Search for Pair Production of Scalar Top Quarks Decaying to a τ Lepton and a b Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We search for pair production of supersymmetric top quarks ($\tilde{t}_1$), followed by R-parity violating decay $\tilde{t}_1 \to \tau b$ with a branching ratio β, using 322 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected by the upgraded Collider Detector at Fermilab. Two candidate events pass our final selection criteria, consistent with the standard model expectation. We set upper limits on the cross section $\sigma(\tilde{t}_1\bar{\tilde{t}}_1) \times \beta^2$ as a function of the top-squark mass $m(\tilde{t}_1)$. Assuming $\beta = 1$, we set a 95% confidence level limit $m(\tilde{t}_1) > 153\ \text{GeV}/c^2$. The limits are also applicable to the case of a third-generation scalar leptoquark (LQ_3) decaying $LQ_3 \to \tau b$.

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In supersymmetric (SUSY) models [1], the spin-1/2 quarks and leptons have spin-0 quark and lepton partners. Experimental data suggest that the superpartners of the first and second generations are heavier than those of the standard model (SM) particles, while the mass of the lighter scalar top quark (top squark or $\tilde{t}_1$) is weakly constrained and can be below that of the top quark [2]. This is due to the mixing between the left- and right-handed interaction eigenstates which is a function of the large Yukawa coupling of the top quark. At the Fermilab Tevatron, scalar top quarks and antiquarks can be produced in pairs in strong interactions ($gg/q\bar{q} \rightarrow \tilde{t}_1\bar{\tilde{t}}_1$). A single top squark could also be produced at the Tevatron, e.g., via $bg \rightarrow \tilde{t}_1\tau$ [3]; however, unlike pair production, this process requires an R-parity (R_p) violating vertex. In regions of parameter space not excluded by data, R_p violating ($\not{R}_p$) couplings are small [4], making single top-squark production negligible compared to pair production. Top squarks can decay into lighter SUSY and SM particles if R_p is conserved or into ordinary quarks and/or leptons if R_p is violated. Within the framework of $\not{R}_p$ SUSY [4], theoretical studies indicate that the dominant decay mode for the light top squark is the lepton number violating decay $\tilde{t}_1 \rightarrow \tau b$ for a wide range of SUSY model parameters, including the region allowed by neutrino oscillation data [5].

Leptoquarks appear in various SM extensions [6]. Charge $2/3$ and $4/3$ third-generation scalar leptoquarks (LQ_3) are expected to decay into τ and b with $\mathcal{B}(LQ_3 \rightarrow \tau b) = 1$ for all LQ_3 states when $m(LQ_3) < m(t)$. The next-to-leading-order (NLO) cross section for $LQ_3\overline{LQ}_3$ production is very close to the $\tilde{t}_1\bar{\tilde{t}}_1$ production cross section $\sigma(\tilde{t}_1\bar{\tilde{t}}_1)$ as diagrams with virtual gluino exchange are strongly suppressed with the existing limits on the gluino mass [7]. Thus, the limits obtained for the $\not{R}_p$ top squark should be fully applicable to the LQ_3 case.

In this Letter, we describe a search for $\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow \tau^+\tau^- b\bar{b}$ with the upgraded Collider Detector at Fermilab (CDF II) [8] and set an upper limit on $\sigma(\tilde{t}_1\bar{\tilde{t}}_1) \times \beta^2$, neglecting additional decay modes that may pass selections of this analysis when $\beta \equiv \mathcal{B}(\tilde{t}_1 \rightarrow \tau b) < 1$. We look for a final state with either an electron or a muon from the decay $\tau \rightarrow \ell\nu_\ell\nu_\tau$ ($\ell = e$ or μ), a hadronically decaying tau τ_h, missing transverse energy $\not{E}_T$ [9] from the neutrinos, and two or more jets. We do not require jets to be consistent with originating from the hadronization of a b quark, as our studies have shown that the increase in purity from such a requirement would be outweighed by the loss in signal acceptance. This analysis uses approximately 3 times more data at a higher $\sqrt{s}$ than the previous CDF result [10] that set a 95% C.L. limit of $m(\tilde{t}_1) > 122\ \mathrm{GeV}/c^2$. The increased $\sqrt{s}$ is expected to give a substantial increase in the $\tilde{t}_1\bar{\tilde{t}}_1$ production rate, e.g., $\sim$35% for $m(\tilde{t}_1) = 155\ \mathrm{GeV}/c^2$.

CDF II features several main subsystems critical to this analysis. The tracking system consists of multilayer silicon detectors and an open-cell cylindrical drift chamber enclosed in a 1.4 T superconducting magnet. At $|\eta| < 1$ [9] charged particle trajectories traverse all chamber layers, while at larger $|\eta|$ the chamber coverage is reduced progressively. The calorimeter system is organized into electromagnetic and hadronic sections segmented in a projective tower geometry and covers $|\eta| < 3.6$. A set of strip and wire chambers is located within the central electromagnetic calorimeter at approximately the depth of shower maximum and aids in reconstructing electrons and photons for $|\eta| < 1.1$. The muon detection system is located outside of the calorimeter and covers $|\eta| < 1.0$.

The analysis begins with a data sample collected by inclusive lepton-plus-track triggers [11]. These triggers select events containing an electron (muon) candidate with $E_T > 8$ GeV ($p_T > 8\ \mathrm{GeV}/c$) and a second track, which is required to be consistent with originating from a tau decay by demanding that there be no other nearby tracks with $p_T > 1.5\ \mathrm{GeV}/c$ between the cones of 0.175 and 0.524 radians around the track. The integrated luminosity of the data sample is $L_{\mathrm{int}} = 322 \pm 19\ \mathrm{pb}^{-1}$ [12].

We select events off-line by identifying at least one lepton with $p_T{}^{\ell} > 10\ \mathrm{GeV}/c$ and at least one τ_h candidate in $|\eta| < 1$. The details of the τ_h identification algorithm can be found in Refs. [13,14]. We require $p_T^{\tau} > 15\ \mathrm{GeV}/c$. Jets are reconstructed using a fixed-cone algorithm with $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ within $|\eta| < 2.4$.

The dominant SM backgrounds are vector boson production, QCD, and $t\bar{t}$ production. In QCD multijet events, for example, semileptonic b quark decays or γ conversions can be selected as lepton candidates, and narrow jets can be misidentified as τ_h candidates. We require the sum of the p_T of the tracks within $\Delta R < 0.4$ around the lepton candidate (I_{trk}) to be less than 2 GeV/c and no jet with $E_T >$ 15 GeV within $0.3 < \Delta R < 0.8$ around the lepton. Further, we reject events where the μ or e candidate is consistent with a cosmic ray muon or γ conversion electron (see Ref. [13] for details). To suppress $Z \rightarrow \ell\ell$ events, we veto those for which the invariant mass of the primary e (μ) and a reconstructed e (μ) candidate, which is required to pass loose identification criteria [13], is $76 < m_{\ell\ell} < 106\ \mathrm{GeV}/c^2$. We also reject events with $76 < m_{e\tau} < 106\ \mathrm{GeV}/c^2$ and azimuthal separation of $|\Delta\phi_{e\tau}| >$ 2.9 rad. To suppress further QCD and $Z \rightarrow \tau\tau$ events [10], we require $S_T \equiv |\vec{p}_T^{\,\ell}| + |\vec{p}_T^{\,\tau_h}| + |\vec{\not{E}}_T|/c > 110\ \mathrm{GeV}/c$.

N_{jet} is the number of jet candidates that have $E_T >$ 20 GeV and are separated from any of e, μ, or τ_h by $\Delta R >$ 0.8. We define six regions in the $m_T(\ell, \not{E}_T) \equiv \sqrt{2p_T^{\ell}\not{E}_T(1 - \cos\Delta\phi_{\ell,\not{E}_T})}$ versus N_{jet} plane and denote them as A_j (B_j) for $m_T \leq 35\ \mathrm{GeV}/c^2$ ($m_T > 35\ \mathrm{GeV}/c^2$) and $j = 0$, 1, or 2 for $N_{\mathrm{jet}} = 0$, 1, or ≥ 2. The minimal values of S_T and jet E_T are optimized for maximum significance in the A_2 region for 140–160 GeV/c^2 $\tilde{t}_1$'s. The $m_T \leq 35\ \mathrm{GeV}/c^2$ cut effectively separates the signal from W + jet and $t\bar{t}$ backgrounds. The $N_{\mathrm{jet}} \geq 2$ requirement strongly suppresses the Drell-Yan contribution. The data in region A_2 are not examined until the analysis procedure is finalized. The regions with $N_{\mathrm{jet}} = 0$ or 1 contain mostly background and are used mainly as control samples for validation. Region B_2 has an appreciable signal acceptance ($\sim$40% of that in region A_2) but a substantially higher background expectation. For statistical interpretation of the data, we employ a likelihood method that, in addition to our primary signal region A_2, utilizes sideband regions A_0, B_0, and B_2, which are used to perform data-driven W + jet background estimations and to improve the sensitivity of the analysis.

The total event acceptance is $\alpha \equiv \epsilon_{\rm MC}\epsilon_{\rm trig}$. Here $\epsilon_{\rm MC}$ is the product of geometrical and kinematical acceptances, efficiencies to identify lepton and τ_h candidates, including isolation requirements, and the efficiency for all of the remaining cuts. We use the PYTHIA Monte Carlo (MC) generator [15] and the GEANT3-based [16] CDF II detector simulation to calculate $\epsilon_{\rm MC}$. Our nominal choice for the parton distribution functions (PDFs) is CTEQ5L [17] with the renormalization scale $Q \equiv \sqrt{m(\tilde{t}_1)^2 + p_T(\tilde{t}_1)^2}$. The trigger efficiency $\epsilon_{\rm trig}$ is measured using data [14]. In region A_2, α increases nearly linearly from about 0.6% at $m(\tilde{t}_1) = 100~\text{GeV}/c^2$ to 2.7% at 170 GeV$/c^2$ for both the e and the μ channels.

The combined systematic uncertainty on α decreases almost linearly from 11% for $m(\tilde{t}_1) = 100~\text{GeV}/c^2$ to 7.2% for 170 GeV$/c^2$ and is similar in both channels. The largest contribution comes from the PDF systematic uncertainty, which is estimated using the uncertainty sets of CTEQ6.1M PDFs [17] and the technique described in Ref. [18]. For a 150 GeV$/c^2$ top squark, this uncertainty on α is 4.0%. The uncertainty due to an imperfect knowledge of the jet energy scale, determined by varying the scale by $\pm 1\sigma$, is 2.9%. The uncertainty due to the amount of initial and final state radiation is found to be 2.5%. Other sources of systematic uncertainty include the uncertainties in lepton and τ_h identification and isolation and $\not\!\!E_T$ resolution and amount to a 5.1% relative contribution. The uncertainty on the integrated luminosity is 6%.

The SM backgrounds come from two sources: (i) events with a true $\ell\tau_h$ pair from $Z/\gamma^*(\to \tau\tau)$ + jets, $t\bar{t}$, WW, WZ, and ZZ production and (ii) events where lepton or τ_h candidates do not originate from a true lepton or tau but from the jets in W + jet, $Z/\gamma^*(\to \ell\ell)$ + jets, and QCD multijet events. We first estimate the background from SM processes excluding the W + jet contribution. Drell-Yan, $t\bar{t}$, and WW production are estimated using PYTHIA and the CDF II detector simulation. For Drell-Yan backgrounds we use scale factors that improve the agreement between the yield predicted in MC simulation and the yield observed in data. The QCD multijet contribution is estimated by extrapolating the number of observed events in data for events with nonisolated leptons, defined by $2 < I_{\rm trk} < 10~\text{GeV}/c$, into the class of events with an isolated lepton, defined by $I_{\rm trk} < 2~\text{GeV}/c$ [13]. The NLO cross sections of 6.7 ± 0.7 [19] and 13.5 ± 0.5 pb [20] for $t\bar{t}$ and WW production, respectively, are used. The contributions from WZ and ZZ are negligible.

TABLE I. Numbers of events observed in data $N_{\rm obs}$ along with the expected numbers of SM background events. The W + jet contributions are shown separately.

		$e + \tau_h$ channel			$\mu + \tau_h$ channel	
		SM backgrounds			SM backgrounds	
Reg	$N_{\rm obs}$	Other	W + jet	$N_{\rm obs}$	Other	W + jet
A_2	**1**	$2.0^{+0.5}_{-0.4}$	$0^{+0.4}_{-0}$	**1**	$1.0^{+0.4}_{-0.2}$	$0^{+0.5}_{-0}$
B_2	4	$2.8^{+0.5}_{-0.3}$	$1.0^{+2.0}_{-1.0}$	4	$2.3^{+0.4}_{-0.3}$	$1.7^{+2.0}_{-1.5}$
A_1	4	$3.3^{+0.5}_{-0.5}$	$0.2^{+1.2}_{-0.2}$	3	$2.6^{+0.6}_{-0.4}$	$0.1^{+0.8}_{-0.1}$
B_1	9	$2.3^{+0.4}_{-0.3}$	$6.7^{+3.2}_{-2.7}$	6	$2.3^{+0.5}_{-0.3}$	$3.8^{+2.7}_{-2.1}$
A_0	11	$9.1^{+1.2}_{-1.1}$	$1.6^{+2.7}_{-1.6}$	8	$5.2^{+0.7}_{-0.5}$	$2.5^{+2.4}_{-2.1}$
B_0	25	$4.5^{+0.7}_{-0.6}$	$21.1^{+5.6}_{-4.3}$	28	$5.4^{+0.8}_{-0.6}$	$23.6^{+4.9}_{-5.7}$

The PYTHIA MC simulation does not accurately predict the absolute rate of the W + jet background contribution (N^W) in this analysis. To estimate N^W in each region, we use the differences between the data and all other backgrounds plus signal in regions A_2, B_2, A_0, and B_0 and the assumption that $\mathcal{R} \equiv [N^W(A_2)/N^W(B_2)] \times [N^W(B_0)/N^W(A_0)] \sim 1$. The ratios in $\mathcal{R}$ are determined by the kinematics of the W + jet events at fixed $N_{\rm jet}$ and are well modeled in the MC simulation. Based on MC predictions and cross checks with data vs MC comparisons, we conclude that $\mathcal{R} = 1.0 \pm 0.5$ is a conservative assumption. We define a likelihood as a function of $\sigma(\tilde{t}_1\bar{\tilde{t}}_1)$ and N^W in one of the regions using Poisson statistics convoluted with the uncertainties on the signal efficiency and on $\mathcal{R}$. The input parameters to the likelihood are the numbers of observed and expected events in each of the four regions.

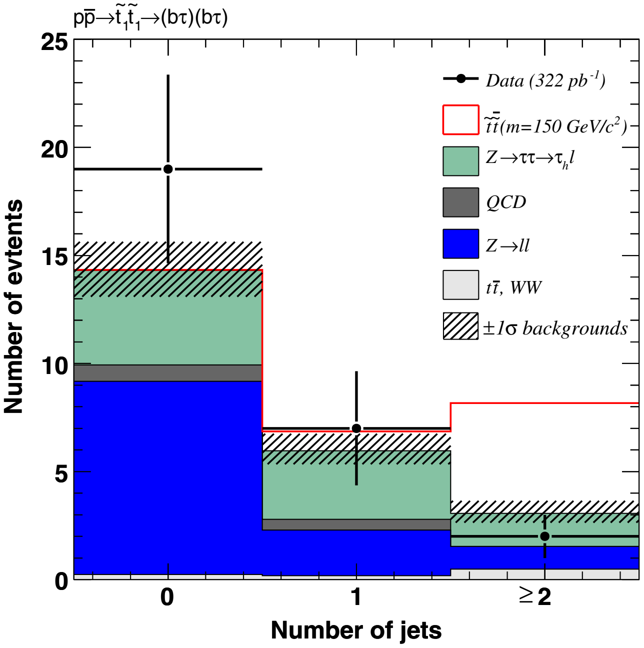

FIG. 1 (color online). Distribution of the number of jets ($E_T > 20$ GeV) for events with $m_T(\ell, \not\!\!E_T) \leq 35~\text{GeV}/c^2$ (regions A_0, A_1, and A_2) compared to the SM expectations and prediction for $\tilde{t}_1\bar{\tilde{t}}_1[m(\tilde{t}_1) = 150~\text{GeV}/c^2]$ events.

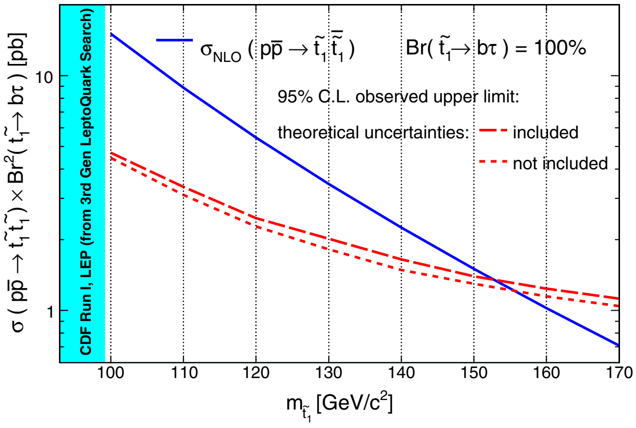

FIG. 2 (color online). 95% C.L. limit curves for $\sigma(\tilde{t}_1\bar{\tilde{t}}_1) \times \beta^2$ for the cases when the theoretical uncertainty on the cross section is (dashed line) and is not (dotted line) considered in the limit calculation (see text for details). The previous constraint $m(LQ_3) > 99$ GeV$/c^2$ [21] is also shown.

The number of expected events in region i is given by $N_i = \sigma(\tilde{t}_1\bar{\tilde{t}}_1) \cdot \mathcal{B}(\tau\tau \to \ell\tau_h) \cdot L_{\rm int} \cdot \alpha_i + N_i^{\rm BG} + N_i^W$, where the branching ratio $\mathcal{B}(\tau\tau \to \ell\tau_h) \simeq 0.23$, $N_i^{\rm BG}$ includes all SM backgrounds except W + jet events, and α_i is the total event acceptance for the signal in region i. To define the likelihood $\mathcal{L}(\sigma(\tilde{t}_1\bar{\tilde{t}}_1) \times \beta^2, N^W(A_2))$, we treat $N^W(A_0)$, $N^W(B_0)$, and the ratio $\mathcal{R} = 1.0 \pm 0.5$ as nuisance parameters with flat prior distributions. Note that $N^W(B_2)$ becomes a function of the above parameters and $N^W(A_2)$ and the large uncertainty on $\mathcal{R}$ does not affect our final results because $N^W(A_2)$ is expected to be small. This two-dimensional likelihood can be used to estimate N^W for each region and to calculate upper limits on $\sigma(\tilde{t}_1\bar{\tilde{t}}) \times \beta^2$. Note that the resulting N^W depends on the observed number of events in the data, $N^{\rm BG}$, and a possible top-squark quark contribution.

In Table I, we show the numbers of events observed in the data along with the SM expectation. In Fig. 1, we present the $N_{\rm jet}$ distribution for events with $m_T \leq 35$ GeV$/c^2$. Two events are found in region A_2, consistent with the SM prediction. To set upper limits on $\sigma(\tilde{t}_1\bar{\tilde{t}}_1) \times \beta^2$, we further integrate out $N^W(A_2)$ in the likelihood function defined above and use a Bayesian technique to calculate a 95% C.L. limit on $\sigma(\tilde{t}_1\bar{\tilde{t}}_1) \times \beta^2$. The electron and muon channels are treated as two separate measurements, taking into account the correlations among the systematic uncertainties.

The 95% C.L. limits on $\sigma(\tilde{t}_1\bar{\tilde{t}}_1) \times \beta^2$ as a function of $m(\tilde{t}_1)$ are shown in Fig. 2 and Table II. The dotted curve is our experimental result, compared to the NLO cross section (solid line) obtained using PROSPINO version 2 [22] with our nominal choice of CTEQ6.1M PDFs [17] and Q. The theoretical uncertainty of ±18% on $\sigma(\tilde{t}_1\bar{\tilde{t}}_1)$ is due to the choice of Q (varying the scale from its nominal value by a factor of 2 or a half) and PDFs. Taking this uncertainty into consideration, the limits are reevaluated (dashed line in Fig. 2). The corresponding mass limits for the first and second cases are 156 (compared to 122 [10]) and 153 GeV$/c^2$, respectively.

TABLE II. 95% C.L. upper limit on $\sigma(\tilde{t}_1\bar{\tilde{t}}_1) \times \beta^2$ (in pb) as a function of $m(\tilde{t}_1)$ for the cases when uncertainty on the theoretical cross section is considered ($\sigma^{95\%}_{\rm with\ uncert} \times \beta^2$) and is not considered ($\sigma^{95\%}_{\rm no\ uncert} \times \beta^2$).

$m(\tilde{t}_1)$ (GeV$/c^2$)	100	110	120	130	140	150	160	170
$\sigma^{95\%}_{\rm with\ uncert} \times \beta^2$ (pb)	4.73	3.37	2.50	1.99	1.61	1.38	1.26	1.14
$\sigma^{95\%}_{\rm no\ uncert} \times \beta^2$ (pb)	4.48	3.11	2.27	1.81	1.47	1.26	1.16	1.04

In conclusion, we have searched for $\tilde{t}_1\bar{\tilde{t}}_1$ production in the final state of a lepton (e or μ), a hadronically decaying tau, and two jets using 322 pb^{-1} of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV. We observe no excess of events in the data over the SM expectation. In an $\not{R}_p$ SUSY scenario, we set a 95% C.L. lower limit on the $\tilde{t}_1$ mass of 153 GeV$/c^2$ taking into account the theoretical uncertainties on the NLO cross section and assuming $\mathcal{B}(\tilde{t}_1 \to \tau b) = 1$. These results are also applicable to LQ_3 pair production.

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