\%, \text{ for leptons,} \quad (5)$$

$$= 80\%/\sqrt{E} \oplus 5\%, \text{ for hadrons,} \quad (6)$$

where  $\oplus$  indicates that the energy dependent and independent terms are added in quadrature and  $E$  is in GeV.

The basic selection cuts are chosen as

$$p_T^\ell, p_T^{jet}, p_T^{\text{miss}} \geq 20 \text{ GeV}, \quad (7)$$

$$\eta_{jet}, \eta_\ell \leq 2.5, \quad (8)$$

$$\Delta R_{jj}, \Delta R_{j\ell} \geq 0.5. \quad (9)$$

Here  $p_T$  denotes 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.

We notice that for the background process (2) and (3) the missing energy comes only from the neutrino of the W decay, while for the signal events the missing energy contains an extra neutralino. From the transverse momentum of the lepton  $\vec{P}_T^\ell$  and the missing transverse momentum  $\vec{P}_T^{\text{miss}}$ , we construct the transverse mass as

$$m_T(\ell, p_T^{\text{miss}}) = \sqrt{(|\vec{P}_T^\ell| + |\vec{P}_T^{\text{miss}}|)^2 - (\vec{P}_T^\ell + \vec{P}_T^{\text{miss}})^2}. \quad (10)$$

As is well-known, if the two components, i.e.,  $\ell$  and  $p_T^{\text{miss}}$  in our case, are from the decay of a parent particle, the transverse mass is bound by the mass of the parent particle. So for  $Wb\bar{b}j$  background events  $m_T(\ell, p_T^{\text{miss}})$  is always less than  $M_W$  and peaks just below  $M_W$ . However, kinematic smearings can push the bound and the peak above  $M_W$ . In order to substantially suppress the large backgrounds (2) and (3) we apply the following cut

$$m_T(\ell, p_T^{\text{miss}}) > 120 \text{ GeV}. \quad (11)$$

We found that the above strong  $m_T(\ell, p_T^{\text{miss}})$  cut suppresses the background process (2) and (3) by roughly three orders of magnitude for the smearing in Eqs. (5) and (6), so that they are much smaller than the other backgrounds we are considering. But since background process (1) contains three neutrinos from different parent particles, it is not suppressed by the  $m_T(\ell, p_T^{\text{miss}})$  cut to a negligible level. There is some model dependence involved in the treatment of  $\tau$  hadronization. To avoid having to consider each of the many hadronic decay modes separately, we assume the invariant mass of the outgoing hadrons to be distributed uniformly from  $m_\pi$  to  $m_\tau$ . Furthermore, we assume a uniform angular distribution in the phase allowed by the invariant mass of the outgoing jet. This assumption is probably reasonable in light of the fact that the parent  $\tau$  is heavily boosted in the lab frame.

With the above selection cuts, the signal and background cross sections are given in Table 1. We see that the signal-to-background ratio can be quite large for light sbottom mass ( $\lesssim 160$  GeV), in which the intermediate sbottom can be materialized as a real particle. When the sbottom becomes heavier than the top quark and thus can only appear as a virtual state, the cross section is severely suppressed by the small branching ratio of the decay.

From the results for Tevatron (1.8 TeV) in Table 1 we conclude that the luminosity Run 1 ( $0.1 \text{ fb}^{-1}$ ) is too low to detect such decays. However, due to the much larger statistics of Run 2 ( $2 \text{ fb}^{-1}$ ) and Run 3 ( $30 \text{ fb}^{-1}$ ), it is possible to observe such decays in these coming runs of the Tevatron. Using the discovery criteria  $S \geq 5\sqrt{B}$ , the discovery limits of  $\lambda''_{33j}$  versus the sbottom mass at Run 2, Run 3 ( $30 \text{ fb}^{-1}$ ) and LHC ( $10 \text{ fb}^{-1}$ ) are plotted in Fig. 3. The region above each curve is the corresponding region of discovery. Since the current bounds on  $\lambda''_{331}$  from the LEP I Z-decay are of  $\mathcal{O}(1)$  for sfermion mass heavier than 100 GeV [17], we see that for a light sbottom, we have a good chance to observe such decays if  $\lambda''_{331}$  is not far below its current upper bounds. In case of nonobservation, meaningful bounds at 95% C.L. can be set, as shown in Fig.4.

Our results for  $\lambda''_{331}$  can be applied to the case of  $\lambda''_{332}$ . Since the current bound from Z-decay is the same on both couplings [17], our conclusions on  $\lambda''_{331}$  can be applied to the case of  $\lambda''_{332}$ .

### 3 Searching for $L$ -violating decay

For  $L$ -violating decay  $t \rightarrow \mu^+ b \tilde{\chi}_1^0$ , there are two contributing graphs, as shown in Fig.2. The first graph proceeds through exchanging a sbottom while the second through ex-

changing a slepton. As in Sec. 2, we assume sbottom can be light and thus concentrate on the first graph. In the opposite case that the slepton is light and sbottom is heavy, our following results still hold with the replacement of sbottom mass by slepton mass. If both sbottom and slepton are light and approximately degenerate (which is quite unlikely in the supergravity scenario of supersymmetry breaking, as will be elaborated on later), then our results for the signal rate should be quadrupled.

Our examination for this decay is similar to the  $B$ -violating decay in the preceding section. We search for the signal given by  $t\bar{t}$  events where one (say  $t$ ) decays via  $L$ -violating coupling,  $t \rightarrow \mu^+ b \tilde{\chi}_1^0$ , while the other ( $\bar{t}$ ) has the SM decays,  $\bar{t} \rightarrow W^- \bar{b}$ . Then there are two possible observing channels for such an event: dilepton+2-jets and single lepton+4-jets, all being associated with missing energies. The dilepton channel has the lower rate and it is difficult to find a mechanism to enhance the S/B rate so as to find the "smoking gun" for the signal. So we search for the single lepton+4-jets channel which has a higher rate. As is shown below, we can find effective selection cuts to enhance the S/B ratio for this signal.

Among the four jets in our signal there are two b-jets (one is  $b$ , the other is  $\bar{b}$ ). We require that at least one b-jet passes b-tagging. The tagging efficiency is 53% at Run 1 and expected to reach 85% at Run 2 and Run 3 [1]. For the LHC we assume the tagging efficiency to be the same as the Tevatron Run 2.

So the signature is  $\ell + 4j/b + \cancel{E}_T$  where  $4j/b$  represents a 4-jets event with at least one of the jets passing the  $b$ -tagging criterion. This is the same as one of the typical signatures for  $t\bar{t}$  event in the SM, except for the different source of missing energy. To suppress the QCD background, we apply the basic selection cuts in Eqs.(7-9). Under the basic selection cuts the QCD background is reduced to about 1/12 of the SM  $t\bar{t}$  events [1]. However, under the basic selection cuts the number of SM  $t\bar{t}$  events far surpasses the number of signal events. In order to extract the signal events, we turn to the transverse mass defined in Eq.(10). For the SM  $t\bar{t}$  events and  $W$ +jets background events the missing energy comes from the neutrino of the  $W$  decay, while for the signal events the missing energy comes from the neutralino in the decay  $t \rightarrow \mu^+ \tilde{b} \rightarrow \mu^+ b \tilde{\chi}_1^0$ . Thus the transverse mass distributions of the SM background and the signal events are different, as shown in Fig.5. In order to enhance the S/B ratio, we apply the following cut, taking into account of the smearing effect,

$$m_T(\ell, p_T^{\text{miss}}) \not\leq 50 \sim 100 \text{ GeV}. \quad (12)$$

Other details in the numerical calculation, such as the smearing of the energy of



the final state particles and the choice of SUSY parameters, are the same as in Sec. 2. In Table 2 we present the signal cross section for sbottom mass of 150 GeV, with the comparison to the SM  $t\bar{t}$  background. One sees that the transverse mass cut can enhance the S/B ratio significantly. With the increase of sbottom mass, the signal cross section drops rapidly, as shown in Table 3.

From Tables 2 and 3 one sees that Run 1 ( $0.1 \text{ fb}^{-1}$ ) of the Tevatron collider is unable to detect such decays for a sbottom heavier than 150 GeV and  $\lambda'_{233} < 1$ . The possibility of observing such a decay is enhanced at Run 2 ( $2 \text{ fb}^{-1}$ ), Run 3 ( $30 \text{ fb}^{-1}$ ) and the LHC. Under the discovery criteria  $S \geq 5\sqrt{B}$ , the discovery limits of  $\lambda'_{233}$  versus sbottom mass are plotted in Fig.6. The nonobservation of a signal is translated to the bounds (at 95% C.L.) shown in Fig.7.

Since the current bounds on  $\lambda'_{233}$  from the LEP I Z-decay are of  $\mathcal{O}(1)$  for sfermion mass heavier than 100 GeV [17], the results in Figs.6 and 7 indicate that the future runs at the upgraded Tevatron and LHC could either reveal the exotic decay or set stronger constraints on the  $L$ -violating coupling  $\lambda'_{233}$ .

Our results for  $\lambda'_{233}$  can be applied to the case of  $\lambda'_{133}$ . But for  $\lambda'_{133}$  the current bound from the  $\nu_e$ -mass, i.e.,  $\lambda'_{133} < 0.0007$  at the  $1 - \sigma$  level [10], is too strong, which makes the corresponding decay  $t \rightarrow e^+ b \tilde{\chi}_1^0$  unobservable.

## 4 Summary and discussion

We have examined the potential for the detection of top quark decays via R-violating SUSY interactions at the Fermilab Tevatron and LHC. We studied two representative decay processes: one is induced by the  $B$ -violating coupling  $\lambda''_{331}$  and the other is induced by the  $L$ -violating coupling  $\lambda'_{233}$ . Both of them have a  $b$ -jet in their decay products and can proceed through the intermediate sbottom which was assumed to be light. For the  $B$ -violating decay we searched for the signal  $\ell + 3j/2b + \cancel{E}_T$  given by  $t\bar{t}$  events, while for the  $L$ -violating decay we searched for the channel  $\ell + 4j/b + \cancel{E}_T$ . We considered the possible backgrounds and performed a Monte Carlo simulation by applying suitable cuts.

The signal cross section is found to drop drastically with the increase of the intermediate sbottom mass. If the sbottom could be as light as  $\sim 160$  GeV, then under the current bounds of the relevant R-violating couplings, these decays can be detectable at the future runs of the Tevatron and LHC. However, because of the small statistics, Run 1 of the Tevatron will not be adequate.

A few remarks are due regarding our results:

- (1) The results are sensitive to the sbottom mass; the signal is observable only for a light sbottom. The possibility of a light sbottom is usually motivated as follows: Firstly, the neutral kaon system gives a strong constraint [31] on the masses of the first and second generation squarks. The third generation sfermions are much less constrained so far. Secondly, in the supergravity scenario of supersymmetry breaking, mass splitting of the third-generation and the other sfermions results from the renormalization group evolution of the masses between the unification scale and the weak scale, even if the sfermions have equal masses at the unification scale. This splitting is due to the effect of the large Yukawa coupling of the top. The bottom and tau sectors are also affected. Thirdly, there are arguments [32] that first and second generation sfermions can be as heavy as 10 TeV without conflicting the naturalness problem, while the third generation sfermions have to be rather light.
- (2) As pointed out in Sec. (1), the two decay processes we considered resemble the favorable cases in which a  $b$ -jet is produced in the decay products. While we can apply our results directly to the cases of  $\lambda''_{332}$  and  $\lambda'_{133}$ , we noticed that similar decays induced by other couplings like  $\lambda''_{312}$  and  $\lambda'_{232}$  give poor signals since there is no  $b$ -quark in their corresponding top decays.
- (3) We noted that apart from the relevant R-violating couplings and the sbottom mass, our results are also dependent on the mass and coupling of the lightest neutralino. In our calculation we only present some illustrative results by fixing a set of SUSY parameters rather than scanning the entire allowed SUSY parameter space. In some unfavorable cases, such as when the mass of the lightest neutralino (LSP) is close to the sbottom mass so that the  $b$ -quark from the sbottom decay ( $\tilde{b} \rightarrow b\tilde{\chi}_1^0$ ) is too soft to pass the selection cuts, these exotic decays would be unobservable even at the LHC.
- (4) As pointed out in Sec. 2, the  $B$ -violating decay gives the unique signal of same sign  $b$ -quarks while the main SM backgrounds give the unlike sign  $b$ -quarks. To be conservative, we assumed in our analysis that the  $b$  tagging is not of sufficient sensitivity to distinguish between a  $b$ -jet and a  $\bar{b}$ -jet. If  $b$  charge identification can be achieved in future detectors, more stringent discovery limits than those we have presented will be possible. Additional improvements will be possible if hadronic

jets from  $\tau$  decays can be clearly identified as such, thus reducing the background from  $\tau$  hadronization.

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Table 1: Signal  $\ell + 3j/2b + \cancel{E}_T$  and background cross sections in units of fb. The basic cuts are  $p_T^{\text{all}} \geq 20$  GeV,  $|\eta_{\text{all}}| \leq 2.5$  and  $\Delta R \geq 0.5$ , and the transverse mass cut is  $m_T \geq 120$  GeV. The signal results were calculated by assuming  $M = 100$  GeV,  $\mu = -200$  GeV and  $\tan \beta = 1$ . The double b-jet tagging with 42% efficiency is assumed. The charge conjugate channels have been included.

Tevatron (1.8 Tev)	Sbottom mass(GeV)	150	155	160	165	170	180	190
	Signal/ $(\lambda''_{331})^2$	11	5.8	2.04	0.27	0.01	0.005	0.003
	Background	2.07						
Tevatron (2 Tev)	Sbottom mass(GeV)	150	155	160	165	170	180	190
	Signal/ $(\lambda''_{331})^2$	16	8.4	3.0	0.4	0.02	0.007	0.004
	Background	3.05						
LHC (14 Tev)	Sbottom mass(GeV)	150	155	160	165	170	180	190
	Signal/ $(\lambda''_{331})^2$	1624	885	371	58	1.7	0.4	0.3
	Background	350						

Table 2: Signal  $\ell + 4j/2b + \cancel{E}_T$  and the SM  $t\bar{t}$  background cross sections for sbottom mass of 150 GeV. The basic cuts are  $p_T^{\text{all}} \geq 20$  GeV,  $|\eta_{\text{all}}| \leq 2.5$  and  $\Delta R \geq 0.5$ , and the transverse mass cut is  $m_T(\ell, p_T^{\text{miss}}) \notin 50 \sim 100$  GeV. The signal results were calculated by assuming  $M = 100$  GeV,  $\mu = -200$  GeV and  $\tan\beta = 1$ . Tagging at least one  $b$ -jet is assumed for 53% efficiency for the Tevatron (1.8 TeV), 85% efficiency for the upgraded Tevatron (2 TeV) and LHC. The charge conjugate channels have been included.

		basic cuts	basic cuts + $m_T(\ell, p_T^{\text{miss}})$ cut
Tevatron (1.8 TeV)	Signal/ $(\lambda'_{233})^2$ (fb)	70	43
	Background (fb)	300	86
Tevatron (2 TeV)	Signal/ $(\lambda'_{233})^2$ (fb)	154	96
	Background (fb)	662	193
LHC (14 TeV)	Signal/ $(\lambda'_{233})^2$ (pb)	12.7	8.2
	Background (pb)	54	16

Table 3: Same as Table 2, but for the signal cross section versus sbottom mass under the basic plus transverse mass cut.

Tevatron (1.8 TeV):								
Sbotttom mass(GeV)	150	155	160	165	170	180	190	200
Signal/ $(\lambda'_{331})^2$ (fb)	42.8	23.7	8.0	0.86	0.04	0.02	0.01	0.007
Tevatron (2 TeV):								
Sbotttom mass(GeV)	150	155	160	165	170	180	190	200
Signal/ $(\lambda'_{233})^2$ (fb)	96	53	19	2.2	0.09	0.04	0.024	0.016
LHC (14 TeV):								
Sbotttom mass(GeV)	150	155	160	165	170	180	190	200
Signal/ $(\lambda''_{233})^2$ (pb)	8.2	4.8	1.86	0.26	0.008	0.003	0.002	0.001



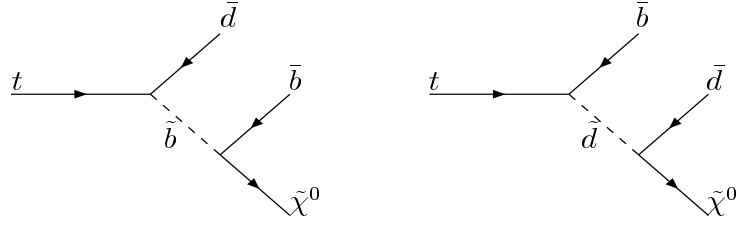


Figure 1: The Feynman diagram for the  $B$ -violating decay induced by  $\lambda''_{331}$ .

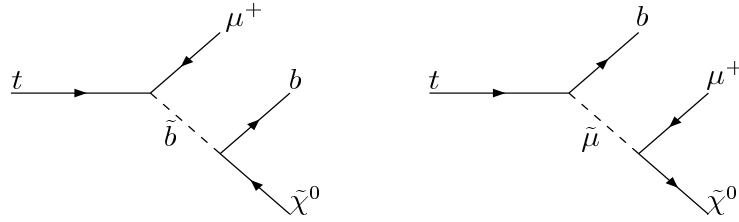


Figure 2: The Feynman diagram for the  $L$ -violating decay induced by  $\lambda'_{233}$ .

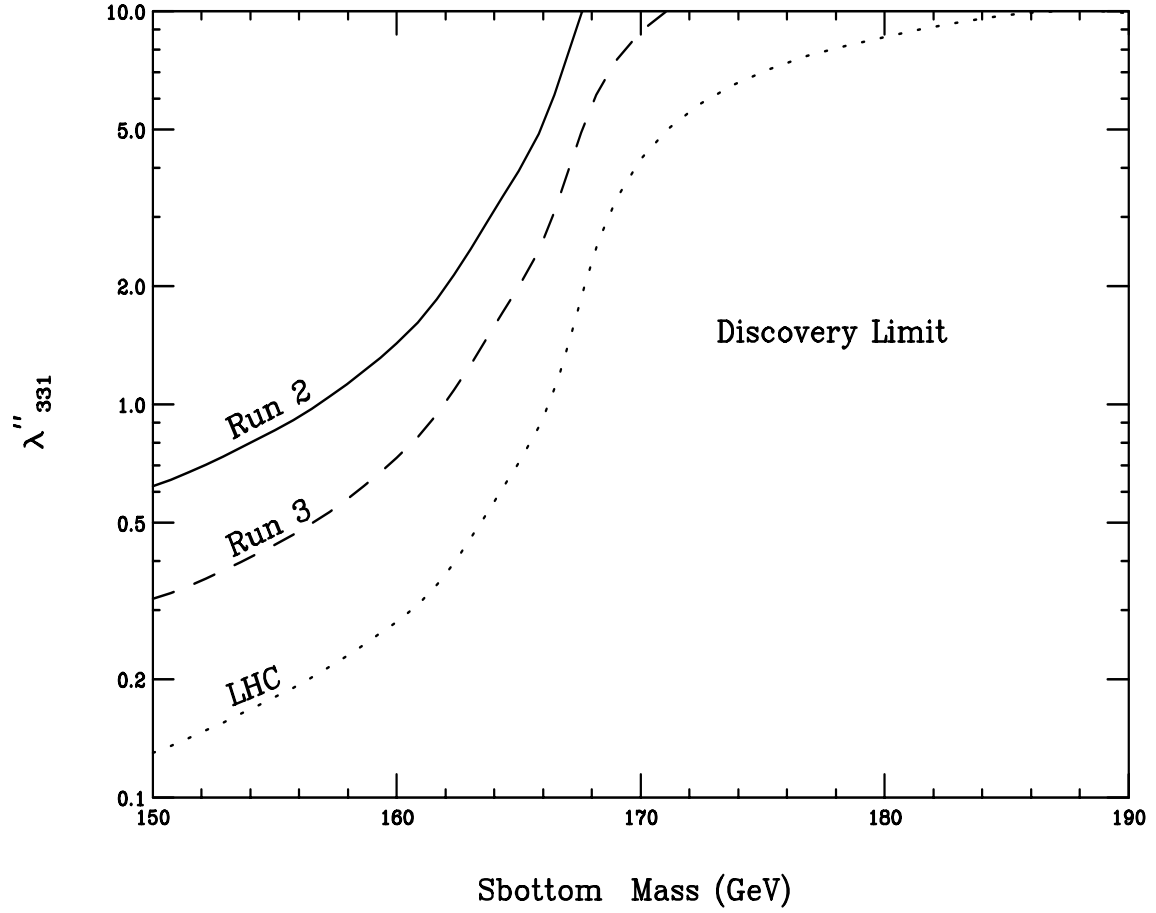


Figure 3: The discovery limits of  $\lambda''_{33j}$  versus sbottom mass at Run 2 ( $2 \text{ fb}^{-1}$ ), Run 3 ( $30 \text{ fb}^{-1}$ ) and LHC ( $10 \text{ fb}^{-1}$ ). The region above each curve is the corresponding region of discovery.

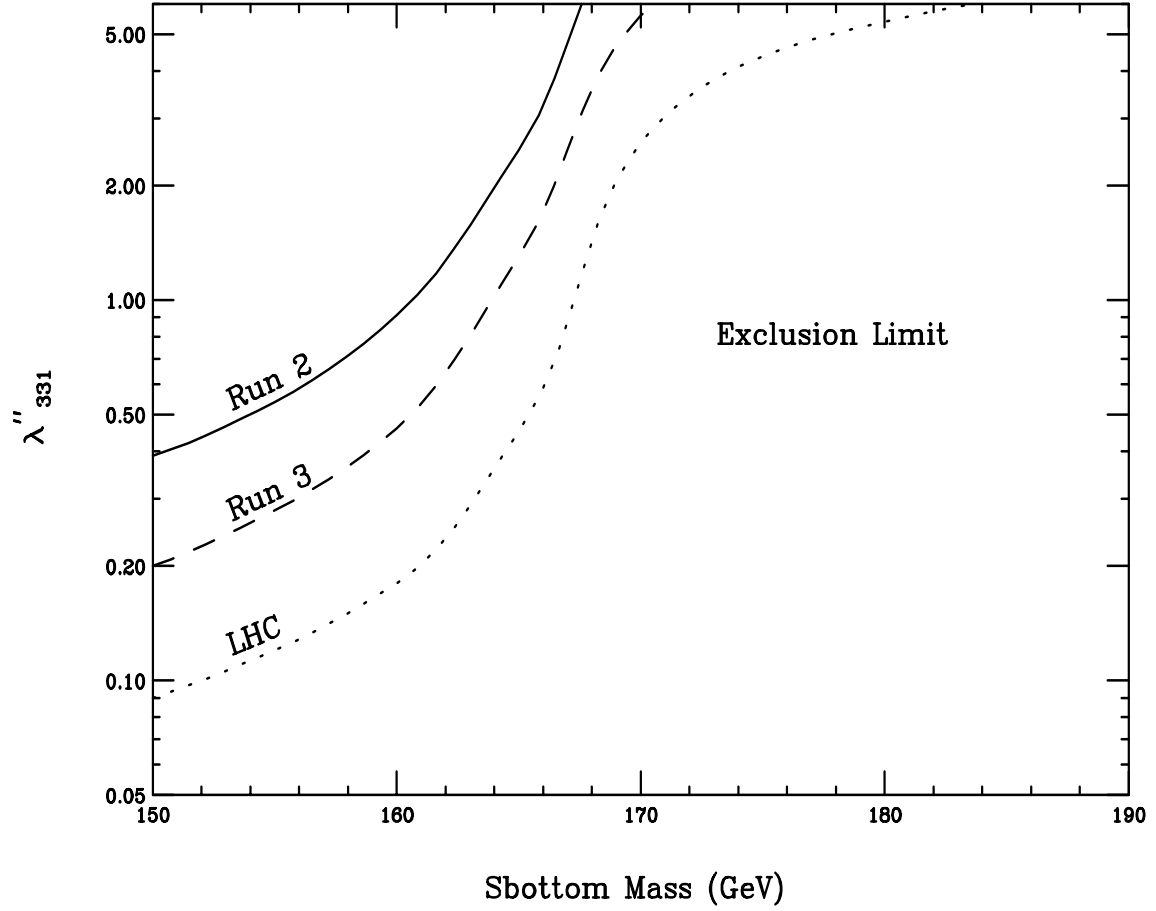


Figure 4: The exclusion limits of  $\lambda''_{33j}$  versus sbottom mass at Run 2 ( $2 \text{ fb}^{-1}$ ), Run 3 ( $30 \text{ fb}^{-1}$ ) and LHC ( $10 \text{ fb}^{-1}$ ). The region above each curve is the corresponding region of exclusion.

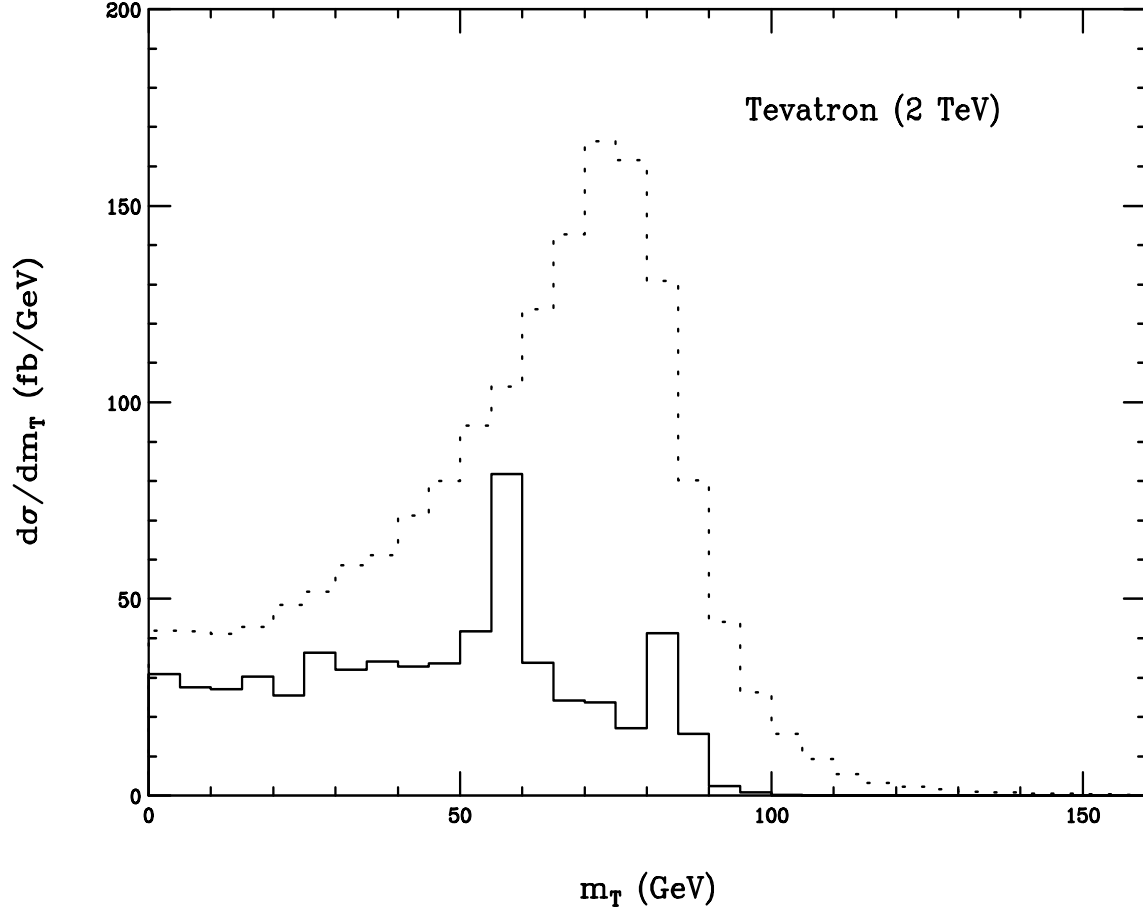


Figure 5: The transverse mass,  $m_T(\ell, p_T^{\text{miss}})$ , distribution of  $\ell+4j/b+\cancel{E}_T$  at the Tevatron collider. The solid curve is for the signal event. The dotted curve is for the SM  $t\bar{t}$  background.

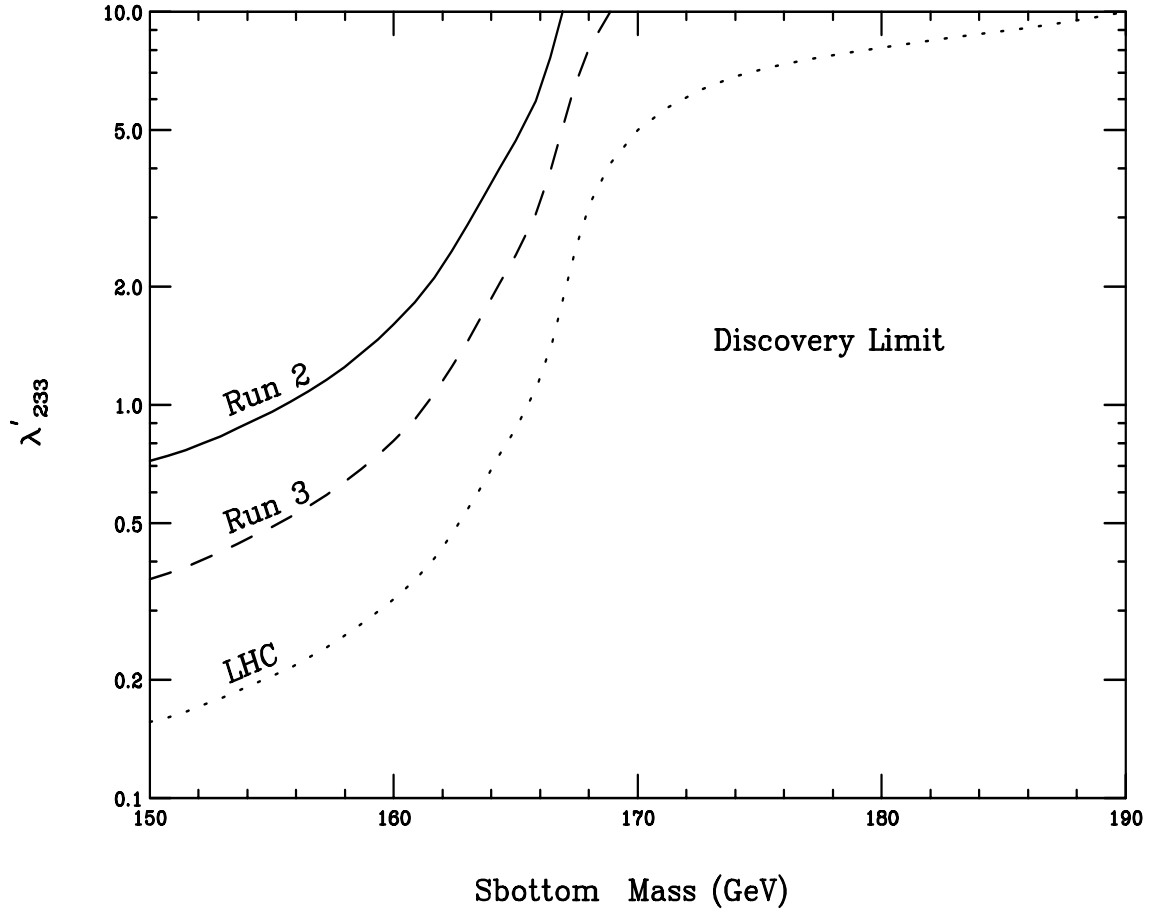


Figure 6: The discovery limits of  $\lambda'_{233}$  versus sbottom mass at Run 2 ( $2 \text{ fb}^{-1}$ ), Run 3 ( $30 \text{ fb}^{-1}$ ) and LHC ( $10 \text{ fb}^{-1}$ ). The region above each curve is the corresponding region of discovery.

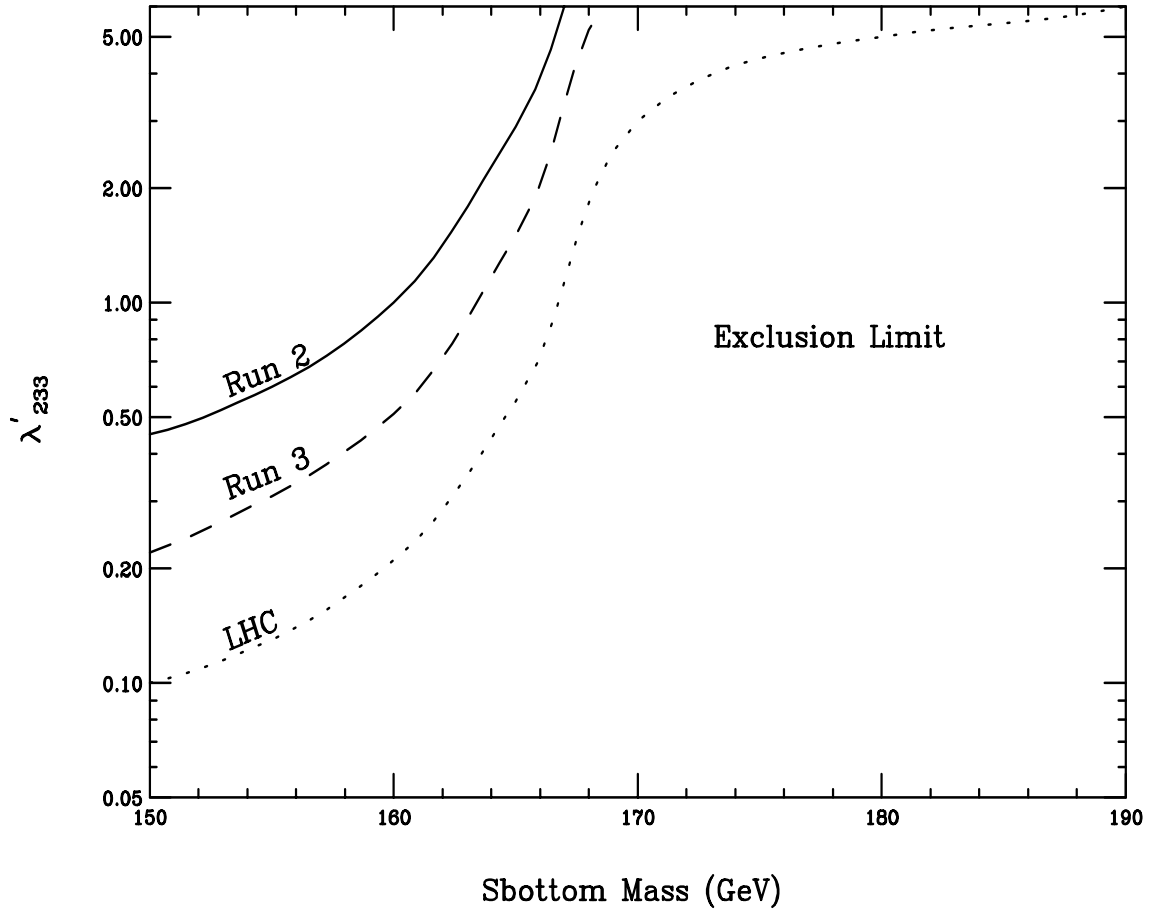


Figure 7: The exclusion (95% C.L.) limits of  $\lambda'_{233}$  versus sbottom mass at Run 2 ( $2 \text{ fb}^{-1}$ ), Run 3 ( $30 \text{ fb}^{-1}$ ) and LHC ( $10 \text{ fb}^{-1}$ ). The region above each curve is the corresponding region of exclusion.

