Search for Stop-Pair Samples in Top-Counting Experiments at Hadron Colliders (Postprint)

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Abstract

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Full Text

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Searching for a stop-pair sample from top counting experiments at hadron colliders

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Abstract

The light stop, if produced at hadron colliders in the form of a ˜t1 ˜¯t1 pair and decaying through the likely chain ˜t1 → ˜ ^+_1 b followed by ˜ ^+_1 → ˜ ^0_1 f ¯f , can closely mimic a top quark event when the stop mass is near that of the top quark. Due to its much lower production rate, the stop event can be buried within the top quark event sample. To uncover stop events,

specific selection cuts must be applied. Through Monte Carlo simulation with suitable kinematic cuts, we find that such stop events can be extracted from the top quark sample and detected by top counting experiments at the upcoming upgraded Tevatron and LHC. However, because of the small statistics from Run 1 of the Tevatron, the stop signal remains hidden.

Introduction

The search for supersymmetric particles represents one of the primary tasks of the upgraded Fermilab Tevatron and the upcoming CERN Large Hadron Collider (LHC). Due to the unknown masses of sparticles and other free parameters, various possibilities and strategies must be considered. Among the plethora of sparticles, the superpartners of the top quark—the stops—particularly the lighter of the two mass eigenstates denoted as ˜t1, are of special interest. This stop has color interactions and is likely to be the lightest sfermion, making it producible in the gluon-rich environment of high-energy hadron colliders. The lightness of the stop is typically argued for several reasons. First, the large top quark Yukawa coupling can lead to substantial negative one-loop contributions to the stop masses, making stops significantly lighter than other sfermions at the electroweak scale through renormalization group evolution, even if all sfermions share a universal mass at the unification scale. Second, since mixing between sfermions corresponding to left- and right-handed states is proportional to the fermion mass, the large top quark mass can cause significant mixing between the two stops, resulting in sizable mass splitting that makes the lighter eigenstate ˜t1 even lighter and accessible to current and future hadron colliders. Third, the existence of a light stop is preferred by electroweak baryogenesis [1]. Finally, from a theoretical perspective, a scenario where first- and second-generation sfermions are as heavy as 10 TeV while third-generation sfermions are substantially lighter conforms to the naturalness principle [2].

In the framework of the minimal supersymmetric standard model (MSSM) with R-parity conservation, several possibilities for light stop searches through top quark decay have been considered in the literature. We recapitulate them briefly below.

If the stop is the next-to-lightest supersymmetric particle (NLSP), its only two-body decay mode is ˜t1 → c ˜ ˆ0_1, where ˜ ˆ0_1 is assumed to be the lightest supersymmetric particle (LSP). This decay proceeds via loops [3]. If the stop is sufficiently light, one can consider the exotic top decay t → ˜t1 ˜ ˆ0_1. Studies showed that this decay chain in t¯t pair events, if realized, would be observable across much of the SUSY parameter space at future Tevatron runs [4].

Another possible decay mode for the stop in R-parity-conserving scenarios, when the stop is light but heavier than the NLSP, is ˜t1 → b ˜ ˆ+_1 through tree-level coupling, where ˜ ˆ+_1 denotes the lightest chargino. This decay mode dominates whenever kinematically allowed. The phenomenology of t¯t production followed by the decay chain t → ˜t1 ˜ ˆ0_1 was studied soon after the top quark discovery [5]. However, the significantly increased lower bounds on the masses of ˜t1 and ˜ ^0_1—approximately 122 GeV [6] and 45 GeV [7] respectively (albeit under certain assumptions)—render these top decay chains less likely.

From the above discussion, we see that discovering the light stop through top quark decay is not a promising avenue. However, the light stop offers a more direct discovery path at the Tevatron and LHC: direct production of stop pairs, assuming the production cross-section is sufficiently large and a suitable decay channel exists for identification. Since stop pair production is a QCD process, the only uncertainty in the production cross-section concerns the stop mass and its decay pattern.

If the stop is the NLSP and thus its only two-body decay mode is ˜t1 → c ˜ ^0_1, the signal from stop pair production at hadron colliders would be only two jets plus missing energy [8]. The large QCD background makes such a signal impossible to uncover. In this article, we examine, within the MSSM with R-parity conservation, the case of a stop with mass close to that of the top quark but heavier than the lightest chargino, so that it decays dominantly through ˜t1 → b ˜ ^+_1, followed by ˜ ^+_1 → ˜ ^0_1 f ¯f via a real or virtual W boson intermediate state, where ˜ ^+_1 is the lightest chargino and ˜ ^0_1 is the LSP. A stop pair event then resembles a top quark pair event and can be easily masked by the latter [9]. Through detailed Monte Carlo simulation, we investigate the possibility of uncovering stop pair events from top quark counting experiments at the Tevatron and LHC. As demonstrated below, for a stop as light as the top quark, the stop sample will generally be buried in the top sample at Run 1 due to insufficient statistics, but at future upgraded Tevatron runs and at the LHC, such a stop sample can be revealed through a series of suitable selection cuts.

2 Stop Pair Production and Signatures

Similar to top quark pair production, stop pairs in hadron collisions can be produced through q¯q annihilation and gluon-gluon fusion via the gˆt1¯˜t1 coupling. We use the lowest-order matrix elements in our Monte Carlo simulation. The squared amplitudes for the two processes are given by:

|M|^2(q¯q → ˜t1¯˜t1) = 2g^4 [(ˆt1ˆu1 - m^2ˆs) / (ˆt1ˆu1) - (2m^2ˆs(ˆt1 - ˆu1)^2) / (ˆt1^{2ˆu1}2)]

|M|^2(gg → ˜t1¯˜t1) = 16g^4 [(1/8 + (m^2ˆs)/(8ˆt1ˆu1) - m$^{4(1/ˆt1}$2 + 1/ˆu1^2)) + (ˆt1/ˆu1 + ˆu1/ˆt1 - (ˆt1^2 + ˆu1$^{2)/ˆs}$2)]

where ˆs is the partonic center-of-mass energy squared, ˆt1 = ˆt - m^2, and ˆu1 = ˆu - m^2, with ˆt and ˆu being the usual Mandelstam variables. For parton distribution functions, we use CTEQ5L with μ = ˆs [10]. For a stop mass near the top quark mass, QCD corrections enhance the total stop pair cross-section by a factor of approximately 1.2 at Tevatron energies and approximately 1.4 at LHC energies [11]. These enhancements are included in our calculations.

Although the QCD coupling in stop production is as strong as in top production, the stop pair production rate at a given energy is much smaller than that for top pairs of similar mass. This suppression arises largely because stops are spin-0 particles: (1) there is no sum over final-state spin projections that could enhance the rate several-fold, and (2) the P-wave coupling in the q¯q annihilation process leads to a ˆ3 dependence [11] that strongly suppresses the cross-section near threshold. While these suppression factors operate at all collider energies, stop production at the Tevatron is more severely affected because the dominant production mechanism is q¯q annihilation.

As stated in the Introduction, we focus on the ˜t1 decay chain ˜t1 → b ˜ ˆ+_1 → b ˜ ˆ0_1 f ¯f . We assume a SUSY spectrum where all sparticles involved in the decay chain are on-shell, with specific mass values given below. As noted earlier, the two-body decay channel ˜t1 → b ˜ ˆ+_1 dominates when the final-state particles are on-shell, so we approximate its branching ratio as 100%. For the subsequent three-body chargino decay, we use the full matrix element in our Monte Carlo simulation and take the total chargino width as the sum of all allowed three-body decay channels ˜ ˆ+_1 → ˜ ˆ0_1 f ¯f . We also assume that charged Higgs bosons, sleptons, and squarks are much heavier than the W boson, so these three-body decays proceed dominantly through W boson intermediate states [3].

Thus, stop pair production ˜t1¯˜t1 followed by the decay chain ˜t1 → b ˜ ˆ+_1 → b ˜ ˆ0_1 f ¯f yields top-like signatures except for two extra neutralinos that escape detection. Three possible observation channels exist for stop-pair events: dilepton + 2-jet, single lepton + 4-jet, and all-hadronic (six-jet). All three channels involve significant missing energy. The all-jet channel has the largest rate but suffers from enormous QCD backgrounds, making it unsuitable for isolating the stop signal. The dilepton channel has the lowest rate, and furthermore lacks a mechanism to enhance the stop/top ratio sufficiently to provide a "smoking gun" for stop pair production. We therefore focus on the remaining single lepton + 4-jet channel, where the optimal signal for distinguishing stop events from top pair events is + 4j/b + E_T. Here 4j/b denotes a 4-jet event with at least one jet passing b-tagging criteria. As shown below, highly effective selection cuts can be found to enhance the stop/top ratio for this signature.

3 Relevant SUSY Parameters

Several SUSY parameters enter our calculations. Most importantly, the stop mass, which we fix at 170 GeV in most numerical examples but vary to determine how heavy the stop can be while remaining observable. For neutralino and chargino masses and couplings, four independent parameters exist: M, M , µ, and tan . Here M is the SU(2) gaugino mass, M is the hypercharge U(1) gaugino mass, µ is the coefficient of the Higgs mixing term µH1H2 in the superpotential, and tan = v2/v1 is the ratio of vacuum expectation values of the two Higgs doublets. We work within the MSSM framework and assume gaugino mass unification, which gives the relation M = (5/3)M tanˆ2 _W

0.5M, reducing the independent parameters to three: M, µ, and tan . For these three parameters, the chargino-neutralino sector divides into two regions: the gaugino-like region (M < |µ|) and the higgsino-like region (M > |µ|).

The gaugino-like region favors stop signal discovery. In this region, the lightest neutralino ˜ ^0_1 is mainly composed of the hypercharge U(1) gaugino (bino), and the lightest chargino ˜ ^+_1 is mainly composed of the charged SU(2) gaugino (wino). Consequently, the ˜ ^0_1 mass is about half that of the ˜ ^+_1. This large mass splitting between ˜ ^0_1 and ˜ ^+_1 is needed to produce sufficiently energetic jets or leptons in the decay ˜ ^+_1 → ˜ ^0_1 f ¯f to pass the necessary kinematic cuts.

Conversely, the higgsino-like region is unfavorable for the stop signal. In this case, both the lightest neutralino ˜ ^0_1 and the lightest chargino ˜ ^+_1 are primarily higgsino fields. As a result, ˜ ^0_1 is nearly degenerate with (but lighter than) ˜ ^+_1. The leptons or jets produced in the decay ˜ ^+_1 → ˜ ^0_1 f ¯f are then too soft to pass our selection cuts, significantly reducing the stop signal and likely leaving it hidden beneath top events even when stop pairs are produced.

In our calculations, we choose the following representative parameter set in the gaugino-like region: M = 100 GeV, µ = -200 GeV, tan = 1. The resulting chargino and neutralino masses in GeV are:

m_{˜ +1} = 120, m{˜ 0_1} = 55, m_{˜ +2} = 220, m{˜ 0_2} = 122, m_{˜ ^0_3} = 200, m_{˜ ^0_4} = 227.

As expected, m_{˜ ^0_1} is about half of m_{˜ ^+_1}.

We note that SUSY parameters are generally not well-constrained experimentally at present. The only robust constraints are the lower bounds on some sparticle masses from LEP and Tevatron [12]. Additionally, intermediate values of tan are favored by low-energy experiments [13]. Therefore, the SUSY parameter values used in our calculations are not unique; they represent a set of allowed values commonly applied in simulations.

4 Selection of + 4j/b + E_T Events

In our analysis, we simulate detector energy resolution by assuming Gaussian smearing of final-state particle energies: ΔE/E = 30%/√E 1% for leptons and ΔE/E = 80%/√E 5% for hadrons, where E is in GeV and indicates quadrature addition of energy-dependent and energy-independent terms.

The basic selection cuts are chosen as follows:

For the Tevatron: - p_T^ 20 GeV - p_T^miss 20 GeV - p_T^jet 15 GeV - | _jet|, | _ | 2.0 - ΔR_jj, ΔR_j 0.5

For the LHC: - p_T^ 20 GeV - p_T^miss 30 GeV - p_T^jet 20 GeV - | _jet|, | _ | 3.0 - ΔR_jj, ΔR_j 0.4

Here p_T denotes transverse momentum, is pseudorapidity, and ΔR = √(Δ ^2 + Δ ^2) is the separation in the azimuthal angle-pseudorapidity plane between a jet and lepton or between two jets.

For the signal, we require at least one b-tag in + 4j/b + E_T events. The tagging efficiency is 53% at Run 1 and expected to reach 85% at Run 2 and Run 3 [14]. For the LHC we assume the same tagging efficiency as Tevatron Run 2.

Under these basic selection cuts and b-tagging, the ratio of top events (+ 4j/b + E_T) to QCD backgrounds is about 12:1 [14], which we use to evaluate QCD backgrounds.

We note that for top events and W+jets background events, missing energy comes only from the neutrino in W decay, while for stop events the missing energy includes two additional neutralinos. From the lepton transverse momentum (P_T^) and missing transverse momentum (P_T^miss), we construct the transverse mass:

m_T(, p_T^miss) = √[(|P_T^ | + |P_T$^{\text{miss|)}}$2 - (P_T^ + P_T$^{\text{miss)}}$2]

As is well known, if P_T^ and p_T^miss originate from a parent particle decay, the transverse mass is bounded by the parent particle mass. For top quark and W+jets background events, where missing energy comes solely from the W decay neutrino, m_T(, p_T^miss) is always less than M_W and peaks just below M_W, though kinematic smearing can push the bound and peak above M_W. For stop events, no such peak exists due to the extra neutralino missing energy.

Figure 1 shows the transverse mass distributions for stop and top quark events. The top quark distribution indeed peaks just below 80 GeV, with significant events above 80 GeV due to smearing. To substantially enhance the stop/top ratio, Figure 1 suggests applying the cut:

m_T(, p_T^miss) [50, 100] GeV

To further enhance the stop/top ratio, we construct four different invariant masses, denoted M(3j), using three of the four jets in each event. We define the combination closest to 175 GeV as the reconstructed top quark mass and denote its value M_top(3j). The M_top(3j) distribution at upgraded Tevatron energy is shown in Figure 2. As expected, top quark events exhibit a peak at the top quark mass M_t = 175 GeV. To further suppress top quark events, we select events with M_top(3j) at least 20 GeV away from the top quark mass:

|M_top(3j) - M_t| 20 GeV

5 Numerical Results

For the parameter values specified in Section 3, Table 1 presents the + 4j/b + E_T cross-sections from stop and top quark events at the Tevatron and LHC under various cuts. The basic selection cuts (Eqs. 7 and 8), necessary for reducing QCD backgrounds, affect the stop cross-section more than the top cross-section, lowering the stop/top ratios below 5%. This occurs because leptons and jets from stop events are relatively softer and thus less likely to pass the selection cuts, making stop discovery impossible when systematic uncertainties are considered. However, the reconstructed top mass cut suppresses top and stop cross-sections by factors of about 12 and 1.6 respectively, drastically enhancing the stop/top ratio. The transverse mass cut further increases the stop/top ratio by suppressing the top cross-section by about 3.3 and the stop cross-section by 1.9.

When extracting new physics signals from top quark events, various uncertainties must be considered beyond experimental statistical and systematic errors. The current uncertainty in the Standard Model t¯t cross-section is at the 5% level [15]. Additional uncertainties from m_t errors will be greatly reduced with the expected precise determination of m_t (within 2.8 GeV and 0.8 GeV for Run 2 and 3 respectively [14]). For illustration, we adopt a total systematic error of 5%. Combined with statistical errors for each run, we obtain the total errors for top quark events listed in Table 2.

In estimating statistical errors, QCD backgrounds (primarily W+jets) are also considered. Under basic selection cuts, they are reduced to about 1/12 of the top events in the + 4j/b + E_T channel [14]. The cut on reconstructed top mass M_top(3j) cannot significantly suppress QCD backgrounds, so we conservatively neglect such suppression. However, the transverse mass cut is expected to suppress QCD W+jets backgrounds significantly because the missing energy originates only from the W decay neutrino, just as in top events. We therefore assume the transverse mass cut suppresses QCD backgrounds by a factor of about 3, as in the top quark case.

As indicated in Tables 1 and 2, although suitable cuts significantly enhance the stop/top ratio, Tevatron Run 1 cannot observe stop events due to insufficient statistics. Even in the favorable case considered (gaugino-like region), stop pair events remain hidden in top pair samples.

For Run 2A with 2 fb^{-1} luminosity, statistical errors remain large. As shown in Table 2, after combining with 5% systematic error, the total errors are 6%, 14%, and 24% under the three selection cuts. Comparing with the stop/top ratios in Table 1 (4%, 30%, and 49% under corresponding cuts), we see that the M_top(3j) and m_T(, p_T^miss) cuts drive sensitivity to the 2 level, still below the discovery limit typically requiring 5 deviation.

For Run 2B (15 fb^{-1}) and Run 3 (30 fb^{-1}), statistical errors are significantly reduced, as shown in Table 2. For example, comparing total errors (5%, 6%, 8% under three cuts) at Run 3 with stop contributions (4%, 30%, 49% under corresponding cuts), we conclude that stop events under M_top(3j) and m_T(, p_T^miss) cuts become observable (5).

At the LHC, large production rates make statistical errors negligible even for low-luminosity runs (e.g., 10 fb^{-1}), so total errors under each selection cut are dominated by the assumed 5% systematic uncertainty. Comparing with stop contributions (5%, 40%, 62% under three cuts), the stop sample after M_top(3j) and m_T(, p_T^miss) cuts will undoubtedly be observable.

In the above stop event results, we fixed the stop mass at 170 GeV. Figures 3 and 4 show the stop/top ratio versus stop mass under basic + m_T(, p_T^miss) + M_top(3j) cuts. The horizontal dotted lines indicate limits required for discovery (5), evidence (3), and exclusion (2) of stop pair production. The LHC (10 fb^{-1}) can discover stops in the 135–215 GeV range, while Tevatron Run 2B (15 fb^{-1}) can discover stops in the 135-175 GeV range. If no discovery occurs, stops lighter than 245 GeV (LHC) or 200 GeV (Tevatron Run 2B) would be excluded at 95% C.L. These results are valid only for the gaugino-like scenario with the specific parameter values from Section 3.

The peaks in Figures 3 and 4 are artifacts of the applied cuts. As stop mass decreases, the stop pair production rate increases, but the b-jet from ˜t1 → ˜ ^+_1 b becomes softer and less likely to pass selection cuts, decreasing the stop/top ratio. At low stop masses, this latter effect dominates, reducing the ratio for decreasing mass. At high stop masses, phase space suppression of the production rate causes the ratio to decrease with increasing mass. The balance of these opposite effects creates the peaks, which shift to higher values for larger partonic center-of-mass energies.

6 Summary and Discussion

We have investigated the detection potential for top-like events from light stop pair production at hadron colliders, considering the case where the lighter stop mass is close to the top quark mass and SUSY parameters allow stop signal extraction. Due to the much lower production rate relative to top quark pair production, extracting stop events from the top sample requires special consideration to enhance the stop/top ratio. Through Monte Carlo simulation with suitable cuts, we find that a stop signal in the +4j/b+ E_T channel may be detectable in top counting experiments at the upgraded Tevatron and LHC.

However, Tevatron Run 1 cannot detect such a stop signal due to insufficient statistics, leaving stop events hidden in top pair samples even if produced. We note that our calculations represent results from a limited set of numerical examples rather than a full scan of the allowed SUSY parameter space. Our results depend on the mass values of the involved sparticles: the stop ˜t1, chargino ˜ ^+_1, and neutralino ˜ ^0_1. To validate our analysis, the stop mass must exceed those of the lightest chargino and neutralino, and their mass spectrum must be gaugino-like. Finally, as noted in Section 3, if the lightest neutralino and chargino are higgsino-like with nearly degenerate masses, the final-state leptons and jets would be too soft to pass our isolation cuts, making the stop signal unobservable and leaving it hidden in top pair samples even at the upgraded Tevatron and LHC.

We emphasize that throughout our analysis we work in the MSSM with R-parity conservation. If R-parity is violated, interesting alternative phenomenology arises in the top-stop sector at Tevatron and LHC energies, some of which has been explored elsewhere [16].

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Cross sections for + 4j/b + E_T from stop and top quark pairs at the Tevatron and LHC. The basic cuts are given in Eqs.(7) and (8). The M_top(3j) and m_T(, p_T^miss) cuts are |M_top(3j) - M_t| > 20 GeV and m_T(, p_T^miss) [50, 100] GeV. Stop events assume M_{˜t1} = 170 GeV, M = 100 GeV, μ = -200 GeV and tan = 1. At least one b-jet tag is assumed with 53% efficiency for Tevatron (1.8 TeV), 85% efficiency for upgraded Tevatron (2 TeV) and LHC. The 'No cut' column gives results with b-tagging but no kinematic cuts. Charge conjugate channels are included.

Expected top quark event numbers in the + 4j/b + E_T channel with associated errors. Total error combines statistical errors and 5% systematic uncertainty.

[Figure 1: see original paper] Transverse mass m_T(, p_T^miss) distribution for + 4j/b + E_T at the Tevatron. Solid curve: stop events with M_{˜t1} = 170 GeV. Dotted curve: top quark events scaled by 0.1.

[Figure 2: see original paper] Reconstructed top quark mass M_top(3j) distribution for + 4j/b + E_T at the Tevatron. Solid curve: stop events with M_{˜t1} = 170 GeV. Dotted curve: top quark events scaled by 0.1.

[Figure 3: see original paper] Solid curve: stop-to-top event ratio versus stop mass under basic + m_T(, p_T^miss) + M_top(3j) cuts for upgraded Tevatron (2 TeV). Horizontal dotted lines show discovery, evidence, and exclusion limits at Run 2B (15 fb^{-1}).

[Figure 4: see original paper] Same as Figure 3, but for LHC with 10 fb^{-1} luminosity.

Note: Figure translations are in progress. See original paper for figures.

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