Search for Pair Production of Light Scalar Top Quarks in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Using 85.2 ± 3.6 pb^{-1} of $p\bar{p}$ collisions collected at $\sqrt{s} = 1.8$ TeV with the D0 detector at Fermilab's Tevatron Collider, we present the results of a search for direct pair production of scalar top quarks ($\tilde{t}$), the supersymmetric partners of the top quark. We examined events containing two or more jets and missing transverse energy, the signature of light scalar top quark decays to charm quarks and neutralinos. After selections, we observe 27 events while expecting 31.1 ± 6.4 events from known standard model processes. Comparing these results to next-to-leading-order production cross sections, we exclude a significant region of $\tilde{t}$ and neutralino phase space. In particular, we exclude the $\tilde{t}$ mass $m_{\tilde{t}} < 122$ GeV/c^2 for a neutralino mass of 45 GeV/c^2.

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Supersymmetry (SUSY) [1–3], one of the major extensions of the standard model (SM), introduces additional particle states. For every bosonic SM particle, it assigns a fermionic "superpartner" and for every SM fermion, a boson. The hypothesized SUSY particles include gauginos and scalar quarks or "squarks." The gauginos, superpartners of the gauge particles, include neutralinos (prime candidates for dark matter). Squarks include the left-handed and right-handed scalar top quarks or top squarks. These weak eigenstates mix to provide the mass eigenstates $\tilde{t}_1$ and $\tilde{t}_2$.

Generic SUSY searches often make the simplifying assumption of mass degeneracy of first and second generation squarks. The scalar top quark masses, however, are expected to be substantially smaller than those of all other squarks [4–6]. If sufficiently light, scalar top quarks should be produced strongly at the Fermilab Tevatron through $q\overline{q}$ annihilation and gluon-gluon fusion with a cross section on the order of that of the top quark [7,8]. According to the next-to-leading order program PROSPINO [9], a 100 GeV/c^2 scalar top quark has a production cross section of about 12 pb and a 120 GeV/c^2 scalar top quark of approximately 4.2 pb.

This analysis is sufficiently general that it applies to a broad class of SUSY models. We make no assumptions about gaugino unification, but assume that the lightest neutralino $\tilde{\chi}_1^0$ is the lightest supersymmetric particle, with conservation of R parity guaranteeing its stability. We consider the special case where the scalar top quark is light enough that $m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi}_1^0}$ and $m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^+}$, precluding the decays $\tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0$, $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{+*}$, and $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{+*}$ ($\tilde{\chi}_1^{+*} \rightarrow l^+\tilde{\nu}$ or $\tilde{\chi}_1^{+*} \rightarrow \tilde{l}^+\nu$). The dominant decay is then $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$, yielding an event signature of two jets with missing transverse energy ($\not{E}_T$). We make no attempt to tag the b or c hadrons in jets.

Characteristics of the scalar top quark signal were studied by generating Monte Carlo (MC) events for various combinations of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$, using ISAJET [10] with its implementation of ISASUSY [11]. These events were processed through a GEANT [12] simulation of the D0 detector, a simulation of the trigger, and the standard D0 reconstruction program.

The major SM backgrounds expected for this signal are multijet events with artificial $\not{E}_T$ and vector boson (VB) production with associated jets. The VB backgrounds include those producing neutrinos and jets ($Z + 2$ jets $\rightarrow \nu\nu + 2$ jets and $W +$ jets, where the W boson decays to a hadronically decaying τ lepton), leptons from VB decays that escape detection, or electrons misidentified as jets. PYTHIA [13] was used to predict the acceptance for $W/Z+$jet production, while the VECBOS [14,15] Monte Carlo generator was used for $W/Z + 2$ jets events. In each case, the calculated cross sections were scaled to match internal D0 reconstruction and acceptance studies for $W/Z + n$ jets. We also used the cross section for $t\bar{t}$ production measured at D0 [16] and the HERWIG generator to calculate the acceptance for the $t\bar{t}$ background arising from top quark decays to an undetected charged lepton, a neutrino, and a jet.

The data correspond to an integrated luminosity of 85.2 ± 3.6 pb^{-1} collected during the 1994–1995 Tevatron run. The D0 detector consisted of a central tracking system and a uranium/liquid-argon calorimeter surrounded by a toroidal muon spectrometer. A detailed description of the D0 detector and data collection system can be found in Ref. [17]. Events were collected using a trigger requiring two jets, one with $E_T > 25$ GeV and the second with $E_T > 10$ GeV, and $\not{E}_T > 25$ GeV, but rejecting events in which the direction of the leading jet and the $\not{E}_T$ are aligned within a polar angle of 14°. Jets are reconstructed off-line using an iterative cone algorithm [18] of radius 0.5 in $\eta - \phi$ space. A requirement of at least two jets with $E_T > 50$ GeV, $\not{E}_T > 40$ GeV, and *all jets* satisfying a difference in azimuth $\Delta\phi(\text{jet}, \not{E}_T) > 30°$ guaranteed full trigger efficiency. To suppress VB backgrounds we removed events with electrons or muons with $E_T > 10$ GeV.

Multijet backgrounds dominate this sample and arise when mismeasured jets or a misidentified interaction vertex induce an apparent $\not{E}_T$. Requiring $\Delta\phi(\text{jet}, \not{E}_T) < 165°$ eliminates events with jets back to back to the $\not{E}_T$. We reduce the number of events with poorly measured jet energies by requiring that the $\Delta\phi$ between the $\not{E}_T$ and the jet with the second highest E_T exceed 60°. We also removed those events in which jets deposited most of their energy within the narrow intercryostat region ($0.8 < |\eta| < 1.2$), where the central and end cap calorimeters meet. We refer to the 354 events surviving these criteria as our *base* sample (see Table I).

To reduce the background from mismeasured vertices, the central drift chamber (CDC) was used to associate charged tracks with jets within the fiducial volume of the CDC, $|\eta_d| < 1$ [19]. Event by event these tracks establish the origin of each jet, which was required to be no farther

TABLE I. Number of events surviving in the jets + $\not{E}_T$ sample after the application of selection criteria. These 88 events form the clean sample.

Selection	Events
2 jets and $\not{E}_T$ trigger	536 678
No detector malfunction or accelerator noise	487 715
Leading jet $E_T > 50$ GeV	205 461
Second jet $E_T > 50$ GeV	106 505
$\not{E}_T > 40$ GeV	13 752
$30 < \Delta\phi(\text{jet}, \not{E}_T) < 165°$	4 650
$60 < \Delta\phi(\text{jet } 2, \not{E}_T)$	2 327
Lepton rejection	2 009
All jets reside outside D0 intercryostat region	354
Vertex confirmation	88

TABLE II. A comparison of standard model and QCD multijet backgrounds to the number of candidates in the clean and final RGS optimized samples. For $W/Z/t\bar{t}$ the first uncertainty is statistical, the second systematic. For QCD and the total observed, the statistical and systematic uncertainties have been added in quadrature.

Source	Events in *clean* sample	Events in optimized sample
W/Z	$63.0 \pm 6.9^{+18.1}_{-12.4}$	$24.2 \pm 3.6^{+9.0}_{-6.3}$
$t\bar{t}$	$3.9 \pm 0.02^{+0.2}_{-0.5}$	$3.4 \pm 0.02^{+0.2}_{-0.04}$
QCD multijet	22.5 ± 7.5	3.6 ± 1.4
Total background	89.5 ± 14.7	31.1 ± 6.4
Data	88	27

than 8 cm from the reconstructed event vertex. This *vertex confirmation* was 80% efficient for $W \rightarrow e\nu$ data samples in which electron tracks matched to electromagnetic calorimeter showers provided well-defined interaction vertices, while keeping the mismatched rate below 2%. Table I lists the observed number of events from the jets plus $\not{E}_T$ sample that survive each selection cut down to this *clean* sample.

To predict the multijet background remaining in the clean sample, we used events from the base sample where the jet vertex position deviated by 15–50 cm from the event vertex. We normalized this *background* sample to the clean sample using events with $\Delta\phi(\text{jet } 2, \not{E}_T) < 60°$ (where jet 2 refers to the jet with the second largest E_T). We chose the 50 cm value because it provides the best agreement between the background prediction and the data for the $\not{E}_T$ region between 30 and 40 GeV, which is dominated by multijet events. Changing this value to 100 cm (the full width of the instrumented interaction region) increases the multijet prediction by 22%, which we take as an estimate of the systematic uncertainty of the method. Reversing the order of the vertex confirmation and $\Delta\phi(\text{jet } 2, \not{E}_T)$ selection with no change in the relative pass rate of events from our base sample showed they provide a legitimate criteria for separating subsets for this study. VB background, which includes, in decreasing order of importance $W \rightarrow \tau + \nu + 2$ jets, $Z \rightarrow \nu + \nu + 2$ jets, and $W \rightarrow \mu + 2$ jets, is comparable to the predicted background from multijet production (see Table II).

A random grid search (RGS) [20] based on the energy of the two leading jets and the $\not{E}_T$ was used to optimize the final selection criteria to apply to the clean sample. RGS uses Monte Carlo–generated scalar top quark events to investigate the region of phase space most heavily populated by signal. The RGS was run for the mass points, $m_{\tilde{t}} = 115\ \text{GeV}/c^2$ and $m_{\tilde{\chi}_0} = 20\ \text{GeV}/c^2$, and $m_{\tilde{t}} = 130\ \text{GeV}/c^2$ and $m_{\tilde{\chi}_0} = 30\ \text{GeV}/c^2$ optimizing rejection of background relative to signal by maximizing the quantity $N_{\text{signal}}/\sqrt{N_{\text{signal}} + N_{\text{background}}}$. This was subject to the requirements of $> 2\%$ efficiency for signal, while restricting multijet backgrounds to account for no more than 50% of the total background. The selection criteria as determined by RGS for each mass point was within 1–2 GeV of our final cuts, chosen to be leading jet $E_T > 60$ GeV, second jet $E_T > 50$ GeV, and $\not{E}_T > 60$ GeV. Our final sample and estimated background are reported in Table II. Figure 1 compares data and background for several physics distributions. The additional contribution for a 130 GeV$/c^2$ scalar top quark, 30 GeV$/c2$ neutralino signal is indicated by the cross-hatched regions on the figure.

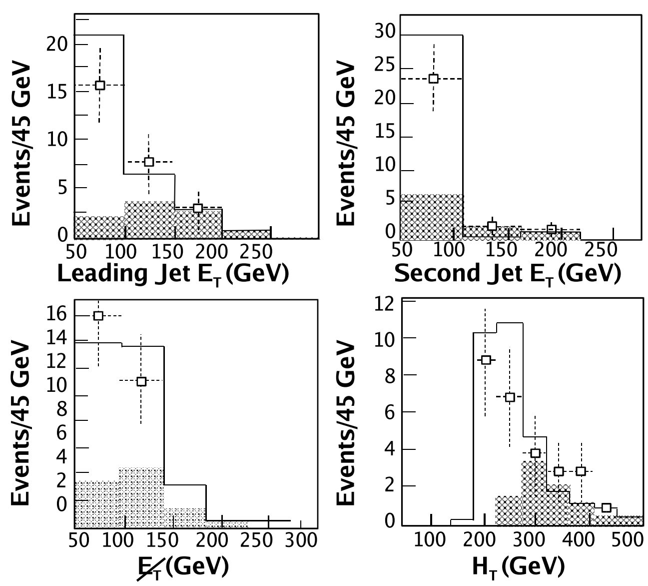

FIG. 1. Data (points) and predicted background (histograms) after final selections. The additional contributions expected from a $M_{\tilde{t}} = 130\ \text{GeV}/c^2$, $M_{\tilde{\chi}_0} = 30\ \text{GeV}/c^2$ scalar top quark are shown by shaded histograms. The plots correspond to the E_T of the leading jet, second jet, $\not{E}_T$ (the three parameters optimized using the RGS), and H_T, where $H_T = \not{E}_T + \Sigma_i E_T(\text{jet}_i)$, to demonstrate agreement with variables not directly optimized via RGS.

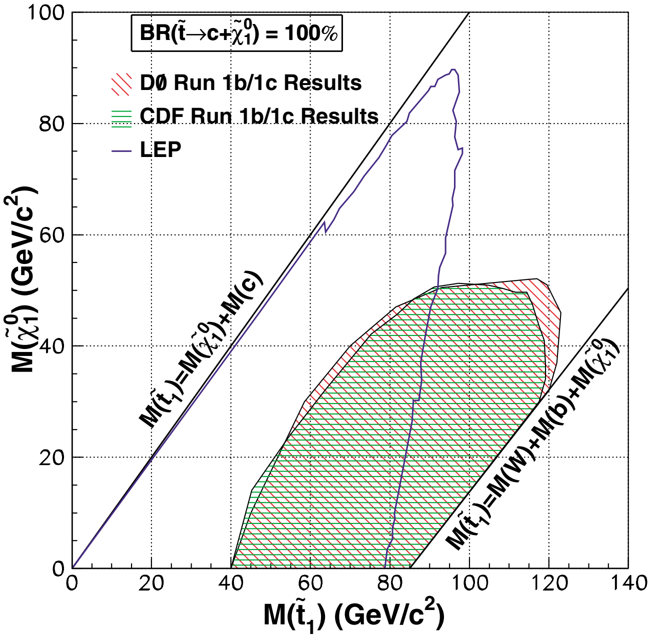

FIG. 2 (color online). Regions in the $(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$ plane excluded at the 95% confidence level assuming 100% branching of $\tilde{t} \rightarrow c\chi_1^0$. Limits from the CERN e^+e^- collider LEP [21] and Collider Detector and Fermilab (CDF) [22] are also shown in the figure. The dashed lines correspond to kinematic cutoffs from the masses of the χ_1^0, m_c, m_b, and m_W.

We find the number of observed events is consistent with expected background. Errors on signal efficiencies and the fraction of background events passing final selection include the statistical uncertainties from finite MC samples and systematics from the jet energy scale (about 7%), luminosity (4.3%), and W/Z cross sections (about 6%). The systematic uncertainty in simulating the trigger is dominated by a hardware trigger response (introducing a 5% uncertainty in acceptance). The systematic uncertainty in identifying leptons in data ranged from 2%–12% (with dependence on the detector $\eta - \phi$ position of the lepton and jet multiplicity), and the vertex confirmation procedure includes a systematic 1% in its efficiency. The signal acceptance of the final selection for a scalar top quark mass of $M_{\tilde{t}} = 115\ \mathrm{GeV}/c^2$, $M_{\tilde{\chi}_0} = 40\ \mathrm{GeV}/c^2$ was $2.7\% \pm 0.1\%$. This null result can be represented by a region of exclusion in the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ plane, which is shown in Fig. 2 (along with results from previous experiments). A Bayesian method, using a flat prior for the signal cross section and Gaussian priors for background and acceptance, sets the 95% confidence level (C.L.) upper limits. The highest excluded scalar top quark mass value excluded is 122 GeV$/c^2$ for a neutralino mass of 45 GeV$/c^2$. The highest excluded neutralino mass excluded is 52 GeV$/c^2$ for a 117 GeV$/c^2$ scalar top quark mass.

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