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Search for the supersymmetric partner of the top quark in $p\bar{p}$ collisions at √s=1.8 TeV

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We report on a search for the supersymmetric partner of the top quark (top squark) produced in $t\bar{t}$ events using 110 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV recorded with the Collider Detector at Fermilab. In the case of a light top squark, the decay of the top quark into a top squark plus the lightest supersymmetric particle (LSP) could have a significant branching ratio. The observed events are consistent with standard model $t\bar{t}$ production and decay. Hence, we set limits on the branching ratio of the top quark decaying into a top squark plus LSP, excluding branching ratios above 45% for a LSP mass up to 40 GeV/c^2.

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With the observation in 1995 of a heavy top quark [1,2], an important prerequisite was met for low energy supersymmetry (SUSY) [3] to explain electroweak symmetry breaking. In the minimal supersymmetric extension of the standard model (MSSM), all known particles of the standard model (SM) acquire supersymmetric partners, or superpartners. For fermions the superpartners are bosons, while for bosons the superpartners are fermions. We assume conservation of a multiplicative quantum number $\mathcal{R}$ parity, which requires these new particles to be produced in pairs and prevents decays of the lightest supersymmetric particle (LSP). From cosmological considerations [4], the LSP is normally assumed to be the lightest neutralino.

The large Yukawa coupling of the top quark opens up the possibility of a large mass splitting in the third generation of fermionic superpartners (the squarks and sleptons). The superpartners of the right-handed and left-handed top quark (the top squarks) combine to form the mass eigenstates. The lightest top squark ($\tilde{t}_1$) could then be lighter than the superpartners of all other squarks. Most limits on squark masses [5] do not apply to the top squark because they are usually based on a model of five degenerate squarks. Current top squark mass limits are significantly lower [6] than these limits or based on the assumption of a very heavy chargino ($\tilde{\chi}_1^{\pm}$) [7]. The latter searches are complementary to the analysis presented here since the top squark decay mode c + LSP does not coexist with the decay mode $b+\tilde{\chi}_1^{\pm}$. If the top squark is light, decays of the top quark into a top squark plus the lightest neutralino could be kinematically allowed. If this neutralino is the LSP it will be stable and only weakly interacting. Such a particle would pass through the detector without interaction, causing a considerable energy imbalance. For the top squark we assume decays analogous to the standard model top quark decay, i.e., into chargino and b quark. The chargino could then decay into a LSP plus either a quark-antiquark pair or a lepton and antineutrino.

Branching ratios as large as 40–50 % for the top decay into a top squark have been suggested [9]. In such scenarios about one-half of $t\bar{t}$ events would have one SM and one supersymmetric top decay. If the SM top decay to a W and a b quark is followed by the leptonic decay of the W, then the selection criteria of the online leptonic trigger, the offline dataset selection, and the $t\bar{t}$ event identification [1] will all be satisfied. The decay of the second top quark can then be used to search for decays into a top squark.

The Collider Detector at Fermilab (CDF) detector [10] is well suited to search for supersymmetric top quark decays. The following components are relevant to this analysis: the central tracking chamber, which is inside a 1.4 T superconducting solenoidal magnet, measures the momentum of charged particles with a resolution of $\delta p_T/p_T=0.001*p_T$ (p_T in GeV/c) [11]. The silicon vertex detector, with an inner radius of 3 cm and an outer of 8 cm, identifies secondary vertices with a resolution of 130 μm in the transverse plane. The electromagnetic and hadronic calorimeters cover the pseudorapidity region $|\eta|<4.2$ and are used to identify jets and electrons, and to measure the missing transverse energy $\not{E}_T$ [11]. An outer layer of drift chambers provides muon identification in the region $|\eta|<1.0$.

The search reported here is based on 110 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV recorded with the Collider Detector at Fermilab during the 1992–1993 and 1994–1995 collider periods. The analysis is a combination of a CDF single lepton plus jet top analysis [1] and a kinematic analysis [12]. The analysis cuts are slightly revised to improve sensitivity.

The leptonic W decay from the SM top decay yields an energetic lepton. Events are selected as in the single lepton plus b-jet top analysis by requiring a central electron ($|\eta|\leq 1.1$) or central muon ($|\eta|\leq 1.0$) with transverse momentum $p_T\geq 20$ GeV/c.

The neutrino from the W decay, as well as any LSP's, will escape the apparatus without detection, resulting in an energy imbalance. The $\not{E}_T$ measured by the calorimeter is corrected if the lepton is a muon. We have increased the $\not{E}_T$ requirement, from $\not{E}_T\geq 25$ GeV in the single lepton plus b-jet top analysis to $\not{E}_T\geq 45$ GeV, as our signal is expected to have a harder $\not{E}_T$ spectrum. To reject non-W background, we require the transverse mass M_T of the lepton and $\not{E}_T$ system to be larger than 40 GeV. While the top analyses are concerned with separating $t\bar{t}$ from W plus jet production, in this analysis we are interested in minimizing W plus multijet background and then focusing on separating SUSY top decays from SM top decays. In both SUSY and SM top decays the W has a substantial transverse momentum. An additional requirement that the lepton $-\not{E}_T$ system have $p_T \geq 50$ GeV/c has therefore been made.

In addition to the b jet from the SM top decay, we have three additional jets from the other top decay when the W or the chargino decays hadronically. We require two jets [13] with transverse energy $E_T\geq 20$ GeV and a third jet with $E_T\geq 15$ GeV, all within $|\eta|\leq 2.0$. Jet energy is corrected according to an average response function prior to event selection [12]. We require one of the jets to be identified as a

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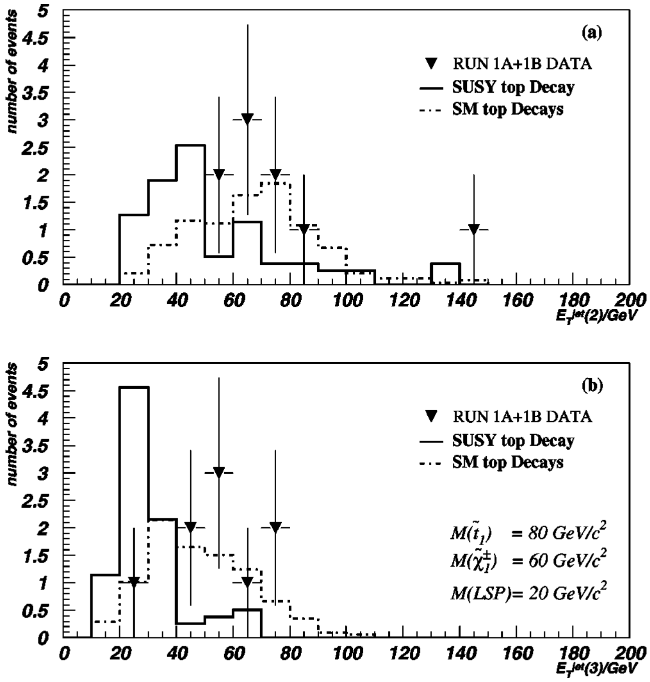

FIG. 1. Transverse energy distribution of (a) the second $E_{\mathrm{T}}^{jet}(2)$ and (b) third jet $E_{\mathrm{T}}^{jet}(3)$ for events with two SM top decays and for events with one SM and one SUSY top decay.

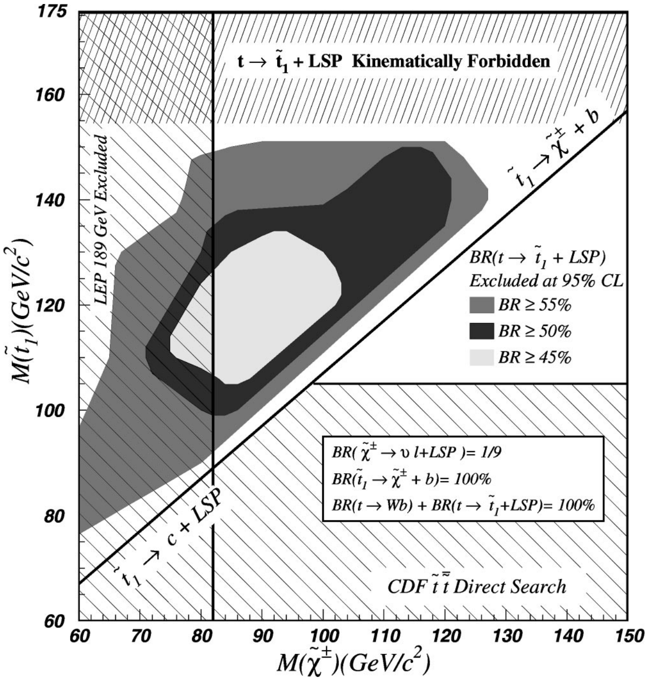

FIG. 3. Top into top squark plus LSP branching ratio limits as a function of top squark and chargino masses for a LSP mass of 20 GeV/c^2.

b-jet candidate. We use a secondary vertex tagging method [1], based on SVX information, that reconstructs secondary vertices from B hadron decays. As in the kinematic top analysis [12], we require the three jets to have large polar angles in the rest frame of the lepton, $\not{E}_{\mathrm{T}}$, and jets $|\cos(\theta^*(\mathrm{jet}_i))|<0.9$, $|\cos(\theta^*(\mathrm{jet}_j))|<0.8$, and $|\cos(\theta^*(\mathrm{jet}_k))|<0.7$, where the jets i,j,k are ordered according to $|\cos(\theta^*)|$. These requirements were relaxed from the requirement of $|\cos(\theta^*(\mathrm{jet}_{i,j,k}))|<0.7$ in [12] in order to obtain a good acceptance for the SM-SUSY top decays. For simplicity, these polar angles are calculated assuming a null longitudinal component for the neutrino. In order to insure that the three jets are well separated in η-ϕ space, we require $\Delta R(\mathrm{jet, jet})\geq 0.9$, where $\Delta R(\mathrm{jet, jet})=\sqrt{\Delta\eta^2+\Delta\phi^2}$ is the minimum distance between the jets.

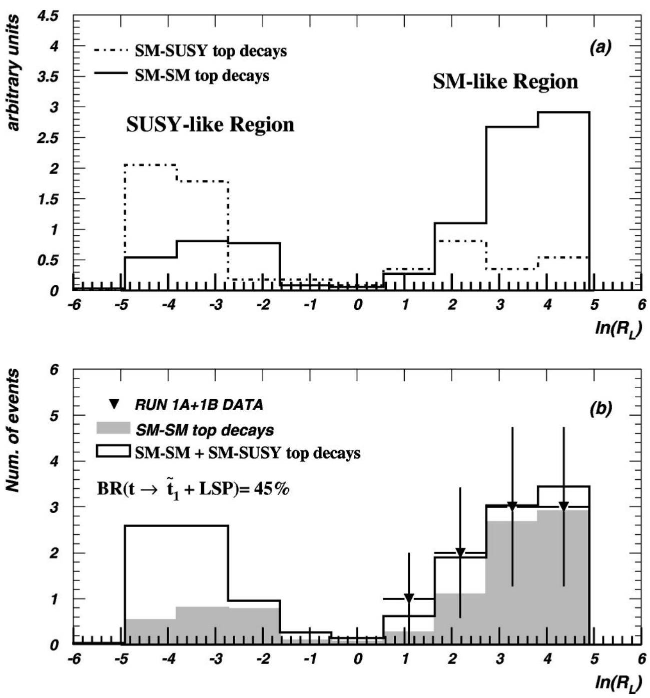

FIG. 2. (a) Comparison of $\ln(R_L)$ for SM-SM top decays and SM-SUSY top decays after all the cuts have been applied. (b) The $\ln(R_L)$ distribution for CDF run 1 data.

With these jet requirements our sample is defined. In the data nine events pass the above cuts. For the theoretical $t\bar{t}$ production cross section of 5 pb [14] we expect 9.5 events. A non-top standard model background contributes less than half an event.

Jets from a SUSY top decay are less energetic than jets from a SM top decay due to the presence of LSP's and possible small chargino mass. In order to best distinguish between SM and SUSY top decays, we combine the transverse energy information of the second and third most energetic jet in a likelihood variable defined as

$$R_L=\frac{\mathcal{P}^{SM-SM}(E_{\mathrm{T}}^{jet2})\times\mathcal{P}^{SM-SM}(E_{\mathrm{T}}^{jet3})}{\mathcal{P}^{SM-SUSY}(E_{\mathrm{T}}^{jet2})\times\mathcal{P}^{SM-SUSY}(E_{\mathrm{T}}^{jet3})},$$

where $\mathcal{P}$ are the expected differential transverse energy distributions $(1/\sigma)d\sigma/dE_{\mathrm{T}}$ evaluated from the Monte Carlo calculator.

Figure 1 shows those E_{T} distributions while Fig. 2 shows the distribution of the likelihood variable for SM and SUSY top decays. Events with one top quark decaying into a top

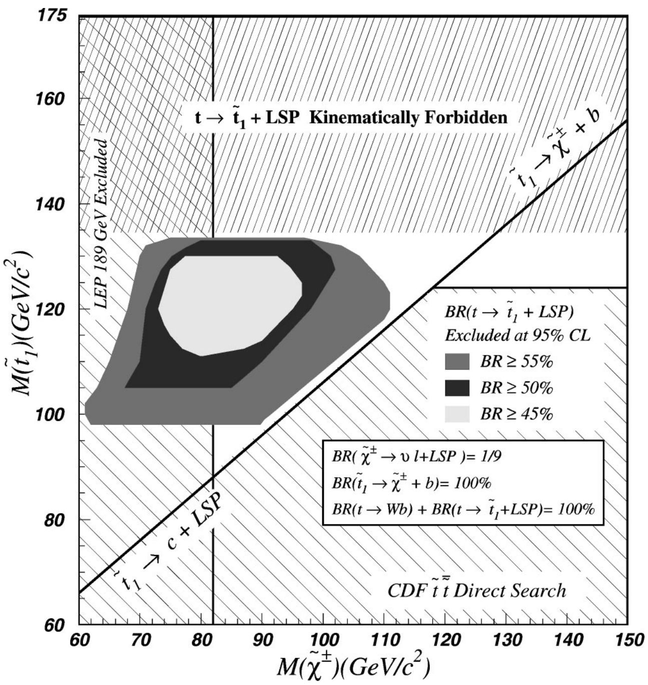

FIG. 4. Top into top squark plus LSP branching ratio limits as a function of top squark and chargino masses for a LSP mass of 40 GeV/c^2.

squark plus LSP are clustered in the region of negative values of $\ln(R_L)$, whereas events with two SM top decays are at positive values [15]. The region $\ln(R_L) < -1$ defines our SUSY search region. The region $\ln(R_L) > -1$ is dominated by double SM top decays and will be used to normalize the expected number of these decays. Our search is then independent of the $t\bar{t}$ production cross section [16].

To study the distributions of the kinematic variables in the supersymmetric top decays, the signals are produced with the ISAJET Monte Carlo generator [17] and passed through detector simulation programs [18]. We have fixed the top quark mass to 175 GeV/c^2 and varied the top squark, chargino, and LSP masses. Different branching ratios for top decaying into a top squark plus LSP are obtained by analyzing the three possible combinations of top decays (SM-SM, SM-SUSY, and SUSY-SUSY) individually and recombining them with appropriate weights.

Systematic uncertainties in the simulation of $t\bar{t}$ events can impact both the expected number of events and the shape of the two jet E_T distributions and thus the likelihood distribution. We have evaluated the systematic uncertainties for multiple points in the parameter space of the top squark and chargino masses. The systematic uncertainties are expected to become significant close to the kinematic bounds. In the region of small chargino mass the uncertainties due to gluon radiation and the calorimeter energy scale are important. The procedure used to evaluate these systematic uncertainties is the same as that of Ref. [19]. The uncertainty due to the $t\bar{t}$ production cross section and to the integrated luminosity is negligible since we normalize the Monte Carlo predictions to the data in the SM dominated region of large likelihood. We note that this normalization has a large statistical uncertainty due to the small number of events in this region. The uncertainty in the mass of the top quark becomes important in the region of large top squark mass, close to the kinematic limit. The effect of using parton distribution functions other than CTEQ-3 (LO) [8] is within the statistical uncertainty of the Monte Carlo samples. The total systematic uncertainty for both the expected number of events and fraction of events with $\ln(R_L) < -1$ from SM-SUSY top quark decays is typically around 40%. The major systematic uncertainty comes from the calorimeter energy scale and it varies between $\pm 15\%$ and $\pm 25\%$ in the region of the analyzed parameter space. The uncertainty on the top quark mass contributes about $\pm 15\%$ for most of the parameter space. The uncertainty due to the gluon radiation, on both number of events and shape, is always less than $\pm 10\%$.

All nine events are observed in the data cluster in the SM-like region of large $\ln(R_L)$. To set a limit on the branching ratio of top decaying into a top squark plus LSP, we calculate the branching ratios that would yield at least one event in the SUSY-like region 95% of the time as a function of top squark, chargino, and LSP mass. The method used is essentially a Bayesian-style integration over the systematic and statistical uncertainties in the SM-SM, SM-SUSY, and SUSY-SUSY contributions, where the uncertainties are assumed to be Gaussian distributed. Figures 3 and 4 show the 95% confidence level top decaying into a top squark plus LSP branching ratio limit as a function of top squark and chargino mass, for a LSP mass of 20 and 40 GeV/c^2. For larger LSP masses the kinematically allowed region shrinks. The sensitivity of this analysis, however, stays rather constant.

In conclusion, we have looked for the top decay into a top squark plus the LSP. In the case of a light top squark, the top is allowed to decay into a top squark plus a LSP. The number of events observed in the data is consistent with the standard model top decay expectation. We exclude branching ratios for top decaying into a top squark above 45% for an LSP mass up to 40 GeV/c^2. The upcoming run at the Tevatron, which will feature an approximately 20-fold increase in the total integrated luminosity as well as a significantly improved CDF detector, should allow these results to be greatly extended.

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