# Search for the Scalar Top Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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0031-9007/02/88(17)/171802(6)$20.00

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(Received 6 August 2001; published 16 April 2002)

We have performed a search for scalar top quark (stop) pair production in the inclusive electron-muon-missing transverse energy final state, using a sample of $p\bar{p}$ events corresponding to 108.3 pb$^{-1}$ of data collected with the D0 detector at Fermilab. The search is done in the framework of the minimal supersymmetric standard model assuming that the sneutrino is the lightest supersymmetric particle. For the dominant decays of the lightest stop, $\tilde{t} \rightarrow b\tilde{\chi}_1^+$ and $\tilde{t} \rightarrow b\ell\tilde{\nu}$, no evidence for signal is found. We derive cross-section limits as a function of stop ($\tilde{t}$), chargino ($\tilde{\chi}_1^+$), and sneutrino ($\tilde{\nu}$) masses.

DOI: 10.1103/PhysRevLett.88.171802 PACS numbers: 14.80.Ly, 12.60.Jv, 13.85.Rm

Supersymmetry (SUSY) [1] provides a theoretically attractive and coherent picture of the microscopic world that retains the standard model's (SM's) successful description of the observed elementary particles and their interactions. A major consequence of the realization of SUSY in nature would be the existence of additional particles (sparticles), with quantum numbers identical to those of the elementary particles of the standard model, but with spins differing by a half unit. From experimental evidence, the sparticle masses also differ from those of their SM partners, i.e., SUSY is a broken symmetry, and it is expected that the mass spectrum of the sparticles has a different pattern than that of the SM. In particular, in several SUSY models, the large mass of the top quark ($m_t$) induces a strong mixing between the supersymmetric partners of the two chirality states of the top quark, leading naturally to two physical states, $\tilde{t}_1$ and $\tilde{t}_2$, of very different mass [2]. The lightest stop quark $\tilde{t}_1$ (called $\tilde{t}$ in this Letter) could therefore be significantly lighter than the other squarks, rendering it a particularly auspicious choice for a direct search.

The production of a pair of stop quarks ($\tilde{t}\bar{\tilde{t}}$) at the Tevatron can proceed through gluon fusion or quark annihilation. The cross section for such a process depends to a large extent only on the stop mass $m_{\tilde{t}}$, and, for a given $m_{\tilde{t}}$, is known at next-to-leading order (NLO) with a precision of ±8% [3]. The phenomenology of stop decays depends on the assumptions of the SUSY model, and this analysis is done in the minimal supersymmetric standard model (MSSM) [4] framework with $R$-parity [5] conservation, implying that the lightest SUSY particle (LSP) is stable. Searches for stop production have already been performed at the Tevatron assuming that the lightest neutralino ($\tilde{\chi}_1^0$) is the LSP [6].

In this Letter we also search for light stop ($m_{\tilde{t}} < m_t$) production, but assume that the sneutrino ($\tilde{\nu}$) is the LSP. Stop searches have been performed under these assumptions at LEP 2 [7] and by CDF Collaboration at the Tevatron [8] yielding a mass limit $m_{\tilde{t}} \gtrsim 123$ GeV for the lowest allowed sneutrino mass, $m_{\tilde{\nu}} \approx 45$ GeV, as determined at LEP 1 [9]. Although these analyses are interpreted in the framework of the MSSM, the results are largely model independent, depending mainly on the masses of the stop and its decay products.

In the stop mass range probed by the Tevatron, either the 2-body decay via a chargino, $\tilde{t} \rightarrow b\tilde{\chi}_1^+$, is kinematically allowed, and thereby dominant, or the chargino mediating the decay is virtual and the dominant decay mode is $\tilde{t} \rightarrow b\ell\tilde{\nu}$. The three other 3-body decays mediated by a chargino, $\tilde{t} \rightarrow b\nu\tilde{\ell}^+ \; (\rightarrow b\nu\ell^+\tilde{\chi}_1^0)$ , $\tilde{t} \rightarrow bW\tilde{\chi}_1^0$, and $\tilde{t} \rightarrow bH^+\tilde{\chi}_1^0$, with subsequent decays $\tilde{\chi}_1^0 \rightarrow \tilde{\nu}\nu$, are disfavored [10] and neglected in the following. In this Letter, the chargino is taken either as virtual, with a propagator mass of 140 GeV, or its mass is varied between its lowest experimental limit (≈103 GeV [11]) and the maximum value allowed by kinematics. The branching fraction for the stop to decay to sneutrinos is assumed to be flavor independent and the masses of the sneutrinos of all three flavors are taken to be equal, except when the channel $\tilde{t} \rightarrow b\tau\tilde{\nu}_\tau$ is assumed to be dominant.

The experimental signature for decays of a $\tilde{t}\bar{\tilde{t}}$ pair consists of two $b$ quarks, two leptons, and missing transverse energy ($\not{E}_T$). The variable $\not{E}_T$ represents the measured imbalance in transverse energy due to the two escaping sneutrinos. The leptons can be $e$, $\mu$, or $\tau$, but $\tau$ leptons are considered only if they decay into $e\nu\bar{\nu}$ or $\mu\nu\bar{\nu}$. We place no requirements on the presence of jets and use only the $e\mu\not{E}_T$ signature since it has less background than the $ee\not{E}_T$ or $\mu\mu\not{E}_T$ channels. The resulting event sample corresponds to 108.3 pb$^{-1}$ of data collected by the D0 experiment at Fermilab during Run I of the Tevatron.

A detailed description of the D0 detector and its triggering system can be found in Ref. [12]. The data and preselection criteria are identical to those used in the published $t\bar{t}$ cross-section analysis for the dilepton channel [13], which includes the selection of events containing one or more isolated electrons with $E_T^e > 15$ GeV, one or more isolated muons with $E_T^\mu > 15$ GeV, and $\not{E}_T > 20$ GeV.

$\not\!\!E_T$ is obtained from the vector sum of the transverse energy measured in the calorimeter and in the muon spectrometer system. Electrons are required to have $|\eta_{\rm det}| < 1.1$, or $1.5 < |\eta_{\rm det}| < 2.5$, where $\eta_{\rm det}$ is the pseudorapidity ($\eta$) defined with respect to the center of the detector. Muons must satisfy $|\eta_{\rm det}| < 1.7$.

The dominant SM processes that provide the $e\mu\not\!\!E_T$ signature are, in order of decreasing importance, (i) multijet processes (called "QCD" in the following) with one jet misidentified as an electron and one true muon originating from another jet (muon misidentification has negligible effects on our final state); (ii) $Z \rightarrow \tau^+\tau^- \rightarrow e\mu\nu\bar{\nu}\nu\bar{\nu}$, (iii) $WW \rightarrow e\mu\nu\bar{\nu}$, (iv) $t\bar{t} \rightarrow e\mu\nu\bar{\nu}jj$, and (v) Drell-Yan $(DY) \rightarrow \tau^+\tau^- \rightarrow e\mu\nu\bar{\nu}\nu\bar{\nu}$. The QCD background was determined from data, following the procedure described in Ref. [14]. The other SM backgrounds were simulated and reconstructed using the full D0 analysis chain.

Simulation of the signal is based on PYTHIA [15], using the CTEQ3M [16] parton distribution functions (PDFs), and the standard hadronization and fragmentation functions in PYTHIA. COMPHEP [17] is used to generate the 2- and 3-body decay of the stop. Detector simulation is performed using the fast D0 simulation/reconstruction program, which has been checked extensively on a reference sample passed through the full D0 analysis chain. The $\tilde{t}\bar{\tilde{t}}$ samples were simulated for stop (sneutrino, chargino) masses varying between 50 (30, 100) and 150 (90, 170) GeV.

Distributions in the kinematic quantities ($E_T^e, E_T^\mu, \not\!\!E_T$) are shown in Figs. 1(a)–1(c). Also shown [Fig. 1(d)] are the distributions for the transverse energy of any associated jets, defined by a cone algorithm and having $E_T^{\rm jet} >$ 15 GeV, and two additional kinematic quantities in which the signal and background display a different response: [Fig. 1(e)] $\Delta_\varphi^{e\mu} \equiv |\varphi_e - \varphi_\mu|$, where $\varphi_\ell$ is the azimuthal angle of the lepton $\ell$, and [Fig. 1(f)] $\Sigma_\eta^{e\mu} \equiv |\eta_e + \eta_\mu|$. Based on simulation studies, two additional criteria, $15° < \Delta_\varphi^{e\mu} < 165°$ and $\Sigma_\eta^{e\mu} < 2.0$, were applied to improve the signal to background ratio in the final sample.

The expected cross sections for the background processes, the normalized numbers of events passing the preselection, and the events passing the final selection are given in Table I, and compared to the expected stop signal for $m_{\tilde{t}}(m_{\tilde{\nu}}) = 120$ (60) GeV. The efficiency for selecting the signal varies typically between 1% and 4% and is largest for high stop masses and low sneutrino masses. The most significant sources of uncertainties on the signal are the trigger and lepton identification efficiencies (≈12%), the stop pair production cross section (8%), the uncertainty due to the PDFs (5%) [18], the effect of the analysis criteria (6%), and the luminosity (5.3%), which combine to approximately 18%. This uncertainty also includes the effect of the variation of the SUSY parameters $\mu_{\rm susy}$ (the Higgs-Higgsino mass parameter) and $m_{\tilde{\chi}_1^+}$ [19]. The systematic error for the background is about 10%. This error is dominated by the uncertainty on the QCD background (7%) and on the cross sections for the background processes (10%–17%).

The agreement between the number of observed events and the expected SM background leads us to set cross-section limits on stop quark pair production. We make the assumption that all non-SM processes, except the ones specifically searched for, can be neglected. This translates into more conservative limits. The 95% confidence

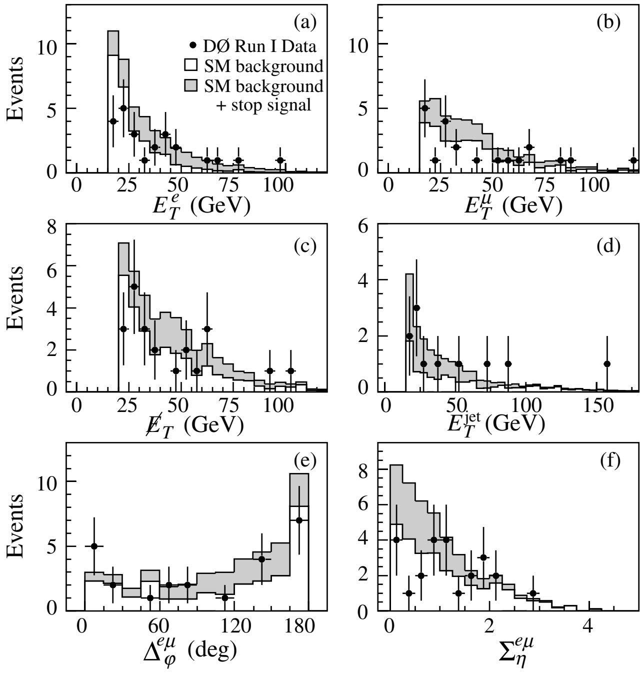

FIG. 1. Distributions after preselection for the total background (open histogram), the sum of the total background and the expected stop signal for $m_{\tilde{t}}$ ($m_{\tilde{\nu}}$) = 120 (60) GeV (shaded histogram) and the data (points) of (a) the transverse energy of the electron, (b) the transverse energy of the muon (three events have $E_T^\mu > 125$ GeV), (c) the missing transverse energy, (d) the transverse energy of the jets, (e) the difference in azimuthal angle between the two leptons, and (f) the absolute value of the sum in $\eta$ of the two leptons.

TABLE I. Cross sections for the background processes, the expected numbers of simulated events passing the preselection and the final analysis criteria, for a luminosity of 108.3 pb$^{-1}$, numbers of events selected in the $e\mu\not\!\!E_T$ data sample, and the expected stop signal assuming $m_{\tilde{t}}$ ($m_{\tilde{\nu}}$) = 120 (60) GeV.

| Process | Cross section (pb) | Events after preselection | Events after final selection |
|---|---|---|---|
| QCD | – | 15.1 ± 1.3 | 6.7 ± 0.5 |
| $Z \rightarrow \tau^+\tau^-$ | 1.70 | 5.3 ± 1.0 | 1.4 ± 0.3 |
| $WW$ | 0.69 | 4.4 ± 0.7 | 3.3 ± 0.3 |
| $t\bar{t}$ | 0.40 | 2.7 ± 0.5 | 2.2 ± 0.4 |
| $DY \rightarrow \tau^+\tau^-$ | 0.35 | 0.18 ± 0.04 | 0.04 ± 0.02 |
| Total background | – | 27.8 ± 2.7 | 13.7 ± 1.5 |
| Data | – | 24 | 10 |
| $\tilde{t}\bar{\tilde{t}}$ | 4.51 | 17.3 ± 3.1 | 13.2 ± 2.3 |

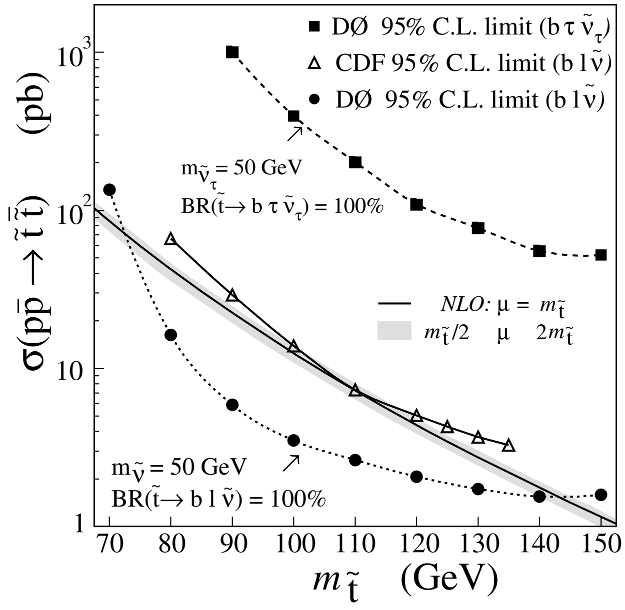

FIG. 2. Cross-section limit as a function of $m_{\tilde{t}}$ for $m_{\tilde{\nu}} = 50$ GeV. The $\tilde{t} \to b\ell\tilde{\nu}$ results of this analysis are compared to those of CDF and to the expected NLO cross section whose error band is obtained by varying the factorization scale $\mu$. The renormalization scale is taken to be equal to $\mu$. Also shown is the limit obtained in the $\tilde{t} \to b\tau\tilde{\nu}_\tau$ channel for $m_{\tilde{\nu}_\tau} = 50$ GeV.

level (C.L.) limits are obtained using a Bayesian approach [20] that takes statistical and systematic uncertainties into account. Assuming that the stop decays via a virtual chargino and $m_{\tilde{\nu}} = 50$ GeV, any stop mass between 73 and 143 GeV is excluded, as shown in Fig. 2. The CDF collaboration has also performed a search in the $\tilde{t} \to b\ell\tilde{\nu}$ [8], but based on a different signature: large missing transverse energy, at least one lepton, one jet identified as a $b$ jet, and at least another jet. The CDF and D0 results are compared in Fig. 2.

In the MSSM, when the ratio of the two vacuum expectation values of the Higgs fields is large ($\tan\beta \gtrsim 10$), the $\tilde{\nu}_\tau$ can be substantially lighter than the $\tilde{\nu}_e$ or the $\tilde{\nu}_\mu$, leading to an enhancement of the decay width for $\tilde{t} \to b\tau\tilde{\nu}_\tau$ [10,21]. In this case, the absence of signal provides a limit on the cross section in this decay channel, as shown in Fig. 2 for $m_{\tilde{\nu}_\tau} = 50$ GeV.

Assuming lepton universality again, the $\tilde{t}\bar{\tilde{t}}$ cross-section limits can be derived for different sneutrino mass values. For a fixed value of $m_{\tilde{t}}$, the cross-section limit becomes stronger with decreasing $m_{\tilde{\nu}}$. For $m_{\tilde{\nu}}$ up to 85 GeV, and for certain values of $m_{\tilde{t}}$, these are below the expected MSSM cross sections. The resulting exclusion contour in the $(m_{\tilde{t}}, m_{\tilde{\nu}})$ plane is displayed in Fig. 3, and compared to those obtained by CDF [8], LEP 1, and most recently at LEP 2 [22]. (Slightly stronger model-dependent indirect limits on the sneutrino mass could be derived [23] from LEP 2 searches for charged sleptons and would exclude a part of the region excluded by this analysis.) The present analysis places limits at significantly higher $m_{\tilde{t}}$ compared to these results. This is mainly because of the higher center of mass energy of the Tevatron compared to LEP, and of the choice of a more sensitive signature compared to CDF. For $m_{\tilde{\nu}} = 45$ GeV, the excluded region extends up to a scalar

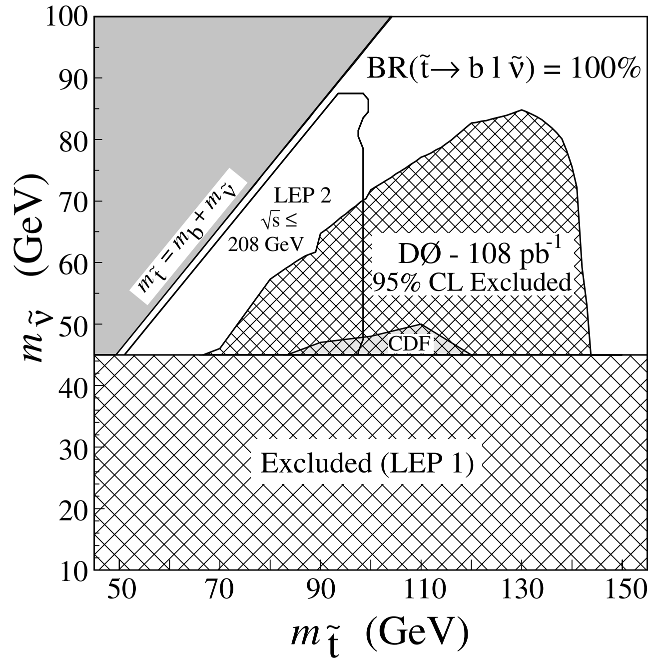

FIG. 3. Excluded regions in the $(m_{\tilde{t}}, m_{\tilde{\nu}})$ plane for the $\tilde{t} \to b\ell\tilde{\nu}$ decay channel in the MSSM. The results of this analysis (labeled DØ 108 pb$^{-1}$) are compared to the exclusion limits obtained in the $\tilde{t} \to \nu\ell\tilde{\nu}$ decay channel at the Tevatron (CDF), and at LEP 2. Also shown is the sneutrino mass limit obtained at LEP 1.

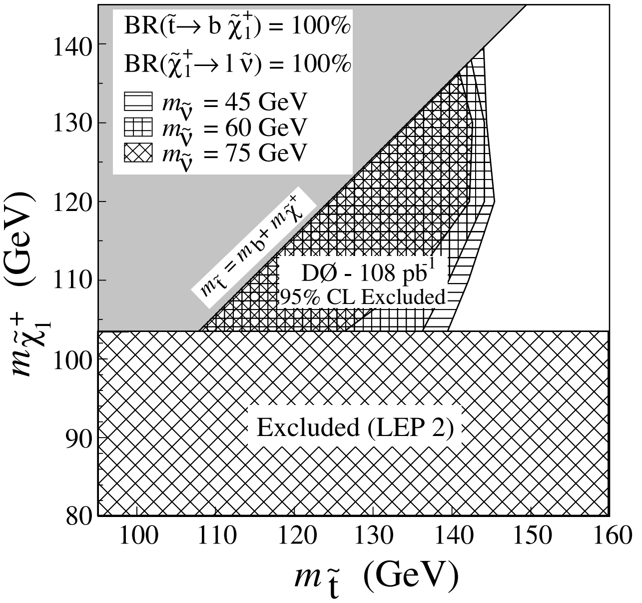

FIG. 4. Excluded regions in the $(m_{\tilde{t}}, m_{\tilde{\chi}_1^+})$ plane for the $\tilde{t} \to b\tilde{\chi}_1^+$ decay channel in the MSSM, for $m_{\tilde{\nu}} = 45$, 60, and 75 GeV. These results are compared to the exclusion limit obtained at LEP 2.

top mass of 144 GeV, to be compared to approximately 123 (98) GeV for CDF (LEP 2).

The 2-body decay into a $b$ quark and a real chargino, $\tilde{t} \rightarrow b\tilde{\chi}_1^+$, was simulated for $m_{\tilde{\chi}_1^+}$ between 100 and 140 GeV, and the $\tilde{\chi}_1^+$ was assumed to decay only into $\ell\tilde{\nu}$, leading to the same final state as $\tilde{t} \rightarrow b\ell\tilde{\nu}$, with similar signal efficiencies. Figure 4 shows exclusion contours as a function of $m_{\tilde{t}}$ and $m_{\tilde{\chi}_1^+}$, assuming $m_{\tilde{\nu}} = 45$, 60, or 75 GeV. They are compared to the exclusion limit obtained at LEP 2, assuming unification of the gaugino masses and decay of the chargino via a $W^*$ [11].

In conclusion, our analysis that assumes the $\tilde{\nu}$ to be the LSP places new limits on the stop mass. Assuming lepton universality and a virtual intermediary chargino, the excluded region at 95% C.L. extends up to a scalar top mass of 144 (130) GeV for $m_{\tilde{\nu}} = 45$ (85) GeV.

We thank the staffs at Fermilab and the collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (U.S.A.), Commissariat à L'Energie Atomique and CNRS/Institut National de Physique Nucléaire et de Physique des Particules (France), Ministry for Science and Technology and Ministry for Atomic Energy (Russia), CAPES and CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), CONICET and UBACyT (Argentina), The Foundation for Fundamental Research on Matter (The Netherlands), PPARC (United Kingdom), Ministry of Education (Czech Republic), and the A. P. Sloan Foundation.

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