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# Search for Scalar Top Quark Production in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.8 TeV

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We have searched for direct production of scalar top quarks at the Collider Detector at Fermilab in 88 $\mathrm{pb}^{-1}$ of $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV. We assume the scalar top quark decays into either a bottom quark and a chargino or a bottom quark, a lepton, and a scalar neutrino. The event signature for both decay scenarios is a lepton, missing transverse energy, and at least two $b$-quark jets. For a chargino mass of 90 $\mathrm{GeV}/c^2$ and scalar neutrino masses of at least 40 $\mathrm{GeV}/c^2$, we find no evidence for scalar top production and present upper limits on the production cross section in both decay scenarios.

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The minimal supersymmetric extension to the standard model (MSSM) [1] assigns a scalar supersymmetric partner for every standard model fermion and a fermionic superpartner for every standard model boson. The weak eigenstates of each scalar superpartner mix, forming mass eigenstates [2]. The splitting of the mass eigenvalues is proportional to the mass of the standard model partner. Therefore, the superpartners of the top quark weak eigenstates, $\tilde{t}_L$ and $\tilde{t}_R$, may have the largest mass splitting of all the scalar quarks (squarks). The running of the squark mass parameters is proportional to the Yukawa coupling of the standard model partners, such that the diagonal elements of the $\tilde{t}_L, \tilde{t}_R$ mass matrix should be smaller than those of the other squarks [2]. Thus, the lighter scalar top mass eigenstate, $\tilde{t}_1$, is the best candidate for the lightest squark and is potentially lighter than the top quark. We report the results of a search for direct production of $\tilde{t}_1\overline{\tilde{t}}_1$ in $88 \pm 4$ $\mathrm{pb}^{-1}$ of data collected during the 1994–1995 Tevatron run using the Collider Detector at Fermilab (CDF).

The CDF detector has been described elsewhere [3]. In this analysis, we used electrons identified in the central electromagnetic calorimeter which covers the pseudorapidity region $|\eta| < 1.1$. We used muons identified by tracks in drift chambers in two detector subcomponents outside the calorimeters. The first muon subsystem is located behind five absorption lengths of material and covers the region $|\eta| < 0.6$. The second is located behind an additional three absorption lengths of material and has the same $\eta$ coverage as the first.

Scalar tops could be strongly produced in the Tevatron via $q\overline{q}$ annihilation and gluon-gluon fusion. We searched for $\tilde{t}_1\overline{\tilde{t}}_1$ production within the framework of the MSSM for the case where $m_{\tilde{t}_1} < m_t$. We assumed $R$ parity [2] is conserved and restricted ourselves to two separate $\tilde{t}_1$ decay modes [4]. In the first, the decay $\tilde{t}_1 \to b\tilde{\chi}_1^+$, where $\tilde{\chi}_1^+$ is the lightest chargino, proceeds with a branching ratio of 100% (unless otherwise noted, decay channels imply their charge conjugates). We required one of the charginos, which decay via a virtual $W$, to decay as $\tilde{\chi}_1^+ \to e^+\nu\tilde{\chi}_1^0$ or $\mu^+\nu\tilde{\chi}_1^0$, where $\tilde{\chi}_1^0$ is the lightest neutralino, with an assumed branching ratio of 11% for each lepton type [5]. For models where $\tilde{t}_1 \to b\tilde{\chi}_1^+$ is not kinematically allowed, we considered a second decay scenario in which $\tilde{t}_1 \to bl^+\tilde{\nu}$, where $\tilde{\nu}$ is a scalar neutrino and each $l = e, \mu, \tau$ has a branching ratio of 33.3%. In these two scenarios, either the $\tilde{\chi}_1^0$ or the $\tilde{\nu}$ is the lightest supersymmetric particle (LSP) and does not decay. A third possible decay scenario in which the $\tilde{t}_1 \to c\tilde{\chi}_1^0$ branching ratio is 100% is the subject of separate CDF searches [6].

In both decay scenarios considered here, the $\tilde{t}_1$ signature is at least one isolated lepton, missing transverse energy ($\not{E}_T$) from the neutral LSP's and at least two jets from the $b$ quarks. This signature is very similar to that of the top quark, with kinematic differences due to the smaller $\tilde{t}_1$ mass in our search region, the presence of two massive neutralinos in the final state, and the absence of a real $W$ in the final state. We therefore expect events with lower lepton $p_T$, lower jet $E_T$ and multiplicity, and without a peak in the lepton-$\not{E}_T$ transverse mass. To remain efficient for the smaller $\tilde{t}_1$ mass, we used data collected with the low-$p_T$ electron and muon triggers described in Ref. [7]. These trigger thresholds were $E_T \geq 8$ GeV for electrons and $p_T \geq 8$ GeV$/c$ for muons.

The data for this analysis were obtained by requiring (i) an electron with $E_T \geq 10$ GeV or muon with $p_T \geq 10$ GeV$/c$ originating from the primary vertex and passing lepton identification cuts, (ii) $\not{E}_T \geq 25$ GeV, and (iii) at least two jets with cone sizes of $R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.7$, one with $E_T \geq 12$ GeV and the second with $E_T \geq 8$ GeV. The lepton identification cuts were identical to those used in previous CDF analyses [8,9]. For electron identification, the electron was required to have lateral and longitudinal shower profiles consistent with those of an electron, have less than 5% of its energy deposited in the hadronic calorimeter, and be well matched to a track from the central tracking chamber (CTC). A muon was required to have tracks in the inner and outer central muon chambers which were well matched to a track from the CTC. We further required the leptons to pass an isolation cut in which the calorimeter $E_T$ in a cone of $R = 0.4$ around the lepton was less than 2 GeV (excluding the lepton tower). No explicit tau identification was conducted, so tau events were recorded via their leptonic decays.

We used the SVX$'$ detector to identify secondary vertices from $b$ quark decays and selected events with at least one secondary vertex. The tagging algorithm is described in Ref. [8] with improvements given in Ref. [10] and efficiency measured in Ref. [11]. We reduced the Drell-Yan background in our sample by removing events with two isolated, opposite-sign leptons. This background was further reduced by removing events with an isolated lepton that reconstructed an invariant mass $\geq 50$ GeV$/c^2$ with any additional, isolated CTC track. Finally, we reduced the background from $b\overline{b}$ events and events with hadrons misidentified as leptons (fake leptons) by requiring that the $\Delta\phi$ between the $\not{E}_T$ direction and the nearer of the two highest-$E_T$ jets be $\geq 0.5$ rad. This reduces fake $\not{E}_T$ due to jet energy mismeasurement. The number of events remaining in our sample after all cuts is 81.

Signal and background selection cut efficiencies were estimated using a variety of Monte Carlo generators followed by a CDF detector simulation. Signal event samples were created using ISAJET version 7.20 [12]. The supersymmetric particle masses used in signal simulation were $m_{\tilde{\chi}_1^\pm} = 90$ GeV$/c^2$, $m_{\tilde{\chi}_1^0} = 40$ GeV$/c^2$, and $m_{\tilde{\nu}} \geq 40$ GeV$/c^2$, which are consistent with current lower limits [13]. The signal selection efficiency increases with $m_{\tilde{t}_1}$ but decreases with $m_{\tilde{\nu}}$ (and would also decrease with $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^0}$), reaching a plateau as event energies advance from cut thresholds [14]. Some specific efficiencies are 5.4% for $\tilde{t}_1 \to bl^+\tilde{\nu}$ ($m_{\tilde{t}_1} = 130$ GeV$/c^2, m_{\tilde{\nu}} = 40$ GeV$/c^2$) and 0.7% for $\tilde{t}_1 \to b\tilde{\chi}_1^+$ ($m_{\tilde{t}_1} = 120$ GeV$/c^2, m_{\tilde{\chi}_1^\pm} = 90$ GeV$/c^2$, and $m_{\tilde{\chi}_1^0} = 40$ GeV$/c^2$). These selection efficiencies include branching ratios of forced decays.

The significant sources of uncertainty for signal selection efficiency are (i) the $b$-jet tagging efficiency, (ii) the trigger efficiencies, (iii) the luminosity, and (iv) initial- and final-state radiation. The effects of some of these sources vary with $m_{\tilde{t}_1}$, but none contribute more than 10% to the overall uncertainty, which is less than 16% for all $m_{\tilde{t}_1}$ considered.

Standard model backgrounds come from any process that can produce two or more jets, either real or fake leptons, and real or fake $\not{E}_T$. This includes heavy flavor quark production, vector boson production with two or more accompanying jets, and inclusive jet production with real or fake leptons. The number of events from the first two processes that we expected in our data sample was predicted using measured or calculated cross sections and selection efficiencies determined from Monte Carlo. Top-pair and single-top production were simulated using HERWIG version 5.6 [15]. For $m_t = 175$ GeV$/c^2$ $\sigma_{t\bar{t}}$ is $5.1 \pm 1.6$ pb [11] and $\sigma_{t\bar{b}}$ for $W$-gluon fusion from a next-to-leading-order (NLO) calculation is $1.70 \pm 0.15$ pb [16]. Vector boson samples were generated using VECBOS version 3.03 [17] and normalized according to CDF measurement [18]. Drell-Yan, $b\overline{b}$, and $c\overline{c}$ samples were generated with ISAJET version 7.06 and normalized to independent CDF data samples.

To determine the number of events with fake leptons in our sample, we used a data sample passing all our selection cuts with the exceptions of a modified $\not{E}_T$ requirement ($15 \leq \not{E}_T \leq 20$ GeV) and no requirement on $\Delta\phi(\not{E}_T$, nearer jet). The number of fake lepton events was normalized to this data sample, which contained negligible signal, after other backgrounds were subtracted. The number of fake lepton events was then extrapolated to the signal region using cut efficiencies determined from an independent fake-lepton event sample [14].

TABLE I. Number of data events and expected background events after all selection cuts. The dominant sources of uncertainty on the numbers of expected events are integrated luminosity, cross section, trigger efficiency, and $b$-jet tagging. (Fake leptons are hadron tracks which have been misidentified as leptons.)

| Process | Number of events expected after all cuts |
|---|---|
| $W^\pm(\to e^\pm\nu$ or $\mu^\pm\nu) + \geq 2$ jets | $44.5 \pm 7.3$ |
| $t\overline{t}$ | $17.8 \pm 4.5$ |
| $b\overline{b}$ | $5.8 \pm 0.8$ |
| $W^\pm(\to \tau^\pm\nu) + \geq 2$ jets | $2.6 \pm 0.4$ |
| $t\overline{b}$ (from $W - g$ fusion) | $1.6 \pm 0.2$ |
| $Z(\to e^+e^-$ or $\mu^+\mu^-) + \geq 2$ jets | $1.4 \pm 0.2$ |
| $Z(\to \tau^+\tau^-) + \geq 1$ jet | $0.4 \pm 0.1$ |
| $\gamma \to l^+l^-$ | $0.4 \pm 0.1$ |
| $c\overline{c}$ | $0.06 \pm 0.02$ |
| Fake lepton events | $12.7 \pm 1.6$ |
| Background total | $87.3 \pm 8.8$ |
| Data | 81 |

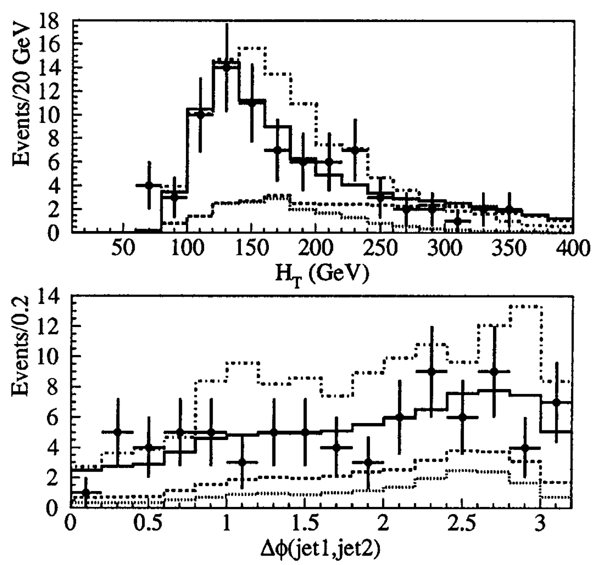


FIG. 1. Results of the two-dimensional fit to $H_T$ and $\Delta\phi$(jet1, jet2) when the $\tilde{t}_1 \to b\tilde{\chi}_1^+$ branching ratio is 100%, $m_{\tilde{t}_1} = 115$ GeV$/c^2$, $m_{\tilde{\chi}_1^\pm} = 90$ GeV$/c^2$, and $m_{\tilde{\chi}_1^0} = 40$ GeV$/c^2$. The quantities $H_T$ and $\Delta\phi$(jet1, jet2) are defined in the text. The points represent the data. There is one $H_T$ overflow. Cumulative contributions from $b\overline{b}$ and fake lepton events, $t\overline{t}$, and $W^\pm \to l^\pm\nu$ + jets are represented by dotted, dashed, and solid lines, respectively. There is no significant contribution from signal. To illustrate the shape difference, a signal distribution with arbitrary normalization has been overlaid with a dot-dashed line.

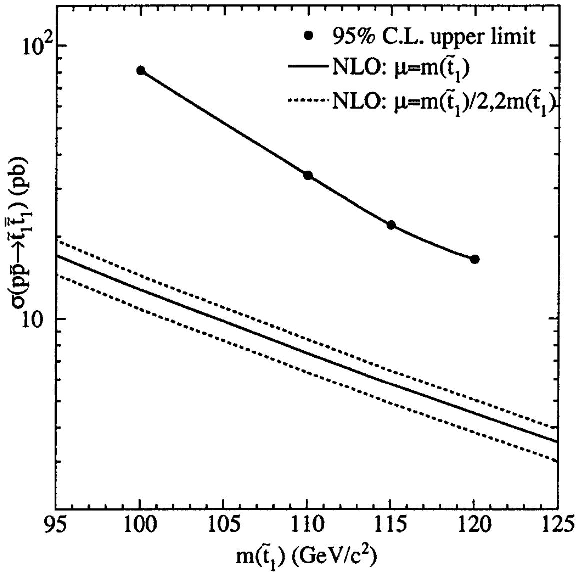


FIG. 2. The points represent the CDF 95% C.L. cross section limit as a function of $\tilde{t}_1$ mass when the $\tilde{t}_1 \to b\tilde{\chi}_1^+$ branching ratio is 100%, $m_{\tilde{\chi}_1^\pm} = 90$ GeV$/c^2$, and $m_{\tilde{\chi}_1^0} = 40$ GeV$/c^2$. The line without markers represents the NLO prediction for $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$ using the renormalization scale $\mu = m_{\tilde{t}_1}$. The dashed lines represent the NLO cross section for $\mu = m_{\tilde{t}_1}/2$ and $\mu = 2m_{\tilde{t}_1}$.

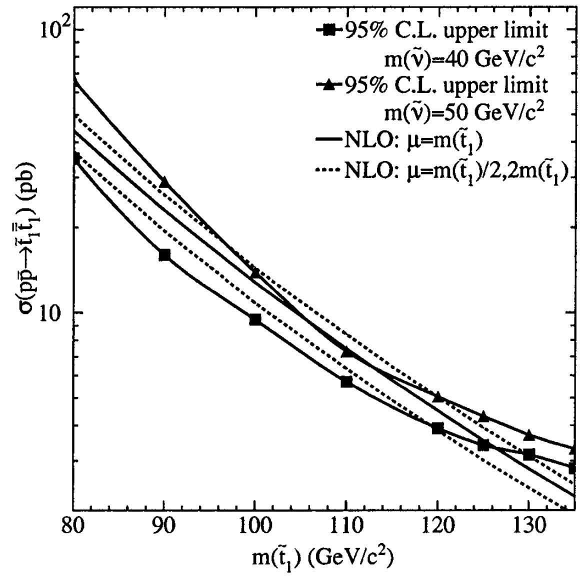


FIG. 3. CDF 95% C.L. cross section limit as a function of $\tilde{t}_1$ mass when the $\tilde{t}_1 \to bl^+\tilde{\nu}$ branching ratio is 100% and $m_{\tilde{\nu}} = 40$ GeV$/c^2$ (squares) or 50 GeV$/c^2$ (triangles). The line without markers represents the NLO prediction for $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$ using the renormalization scale $\mu = m_{\tilde{t}_1}$. The dashed lines represent the NLO cross section for $\mu = m_{\tilde{t}_1}/2$ and $\mu = 2m_{\tilde{t}_1}$.

The complete list of backgrounds and the number of expected events remaining after all cuts is given in Table I. The significant backgrounds are $t\bar{t}$, $b\bar{b}$, $W^\pm(\to l^\pm\nu) + \geq 2$ jets, and fake lepton events. The number of data events agrees well with the expected background.

To determine the number of potential signal events in this final data sample, we performed extended, unbinned likelihood fits for each $\tilde{t}_1$ mass considered for both decay scenarios. The likelihood fits compared the shapes of distributions of the signal and background and included Gaussian terms tying the fit background levels to their predicted levels. The fit parameters were the numbers of signal events, $t\bar{t}$ events, $b\bar{b}$ plus fake lepton events, and vector boson events (represented in the fit by the $W^\pm + \geq 2$ jets distributions). We used the Kolmogorov statistic applied to the simulated distributions of signal and combined backgrounds to determine the most sensitive kinematic distributions to use in the fit. The kinematic distributions evaluated include lepton $p_T$, $H_T$ (the scalar sum of lepton $E_T$, $\not{E}_T$, and jet $E_T$ for all jets with $E_T \geq 8$ GeV), jet multiplicity, and $\Delta\phi$(jet1, jet2), where jets are ordered in $E_T$.

For the $\tilde{t}_1 \to b\tilde{\chi}_1^+$ decay, sensitivity to signal was greatest for a two-dimensional fit to the combined probability distributions for $H_T$ and $\Delta\phi$(jet1, jet2). Fit results at all masses were consistent with zero signal events. The fit result for $\tilde{t}_1 \to b\tilde{\chi}_1^+$ with $m_{\tilde{t}_1} = 115$ GeV$/c^2$, $m_{\tilde{\chi}_1^\pm} = 90$ GeV$/c^2$, and $m_{\tilde{\chi}_1^0} = 40$ GeV$/c^2$ is shown in Fig. 1. The 95% C.L. limits on $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$ for this decay are shown in Fig. 2 as a function of $m_{\tilde{t}_1}$ [19]. The NLO prediction for $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$ using the renormalization scale $\mu = m_{\tilde{t}_1}$ and parton distribution function CTEQ3M is shown in Fig. 2 for comparison [20].

For the $\tilde{t}_1 \to bl^+\tilde{\nu}$ decay scenario, sensitivity to signal was greatest for a fit to the $H_T$ distribution. Again, all fit results were consistent with zero signal events. The 95% C.L. limits on $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$ for the $\tilde{t}_1 \to bl^+\tilde{\nu}$ decay are shown in Fig. 3 for $m_{\tilde{\nu}} = 40$ and 50 GeV$/c^2$. We consider the

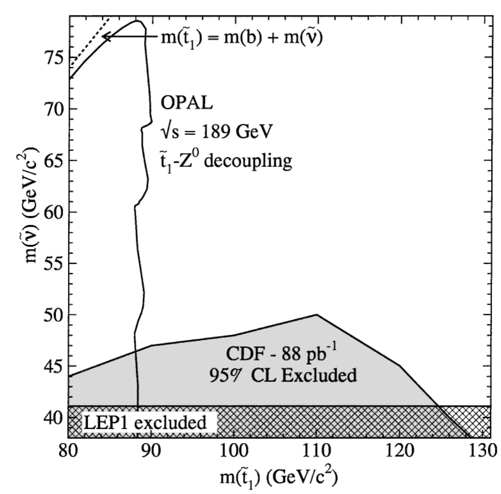


FIG. 4. 95% C.L. excluded region in the plane of $m_{\tilde{t}_1}$ versus $m_{\tilde{\nu}}$ when the $\tilde{t}_1 \to be^+\tilde{\nu}$, $\tilde{t}_1 \to b\mu^+\tilde{\nu}$, and $\tilde{t}_1 \to b\tau^+\tilde{\nu}$ branching ratios are 33.3%. We define the exclusion region as that region of supersymmetric parameter space for which the 95% C.L. limit on $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$ is less than the NLO prediction ($\mu = m_{\tilde{t}_1}$). The LEP1 $m_{\tilde{\nu}}$ limit and OPAL excluded region in the $m_{\tilde{t}_1}$ versus $m_{\tilde{\nu}}$ plane are also shown [21]. The OPAL excluded region corresponds to the case in which the $\tilde{t}_1$ decouples from the $Z^0$.

regions of supersymmetric parameter space for which the 95% C.L. limit on $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$ is less than the NLO prediction ($\mu = m_{\tilde{t}_1}$) to be excluded. The resulting excluded region in the plane of $m_{\tilde{t}_1}$ versus $m_{\tilde{\nu}}$ is shown in Fig. 4.

To conclude, we have searched for direct $\tilde{t}_1\bar{\tilde{t}}_1$ production in 88 $\pm$ 4 pb$^{-1}$ of data collected using the CDF detector during the 1994–1995 Tevatron run. We found no evidence for $\tilde{t}_1\bar{\tilde{t}}_1$ production for either $\tilde{t}_1 \to b\tilde{\chi}_1^+$ or $\tilde{t}_1 \to bl^+\tilde{\nu}$ and present upper limits on $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$ as a function of $m_{\tilde{t}_1}$.

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