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Search for admixture of scalar top quarks in the $t\bar{t}$ lepton+jets final state at $\sqrt{s} = 1.96$ TeV

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A search for pair production of the lightest supersymmetric partner of the top quark, $\tilde{t}_1$, is performed in the lepton+jets channel using 0.9 fb^{-1} of data collected by the D0 experiment. Kinematic differences between $\tilde{t}_1\bar{\tilde{t}}_1$ and the dominant top quark pair production background are used to separate the two processes. First limits from Run II of the Fermilab Tevatron Collider for the scalar top quark decaying to a chargino and a b quark ($\tilde{t}_1 \to \tilde{\chi}_1^+ b$) are obtained for scalar top quark masses of 130–190 GeV and chargino masses of 90–150 GeV.

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Supersymmetry [1] introduces a superpartner for each of the left and the right-handed top quarks. Because of the large top quark mass, the mixing between those two can be substantial and lead to a large difference in the mass eigenvalues of the two scalar top ("stop") quarks. Thus, the lighter stop quark $\tilde{t}_1$ could possibly be the lightest scalar quark and within reach at the Fermilab Tevatron Collider. In the Minimal Supersymmetric Standard Model (MSSM) stop quarks are produced mainly in pairs ($\tilde{t}_1\bar{\tilde{t}}_1$) via the strong interaction, the same mechanism as for top quark pair production ($t\bar{t}$) [2]. The expected next-to-leading-order (NLO) cross section at a center of mass energy of 1.96 TeV for a stop quark of mass equal to 175 GeV is $(0.58^{+0.16}_{-0.13})$ pb [3], while for a top quark of the same mass the cross section is (6.8±0.6) pb [4]. The stop quark pair production cross section strongly depends on the mass of the stop quark.

The different possible decay modes of the stop quark result in a number of distinct final state signatures. The branching ratios for stop quark decays depend on the parameters of the model, in particular the masses of the supersymmetric particles involved. The decays to a c quark and the lightest neutralino ($\tilde{t}_1 \to c\tilde{\chi}^0_1$) [5] and to a b quark, a lepton, and a sneutrino ($\tilde{t}_1 \to b\ell^+\tilde{\nu}_\ell$) [6] have already been explored at D0 in Run II of the Tevatron. For stop quarks lighter than the top quark the decay channel $\tilde{t}_1 \to \tilde{\chi}^+_1 b$, with subsequent decay of the lightest chargino $\tilde{\chi}^+_1$ to the lightest neutralino $\tilde{\chi}^0_1$ and a W boson, can dominate, if kinematically allowed. In this Letter we assume that the branching ratio $B(\tilde{t}_1 \to \tilde{\chi}^+_1 b) = 1$. This channel has been explored only once before by the CDF collaboration in Run I of the Tevatron at $\sqrt{s} = 1.8$ TeV for stop quark masses of 100–120 GeV [7]. With a dataset more than ten times larger, we obtain first limits in this channel at $\sqrt{s} = 1.96$ TeV for stop quark masses in the range 130–190 GeV.

The $\tilde{t}_1\bar{\tilde{t}}_1$ event signature in the studied decay channel can be similar to the $t\bar{t}$ signature, making it possible for the $\tilde{t}_1\bar{\tilde{t}}_1$ signal to be embedded in the $t\bar{t}$ event sample. The goal of this analysis is to search for this possible hidden admixture. The main difference relative to $t\bar{t}$ production is the additional presence of neutralinos in the event. However, this does not lead to significantly higher missing transverse energy ($\not\!\!E_T$), since the neutralinos are mostly produced back-to-back. We consider the decay channel with one W boson decaying to hadrons and the other one to an electron or muon and a neutrino. Scenarios with both on-shell and off-shell W bosons provide the same signature. The final state consists of one high-p_T lepton, $\not\!\!E_T$ from the neutrino and the neutralinos, two jets originating from b quarks ("b jets"), and two light-quark jets. This is referred to as the "lepton+jets" channel. We consider twelve mass points, for which the studied decay can dominate. We fix the neutralino mass to 50 GeV, a value close to the experimental limit from LEP [8], and we vary the stop quark mass from 130 to 190 GeV and the chargino mass from 90 to 150 GeV to obtain the desired event signature. For larger neutralino masses the signature changes and the sensitivity of this study decreases.

The search is conducted using data collected by the D0 detector [9] in $p\bar{p}$ collisions at the Fermilab Tevatron Collider. Triggers require an electron or muon and at least one jet with large transverse momentum (p_T). The dataset comprises an integrated luminosity of 913 pb^{-1} for events containing electrons in the final state, and 871 pb^{-1} for events with muons.

We select events with one isolated electron with $p_T >$ 20 GeV and pseudorapidity $|\eta| < 1.1$, or one isolated muon with $p_T > 20$ GeV and $|\eta| < 2.0$, and $\not\!\!E_T >$ 20(25) GeV in the electron (muon) channel [10]. To reject events with mismeasured leptons, the lepton momentum vector and the $\not\!\!E_T$ vector are required to be separated in azimuth. In addition, we only accept events with ≥3 jets, each with $p_T > 15$ GeV and $|\eta| < 2.5$, of which the jet with largest p_T ("leading jet") has to have $p_T > 40$ GeV. Events with a second isolated electron or muon with $p_T > 15$ GeV are rejected. Details about object identification, jet energy corrections, and trigger requirements can be found in Ref. [10]. In addition, we require at least one b-tagged jet in each event, where the b jets are identified through a neural network algorithm [11].

For events with four or more jets, a kinematic fitting algorithm [12] is used to reconstruct the objects to a $t\bar{t}$ hypothesis, which is used to separate $\tilde{t}_1\bar{\tilde{t}}_1$ from $t\bar{t}$ events. The fitter minimizes a χ^2 statistic within the constraints that both candidate W boson masses are 80.4 GeV and that the masses of the two objects reconstructed as top quarks are the same. The fitter considers only the four jets of highest p_T, uses b-tagging information to minimize combinatorics, and varies the four-vectors of the detected objects within their resolution. Only events for which the fit converges (86–95% of signal events depending on the mass point and lepton flavor) are selected for further analysis.

The events are classified into four distinct subsamples, according to jet multiplicity (3 jets or ≥ 4 jets) and lepton flavor (e+jets or μ+jets). All subsamples are used to obtain the final limit.

Because of their topological similarity to the signal, $t\bar{t}$ events are the most challenging background. Of the other background processes, production of W bosons in association with jets (W+jets), and multijet events, where jets are misidentified as isolated leptons, are most important. Far smaller contributions arise from Z+jets, single top quark, and diboson production.

Except for the multijet background, the shape of distributions in all processes are modeled through Monte Carlo (MC) simulation. The $\tilde{t}_1\bar{\tilde{t}}_1$ signal is generated by PYTHIA v6.323 [13] in its general MSSM mode, where the top trilinear coupling A_t and the SU(2) gaugino mass M_2

TABLE I: Expected numbers of events with total uncertainties and observed numbers of events after the final selection.

Sample	=3 jets		$\geq$ 4 jets	
	e+jets	μ+jets	e+jets	μ+jets
Signal				
$m_{\tilde{t}_1}$[GeV]/$m_{\tilde{\chi}_1^\pm}$[GeV]				
190/150	$3.2^{+0.3}_{-0.3}$	$2.2^{+0.2}_{-0.2}$	$2.9^{+0.4}_{-0.4}$	$2.1^{+0.3}_{-0.3}$
130/90	$10.4^{+1.0}_{-1.4}$	$6.5^{+0.6}_{-0.8}$	$5.2^{+0.7}_{-1.1}$	$3.2^{+0.6}_{-0.6}$
Background				
$t\bar{t}$	$77.6^{+16.0}_{-15.3}$	$58.5^{+12.0}_{-19.6}$	$103.0^{+22.8}_{-22.8}$	$84.2^{+18.0}_{-19.2}$
W+jets	$67.7^{+25.5}_{-24.4}$	$77.4^{+19.1}_{-19.3}$	$17.1^{+12.8}_{-12.8}$	$21.6^{+7.8}_{-7.0}$
Z+jets	$5.2^{+1.5}_{-1.1}$	$6.9^{+2.0}_{-1.3}$	$2.8^{+0.8}_{-0.7}$	$3.3^{+0.9}_{-0.8}$
Single top	$9.3^{+1.6}_{-1.5}$	$7.5^{+1.3}_{-1.2}$	$3.1^{+0.7}_{-0.7}$	$2.5^{+0.7}_{-0.6}$
Diboson	$4.2^{+1.1}_{-0.9}$	$3.8^{+1.0}_{-0.9}$	$1.4^{+0.5}_{-0.3}$	$1.2^{+0.4}_{-0.3}$
Multijet	22.3±4.2	3.0±2.4	10.7±2.6	3.3±2.7
Total	$186.2^{+31.4}_{-29.1}$	$157.2^{+22.9}_{-29.6}$	$138.1^{+26.8}_{-26.6}$	$116.0^{+20.9}_{-20.9}$
Data	193	163	133	135

are varied to set the stop quark mass and the chargino mass, respectively. The neutralino mass is kept at the same value by keeping the U(1) gaugino mass M_1 constant. The $t\bar{t}$ background is also generated by PYTHIA, using a top quark mass of 175 GeV. The W+jets and Z+jets processes are generated by ALPGEN 2.05 [14] for the matrix element calculation, with subsequent parton showering and hadronization generated with PYTHIA. Single top quark events are generated by COMPHEP-SINGLETOP [15] and diboson production is modeled by PYTHIA. All generated events are passed through a GEANT-based [16] simulation of the D0 detector and reconstructed using the same software as for data. To improve agreement between data and MC simulation, additional corrections [10] are applied to the simulation before selection.

The contribution of the multijet background for each jet multiplicity and lepton flavor is determined from data using a method which exploits the fact that this background contains jets that mimic leptons, whereas the other processes have a true isolated lepton [17]. The normalization of the W+jets background is estimated before imposing the b-tagging requirement, by subtracting from data: (i) the estimated multijet background, and (ii) the $t\bar{t}$, Z+jets, single top, and diboson contributions as calculated from their next-to-leading order cross sections [4, 18]. The remaining events are assumed to be W+jets background, where we have scaled the heavy flavor component ($Wb\bar{b}$ plus $Wc\bar{c}$) by a relative factor of 1.17±0.18. This factor was derived on a statistically independent sample with two jets and at least one b-tag.

Table I shows the numbers of expected and observed events after the final selection, found to be in good agreement. For signal events the mass points with the highest and lowest event yield are shown as examples.

Because of the similarity of the $\tilde{t}_1\bar{\tilde{t}}_1$ and $t\bar{t}$ final states [19], a multivariate likelihood discriminant [20] is employed to discriminate between the two processes. We study the kinematic differences and choose the variables of greatest discrimination and low correlation as input to the multivariate discriminant. For events with three jets, where the two jets besides the leading b-tagged jet are referred to as light jets j, the following five variables are used: (i) the invariant mass of the three jets, (ii) $K_T^{\rm min} = \Delta R_{jj}^{\rm min} p_T^{\rm min}$, where $\Delta R_{jj}^{\rm min}$ is the minimum ΔR [10] separation between a pair of jets (in rapidity-azimuth space) and $p_T^{\rm min}$ is the minimum jet p_T in that pair, (iii) the smaller of the ΔR separations between the leading b-tagged jet and either the lepton or the vector sum of the two light jets, (iv) the p_T of the system of the two light jets, and (v) the lepton-$\not\!\!E_T$ transverse mass [21]. For events with four or more jets, the following five variables are used: (i) the top quark mass as reconstructed by the kinematic fitter, (ii) the scalar sum of the p_T of the four leading jets, (iii) the invariant mass of the system of the second and third leading jet, excluding the leading b-tagged jet, (iv) $K_T^{\rm min}$, and (v) the p_T of the fourth leading jet.

Figure 1 shows the variable with the greatest separation for each jet multiplicity as a comparison between data and the prediction. Figure 2 shows the resulting discriminant for the mass point with $m_{\tilde{t}_1}$=175 GeV and $m_{\tilde{\chi}_1^\pm}$=135 GeV in the 3-jet and the 4-jet subsample, comparing the prediction with data. The prediction for $\tilde{t}_1\bar{\tilde{t}}_1$ signal (solid line) peaks at 1, while it peaks at 0 for $t\bar{t}$.

We use a Bayesian approach [22] to extract upper limits on the stop quark pair production cross section ($\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$) from the discriminant distributions. We construct a binned likelihood as a product over all bins in the discriminant distribution as well as each of the four channels considered, assuming a Poisson distribution for the observed counts per bin. For the signal cross section, we assume a flat non-negative prior probability. By integrating over signal acceptance, background yields and integrated luminosity using Gaussian priors for each systematic uncertainty, we obtain the posterior probability density as a function of cross section for signal. The upper limit on $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$ at 95% confidence level is the point where the integral over the posterior probability density reaches 95% of its total.

We differentiate between systematic uncertainties that change the yield uniformly for all bins of the discriminant, and those that affect each bin differently. The effects are given as a percentage on the event yield of the affected process; they can vary widely, depending on the subsample and the physics process. The sources changing the yield uniformly include the uncertainties on integrated luminosity (6.1%) [23], efficiency of the event-based data quality selection (0.5%), theoretical cross sections (13–20%), top quark mass (1.3–7%), estimation of the W+jets background (24–74%, depending on the jet multiplicity and lepton flavor subsample), influence of

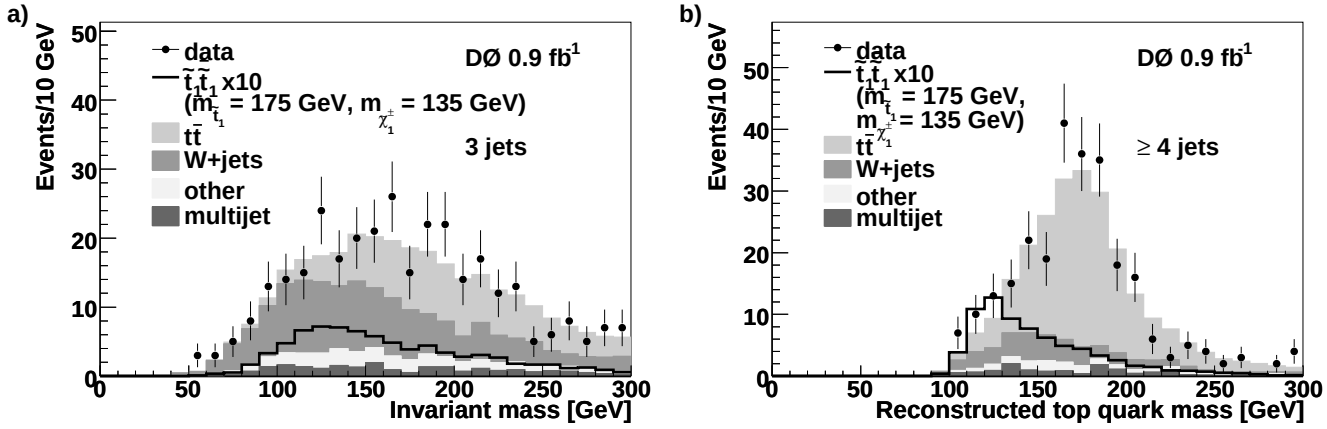

FIG. 1: Comparison of the prediction with data after the final selection for the e+jets and μ+jets channels combined, a) the invariant mass of the three jets in events with 3 jets, b) the reconstructed top quark mass in events with ≥4 jets. The solid line shows the distribution for a signal point, enhanced by a factor of ten.

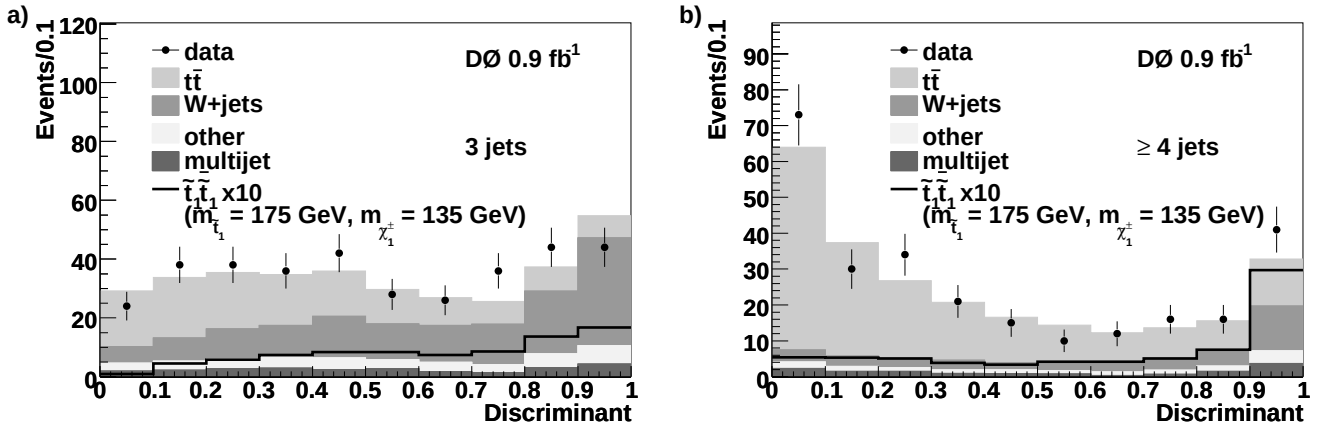

FIG. 2: Comparison of the discriminant distribution for data with the prediction after the final selection for the e+jets and μ+jets channels combined, for events with a) 3 jets, and b) ≥4 jets. The solid line shows the distribution for a signal point, enhanced by a factor of ten.

the signal on the W+jets normalization (0.8–3.4%), estimation of the multijet background (19–84%, depending on the subsample), lepton identification and reconstruction efficiencies (2.2–2.5%), primary vertex identification efficiency (2.7%), and trigger efficiencies (1.2–2.7%). The sources that also change the shape of the discriminant distribution include jet energy scale calibration (0.6–30%), and b-tagging (0.1–27%). Limits on the stop quark pair production cross section are degraded by about a factor of two when all systematic uncertainties are accounted for.

Table II shows the results for each mass point for the combination of all channels. The results are also illustrated in Fig. 3. The expected limits are derived from the sum of all selected background samples without a $\tilde{t}_1\bar{\tilde{t}}_1$ contribution, but including the $t\bar{t}$ background according to its theoretical cross section. The observed limits on the cross section are a factor of $2-13$ larger than the theory prediction and agree with the expected limits within uncertainties. In some cases, most notably for the mass point with $m_{\tilde{t}_1} = 175$ GeV and $m_{\tilde{\chi}_1^\pm} = 135$ GeV, the observed limit is higher than the expected limit, pointing to an excess of signal-like data. To quantify the significance, the peak position of the posterior probability is compared to its width. In this case, the peak is 1.62 standard deviations away from zero.

In summary, we present first limits on the $\tilde{t}_1\bar{\tilde{t}}_1$ production at the Tevatron Run II for a light stop quark of 130–190 GeV decaying to a b quark and the lightest chargino. In the MSSM scenarios studied by this search, we derive upper limits on the cross section that are a factor of $2-13$ above the theory prediction and agree with the expected limits within uncertainties.

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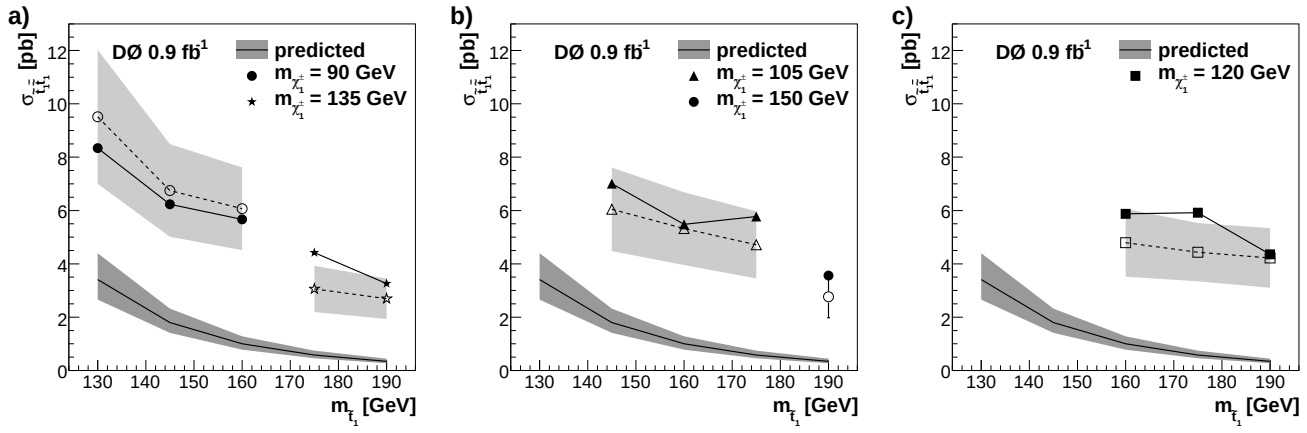

FIG. 3: Expected (open markers and dashed lines) and observed (filled markers and solid lines) Bayesian limits at 95% confidence level on the $\tilde{t}_1\bar{\tilde{t}}_1$ cross section for all channels combined. Also shown is the ± 1 standard deviation band on the expected limit as well as the uncertainty on the theoretical prediction caused by the choice of factorization and renormalization scales. a) For chargino masses of 90 GeV and 135 GeV, b) for chargino masses of 105 GeV and 150 GeV, c) for a chargino mass of 120 GeV.

TABLE II: The predicted $\tilde{t}_1\bar{\tilde{t}}_1$ cross section and the expected and observed Bayesian upper limits on the $\tilde{t}_1\bar{\tilde{t}}_1$ cross section at the 95% confidence level for different assumed values of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^\pm}$. We assume $m_{\tilde{\chi}_1^0} = 50$ GeV and $B(\tilde{t}_1 \to \tilde{\chi}_1^+ b) = 1$. The uncertainties on the theoretical prediction result from the simultaneous variation by a factor of two of the factorization and renormalization scales about their nominal values, set equal to the stop quark mass. The uncertainties on the expected limits represent the one standard deviations estimated via background-only pseudo-experiments.

masses [GeV]		$\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$ [pb]		
$m_{\tilde{t}_1}$	$m_{\tilde{\chi}_1^\pm}$	theory	exp. limit	obs. limit
190	150	$0.34^{+0.10}_{-0.07}$	2.76±0.79	3.56
190	135	$0.34^{+0.10}_{-0.07}$	2.69±0.75	3.26
190	120	$0.34^{+0.10}_{-0.07}$	4.22±1.12	4.36
175	135	$0.58^{+0.16}_{-0.13}$	3.06±0.87	4.42
175	120	$0.58^{+0.16}_{-0.13}$	4.44±1.09	5.92
175	105	$0.58^{+0.16}_{-0.13}$	4.71±1.26	5.78
160	120	$1.00^{+0.28}_{-0.22}$	4.79±1.27	5.87
160	105	$1.00^{+0.28}_{-0.22}$	5.32±1.37	5.48
160	90	$1.00^{+0.28}_{-0.22}$	6.07±1.55	5.67
145	105	$1.80^{+0.52}_{-0.39}$	6.04±1.56	7.01
145	90	$1.80^{+0.52}_{-0.39}$	6.75±1.74	6.23
130	90	$3.41^{+0.99}_{-0.75}$	9.51±2.51	8.34

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