Search for the lightest scalar top quark in R-parity violating decays at the LHC

Debajyoti Choudhury[1], Madhumita Datta[2] and Manas Maity[2]

[1] Department of Physics and Astrophysics, University of Delhi, Delhi 110 007, India
[2] Department of Physics, Visva-Bharati, Santiniketan 731 235, India

Abstract

The scalar partner of the top quark (the stop) is relatively light in many models of supersymmetry breaking. We study the production of stops at the Large Hadron Collider (LHC) and their subsequent decays through baryon-number violating couplings such that the final state contains no leptons. A detailed analysis performed using detector level observables demonstrate that stop masses upto $\sim 600\,\text{GeV}$ may be explored at the LHC depending on the branching ratios for such decays and the integrated luminosity available. Extended to other analogous scenarios, the analysis will, generically, probe even larger masses.

The status of global symmetries in particle physics is a much debated one. Of particular relevance are fortuitous symmetries such as baryon number (B) and lepton number (L). Apparently a consequence of the particular choice of the field assignments within the Standard Model (SM), each is left intact to all orders within perturbation theory, only for a combination to be broken by nonperturbative effects. While guaranteeing the stability of the proton, this leaves no room for the observed baryon asymmetry in the universe. As is well known, the latter needs, apart from enhanced levels of CP violation and a phase transition (or, at least, a non-equilibriated state of the universe), additional sources of B–violation (or L–violation for leptogenesis).

This has led to a sustained study of models of physics going beyond the SM admitting B-violation. Particularly well-motivated scenarios pertain to grand unification and supersymmetry (SUSY), whether considered separately or in conjunction. Indeed, low energy supersymmetry is considered to be, perhaps, the most attractive extension of the SM. The most general superpotential of the minimal supersymmetric standard model (MSSM) contains, apart from the generalizations of the Yukawa terms and the Higgs potential of the SM, additional terms violating B and L. Since, this would, nominally, lead to rapid proton decay, such terms need to be eliminated, and a global symmetry was introduced [1, 2] for this very purpose. Subsequently, a discrete symmetry, R-parity, was shown to prohibit all dimension-four B– or L–violating terms [3]. However, as has long been realised, proton decay can be eliminated even when R-parity is broken provided at least one of B and L are conserved. This is a particularly fascinating situation, for it admits a whole host of phenomenological consequences absent in the R-parity conserving MSSM. Indeed, the collider signatures of supersymmetric particle production now undergoes a sea-change, for the lightest of the SM–superpartners is no longer stable. And while it has been argued that the introduction of R-parity violation would deprive the MSSM of one of its most atractive features, namely a natural Dark Matter candidate, note that the gravitino could yet be stable on cosmological scales.

In this paper, we shall concentrate on the case where B is broken, but L is not. Such a situation is well motivated in a class of supersymmetric grand unified theories

(GUTs) [4]. This, then, allows for terms in the superpotential of the form

$$W_{\not R} \ \ni \ \lambda''_{ijk} \bar{U}^i_R \bar{D}^j_R \bar{D}^k_R \ , \tag{1}$$

where $\bar{U}^i_R$ and $\bar{D}^j_R$ denote the right-handed up-quark and down-quark superfields respectively and the couplings λ''_{ijk} are antisymmetric under the exchange of the last two indices. The corresponding Lagrangian can then be written in terms of the component fields as

$$\mathcal{L}_{\not R} = \lambda''_{ijk} \left(u^c_i d^c_j \tilde{d}^*_k + u^c_i \tilde{d}^*_j d^c_k + \tilde{u}^*_i d^c_j d^c_k \right) + \text{h.c.}, \tag{2}$$

thus allowing a squark to decay into a pair of anti-quarks[1] violating B and R.

At a hadron collider, the couplings of eqn.(2) would lead to resonant production of a scalar, with the rates being potentially large if at least one of the quark fields belongs to the first generation. This could, in principle, lead to spectacular signatures both for dijets (invariant mass spectrum) or more complicated final states [5, 6]. However, many of the λ'' couplings are severely constrained by a variety of low-energy observables [7–9], especially for operators involving at least two fields of the first generation[2]. Given these two contrasting pulls, we restrict ourselves to the (λ''–independent) pure supersymmetric-QCD processes as far as squark production is concerned, and consider a role for λ'' only in their decays.

The mechanism of SUSY breaking is open to speculation. However, most such mechanisms postulate that the sfermion masses be unified at some high scale, the extent of unification being model-dependent. This has the additional benefit of suppressing potentially large flavour changing neutral currents. In coming down to the electroweak scale, though, the masses would suffer substantial renormalization group evoulution. Furthermore, the large Yukawa coupling of the top quark plays a role not only in this evolution, but also in engendering a mixing between the two super-partners of the top quark (the stops). Together, these effects very often result in the lighter stop being rendered the lightest of the strongly interacting superpartners.

Thus, it is phenomenologically interesting to search for top squarks in the hadron colliders in the following scenario: (almost model independent) pair production of $\widetilde{t}_1\widetilde{t}_1^*$ via strong interaction and decays thereafter via R-parity violating process controlled by the parameter λ'' [10].

It may be noted that there are scenarios beyond the SM other than SUSY in which a strongly interacting elementary particle may decay into a pair of quarks. GUTs, for example, abound in these [11]. Such "diquarks", of which squarks in the R-parity violating theory constitute but one example, can occur in various forms. They could be Lorentz scalars or vectors, $SU(2)_L$ singlets, doublets or triplets and, under, $SU(3)_c$ transform either as a $\bar{\mathbf{3}}$ or a $\mathbf{6}$. While only some of the above combinations could appear in a trilinear coupling with two quark fields, others can participate if a quadrilinear term involving, say the Higgs, is considered [12]. In the latter case, although the effective diquark-quark-quark vertex would exist only after the electrweak symmetry breaks, there is no *a priori* reason to relate the coupling to the quark mass terms. Diquarks, in particular, have

[1] Unless otherwise mentioned, for every process, the charge conjugated process is also implied.

[2] Some of the couplings involving the third generation can be quite large though.

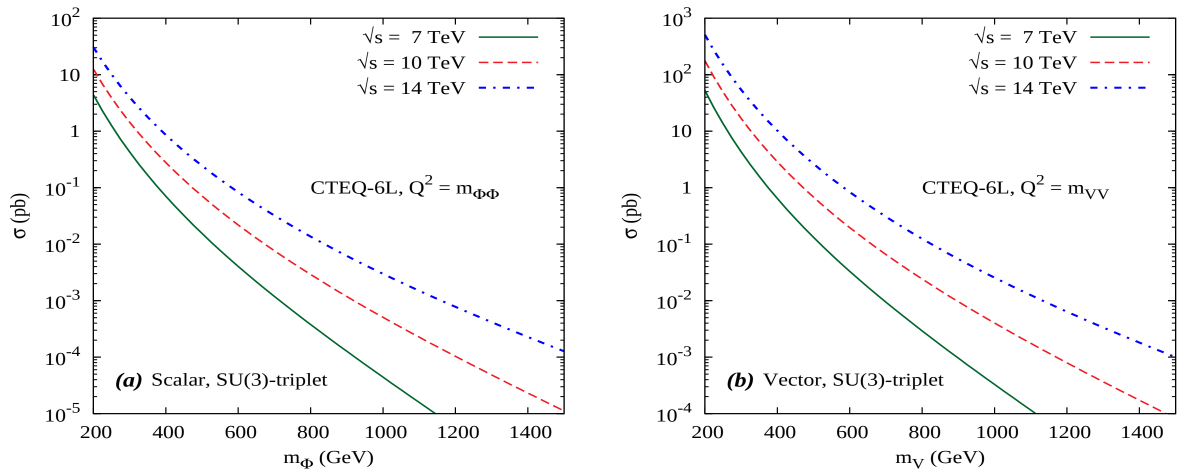

Figure 1: *Production cross-sections for scalar (left) and vector (right) particles at the LHC for different collision energies.*

been shown [13] to be leading contenders for explaining the anomalously large forward-backward asymmetry in top production as reported by CDF [14].

Yet another class of strongly interacting particles may decay into a pair of jets[3], namely color-octets like axigluons [15], colorons [16] or Kaluza-Klein excitations of gluons [17] or even color-triplets like excited quarks [18]. Such objects, though, can be formed as resonances, often with unsuppressed couplings, rendering the search for them to be much simpler [19, 20]. We will not consider such possibilities and would limit ourselves to the more difficult task of diquarks (squarks) with a small coupling to a pair of quarks.

As is well-known, considerations of the ρ-parameter stipulates that the mass-splitting between members of a $SU(2)_L$ must be small. Thus, all other quantum numbers being equal, the $SU(2)_L$ singlet diquark would have the smallest QCD production cross section. Similarly, for all coloured $SU(2)_L$ singlet scalars, the one in the $SU(3)_c$ triplet representation would have the lowest production cross-section.

As for vector diquarks, various inequivalent choices for the kinetic term (and, hence, for the coupling with the gluon) are possible (see Ref. [21]). Restricting ourselves to the case of minimal coupling[4], we find that the resultant cross-sections are significantly larger than is the case for the corresponding scalar (see Fig.1). Thus, the choice of the squark as our template diquark is the most conservative one.

Of course, the signal size at a collider detector depends not only on the total cross section, but on the kinematic distributions as well. It is worthwhile to note—see Fig.2(a, b)—that the scalar and vector diquark have very similar angular distributions. In other words, the rapidity-dependence of the efficiencies would be very similar for the two cases. On

[3] Distinguishing decays into a quark-antiquark pair or into a quark-gluon pair from a decay into a quark-pair (or an antiquark pair) is possible only if both the daughters carry a heavy flavour.

[4] Note that while this choice results in a smaller production cross section than is the case for a Yang-Mills type coupling, it is possible to get marginally smaller cross sections by tuning the anomalous dipole and quadrupole moments.

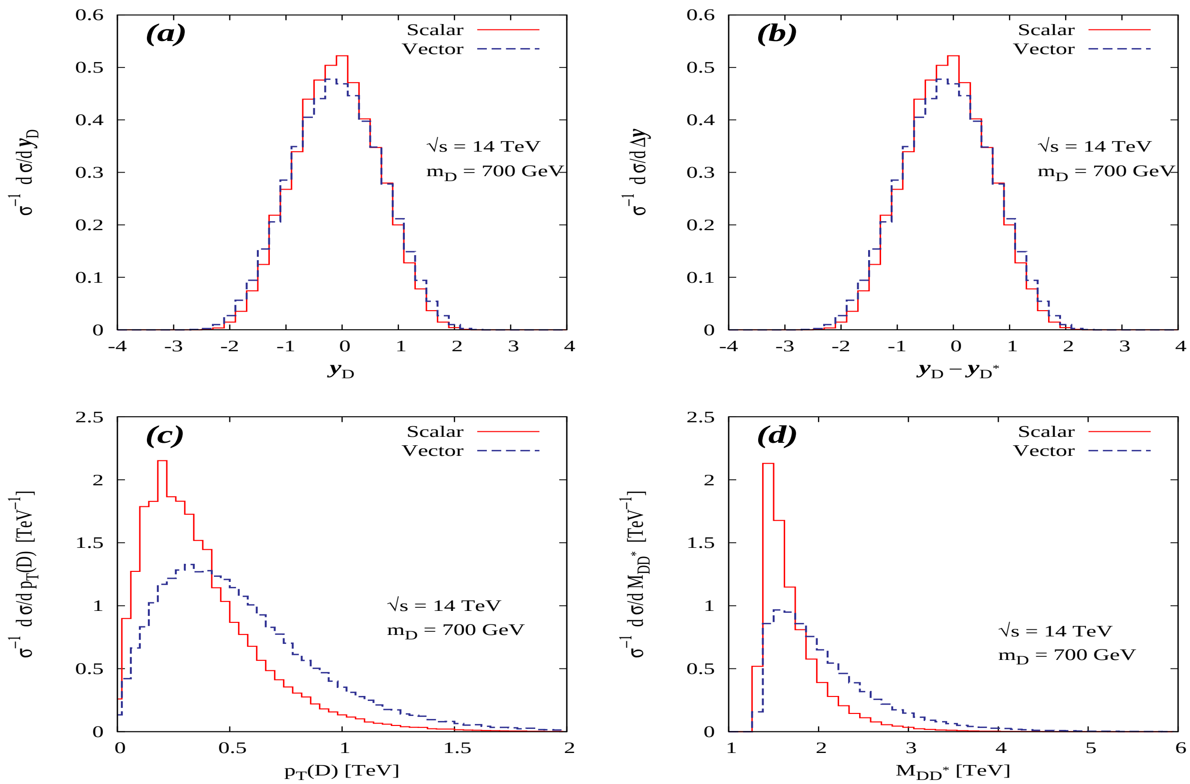

Figure 2: *Normalized kinematic distributions for QCD-driven pair-production of a diquark pair.* (*a*) *the rapidity;* (*b*) *the rapidity gap;* (*c*) *the transverse momentum; and* (*d*) *the invariant mass.*

the other hand, the spectrum is decidedly harder—see Fig.2(c, d)—for the vector case, a reflection of the momentum dependence of its coupling to the gluon. Since we would need to impose strong p_T-cuts, the overall efficiency would be better for the vector case. Thus, on this count too, the choice of the squark as a template is a conservative one.

Several searches—both in *R-parity* conserving and violating scenarios—have been made at LEP [22] and Tevatron [23] without success. These searches claim to exclude, depending on the relevant SUSY parameters, $m_{\tilde{t}_1}$ upto $\sim 200\,$GeV assuming 100% branching ratio for the respective decays. Such bounds, of course, weaken in the presence of other decay channels [24].

The high statistics data expected from the Large Hadron Collider (LHC) at $\sqrt{s} =$ 14 TeV provides an attractive option of looking for the $\widetilde{t}_1$ in its R-parity violating decay mode(s). At the partonic level, our signal events would read

$$pp \to \widetilde{t}_1 \widetilde{t}_1^{\,*} \to (\bar{b}\bar{q})(bq) \ .$$

We use Pythia6 [25] to generate both signal and background ($t\bar{t}$, W^+W^-, ZZ) events. Pure QCD background events ($b\bar{b}$+2-jets) have been generated at the parton level with Alpgen2 [26] and interfaced with Pythia.

In Pythia, partons in an event go through the quarks from hard processes undergo parton shower development and hadronization followed by decays. Pythia also emulates the initial (ISR) and final state radiation (FSR) from the partons for all the event samples. Tools provided by Pythia have been used to define a toy calorimeter with the broad features of the LHC detectors: pseudo-rapidity coverage ($-4.5 \leq \eta \leq 4.5$) and segmentation ($\Delta\eta \times \Delta\phi = 0.1 \times 0.087$) [27]. To simulate the finite energy resolution, the jet momenta are smeared with a Gaussian function with a energy-dependent width δE given by

$$\frac{\delta E}{E} = \frac{1}{\sqrt{E\,(\,\mathrm{GeV})}} \oplus 0.05$$

with the two contributions being added in quadrature. The final state particles are passed through this toy calorimeter for forming jets. We also look for leptons ($\ell = e, \mu$) but within the more restricted tracking coverage of the LHC detectors. Since leptons are measured quite accurately, we use the generated values of their energy, momentum and direction. Events are reconstructed in the following manner:

- Calorimeter cells with $E_T > 1$ GeV are used for jet reconstruction. The cone algorithm with, $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.7$, has been used requiring $E_T^{jet} \geq 30$ GeV.
- Leptons with $-2.4 \leq \eta \leq 2.4$ and $E_T \geq 5$ GeV are deemed identified.
- A jet originating from a b-quark (b-jet) is identified by the decay length of the B-hadron(s) within it. The efficiency for tagging b-jets is tuned to the expected value ($\sim 50\%$ for b-jets in $t\bar{t}$ events).

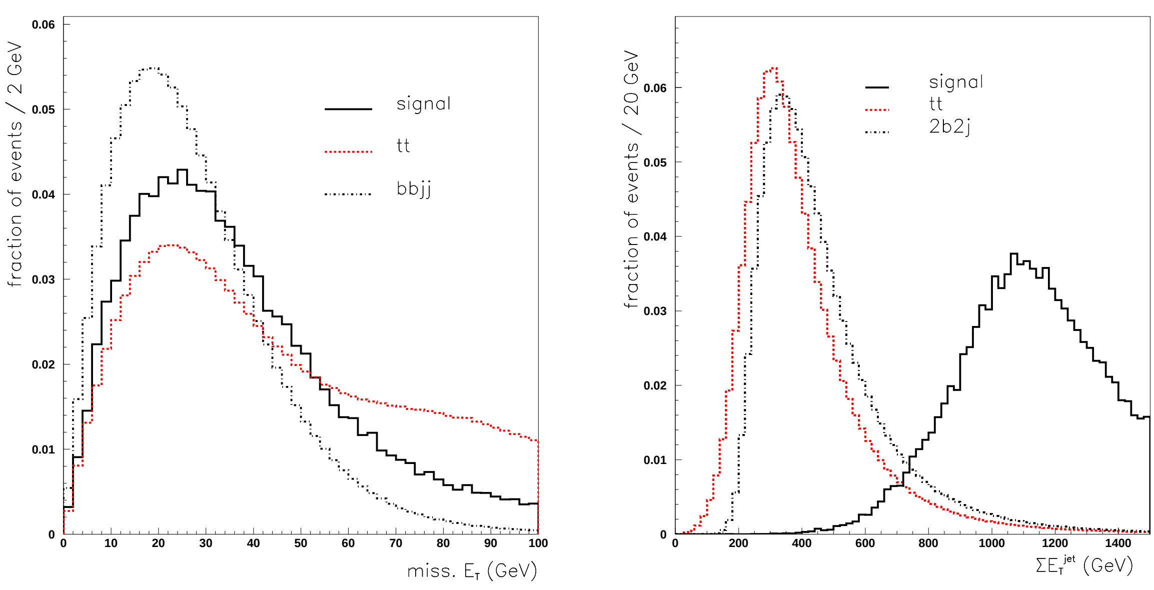

Figure 3: *Distribution of $\not{E}_T$ and $\sum E_T^{jet}$ for signal events ($m_{\tilde{t}_1} = 550$ GeV) and two major background sources before any selection has been applied.*

For the signal events, we expect four jets with high E_T and no lepton with a high p_T. We should not expect any $\not{E}_T$ except for that arising due to mis-measurement of the jets and neutrinos from secondary and tertiary decays of long lived particles. There may be additional objects (extra jets, $\not{E}_T$, leptons, etc) arising from underlying events (a serious concern at the high luminosity runs of the LHC) as well as due to ISR and FSR. But such objects are expected to fail hard cuts used in this analysis. At this juncture, we could have considered imposing an upper cut on $\not{E}_T$ to remove, say, the $t\bar{t}$ background. However,

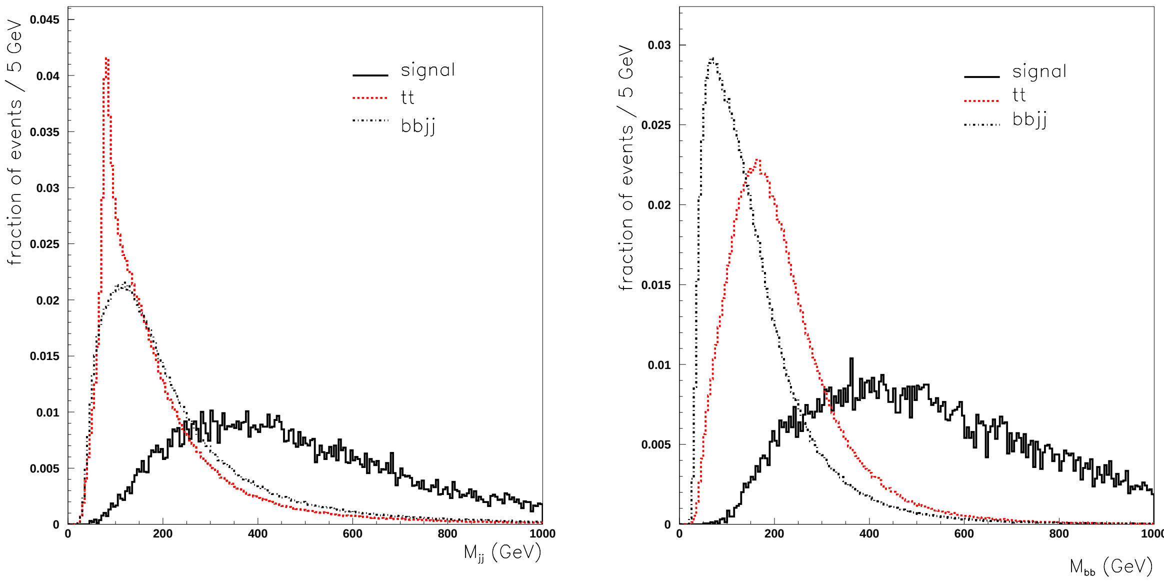

Figure 4: *Distribution of M_{jj} and M_{bb} for signal events ($m_{\tilde{t}_1} = 550$ GeV) and two major background sources after the cut on the number of ordinary and b-tagged jets has been applied.*

since the jets from the $\tilde{t}_1$ decays have a high E_T, even a small relative mis-measurement could result in a substantial $\not{E}_T$ leading to the rejection of a large fraction of the signal events (see Fig.3). Given this, and the relative unimportance of the $t\bar{t}$ background, we choose not to impose such a criterion.

Instead, we use the following criteria for selecting signal events and rejecting backgrounds.

1. There should be only four jets in the event ($N_{jet} = 4$) with $E_T^{jet} \geq E_{T\,\min}^{jet}$. Of these, two are tagged b-jets ($b_1,\ b_2$) while the other two ($j_1,\ j_2$) are ordinary jets, i.e., they do not satisfy b-tagging criteria. (**Sel 1**).
   The jets are ordered descending in E_T.

2. Events containing any isolated lepton with $p_T \geq 15$ GeV are rejected. (**Sel 2**)

3. We also require $m_{b_1 b_2}, m_{j_1 j_2} \notin \{70, 100\}$ GeV (see plots in Fig.4) to reject events with genuine W or Z (**Sel 3**). The plot for M_{jj} for $t\bar{t}$ events in Fig. 4 expectedly shows the W mass peak.

4. To eliminate the huge soft QCD background which may mimic signal with fake b-jet tagging, we require (see right plots in Fig. 3) $\sum E_T^{jet} \geq S_{\min}$. (**Sel 4**)

For each value of $m_{\tilde{t}_1}$, nine different combinations of **Sel 1** and **Sel 4**, *viz*, $E_{T\,\min}^{jet} = \{30, 50, 75\}$ GeV and $S_{\min} = \{400, 500, 600\}$ GeV along with **Sel 2** and **Sel 3**, were tried and the combination that gave the best signal visibility has been used for the final result. It may be noted that, in this analysis, we have used calorimetric observables which may be estimated fairly well both in magnitude and direction using parametric simulation.

The events are sought to be reconstructed by computing the invariant masses of a pair of jets, one being tagged a B-jet, and the other not so. Clearly, four such pairings

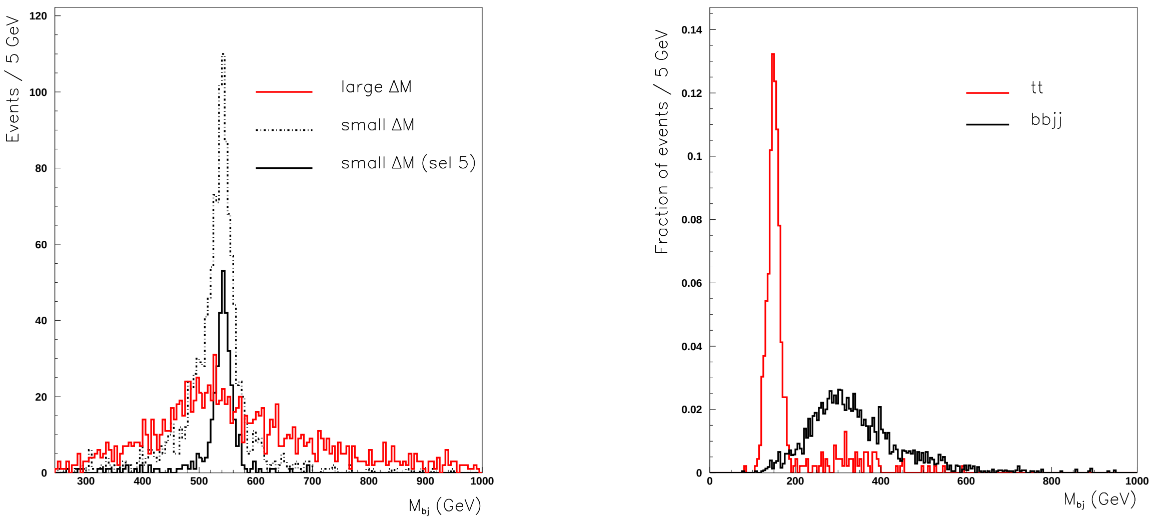

Figure 5: *The left plot shows distributions (normalized to arbitrary luminosity) of* m^{avg}_{right} *(black dashed line) and* m^{avg}_{wrong} *(red solid line) for signal events (*$m_{\widetilde{t}_1} = 550\,\text{GeV}$*) along with* m^{avg}_{right} *after Sel 5 (black solid line). The right plot shows distributions of* m^{avg}_{right} *(normalized to shape) after Sel 5 for two major background sources.*

occur, viz. $\{b_1j_1, b_2j_2, b_1j_2, b_2j_1\}$. Either b_1j_1, b_2j_2 (**combination 1**) or, b_1j_2, b_2j_1 (**combination 2**) represents the *right combination* in terms of the quarks from the hard processes (the decays) while the other represents the *wrong combination*. The two invariant masses belonging to the right combination would be expected to have a difference smaller than that for the wrong combination. To further reduce the chance of choosing the wrong combination due to accidental large mismeasurement of jet energies, we require (**Sel 5**)

$$\Delta m = min\{|m_{b_1j_1} - m_{b_2j_2}|, |m_{b_1j_2} - m_{b_2j_1}|\} \leq 20\,\text{GeV} \ .$$

The average mass of the right combination m^{avg}_{right}: $(m_{b_1j_1} + m_{b_2j_2})/2$ or $(m_{b_1j_2} + m_{b_2j_1})/2$ as specified by Sel 5 is then plotted in Fig.5. The other average is named m^{avg}_{wrong}. The plot for m^{avg}_{right} in signal events shows the peak close to the input value of $m_{\widetilde{t}_1}$ while the plot for m^{avg}_{wrong} (the wrong combination) is expectedly much wider though it may contain some 'right' combinations due to accidental large fluctuation.

Finally, we proceed to estimate the signal significance (S) using signal and background events passing all the selection cuts mentioned above and use leading order cross-sections for signal as well as background processes. The effective cross-section for the signal events is

$$\sigma_{eff} = \sigma(pp \to \widetilde{t}_1\,\widetilde{t}_1^{\,*})B^2 \ ,$$

where B is the total branching ratio[5] for the R-parity violating decays of the $\widetilde{t}_1$ involving a $\bar{b}$-quark, namely $\widetilde{t}_1 \to \bar{b}\bar{d}, \bar{b}\bar{s}$. It may be noted that the fraction of signal events passing the selection criteria increases with $m_{\widetilde{t}_1}$ although $\sigma(pp \to \widetilde{t}_1\widetilde{t}_1^{\,*})$ falls rapidly. We choose a 25 GeV wide window in the m^{avg}_{right} distribution in which the signal is most abundant and has the right shape and determine the fraction of generated signal events (f_{sig}) falling within this window. Finally the estimated number of signal events is obtained through

$$N_S = f_{sig}.\sigma_{eff}.\mathcal{L}_{int} \ , \tag{3}$$

[5]Note that limits from flavour changing neutral current processes constrain products of λ'' couplings [8]. The present study, though, is insensitive to how many channels share B.

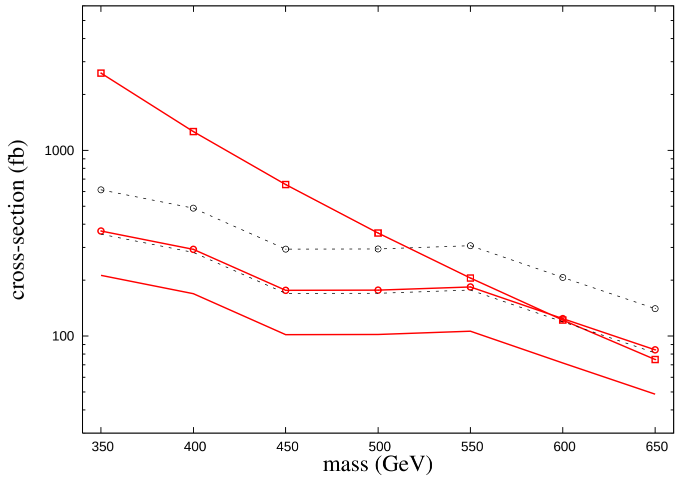

Figure 6: *The minimum value of σ_{eff} (see text) required for excluding signal at 3σ for $\mathcal{L}_{int} = 100\ fb^{-1}$ (solid line with open circles) and $\mathcal{L}_{int} = 300\ fb^{-1}$ (solid line). The same required for observing a 5σ excess over the background are shown for $\mathcal{L}_{int} = 100\ fb^{-1}$ (dashed line with open circles) and $\mathcal{L}_{int} = 300\ fb^{-1}$ (dashed line). For comparison, the solid line with open squares shows $\sigma(pp \to \widetilde{t_1}\widetilde{t_1}^*)$.*

where $\mathcal{L}_{int}$ is the assumed value of integrated luminosity. Similarly, for each background process the number of events falling within the invariant mass window is determined and added up to obtain N_B. The statistical significance may be estimated as

$$S = \frac{N_S}{\sqrt{N_B}} \ . \tag{4}$$

Next, we use eqns.(3 & 4) to calculate the minimum value of effective signal cross-section (σ_{eff}^{min}) required to obtain $S = 3$ and $S = 5$ for a given luminosity (we use $\mathcal{L}_{int} = 100\,\text{fb}^{-1}, \quad 300\,\text{fb}^{-1}$). The values of $\widetilde{t_1}\widetilde{t_1}^*$ production cross-section and σ_{eff}^{min} have been listed in Table 1 and plotted in Fig. 6. It is evident that a large range of parameter space may be explored with $\mathcal{L}_{int} = 100\,\text{fb}^{-1}$.

Jet reconstruction and determination of invariant mass of a particle decaying into two or more jets become difficult at the LHC due to the presence of underlying events, hard radiation from the partons and large p_T of the decaying particle. It has been claimed that a better invariant mass reconstruction is possible using more sophisticated jet reconstruction and analysis techniques and hence increase the signal significance [28]. As such techniques mature, they will help enlarge the scope of this analysis.

In conclusion, we have explored the possibility of observing, at the LHC, a particle decaying into a pair of jets, of which one has a b-quark as the originator. Concentrating on the scalar top quark in a supersymmetric extension of the Standard Model, we demonstrate that simple and robust detector level observables may be used to explore a fairly wide range of the stop mass with integrated luminosities expected from the LHC. In addition, a fairly good estimate of the mass can also be obtained. And while our analysis has concentrated on a particular scenario, we have also demonstrated that it represents the most conservative choice amongst a class of such particles that appear naturally in a

$m_{\tilde{t}_1}$	$\sigma(pp \to \tilde{t}_1 \tilde{t}_1^*)$ (fb)	σ_{eff}^{min} (fb) required for			
		S = 3		S = 5	
		$\mathcal{L}_{int} = 100\ fb^{-1}$	$\mathcal{L}_{int} = 300\ fb^{-1}$	$\mathcal{L}_{int} = 100\ fb^{-1}$	$\mathcal{L}_{int} = 300\ fb^{-1}$
300	5876	494	285	824	476
350	2606	368	212	613	354
400	1262	293	169	488	282
450	655	176	102	294	167
500	359	177	102	294	170
550	205	184	106	306	177
600	122	124	72	207	119
650	75	84	49	140	81

Table 1: *Table shows the minimum value of σ_{eff} (see text) required for different values of $m_{\tilde{t}_1}$ (column 1) for exploring signal at 3σ for $\mathcal{L}_{int} = 100\ fb^{-1}$ (column 3) and $\mathcal{L}_{int} = 300\ fb^{-1}$ (column 4). The same required for observing a 5σ excess over the background are shown for $\mathcal{L}_{int} = 100\ fb^{-1}$ (column 5) and $\mathcal{L}_{int} = 300\ fb^{-1}$ (column 6). Production cross-sections for the signal are shown in column 2.*

large variety of theories. Consequently, this analysis can be easily extended to such other scenarios allowing one to explore masses significantly larger than what this particular model allows us to. Aiding this assertion is the observation that, in many of such models such as those incorporating diquarks or excited quarks, the branching fraction into the relevant decay mode is overwhelmingly the dominant one.

Acknowledgements: DC thanks the IPMU for hospitality as this work was being finalized. This work was supported by the DST, India under project SR/MF/PS-03/2009-VB-I and the World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan.

References

[1] A. Salam and J. Strathdee, Nucl. Phys. B**87** (1975) 85.

[2] P. Fayet, Phys. Lett. B**69**, 489 (1977).

[3] S. Dimopoulos and H. Georgi, Nucl. Phys. B**193** (1981) 150;
N. Sakai, Z. Phys. C**11** (1981) 153;
H. P. Nilles and S. Raby, Nucl. Phys. B**198** (1982) 102;
N. Sakai and T. Yanagida, Nucl. Phys. B**197** (1982) 533;
S. Dimopoulos, S. Raby and F. Wilczek, Phys. Lett. B**112** (1982) 133.

[4] K. Tamvakis, Phys. Lett. B**382**, 251 (1996).

[5] CDF Collaboration, Phys. Rev. D**55**, 5263 (1997).

[6] E. L. Berger, B. W. Harris and Z. Sullivan, Phys. Rev. Lett. **83**, 4472 (1999) [arXiv:hep-ph/9903549]; Phys. Rev. D **63**, 115001 (2001) [arXiv:hep-ph/0012184].

[7] J.L. Goity and M. Sher, Phys. Lett. B**346**, 69 (1995);
C.E. Carlson, P. Roy and M. Sher, Phys. Lett. B**357**, 99 (1995);
B. Brahmachari and P. Roy, Phys. Rev. D**50**, R39 (1995).

[8] G. Bhattacharyya, D. Choudhury and K. Sridhar, Phys. Lett. B**355**, 193 (1995);
D. Chakraverty and D. Choudhury, Phys. Rev. D**63**, 075009 (2001) [arXiv:hep-ph/0008165]; Phys. Rev. D**63**, 112002 (2001) [arXiv:hep-ph/0012309].

[9] G. Bhattacharyya, arXiv:hepph/9709395;
R. Barbier *et al.*, arXiv:hep-ph/9810232;
B. C. Allanach, A. Dedes and H. K. Dreiner, Phys. Rev. D**60**, 075014 (1999);
R. Barbier *et al.*, Phys. Rep. **420** (2005) 1.

[10] For detailed discussion, see D. Choudhury, M. Datta and M. Maity, Phys. Rev. D**73**, 055013 (2006) and references therein.

[11] F. Zwirner, Int. J. Mod. Phys. **A3** (1988) 49;
J.L. Hewett and T.G. Rizzo, Phys. Rep. **183** (1989) 193 and references therein.

[12] T. Han, I. Lewis and Z. Liu, JHEP **1012**, 085 (2010) [arXiv:1010.4309].

[13] J. Shu, T. M. P. Tait and K. Wang, Phys. Rev. D **81**, 034012 (2010) [arXiv:0911.3237 [hep-ph]];
D. Choudhury, R. M. Godbole, S. D. Rindani and P. Saha, arXiv:1012.4750 [hep-ph];
M. I. Gresham, I. W. Kim and K. M. Zurek, arXiv:1103.3501 [hep-ph].

[14] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **101**, 202001 (2008) [arXiv:0806.2472 [hep-ex]];
CDF Conference Note 9724, http://www-cdf.fnal.gov/physics/new/top/public_tprop.html;
CDF Conference Note 10185, http://www-cdf.fnal.gov/physics/new/top/public_tprop.html;
T. Aaltonen *et al.* [The CDF Collaboration], arXiv:1101.0034 [hep-ex].

[15] P. H. Frampton and S. L. Glashow, Phys. Lett. B **190**, 157 (1987); Phys. Rev. Lett. **58**, 2168 (1987);
P. H. Frampton, J. Shu and K. Wang, Phys. Lett. B**683**, 294 (2010) [arXiv:0911.2955 [hep-ph]].

[16] C. T. Hill, Phys. Lett. B**266**, 419 (1991); Phys. Lett. B**345** (1995) 483 [arXiv:hep-ph/9411426];
R. S. Chivukula, A. G. Cohen and E. H. Simmons, Phys. Lett. B**380**, 92 (1996) [arXiv:hep-ph/9603311];
E. H. Simmons, Phys. Rev. D**55**, 1678 (1997) [arXiv:hep-ph/9608269].

[17] T. Appelquist, H. C. Cheng and B. A. Dobrescu, Phys. Rev. D **64**, 035002 (2001) [arXiv:hep-ph/0012100].

[18] K. Hagiwara, S. Komamiya and D. Zeppenfeld, Z. Phys. C**29** (1985) 115;
U. Baur, M. Spira and P.M. Zerwas, Phys. Rev. D**42** (1990) 815;
F. Boudjema, A. Djouadi and J.L. Kneur, Z. Phys. C**57** (1993) 425.

[19] F. Abe et al. [CDF Collaboration], Phys. Rev. D**55**, 5263 (1997) [arXiv:hep-ex/9702004];
M. P. Giordani [CDF and D0 Collaborations], Eur. Phys. J. C**33**, S785 (2004).

[20] I. Bertram and E. H. Simmons, Phys. Lett. B**443** (1998) 347 [arXiv:hep-ph/9809472];
M. Arai, N. Okada, K. Smolek and V. Simak, Phys. Rev. D**70**, 115015 (2004) [arXiv:hep-ph/0409273]; Phys. Rev. D**75** (2007) 095008 [arXiv:hep-ph/0701155];
K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez and J. Virzi, arXiv:hep-ph/0612015;
M. Guchait, F. Mahmoudi and K. Sridhar, arXiv:hep-ph/0703060;
B. Lillie, L. Randall and L. T. Wang, arXiv:hep-ph/0701166;
D. Choudhury, R. M. Godbole, R. K. Singh and K. Wagh, Phys. Lett. B **657**, 69 (2007) [arXiv:0705.1499 [hep-ph]];
S. Bhattacharya, S. S. Chauhan, B. C. Choudhary and D. Choudhury, Phys. Rev. D **76**, 115017 (2007) [arXiv:0705.3472 [hep-ph]]; Phys. Rev. D **80**, 015014 (2009) [arXiv:0901.3927 [hep-ph]].

[21] J. Blumlein, E. Boos and A. Kryukov, Z.Physik C**76** (1997) 137 [hep-ph/9610408].

[22] ALEPH Collaboration, Phys. Lett. B**413**, 431 (1997); Phys. Lett. B**434**, 189 (1998); Phys. Lett. B**469**, 303 (1999); Phys. Lett. B**488**, 234 (2000); Phys. Lett. B**499**, 67 (2001);
DELPHI Collaboration, Phys. Lett. B**489**, 38 (2000);
L3 Collaboration, Phys. Lett. B**471**, 308 (1999);
OPAL Collaboration, Phys. Lett. B**456**, 95 (1999).

[23] DØ Collaboration, Phys. Rev. Lett. **101**, 071802 (2008); Phys. Lett. B**659**, 500 (2008); Phys. Lett. B**665**, 1 (2008); Phys. Lett. B**674**, 4 (2009); Phys. Lett. B**675**, 289 (2009);
CDF Collaboration, Phys. Rev. Lett. **101**, 071802 (2008).

[24] S.P. Das, A. Datta and M. Maity, Phys. Lett. B**596**, 293 (2004).

[25] T. Sjöstrand, P. Edén, C. Friberg, L. Lönnblad, G. Miu, S. Mrenna and E. Norrbin, Comp. Phys. Comm. **135**, (2001) 238.

[26] M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A. Polosa, JHEP **0307**, 001 (2003).

[27] ATLAS Collaboration, ATLAS Detector and Physics Performance, Technical Design Report, Vol I, **CERN-LHCC-1999-14**; ATLAS Detector and Physics Performance, Technical Design Report, Vol II, **CERN-LHCC-1999-15**;
CMS Collaboration, CMS Physics Technical Design Report Vol. I, **CERN-LHCC-2006-001** ; CMS Physics Technical Design Report, Vol. II, J. Phys. G, **34** 995 (2007).

[28] J.M. Butterworth, A.R. Davison, M. Rubin and G.P. Salam, Phys. Rev. Lett. **100**, 242001 (2008);
S.D. Ellis, C.K. Vermilion and J.R. Walsh, Phys. Rev. D**80**, 051501 (2009); Phys. Rev. D**81**, 094023 (2010);
D. Krohn, J. Thaler, L and Wang, JHEP **1002**, 084 (2010).