Search for pair production of the scalar top quark in the electron+muon final state

Supersymmetric theories\(^1\) predict the existence of scalar partners for each of the standard model (SM) fermions. In the minimal supersymmetric standard model (MSSM)\(^2\), the mixing between the chiral states of the scalar partners of the SM fermions is greatest for the partners of the top quark due to its large Yukawa coupling\(^3\). Thus, it is possible that the scalar top quark (\(\tilde{t}_1\)) is the lightest squark and has the largest production cross section. If \(R\)-parity\(^4\) is conserved, then scalar top quarks would be produced by \(p\bar{p}\) collisions in pairs with the dominant processes being quark-antiquark annihilation and gluon fusion\(^5\).

In this letter we report on a search for the production of \(\tilde{t}_1\tilde{t}_1\) pairs in the \(b\bar{b}c\bar{c}\mu^\pm\nu\bar{\nu}\) final state. We assume that the \(\tilde{t}_1\) has a 100% branching fraction in this three-body decay mode with equal fraction to each lepton type, that \(R\)-parity is conserved, and that the sneutrino (\(\tilde{\nu}\)) is the lightest supersymmetric particle or decays invisibly into a neutrino and a neutralino (\(\tilde{\chi}^0\)). This analysis uses data corresponding to an integrated luminosity of 5.4 \(\text{fb}^{-1}\) collected using the D0 detector operating at the Fermilab Tevatron collider at \(\sqrt{s} = 1.96\) TeV. The data were collected from April 2002 through June 2009. The D0 Collaboration has previously searched\(^6\) for top squark

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pair production in the final states $b\bar{b}\ell^+\ell^-\nu\bar{\nu}$ where the lepton pair is $e$, $\mu$, or $e\mu$. Two of these earlier searches used subsets of this data set corresponding to integrated luminosities of 0.43 fb$^{-1}$ and 1.1 fb$^{-1}$, while the earliest search used data from the Tevatron Run I, corresponding to an integrated luminosity of 0.11 fb$^{-1}$. Searches for top squark pair production in the $b\bar{b}\ell^+\ell^-\nu\bar{\nu}$ final states have also been reported by the CDF collaboration [7] and by the ALEPH, L3, and OPAL Collaborations [8].

The main components of the D0 detector [9] include a central tracking system located inside a 2 T superconducting solenoid. The innermost tracking element is the silicon microstrip tracker (SMT), followed by a scintillating fiber tracker. These two detectors together measure the momenta of charged particles. The tracking system provides full coverage in the azimuthal ($\phi$) direction for $|\eta| < 1.5$ GeV and $|\eta| > 1.6$ around the muon track divided by $p_T^\mu$ must be less than 0.15. For the central tracker isolation, the sum of the transverse energy of the tracks in the hollow cone 0.1 $< \eta < 0.5$ divided by $p_T^\mu$ must be less than 0.15.

Events are required to have exactly one electron and one muon with opposite charge and to have a minimum separation between the electron and the muon $\Delta R(e, \mu) > 0.5$. The missing transverse energy ($E_T$) is calculated from the calorimeter energy corrected for the jet and electron calibrations. It is then adjusted to account for the transverse momentum of the muon. All retained events are required to have $E_T > 7$ GeV. We refer to this preliminary set of selection requirements as the preselection.

Signal Monte Carlo (MC) events are generated in a 2-D grid, i.e., for $t\bar{t}$ masses ranging from 100 GeV to 240 GeV, and for $\tilde{\nu}$ masses ranging from 40 GeV to 140 GeV, each in 10 GeV steps. For each point, the MSSM decay parameters are calculated with SUSPECT [12] and SDECAY [13]. MADGRAPH/MADEVENT [14] is used to generate four-vectors for the signal events with PYTHIA [15] providing the showering and hadronization. The next-to-leading order (NLO) cross section for $t\bar{t}$ pair production is calculated by PROSPINO 2.0 [10] with the CTEQ6.1M [17] parton distribution functions (PDFs). The calculations are performed with the factorization and renormalization scales set to one, one half, and two times the $t\bar{t}$ mass to determine the nominal value and the negative and positive uncertainties. The scale factor uncertainties are combined quadratically with the PDF uncertainties [17] [18] to give the total theoretical uncertainties for the signal cross sections.

The dominant SM backgrounds for this decay are $Z/\gamma^* \rightarrow \tau\tau$ with $\tau \rightarrow l\nu$; diboson production including $WW$, $WZ$, and $ZZ$; top quark pairs; $W +$ jets; and instrumental background coming from multijet (MJ) processes where jets are misidentified as electrons or contain muons that pass the isolation criterion and with $E_T$ arising from energy mismeasurement. All the background
processes in this analysis except for MJ are modeled using MC simulation. Vector boson pair production is simulated with PYTHIA, while all other backgrounds are simulated at the parton level with ALPGEN, with PYTHIA used for hadronization and showering. In order to simulate detector noise and multiple $p\bar{p}$ interaction effects, each MC event is overlayed with a data event from randomly chosen $p\bar{p}$ crossings.

MC correction factors determined from data are applied to make distributions consistent between data and MC. These corrections include factors for the luminosity profile, beam spot position, muon and electron identification efficiencies, boson transverse momentum, and jet, electron, and muon energy resolutions.

The MJ background is estimated from a selection of data events not overlapping with the search sample and is selected by inverting the electron likelihood and muon isolation requirements. This sample is used to determine the shape of the MJ background. Because most same-sign di-lepton events come from MJ processes, we obtain the normalization factor by taking the ratio of the number of same-sign events that pass the likelihood and isolation requirements to the number of same-sign events that fail these requirements. To remove $W+\text{jet}$ events from the MJ same-sign sample, we make the additional requirement $E_T < 20$ GeV, since $W+\text{jet}$ events tend to have large $E_T$. We also correct this ratio for non-MJ SM processes that produce like-sign leptons, using the MC samples.

Data events are required to satisfy at least one of a suite of single-electron or single-muon triggers. The efficiency of the combination of the single-electron triggers is measured using a subset of the search sample in which at least one of the single-muon triggers fired, and vice-versa for the single muon triggers. The combination of these two efficiencies, taken to be the overall trigger efficiency, is then applied as a correction to the MC samples.

The mass difference, $\Delta M = M_{\ell_1} - M_{\ell_2}$ determines the kinematics of the final state. A larger $\Delta M$ will lead, on average, to larger $E_T$, larger jet energy, and higher $p_T$ charged leptons. We divide the range of $\Delta M$ into a “large-$\Delta M$” region ($\Delta M > 60$ GeV) and “small-$\Delta M$” region ($\Delta M < 60$ GeV). To illustrate these regions, we have chosen two benchmark points, $(M_{\ell_1}, M_{\ell_2}) = (200$ GeV, 100 GeV) and (110 GeV, 90 GeV), which will be referred to as the large-$\Delta M$ and small-$\Delta M$ benchmarks, respectively. Since there are many signal points and their characteristics differ significantly, the analysis strategy is to optimize the signal selection as a function of $\Delta M$.

For all values of $\Delta M$, the largest background after pre-selection is $Z/\gamma^* \rightarrow \tau\tau$. A two-dimensional plot of the azimuthal angle between the electron and muon, $\Delta \phi(e, \mu)$, vs. $E_T$ for $Z/\gamma^* \rightarrow \tau\tau$ MC events is shown in Fig. 1. The two leptons from $Z/\gamma^* \rightarrow \tau\tau$ tend to be back-to-back in $\phi$, and tend to have low $E_T$. We therefore reject events in which $\Delta \phi(e, \mu) > 2.8$ and $E_T < 20$ GeV and label this as “Selection 1”.

Figure 2 compares $E_T$, electron $p_T$, and muon $p_T$ of the data and the sum of all backgrounds at this stage of the analysis. The agreement confirms our understanding of the SM backgrounds, of the trigger efficiency, and of other MC corrections. After selection 1, the three largest backgrounds are $Z/\gamma^* \rightarrow \tau\tau$, $WW$, and $t\bar{t}$ production. To discriminate these backgrounds from signal we create for each of them a composite discriminant variable from a linear combination of kinematic quantities. We use the R software package [20] to calculate the maximum likelihood coefficients $\vec{\beta}$ for a generalized linear model (GLM) [21] of the form

$$\delta A = \ln \frac{\mu}{1 - \mu} = \beta_0 + \vec{\beta} \cdot \vec{X}$$

(1)

to discriminate between signal and a specific background source $A$. Here, $\mu$ is the probability that an event is signal, $\beta_0$ is a constant, $\vec{\beta}$ is the vector of coefficients, and $\vec{X}$ is the vector of event kinematic variables. By construction, $\delta A = 0$ when $\mu = 0.5$, and signal-like events have positive $\delta A$. The discriminant $\delta Z$ is constructed to separate signal from $Z/\gamma^* \rightarrow \tau\tau$ background, using an equal number of signal and $Z/\gamma^* \rightarrow \tau\tau$ MC events to determine the coefficients $\beta_0$ and $\vec{\beta}$. For $\vec{X}$ we use the following variables: $\ln(E_T)$, $\ln(p_T^{e})$, $\ln(p_T^{\mu})$, $\Delta \phi(e, \mu)$, $\Delta \phi(e, E_T)$, $\Delta \phi(\mu, E_T)$, and $\Delta \phi(e, \mu) \times \Delta \phi(\mu, E_T)$. For each value of $\Delta M$, ranging from 20 to 200 GeV, we use the same variables with re-optimized coefficients. We use a similar method for creating the discriminants $\delta WW$ and $\delta t\bar{t}$ to separate signal from $WW$ and $t\bar{t}$ backgrounds. For $\delta WW$ we use the variables $\ln(E_T)$, $\ln(p_T^{e})$, $\ln(p_T^{\mu})$, number of jets, $\Delta \phi(e, \mu)$, and $\ln(WW_{\text{tag}})$. Here $WW_{\text{tag}}$ is the magnitude of the vector sum of $p_T^e$, $p_T^\mu$, and $E_T$, which should be close to zero for $WW$ events. For $\delta t\bar{t}$, we use the variables $\ln(E_T)$, $\ln(p_T^{e})$, $\ln(p_T^{\mu})$, $\ln(1 + H_T)$, the
energy of the second most energetic jet, and $WW_{\text{tag}}$. The variable $H_T$ is the scalar sum of the transverse energies of all jets in an event.

We first apply a requirement using the most effective discriminator of the three. For $\Delta M < 60$ GeV, we require $\delta t\bar{t} > 0$. The efficiency of this requirement is 0.95 for the small-$\Delta M$ signal benchmark and 0.03 for $t\bar{t}$. For $\Delta M \geq 60$ GeV, we require $\delta Z > 0$. The efficiency of this requirement is 0.96 for the large-$\Delta M$ signal benchmark and 0.01 for $Z/\gamma^* \rightarrow \tau\tau$. After making these require-

ments on one variable, we build 2-D distributions of the two remaining discriminants. Figure 3 shows these distributions for the small-$\Delta M$ benchmark signal and the two most significant remaining backgrounds. In calculating the signal exclusion confidence limits, we use only the bins in the upper right quadrant where the signal is concentrated.
We have excluded stop pair the previous limits on the top squark mass by more than 40 GeV for sneutrino masses less than 90 GeV and the limits on the sneutrino mass by more than 30 GeV for top squark mass equal to 150 GeV.

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<th>Sample</th>
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<tr>
<td>Z → ℓℓ</td>
<td>1516 ± 150</td>
<td>582 ± 61</td>
<td>515 ± 54</td>
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<tr>
<td>Z → μμ</td>
<td>33.1 ± 4.7</td>
<td>22.9 ± 3.7</td>
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<td>Z → ee</td>
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<td>12.0 ± 1.5</td>
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<td>295 ± 32</td>
<td>268 ± 30</td>
<td>157 ± 18</td>
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<td>2.2 ± 0.3</td>
<td>2.0 ± 0.3</td>
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<td>t̄t̄</td>
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<td>204 ± 28</td>
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<td>1195 ± 73</td>
<td>785 ± 57</td>
<td>513 ± 37</td>
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<td>1147</td>
<td>776</td>
<td>472</td>
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<th>Sample</th>
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<th>Selection 2</th>
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<tbody>
<tr>
<td>Small-ΔM Benchmark (110 GeV,90 GeV)</td>
<td>35 ± 5.6</td>
<td>25.5 ± 4.2</td>
<td>23.8 ± 3.9</td>
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<tr>
<td>Large-ΔM Benchmark (200 GeV,100 GeV)</td>
<td>55 ± 9.3</td>
<td>53.4 ± 9.0</td>
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</table>

TABLE I: Expected numbers of background and signal events, and the number of events observed in the data at each stage of the analysis. The errors include statistical and systematic uncertainties. For ΔM < 60 GeV, Selection 2 is δt̄t̄(ΔM = 20 GeV)> 0, and for ΔM ≥ 60 GeV, Selection 2 is δZ(ΔM = 100 GeV)> 0.

For ΔM < 60 GeV, we use the two dimensional histograms of the positive values of δZ and δWW in the limit setting procedure. For ΔM ≥ 60 GeV, we use the positive values of δt̄t̄ and δWW. A modified frequentist approach [22] is used to determine the 95% C.L. exclusion limits on scalar top quark production as a function of the δt̄ and δZ masses, as shown in Fig. 4. Also shown are the exclusion regions from the CERN LEP experiments [8], previous D0 searches [2,3], and a CDF search [4].

In conclusion, we set 95% C.L. exclusion limits on the cross section for scalar top quark pair production assuming a 100% branching fraction to b̄b̄t̄ + l̄l̄ν̄ν̄ using 5.4 fb⁻¹ of integrated luminosity from the D0 experiment at the Fermilab Tevatron collider. We have excluded stop pair production for M_{t̄1} < 210 GeV when M_{b̄} < 110 GeV and the difference M_{t̄1} − M_{b̄} > 30 GeV. This extends the previous limits on the top squark mass by more than 40 GeV for sneutrino masses less than 90 GeV and the limits on the sneutrino mass by more than 30 GeV for top squark mass equal to 150 GeV.

[8] LEP SUSY Working Group (ALEPH, DELPHI, L3, and
FIG. 4: (color online) The observed (expected) 95% C.L. exclusion region includes all mass points below the solid (dashed) line. The shaded band around the expected limit shows the effects of the scalar top quark pair production cross section uncertainty. The kinematically forbidden region is represented in the upper left, and the regions excluded by LEP I and LEP II [8], by previous D0 searches [9, 10], and by a previous CDF search [11] are also shown.