Search for Scalar Top Quark Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report on a search for the supersymmetric partner of the top quark (scalar top) decaying into a charm quark and a neutralino in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The data sample, collected by the CDF II detector at the Fermilab Tevatron, corresponds to an integrated luminosity of 2.6 fb^{-1}. Candidate events are selected by requiring two or more jets and a large imbalance in the transverse momentum. To enhance the analysis sensitivity, at least one of the jets is required to be identified as originating from a charm quark using an algorithm specifically designed for this analysis. The selected events are in good agreement with standard model predictions. In the case of large mass splitting between the scalar top quark and the neutralino we exclude a scalar top quark mass below 180 GeV/c^2 at 95% confidence level.

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The standard model (SM) of elementary particles and fundamental interactions, however successful, is still incomplete since it does not explain the origin of electroweak symmetry breaking and does not give an answer to the gauge hierarchy problem [1]. A possible extension of the SM, supersymmetry (SUSY) [2], solves these problems by introducing a symmetry that relates particles of different spin. R-parity [2] conserving SUSY models also provide a prime candidate for the dark matter in the universe [3], namely the stable lightest supersymmetric particle (LSP). In these models, the left-handed and right-handed quarks have scalar partners, respectively denoted as $\tilde{q}_L$ and $\tilde{q}_R$, which can mix to form scalar quarks with mass eigenstates $\tilde{q}_{1,2}$. Several models [4] predict that this mixing can be substantial for the scalar top (stop), yielding a stop mass eigenstate ($\tilde{t}_1$) significantly lighter than other scalar quarks. If the $\tilde{t}_1$ is sufficiently light, it can be pair-produced copiously in proton-antiproton collisions at center-of-mass energy of $\sqrt{s} = 1.96$ TeV at

the Tevatron. A stop in the mass range accessible at the Tevatron is expected to decay predominantly into a charm quark and the lightest neutralino ($\tilde{\chi}_1^0$), which is often assumed to be the LSP. Assuming R-parity conservation, stops are produced in pairs. We consider a scenario where $m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}^+}$ (where $\tilde{\chi}^+$ is a chargino), and $m_{\tilde{t}_1} < m_W + m_b + m_{\tilde{\chi}_1^0}$. Under these conditions the decay $\tilde{t}_1 \to c\tilde{\chi}_1^0$ is dominant. Results from searches using this final state at the Tevatron have been previously reported in [5, 6].

In this Letter, we report the search for $\tilde{t}_1 \to c\tilde{\chi}_1^0$ decays in $p\bar{p}$ collision data from 2.6 fb^{-1} of integrated luminosity collected by the upgraded Collider Detector at Fermilab (CDF II) at the Tevatron. The final state contains two c jets from the hadronization of the c quarks and features an imbalance in transverse momentum ("missing transverse energy" or $\not\!\!E_T$ [7]) from the two LSPs escaping detection.

CDF II is a multipurpose detector, described in detail elsewhere [8]. The charged-particle tracking system consists of silicon microstrip detectors and a cylindrical open-cell drift chamber, both of which are immersed in a 1.4 T solenoidal magnetic field coaxial with the beam line. The silicon detectors provide coverage in the pseudorapidity [7] range $|\eta| \leq 2$ and are used to identify events with long-lived particle decays. The drift chamber surrounds the silicon detectors, has maximum tracking efficiency up to $|\eta| = 1$, and is used for charged particle momentum measurements. Segmented sampling calorimeters, which surround the tracking system, are arranged in a projective tower geometry and are used to measure the energy of interacting particles in the region $|\eta| < 3.6$. Muon candidates are identified by drift chambers, which extend up to $|\eta| = 1.5$, and are located outside the calorimeter volume. Jets are reconstructed from the energy depositions in the calorimeter cells using an iterative cone jet-clustering algorithm [9], with a cone size of radius $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.7$ [7]. Energy corrections [10] are applied to account for effects such as non-linear calorimeter response, underlying event, and the position of the interaction point, that influence the measured transverse jet energy.

Candidate events used for this search are selected by an online event selection system (trigger) that requires $\not\!\!E_T \geq$ 35 GeV and two jets. Further selections are applied offline to remove accelerator-produced and detector-related backgrounds as well as cosmic-ray events. After offline event reconstruction, the events are required to have $\not\!\!E_T \geq 50$ GeV, and at least two jets with $|\eta| \leq 2.4$ and $E_T \geq 25$ GeV. The highest-E_T jet is required to have $E_T \geq 35$ GeV and at least one of the selected jets is required to be in the region $|\eta| \leq 0.9$.

The hadrons in jets coming from b or c quark fragmentation, heavy-flavor (HF) jets, have a measurable flight path, yielding secondary vertices relative to the $p\bar{p}$ inter-

action point (primary vertex). We require the events to have exactly one jet identified as a HF jet by the secondary-vertex tagging algorithm [11], since requiring two HF-identified jets enhances the sample with events containing two b quarks and reduces the signal acceptance. This criteria defines a preselection which is used as the basis of background studies and further optimization for the signal sample, as described below.

Dominant SM backgrounds are pair and single top-quark production, electroweak single and di-boson production, HF multijet production, and light-flavor multijet events where one of the jets is falsely tagged as a HF jet (mistag). The latter two background contributions are estimated from data. The ALPGEN [12] event generator interfaced with the parton-shower model from the PYTHIA [13] event generator is used to estimate the electroweak boson production, the MADEVENT [14] generator is used to model the single top events, while the PYTHIA event generator is used to model the top-quark pair and diboson backgrounds. For the event generation the CTEQ5L [15] parton distribution functions (PDFs) are used. Simulated events are passed through the GEANT3-based [16] CDF II detector simulation [17] and are weighted by the probability that they would pass the trigger selection. The single top-quark and diboson contributions are normalized to the theoretical cross sections [18–20]. The contributions for the electroweak boson samples are normalized to the next-to-leading order cross sections calculated with MCFM [21]. We use the measured top-quark pair production cross section of $\sigma_{t\bar{t}} = 7.02 \pm 0.63$ pb [22]. Mistags are estimated based on the mistag rate [11] observed in inclusive jet data. The mistag rate is parametrized as a function of jet E_T, $|\eta|$, secondary-vertex track-multiplicity, the number of primary vertices in the event, primary vertex z-position, and the scalar sum of E_T of all jets in the event. To estimate the HF multijet background from data, we use a multijet tag rate estimator (MUTARE) described elsewhere [23, 24]. The HF multijet prediction from MUTARE is scaled by a multiplicative factor that is obtained in a signal-free region.

To avoid potential biases when searching for new physics, we test the various background contributions in distinct control regions that are defined *a priori*. The three control regions used to validate the SM prediction are denoted as multijet, lepton, and pre-optimization regions. The multijet control region is defined to have the second leading E_T jet direction ($\vec{j}_2$) aligned with the $\vec{\not\!\!E}_T$ [7], where aligned means $\Delta\phi(\vec{\not\!\!E}_T, \vec{j}_2) \leq 0.4$ rad. This HF multijet enriched region is used to obtain the MUTARE parameterization to predict the HF multijet background in the other control and signal regions. The lepton control region is defined to have $\vec{j}_2$ direction not aligned with the $\vec{\not\!\!E}_T$ ($\Delta\phi(\vec{\not\!\!E}_T, \vec{j}_2) \geq 0.7$ rad) and at least one isolated charged lepton (e or μ) with $p_T \geq 10$ GeV/c. This lepton region is used to validate the modeling of

TABLE I: Comparison of the total number of expected and observed events in the control regions. The total uncertainty is computed by taking into account the (anti)correlations between the partial uncertainties. In the lepton region the HF multijet prediction is scaled to match the observed events in order to perform shape comparisons only.

Regions:	Multijet	Lepton	Pre-optimization
W/Z + jets	457 ± 190	375 ± 156	1551 ± 644
Diboson	17 ± 2	45 ± 5	118 ± 13
Top pair	188 ± 21	547 ± 60	870 ± 96
Single top	11 ± 2	71 ± 10	130 ± 19
HF multijets	75407 ± 23376	268 ± 83	12935 ± 4010
Light-flavor jets	65839 ± 8427	720 ± 92	7741 ± 991
Total expected	141919 ± 24849	2026 ± 208	23345 ± 4182
Observed	143441	2026	22792

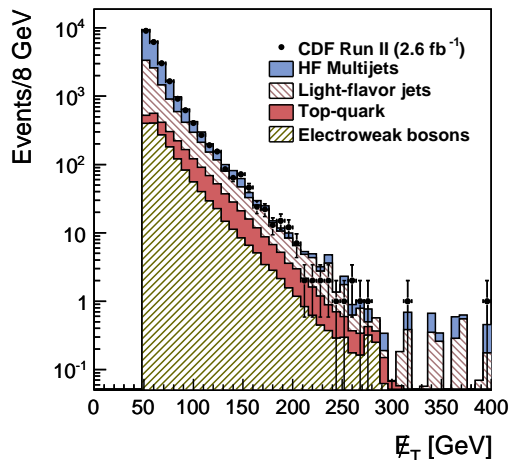FIG. 1: Distribution of $\displaystyle{\not}E_T$ in the pre-optimization region. SM prediction (stacked histograms) and observed distribution (dots) are shown, where HF multijets and light-flavor jets are predicted from data.

the top quark and electroweak W/Z boson backgrounds. The pre-optimization control region is defined to have the leading and second leading E_T jets not aligned with the $\overrightarrow{\not}E_T$ and to have no identified leptons. We studied kinematic distributions such as jet E_T, $\not{E}_T$, as well as the total numbers of events predicted. All these quantities are in agreement with observations in the three control regions. As an example, the $\not{E}_T$ distributions for the pre-optimization region are shown in Fig. 1. Table I presents the expected event yields for various background processes in the control regions under study.

We optimize the sensitivity to stop production by applying additional event selection criteria using a set of cuts suppressing the HF multijet background. We

select events with exactly two jets, as expected from the signal, and fulfilling the condition $\Delta\phi(\overrightarrow{\not}E_T, \overrightarrow{\not}E_T^{trk}) < \pi/2$. This variable is the angular difference between the calorimetry-based $\overrightarrow{\not}E_T$ and the same quantity calculated using tracks ($\overrightarrow{\not}E_T^{trk}$) [7]. When the $\not{E}_T$ in the event is real, these two quantities are usually aligned in ϕ. However, when the $\not{E}_T$ comes from calorimetry mis-measurements, as in HF multijet events with no real $\not{E}_T$, the angular difference between the two quantities is randomly distributed.

To further improve the sensitivity we apply a neural network (NN) trained with the TMVA package [25], to reduce the remaining HF multijet background. We train the NN using jet E_T, jet η, the minimum $\Delta\phi$ between the $\overrightarrow{\not}E_T$ and any of the selected jets, $\Delta\phi(\overrightarrow{\not}E_T, \overrightarrow{\not}E_T^{trk})$, $\Delta\phi(\vec{j}_1, \vec{j}_2)$, $\not{E}_T$, $\not{E}_T^{trk}$, and the summed E_T of all the jets in the event. We choose a reference signal point with $m(\tilde{t}_1) = 125$ GeV/c^2 and $m(\tilde{\chi}_1^0) = 70$ GeV/c^2 to perform the optimization. The signal acceptance is obtained using the PYTHIA event generator and CTEQ5L PDFs. Total signal yields are normalized to the NLO production cross section determined with the PROSPINO event generator [26] and the CTEQ6M [27, 28] PDFs. The uncertainty of the NLO production cross section is estimated to be 20%, arising from the scale dependence and the uncertainties on the PDFs. The NN output lies within -1 and 1, where the background peaks at -1 and the signal peaks at 1. We define our signal region as events with NN output scores > 0.

The final stage in the optimization is the application of a charm hadron analysis oriented separator (CHAOS) technique [24], explicitly designed for this analysis to obtain a sample enriched in c jets. CHAOS is a NN producing a two-dimensional output and trained with the SNNS v4.3 package [29] to determine whether a jet identified as HF has been produced from the hadronization process of a light quark falsely tagged as a HF jet, a b quark, or a c quark. The two-dimensional output structure allows the separation of the three different targets during the same training process. Depending on the flavor of the original parton, the jet identified as HF and its secondary vertex have different characteristics, mainly related to the tracking. Using properties of the tracks forming the secondary vertex and the tracks of the jets within a neural network, CHAOS allows enhancement of the jet selection with a desired flavor, in particular c jets. We apply CHAOS to the jet identified as HF and we find that the optimal cut has a selection efficiency [24] of 34% for c jets, 7.3% for b jets, and 4.9% for light jets.

The systematic uncertainties on the signal and the background predictions, taking into account correlated and uncorrelated uncertainties, are studied. Correlated uncertainties, affecting both the background prediction and signal acceptance, are dominated by the uncertainties on the performance of the b-tagging algorithm and

TABLE II: Number of expected and observed events in the signal region before and after CHAOS application. Prediction for the signal point $(m(\tilde{t}_1) = 125 \text{ GeV}/c^2$, $m(\tilde{\chi}_1^0) = 70 \text{ GeV}/c^2$) is also shown. Correlated and uncorrelated uncertainties in the total background and expected signal were treated separately in the analysis although they are combined here.

Signal region	Before CHAOS	Final (after CHAOS)
W/Z + jets	423.6 ± 185.0	60.9 ± 26.6
Diboson	36.9 ± 6.5	10.7 ± 1.9
Top pair	61.9 ± 15.5	4.6 ± 1.3
Single top	39.0 ± 9.7	3.2 ± 0.8
HF Multijets	279.6 ± 208.3	20.4 ± 15.2
Light-flavor jets	658.3 ± 259.6	32.2 ± 12.7
Total expected	1499.3 ± 277.1	132.0 ± 24.4
Observed	1496	115
$\tilde{t}_1$ signal	250.0 ± 66.2	90.2 ± 23.9

CHAOS, which are 4.4% [11] and 9.2% respectively, and the luminosity (6%) [8]. Uncorrelated systematic uncertainties on the background predictions are dominated by uncertainties on the MUTARE parameterization (30%), the mistag rate (16% [11] for light-flavor multijets), the top-quark pair-production cross section (11%), the single top-quark production cross section (13%), and the diboson production cross section (10% for WW/WZ and 20% for ZZ). The uncertainty on the normalization of the boson plus HF jets to the total inclusive boson production cross section translates into a 10% uncertainty in the SM predictions. Correlated and uncorrelated uncertainties are evaluated separately and combined in quadrature.

The signal region is analyzed after the background predictions are determined. We observe 115 events, where 132.0 ± 24.4 are expected from background, as summarized in Table II where yields before selecting events based on CHAOS output are also shown. Since no significant deviation from the SM prediction is observed, the results are used to calculate a 95% C.L. exclusion limit for the $\tilde{t}_1$ pair production cross section.

We have used the differences in shape of the NN output to set the limits. These limits are computed using a Bayesian likelihood method [31] with a flat prior probability for the signal cross section and Gaussian priors for the uncertainties on acceptance and backgrounds. Figure 2 shows the expected and observed limits as a function of $m(\tilde{t}_1)$ for a neutralino mass of 80 GeV/c^2.

We exclude, assuming BR($\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$) = 100%, $\tilde{t}_1$ masses up to 180 GeV/c^2 at 95% C.L. In addition, a 95% C.L. limit is obtained in the mass parameter plane of the model. Figure 3 shows the excluded region in the stop-neutralino mass plane of the analysis, compared with results from previous analyses [5, 6, 30]. The limit obtained with the present analysis improves the results of previous searches using a similar topology, and repre-
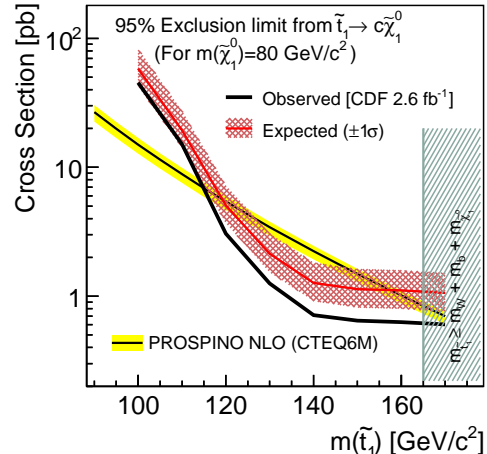

FIG. 2: Observed (solid line) and expected (solid line with dashed band) 95% C.L. upper limit on the stop cross section (solid line with shaded band) as a function of the stop mass for an assumed value of the neutralino mass. The shaded band denotes the uncertainty on the NLO stop pair-production cross section.
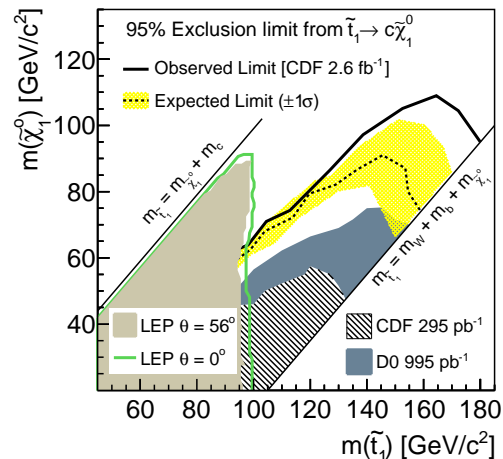

FIG. 3: Excluded region at 95% C.L. in the $m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$ plane. The result is compared to the previous results from CDF [5], from D0 [6], and from LEP [30] experiments at CERN.

sents the world's best limit in the region of large mass splitting.

To summarize, we have searched for the pair production of stop decaying into a charm quark and a neutralino, in 2.6 fb^{-1} of CDF Run II data. We observe 115 candidate events, which are in agreement with SM background expectations of 132.0 ± 24.4 events. No evidence for stop is observed, and we exclude a region in the stop and neu-

tralino mass plane at 95% C.L. as shown in Fig. 3. Assuming BR($\tilde{t}_1 \to c\tilde{\chi}_1^0$) = 100%, we exclude stop masses up to 180 GeV/c^2 at 95% C.L. for a neutralino mass of 90 GeV/c^2.

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