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Boosted top quarks in supersymmetric cascade decays at the LHC

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Abstract

At the LHC, a generic supersymmetric cascade can be a source of top quark. Specifically third generation squarks and gluino are the major sources of top quark which could also be boosted. In this article, we have shown that jet substructure algorithm can be very useful in identifying such boosted top quarks in the cascade. We take inclusive three jets plus zero lepton plus missing energy final state and try to reconstruct at least one hadronically decaying top quark by using top tagging technique which has good prospect at the LHC.

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I Introduction

Standard Model (SM) has been successful in explaining a wide variety of phenomena and most of the experimental results are consistent with the SM [1]. However, there are some issues that make it incomplete as a theory. One of the most important issues is the mass of the Higgs boson, the particle responsible for giving mass to the fermions and the gauge bosons, is itself radiatively unstable. There is no solution to this puzzle in the SM and hence one feels justified to go beyond the SM and look for new physics. Supersymmetry (SUSY) [2] is one of the possible extension of SM which can protect Higgs mass and in principle solve the problem. Supersymmetry predicts superpartners of SM particles. Since no super partner has been observed so far, they must be heavier than the corresponding experimental limits [3]. This simply implies that the supersymmetry must be broken. Unfortunately, the SUSY breaking mechanism is completely unknown. For this reason, low energy SUSY spectrum can be completely arbitrary and it needs more than 100 parameters to specify the masses and couplings of the SUSY particles. Practically it is very difficult to explore such a multi-dimensional parameter space and study its collider signatures [4]. Therefore, it is necessary to adopt some specific assumptions for SUSY breaking mechanisms. There are several phenomenologically viable SUSY breaking mechanisms. Gravity mediated supersymmetry breaking model like constrained MSSM (cMSSM) [5] is the most popular amongst all. In cMSSM, the full spectrum is completely determined only by four and half parameters specified at the high scale. These are universal scalar mass (m_0), universal gaugino mass ($m_{1/2}$), tri-liner coupling constant (A_0), the ratio between the vacuum expectation values of up and down type Higgs fields ($\tan\beta$) and the sign of Higgs mixing term (μ) in the super-potential. This small set of parameters makes the model very predictive.

In a R parity[1] conserving supersymmetric model, sparticles must be produced in pair and eventually cascade down to the lightest SUSY particle (LSP) which can not decay to SM particles. Now, if neutralino is the LSP, because of its weakly interacting nature it could be a good dark matter candidate. In a collider experiment it is impossible to detect such weakly interacting particle, thus contributes as missing energy in the final state. In general, the pair production of SUSY particles will lead to final states with multiple jets and leptons plus missing energy. So far, many detailed studies have been carried out to discover SUSY at the LHC [6], particularly in the context of cMSSM. Such studies indicate that inclusive jets plus missing energy channel with zero lepton has the highest reach in the cMSSM parameter space [7]. The final state with isolated leptons are also important, since the requirement of one or more isolated leptons can suppress huge QCD background, although such channels have lower reach than the zero lepton channels [8].

If low scale supersymmetry exists in nature, the study of third generation squarks at the LHC is of a special interest. This is because, the third generation Yukawa coupling is relatively larger than the rest, which results in relatively larger mass splitting between the mass eigenstates. Thus the lighter eigenstates could become light enough and might be discovered at the Tevatron or in the early stage of LHC [9].

[1] R parity is a discrete symmetry defined as a R_p=$(-1)^{(3B+2S+L)}$, where L, B and S are lepton number, baryon number and spin of the particle respectively.

Third generation squarks ($\tilde{t}_1$, $\tilde{t}_2$ and $\tilde{b}_1$, $\tilde{b}_2$) can be pair produced at the LHC and these can be produced from the decay of SUSY particles. Depending on the parameter space, the dominant decay modes of stop squarks ($\tilde{t}_1$, $\tilde{t}_2$) are $t\ \tilde{\chi}^0_{1,2,3,4}$ and $b\ \tilde{\chi}^{\pm}_{1,2}$. Similarly sbottom squarks ($\tilde{b}_1$, $\tilde{b}_2$) can decay to $t\ \tilde{\chi}^{\pm}_{1,2}$ and $b\ \tilde{\chi}^0_{1,2,3,4}$. If the squarks are heavier than gluino except the third generation, gluino will decay entirely to the third generation squarks. If all squarks are heavier than gluino, the gluino will decay to three body final state through off shell squarks. In general, stop and sbottom squarks, being lighter than the first two generation squarks, contribute more to the gluino three body decay. This is why, final states with top and bottom quarks in the gluino three body decay are relatively more favoured. Final states with b jets accompanying with multiple jets, leptons and missing energy have been studied extensively. Another interesting possibility is top rich final states from gluino decay. It is thus important to identify the presence of top quark in the SUSY cascade, as it carries information about third generation squarks. However, top quark identification in a SUSY cascade is not an easy task. Top quark mostly decays to W and b quark unless charged Higgs boson is lighter than top quark. In case of leptonic decay of W, the neutrino, that is present in the final state also contributes to the missing energy, in addition to the missing energy from the lightest neutralino. In order to reconstruct semileptonically decaying top, we have to separate out the neutrino missing energy contribution coming from the top quark. This is why, it is difficult to reconstruct a top quark by its semileptonic decay in the cascade. On the other hand, hadronically decaying top quark has no real missing energy contribution. However, it is very difficult to choose the correct combination of three jets from multiple jets (which are always present in a typical SUSY cascade) as it suffers from combinatorial backgrounds. It is thus difficult, although, not impossible to identify top quarks in a SUSY cascade. Beside this, top quarks in SUSY cascade can be highly boosted due to the usual separation between strong and electroweak sector of MSSM. Because of the high boost, the decay products of top quark are generally collimated. It makes it very difficult to isolate the decay products as separate jets or leptons; and often ends up with a single fat jet in the final state.

From the above discussion we have seen that the identification of top quark in SUSY cascade faces two types of difficulties, e.g., combinatorial background in top reconstruction and collimation of the decay products of the highly boosted top quarks. Recently, a new method has been proposed to distinguish jets originated from boosted heavy particles by the method of jet substructure. By using this method, one can fully reconstruct the decaying heavy particle through its hadronic final state. A number of recent studies have used this technique to identify boosted top quarks [10, 11, 12], Higgs bosons [13], or W/Z bosons [14] and the results are very encouraging. It is therefore, a good idea to use the above mentioned technique to reconstruct the top signals in the SUSY cascade.

In this paper we systematically study the top quark production in the SUSY cascade and its identification by newly developed top tagging method at the LHC with centre of mass energy 14 TeV. We take inclusive three jets plus zero lepton plus missing energy final state and try to reconstruct at least one hadronically decaying top quark by using top tagging technique, described in [12]. Of course, the production of the boosted top will depend on the mass of the parent squark (stop and sbottom), or gluino and their corresponding branching fraction to the top quark. In ref [15] authors have studied the pair production of lightest stop squarks assuming the branching $\tilde{t}_1 \to t\tilde{\chi}_1^0$ to be equal to 1 and they have shown that it is possible to extract the stop ($\tilde{t}_1$) - neutralino ($\tilde{\chi}_1^0$) mass difference. However, this assumption does not hold as we change the parameter space.

The article is organized as follows. In section II we describe the origin of top quark final states from the decay of third generation squarks and gluino and also discuss the effective branching to top quark for different scenarios. In section III, we define our benchmark points for the analysis. We discuss our results, briefly addressing the top tagging technique in section IV. Finally we conclude in section V discussing the possible issues of this work.

II Possible Scenarios

In this section we shall describe the possible sources of top quark from the decay of sparticles. In general, the squark mass spectra are very different as one goes from first two generations to third generation. The off diagonal term in the squark mass matrix is given by $m_f(A_f + \mu R_f)$ where $R_f = \cot\beta$ for up type squark and $R_f = \tan\beta$ for down type squark and m_f is the corresponding quark mass [16]. As first two generation quark masses are negligible, we can neglect the off diagonal terms in the mass matrix. The general hypothesis of flavour blind soft parameter for first two generations avoid potentially dangerous FCNC and CP-violating effects in MSSM. However, masses of the third generation squarks are more complicated because of the Yukawa couplings and the corresponding changes in RG equations. Due to large mixing through the off diagonal terms, there could be large splittings between the mass eigenvalues. Thus, in general the third generation masses are quite non-degenerate and lighter ones ($\tilde{t}_1$, $\tilde{b}_1$) can become rather light.

We are now ready to discuss the possible decay modes of third generation squarks. If third generation squarks are heavier than gluino, preferably decay to corresponding quark and gluino, if kinematically allowed. In case, gluino is heavier than stop or sbottom squark, there are several possible interesting channels like

$$\begin{array}{ll} \tilde{t}_{1,2} \to t\tilde{\chi}_i^0 \text{ (i=1-4)} & \tilde{t}_{1,2} \to b\tilde{\chi}_i^\pm \quad \text{(i=1-2)} \\ \tilde{b}_{1,2} \to b\tilde{\chi}_i^0 \text{ (i=1-4)} & \tilde{b}_{1,2} \to t\tilde{\chi}_i^\pm \quad \text{(i=1-2)}\ . \end{array}$$

If the mass difference between $\tilde{t}_2$ ($\tilde{b}_2$) and $\tilde{t}_1$ ($\tilde{b}_1$) or $\tilde{t}_2$ ($\tilde{b}_2$) and $\tilde{b}_1$ ($\tilde{t}_1$) is large enough, the following decays [17]

$$\begin{array}{ll} \tilde{t}_2 \to \tilde{t}_1 \;\; Z,/H,/A & \tilde{t}_2 \to \tilde{b}_1 \;\; W^+/H^+ \\ \tilde{b}_2 \to \tilde{b}_1 \;\; Z,/H,/A & \tilde{b}_2 \to \tilde{t}_1 \;\; W^+/H^+ \end{array}$$

are also possible. Several studies have been performed in this context of CP conserving [18] and CP violating MSSM [19]. For a wide range of parameter space, all tree level two body decay modes of lightest stop squark are forbidden and the loop decay $\tilde{t}_1 \to c\tilde{\chi}_1^0$ becomes significant [20]. In the case where $\tilde{t}_1$ is the NLSP, it decays to three body [21] or four body final state [22]. In the next few paragraphs, we discuss the effective decay

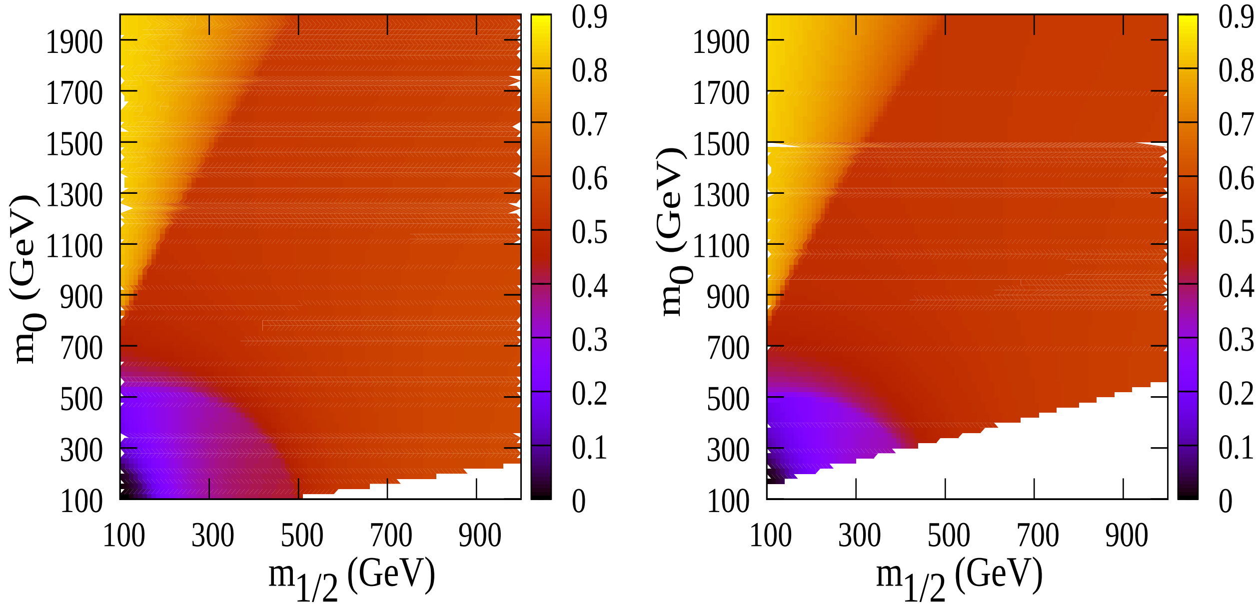

Figure 1: Branching fraction of $\tilde{t}_1 \to t\tilde{\chi}_i/\tilde{g}$ for $\tan\beta$=10 (left) and $\tan\beta$=50 (right) in $m_0 - m_{1/2}$ plane for $A_0 = 0$, and μ >0.

branching fractions to top quark from squark and gluino including third generation. We use SUSY-HIT [23] for the calculation of decay branching fractions in our analysis.

$\tilde{t}_1$, $\tilde{t}_2$ to top quark: We have already mentioned the possible decay modes of $\tilde{t}_1$ and $\tilde{t}_2$ squarks. We expect that the top quark contribution from $\tilde{t}_1$ will be more than $\tilde{t}_2$, because of higher mass value of later. In most of the cases $\tilde{t}_1$ is much lighter than $\tilde{t}_2$ and thus $\tilde{t}_1$ pair production cross section is significant. In order to understand the relevant branching of lightest stop squark to top quark, we scan over m_0-$m_{1/2}$ plane of the cMSSM parameter space for $\tan\beta$ =10 and 50, A_0 =0 and $\mu > 0$. We vary m_0 from 100 to 2000 GeV and $m_{1/2}$ from 100 to 1000 GeV. In Figure 1, we show the $\tilde{t}_1$ to top branching ratio in the m_0 - $m_{1/2}$ plane. Here we have included $\tilde{t}_1 \to t\tilde{\chi}_i^0$ and $\tilde{t}_1 \to t\tilde{g}$ branching fractions. The white region is excluded because $\tilde{\tau}_1$ is the LSP in that region. We have seen that for small m_0 and $m_{1/2}$, $\tilde{t}_1$ to top quark branching is small ($\sim$ 0.2 to 0.3) for both values of $\tan\beta$. In this region, $\tilde{t}_1$ is light and $\tilde{t}_1 \to t\tilde{\chi}_i^0$ is phase space suppressed and $\tilde{t}_1 \to b\tilde{\chi}_i^{\pm}$ is dominant. The another reason for it is that, in cMSSM, $\tilde{\chi}_1^0$ is often bino like and $\tilde{\chi}_1^{\pm}$ is wino like and bino-squark-quark coupling is small compared to wino-quark-squark coupling. For large value of m_0 and small $m_{1/2}$, $\tilde{t}_1$ is heavier than gluino and $\tilde{t}_1 \to t\tilde{g}$ is dominant due to the strong coupling (see yellow region of Figure 1). But in this case, stop squarks are very heavy and production cross section is negligibly small. For considerably large value of stop mass, $m_{\tilde{t}_1}$ is larger than $m_{\tilde{\chi}_2^0} + m_t$. Since $\tilde{\chi}_2^0$ is wino like in most of the cases in cMSSM model, $\tilde{t}_1 \to \tilde{\chi}_2^0\, t$ is significant (see red region of Figure 1). In the similar way, $\tilde{t}_2$ squark can also produce top quarks, but, such effects are in general negligible due to small cross section.

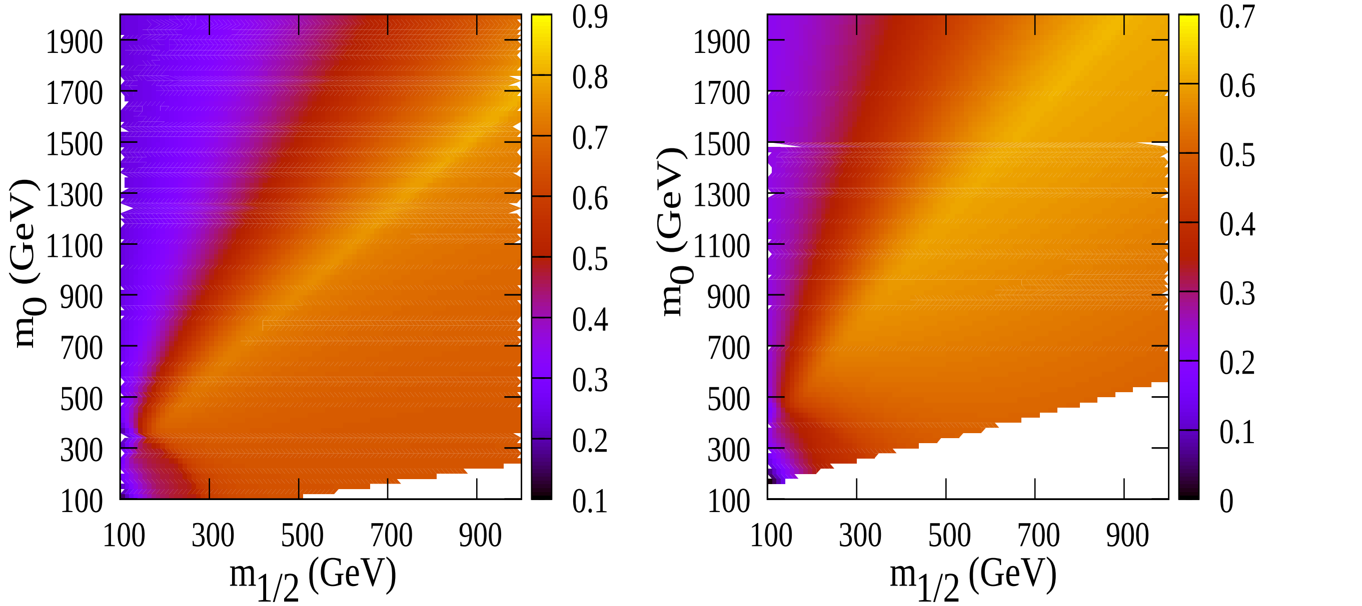

Figure 2: Branching fraction of $\tilde{b}_1 \to t\tilde{\chi}_i^-$ for $\tan\beta$=10 (left) and $\tan\beta$=50 (right) in $m_0 - m_{1/2}$ plane for $A_0 = 0$, and μ >0.

$\tilde{b}_1$, $\tilde{b}_2$ to top quark: In Figure 2, we show the branching of $\tilde{b}_1 \to t\tilde{\chi}^{\pm}_{1,2}$ in the m_0 - $m_{1/2}$ plane for $\tan\beta$ =10 and 50. We can see from the figure that, where $\tilde{t}_1 \to t\tilde{\chi}_i$ branching fraction is large, the branching $\tilde{b}_1 \to t\tilde{\chi}^{\pm}_1$ is small. This behaviour remains the same going from $\tan\beta$ = 10 to 50, though for the later case it shrinks a bit. For large m_0 and small $m_{1/2}$, higgsino component in the chargino is enhanced because in this region μ becomes small compared to bino (M_1) and wino (M_2) soft mass parameters. Otherwise as mentioned earlier that $\tilde{\chi}^{\pm}_1$ is wino like in most of the cMSSM parameter space and for this reason $\tilde{b}_1 \to t\tilde{\chi}^{\pm}_1$ is favoured rather than $\tilde{b}_1 \to b\tilde{\chi}^0_1$. This complementary behaviour adds to an extra motivation for the search of boosted top quarks in the SUSY cascade in which $\tilde{b}_1$ is present. In general, sbottom squarks are heavier than stop squarks and thus, the contributions to top quark production may be small. Similarly, $\tilde{t}_2$, $\tilde{b}_2$ also contribute to the top quark final state.

$\tilde{g}$ contribution to top quark: If the gluino mass is above the third generation scalar quark mass, gluino decays through $\tilde{g} \to q\tilde{q}^*$. The corresponding branching fractions to different flavour modes depend on the associated mass values of the quarks and squarks. Otherwise if gluino is lighter than squarks, it can still decay to top quark via three-body decay [24]. Figure 3 describes the gluino to top branching fraction via two-body and three-body decays in cMSSM scenario for $\tan\beta$=10 and 50. There are fair amount of regions where Br($\tilde{g} \to t\tilde{t}_1^*$) can be very high, whereas, Br($\tilde{g} \to b\tilde{b}_1^*$) in such regions is very low (see Figure 4). There is another interesting region in Figure 4 (see conical region) where $\tilde{g}$ almost decays to $b\tilde{b}_1^*$. This is because, in this region, both stop and sbottom squarks are lighter than gluino, but, $m_{\tilde{g}} - m_{\tilde{t}_1}$ is less than SM top quark mass. Here the only allowed two body decay mode of gluino is $\tilde{b}_1 b$. The size of such region increases for

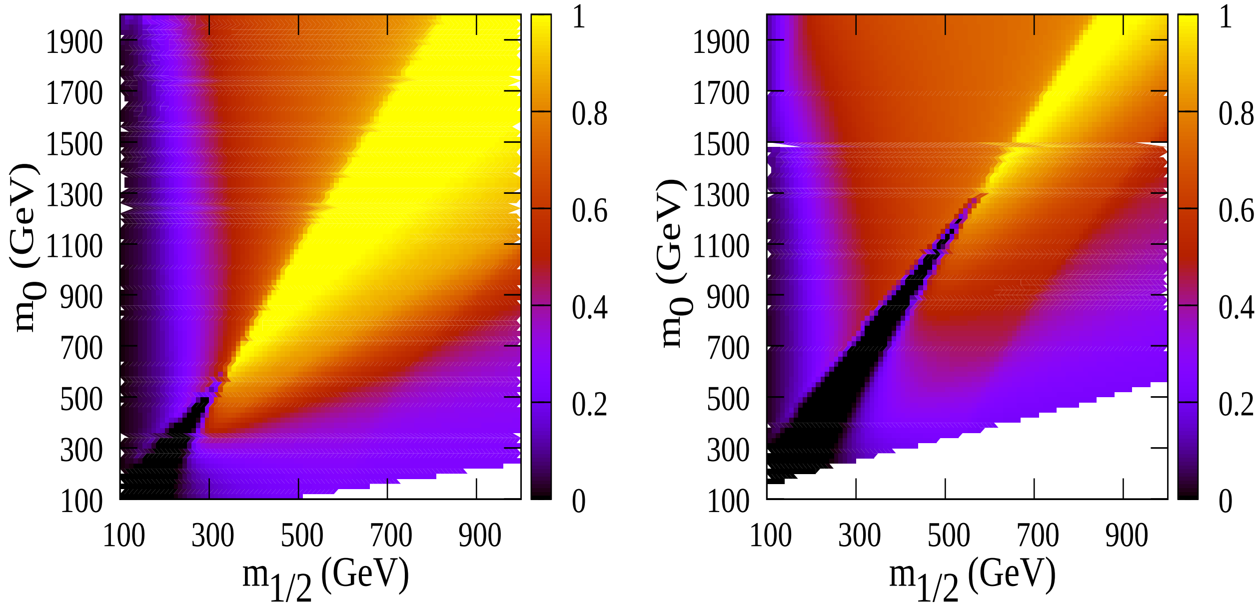

Figure 3: Branching fraction of $\tilde{g}$ to top quark via two body and three body channels for $\tan\beta$=10 (left) and $\tan\beta$=50 (right) in the $m_0 - m_{1/2}$ plane for $A_0 = 0$ and $\mu > 0$.

large value of $\tan\beta$ [25].

If the gluino mass is lower than the stop and sbottom masses, the gluino decays through three body channel to $q\bar{q}\tilde{\chi}_i^0$ or $q\bar{q}^{'}\tilde{\chi}_i^{\pm}$. The $\tilde{t}_1$ or $\tilde{b}_1$ squarks are generally lighter than other squarks and these contribute to the mode $t\bar{t}\tilde{\chi}_i^0$ and $t\bar{b}\tilde{\chi}_i^{\pm}$. A region of this kind is possible for higher values of m_0 relative to $m_{1/2}$. In the left black region gluino three body decay to top quark is kinematically disallowed. Gluino three body decay to top quarks may play a major role in the discovery of focus point region of cMSSM, in which only gauginos are light and squarks can be very heavy [26].

$\tilde{q}$ **contribution to top quark:** If squarks are heavier than gluino, these can decay to gluino and eventually, gluino decays through three body channels discussed before. In this case, the gluino three body final states may contain top quarks. The other possibility is that, the gluino can be lighter than first two generations, but, it may be heavier than the third generation squarks. In that case, the decay chain like $\tilde{q} \to \tilde{g}q \to \tilde{t}_1 tq$ is possible.

III Benchmark Points

In the previous section, we have discussed the possible sources of top quarks in the SUSY cascade in the context of cMSSM. Now, we explore such possibilities by choosing some benchmark points in the $m_0 - m_{1/2}$ plane. The cMSSM model is constrained by different low energy observables as well as direct searches like LEP, Tevatron and LHC. We have considered such bounds while defining the benchmark points. We scan over m_0 -$m_{1/2}$ plane for two fixed values of $\tan\beta$: 10 and 50 with sign of $\mu > 0$ and A_0 =0. We

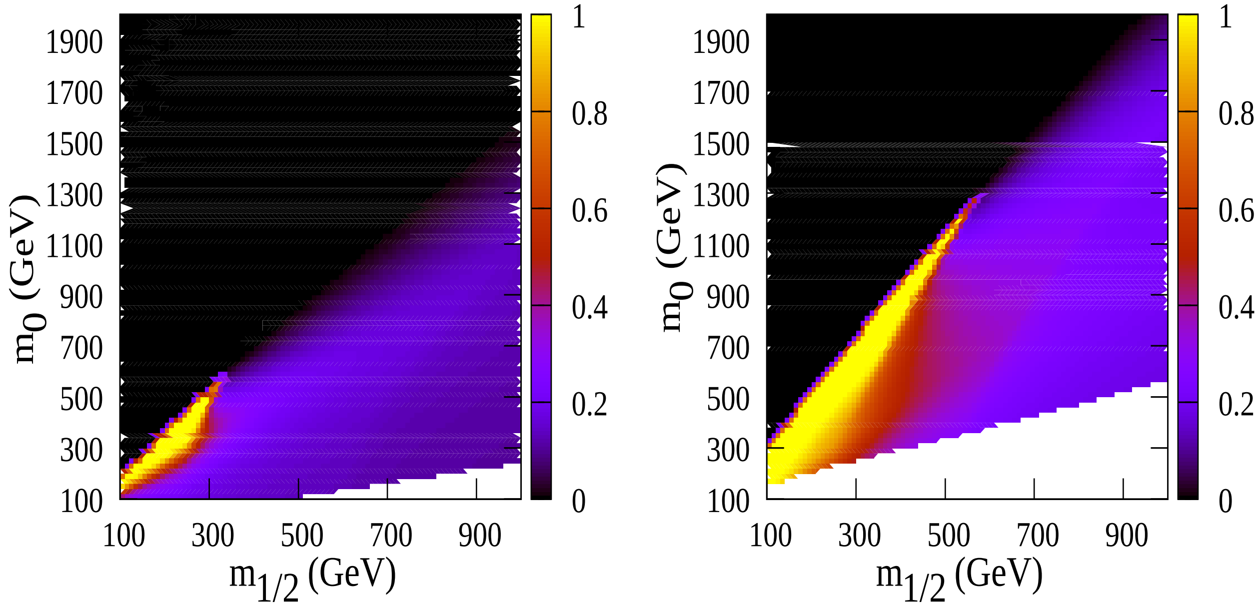

Figure 4: Branching fraction of $\tilde{g} \to (\bar{b}\tilde{b}_1 + c.c)$ for $\tan\beta$=10 (left) and $\tan\beta$=50 (right) in the $m_0 - m_{1/2}$ plane for $A_0 = 0$ and $\mu > 0$.

take low energy bounds such as $b \to s\gamma$, $B_s \to \mu^+\mu^-$ and anomalous magnetic moment of muon. We closely follow the reference [27] in our calculation and we use SuperIso [28] software for this. We also consider recent bounds from 7 TeV LHC data with an integrated luminosity 35 pb^{-1} on cMSSM parameter space in the inclusive multi-jet plus missing energy channel. The current experimental lower bound on SM Higgs mass from LEP is 114.4 GeV and this bound is applicable to supersymmetric lightest Higgs, except for some specific regions in the SUSY parameter space. However, there is an estimated theoretical uncertainty of about 3 GeV on the Higgs mass due to higher order effects [29]. For this reason we draw separate contours for M_h =111 GeV and 114 GeV. In Figure 5 we have shown corresponding bounds discussed above in the m_0 -$m_{1/2}$ for $\tan\beta$ 10 and 50. The region bounded by red box is favoured by magnetic moment of muon. The shaded region is excluded because in this region $\tilde{\tau}_1$ is the LSP. We have not shown $B_s \to \mu^+\mu^-$ bound for $\tan\beta$=10, because it is much weaker than other bounds considered here.

We shall tag the top quarks using jet substructure algorithm. This technique can only be applicable for highly boosted top quarks. The boost of top quarks in the SUSY cascade will depend on the relative separation between decaying particle, e.g., gluino, stop or sbottom squark and the decay products like neutralino and chargino. The mass difference between squark-gluino sector and electroweak gaugino sector is generally large in the cMSSM model. To cover different possibilities, we have chosen three specific benchmark points for further analysis.

We choose the following low mass point, which is just above the current LHC bound

$$m_0 = 600\,\text{GeV} \qquad \text{m}_{1/2} = 350\,\text{GeV} \qquad \text{A}_0 = 0\,\text{GeV} \quad \mu > 0 \quad \text{and} \quad \tan\beta = 10.$$

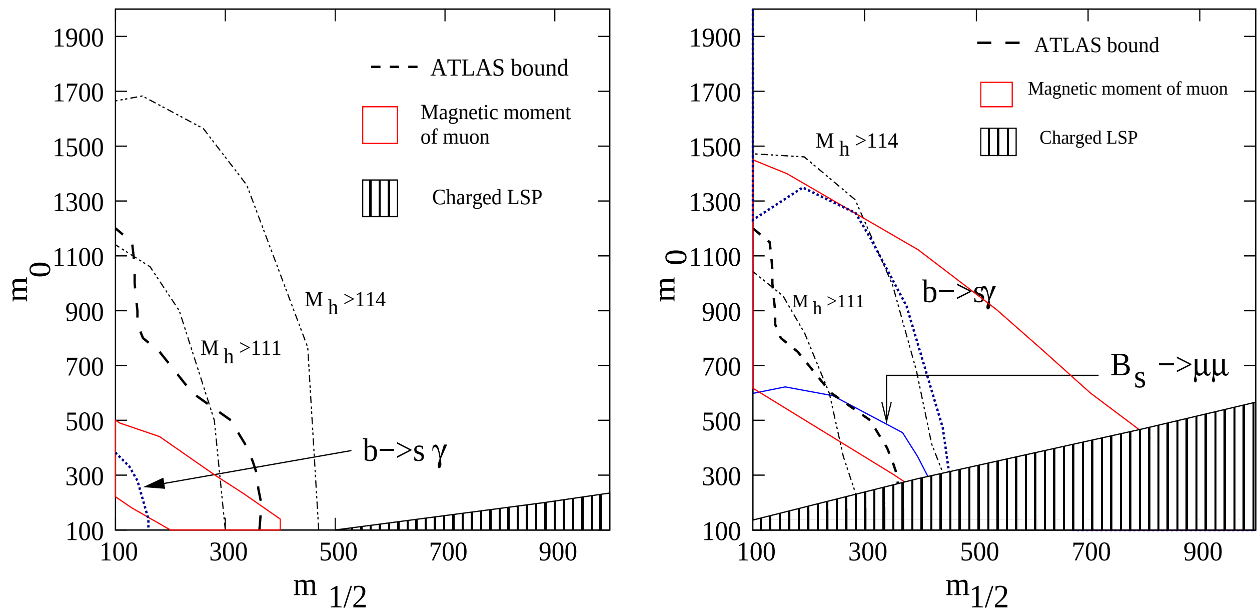

Figure 5: Low energy and collider bounds in m_0-$m_{1/2}$ plane for $\tan\beta$=10, and $\tan\beta$=50.

For this point the masses of $\tilde{t}_1$, $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$ are 675 GeV, 267 GeV and 142 GeV respectively [2]. This ensures enough boost to the top, specially the one coming from $\tilde{t}_1 \to t\tilde{\chi}^0_1$. In this point Br($\tilde{t}_1 \to t\tilde{\chi}^0_1$)=18% and Br($\tilde{t}_1 \to t\tilde{\chi}^0_2$)=10%. This implies that about 28% of the stop squark will decay to a top quark. The stop squark mass is in the higher region and the pair production cross section is 93 fb which is much smaller than the total SUSY cross section of this point (about 5pb). We also take $\tilde{b}_1\tilde{b}_1^*$ contribution for the analysis, which is about 22 fb, as the parameter point results in slightly heavier sbottom ($m_{\tilde{b}_1} = 846$ GeV). The branching fraction of $\tilde{b}_1$ to the top and chargino mode is $\sim 70\%$ (from Figure 2a). The chargino in this case can decay to a $W^\pm$ and a neutralino and the former can be a source of additional jets or leptons.

Interestingly, there is another mode which could also give rise to top quark. This is $\tilde{b}_1 \to \tilde{t}_1 W^-$, where the $\tilde{b}_1$ first decay to $\tilde{t}_1$ and the $\tilde{t}_1$ decays as usual. As Br($\tilde{b}_1 \to \tilde{t}_1 W^-$) $\sim 8\%$, contribution to top, neutralino and $W^\pm$ final state is really small.

Gluino pair production cross section for this point is ~ 709 fb for $m_{\tilde{g}} = 859$ GeV, which adds to the third generation squarks through its decay, with an extra possible boosted top quark. The dominant decay mode of gluino is $\tilde{g} \to t\tilde{t}_1^*$ with Br($\tilde{g} \to t\tilde{t}_1^*$) $\sim 95\%$ (see Figure 3). The squark gluino production is about 2.3 pb and it has the major contribution to the top final state through the gluino decay to top quark.

Next, we consider the contribution of gluino decay to sbottom squark. For this purpose, we choose the following parameter point from Figure 4 as benchmark point 2

[2]For our analysis the top is taken to be 173 GeV.

$$m_0 = 900\,\text{GeV} \qquad \text{m}_{1/2} = 400\,\text{GeV} \qquad \text{A}_0 = 0\,\text{GeV} \quad \mu > 0 \quad \text{and} \quad \tan\beta = 50$$

where Br($\tilde{g} \to b\tilde{b}_1^* + c.c$) = 100%. The lightest sbottom squark produced from gluino further decays to top quark and chargino with branching fraction $\sim$ 59%. This choice leads us with $m_{\tilde{g}} = 985$ GeV and $m_{\tilde{b}_1} = 961$ GeV. For this benchmark point, lightest stop squark mass is about 840 GeV which gives no room for gluino decays to top quark.

So far, we have chosen benchmark points which are consistent with low energy constraints and direct search bounds. Now, we consider benchmark point 3 which satisfies the dark matter relic density constraint as well as other bounds

$$m_0 = 540\,\text{GeV} \qquad \text{m}_{1/2} = 490\,\text{GeV} \qquad \text{A}_0 = 0\,\text{GeV} \qquad \mu > 0 \quad \text{and} \quad \tan\beta = 50 \ .$$

The mass of the lightest neutralino is 203 GeV and heavier Higgs masses are about 480 GeV. The decay widths of heavy Higgs bosons are large and these are about 15-20 GeV. Neutralinos can annihilate through heavy Higgs mediating s-channel processes and satisfy current bound of relic density. We compute the relic density of this point by using micrOMEGAs [30] and we find that Ωh^2 is 0.107 for top quark mass 173 GeV which is consistent with WMAP bound $\Omega h^2 = 0.112 \pm 0.007$ at 95% CL [31].

In this point left handed first two generation squarks are slightly heavier than gluino but right handed squarks are lighter. The gluino mass is about 1146 GeV. The branching fractions of gluino to stop and sbottom squarks are 36% and 21% respectively. First two generation left handed squarks dominantly decay to electroweak gauginos, so, their branching to gluino is very small (about $2 - 3\%$).

IV Analysis

The identification of boosted top quarks has been described in the literature. Here we briefly describe our algorithm to identify boosted top quarks in the SUSY cascade. We have used PYTHIA[33] event generator for generating the events and hadronizations. We use FASTJET [34] package for jet formation instead of default subroutine PYCELL in PYTHIA. The mass spectrum and decay branching fractions have been generated by SUSY-HIT. Here we define set of cuts used in our analysis.

- We select events with at least 3 jets. The jets are formed by using Cambridge Aachen algorithm with a fixed R parameter to be equal to 1 [32]. One may vary this parameter to optimize the signal significance. The leading jet p_T must be greater than 300 GeV and other two sub leading jets should have p_T greater than 150 and 100 GeV respectively. Note that, p_T of the jets are greater than the quoted value used by CMS collaboration for SUSY search in inclusive multi-jet plus missing energy channels [7]. The absolute value of pseudorapidity of the leading jet must be less than 1.7.

- The missing p_T must be greater than 300 GeV.
- We put veto on events with isolated leptons with p_T greater than 10 GeV.
- We use variable R_1 and R_2 which are given by $R_1 = \sqrt{\delta\phi_2^2 + (\pi - \delta\phi_1)^2}$ and $R_2 = \sqrt{\delta\phi_1^2 + (\pi - \delta\phi_2)^2}$. Here $\delta\phi_1$ ($\delta\phi_2$) is the difference between azimuthal angle of missing transverse momentum and azimuthal angle of first (second) jet, i.e., $\delta\phi_{1,2} = |\phi_{\not p_T} - \phi_{J_{1,2}}|$. The R_1 and R_2 must be greater than 0.5 radian. Also $|\phi_{\not p_T} - \phi_J|$ must be greater than 0.3 radian. Also we take $|\phi_{\not p_T} - \phi_{J_2}|$ to be greater than 20°. These cuts are very useful to reject QCD backgrounds, where the source of missing energy is jet energy mis-measurements.
- The effective mass (M_T) of the event must be greater than 500 GeV. Here M_T is defined as the scalar sum of second, third and fourth (if present) jets and $\not p_T$.

After passing the above mentioned cuts we choose events for further analysis. We take the hardest jet and decluster it into two subjets, if the p_T of both subjets are greater than 5% of the parent jet p_T and these are not too close, i.e. $|\delta\eta|+|\delta\phi| > 0.1$. If the declustering is possible, then we take the declustered objects and repeat the same procedure on those objects. This procedure is terminated if only one calorimeter cell is left. For our work we take a calorimeter cell of 0.1 in both η and ϕ. If we start with a top jet (for hadronic top decay), we will end up with three or four subjets. The jet mass of the top jet should lie in between 150 to 200 GeV. One combination of invariant mass of the two subjets among these 3 or 4 jets must be around W boson mass. Also we demand the cosine of helicity angle to be greater than 0.7, where the helicity angle is defined as the angle between the top quark direction and one of the decay product of W, in the W rest frame. It is also possible to tag one subjet as a b jet. However we do not apply b tagging condition in our analysis. If the p_T of the other sub leading jets are greater than 300 GeV, we apply the same algorithm on it and if it satisfies all the criteria, we declare that jet as a top jet.

In Figure 6 we show the normalized p_T distribution of partonic top quarks present in the SUSY cascade for three chosen benchmark points. From this plot we have seen that a large fraction of top quark events have momenta, greater than 300 GeV. In the right hand side of Figure 6 we show the jet mass distribution of events which satisfy all but the jet mass cut of the top quark. We observe peaks around top mass in the jet mass distributions which verify correctness of the top tagging technique used in the analysis. Depending on the parameter space, the peak could be broad as it suffers from SUSY contamination in cascade decays. QCD, $W/Z+$ jets, di-boson + jets backgrounds are not taken in the analysis, though the most significant background, $t\bar{t}$ has been analysed. CMS quotes [7] total backgrounds to be of the order of 250 fb for similar type of analysis (with less harder cuts used in our analysis) and QCD contribution to it is around 100 fb. Here, we have taken much harder cuts on jet p_T and missing transverse energy compared to CMS cuts[3] and this would further reduce the background. One should note that we have used different jet formation algorithm with larger jet cone size. Therefore, the size of the SM backgrounds can be different from the CMS analysis. However, the probability of a QCD jet, mistagged as a top jet is very small and it is $\sim 1\%$ for jet p_T 300 GeV [12]. Further, it is possible to add b-tagging criterion that will also help to reduce QCD and

[3]We take leading jet p_T to be greater than 300 GeV, where they have used 180 GeV cut on it. For comparison see reference [7].

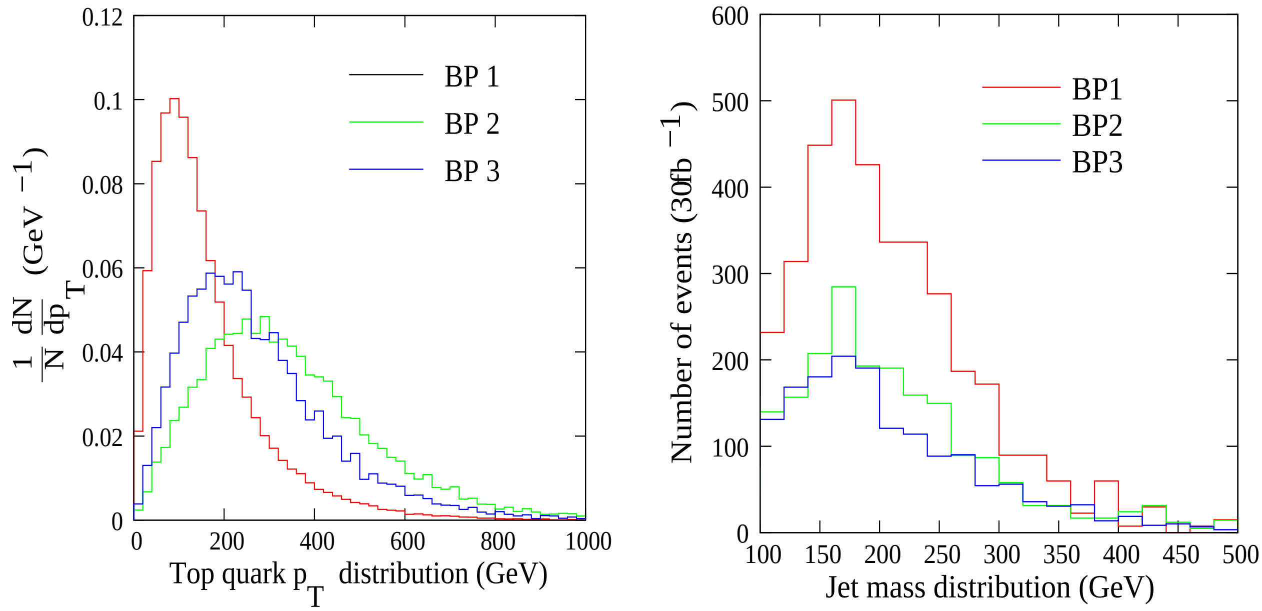

Figure 6: p_T distribution of the top quark (left) and the jet mass distribution after selection cuts (right).

W backgrounds.

In Table 1, we show the individual contributions coming from $\tilde{t}_1\tilde{t}_1^*$, $\tilde{b}_1\tilde{b}_1^*$ and $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{g}$ productions in the top signal for the three benchmark points. We do not show the contributions from $\tilde{t}_2$ and $\tilde{b}_2$ separately, but these are added to the total contribution. We may recall that the first two generation squarks are heavier than gluino in our benchmark points. These also contribute to the top quark final state through gluino decay. The background coming from top quark pair production is not large and it is about 4-5 fb. We present our result for integrated luminosity of 30 fb^{-1}. The numbers indicate that even if all backgrounds are considered, the signal would be sufficient enough to be observed with 30 fb^{-1} of integrated luminosity at the LHC with $\sqrt{s} = 14$ TeV. The Table also shows that the gluino contribution is much larger than other contributions like stop and sbottom and it is true for all benchmark points. As gluino contribution is too large, it may be difficult to determine the hierarchy among the third generation squarks and gluino. A detailed study should be worked out to see the prospect of such analysis.

V Conclusion

In this paper we have studied the production of boosted top quarks in the SUSY cascade at the LHC. In particular, we have taken a specific SUSY breaking mechanism, cMSSM, although the outcome of the study is applicable to any general SUSY breaking scenarios or any other BSM scenarios. We systematically discussed different possibilities of top quark final state in the SUSY cascade. Top quark identification is difficult in cascade decays due to the combinatorial backgrounds. Depending on the parameter space, SUSY cascade

No.	Benchmark points	$\tilde{t}_1\tilde{t}_1^*$ (30 fb^{-1})	$\tilde{b}_1\tilde{b}_1$ (30 fb^{-1})	$\tilde{g}\tilde{g}$ (30 fb^{-1})	$\tilde{g}\tilde{q}$ (30 fb^{-1})	Total (30 fb^{-1})
1	BP1	15	6	142	618	992
2	BP2	8	3	110	336	591
3	BP3	7	5	42	282	463

Table 1: Event rates after top tagging for the benchmark points with an integrated luminosity of 30 fb^{-1}. The $t\bar{t}$ contribution is 132 events assuming same integrated luminosity.

may have top quarks with high p_T. We take advantage of this high p_T behaviour of top quark for its identification by using jet substructure algorithm. This helps to enhance the signal significance for the top final state. It has been vindicated in our study that for wide range of SUSY parameter space, this technique is fairly applicable. This study will help to understand the third generation squarks and gluino masses and decay modes. This could also be useful to probe the regions in SUSY parameter space, where squarks are inaccessible at the LHC but gluino is in the lighter side. However, we have not done detailed background analysis which would be crucial. Also, supersymmetric backgrounds may affect the signal significance and it is very much parameter space dependent. One should invoke a more sophisticated analysis to overcome such backgrounds which is beyond the scope of our study.

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