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Search for Light Top Squarks in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.8 TeV

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Abstract

We present a search for pair produced top squarks, the supersymmetric partners of the top quark, using the DØ detector at the Fermilab Tevatron $p\bar{p}$ collider. We consider a scenario in which the lighter of the two top squarks $\tilde{t}_1$ decays with 100% branching fraction to a charm quark and the lightest neutralino $\tilde{\chi}_1^0$ yielding a signal of two acollinear jets with missing transverse energy. We observe 3 events while we expect 3.5 ± 1.2 events from the known Standard Model processes. We exclude at the 95% confidence level a significant region of the $m_{\tilde{t}_1}$- $m_{\tilde{\chi}_1^0}$ parameter space. The highest $m_{\tilde{t}_1}$ value we exclude is 93 GeV/c^2 with a corresponding $m_{\tilde{\chi}_1^0}$ value of 8 GeV/c^2.

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Supersymmetry (SUSY), a spacetime symmetry, links bosons to fermions by introducing supersymmetric partners (sparticles) to all the Standard Model (SM) particles. SUSY offers a natural solution to the fine–tuning problem of the SM and provides a candidate for dark matter. When combined with Grand Unification Theories, it can produce models consistent with the experimental proton lifetime limit.

We have recently reported the results of a search for squarks and gluinos (the SUSY partners of quarks and gluons) with the DØ detector [1]. There we set limits on squark mass under the assumption that the considered squark $(\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b})$ masses are degenerate. This was justified by a minimal supergravity model which argues that all scalar particles share a common mass above the energy scale where SUSY is broken [2]. A heavy top quark [3], however, means a substantial top quark Yukawa coupling which can drive the top squark mass lower than that of all other squarks, breaking the degeneracy. In addition, possible mixing of the top squark left/right weak eigenstates may result in further splitting of the mass eigenstates, making the lighter state $\tilde{t}_1$ the lightest squark [4]. If such a top squark exists, it could be within the reach of the Tevatron, and if lighter than the top quark, its existence could alter the expected decay patterns of the top quark. The direct production of $\tilde{t}_1\bar{\tilde{t}}_1$ pairs could prove to be a source of additional background to $t\bar{t}$ pair production. The existence of the top squark could also explain the discrepancy between the measured and expected values for $\Gamma(Z \to b\bar{b})$ [5] through a loop diagram at the $Zb\bar{b}$ vertex [6].

In this letter, we present a search for $\tilde{t}_1\bar{\tilde{t}}_1$ pairs produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. We assume conservation of R–parity which implies that sparticles are produced in pairs and that the Lightest Supersymmetric Particle (LSP) must be stable. In addition we assume the lightest neutralino $\tilde{\chi}_1^0$ (a mixture of the SUSY partners of γ, Z, and the neutral Higgs bosons) is the LSP, as is the case in a wide class of SUSY models. We also assume that the decays $\tilde{t}_1 \to b\tilde{\chi}_1^+$, $\tilde{t}_1 \to b\tilde{\chi}_1^{+*}$ ($\tilde{\chi}_1^{+*} \to l\tilde{\nu}$ or $\tilde{\chi}_1^{+*} \to \nu\tilde{l}$), and $\tilde{t}_1 \to bW\tilde{\chi}_1^0$ are kinematically forbidden, where $\tilde{\chi}_1^+$ (a mixture of the SUSY partners of $W^\pm$ and the charged Higgs boson) is the lightest chargino, and $\tilde{\nu}$ and $\tilde{l}$ are the supersymmetric partners of neutrinos and leptons, respectively. Under these assumptions, the top squarks will decay with 100% branching fraction to $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$, yielding an event signature of two acollinear jets (we make no attempt to identify flavor) with missing transverse energy $\not\!\!E_T$ [7]. The major SM backgrounds expected for this signal are multijet events with mismeasured $\not\!\!E_T$ and vector boson production with associated jets.

While the top squark production occurs via gluon fusion and $q\bar{q}$ annihilation [8] and is thus fixed by QCD in terms of $m_{\tilde{t}_1}$, its decay topology is solely determined by $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$. For $m_{\tilde{t}_1} \leq 110$ GeV/c^2, the expected production cross section for $\tilde{t}_1\bar{\tilde{t}}_1$ pairs is larger than the observed production cross section for $t\bar{t}$ pairs as reported by DØ for their central mass value. For $m_{\tilde{t}_1} = 65$ GeV/c^2, the cross section is about 100 pb and for $m_{\tilde{t}_1} = 105$ GeV/c^2, it is about 10 pb.

To analyze the top squark signal characteristics, we generate Monte Carlo (MC) simulated events for various combinations of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$ in the search region of the parameter space using ISAJET 7.13 [9]. This version of ISAJET incorporates the latest implementation of ISASUSY [10]. These events are then processed through a GEANT [11] simulation of the DØ detector and reconstructed.

To study the vector boson associated background, we generate W/Z + jets samples using the MC generator VECBOS [12], interfaced with ISAJET for fragmentation and hadronization. VECBOS allows us to specify the number of primary jets associated with the vector boson production. In counting the final number of jets in an event, hadronic decays of the tau lepton are included in the total. These background samples are passed through the same detector simulation and event reconstruction as the signal events. To study the multijet background, we use data collected using a low E_T single jet trigger.

Data corresponding to a total integrated luminosity of 13.5 ± 0.7 pb^{-1} have been collected using the DØ detector during its 1992–1993 run. DØ is a general purpose detector consisting of a central tracking system and a nearly hermetic uranium–liquid argon calorimeter surrounded by a toroidal muon spectrometer. A detailed description of the DØ detector and data collection systems can be found elsewhere [13]. Events for this analysis were collected using a trigger which required $\not\!\!E_T > 35$ GeV. Jets are found from calorimeter information using a cone algorithm of radius 0.5 in η–ϕ space [14]. The $\not\!\!E_T$ is calculated from the energy deposits in the individual calorimeter cells and is defined to be the negative of the vector sum of the cell transverse energies. More detailed descriptions of the trigger, event filtering, and reconstruction algorithms for electrons, muons, jets, and $\not\!\!E_T$ are given in Ref. [15].

To ensure an unambiguous $\not\!\!E_T$ calculation, we require events to have only one primary vertex. An algorithm that combines timing information from a set of trigger counters with reconstructed scalar E_T and the number of vertices found from tracking information is used to select single interaction events and reduces our data set to a single interaction equivalent luminosity of 7.4 ± 0.4 pb^{-1}.

To select signal events with good efficiency and substantially reduce the multijet background we require $\not\!\!E_T > 40$ GeV and at least two jets with $E_T > 30$ GeV. Sample distributions of $\not\!\!E_T$ and jet E_T for several values of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$ are shown in Fig. 1. The presence of two LSP's suggests that the two highest E_T jets in our signal, $j1$ and $j2$ (ordered in decreasing magnitude of E_T), be acollinear. In Fig. 2(a), distributions of the opening angle between the two jets are shown. We place a cut at $\Delta\phi(j_1, j_2) < 165°$ in order to discriminate against the SM multijet events which tend to have two back–to–back leading jets. An additional cut of $\Delta\phi(j_1, j_2) > 90°$ preserves 70–75% of the signal, while reducing the vector boson background, which tends to exhibit a flatter distribution in $\Delta\phi(j_1, j_2)$ (Fig. 2(b)).

Poorly measured jets can produce apparent $\not\!\!E_T$, but such events usually show a correlation between the jet and $\not\!\!E_T$ directions. If a jet is identified as the leading object in an event by an overestimate of its energy, a false $\not\!\!E_T$ signal will be induced in the direction opposite to that of the jet. Jets with underestimated energy will tend to be aligned with the apparent $\not\!\!E_T$. To suppress these events, we require that $10° < \Delta\phi(\not\!\!E_T, j_1) < 125°$ and for any additional reconstructed jets $10° < \Delta\phi(\not\!\!E_T, j_{2,3,4})$.

Vector boson backgrounds frequently have leptons with large E_T, while signal events have low E_T leptons from charm jets. We remove events with electrons or muons with $E_T > 10$ GeV. This rejects 61% of all events containing leptonic vector boson decays with associated jets, while retaining over 98% of all signal events.

After applying the above selection criteria to our data sample, we obtain a total of three top squark candidate events. Table I summarizes our event selection criteria and the number of events surviving each stage of the selection.

To determine the vector boson associated background in our final sample, we apply the same trigger and event selection criteria to VECBOS Monte Carlo events. Our estimates are shown in Table II. The sum of the predicted W and Z backgrounds is 3.5 ± 1.2 events. To estimate the contribution from Standard Model multijet production, we fit the $\not\!\!E_T$ spectrum of low E_T single jet trigger events and determine the fraction of such events that pass our selection criteria as a function of $\not\!\!E_T$. For our final selection criteria, Standard Model multijet contribution is predicted to be negligible. In order to convince ourselves of the validity of our background estimates, we study the change in the number of candidate events compared with our background estimate as we vary each of the cut values of our selection criteria. Figure 3 shows the behavior of the candidate events observed in the data and the total number of estimated background events when we vary the $\not\!\!E_T$ cut. The background prediction follows the number of candidates extremely well. We obtain similarly good agreement for other cut variables. We conclude that our background estimates are reliable and that we observe no significant excess beyond events explained by the Standard Model.

In order to interpret the null search result for top squark events as an excluded region in the $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ plane, signal detection efficiencies are determined for a grid of values in the plane. The distributions of errors for all parameters are represented as Gaussians. Errors on signal efficiencies and the fraction of background events passing the signal selection cuts include statistical uncertainties from finite MC samples and a systematic uncertainty from the energy scale (about 5%). Uncertainty on the vector boson cross sections includes the systematic uncertainty from VECBOS (10% per jet). Known correlations between signal efficiency and estimated backgrounds were maintained in the calculation. We use a Bayesian approach [16] which applies a flat prior distribution for the signal cross section to determine our 95% confidence level (CL) upper limit.

Our background subtracted 95% CL exclusion limit contour is shown in Fig. 4 along with a previously published limit [17]. This contour intersects the $m_{\tilde{t}_1} = m_{\tilde{\chi}_1^0} + m_b + m_W$ line at $m_{\tilde{\chi}_1^0} = 8$ GeV/c^2 and $m_{\tilde{t}_1} = 93$ GeV/c^2, the highest $m_{\tilde{t}_1}$ value we exclude. The maximum excluded value for $m_{\tilde{\chi}_1^0}$ is 44 GeV/c^2 for $m_{\tilde{t}_1} = 85$ GeV/c^2.

Signal efficiencies are 4–5% along the right edge (where the contour drops off to the $m_{\tilde{t}_1} = m_{\tilde{\chi}_1^0} + m_b + m_W$ line due to the falling cross section). This edge is limited by luminosity, and additional data should push the contour to slightly higher $\tilde{t}_1$ masses. Efficiencies vary between 1 and 3% along the contour's upper edge and vanish within the gap between the LEP limit and our own exclusion region. The gap reflects the impact of our $\not\!\!E_T$ cut which was effectively fixed by the $\not\!\!E_T$ trigger threshold.

In conclusion, we observe three top squark candidate events, a result consistent with SM background predictions. We interpret the null search result for top squark events as an excluded region in the $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ plane. This interpretation is valid under the Minimal Supersymmetric Standard Model as well as a large variety of additional SUSY models. We exclude a significant region of parameter space beyond the LEP limit. The highest $m_{\tilde{t}_1}$ value we exclude is 93 GeV/c^2 with a corresponding $m_{\tilde{\chi}_1^0}$ value of 8 GeV/c^2.

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TABLES

TABLE I. A summary of the selection cuts and the number of events passing each cut.

Selection Cut	Number of Events Passing
Missing E_T trigger/filter	83474
Single primary vertex	44796
Preselection: $\not\!\!E_T > 30$ GeV with two reconstructed jets $\Delta\phi(j_1, j_2) < 170°$ $10° < \Delta\phi(j_{1,2}, \not\!\!E_T)$	2270
$\not\!\!E_T > 40$ GeV	930
$E_T^{j_2} > 30$ GeV	185
$90° < \Delta\phi(j_1, j_2) < 165°$	102
$\Delta\phi(j_1, \not\!\!E_T) < 125°$ $10° < \Delta\phi(j_{3,4}, \not\!\!E_T)$	9
Veto leptons with $E_T > 10$ GeV	3

TABLE II. Predicted vector boson backgrounds generated using VECBOS/ISAJET. Shown with the efficiencies are first the statistical, and then systematic, errors. All uncertainties, including the systematic uncertainty in luminosity, have been combined in the number of predicted events, N_{pred}.

Process	Efficiency	N_{pred} in 7.4 pb^{-1}
$W \to e\bar{\nu}$	$0.036 \pm 0.021^{+0.006}_{-0.001}$	0.50 ± 0.31
$W \to \mu\bar{\nu}$	$0.061 \pm 0.027^{+0.012}_{-0.000}$	0.82 ± 0.38
$W \to \tau\bar{\nu}$	$0.050 \pm 0.041^{+0.052}_{-0.016}$	1.66 ± 0.74
$Z \to \mu\bar{\mu}$	$0.040 \pm 0.040^{+0.003}_{-0.040}$	0.05 ± 0.04
$Z \to \nu\bar{\nu}$	$0.051 \pm 0.051^{+0.043}_{-0.000}$	0.38 ± 0.26
$Z \to \tau\bar{\tau}$	$0.013 \pm 0.009^{+0.000}_{-0.000}$	0.08 ± 0.06
Total		3.49 ± 1.17

FIGURES

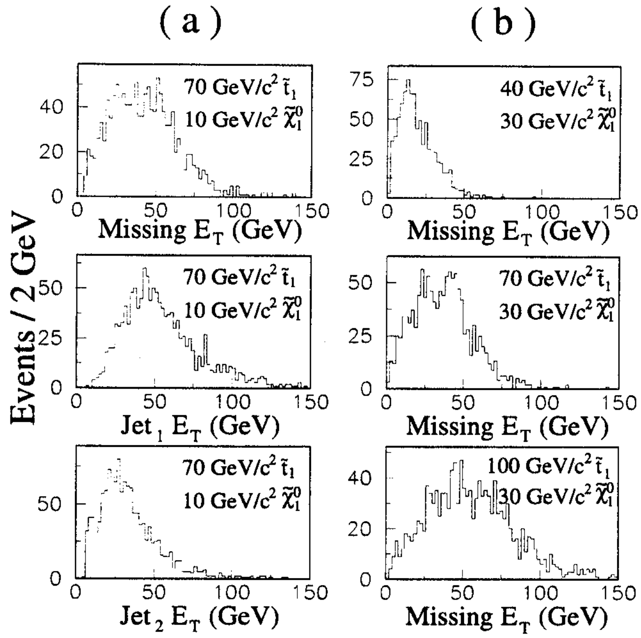

FIG. 1. (a) Monte Carlo $\not{E}_T$ and Jet E_T distributions for $m_{\tilde{t}_1} = 70\ \mathrm{GeV}/c^2$ and $m_{\tilde{\chi}_1^0} = 10\ \mathrm{GeV}/c^2$. (b) Sample $\not{E}_T$ distributions for selected values of $m_{\tilde{t}_1}$ with $m_{\tilde{\chi}_1^0} = 30\ \mathrm{GeV}/c^2$.

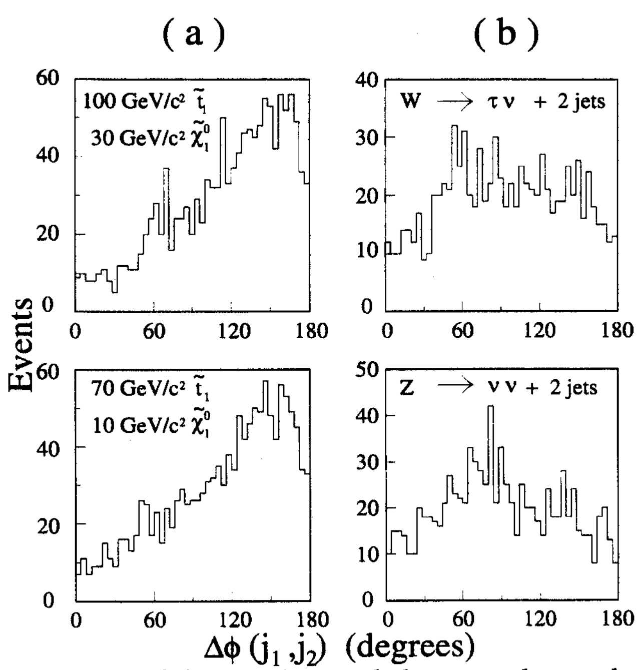

FIG. 2. Sample distributions of the opening angle between the two leading jets for Monte Carlo (a) signal events and (b) selected vector boson backgrounds.

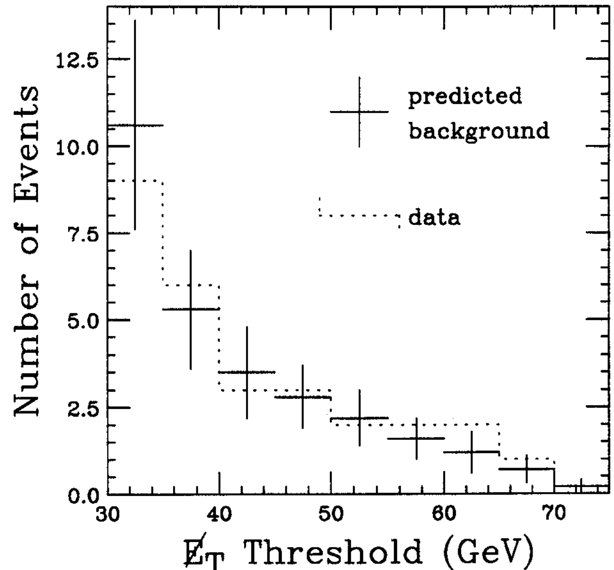

FIG. 3. The effect of varying the $\not{E}_T$ cut. The predicted background is a sum of VECBOS and SM multijet contributions.

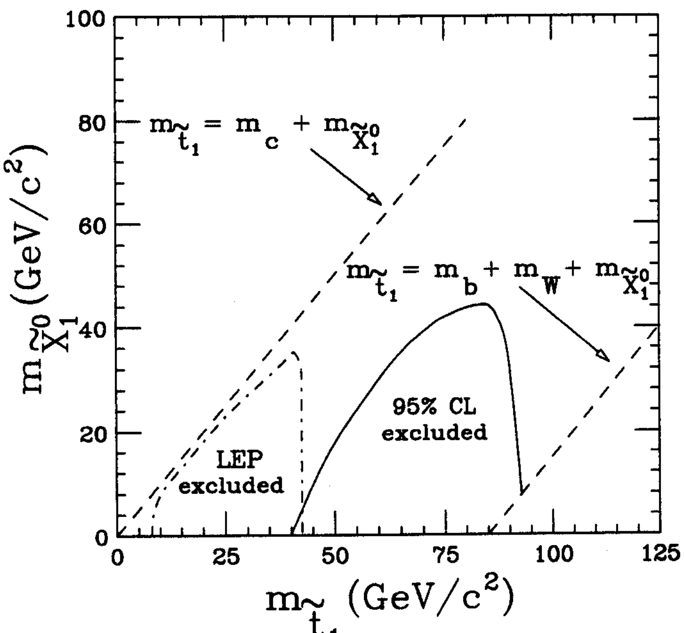

FIG. 4. The DØ 95% Confidence Level exclusion contour. Also shown is the result from the OPAL experiment at LEP [17].