Search for Pair Production of Scalar Top Quarks in *R*-Parity Violating Decay Modes in *pp* Collisions at s√=1.8 TeV

CDF Collaboration

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Abstract

We present the results of a search for pair production of scalar top quarks (t˜1) in an R-parity violating supersymmetry scenario in 106 pb−1 of pp¯ collisions at s√=1.8 TeV collected by the Collider Detector at Fermilab. In this mode each t˜1 decays into a τ lepton and a b quark. We search for events with two τ's, one decaying leptonically (e or μ) and one decaying hadronically, and two jets. No candidate events pass our final selection criteria. We set a 95% confidence level lower limit on the t˜1 mass at 122 GeV/c2 for Br(t˜1→τb)=1.

Reference

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Search for Pair Production of Scalar Top Quarks in R-Parity Violating Decay Modes in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We present the results of a search for pair production of scalar top quarks ($\tilde{t}_1$) in an R-parity violating supersymmetry scenario in 106 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected by the Collider Detector at Fermilab. In this mode each $\tilde{t}_1$ decays into a τ lepton and a b quark. We search for events with two τ's, one decaying leptonically (e or μ) and one decaying hadronically, and two jets. No candidate events pass our final selection criteria. We set a 95% confidence level lower limit on the $\tilde{t}_1$ mass at 122 GeV/c^2 for $\text{Br}(\tilde{t}_1 \rightarrow \tau b) = 1$.

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Many supersymmetry (SUSY) models [1] predict that the first two generations of SUSY partners of the quarks and the leptons (squarks and sleptons) are approximately mass degenerate and heavy. However, the mass of the lightest top squark ($\tilde{t}_1$ or "stop") can be relatively light due to a large mixing between the interaction eigenstates, $\tilde{t}_L$ and $\tilde{t}_R$. This mixing depends on the top Yukawa coupling. Because of the heavy top (t) quark mass, M_t, it is possible that $M_{\tilde{t}_1} < M_t$ [2].

R parity (R_p) is a multiplicative quantum number defined as $R_p \equiv (-1)^{3B+L+2S}$, where S, B, and L are the spin, baryon, and lepton numbers of a particle [3]. R_p distinguishes standard model (SM) particles ($R_p = +1$) from SUSY particles ($R_p = -1$). Conservation of R_p requires SUSY particles to be produced in pairs and to decay ultimately to SM particles plus the stable lightest SUSY particle. R_p conservation is not required by SUSY. It is motivated phenomenologically by limits on the proton lifetime, the absence of flavor-changing neutral currents, etc. Viable R_p violating ($\not{R}_p$) models can be built by adding explicit $\not{R}_p$ terms with trilinear couplings (λ_{ijk}, λ'_{ijk}, λ''_{ijk}) and spontaneous $\not{R}_p$ terms with bilinear couplings (ϵ_i) to the SUSY Lagrangian [4,5], where i, j, and k are generation indices. These couplings allow B or L violating interactions and, if λ'_{33k} or ϵ_3 is nonzero, a $\tilde{t}_1$ may decay directly to SM final states which are experimentally observable.

In $p\overline{p}$ collisions, stop pairs can be produced via R_p-conserving processes. In $\not{R}_p$ scenarios each stop could decay into a tau (τ) lepton and a bottom (b) quark with a branching ratio, Br, which depends on the coupling constants of the particular model. A good final state topology identifies either an electron or a muon ($\ell = e$ or μ) from the $\tau \rightarrow \ell \nu_\ell \nu_\tau$ decay, as well as a hadronically decaying tau (τ_h) lepton, and two or more jets.

We present the results of a search for $\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow \ell \tau_h jj$ events, in the framework of $\not{R}_p$–minimal supersymmetric standard model (MSSM), using 106 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected by the Collider Detector at Fermilab (CDF) [6,7] during the 1992–1995 run of the Tevatron (Run 1). In CDF the $p\overline{p}$ collision vertex (z_{vtx}) [8] is measured with a time projection chamber. The transverse momentum (p_T) of charged particles having $|\eta| <$ 1.0 is measured by a central tracking chamber (CTC) immersed in a uniform 1.4 T solenoidal magnetic field [8]. Electromagnetic (EM) and hadronic (HAD) calorimeters, segmented in a projective tower geometry, surround the solenoid and cover the region $|\eta| < 4.2$. They identify electrons, taus, and jets and measure the missing transverse energy ($\not{E}_T$). The central strip chamber (CES), embedded in the central EM calorimeter near shower maximum, aids in electron identification and $\pi^0 \to \gamma\gamma$ identification from τ_h decays. A muon subsystem is located outside the HAD calorimeter and has trigger coverage for the region $|\eta| < 0.6$.

Events must pass a three-level trigger system [6] which requires a single lepton (e or μ) with $p_T > 8$ GeV/c ($|\eta| < 1.0$ for electrons and $|\eta| < 0.6$ for muons) [9]. Offline, the lepton must have $p_T > 10$ GeV/c, originate from the event vertex, and pass more restrictive identification and isolation requirements [7,10]. An event is removed as a Z boson candidate if it contains a second, loosely identified same-flavor opposite-sign lepton with $76 < M_{\ell\ell} < 106$ GeV/c^2. All events are required to have $|z_{\rm vtx}| \leq 60$ cm.

An inclusive $\ell\tau_h$ subsample is made by requiring each event to further contain a high p_T, isolated, hadronically decaying τ lepton candidate with $p_T^{\tau_h} > 15$ GeV/c [11] and $|\eta| < 1.0$. A τ_h candidate is identified as a calorimeter cluster satisfying the following requirements [12]: (i) not identified as an e or a μ; (ii) one or three tracks with $p_T > 1$ GeV/c in a 10° cone around the calorimeter cluster center; (iii) the scalar sum of the p_T of all tracks in $\Delta R = 0.4$ around the cluster center, excluding those in the 10° cone, less than 1 GeV/c; (iv) fewer than three $\pi^0 \to \gamma\gamma$ candidates identified in the CES; (v) more than 4 GeV of E_T measured in the calorimeter; (vi) $0.5 < E_T/p_T^{\tau_h} < 2.0$ (1.5) for one track (three tracks); (vii) the width of the calorimeter cluster in η-ϕ space less than 0.11 (0.13)–0.025(0.034) $\times E_T$ [GeV]/100 for one track (three tracks); and (viii) the invariant mass reconstructed from tracks and π^0's less than 1.8 GeV/c^2. The charge of the τ_h is defined as the sum of the track charges, and is required to have unit magnitude and have the opposite-sign (OS) of the ℓ. A total of 642 events pass the above requirements; 16 of these have two or more jets (reconstructed by a fixed cone algorithm with $\Delta R = 0.4$ [13]) with $E_T > 15$ GeV and $|\eta| < 2.4$. The four $\ell\tau_h$ + jets candidates found in the search for $t\bar{t} \to (W^+b)(W^-\bar{b})$ [12] pass the kinematic requirements for this search.

The dominant backgrounds come from $Z/\gamma^*(\to \tau^+\tau^-)$ + jets, $t\bar{t}$, diboson (W^+W^-, $W^\pm Z$, ZZ) production, and fake $\ell\tau_h$ combinations from W + jets and QCD events. Monte Carlo (MC) programs with CTEQ4L parton distribution functions (PDFs) [14] and a detector simulation are used to estimate the background rates from Z/γ^*, W, $t\bar{t}$, and diboson events. All SM processes except W/Z + jets events are generated using ISAJET [15]; VECBOS [16] is used for vector boson plus jets production and decay, followed by HERWIG [17] for the fragmentation and hadronization of the quarks and gluons. The cross sections for Z/γ^*, $t\bar{t}$, and WW production are normalized to CDF measurements [18–21] and next-to-leading order (NLO) calculations for WZ and ZZ production are used [22]. The number of QCD fake events is estimated from the data assuming that the number of OS events, after subtracting off the nonfake contribution, is identical to the number of like-sign (LS) events observed in the data as expected from QCD sources, i.e., $N_{QCD}^{OS} = N_{\rm data}^{LS} - N_{MC}^{LS}$.

The final data selection is optimized to maximize the sensitivity for $\tilde{t}_1\bar{\tilde{t}}_1$ production over simulated SM backgrounds and LS data. To reduce the W + jets events we require $M_T(\ell, \not{E}_T) < 35$ GeV/c^2 where $M_T(\ell, \not{E}_t)$ is the transverse mass of the ℓ and $\not{E}_T$, defined as $M_T(\ell, \not{E}_T) \equiv \sqrt{2p_T^\ell \not{E}_T(1 - \cos\phi_{\ell\not{E}_T})}$, and $\phi_{\ell\not{E}_T}$ is the azimuthal angle difference between the ℓ and $\not{E}_T$. To reduce the QCD backgrounds we require $\sum p_T(\ell, \tau_h, \not{E}_T) \equiv p_T^\ell + p_T^{\tau_h} + \not{E}_T > 75$ GeV/c. The $M_T(\ell, \not{E}_T)$ cut precedes the $\sum p_T(\ell, \tau_h, \not{E}_T)$ cut because of possible charge correlations between the lepton from W decay and a fake τ_h from a jet. Figure 1 shows the $M_T(\ell, \not{E}_T)$ and $\sum p_T(\ell, \tau_h, \not{E}_T)$ distributions for the OS $\ell\tau_h + \geq 2$ jet sample. A control sample of $\ell\tau_h + 0$ jet events with similar kinematic requirements $[M_T(\ell, \not{E}_T) < 25$ GeV/c^2, $|\vec{p}_T^{\,\ell} + \vec{\not{E}}_T| > 25$ GeV/$c]$ is selected to show that the backgrounds are well modeled, dominated by real $Z \to \tau^+\tau^-$ production, and for later use in the acceptance calculations. Figure 2

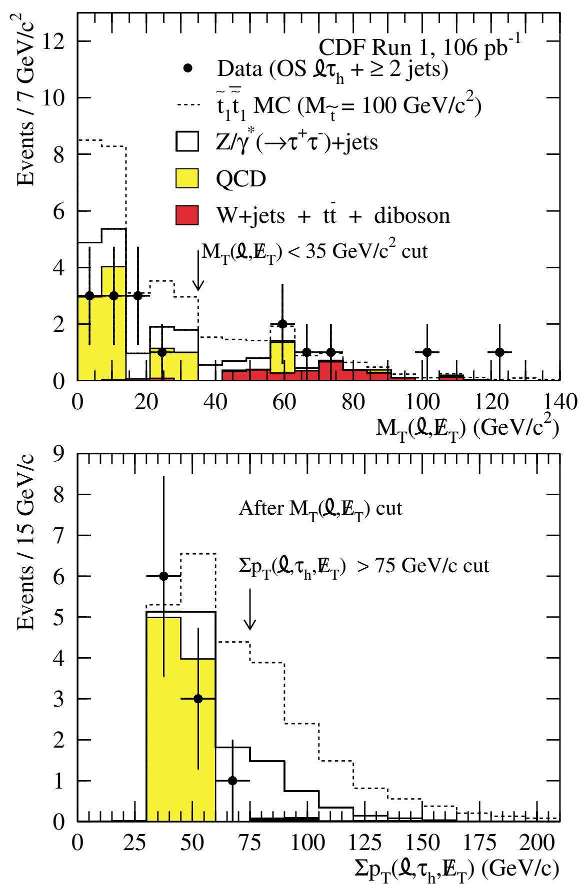

FIG. 1 (color online). The final data selection criteria for the OS $\ell\tau_h + \geq 2$ jet sample. The arrows show the final event selection requirements.

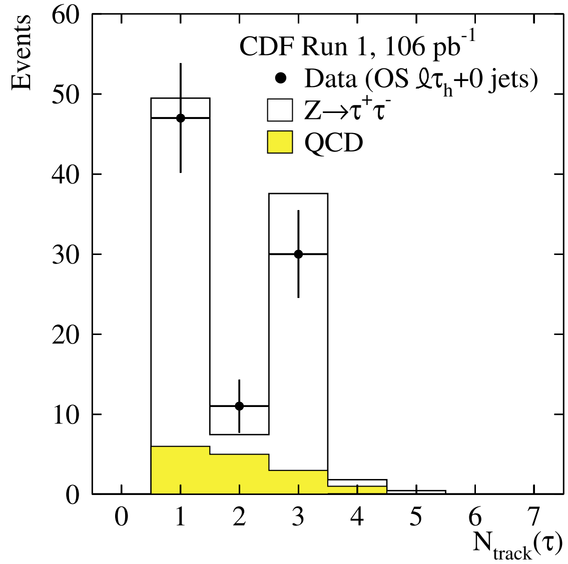

FIG. 2 (color online). The number of charged tracks in each τ_h candidate for the opposite-sign (OS) $\ell\tau_h + 0$ jet control sample. The data are compared to the MC expectation (all backgrounds are summed) which is dominated by real τ_h's from $Z \rightarrow \tau^+\tau^-$ production.

shows the charged track multiplicity of the τ_h's (removing the 1 and 3-prong requirements) for this sample.

A breakdown of the backgrounds and data is given in Table I. The backgrounds appear well modeled. A total of $3.2^{+1.4}_{-0.3}$ events are predicted from all SM sources, dominated by $Z(\rightarrow \tau^+\tau^-)$ + jets production. No candidate events pass the final $\tilde{t}_1\bar{\tilde{t}}_1$ selection criteria, which is expected in ~3% of experiments when taking into account the statistical and systematic uncertainties.

In order to set limits on $\tilde{t}_1\bar{\tilde{t}}_1$ production and decay, the acceptances and efficiencies are normalized to the rate of $Z(\rightarrow \tau^+\tau^-) + 0$ jet decays using the following relation:

$$\sigma(\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow \tau^+\tau^- b\bar{b}) = \left(\frac{N^{\rm obs}_{\tilde{t}_1\bar{\tilde{t}}_1} - N^{BG}_{\tilde{t}_1\bar{\tilde{t}}_1}}{N^{\rm obs}_Z - N^{BG}_Z}\right) \cdot R_{\rm acc} \cdot R_{\rm trig} \cdot \sigma_Z \cdot {\rm Br}(Z \rightarrow \tau^+\tau^-), \quad (1)$$

where $N^{\rm obs}_{\tilde{t}_1\bar{\tilde{t}}_1}$ and $N^{BG}_{\tilde{t}_1\bar{\tilde{t}}_1}$ ($N^{\rm obs}_Z$ and N^{BG}_Z) are the number of candidates observed in the data and expected backgrounds in the ≥ 2 jet/$\tilde{t}_1\bar{\tilde{t}}_1$ (0 jet/Z) selections, $R_{\rm acc}$ is the ratio of the Z to $\tilde{t}_1\bar{\tilde{t}}_1$ acceptances and $R_{\rm trig}$ is the ratio of the trigger efficiencies. The primary advantage of this approach is that potential systematic uncertainties in the estimate of identification and isolation efficiencies are reduced in the ratio of $\tilde{t}_1\bar{\tilde{t}}_1$ to Z production.

The 95% confidence level (C.L.) limits on $\sigma(\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow \tau^+\tau^- b\bar{b})$ in the e, μ, and combined channels are found using Eq. (1) and come from a Bayesian integration of the likelihood as a function of the cross section, integrating over the correlated and uncorrelated systematic uncertainties on the expected signal with a flat prior. The $R_{\rm acc}$ is a function of the $M_{\tilde{t}_1}$ and varies in the range $0.34 < R^e_{\rm acc} < 2.15$ ($0.35 < R^\mu_{\rm acc} < 1.87$) for the e (μ) channel over the range $70 < M_{\tilde{t}_1} < 130$ GeV$/c^2$. The $R_{\rm trig}$ varies between $0.95 < R^e_{\rm trig} < 0.97$ ($0.99 < R^\mu_{\rm trig} < 1.00$) for the e (μ) channel with an uncertainty of ~1%. [The acceptance and trigger efficiencies for the Z control sample are 1.19% (0.69%) and 74.5% (83.0%) for the e (μ) channel.] Assuming lepton universality gives $\sigma_Z \cdot {\rm Br}(Z \rightarrow \tau^+\tau^-) = \sigma_Z \cdot {\rm Br}(Z \rightarrow \ell^+\ell^-) = 231 \pm 12$ (stat + sys) pb [23]. The dominant uncertainty is due to the statistical uncertainty in $N^{\rm obs}_Z - N^{BG}_Z$ and is 17.0% (24.9%) [24]. Additional uncertainty comes from our estimation of $R_{\rm acc}$ which is dominated by the variation in the $\tilde{t}_1\bar{\tilde{t}}_1$ acceptance from choices of the QCD renormalization scale Q^2, PDFs, amount of gluon radiation, the jet energy scale, and the statistical uncertainty in the MC samples [25]. The total uncorrelated uncertainties vary between 17.1 and 17.7% (25.1 and 25.4%), and the total correlated uncertainties vary between 9.3 and 14.1%.

Figure 3 shows the final 95% C.L. upper limits on the cross section times Br for the e, μ, and combined channels, along with the NLO prediction of the production cross section [26]. The lower limits on $M_{\tilde{t}_1}$ are 110 and 75 GeV$/c^2$ for the e and μ channels, where we have assumed Br = 1. Combining the two results yields a limit of 122 GeV$/c^2$. Since our analysis does not distinguish the quark flavors in jet reconstruction, these results are equally valid for any λ'_{33k} coupling. These results substantially improve on the currently most stringent mass limit [27] which excludes $M_{\tilde{t}_1}$ below 93 GeV$/c^2$.

In conclusion, we searched for $\tilde{t}_1\bar{\tilde{t}}_1$ production using 106 pb^{-1} data in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. We examined the $\ell\tau_h + \geq 2$ jet final state within an $\not{R}_p$ SUSY scenario in which each $\tilde{t}_1$ decays to a τ lepton

TABLE I. Summary of the number of OS events in the data and expectations for the background sources as each selection requirement is applied.

Sample	$t\bar{t}$	Diboson	W + jets	$Z/\gamma^* \rightarrow \tau^+\tau^-$	QCD	Tot	$N_{\rm obs}$
OS $\ell\tau_h$	1.2 ± 0.3	2.3 ± 0.8	101 ± 6	225 ± 9	301 ± 18	631 ± 21	642
$\ell\tau_h + \geq 2$ jets	1.0 ± 0.2	0.4 ± 0.1	3.4 ± 0.4	7.7 ± 0.5	8 ± 3	21 ± 3	16
$M_T(\ell, \not{E}_T) < 35$ GeV$/c^2$	0.15 ± 0.07	0.14 ± 0.06	0.5 ± 0.2	6.0 ± 0.4	8 ± 3	15 ± 3	10
$\sum p_T(\ell, \tau_h, \not{E}_T) > 75$ GeV$/c$	0.15 ± 0.07	0.08 ± 0.03	0.2 ± 0.1	2.8 ± 0.3	$0^{+1.4}_{-0}$	$3.2^{+1.4}_{-0.3}$	0

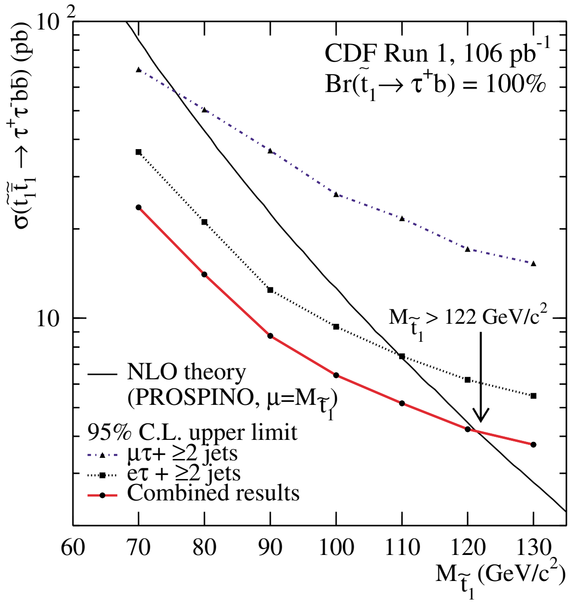

FIG. 3 (color online). The 95% C.L. upper limit on cross section times Br for $\tilde{t}_1\bar{\tilde{t}}_1$ production compared to the NLO calculations.

and a b quark via nonzero λ'_{333} or ϵ_3 couplings. No events pass our selection criteria and we set a 95% C.L. lower limit on the $\tilde{t}_1$ mass at 122 GeV$/c^2$ for Br $= 1$.

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[1] H. P. Nilles, Phys. Rep. **110**, 1 (1984); H. E. Haber and G. L. Kane, *ibid.***117**, 75 (1985).

[2] K. Inoue, A. Kakuo, H. Komatsu, and S. Takeshita, Prog. Theor. Phys. **68**, 927 (1982); **71**, 413 (1984); L. E. Ibanez and C. Lopez, Nucl. Phys. **B233**, 511 (1984); J. R. Ellis and S. Rudaz, Phys. Lett. **128B**, 248 (1983).

[3] A. Salam and J. Strathdee, Nucl. Phys. **B87**, 85 (1975); P. Fayet, *ibid.* **B90**, 104 (1975); G. Farrar and P. Fayet, Phys. Lett. **76B**, 575 (1978).

[4] S. Weinberg, Phys. Rev. D **26**, 287 (1982); G. Farrar and S. Weinberg, *ibid.* **27**, 2732 (1983); S. Dawson, Nucl. Phys. **B261**, 297 (1985).

[5] For recent reviews on R_p violating SUSY, see H. K. Dreiner, hep-ph/9707435; F. de Campos *et al.*, hep-ph/9903245.

[6] CDF Collaboration, F. Abe *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **271**, 387 (1988).

[7] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **50**, 2966 (1994).

[8] We use a coordinate system where θ and ϕ are the polar and azimuthal angles with respect to the proton beam direction (z axis). The pseudorapidity η is defined as $-\ln[\tan(\theta/2)]$. The transverse momentum of a particle is denoted as $p_T = p\sin\theta$. The analogous quantity using energies, defined as $E_T = E\sin\theta$, is called transverse energy. The missing transverse energy, $\not{E}_T$, is a magnitude of $\vec{\not{E}}_T \equiv -\sum E_T^i \hat{n}_i$, where $\hat{n}_i$ is the unit vector in the transverse plane pointing from the interaction point to the energy deposition in calorimeter cell i.

[9] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **58**, 092002 (1998).

[10] Each lepton is required to have less than 4 GeV of E_T (as measured in the calorimeter) in a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ around the lepton, excluding the lepton energy. Similarly, the isolation in CTC is also required to be less than 4 GeV$/c$. Also, see CDF Collaboration, T. Affolder *et al.*, Phys. Rev. Lett. **87**, 251803 (2001).

[11] $p_T^{\tau_h}$ is defined as the sum of the p_T of any tracks in a 10° cone around the center of the candidate, plus the E_T of any identified π^0's, as measured in the EM calorimeter.

[12] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 3585 (1997).

[13] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **45**, 1448 (1992).

[14] H. L. Lai *et al.*, Phys. Rev. D **55**, 1280 (1997).

[15] H. Baer, F. E. Paige, S. D. Protopopescu, and X. Tata, hep-ph/0001086. We use ISAJET version 7.44.

[16] F. A. Berends, W. T. Giele, H. Kuijf, and B. Tausk, Nucl. Phys. **B357**, 32 (1991); W. T. Giele, E. W. N. Glover, and D. A. Kosower, Nucl. Phys. **B403**, 633 (1993).

[17] G. Marchesini and B. R. Webber, Nucl. Phys. **B310**, 461 (1988); G. Marchesini *et al.*, Comput. Phys. Commun. **67**, 465 (1992).

[18] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **76**, 3070 (1996).

[19] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **49**, 1 (1994).

[20] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **80**, 2773 (1998).

[21] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **78**, 4536 (1997).

[22] J. Ohnemus, Phys. Rev. D **44**, 3477 (1991); J. Ohnemus and J. Owens, Phys. Rev. D **43**, 3626 (1991).

[23] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **77**, 448 (1996).

[24] For the electron channel we have $N_Z^{\rm obs} - N_Z^{BG} = 54 - (8.1 \pm 2.5)$ events which gives 46 ± 8 events when statistical uncertainties are taken into account. Similarly, for the muon channel we have $23 - (2.9 \pm 1.5)$ which gives 20 ± 5 events.

[25] The estimated systematic uncertainties in $R_{\rm acc}$ due to $\tilde{t}_1\bar{\tilde{t}}_1$ production and decay for the stop mass range

from 130 to 70 GeV$/c^2$ are between 4.5 and 8.2% due to choice of the Q^2 scale (taken to be correlated, and equal for the e and μ cases), 2.0 and 4.6% due to the choice in PDFs (again taken to be correlated and equal for e and μ), 2.3 and 6.4% due to uncertainty in the initial and final state gluon radiation (correlated, and averaged between e and μ), 1.1 and 3.7% due to jet energy scale (correlated and averaged), and 1.7 and 4.7% for e's and 2.3 and 4.8% for μ's due to MC statistics (uncorrelated).

[26] W. Beenakker, R. Höpker, M. Spira, and P. M. Zerwas, Nucl. Phys. **B492**, 51 (1997). The calculation of NLO cross section for $\tilde{t}_1\bar{\tilde{t}}_1$ production is made using the PROSPINO program with CTEQ4M, hep-th/9611232 (1996). The theoretical uncertainty on the NLO squark production cross section is a function of the squark mass and ranges from 11% to 22% for the mass range 30 to 150 GeV$/c^2$.

[27] ALEPH Collaboration, R. Barate *et al.*, Eur. Phys. J. C **19**, 415 (2001).