

Looking for the top squark at the Fermilab Tevatron with four jets

Debajyoti Choudhury,¹ Madhumita Datta,² and Manas Maity²

¹*Department of Physics and Astrophysics, University of Delhi, Delhi 110 007, India*

²*Department of Physics, Visva-Bharati, Santiniketan 731 235, India*

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The scalar partner of the top quark is relatively light in many models of supersymmetry breaking. We study the production of top squarks (stops) at the Tevatron collider and their subsequent decay through baryon-number violating couplings such that the final state contains no leptons. Performing a detector-level analysis, we demonstrate that, even in the absence of leptons or missing energy, stop masses up to 210 GeV/ c^2 can be accessible at the Tevatron.

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The conservation of either of baryon (B) and lepton (L) numbers is not dictated by any fundamental principle and is but an accidental feature of the perturbative sector of the standard model (SM). Indeed, any explanation of the observed baryon asymmetry of the universe needs at least one of B or L to be broken to a significant degree. Many extensions of the SM, whether supersymmetric or not, naturally admit both B and L violation and care must be taken that both are not violated strongly so as to render the proton very unstable. As can be easily appreciated, breaking of either B or L would lead to significant alteration in phenomenology, and, in particular, collider signatures for physics beyond the SM. While numerous studies have been undertaken in the context of L violation, in this article we seek to examine the experimentally more challenging case of a broken baryon-number.

Low-energy supersymmetry (SUSY) is widely considered to be a benchmark for scenarios going beyond the SM. Since the most general renormalizable Lagrangian consistent with both gauge symmetries and SUSY contain terms that break both B and L , stability of the proton is normally ensured by the imposition of an *ad hoc* discrete symmetry, namely R -parity [1]. However, since the same end can be achieved by the imposition of L alone, we allow, in the superpotential, terms of the form [2]

$$W_{\mathcal{R}} = \lambda''_{ijk} \bar{U}_R^i \bar{D}_R^j \bar{D}_R^k, \quad (1)$$

where \bar{U}_R^i and \bar{D}_R^i denote the right-handed up-quark and down-quark superfields, respectively. The Yukawa 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:

$$\mathcal{L}_{\mathcal{R}} = \lambda''_{ijk} (u_i^c d_j^c \bar{d}_k^* + u_i^c \bar{d}_j^* d_k^c + \tilde{u}_i^* d_j^c d_k^c) + \text{h.c.}, \quad (2)$$

thus allowing a squark to decay into a pair of quarks. While resonant production in a hadron collider is possible as well [3,4], the corresponding rates are limited by the size of the couplings λ'' . As can be expected, the latter are constrained by various low-energy observables [5,6], though the couplings involving the second and third-generation fields alone can be relatively large [7]. It, thus, may be advisable

to concentrate on the (model-independent) strong interactions for squark production and consider the effect of λ'' only in the decays.

In most SUSY models, the large top Yukawa coupling results in the lighter stop, \tilde{t}_1 , being light compared to the other squarks. Since the realization of the mechanism of electroweak baryogenesis within the context of the MSSM requires light stops, with masses of about or smaller than the top quark mass [8], there is an added motivation to consider such scenarios.

At hadron colliders, stop production proceeds overwhelmingly via the strong interaction and the corresponding cross sections are well known at leading order [9]. The next-to-leading order QCD and SUSY-QCD corrections have been computed [10] and implemented numerically in PROSPINO [10,11], which we use along with the CTEQ5 parton distribution functions [12]. We further assume that the masses of the gluino and the other squarks are larger than about 250 GeV so that they do not alter the NLO crosssection significantly [10]. This, furthermore, precludes any significant enhancement of the stop production cross sections via cascade decays thereby making our estimates *conservative*.

The prospects for stop discovery at the Tevatron have been examined both in the context of R -conserving supergravity inspired scenarios [13] as well as in the context of low-energy SUSY breaking [14]. Search efforts at the LEP and the Tevatron, irrespective of the stop decay mode, have only proved unsuccessful [15]. The reach, at Run II, depends crucially on the decay chain (and, hence, the SUSY spectrum) and, for an integrated luminosity of 2 fb⁻¹ typically ranges between 165–190 GeV. For a stop light enough such that $\tilde{t}_1 \rightarrow \tilde{\chi}^+ b$ is kinematically forbidden, the details of the decay depend very sensitively on the mass splitting between the stop and the lightest neutralino (note that if R -parity is broken, the stop is even allowed to be the lightest SUSY particle or LSP). If, for example, $m_{\tilde{t}} < m_W + m_b + m_{\tilde{\chi}_1^0}$, only two R -conserving decay modes are kinematically accessible, namely, (i) the loop-induced flavor-changing two-body decay $\tilde{t} \rightarrow c \tilde{\chi}_1^0$ and (ii) the four-body decay via a virtual W boson, $\tilde{t} \rightarrow W^{*+} b \tilde{\chi}_1^0 \rightarrow qq b \tilde{\chi}_1^0$ or

$\ell\nu b\tilde{\chi}_1^0$. It is easy to see that either of these partial widths are small and may be superseded by R -violating modes even for moderate values of λ'' . For the rest of this paper, we shall assume that at least one of the modes $\tilde{t}_1 \rightarrow \bar{b} + \bar{s}(\bar{d})$ has a significant branching fraction. (We refrain from discussing $\tilde{t}_1 \rightarrow \bar{d} + \bar{s}$ for reasons of experimental sensitivity.)

At this stage, we digress to point out that the stop (or any other squark) is not the only conjectured strongly-interacting particle that may decay into a pair of quarks. Even in the simplest nonsupersymmetric grand unified theories (GUTs), B may be violated in both the gauge and the scalar sector interactions. The corresponding elementary particles, namely, diquarks, can be either spin-0 or spin-1 and have baryon and lepton numbers $2/3$ and 0 respectively [16]. A generic diquark may transform as $\mathbf{3}$ or $\bar{\mathbf{6}}$ under $SU(3)_c$, as triplet or singlet under $SU(2)_L$ and can have electric charges $|Q_{\mathcal{D}}| = 1/3, 2/3$ or $4/3$. Compared to the λ'' s, diquark couplings are typically less restricted both in terms of symmetry requirements (allowing, for example, the experimentally easier mode $\mathcal{D} \rightarrow b + b$ [17]) as well as low-energy constraints [6]. As far as scalar diquarks are concerned, a $SU(3)_c$ triplet has the same production cross section (and phase space distributions) as a stop of identical mass, while a sextet has a larger one on account of the color-factor. The cross section for a vector diquark depends on the exact nature of its gauge interactions and is significantly larger. Moreover, a generic diquark tends to decay dominantly into a pair of quarks. Similarly, models of quark-compositeness [18] generically contain relatively light colored fields, whether vector or scalar, charged or neutral, that could decay into a b - and a non- b -quark. The stop, thus, is the *most conservative* choice from this genre.

At the partonic level, our final state, thus, consists of $(bq)(\bar{b}\bar{q})$ where q is either a d - or an s -quark and the parenthetical pairing is to denote that the combinations arise from the decay of an (anti-)stop. The SM backgrounds were generated with both MADGRAPH [19] and PYTHIA 6.206 [20] and tested for consistency. Using the latter, we generate complete events with initial and final state radiation, multiple interactions, etc., and complete evolution (hadronisation and decays) of the partons into final state particles. The latter are passed through a toy detector simulation (using tools in PYTHIA) and event reconstruction algorithm mimicking a typical Tevatron RunII detector. The toy calorimeter has cell sizes of $\Delta\eta = 0.1$ and $\Delta\phi = 15^\circ$. Jet reconstruction has been done employing the cone algorithm with $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.7$ and using calorimeter clusters with $E_T > 1.0$ GeV as seeds for jet formation. Only jets with $|\eta_{\text{jet}}| \leq 2.4$ and $E_T > 15$ GeV and leptons with $|\eta_\ell| \leq 2.4$ are considered. Tagging of b -jets has been done using decay lengths of b -hadrons such that $\sim 60\%$ of $t\bar{t}$ events have at least one b -jet tagged [21]. Apart from

vertex tagging, soft lepton tag may be used to enhance b -tagging. Since the event features used in this analysis, viz., jet and lepton P_T and η , jet multiplicity, \cancel{E}_T and b -tag are rather robust and easy to implement, our results would be fairly independent of the detailed features of a particular detector.

The signal events would be characterized by four hard jets, two of them being b -jets. Since leptons or neutrinos in such events can occur only as decay products of hadrons, these would be soft. This then inspires our selection criteria

$$\begin{aligned} \cancel{E}_T &\leq 15 \text{ GeV}/c && \text{no lepton with } P_T^\ell \geq 15 \text{ GeV} \\ N_{\text{jet}} &= 4 && \sum_{\text{jet}} E_T > 200 \text{ GeV} \\ N_{\text{btag}} &= 2 && M_{bb}, M_{jj} \in (70 \text{ } 100) \text{ GeV}/c^2. \end{aligned} \quad (3)$$

Apart from the ZZ process (which is largely eliminated by the last requirement above), backgrounds also arise from $t\bar{t}$ events with both tops decaying hadronically (these typically have more than four jets, see Fig. 1) as well as $b\bar{b}jj$ events (hereafter denoted as bb events), where the additional jets could result from either or both of hard QCD/QED processes as well as multiple interactions. Although $b\bar{b}$ events have a huge cross-section, the cut on $\sum_j E_T^j$ is very effective with a rejection factor of about 10^4 as Fig. 1 amply demonstrates.

This still leaves a large background. However, in $\tilde{t}_1\tilde{t}_1^*$ events, of the two jet pairings viz. (b_1j_1, b_2j_2) and (b_1j_2, b_2j_1) , the one representing the decaying stops should

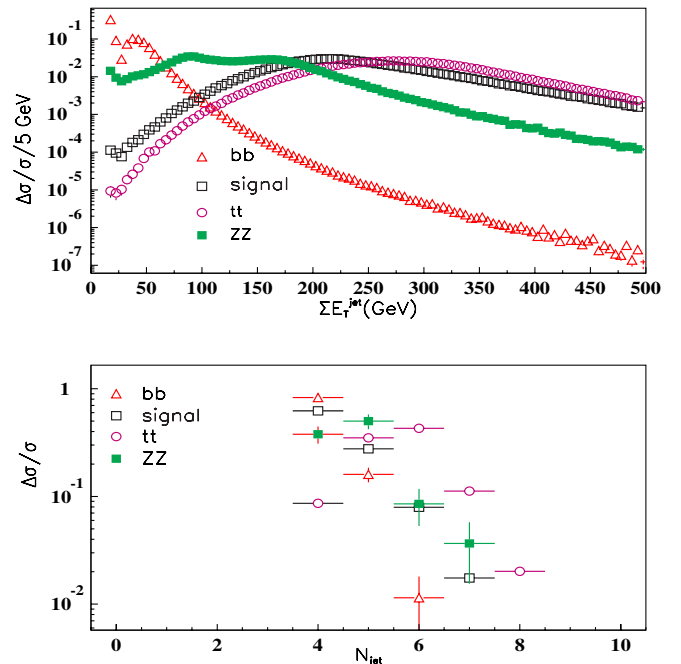


FIG. 1 (color online). Differential distributions (normalized to unity) in different variables for both signal ($m_{\tilde{t}_1} = 120 \text{ GeV}/c^2$) and various SM backgrounds. The top panel correspond only to the acceptance cuts. For the bottom one, all selection criteria of Eq. (3) other than that on N_{jet} have been imposed as well.

be associated with only a small difference in the reconstructed invariant masses. Hence, our final selection criterion is that

$$|M_{bj}^1 - M_{bj}^2| \leq 20 \text{ GeV}/c^2 \quad (4)$$

for at least one pairing. For the signal events, the corresponding average of the two masses is expected to show a sharp peak around $m_{\tilde{t}_1}$ as is evinced by Fig. 2, whereas the other pairing has a rather flat distribution.

We have simulated 10^6 events for each $m_{\tilde{t}_1}$ and also for $t\bar{t}$ and ZZ events. Though $b\bar{b}$ events have a very small selection efficiency, they have a very large cross-section, and constitute the bulk of the background events passing the selection cuts. Hence, a very large set of $b\bar{b}$ events ($\sim 2.5 \times 10^8$) have been generated to get a good estimate of the background distribution. As for the signal events, for low $m_{\tilde{t}_1}$, a large fraction of the events fail to satisfy the jet selection criteria leading to a small selection efficiency ϵ (Fig. 3). As $m_{\tilde{t}_1}$ increases, the situation improves rapidly; however beyond $150 \text{ GeV}/c^2$, this effect saturates and is more than offset by the rejection on account of hardening of lepton P_T and \cancel{E}_T . The rapid fall in the effective cross-section ($\sigma \cdot \epsilon$) is, of course, reflective of the p -wave nature of scalar production.

Whereas the signal events show a sharp peak in M_{bj}^{avg} , the background is much flatter (Fig. 3). This allows us to identify a range in M_{bj}^{avg} where the signal is most significant and calculate the χ^2 . Working with a conservative choice of a $50 \text{ GeV}/c^2$ bin, we use this χ^2 to obtain an exclusion plot in the $BR(\tilde{t}_1 \rightarrow \bar{b}\bar{q}) - m_{\tilde{t}_1}$ plane (Fig. 4) that may be reached by the Tevatron experiments. With as little as 2 fb^{-1} data, such an analysis would have a reach up to $185 \text{ GeV}/c^2$ (for $BR(\tilde{t}_1 \rightarrow \bar{b}\bar{q}) = 100\%$), and on the other hand probe down to $BR(\tilde{t}_1 \rightarrow \bar{b}\bar{q}) \sim 15\%$ for $m_{\tilde{t}_1} = 70 \text{ GeV}/c^2$. Similarly, we may be able to put an upper

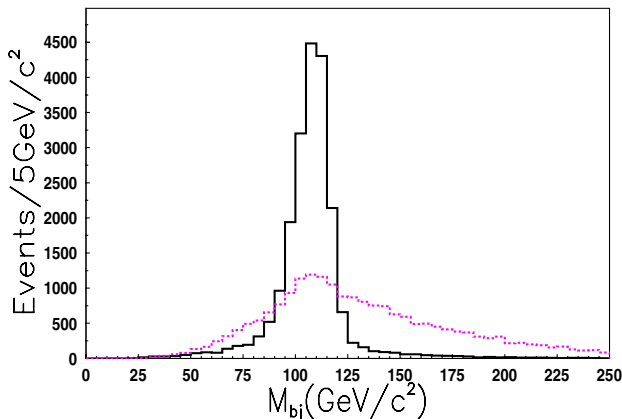


FIG. 2 (color online). Distribution of the average reconstructed mass for $\tilde{t}_1\bar{\tilde{t}}_1$ events for $m_{\tilde{t}_1} = 120 \text{ GeV}/c^2$ (10^6 events generated). The dark (black) line corresponds to the combination with the smaller difference between the two invariant masses; the light (purple) line represents the other combination.

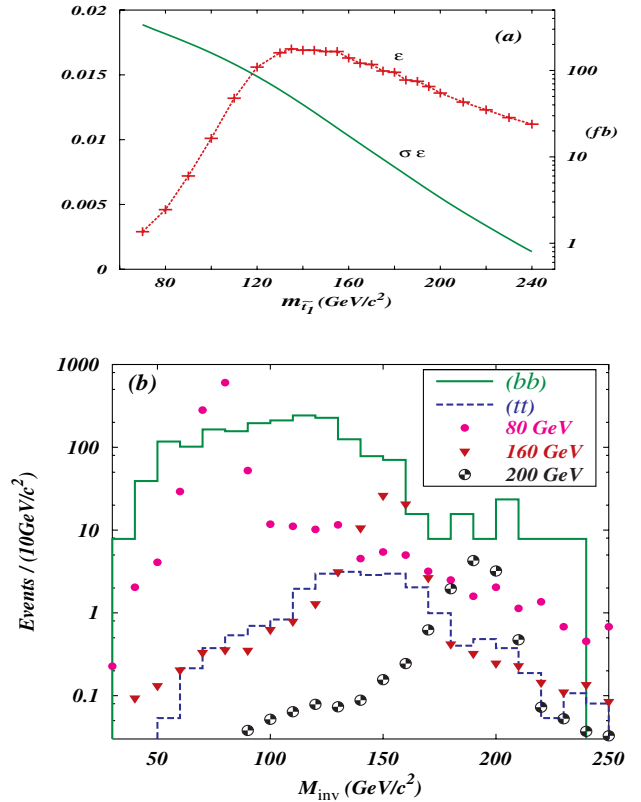


FIG. 3 (color online). (a) The detection efficiency for stop-pair production and its product with the cross-section as a function of the mass. (b) The distribution in the average of the two masses M_{bj} corresponding to the minimum difference. While the signal profile for three different stop masses are given by the points, the solid and dashed lines show the backgrounds from $b\bar{b}$ (overwhelmingly dominant) and $t\bar{t}$ events. The ZZ rate falls below the scale of the figure.

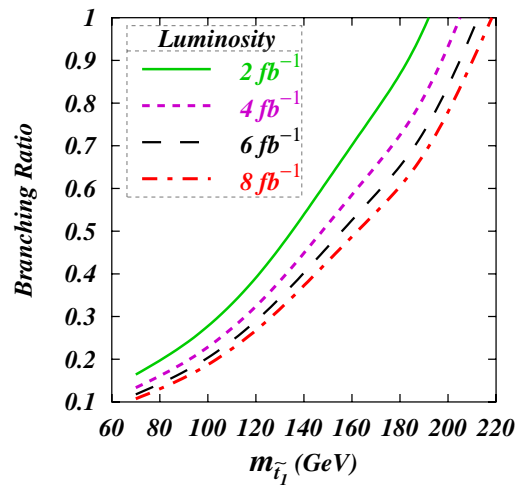


FIG. 4 (color online). Exclusion contours at 90% CL in the $BR(\tilde{t}_1 \rightarrow \bar{b}\bar{q}) - m_{\tilde{t}_1}$ plane that may be achieved for different values of total integrated luminosity.

bound on the $BR(\tilde{t}_1 \rightarrow \bar{b} \bar{q})$ for stop masses up to $200 \text{ GeV}/c^2$ with $\mathcal{L}_{\text{int}} = 4 \text{ fb}^{-1}$. A combined analysis of the data from the two Tevatron RunII experiments would serve to push the limits even further.

Finally, we must compare our results with those for single top-squark production [4]. Note that, for the latter, the dominant contribution there accrues from the λ''_{tds} coupling, one which we assume to be vanishing; thus, their limits would worsen slightly. More importantly, (i) the analysis of Ref. [4] requires relatively large branching fraction for the decay mode $\tilde{t} \rightarrow b + \tilde{\chi}_1^+$ and (ii) for smaller stop-masses ($\leq 250 \text{ GeV}$), their signal to background ratio becomes somewhat worse [4]. Thus, the two strategies are complementary in their region of applicability. Apart from the identity of the λ'' -coupling, the first factor above makes their analysis inappropriate for the case of the stop being the LSP or NLSP, and, by the same token, for nonsupersymmetric analogues such as diquarks. In such cases, the method outlined here remains the only viable one suggested so far.

In summary, we have outlined above a robust stop-search strategy based on selection criteria which are easy

to implement. Most importantly, a final state devoid of leptons or missing energy is shown to be very promising and competitive with other modes that have been used so far. Specific features dependent on detector capabilities may be used, particularly in a multidimensional analysis, to better discriminate signal and background and probe added regions in the parameter space. Furthermore, the sensitivity can be enhanced by considering $m_{\tilde{t}_1}$ -dependent selection criteria rather than the universal cuts that we have chosen to impose. In fact, even an analysis of the currently accumulated data would serve to probe a significant region of the SUSY parameter space that has not lent itself to an examination so far. And as we have already pointed out, the analysis is not limited to the top-squark or supersymmetry alone but can be readily extended to diquarks, which, in fact, are generically associated with even larger cross sections.

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