

# Multi-leptons and top-jets in the hunt for gluinos in R-parity violating supersymmetry

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**ABSTRACT:** The presence of R-parity ( $\mathcal{R}_p$ ) violation offers interesting decay channels for the gluinos. In this work we present a new search strategy for the gluinos in the presence of semileptonic  $\mathcal{R}_p$  violating couplings  $\lambda'_{133}$  and  $\lambda'_{233}$ . We consider two scenarios (i)  $\lambda'$  induced 3-body decay of gluinos to a top quark ( $t$ ), a bottom quark ( $b$ ) and a light lepton ( $\ell$ ) (ii) cascade decay of gluinos to top quarks and neutralinos ( $\tilde{\chi}_1^0$ ) followed by the decay of  $\tilde{\chi}_1^0$  to  $t$ ,  $b$  and  $\ell$  through  $\lambda'$  couplings. We present two different search procedures which are common to both the scenarios. While the first one involves the traditional approach with multi-leptons and  $b$ -tagged jets, the second one employs the more recent technique to reconstruct highly energetic hadronically decaying top quarks. We perform a detailed simulation of the signal as well as all the relevant Standard Model backgrounds to show that the second procedure offers slightly better sensitivity for gluino discovery. In both the procedures, a  $\geq 5\sigma$  discovery is possible for the gluino mass in the range 1.5–1.7 TeV at 14 TeV LHC with  $50 \text{ fb}^{-1}$  integrated luminosity.

**KEYWORDS:** Supersymmetry Phenomenology

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## 1 Introduction

The discovery of the Standard Model (SM) higgs-like particle [1, 2] in the successful 8-TeV run of the Large Hadron Collider (LHC) has left us in a situation, as never before, where any significant excess of signal would now definitely point towards new physics (NP) beyond the SM. The Minimal Supersymmetric Standard Model (MSSM) [3–6], being one of the most attractive possibilities beyond the SM, would be the prime candidate to be searched for in various possible channels at the 14-TeV LHC. While Supersymmetry (SUSY) is clearly a broken symmetry, the demand of naturalness of the electroweak scale strongly suggests that at least some of the SUSY partners of the SM particles appear around a (few) TeV scale. The large amount of data collected at the 7 and 8-TeV run of the LHC, however, has already pushed the lower bounds of many of the SUSY partners well above a TeV. For example, the bound on the mass of the gluinos and the first two generation of squarks stand roughly around 1.5 TeV in the constrained version of the R-parity ( $\mathcal{R}_p$ ) conserving MSSM [7, 8]. Indirect bounds from the measured value of the higgs boson mass and the low energy flavour observables also stand in the same ballpark [9–13].<sup>1</sup>

While in one hand this has made many theorists suspicious about the idea of naturalness, on the other hand this has also motivated many others to question the assumptions underlying the LHC searches, e.g., the assumption of  $\mathcal{R}_p$  conservation. Note that the conservation of  $\mathcal{R}_p$  renders the lightest SUSY particle (LSP) stable which often leads to large

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<sup>1</sup>However, in general MSSM scenarios the bounds from higgs mass and flavour observables are much weaker.

missing energy ( $\cancel{E}_T$ ) in the detectors. As large  $\cancel{E}_T$  has been widely used by the experimental searches to suppress backgrounds, the  $\mathcal{R}_p$  violating scenarios not only help evade the existing experimental constraints, but also open up a plethora of new possibilities and rich collider phenomenology.

Note that the lower bound on the mass of the top squark (stop) is rather model dependent even for the  $\mathcal{R}_p$  conserving case; its mass around a TeV (or a few hundred GeV less) is perfectly allowed in spite of the wealth of LHC data [14, 15]. A large number of phenomenological studies has been devoted to stop searches both in the  $\mathcal{R}_p$  conserving [16–24] as well as  $\mathcal{R}_p$  violating [25–28] scenarios. On the other hand, the bound on the gluino mass, in general, is stronger and the current lower value is more than a TeV even in most of the simplified scenarios (if the neutralino is not too heavy) [8, 29]. Hence, the  $\mathcal{R}_p$  violating MSSM (thus, a very low MET) is an attractive possibility to realize TeV scale gluinos. This has motivated a number of studies focusing on signatures of gluino pair production in specific  $\mathcal{R}_p$  violating scenarios [27, 30–35]. For example, in reference [33] the authors considered the baryonic  $\mathcal{R}_p$  violating couplings and obtained a lower bound of 800 GeV on the gluino mass using the CMS data in the same sign di-lepton +  $\cancel{E}_T$  +  $b$ -jet channel. These authors also reported an expected bound of 1.45 TeV on the gluino mass in their simplified scenario from the 14 TeV LHC with  $100 \text{ fb}^{-1}$  integrated luminosity. On the experimental front also many of the  $\mathcal{R}_p$  violating scenarios are now being challenged; both the ATLAS and CMS collaborations have reported bounds on the masses of some MSSM particles in several  $\mathcal{R}_p$  violating simplified scenarios [36–40].

In this work, we consider the presence of semileptonic  $\mathcal{R}_p$  violating operators in the context of the gluino searches. We reiterate that the bound on the gluino mass is less model dependent (apart from the requirement of large MET) than the bound on stop mass as the production and decay of the gluinos mainly involve the QCD part of the MSSM lagrangian. However, in the decay cascade other parameters also come into play bringing in additional model dependence. In view of this, here we consider two simplified models consistent with the latest bounds. In the first case we assume that the top squark is heavier than the gluino ( $m_{\tilde{g}} < m_{\tilde{t}_1}$ ) so that the  $\tilde{g}$  decays through  $\tilde{g} \rightarrow t b \ell$  via an off-shell top squark ( $\tilde{t}_1$ ) (see section 2 and 3 for details). In this case the top squark is required to be left-handed in order that it decays through the  $\lambda'$  coupling (see next section). Note that in this scenario the heavy-ness of the stop evades the possible bound from the  $b$ - $\ell$  resonance searches at the LHC [41–45]. In the second scenario we assume the opposite hierarchy  $m_{\tilde{g}} > m_{\tilde{t}_1}$  so that the gluinos decay through  $\tilde{g} \rightarrow \tilde{t}_1 (\rightarrow t \tilde{\chi}_1^0) t$ . The  $\tilde{\chi}_1^0$  now decays through  $\tilde{\chi}_1^0 \rightarrow t b \ell$  in the presence of the same  $\lambda'$  coupling.

In both the cases the final state has top quarks, multiple leptons and  $b$ -jets. At first we investigate the traditional tri-leptons +  $2b$ -jets final state. Note that we have chosen this final state in order that the same analysis can be applied to both the cases mentioned above. Proceeding further, we then point out that owing to the high mass of the gluinos some of the top quarks in the final state would often carry rather large transverse momentum and would give rise to collimated jets. We find that the use of jet-substructure techniques to tag these energetic “top-jets” are indeed very powerful to discover a signal.

The paper is organized as follows. In the next section we briefly discuss the simplified  $\mathcal{R}_p$  violating scenario that we consider in our study. The details of signal and the back-

grounds along with our search strategy is discussed in section 3. In section 4 we present the summary of our simulation and discuss the results. Finally, we conclude in section 5.

## 2 RPV SUSY

R-parity is a discrete symmetry of the MSSM lagrangian defined such a way that all the SM particles have  $\mathcal{R}$ -charge +1 and all their superpartners have  $\mathcal{R}$ -charge -1. The above charge assignment allows  $\mathcal{R}_p$  to be related to the Baryon ( $B$ ) and Lepton ( $L$ ) numbers by the following simple formula,

$$\mathcal{R}_p = (-1)^{2S} (-1)^{3(B-L)}, \tag{2.1}$$

where  $S$  is the spin of the particle. The above formula makes it explicit that the conservation of  $\mathcal{R}_p$  forbids all the dimension-4 and 5 proton decay operators. As all the SUSY particles are odd under  $\mathcal{R}_p$ , this also makes the LSP stable providing a good dark matter candidate.

However, it is possible that  $\mathcal{R}_p$  is violated in specific ways that do not introduce fatal rates for proton decay. For example, switching on either  $B$  or  $L$  violating  $\mathcal{R}_p$  violating couplings but not the both still forbids the dangerous proton decay operators.

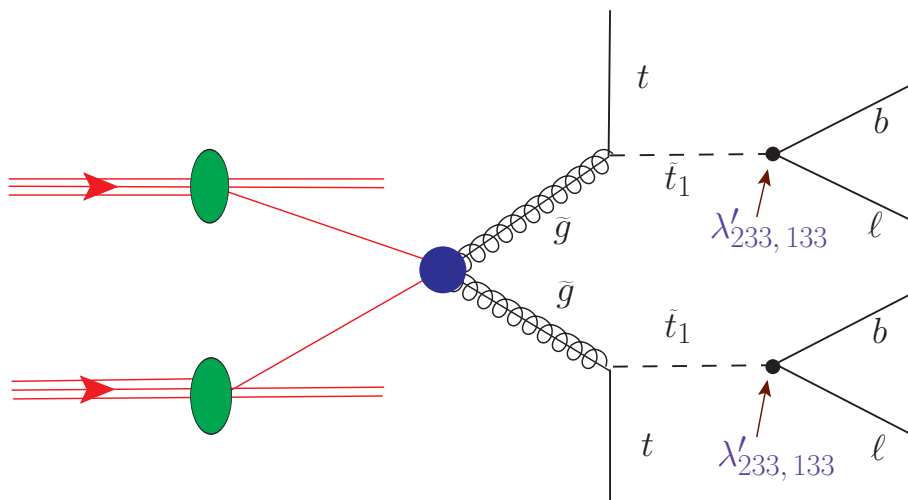
In the absence of  $\mathcal{R}_p$  the additional marginal and relevant terms allowed by gauge invariance in the MSSM superpotential can be written as [46–48],

$$W_{\mathcal{R}_p} \supset \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c + \mu_i L_i H_u \tag{2.2}$$

where  $L_i$  ( $E_i^c$ ) are left-handed lepton doublet (right-handed lepton) superfields,  $Q_i$  ( $U_i^c, D_i^c$ ) the left-handed quark doublet superfields (right-handed Up-type and Down-type quark superfields, respectively) and  $H_u$  is the Higgs superfield that gives mass to the up-type quarks.

Clearly, the couplings  $\lambda''$  violate  $B$ , while the couplings  $\lambda$  and  $\lambda'$  violate  $L$ . As both  $B$  and  $L$  number must be violated to induce proton decay, it is still possible to turn on either  $\lambda'$  or  $\lambda''$  coupling without spoiling proton stability. Certain combinations of these  $\mathcal{R}_p$  violating couplings are also constrained from various low energy observables (such as FCNC decays, neutron-antineutron oscillation, neutrino oscillation data, neutrino-less double beta decay, decays of tau lepton, meson mixing etc.) as well as data from high energy colliders e.g., LEP and Tevatron, see e.g., [49] and the references therein.

In this work we consider the presence of  $\lambda'$  couplings in particular,  $\lambda'_{133}$  and  $\lambda'_{233}$ , giving rise to the possibility of stop (coming from gluino decays in our case) decaying to a  $b$ -quark and light leptons (electron for  $\lambda'_{133}$  and muon for  $\lambda'_{233}$ ). Note that the  $\lambda'$ -type couplings are also constrained to some extent by the various measurements mentioned above. However, the constraints on the couplings  $\lambda'_{133}$  and  $\lambda'_{233}$  are less severe as these involve the third generation quarks. The strongest bounds arise from the Majorana neutrino mass [49, 50] and flavor violating top decays [51]. The  $Z$ -partial width also constrains these couplings but to a lesser extent than the previous ones [52]. However, these bounds are not strong enough to make the gluinos and neutralinos stable in the detectors.



**Figure 1.** The relevant Feynman diagram for gluino production followed by its decay to  $(tb\ell)$  final state in the presence of  $\lambda'$  couplings in our  $\mathcal{R}_p$  violating scenario-1.

Although, ideally one should explain why some of these couplings are extremely small and some other are not, this is certainly quite interesting phenomenologically as it opens up many new decay channels of the MSSM particles leading to a rich phenomenology which should be studied in the colliders. As mentioned in the introduction, because of the absence of sufficient  $\cancel{E}_T$  this also lowers the bounds on some of the SUSY particles.

In the next section we will now discuss the specific decay topologies which are considered in this work along with the details of our simulation procedures.

### 3 Signal, backgrounds and our search strategy

As mentioned in the introduction, in this work we consider gluino pair production followed by two different decay chains. In the first case, the  $\tilde{g}$  decays to  $(tb\ell)$  through an off-shell stop:

$$pp \rightarrow \tilde{g}\tilde{g}, \quad \tilde{g} \rightarrow t b \ell \quad (\text{scenario - 1}).$$

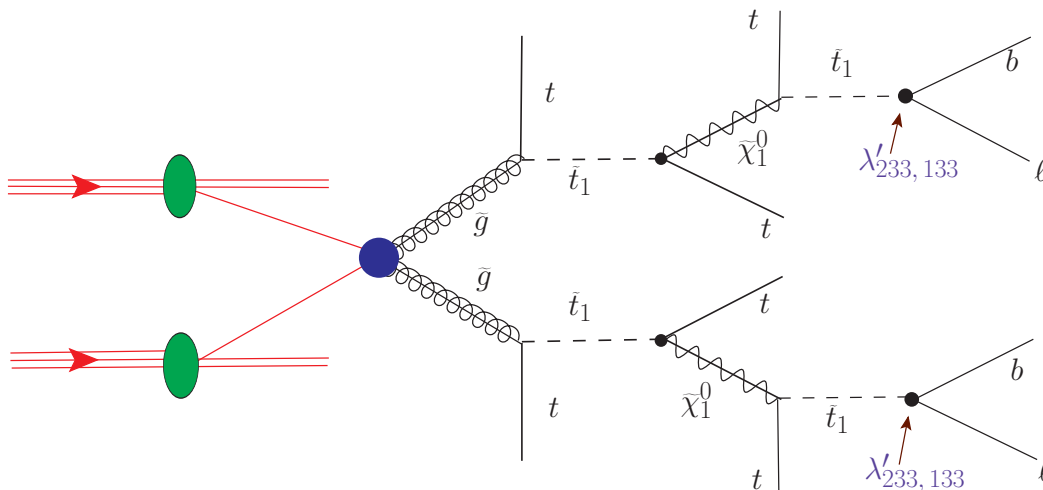
A sample Feynman diagram is shown in figure 1. Looking at the structure of the  $\lambda'$  coupling (eq. (2.2)) reveals that the top squark in this case has to have large left-handed component.

In the second case we assume the decay chain,

$$pp \rightarrow \tilde{g}\tilde{g}, \quad \tilde{g} \rightarrow \tilde{t}_1 t, \quad \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0, \quad \tilde{\chi}_1^0 \rightarrow t b \ell \quad (\text{scenario - 2}).$$

Figure 2 shows a sample Feynman diagram for this process where the  $\tilde{\chi}_1^0$  is assumed to decay through the left-handed component of an off-shell stop.<sup>2</sup>

<sup>2</sup>The same decay  $\tilde{\chi}_1^0 \rightarrow t b \ell$  can also proceed via an off-shell left-handed slepton. However, in that case the branching ratio can not be too high (typically less than 0.5) because of the presence of the left-handed sneutrino in the spectrum with the same mass (as the left-handed charged slepton), thus giving rise to also the decay  $\tilde{\chi}_1^0 \rightarrow b \bar{b} \nu$ . In fact, exactly these two decay chains (starting from stop pair production) were considered by the CMS collaboration to obtain a bound of about 700 GeV on the stop mass if  $\tilde{\chi}_1^0$  is not too heavy [36].



**Figure 2.** The relevant Feynman diagram for gluino production followed by its cascade decay to  $t$ ,  $b$  and leptons through  $\lambda'$  couplings in our  $\mathcal{R}_p$  violating scenario-2.

In the following section we describe the details of our simulation procedure as well as the kinematic selection cuts for the signal and the relevant backgrounds. For simplicity, we will assume all the relevant branching ratios to be unity while presenting the results. For other values of the branching ratios our results can be easily scaled down appropriately.

### 3.1 Multilepton signal

We are now in a position to discuss the details of our event selection procedure. In this section we describe our analysis with multi-leptons and  $b$ -tagged jets. The analysis involving the tagging of top-jets will be discussed in the next subsection.

In the multi-lepton analysis, we first reconstruct the jets using the simple cone algorithm with the value of the radius parameter  $R=0.4$ . We consider only those jets which satisfy a transverse momentum cut  $p_T^j \geq 20$  GeV and the pseudo-rapidity  $|\eta| \leq 2.5$ . Leptons are also selected with a transverse momentum  $p_T^\ell \geq 10$  GeV and the pseudo-rapidity  $|\eta| \leq 2.5$ . We call a lepton isolated if it satisfies

- (i) The distance between the lepton and any of the jets  $\Delta R(j \ell) > 0.4$
- (ii) The distance between the lepton and any of the other leptons  $\Delta R(\ell \ell) > 0.2$
- (iii) The ratio of the total hadronic transverse energy deposit within a cone of  $\Delta R = 0.2$  around the lepton to the lepton transverse energy is  $\leq 0.15$ .

A jet is identified as a  $b$ -jet if it is close ( $\Delta R < 0.2$ ) to a  $b$ -quark. For the  $b$ -tagging efficiency ( $\epsilon_b$ ) we use the prescription from reference [53] which gives  $\epsilon_b = 0.71$  for  $90 < p_T < 170$  GeV and at higher (lower)  $p_T$  it decreases linearly with a slope of  $-0.0004$  ( $-0.0047$ )  $\text{GeV}^{-1}$ . Moreover, the probability of mis-tagging a  $c$ -jet (light jet) as a  $b$ -jet is taken to be 20% (0.73%) [54]. Once the leptons and jets are constructed we use further analysis cuts for selecting events. Since the decay topologies in the two scenarios considered here

are quite different,  $p_T$  distributions of the observed leptons are expected to be different as well. In scenario-1, leptons are coming directly from the decay of a heavy gluino. Hence they are much more likely to pass harder  $p_T$  cuts. On the other hand, leptons coming at a much later stage in the decay chain in scenario-2, are expected to be less energetic on the average. Therefore, it seems legitimate to employ different sets of lepton  $p_T$  cuts for the two scenarios. We also reject (veto) an event if it has two opposite-charge-same-flavor leptons with invariant mass around the  $Z$ -boson mass.

We use the following set of selection criteria in scenario-1:

- Cut-I: we demand that the event contains at least 3 isolated leptons. The three leptons must satisfy  $p_{T_{\ell_1}} > 50$  GeV,  $p_{T_{\ell_2}} > 40$  GeV and  $p_{T_{\ell_3}} > 30$  GeV. In addition, we also require that the event has at least 2 jets.
- Cut-II: veto on  $Z$ -boson. We choose the mass window to be  $M_Z \pm 10$  GeV.
- Cut-III: the event must have at least two  $b$ -tagged jets.
- Cut-IV: we define the effective mass of an event to be  $M_{\text{eff}} = \sum_j p_T^j + \sum_\ell p_T^\ell + \cancel{E}_T$  and demand that the event satisfies  $M_{\text{eff}} > 1000$  GeV.

In scenario-2 we slightly change the  $p_T$  cuts on the final state leptons. We demand the 3 leptons satisfy the  $p_T$  cuts of 40, 30 and 20 GeV respectively instead of 50, 40 and 30 GeV as used in the previous case.

For the simulation of signal events we have used Pythia-6.4.24 [55]. The Standard Model backgrounds have been generated using Alpgen v2.13 [56] with the MLM prescription [57] for the matching of matrix element hard partons and shower generated jets. We have used the CTEQ6L [58] parton distribution function for our simulations.

### 3.2 Boosted top

In this subsection we describe our second search strategy which involves tagging an energetic top quark using the jet substructure technique. We use the Johns Hopkins top tagger (JHTopTgger) [59] in this work. We now briefly discuss the steps of the JHTopTgger algorithm mentioning our choice of specific parameters as and when the occasion arises.<sup>3</sup> Here we closely follow the discussion in [59].

1. In the first step of the algorithm all the hadronic final states are clustered into the so-called ‘fat-jets’ using the Cambridge-Aachen (CA) algorithm [62] with the angular distance parameter  $R = 1.0$ . In the CA algorithm one starts with all the four-momenta of the hadronic final states and then combine the pair which has the smallest  $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$  (and  $\Delta R < R$ ). The process is continued until there are no four-momenta left with  $\Delta R < R$ . The list of four-momenta which survive at this stage are then identified as jets.

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<sup>3</sup>We have used the public package FastJet [60, 61] where this algorithm has been implemented.



2. In the second step of the algorithm one fat-jet (say,  $J$ ) is considered at a time and it's 4-momenta  $p^{(J)}$  is declustered into the 4-momenta ( $p^{(j1)}$  and  $p^{(j2)}$ ) of the two subjets ( $j1$  and  $j2$ ) which were combined to get the fat-jet  $J$ . As the clustering history is stored at each stage of the CA algorithm, this step is same as reversing the clustering process mentioned in the previous paragraph.

3. Three quantities are now computed,

$$\delta_1 = p_T^{(j1)}/p_T^{(J)}, \delta_2 = p_T^{(j2)}/p_T^{(J)} \text{ and } \delta = |\eta^{j1} - \eta^{j2}| + |\phi^{j1} - \phi^{j2}|.$$

The fat-jet  $J$  is considered irreducible and having no substructure if the algorithm encounters at least one of the following two situations,

- $\delta_1, \delta_2 < \delta_p$
- $\delta < \delta_r$

Here  $\delta_p$  and  $\delta_r$  are two adjustable parameters of the algorithm. In our analysis we set their values to  $\delta_p = 0.1$  and  $\delta_r = 0.2$ .

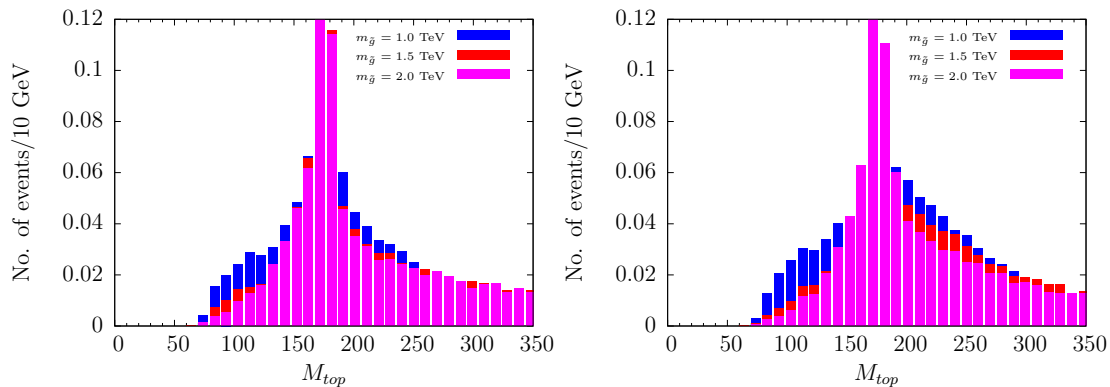
4. If one of  $\delta_1$  or  $\delta_2$  comes out to be less than  $\delta_p$ , the corresponding subjet is discarded and the declustering procedure is applied to the other harder subjet. If both  $\delta_1$  or  $\delta_2$  are greater than  $\delta_p$  then the declustering procedure is applied on both of them. This procedure stops when one of the conditions mentioned in step-3 is encountered or there is only one calorimeter cell left for the jet to be declustered.

5. The fat-jets with 3 or 4 subjets are kept for further analysis. The following three additional kinematic criteria are imposed before calling a fat-jet top tagged,

- The 3 or 4 subjets should reconstruct near the top quark mass. We use the top quark mass window to be  $m_t \pm 20$  GeV.
- One pair of subjets (one of the combinations (1,2), (1,3), (1,4), (2,3), (2,4), (3,4)) should reconstruct near the  $W$  mass. The  $W$  mass window is chosen to be (60-100) GeV in our analysis.
- The  $W$  helicity angle  $\theta_h$  satisfies  $\cos\theta_h < 0.7$ . The helicity angle is defined as the angle between the 3-momentum of the reconstructed top quark and that of one of the the  $W$  boson's decay products (the lower  $p_T$  subjet in this case, as was proposed in the original work [59] also), as measured in the rest frame of the reconstructed  $W$ .

Once the fat-jet satisfies the above kinematic cuts it is considered to be a true top candidate. Note that the subjet (or the hardest of the two subjets in case of four subjets) which is left after the  $W$  reconstruction (we call this subjet as the non- $W$  subjet) is expected to be a  $b$ -jet for a true top candidate. In this work however, we do not demand that the non- $W$  subjet be  $b$ -tagged. In figure 3 we show the reconstruction of top quark mass for our signal benchmark points (see table 1).





**Figure 3.** The distribution of the mass of the reconstructed top quark from the hardest fat-jet in our  $\mathcal{R}_p$  violating scenario-1 (left panel) and scenario-2(right panel) for the benchmark points chosen in table 1 and table 2 respectively. The total number of events has been normalized to unity.

Once we find a top quark in an event (Cut-I) we then apply a few more selection criteria in order to combat the backgrounds. We discuss them below one by one.

**Cut-II** We demand at least two isolated leptons ( $\ell 1$  and  $\ell 2$ ) with  $p_T > 50$  GeV. We use the same isolation criteria used in the previous section 3.1.

**Cut-III** Apart from the  $b$ -jets coming from the top decays, the signal also has additional  $b$ -jets coming from gluino or neutralino decays. Keeping this mind we demand 2  $b$ -tagged jets ( $b1$  and  $b2$ ) which are far ( $\Delta R > 0.8$ ) from the non- $W$  subjet of the reconstructed top quark. If an event has more than one reconstructed top quarks then only the hardest of them is used. The  $b$ -tagging procedure is again identical to that used in the previous subsection.

**Cut-IV** As a final selection criterion we demand that the effective mass of an event satisfies  $M_{\text{eff}} > 1250$  GeV. The definition of  $M_{\text{eff}}$  is identical to that used in the previous section.

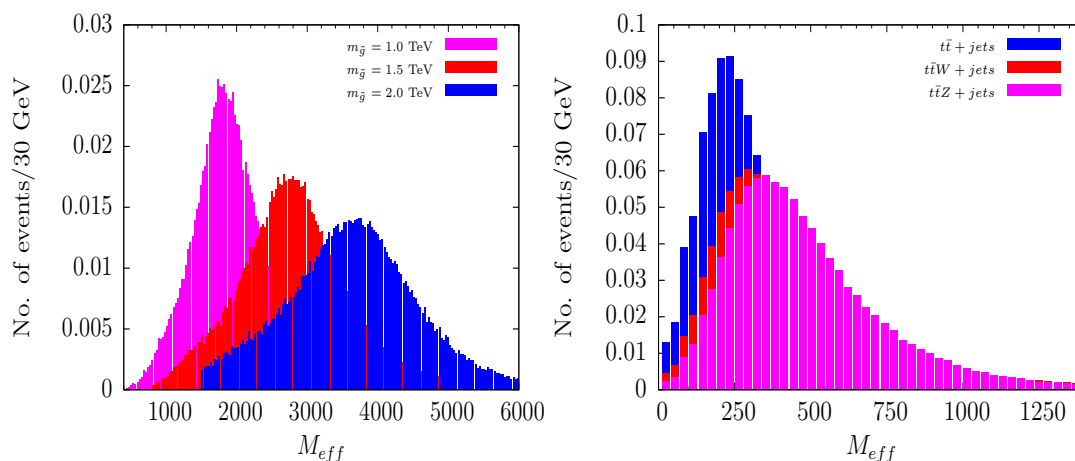
## 4 Results and discussion

### 4.1 Multi-lepton signal

In table 1 and 2, we present the result of our analysis with  $3\ell + 2b + \text{jets}$  (section 3.1) for scenarios 1 and 2 respectively. The first three columns show the processes studied, the raw production cross-section and the number of events generated for the signal and background processes. The raw production cross-sections for the signal points correspond to the next-to-leading-order value calculated using Prospino [63] with default choices for the scale and the parton distribution function. For the background processes we use either the NLO cross-sections if they are available in the literature or the cross-sections obtained from Alpgen. For both the signal as well as the backgrounds the total number of events simulated is of the same order or more than the number expected in the 14 TeV LHC with  $50 \text{ fb}^{-1}$  luminosity (except for  $t\bar{t} + \text{jets}$ ). In the columns 4–7 the number of events after

			No. of events after the cut				
Process	Production cross-section	Simulated events	C1	C2	C3	C4	Final cross-section (fb)
Signal: $\tilde{g} \rightarrow t b \ell$ (scenario-1)							
$m_{\tilde{g}} = 1.0$	370 fb [63]	$5 \times 10^4$	7704	7427	2463	2412	17.85
$m_{\tilde{g}} = 1.5$	19 fb [63]	$5 \times 10^4$	6971	6846	2185	2184	0.83
$m_{\tilde{g}} = 2.0$	1.56 fb [63]	$5 \times 10^4$	6218	6116	1846	1846	0.058
Backgrounds							
$t\bar{t} + \text{jets}$	953.6 pb [64]	11607567	4	4	< 1	< 1	0.0001
$t\bar{t}Z + \text{jets}$	1.121 pb [65]	140734	2667	842	306	19	0.15
$t\bar{t}W + \text{jets}$	769 fb [66]	169973	447	394	226	9	0.04
$ZZW + \text{jets}$	44.3 fb [56]	87650	272	52	4	1	0.0005
$WWZ + \text{jets}$	137.5 fb [56]	65090	411	116	1	< 1	—
$WWW + \geq 2 \text{ jets}$	94.1 fb [56]	26268	18	8	< 1	< 1	—
Total Background							0.190

**Table 1.** Event summary after individual selection cuts both for the MSSM benchmark points (in scenario-1) as well as the SM backgrounds for the multi-lepton analysis. The final cross-sections after all the selection cuts are shown in the last column. All the masses are in TeV.



**Figure 4.**  $M_{\text{eff}}$  distribution for three signal benchmark points as well as the dominant backgrounds. The total number of events has been normalized to unity.

each selection cut (described in section 3.1) are shown while the final column shows the cross-section after all the cuts have been imposed.

The dominant backgrounds in this case are  $t\bar{t}Z + \text{jets}$ ,  $t\bar{t}W + \text{jets}$  and  $t\bar{t} + \text{jets}$ . In case of  $t\bar{t} + \text{jets}$  the semileptonic decay of the  $B$ -mesons (in addition to the two leptons from the  $W$ 's) can contribute to the tri-lepton final state. Although the number of these events can be reduced to a good extent by requiring the isolation criteria as described in section 3.1, the enormous cross-section of the  $t\bar{t} + \text{jets}$  process makes them significant background unless we impose hard lepton  $p_T$  cuts. In fact, we have been able to reduce events from  $t\bar{t} + \text{jets}$

Process	Production cross-section	Simulated events	No. of events after the cut				Final cross-section (fb)
			C1	C2	C3	C4	
Signal: $\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t b \ell$ (scenario-2)							
$(m_{\tilde{g}}, m_{\tilde{t}}) = (1.0, 0.8)$	370 fb [63]	$5 \times 10^4$	10609	8718	5663	5491	40.63
$(m_{\tilde{g}}, m_{\tilde{t}}) = (1.5, 1.0)$	19 fb [63]	$5 \times 10^4$	10241	8794	6060	6058	2.3
$(m_{\tilde{g}}, m_{\tilde{t}}) = (2.0, 1.0)$	1.56 fb [63]	$5 \times 10^4$	8706	7554	4823	4823	0.15
Backgrounds							
$t\bar{t}$ + jets	953.6 pb [64]	11607567	316	300	87	10	0.82
$t\bar{t}Z$ + jets	1.121 pb [65]	140734	2870	887	350	21	0.167
$t\bar{t}W$ + jets	769 fb [66]	169973	594	512	272	15	0.067
$ZZW$ + jets	44.3 fb [56]	87650	320	34	3	1	0.0005
$WWZ$ + jets	137.5 fb [56]	65090	467	162	2	1	0.002
$WWW + \geq 2$ jets	94.1 fb [56]	26268	34	23	< 1	< 1	—
Total Background							1.05

**Table 2.** Event summary after individual selection cuts both for the MSSM benchmark points (in scenario-2) as well as the SM backgrounds for the multi-lepton analysis. The final cross-sections after all the selection cuts are shown in the last column. All the masses are in TeV. We have taken the mass of  $\tilde{\chi}_1^0$  to be 300 GeV in this case.

drastically after imposing 50 GeV, 40 GeV and 30 GeV cuts respectively on first three hardest leptons (see table 1). Some events remain in scenario-2 (see table 2) where we lessen the  $p_T$  cuts on leptons. The other dominant (the leading one in scenario-1) contribution comes from the  $t\bar{t}Z$  + jets background where additional leptons can originate from the  $Z$  boson decay. A  $Z$  veto reduces this background substantially. The process  $t\bar{t}W$  + jets also constitutes a background to our signal but its contribution is much less than  $t\bar{t}Z$  + jets as can be seen from table 1 and 2. We have also generated other potential backgrounds e.g.,  $ZZW$  + jets,  $WWZ$  + jets and  $WWW$  + jets whose contributions are negligible compared to the previous ones when a  $Z$  veto and the requirement of 2  $b$ -jets are also imposed. The use of the effective mass in the final step of the algorithm reduces backgrounds quite efficiently without affecting the signal almost at all. As the effective mass of an event for the signal is closely related to  $2m_{\tilde{g}}$  the distribution peaks at very high values of the effective mass, see figure 4a where we show the effective mass distributions for three of our benchmark points with different choices of the gluino mass (in scenario-1). In figure 4b we present the same distribution for the dominant backgrounds.

## 4.2 Boosted top

In this subsection we present our results using the techniques described in section 3.2. The summary of our findings is shown in table 3 where the same conventions as in table 1 and 2 have been used. In columns 4-7 the number of events after each selection cut (see section 3.2) are shown. The final column shows the final cross-section after all the selection cuts.

Process	Production cross-section	Simulated Events	No. of events after the cut				Final cross-section (fb)
			C1	C2	C3	C4	
Signal: $\tilde{g} \rightarrow t b \ell$ (scenario-1)							
$m_{\tilde{g}} = 1.0$	370 fb [63]	$5 \times 10^4$	7855	5257	2690	2681	19.83
$m_{\tilde{g}} = 1.5$	19 fb [63]	$5 \times 10^4$	9007	6290	3044	3044	1.16
$m_{\tilde{g}} = 2.0$	1.56 fb [63]	$5 \times 10^4$	9297	6521	2958	2958	0.09
Signal: $\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t b \ell$ (scenario-2)							
$(m_{\tilde{g}}, m_{\tilde{t}}) = (1.0, 0.8)$	370 fb [63]	$5 \times 10^4$	11982	3819	3023	2842	21.03
$(m_{\tilde{g}}, m_{\tilde{t}}) = (1.5, 1.0)$	19 fb [63]	$5 \times 10^4$	15935	5438	4545	4534	1.72
$(m_{\tilde{g}}, m_{\tilde{t}}) = (2.0, 1.0)$	1.56 fb [63]	$5 \times 10^4$	18130	5954	4973	4972	0.155
Backgrounds							
$t \bar{t} + \text{jets}$	953.6 pb [64]	31712564	424944	166	20	4	0.12
$t \bar{t} Z + \text{jets}$	1.121 pb [65]	226110	9105	210	12	1	0.005
$t \bar{t} W + \text{jets}$	769 fb [66]	276807	12105	164	10	1	0.003
$t \bar{t} h + \text{jets}$	700 fb [67]	231064	10926	67	8	1	0.003
Total Background							0.131

**Table 3.** Event summary after individual selection cuts both for the MSSM benchmark points as well as the SM backgrounds for the boosted top analysis. The final cross-sections after all the selection cuts are shown in the final column. All the masses are in TeV. We have taken the mass of  $\tilde{\chi}_1^0$  to be 300 GeV in scenario-2.

A comparison of columns 3 and 4, both for the signal and the backgrounds, clearly reveals the effectiveness of tagging an energetic top quark. In case of the  $t \bar{t} + \text{jets}$  background the number of events get reduced by almost a factor of 75 while for the signal the loss is only by a factor of 5. Such a large gain is due to the large average transverse energy (hence collimated jets) of the top quark in the signal compared to the background. For the background events the jets from the decay of a top quark are highly separated from each other and are not captured by a fat-jet which in turn reduces the tagging efficiency. The demand of two isolated leptons as well as two  $b$ -tagged jets also helps tame the background to a large extent. Note that these  $b$ -jets are far from the non- $W$  candidate of the tagged top quark (see section 3.2 for details). This criteria makes sure that the  $b$ -jets, most of the time, are not from the decay of the top quark which has been reconstructed.

In the last step of the analysis, the  $M_{\text{eff}}$  cut brings down the background to a minuscule level keeping a handful of signal events. We have checked that the processes  $t Z + \text{jets}$ ,  $t W + \text{jets}$  and  $t h + \text{jets}$  do not contribute to our final number of background events.

### 4.3 Comparison of the two analyses

In table 4 we compute the signal significance obtained from the two analyses described above and compare them. We define the significance  $\sigma$  as  $\sigma = S/\sqrt{S+B}$  where  $S$  and  $B$  are the absolute number of signal and background events respectively for a particular

Gluino mass (in GeV)	Scenario-1		Scenario-2	
	multi-lepton	boosted-top	multi-lepton	boosted-top
1000	29.71 (42.02)	31.38 (44.38)	44.5 (62.9)	32.32 (45.71)
1500	5.81 (8.22)	7.21 (10.20)	8.88 (12.56)	8.93 (12.64)
2000	0.82 (1.16)	1.35 (1.91)	0.96 (1.37)	2.04 (2.89)

**Table 4.** The statistical significance of our signal for the two analysis strategies discussed in the text. The numbers outside (inside) the parentheses corresponds to an integrated luminosity of  $50 \text{ fb}^{-1}$  ( $100 \text{ fb}^{-1}$ ).

luminosity. At first we should mention that the raw signal cross-section reduces very fast as the gluino mass is increased; the cross-section drops to  $1.56 \text{ fb}$  for a gluino mass of  $2 \text{ TeV}$  from a healthy  $370 \text{ fb}$  for a gluino mass of  $1 \text{ TeV}$ . This is the primary reason for the significance to drop dramatically with increasing  $\tilde{g}$  mass, as can be seen from table 4.

We present the significance assuming two integrated luminosities,  $50 \text{ fb}^{-1}$  and  $100 \text{ fb}^{-1}$  (the numbers within the parentheses). It can be seen that for our first analysis strategy the significance is more than 8 (12) for the  $\mathcal{R}_p$  violating scenario-1 (scenario-2) with  $\tilde{g}$  mass of  $1.5 \text{ TeV}$  and assuming  $100 \text{ fb}^{-1}$  data set. Even at  $50 \text{ fb}^{-1}$  integrated luminosity the significance  $\sim 6(9)$  is achieved in scenario-1 (scenario-2). For a  $2 \text{ TeV}$   $\tilde{g}$  mass the significance drops dramatically as can be seen from the last row of table 4.

On the other hand, for the second analysis strategy the significance is about 7.2 (compared to about 5.8 in the multilepton case) in the scenario-1 for the  $\tilde{g}$  mass of  $1.5 \text{ TeV}$  and  $50 \text{ fb}^{-1}$  integrated luminosity. In scenario-2, however, both the analysis give similar results.

It is worth mentioning here that while calculating the significance we have not taken into account any systematic uncertainty which is very difficult to estimate in a reliable way. We believe that for the cases where the significance is large enough (say,  $\geq 5$ ) the effect of including systematic uncertainties should not be large. For example, in the multilepton analysis in scenario-1 with gluino mass  $1.5 \text{ TeV}$ , adding a 30% systematic uncertainty on the background crosssection reduces the significance from 5.81 (8.22) to 5.65 (7.99) for  $50 \text{ fb}^{-1}$  ( $100 \text{ fb}^{-1}$ ) integrated luminosity.

## 5 Conclusion

Introduction of  $\mathcal{R}_p$  violation in the MSSM lagrangian is a phenomenologically attractive way to evade strong bounds on the masses of SUSY particles obtained in the R-parity conserving scenario. This has fueled a significant amount of effort from both the experimentalists and theorists in investigating new signal topologies present in the R-parity violating case. However, there exists many more potentially interesting possibilities which still need to be covered. In this work, we have concentrated on two such topologies which exist in the presence of semileptonic R-parity violation with  $\lambda'_{133, 233}$  couplings. We have considered gluino pair production with their subsequent decay to top quarks, leptons and  $b$ -jets. Two analysis strategies have been considered, one with the canonical multi-leptons and  $b$ -jets and the other one with more recent technique to reconstruct highly energetic

top quarks. We performed a detailed simulation of the signal and all possible background processes to estimate and compare the effectiveness of these two procedures.

In order to present our results in a clear way we have chosen a few benchmark scenarios for both the topologies considered. Our results have been summarized in table 1, 2 and 3 and a comparison of the effectiveness of the two analyses procedures have been presented in table 4. We observe that our second strategy which involves reconstructing a top quark from the final state was slightly more effective compared to the traditional multi-leptons +  $b$ -jets analysis. While in the multi-lepton with  $b$ -jets search the significance can reach up to as high as 5.8 (8.9) for a gluino mass of 1.5 TeV in the  $\mathcal{R}_p$  violating scenario-1 (scenario-2) with a  $50 \text{ fb}^{-1}$  data set, the second analysis does somewhat better in scenario-1 (significance rises to 7.2) and provides comparable sensitivity ( $\sim 9$ ) in the second scenario.

Note that, although we present our results in two simplified scenarios just for clear illustration of the procedures, our analysis can be applied to any other situations with similar final state. We would also like to mention that we have not considered any detector effects and pile-up contaminations which are rather difficult for us to simulate in a reliable way. However, we believe that our analysis can be taken as a guiding reference for more detailed and realistic analysis on real data by our experimental colleagues.

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