Physics

Physics Research Publications

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Search for the supersymmetric partner of the top quark in dilepton events from p(p)over-bar collisions at root s=1.8 TeV

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Search for the Supersymmetric Partner of the Top Quark in Dilepton Events from $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We have searched for pair production of the supersymmetric partner of the top quark (stop) in 107 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected by the Collider Detector at Fermilab (CDF). Each stop is assumed to decay into a lepton, bottom quark, and supersymmetric neutrino. Such a scenario would give rise to events with two leptons, two hadronic jets, and a substantial imbalance of transverse energy. No evidence of such a stop signal has been found. We exclude stop masses in the region ($80 \leq m_{\tilde{t}} \leq 135$ GeV$/c^2$) in the mass plane of stop versus sneutrino.

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Some of the most promising extensions of the standard model (SM) are based on supersymmetry, e.g., the minimal supersymmetric standard model (MSSM) [1]. It predicts that each SM particle has a superpartner (sparticle) with the same quantum numbers, except for spin which differs by one-half unit. Experimental results indicate that supersymmetric (SUSY) particles are generally not as light as their SM partners. SUSY, therefore, is broken at or above the electroweak scale, and we treat the sparticle masses as free parameters. Because of the large top quark mass, there may be a large mixing between the superpartners of the left and right helicity states of the top quark [2]. This can lead to substantial mass splitting of the squark (stop) mass eigenstates ($\tilde{t}_1$, $\tilde{t}_2$) with the lighter one (denoted $\tilde{t}$ from now on) potentially being the lightest squark.

Stop-antistop pairs ($\tilde{t}\bar{\tilde{t}}$) are strongly produced in the $p\overline{p}$ collisions at the Fermilab Tevatron if kinematically accessible. The production cross section has been calculated using QCD in the next-to-leading order (NLO) approximation [3]. For a given stop mass ($m_{\tilde{t}}$), the cross section depends weakly on the other parameters of the MSSM. In the mass region of interest to our search ($m_{\tilde{t}} =$ 80–140 GeV$/c^2$), the cross section drops from 44 to 1 pb.

We assume SUSY R-parity [4] conservation, from which the stability of the lightest supersymmetric particle (LSP) follows. All SUSY particles, including the stop, eventually decay into this LSP. Stop decays into the top quark are kinematically not accessible in our region of interest due to the high top mass ($m_{\tilde{t}} < m_t$). For the stop decay into a bottom quark and an on-shell chargino ($\tilde{\chi}_1^{\pm}$), only a very small window of opportunity remains at the Fermilab Tevatron due to the $\tilde{\chi}_1^{\pm}$ mass limit from LEP2 [5]. Another possible two-body stop decay would be the flavor-changing, $\tilde{t} \to c\tilde{\chi}_1^0$, decay [6]. It would proceed via higher order loop diagrams and is highly suppressed. The three-body decay into a charged supersymmetric lepton, $\tilde{t} \to \tilde{l}\nu b$, is closed for most of the stop region currently within the reach of the Collider Detector at Fermilab (CDF) because of the slepton mass limit of LEP2 [5]. The existing mass limit of the supersymmetric neutrino, $m_{\tilde{\nu}} \geq 45$ GeV$/c^2$ [7], leaves the decay into sneutrino, $\tilde{t} \to l\tilde{\nu}b$, open. We assume equal e, μ, and τ branching ratios.

Stop pair production with the $\tilde{t} \to l\tilde{\nu}b$ decay yields two leptons with opposite electric charge, two hadronic jets from the bottom quarks, and considerable transverse energy imbalance ($\not{E}_T$) in the detector [8] due to the escaping sneutrinos. CDF has reported earlier on an analysis based on B identification [9]. In this Letter, we use dilepton events. Only a few SM processes yield dileptons and can thus mimic our stop signature. The most significant ones are $t\bar{t}$ production, $b\bar{b}$ and $c\bar{c}$ with semileptonic decays, Drell-Yan production with hadronic jets from higher order processes, diboson production (WW, WZ, and ZZ), lepton pairs from the decay of vector mesons, such as J/ψ and Υ, and events without two genuine prompt leptons, where a hadron is misidentified as a lepton, or decays in flight to a lepton.

The search presented here is based on 107 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected by the CDF during the 1992 to 1995 running period of the Tevatron. A detailed description of the CDF detector can be found in Ref. [10]. Online triggers selected approximately 6.4×10^6 single lepton events and an additional 3.3×10^6 dilepton events. All of those events have been reconstructed, and 13 295 events were selected as a dilepton sample, by requiring at least one tight electron ($E_T \geq 10$ GeV, $|\eta| \leq 1.0$) or muon ($p_T \geq 10$ GeV$/c$, $|\eta| \leq 0.6$) candidate, and a second loose electron ($E_T \geq 6$ GeV, $|\eta| \leq 1.0$) or muon ($p_T \geq 6$ GeV$/c$, $|\eta| \leq 1.0$) candidate. No explicit tau lepton identification was done, but taus can enter the search sample if they decay leptonically. Electrons are identified by energy deposition in the electromagnetic calorimeter with a track of corresponding energy in the central drift chamber (CTC) pointing to it. Muons are identified by track segments in both the CTC and the muon drift chambers that are located behind 4.5 to 10 interaction lengths of absorber. Standard lepton identification cuts are used and described elsewhere [11]. Each lepton is required to be isolated; i.e., we require the total p_T of all other tracks within a cone $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq 0.4$ around the lepton's track not to exceed 4 GeV$/c$. The jets were reconstructed with a cone algorithm with cone radius $\Delta R = 0.7$ [12]. We require at least one jet in the central region of the calorimeter ($|\eta| \leq 1.0$) with $E_T \geq 15$ GeV, that is separated by $\Delta R \geq 0.7$ from both leptons in the event. For increased efficiency, we require only one of the two jets to be identified. Sequential B decays, J/ψ, Υ, and Z events were removed requiring the invariant dilepton masses $m_{ll'} \geq 6$ GeV$/c^2$ or $m_{ll} \geq 12$ GeV$/c^2$ and excluding $76 < m_{ll} < 106$ GeV$/c^2$ (where prime indicates any mixture of e and μ flavors and no prime indicates same-flavor dileptons). At the preselection level, we start with $\not{E}_T \geq 15$ GeV. Experimental backgrounds, like electrons from conversions and muons from cosmic rays are removed with additional cuts [13]. 176 events fulfill the above preselection requirements.

To estimate the number of SM and stop events in the sample, events of the various physics processes are generated by ISAJET [14] and simulated for the CDF detector. We have used CTEQ-3 parton distribution functions (PDF) [15]. The stop production cross section was calculated with PROSPINO [16] and the ISAJET cross section was adjusted accordingly. We have generated events over a large range of stop (80–140 GeV$/c^2$) and sneutrino (45–90 GeV$/c^2$) masses.

The Drell-Yan and $t\bar{t}$ production cross sections were normalized to CDF measurements [17]. The Monte Carlo (MC) $b\bar{b}$ and $c\bar{c}$ cross sections were verified by inclusive electron-muon samples. The $B^0\bar{B}^0$ oscillation effect was added based on the CDF measured inclusive χ mixing fraction [18]. The diboson production cross sections of the MC data were scaled to those of NLO calculations [19].

For low p_T leptons, the contribution due to misidentification can be significant and is calculated in two steps [13]. First, we measure in various data samples the so-called "fake lepton probabilities" (momentum-dependent, separately for electrons and muons, and dependent on detector region). These fake lepton probabilities include hadrons being misidentified as electrons or muons, and also include leptons from in-flight decays of pions and kaons. We measure misidentification probabilities between 0.4% and 7% for both e and μ [13].

Second, in a single lepton sample we use these "fake lepton probabilities" successively on each track in the event to simulate dilepton events. We use the "fake lepton probabilities" to simulate both the number of misidentified-lepton events as well as their kinematic properties.

The major background to the preselection sample comes from heavy flavor production, with about a quarter of the events having leptons of the same charge. Another significant background comes from Drell-Yan processes. In those events, the $\not{E}_T$ comes from τ decays or jet and lepton energy mismeasurements due to uninstrumented detector regions. We expect a total background of 155 ± 55 events, while a stop and sneutrino mass combination of 100 and 75 GeV$/c^2$ would contribute 24 ± 9 events. Table I shows the expected contributions for like-sign (LS) and opposite-sign (OS) charge leptons. To verify our background calculation further, we compare kinematic distributions of the data and the expected background. Figure 1 shows a few such distributions. Top and diboson production yield generally more energetic leptons than $b\bar{b}$, $c\bar{c}$, or misidentified leptons. The p_T distributions of the leptons show that both high and low p_T lepton sources agree well with the data. The $\not{E}_T$ distribution

TABLE I. Data, expected backgrounds for the preselection sample, and expected stop signal for $m_{\tilde{t}}$ ($m_{\tilde{\nu}}$) = 100 (75) GeV$/c^2$. The stop event acceptance is 2.5% at this stage.

Source	OS	LS
Drell-Yan	52.2 ± 13.7	0.4 ± 0.4
$b\bar{b}$, $c\bar{c}$	43.5 ± 32.1	16.4 ± 17.6
$t\bar{t}$	9.5 ± 2.9	0.6 ± 0.2
WW, WZ, ZZ	3.8 ± 0.9	0.4 ± 0.1
Misidentified leptons	16.3 ± 4.4	12.4 ± 3.4
Total background	125.2 ± 46.7	30.1 ± 18.4
Data	128	48
Expected $\tilde{t}\bar{\tilde{t}}$	22.6 ± 8.9	1.0 ± 0.4

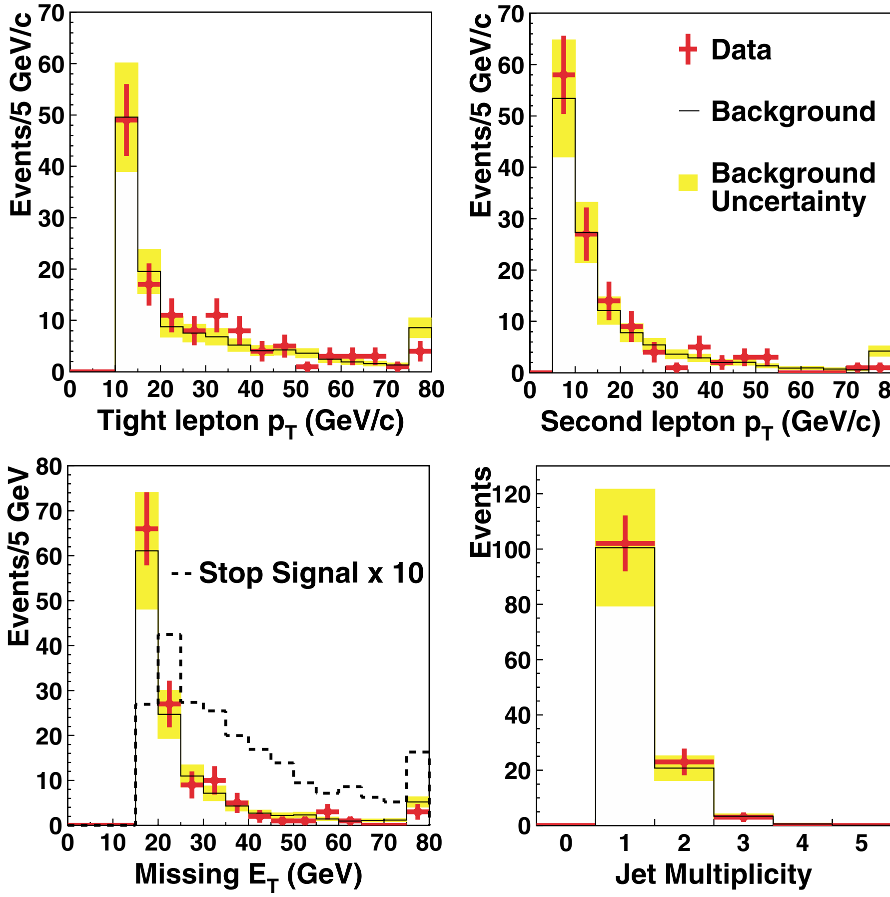

FIG. 1 (color online). Data and expected background after preselection. Tight and second lepton transverse energies, missing transverse energy [for comparison we also show the missing E_T distribution for a 10 times stop signal of $m_{\tilde{t}}(m_{\tilde{\nu}}) = 100(75)\ \mathrm{GeV}/c^2$], and jet multiplicity shown for events with opposite charge leptons. The last high bins contain overflows.

agrees both at low $\not{E}_T$, where detector effects dominate, and at high $\not{E}_T$, where neutrinos from W and Z bosons determine the spectrum. The parton shower MC program describes well the observed jet multiplicity. From the signal (S) to background (B) ratio, it is clear that the preselection sample does not have sufficient sensitivity to answer the question of stop pair production. In contrast to an earlier search [20], we select a kinematic region in which we expect higher S/B.

In less than 5% of stop events, the two leptons are LS due to the semileptonic decay of one of the b quarks. However, 20% of the SM background yields LS lepton events. We thus focus our search on events with OS leptons. For R_p-conserving supersymmetry, we expect large missing energy from the rather heavy sneutrinos. In Fig. 1, we see most of the background events clustering at low missing $\not{E}_T$. A $\not{E}_T$ cut of 30 GeV removes 77% of the SM background but keeps about 57% of the stop events. Energy mismeasurement of leptons, or the presence of neutrinos from Drell-Yan τ decays, would cause the leptons (and the dilepton system as well) to be aligned with the $\not{E}_T$ direction. This is not typical for the signal, where we expect true $\not{E}_T$ and the individual leptons and the dilepton system $\Delta\phi_{l_1}^{\not{E}_T}$, $\Delta\phi_{l_2}^{\not{E}_T}$, and $\Delta\phi_{l_1 l_2}^{\not{E}_T}$ to be larger than 30°.

In Drell-Yan plus jets events or when $b\bar{b}$ or $c\bar{c}$ events originate from gluon splitting (initial or final state) events, the two leptons balance the jets in the transverse plane. We veto events where the angle between either lepton and the most energetic central jet, $\Delta\phi_{l_1}^{\not{E}_T}$ and $\Delta\phi_{l_2}^{\not{E}_T}$, is larger than 90°.

Events from top pair production pass the above cuts with efficiencies similar to stop pair events and are now the dominant source of SM background. In top events, the leptons come from W decay and are very energetic. In the case of stop, we have three-body decays containing a very heavy sneutrino. The amount of available energy in the decay depends on the stop-sneutrino mass difference, $\Delta m_{\tilde{t}-\tilde{\nu}}$. For small mass difference, the leptons and jets are quite soft and a large fraction of the event energy escapes detection through the sneutrinos, unlike a $t\bar{t}$ event. For best stop sensitivity at small $\Delta m_{\tilde{t}-\tilde{\nu}}$, we require the scalar sum of lepton p_T, $p_T^{l_1} + p_T^{l_2} \leq 75\ \mathrm{GeV}/c$, and the p_T of the dilepton system, $p_T^{l_1 l_2} \leq 30\ \mathrm{GeV}/c$. Although a large amount of energy escapes undetected, the sneutrinos tend to be back to back, thus reducing the measured $\not{E}_T$. We also require the sum of the most energetic central jet E_T and the missing E_T, $E_T^{\rm jet} + \not{E}_T \leq 160$ GeV.

For large stop-sneutrino mass difference, the leptons are more energetic and we can increase our lepton p_T requirement to 10 GeV/c without much loss in stop efficiency. However, leptons and jets are still significantly softer than in $t\bar{t}$ events. We place the same jet, missing E_T, and lepton requirements as at small $\Delta m_{\tilde{t}-\tilde{\nu}}$, $E_T^{\rm jet} + \not{E}_T \leq 160$ GeV, and $p_T^{l_1} + p_T^{l_2} \leq 75$ GeV/c but loosen the requirement on the dilepton p_T to $p_T^{l_1 l_2} \leq 55$ GeV/c.

Table II shows the expected number of stop events for the two search regions. We start our search at stop masses of 80 GeV/c^2 to overlap with previous LEP limits. Near the kinematic limit of the stop decay, $m_{\tilde{t}} = m_{\tilde{\nu}} + m_b$, lepton and jet energies become very soft, limiting our stop detection capabilities. At high stop mass, our sensitivity is limited by the steeply falling production cross section. In the region of interest to this search, the final stop event acceptance varies between 0.3% and 2.3%.

The biggest source of uncertainty on the number of expected stop events arises from the choice of the renormalization and factorization scale, Q^2, which characterizes the amount of energy transferred during the collision. The $\not{E}_T$ is reduced (due to the sneutrinos being more back to back) when Q is increased, and the jet E_T gets softer when Q is decreased. By varying Q by a factor of 2 up and down, we determine the uncertainty due to the choice of Q^2 to be 32%. Other significant sources of uncertainty are the choice of PDF (11%); the absolute energy scale of the detector (11%); the amount of gluon radiation (7%); the trigger, lepton, and isolation efficiency (5%), and the luminosity measurement (4%). The statistical uncertainties of the MC samples are about 8%. Combining the statistical and systematic uncertainties, we obtained a total uncertainty of 38% for the signal expectation. Similarly, we evaluated the uncertainty of the background calculation to be 30%.

After establishing the selection cuts by using a "blind" analysis technique, we apply the cuts to the preselection data. We observe zero events for both the small and the large $\Delta m_{\tilde{t}-\tilde{\nu}}$ sets of cuts, consistent with our background

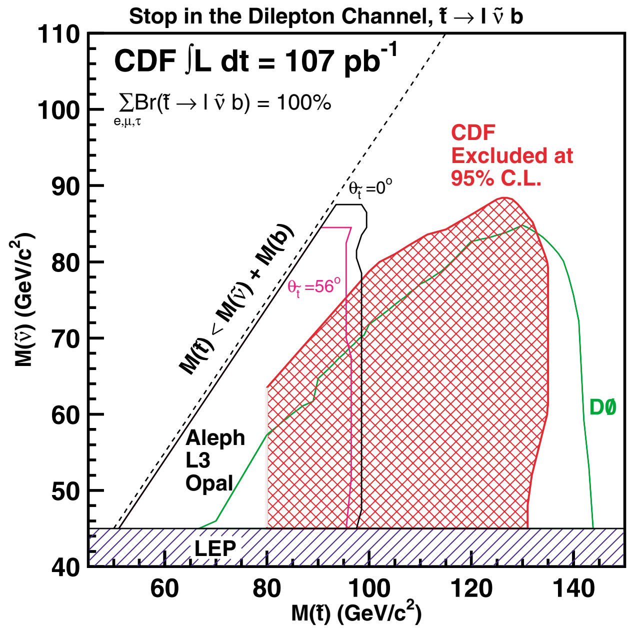

FIG. 2 (color online). Stop and sneutrino mass plane showing the CDF 95% C.L. excluded region as hatched area. For the three-body stop decay, $\tilde{t} \rightarrow l\tilde{\nu}b$, a 33.3% branching ratio to each of the three lepton flavors is used.

expectation of 1.52 ± 0.47 and 2.07 ± 0.46 events. We use the frequentist method with zero observed events, no background subtraction, and a total uncertainty of 38% on the predicted signal to calculate a 95% confidence level (C.L.) upper limit of 4.01 stop events. Consequently, we exclude all stop-sneutrino mass combinations that would yield more than 4.01 events. Figure 2 shows our result compared to LEP2 [5] and DØ [20].

In conclusion, we have searched for stop pair production in 107 pb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected by CDF. The observed dilepton, jet, and missing E_T events are consistent with expectations from SM sources. We exclude stop masses up to $m_{\tilde{t}} = 135$ GeV/c^2 (at $m_{\tilde{\nu}}$ of 72–79 GeV/c^2) and sneutrino masses up to 88.4 GeV/c^2 (at $m_{\tilde{t}}$ of 126 GeV/c^2) at 95% C.L.

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TABLE II. Data, expected background, and expected stop signals after final cuts. Stop A scenario represents a small $\Delta m_{\tilde{t}-\tilde{\nu}}$ with $m_{\tilde{t}}$ ($m_{\tilde{\nu}}$) = 100 (75) GeV/c^2. Stop B scenario represents a large $\Delta m_{\tilde{t}-\tilde{\nu}}$ with $m_{\tilde{t}}$ ($m_{\tilde{\nu}}$) = 120 (60) GeV/c^2

Selection	Data	Background	Stop A	Stop B
Preselection	176	155.3 ± 50.2	23.6 ± 8.9	34.5 ± 13.0
OS and $\not{E}_T$	26	28.7 ± 8.6	12.9 ± 4.9	25.1 ± 9.5
$\Delta\phi_{l,ll}^{\not{E}_T}$ and $\Delta\phi_l^{\rm jet}$	4	8.1 ± 2.4	6.7 ± 2.5	14.8 ± 5.6
Small $\Delta m_{\tilde{t}-\tilde{\nu}}$	0	1.5 ± 0.5	5.7 ± 2.1	⋯
Large $\Delta m_{\tilde{t}-\tilde{\nu}}$	0	2.1 ± 0.5	⋯	8.2 ± 3.1
95% C.L. cross section limit			9.0 pb	2.2 pb

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