

Study of the baryonic R -parity violating MSSM using the jet substructure technique at the 14 TeV LHC

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We study the discovery reach of the gluino ($\tilde{g}$) and the lightest stop squark ($\tilde{t}_1$) with baryonic R -parity violation (UDD type) in the context of the minimal supersymmetric standard model (MSSM) at the 14 TeV run of the LHC. We consider the gluino pair production process followed by its decay to a top quark and a real or virtual stop squark. The top quark produced from the decay of the gluino can have sufficient transverse momentum to appear as a single fat jet. We apply the jet substructure technique to tag such a hadronically decaying boosted top quark and find that gluino mass up to 1.65 TeV can be discovered whereas the exclusion limit extends up to 1.9 TeV at the 14 TeV LHC with 300 fb^{-1} luminosity. We also briefly discuss the discovery prospect of the boosted stop squark, which may be identified as a narrow resonance in the jet mass distribution.

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I. INTRODUCTION

The ATLAS and CMS Collaborations of the Large Hadron Collider (LHC) experiment have announced the discovery of a standard model (SM) Higgs boson-like particle with a mass of $\sim 125 \text{ GeV}$ [1,2]. They have collected about 25 fb^{-1} of data each at the end of their 7/8 TeV run and put severe constraints on a large region of R -parity conserved minimal supersymmetric standard model (MSSM) parameter space. So far no evidence of supersymmetry (SUSY) has been found at the LHC, which eventually forces the gluino ($\tilde{g}$) and first two generations of squarks ($\tilde{q}$) to be in the TeV scale. The present bound on the gluino mass obtained by the ATLAS Collaboration in the constrained MSSM (cMSSM) is about 1.7 TeV for $m_{\tilde{g}} \approx m_{\tilde{q}}$ and about 1.35 TeV for $m_{\tilde{g}} \ll m_{\tilde{q}}$, where the lightest neutralino is assumed to be massless [3]. The CMS Collaboration also puts similar strong limits on the masses of squarks and gluino [4]. Both the ATLAS and the CMS Collaborations have searched for the signal of scalar partner of top and bottom quark, namely stop and sbottom, and placed strong limits on their masses. The CMS Collaboration has analyzed about 19.5 fb^{-1} of data at 8 TeV center of mass energy and excluded stop mass up to $m_{\tilde{t}_1} \approx 650 \text{ GeV}$ [5] while the ATLAS Collaboration ruled out stop masses about 660 GeV for a range of lightest neutralino masses [6]. Most of these SUSY search techniques rely on large missing transverse energy signatures originating from the lightest supersymmetric particle (LSP) which is stable in a R -parity conserved scenario and is a good candidate of nonbaryonic dark matter.

Applying a hard cut on the missing transverse energy, SM backgrounds can be significantly reduced, which in turn puts strong constraint on the SUSY parameter space. On the other hand, there are broad class of SUSY models that preserve R -parity but lack large missing energy signatures and thus such models are less constrained compared to conventional SUSY models. One such possibility is the degenerate SUSY spectrum [7]. As the exact SUSY breaking mechanism is still unknown to us, the possibility to have a degenerate SUSY spectrum is still an open issue. If such a possibility indeed exists, the current bounds on different SUSY particle masses at the LHC will be drastically reduced. For example, the gluino mass bound in such a compressed SUSY spectrum is relatively less constrained, about 500(600) GeV at the 7(8) TeV run of LHC [3,8,9]. No significant improvement of degenerate gluino mass bound is expected at the 14 TeV run of LHC and the limit may extend up to about 1 TeV [10]. Another interesting possibility is the stealth SUSY spectra [11] where additional particles are introduced which leads to nearly degenerate fermion/boson pairs with small mass splitting. Current CMS exclusion limit on squark mass in stealth SUSY model is about 1.43 TeV [12].

As we have already discussed, supersymmetric theories with conserved R -parity provide a colorless and electrically neutral stable particle which can act as a good dark matter candidate. However, the conservation of R -parity is not guaranteed and in the case of R -parity violation, the LSP can decay to SM particles. R -parity is actually connected with baryon and lepton numbers and is defined by $R = (-1)^{3B+L+2s}$, where B and L are baryon and lepton numbers, and s is the particle spin. All SM particle fields have $R = +1$ while all its superpartner fields have $R = -1$. Models where R -parity is conserved, superpartners are

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always produced in pairs, however inclusion of RPV interactions in the theory will allow single production of SUSY particles. From the definition of R -parity, it is evident that the violation of R -parity would automatically mean B and/or L violation. However, there are certain difficulties associated with these kind of violations unless R -parity violating interactions are sufficiently small. Within the SM framework, both L and B are conserved quantity and so proton is stable with a lifetime of $\sim 10^{34}$ years. However, in the R -parity conserving MSSM framework the proton is stable due to absence of L and B violating terms in the generic MSSM superpotential. In the case of R -parity violation, if both B and L violating terms are present, proton lifetime will become quite short unless those R -parity violating couplings are sufficiently small. Another interesting implication of L -violating interactions arising from R -parity violations is the generation of neutrino masses. Strong constraints have already been imposed on squark/gluino masses in the context of MSSM with lepton number violation using multilepton searches at the LHC [13]. On the other hand, if R -parity is broken by coupling that violate only baryon number, bounds on squark/gluino masses are comparatively less constrained and we may have a chance to observe such strongly interacting MSSM particles with masses around 1 TeV at the 14 TeV LHC. For this reason, B violating R -parity violation has gained recent attention both in the context of model building [14] and collider phenomenology [15].

In this paper, we focus on the baryon number violating (UDD-type R -parity violation) scenario neglecting other forms of R -parity violations. The final state signature is mainly multijets with no (or small) missing energy which makes it the most challenging scenario to be searched at the LHC environment. We consider the following two possibilities: (i) the gluino LSP decaying to the top quark plus jets and (ii) the lighter stop squark LSP with light gluino. When the lighter stop squark is the LSP, the gluino can directly decay to stop squark and top quark. In both cases, the final state involves top quarks with additional jets. Top quarks coming from the decay of gluino are generally boosted unless the mass difference between gluino and stop squark is small. Jet substructure technique can be very useful to identify such boosted top quark. We study the search prospect of gluino in the two above mentioned scenarios and also discuss the possibility to discover stop squark resonance at the 14 TeV LHC. The paper is arranged as follows: In Sec. II we briefly introduce R -parity violating MSSM and discuss current bounds on SUSY particles. In Sec. III we investigate the future prospects of gluino search performing a detailed collider simulation and also present our results. In Sec. IV we study a representative benchmark point and discuss the possibility to identify a boosted stop squark as a resonance in the jet mass distribution. Finally in Sec. V we summarize our results.

II. R -PARITY VIOLATION OF UDD OPERATOR AND CURRENT BOUNDS

The superpotential of supersymmetric models with R -parity violating interactions (W_{RPV}) includes three trilinear terms parametrized by the Yukawa couplings λ_{ijk} , λ'_{ijk} , and λ''_{ijk} :

$$W_{\text{RPV}} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k, \quad (1)$$

where i, j , and k are generation indices; L and Q are the $SU(2)_L$ doublet superfields of the lepton and quark; and the $\bar{E}$, $\bar{D}$, and $\bar{U}$ are the $SU(2)_L$ singlet superfields of the charged lepton, down-like quark, and up-like quark. The third term violates baryon number conservation, while the first and second terms violate lepton number conservation. In this present work, we will focus on the last term and assume that the lepton number is conserved, i.e.,

$$W_{\text{RPV}} = \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k, \quad (2)$$

where λ''_{ijk} are some arbitrary couplings that violate R -parity and i, j, k are generation indices. Constraints on these UDD type operators come from direct collider searches and additionally from indirect experimental observations like $n - \bar{n}$ oscillation, renormalization group evolution, etc. Detailed discussion of different indirect constraints on these parameters can be found in Ref. [16–19]. For detailed discussions on theoretical and phenomenological aspects of R -parity violation see Ref. [20]. As far as direct constraints are concerned, the presence of R -parity violation makes the collider phenomenology much more complicated than the usual R -parity conserved case. Unlike R -parity conserving case, nonzero values of λ''_{ijk} couplings allows the LSP to decay to SM particles, and thus the final state signature mainly depends on the choice of LSP and the indices of λ'' couplings. If the particle spectrum is such that gluino or neutralino is the LSP, it can decay to three quarks through R -parity violating couplings. Moderate constraint on gluino LSP comes from a 3-jet resonance search by the CDF Collaboration of the Tevatron experiment ($144 \text{ GeV} < m_{\tilde{g}}$) [21], while the CMS Collaboration of the LHC experiment puts bounds on $m_{\tilde{g}}$ between 200 and 460 GeV [22]. Unlike the resonance search, the recent study by the ATLAS Collaboration [23] based on counting of signal and background events puts very strong constraints on gluino mass at the 8 TeV run of LHC with $\mathcal{L} = 20.3 \text{ fb}^{-1}$ of integrated luminosity assuming several possibilities as listed below:

- (i) $m_{\tilde{g}} < 917 \text{ GeV}$: gluino is assumed to be the LSP and $\text{Br}(\text{gluino} \rightarrow \text{light quarks}(u, d, s)) = 1$
- (ii) $m_{\tilde{g}} < 929 \text{ GeV}$: gluino is assumed to be the LSP and $\text{Br}(\text{gluino} \rightarrow \text{bottom quark}) = 1$
- (iii) $m_{\tilde{g}} < 874 \text{ GeV}$: gluino is assumed to be the LSP and $\text{Br}(\text{gluino} \rightarrow \text{bottom, top quark}) = 1$

- (iv) $m_{\tilde{g}} < 800$ GeV: lightest neutralino is the LSP and gluino decays to neutralino assuming $\text{Br}(\text{neutralino}, \text{gluino} \rightarrow \text{lightquarks}) = 1$, neutralino mass = 50 GeV
- (v) $m_{\tilde{g}} < 1050\text{--}1150$ GeV: lightest neutralino is the LSP and gluino decays to neutralino assuming $\text{Br}(\text{neutralino}, \text{gluino} \rightarrow \text{lightquarks}) = 1$, neutralino mass = 600 GeV

On the other hand, when the lightest stop squark is the LSP, it can decay to a pair of jets. Thus for stop pair production, the final state consists of four hard jets which can be overshadowed by a large QCD background. So far, no bound exists on stop squark mass when it decays to jets [24]. However, if the final state contains b jets, the SM background may be small and there is a chance to discover stop squark with mass up to 200 GeV with 20 fb^{-1} of integrated luminosity at the 8 TeV LHC [25]. At the 14 TeV run of LHC, the expected discovery reach of stop squark with multijet final state is about 800 GeV with 300 fb^{-1} data [26].

We can see from the above discussion that the current limit on gluino mass is less than 1 TeV in a UDD-type R -parity violating scenario and the bounds depend on specific choices of gluino decay modes. Additionally a stop squark mass ~ 100 GeV is still allowed if it decays to a pair of jets. This implies that there are several possibilities where the bounds are not directly applicable, providing the opportunity to perform further studies in this direction.

III. DETAILS OF COLLIDER SIMULATION AND RESULTS

We already discussed that in the presence of R -parity violating (RPV) couplings we have the freedom to choose the lightest supersymmetric particle (LSP) and its decay to various SM particles. Here we consider a simplified version of RPV MSSM where the lighter stop squark ($\tilde{t}_1$) and the gluino ($\tilde{g}$) are within the reach of LHC while other SUSY particles are relatively heavy. Thus, we have the option to choose either the lighter stop squark or gluino as the LSP candidate. When stop is the LSP candidate, then gluino will decay to a top quark and stop squark ($\tilde{t}_1$). Note that in order to allow the decay of $\tilde{t}_1$ to SM particles, the first index of λ''_{ijk} coupling should be equal to 3 (i.e., λ''_{3jk}) and the corresponding decay of $\tilde{t}_1$ is

$$\tilde{t}_1 \rightarrow jj, \quad (3)$$

where one of the jets may be a b jet depending upon the choice of indices j and k . This leads to the final state from the decay of gluino as follows

$$\tilde{g} \rightarrow t\tilde{t}_1 \rightarrow tjj. \quad (4)$$

Here we assume that the mass difference between the gluino and stop squark is always greater than top quark mass.

On the other hand, when gluino is the LSP and the assumed RPV coupling is λ''_{3jk} , then gluino will decay via three body final states, i.e.,

$$\tilde{g} \rightarrow tjj \quad (5)$$

On a passing note, since gluino is a Majorana particle, we may get same sign top quarks from the gluino pair production and thus final state may contain same sign di-leptons. The expected sensitivity of 14 TeV LHC with high luminosity option in this channel have already been discussed [27]. However, if the top quarks coming from the decay of gluino is highly boosted, the decay products of top quark are not generally isolated. As a result, the probability to have final states involving isolated leptons are relatively small compared to the conventional scenario with low p_T top quarks. Here we focus on the gluino pair production process with gluino decaying via both the two body Eqn. (4) and three body Eqn. (5) decay modes, provided they are kinematically allowed.

$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow tt + \text{jets} \quad (6)$$

Hence, the final state signature includes at least two top quarks with additional jets. Throughout our analysis we assume that the λ'' couplings lead to short enough lifetimes of gluino and stop squark such that they decay promptly. For a gluino with mass in the TeV regime, the top quark produced from the gluino decay can have sufficient transverse momentum to appear as a single fat jet. One can thus apply the Jet substructure technique to reconstruct the invariant mass of the top quark. Similarly, the stops may also have sufficient transverse boost to appear as a fat jet. In the next section, we explore the possibility to have a boosted stop squark and find that the jet substructure is a useful technique to reconstruct the stop from the busy LHC environment. There are SM processes which can give rise the final state signature we are interested in and thus contribute to the background for our signal. In our analysis, we consider the two most important backgrounds namely $t\bar{t} + \text{jets}$ (up to two jets) and QCD jets which can play a significant role in our region of interest.¹ As our final state signature do not include any lepton, we require special attention to reduce the contamination of the QCD background thereby enhancing the signal significances. We use PYTHIA6.4.24 [28] for the generation of the signal events while MADGRAPH5 [29] generates the background events and subsequently the MADGRAPH-PYTHIA6 interface is used to perform the parton showering and implement our event selection cuts. We include the matching of the matrix

¹We also consider single top quark production (top + b quark, top + light quark and top + W) and we find that it can be reduced to a negligible level after imposing our final optimized selection cuts.

element hard partons and shower generated jets following the MLM prescription [30]. We use the FASTJET (version 3.0.4) [31] for the reconstruction of jets and the implementation of the jet substructure analysis for the reconstruction of the top quark. As we already mentioned, it is always a challenging task to get rid of the QCD backgrounds when the signal do not contain any lepton. On the other hand, we expect hard jets coming from the decay of massive gluino (TeV scale) or stop squark and the scalar sum of the transverse momentum of final state visible particles should be above 1 TeV. Keeping this in mind, we proceed to generate the event sample for QCD multijets for four different region of the effective mass (S_T) variable namely $S_T > 1200$ GeV, $1200 \text{ GeV} < S_T < 2000$ GeV, $S_T > 2000$ GeV, and finally $S_T > 3000$ GeV where S_T is defined as follows:

$$S_T = \sum_{j=1}^4 p_T^j.$$

For wide separation of gluino and stop squark masses, both stop squark and top quark may appear as fat jets and we can expect four fat jets at the parton level. That is why we are interested in four high p_T fat jets in the final state. While simulating the QCD background events, we restrict ourselves up to four jets at the parton level due to our computational limitations. However, the QCD event sample includes events with higher (> 4) jet multiplicities as we allow parton showering of four-jet samples. For the $t\bar{t}$ + jets, we also generate sufficient number of events for both low and high p_T samples to cover the entire phase space.

Though the final state signature we are interested in includes at least one top quark, however to make our analysis more general, we consider three possibilities: (i) final state with no tagged top quark jet, (ii) at least one tagged top quark jet, and (iii) at least two tagged top quark jets. We tag the top quarks using the publicly available Heidelberg-Eugene-Paris Top-tagger (HEPTopTagger) [32,33] package with its default settings assuming that the top quark decays hadronically to produce jets in the final state. The top-tagging technique is primarily based on the Cambridge-Aachen (C/A) [34] jet algorithm and a mass drop criteria along with a filtering technique (for details, see [33,35]). We also use C/A algorithm with jet radius $R = 1.2$ to reconstruct the fat jets and then fed these jets as the input of the top-tagging algorithm.

We will now describe the details of our simulation procedure as well as the kinematic cut optimization technique opted to enhance the signal significances. Before we proceed, we would like to discuss the choice of the parameters that are involved in our analysis. The values of M_1 and M_2 are set to 5 TeV as these are irrelevant for the parameter space of our interest. The higgsino mass parameter μ is taken to be 5 TeV and $\tan\beta$, the ratio of the

vacuum expectation values of the two Higgs doublets, is fixed at the value of 5. The masses of the first two generation of squarks and all the three generation of sleptons along with the right handed third generation squark (sbottom) mass parameter are also set to 5 TeV as they will not play any significant role in our study. All the trilinear couplings A_t , A_b , and A_τ are set to zero as these couplings have very little impact on our analysis. As we discuss, we are mainly interested in the decay of gluino to a top quark, the two important parameters that have significant impact on these decay modes are gluino mass parameter M_3 and the right handed third generation squark (stop) mass parameters $m_{\tilde{t}_R}$. We perform a dedicated scan in the $M_{\tilde{g}}-M_{\tilde{t}_1}$ plane in order to understand the sensitivity of our search strategy over a wide range. So, we start with the gluino mass from 500 GeV to 2 TeV, while stop mass varies from 100 GeV to 2 TeV with smaller bin sizes ($\sim 25/50$ GeV). We use PROSPINO2.1 [36] to calculate the gluino pair production cross section at the next-to-leading order at the 14 TeV LHC. Additionally, we also study the three-body decay mode of gluino, i.e., $\tilde{g} \rightarrow tjj$, varying the gluino mass from 500 GeV to 2 TeV in step of 50 GeV fixing $M_{\tilde{t}_1}$ at 3 TeV while other parameters are the same as mentioned above. We use the top quark mass 173.1 GeV in our whole analysis [37].

Our final state topology do not include any isolated lepton, hence we will not consider any observable associated with the kinematics of the lepton. Besides, we consider the hadronically decaying top quark, thus there is no lepton and no real source of missing energy (E_T) like the neutrinos. Hence, we will not consider p_T as a relevant kinematic observable in our analysis, rather the most interesting observables are actually the transverse momentum of the jets and the effective mass (S_T) constructed using the transverse momentum of the jets.

The basic idea behind this cut optimization technique is to find out the possible combinations of the five relevant observables, namely $p_T^{j_1}$, $p_T^{j_2}$, $p_T^{j_3}$, $p_T^{j_4}$, and S_T , such that signal significance (S) takes the maximum value. We vary these observables in the following ranges with small step sizes ($\sim 50/100$ GeV):

$$\begin{aligned} 100 < p_T^{j_1} < 1000, & \quad 100 < p_T^{j_2} < 1000, \\ 50 < p_T^{j_3} < 500, & \quad 50 < p_T^{j_4} < 500, \\ 1200 < S_T < 3500. \end{aligned} \quad (7)$$

For each point corresponding to this five-dimensional parameter space, we calculate the signal significance (S) as defined below using the signal and combined background events,

$$S = \frac{N_S}{\sqrt{N_B + (\kappa N_B)^2}}, \quad (8)$$

where N_S and N_B are the number of signal and background events, respectively, and κ is the measure of the systematic uncertainty. We assume $\kappa = 20\%$ and $\mathcal{L} = 300 \text{ fb}^{-1}$ of luminosity at the 14 TeV run of LHC. We calculate S for nearly ~ 53000 possible combinations of these observables for zero, one, and two top-tagged samples separately. We choose a few optimized set of kinematic cuts to discuss the signal and background characteristics, as shown in Table I. We define the discovery and exclusion limits if S is greater than 5 and 2, respectively, for a particular choice of gluino/stop mass. We denote the signal regions as $SRXn$, where X is an arbitrary label corresponding to various set of cuts ($X \equiv A-C$) and the quantity n here denotes the number of tagged top quark.

We find that the signal involves sizeable number of events with jet multiplicity greater than four. For this reason we further consider events with five and six jets and take approximately 50 possible combinations of the jet transverse momentum and S_T around the four jet optimized cuts. We would like to remind our readers that our five-jet and/or six-jet limits may not be so robust compared to four-jet limits due to our inability to generate five-jet and six-jet background samples at the parton level, still they can be considered as an approximate estimation of the discovery reach at the LHC.

We get two distinct signal regions for the one top-tagged sample. For large values of gluino masses SRA1 helps to get the 5σ discovery reach for the one top-tag sample, which includes five jets, while for relatively small values of gluino masses, a cut set similar to SRB2 helps. For the two top-tagged sample, the signal region SRC2 is the most efficient cut set with highest LHC discovery reach. On the other hand, the discovery limit for the zero top-tagged case is much weaker than that of the one and/or two top-tagged scenario. This means top-tagging is quite efficient for the reduction of backgrounds, while keeping a sufficient number of signal events, thereby enhancing the signal significance.

In Table II, we display the number of events survive after each cut set for both the signal and the background events. To describe the signal event, we consider a representative benchmark point (BP-1) where the gluino mass is fixed at 1.2 TeV and the lighter stop mass at 550 GeV keeping other parameters the same as before.

TABLE I. Details of three optimized kinematic cuts which provide the maximum sensitivity in the search for stop ($\tilde{t}_1$) and gluino ($\tilde{g}$). The last column indicates the number of tagged top quarks in the final state. All the jet momenta along with the effective mass parameter (S_T) are expressed in units of GeV.

	$P_T^{j_1}$	$P_T^{j_2}$	$P_T^{j_3}$	$P_T^{j_4}$	$P_T^{j_5}$	$P_T^{j_6}$	S_T	# of top-tag
SRA1	400	400	400	400	400	—	—	1
SRB2	300	200	200	200	—	—	—	2
SRC2	800	600	500	400	—	—	2500	2

TABLE II. Number of events survive after each cut set (see Table I) for both the signal and the background events. We consider a sample benchmark point (BP-1) with $M_{\tilde{g}} = 1.2 \text{ TeV}$ and $M_{\tilde{t}_1} = 550 \text{ GeV}$. We assume $\mathcal{L} = 300 \text{ fb}^{-1}$ with 20% systematic uncertainty at 14 TeV run of LHC.

	SRA1	SRB2	SRC2
QCD jets	12	30	30
$t\bar{t}$ + jets	22	72	15
Total bkg	34	102	45
BP-1	49	180	58
Significance (S)	5.5	7.9	5.2

In Fig. 1, we display the projected discovery reach in the $M_{\tilde{t}_1} - M_{\tilde{g}}$ plane in the context of 14 TeV run of LHC. The straight (blue) line $M_{\tilde{g}} - M_{\tilde{t}_1} = M_t$ separates two regions with distinct kinematics, below which the gluino decays in two body final state while in the above region three body decay mode is important. Near this line, the stop ($\tilde{t}_1$) and top are produced almost at rest and thus the transverse momentum of top quark is very small, thereby reducing our acceptance limit. We find that SRC2 gives the best sensitivity where we tag two top quarks, however the limit obtained from SRA1 (signal with one top tag) is slightly weaker. We also find that the gluino mass as high as 1.4 TeV is achievable for stop mass $\sim 1 \text{ TeV}$ with 300 fb^{-1} of data at the 14 TeV LHC. It is to be noted that, in the case of zero top-tagged sample, one can achieve 5σ signal significance for gluino masses up to 800 GeV at the 14 run of LHC. For the region above the straight (blue) line, the gluino dominantly decays to top quark and light jets. The 5σ reach in the gluino mass is approximately 1.4 TeV for

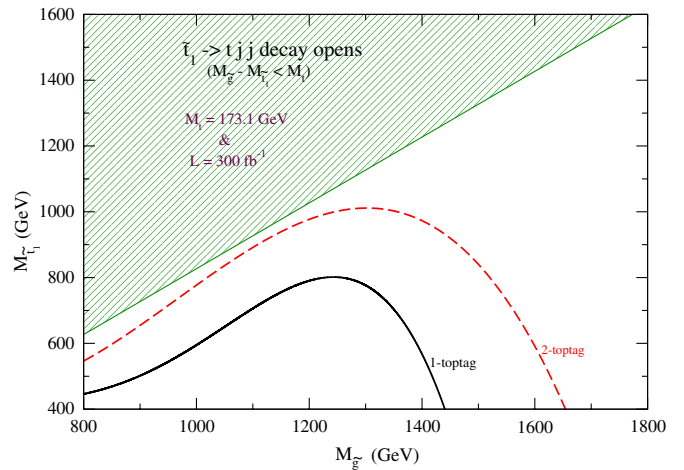


FIG. 1 (color online). The 5σ discovery limit in the $(M_{\tilde{g}} - M_{\tilde{t}_1})$ plane for UDD-type R -parity violating MSSM. The diagonal line $M_{\tilde{g}} - M_{\tilde{t}_1} = M_t$ separates two regions with distinct kinematics. The solid black line represents the one top-tagged limit, while dashed red (light grey) denotes the limits for the two top-tagged sample. We assume $\mathcal{L} = 300 \text{ fb}^{-1}$ luminosity and 20% systematic uncertainty at the 14 TeV LHC.

300 fb⁻¹ of luminosity, the limit do not dependent on the choice of stop mass. We also study the sensitivity of our results considering 50% enhancement in total SM background estimation and find that the discovery reach is reduced by about 150–200 GeV. The gluino exclusion limits for the above mentioned two possibilities are about 1.9 TeV (gluino two-body decay) and 1.7 TeV (gluino three-body decay), respectively.

Before we conclude this section we would like to comment on some important issues:

- (i) In addition to light jets, b jets may also appear in the final state either from the decay of top or from stop decay. In our analysis we do not identify b jets in the final state rather we assume these as inclusive jets.
- (ii) Improvement can be expected with the High Luminosity LHC (HL-LHC) run, with 3000 fb⁻¹ of luminosity if we impose harder cuts on p_T and S_T of the jets. However, with such high luminosity, pile up is an important issue which can increase the systematic uncertainty. In that case the discovery limits on gluino and stop masses may not change significantly.
- (iii) Although we assume that the strength of λ'' coupling is such that gluino and stop decay promptly, the lifetime of these particles can be large enough. This may lead to displaced vertices, stable gluino/stop for collider, etc. In order to study such signals, dedicated analysis taking care of detector effects are required which is beyond the scope of this paper.
- (iv) Triggering is an important issue in R -parity violating searches at the LHC. The CMS Collaboration has studied the signatures of multijets in the context of R -parity violating MSSM using both 7 and 8 TeV data [22,38], where the trigger used to select signal events are based on the scalar sum of the transverse momentum of all the jets (H_T) measured using calorimeter information. In addition, to reduce the effects of multiple pp interactions, the jets are selected with $p_T > 40$ –60 GeV. Here, we study the discovery reach at the LHC in the presence of a number of energetic jets in the final state in the context of RPVMSSM. A trigger, very much similar to that of the CMS Collaboration, as discussed above, will be sufficient enough to select our signal events. We check that a choice of $H_T > 1000$ GeV as our trigger with jets having $p_T > 50$ GeV, will select almost 99% of our signal events.

IV. A SIMPLIFIED BENCHMARK STUDY

In this section, we discuss the possibility to discover the lighter stop squark at the LHC performing a simplified benchmark study. Gluinos are pair produced at the LHC followed by a direct decay of gluino to a top quark and a stop squark and the stop squark decays to a pair of jets. We assume a wide separation of mass between the stop and

gluino such that the stop squarks produced from the decay of gluino will be sufficiently boosted. The most important feature of a boosted particle decaying into multiple hadronic jets is that the final states remain highly collimated because of large transverse momenta of the parent particle, thus appearing as a single fat jet. Conventional jet finding algorithms will have less sensitivity in such cases, this realization has led to the idea of the jet substructure [35] technique.² Interestingly, the situation is very similar to the Higgs decay to a pair of b jets, which also appear as a single fat jet when the Higgs has relatively large transverse momentum. The BDRS Higgs tagger [35] which is based on the jet substructure technique was developed primarily to study the boosted Higgs fat jets. Here we apply this Higgs tagging technique to look for the signatures of the stop resonances at the LHC. Our stop tagging algorithm is as follows:

- (i) Final state jets (from $\tilde{t}_1 \rightarrow jj$) are formed based on a Cambridge-Aachen jet clustering algorithm with jet radius $R = 1.2$.
- (ii) We investigate the subjet kinematics step by step and apply the mass drop criteria along with the filtering technique at the subjet level.
- (iii) Select the best subjets to form the fat jet mass, which essentially should correspond to the parent particle mass.

We fix the gluino mass parameter $M_{\tilde{g}}$ at 1.2 TeV and the stop mass $M_{\tilde{t}_1}$ at 550 GeV, keeping other parameters fixed at the values as mentioned in Sec. III. In Fig. 2, we show the jet mass distribution reconstructed using the above mentioned substructure algorithm. From the figure it is clear that we get a resonance peak around 550 GeV, which is indeed equal to the mass of the lightest stop ($\tilde{t}_1$) present in this event. Here we assume $\mathcal{L} = 100$ fb⁻¹ of luminosity at the 14 TeV run of the LHC. One should note that the width of stop squark is small compared to detector resolution as the RPV coupling is very small. However, we get sizeable width in the jet mass distribution due to the presence of various effects like smearing, multiple interaction, etc. One may expect to observe a resonance peak at or around the gluino mass, using the invariant mass distribution of the reconstructed top and stop. However, it is not possible to have such a resonance like structure as gluino decay width is mostly determined by the QCD couplings and it is always very large, resulting into a broad jet mass distribution. One should also note that the resonance peak will disappear for small mass difference between gluino and stop squark due to small boost of the produced stop squarks.

V. CONCLUSION

Supersymmetric theories with conserved R -parity naturally provide a stable lightest SUSY particle (LSP) which

²For direct stop pair production, one can also apply jet substructure technique. For details, see Ref. [39].

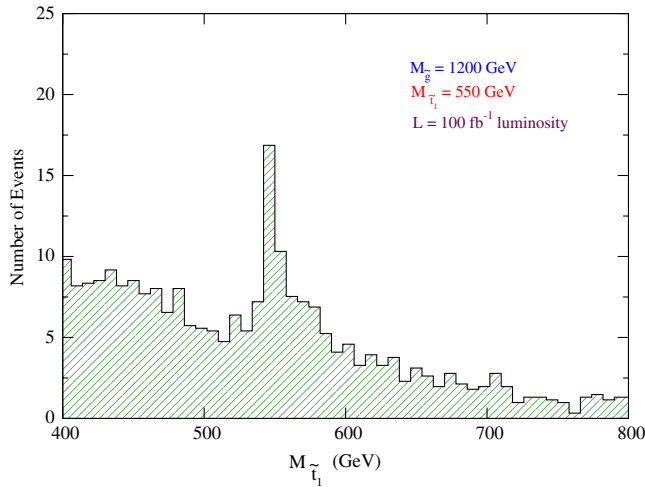


FIG. 2 (color online). Invariant mass distribution of the reconstructed jets using the boosted jet substructure technique for a sample benchmark point. Here we assume $M_{\tilde{t}_1} = 550$ GeV and $M_{\tilde{g}} = 1.2$ TeV. We see clear resonance peak with 100 fb^{-1} luminosity at the 14 TeV run of LHC.

can be a good dark matter candidate. However, in the presence of R -parity violating couplings in the superpotential, the LSP can now decay to SM particles which leads to final state signatures with small missing transverse energy. For example, the UDD type of R -parity violation allows the LSP to decay to multiple jets which makes it a very challenging scenario to search at the LHC environment. In this paper, we focus on this UDD type of R -parity violation, assuming the following two cases: (i) the stop ($\tilde{t}_1$) is the LSP or (ii) the gluino ($\tilde{g}$) is the LSP. We further

assume the multijet final states originating from the decay of the gluino contains top quark with sufficient transverse momentum. We apply the jet substructure technique to reconstruct these hadronically decaying top quarks and calculate discovery as well as exclusion limits on the mass of the gluino. We find that gluino masses up to 1.65 TeV can be discovered with 300 fb^{-1} of luminosity at the 14 TeV LHC run. With higher luminosities, one may expect some improvement in the discovery reach on the gluino mass, however it is to be noted that pile up will play significant role with such high luminosities. We also discuss how jet substructure technique can be very useful to search for the resonance peak of the stop squark ($\tilde{t}_1$) in the early run of 14 TeV LHC. This method to identify stop squark as a single fat jet is efficient only if the mass gap between gluino and stop squark is large.

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- [1] G. Aad *et al.* (ATLAS Collaboration), *Phys. Lett. B* **716**, 1 (2012).
 - [2] S. Chatrchyan *et al.* (CMS Collaboration), *Phys. Lett. B* **716**, 30 (2012); S. Chatrchyan *et al.* (CMS Collaboration), *J. High Energy Phys.* **06** (2013) 081.
 - [3] ATLAS Collaboration, Report No. ATLAS-CONF-2013-047.
 - [4] CMS Collaboration, Report No. CMS-PAS-SUS-13-012.
 - [5] CMS Collaboration, Report No. CMS-PAS-SUS-13-011.
 - [6] ATLAS Collaboration, Report No. ATLAS-CONF-2013-024.
 - [7] C. H. Chen, M. Drees and J. F. Gunion, *Phys. Rev. D* **55**, 330 (1997); **60**, 039901(E) (1999); H. Murayama, Y. Nomura, S. Shirai, and K. Tobioka, *Phys. Rev. D* **86**, 115014 (2012); S. Krippendorff, H. P. Nilles, M. Ratz, and M. W. Winkler, *Phys. Rev. D* **88**, 035022 (2013).
 - [8] H. K. Dreiner, M. Kramer, and J. Tattersall, *Europhys. Lett.* **99**, 61001 (2012).
 - [9] B. Bhattacharjee and K. Ghosh, *arXiv:1207.6289*.
 - [10] B. Bhattacharjee, A. Choudhury, K. Ghosh, and S. Poddar, *Phys. Rev. D* **89**, 037702 (2014).
 - [11] J. Fan, M. Reece, and J. T. Ruderman, *J. High Energy Phys.* **11** (2011) 012.
 - [12] S. Chatrchyan *et al.* (CMS Collaboration), *Phys. Lett. B* **719**, 42 (2013).
 - [13] ATLAS Collaboration, Report No. ATLAS-CONF-2013-036.
 - [14] G. Krnjaic and D. Stolarski, *J. High Energy Phys.* **04** (2013) 064; R. Franceschini and R. N. Mohapatra, *J. High Energy Phys.* **04** (2013) 098; C. Csaki and B. Heidenreich, *Phys. Rev. D* **88**, 055023 (2013); A. Florez, D. Restrepo, M. Velasquez and O. Zapata, *Phys. Rev. D* **87**, 095010 (2013); G. Krnjaic and Y. Tsai, *J. High Energy Phys.* **03** (2014) 104; A. Monteux, *Phys. Rev. D* **88**, 045029 (2013); L. Di Luzio, M. Nardecchia and A. Romanino, *Phys. Rev. D* **88**, 115008 (2013); I. Gogoladze, F. Nasir and Q. Shafi, *J. High Energy Phys.* **11** (2013) 173; A. Arvanitaki,

- M. Baryakhtar, X. Huang, K. Van Tilburg and G. Villadoro, *J. High Energy Phys.* **03** (2014) 022.
- [15] B. C. Allanach and B. Gripaios, *J. High Energy Phys.* **05** (2012) 062; M. Asano, K. Rolbiecki and K. Sakurai, *J. High Energy Phys.* **01** (2013) 128; D. Curtin, R. Essig, and B. Shuve, *Phys. Rev. D* **88**, 034019 (2013); Z. Han, A. Katz, M. Son, and B. Tweedie, *Phys. Rev. D* **87**, 075003 (2013); B. Bhattacharjee, J. L. Evans, M. Ibe, S. Matsumoto, and T. T. Yanagida, *Phys. Rev. D* **87**, 115002 (2013); T. Cohen, E. Izaguirre, M. Lisanti and H. K. Lou, *J. High Energy Phys.* **03** (2013) 161; J. Berger, M. Perelstein, M. Saelim, and P. Tanedo, *J. High Energy Phys.* **04** (2013) 077; G. Durieux and C. Smith, *J. High Energy Phys.* **10** (2013) 068; K. S. Babu, E. Kearns, U. Al-Binni, S. Banerjee, D. V. Baxter, Z. Berezhiani, M. Bergevin, and S. Bhattacharya *et al.*, [arXiv:1311.5285](#).
- [16] F. Zwirner, *Phys. Lett.* **132B**, 103 (1983).
- [17] J. L. Goity and M. Sher, *Phys. Lett. B* **346**, 69 (1995); **385**, 500(E) (1996).
- [18] D. Chang and W.-Y. Keung, *Phys. Lett. B* **389**, 294 (1996).
- [19] D. K. Ghosh, S. Raychaudhuri, and K. Sridhar, *Phys. Lett. B* **396**, 177 (1997).
- [20] G. Bhattacharyya, *Nucl. Phys. B, Proc. Suppl. A* **52**, 83 (1997); H. K. Dreiner, in *Perspectives on Supersymmetry II* edited by G. L. Kane (World Scientific, Singapore, 2010), p. 565; R. Barbier, C. Berat, M. Besancon, M. Chemtob, A. Deandrea, E. Dudas, P. Fayet, and S. Lavignac *et al.*, *Phys. Rep.* **420**, 1 (2005).
- [21] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **107**, 042001 (2011).
- [22] S. Chatrchyan *et al.* (CMS Collaboration), *Phys. Lett. B* **718**, 329 (2012).
- [23] The ATLAS Collaboration, Report No. ATLAS-CONF-2013-091.
- [24] J. A. Evans and Y. Kats, *J. High Energy Phys.* **04** (2013) 028.
- [25] R. Franceschini and R. Torre, *Eur. Phys. J. C* **73**, 2422 (2013).
- [26] D. Duggan, J. A. Evans, J. Hirschauer, K. Kaadze, D. Kolchmeyer, A. Lath, and M. Walker, [arXiv:1308.3903](#).
- [27] M. Saelim and M. Perelstein, [arXiv:1309.7707](#).
- [28] T. Sjostrand, S. Mrenna, and P. Z. Skands, *J. High Energy Phys.* **05** (2006) 026.
- [29] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, *J. High Energy Phys.* **06** (2011) 128.
- [30] S. Hoeche, F. Krauss, N. Lavesson, L. Lonnblad, M. Mangano, A. Schalicke, and S. Schumann, [arXiv:hep-ph/0602031](#).
- [31] M. Cacciari, G. P. Salam, and G. Soyez, *Eur. Phys. J. C* **72**, 1896 (2012).
- [32] T. Plehn, M. Spannowsky, M. Takeuchi, and D. Zerwas, *J. High Energy Phys.* **10** (2010) 078; T. Plehn, G. P. Salam, and M. Spannowsky, *Phys. Rev. Lett.* **104**, 111801 (2010).
- [33] T. Plehn and M. Spannowsky, *J. Phys. G* **39**, 083001 (2012).
- [34] Y. L. Dokshitzer, G. D. Leder, S. Moretti, and B. R. Webber, *J. High Energy Phys.* **08** (1997) 001.
- [35] J. M. Butterworth, A. R. Davison, M. Rubin, and G. P. Salam, *Phys. Rev. Lett.* **100**, 242001 (2008).
- [36] W. Beenakker, R. Hopker, and M. Spira, [arXiv:hep-ph/9611232](#); W. Beenakker, R. Hopker, M. Spira, and P. M. Zerwas, *Nucl. Phys. B* **492**, 51 (1997).
- [37] J. Beringer *et al.* (Particle Data Group Collaboration), *Phys. Rev. D* **86**, 010001 (2012).
- [38] S. Chatrchyan *et al.* (CMS Collaboration), *Phys. Lett. B* **730**, 193 (2014).
- [39] Y. Bai, A. Katz, and B. Tweedie, *J. High Energy Phys.* **01** (2014) 040.