# Search for 3- and 4-body decays of the scalar top quark in $p$ collisions at $\sqrt{s} = 1.8$ TeV

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# Search for 3- and 4-body Decays of the Scalar Top Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

DØ Collaboration

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## Abstract

We have searched for the signature of 3- and 4-body decays of pair-produced scalar top quarks (stop) in the inclusive final state containing an electron, a muon, and significant missing transverse energy using a sample of $p\bar{p}$ events corresponding to 108.3 $\text{pb}^{-1}$ of data collected with the DØ detector at Fermilab. The search is done in the framework of the minimal supersymmetric standard model assuming that the neutralino ($\tilde{\chi}_1^0$) is the lightest supersymmetric particle and is stable. No evidence for a signal is found and we derive cross-section upper limits as a function of stop ($\tilde{t}$) and neutralino masses in different decay scenarios leading to the $b\ell\nu\tilde{\chi}_1^0$ final state.

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Supersymmetry (SUSY) [1] is a hypothetical symmetry between bosons and fermions that could lead to an extension of the standard model (SM). SUSY predicts additional elementary particles with quantum numbers identical to those of the SM, except for their spins which differ by a half unit. Their masses must also differ since no evidence has been found for new particles with masses equal to those of the SM. In several SUSY models, the large mass of the top quark induces a strong mixing between the supersymmetric partners of the two chirality states of the top quark leading naturally to two physical states of very different mass [2]. The lightest stop, denoted $\tilde{t}$ 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 stops at the Tevatron proceeds through gluon fusion or quark-antiquark annihilation, and its cross-section, for a given stop mass ($m_{\tilde{t}}$), is known at next-to-leading order (NLO) with a precision of 8% [3]. The phenomenology of stop decays depends on the assumptions made in the SUSY model. In the framework of the minimal supersymmetric standard model (MSSM) [4] with $R$-parity [5] conservation, the lightest SUSY particle (LSP) is stable. In a previous publication [6] we performed this search assuming that the scalar neutrino (sneutrino, $\tilde{\nu}$) is the LSP and derived exclusion limits reaching higher stop masses than those of previous similar searches [7, 8]. In this Letter we assume that the neutralino is the LSP.

We consider alternative scenarios to what has been done in most of the searches at the CERN LEP collider [8] or at the Fermilab Tevatron [9, 10, 11]. Those studies searched for the 2-body decays, $\tilde{t} \to c\tilde{\chi}^0_1$ or $\tilde{t} \to b\tilde{\chi}^+_1$ (where $\tilde{\chi}^+_1$ is the lightest chargino of the MSSM); it has been recently realized [12] that even if the $\tilde{t} \to b\tilde{\chi}^+_1$ decay is kinematically forbidden, as will be assumed in the following, the $\tilde{t} \to c\tilde{\chi}^0_1$ channel may not be the dominant one for stop masses accessible at LEP or the Tevatron ($m_{\tilde{t}} \gtrsim 90$ GeV) when the ratio of the two vacuum expectation values of the Higgs fields is not large ($\tan\beta \lesssim 5$) [13]. The 3-body decays $\tilde{t} \to bW\tilde{\chi}^0_1$ and/or $\tilde{t} \to b\ell\tilde{\nu}$ could be kinematically allowed, and if not, the corresponding 4-body decays $\tilde{t} \to bf\bar{f}'\tilde{\chi}^0_1$ (where $f\bar{f}'$ originate from the decay of the virtual $W$ boson produced by $\tilde{t} \to b\tilde{\chi}^+_1$ followed by $\tilde{\chi}^+_1 \to W\tilde{\chi}^0_1$) and $\tilde{t} \to b\ell\nu\tilde{\chi}^0_1$ (with $\nu\tilde{\chi}^0_1$ from the decay of the virtual sneutrino produced by $\tilde{\chi}^+_1 \to \tilde{\nu}\ell$) are generally allowed, *i.e.* as soon as $m_{\tilde{t}} \geq m_{\tilde{\chi}^0_1} + m_b + m_\ell$. Thus, as the stop can dominantly decay to 3 or 4 bodies when $\tan\beta \lesssim 5$, the search strategies must be modified.

The experimental signature for such decays of a $\tilde{t}\bar{\tilde{t}}$ pair consists of two $b$ quarks, two fermions, and missing transverse energy. Since our search is based on the presence of charged leptons in the final state, we have access only to the case where the fermion $f$ ($f'$) is a neutral (charged) lepton. The final states of all these 3- and 4-body decays are thus identical ($b\ell\nu\tilde{\chi}^0_1$). The underlying process depends on the SUSY parameters, and can be a mixture of the described processes. In the following, the analysis is performed assuming the complete dominance of each of these four cases in turn, and will be referred to as 3- or 4-body decay in the "$W$" or "light $\tilde{\nu}$" exchange scenario.

In our search, 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 missing transverse energy ($\not{E}_T$) represents the measured imbalance in transverse energy due to the escaping neutrinos and neutralinos, and is obtained experimentally from the vector sum of the transverse energy measured in the calorimeter and in the muon spectrometer system. The event sample corresponds to 108.3 $\mathrm{pb}^{-1}$ of data collected by the DØ experiment at Fermilab during the Run I of the Tevatron.

A detailed description of the DØ detector and its triggering system can be found in Ref. [14]. This analysis is mainly based on three subsystems: the uranium/liquid-argon calorimeter for identifying electron candidates and measuring electromagnetic and hadronic energies; the inner detector for tracking charged particles and to differentiate photons from electrons; and the muon spectrometer to identify and measure the required muon.

The data and pre-selection criteria are identical to those published in Ref. [6], however for the new channels considered in this analysis ($W$ exchange scenario, and 4-body decay in the light sneutrino scenario), we apply a stricter final selection. The initial selection requires events having one or more isolated electrons with transverse energy $E_T^e > 15$ GeV, one or more isolated muons with $E_T^\mu > 15$ GeV, and $\not\!\!E_T > 20$ GeV. A lepton is isolated if its distance in the $\eta$-$\varphi$ plane from the closest jet is greater than 0.5, where $\eta$ and $\varphi$ are the standard pseudorapidity and azimuthal angle variables. Jets are found using a cone algorithm with a radius of 0.5 in the $\eta$-$\varphi$ plane. We also require $15^\circ < \Delta_\varphi^{e\mu} < 165^\circ$ and $\Sigma_\eta^{e\mu} < 2.0$. $\Delta_\varphi^{e\mu} \equiv |\varphi_e - \varphi_\mu|$, where $\varphi_\ell$ ($\eta_\ell$) is the azimuthal angle (pseudorapidity) of the lepton $\ell$, and $\Sigma_\eta^{e\mu} \equiv |\eta_e + \eta_\mu|$ are two kinematic quantities which increase rejection of the SM background [15]. The distributions of these kinematic quantities after these requirements are shown in Fig. 1(a,b,c,e,f).

For the final selection, we apply an additional requirement compared to those in Ref. [6]: if the event has one (two or more) jet(s) with transverse energy greater than 15 GeV, we require that the distance(s) in the $\eta$-$\varphi$ plane $D_{\eta\varphi}^{l_1,j_1}$ (and $D_{\eta\varphi}^{l_2,j_2}$) $< 1.5$. $D_{\eta\varphi}^{l_1,j_1}$ is defined as the smaller of the two distances between the highest energy jet and each of the two leptons. $D_{\eta\varphi}^{l_2,j_2}$ is defined as the distance between the second highest energy jet and the lepton that was not used to define $D_{\eta\varphi}^{l_1,j_1}$. This requirement reduces the SM background by about a factor of two and removes only a small part ($< 5\%$) of the signal in the present analysis. The distributions of the transverse energy of any associated jets and $D_{\eta\varphi}^{l_1,j_1}$ are shown in Fig. 1(d,g), before applying this requirement.

The dominant SM processes that result in the $e\mu\not\!\!E_T$ signature are, in order of decreasing importance: *i)* multi-jet processes (called "QCD" in the following) with one jet misidentified as an electron and one true muon originating from another jet (muon misidentification in our final sample is negligible); *ii)* $Z \to \tau\tau \to e\mu\nu\bar{\nu}\nu\bar{\nu}$; *iii)* $WW \to e\mu\nu\bar{\nu}$; *iv)* $t\bar{t} \to e\mu\nu\bar{\nu}jj$. The Drell-Yan process $(DY) \to \tau\tau \to e\mu\nu\bar{\nu}\nu\bar{\nu}$ contributes less than 0.02 events after the final event selection. The QCD background is determined using the data, following the procedure described in Ref. [16]. The other SM backgrounds are estimated using MC samples processed through the full data analysis chain.

For simulation of the signal, we use the PYTHIA [17] event generator with its standard hadronization and fragmentation functions and the CTEQ3M [18] parton distribution functions. The stop decay is generated using COMPHEP [19]. Detector simulation is performed using the fast DØ simulation/reconstruction program, which agrees with reference samples passed through the full DØ analysis chain. The $\tilde{t}\bar{\tilde{t}}$ samples are simulated for stop (neutralino) masses varying between 80 (30) and 145 (85) GeV. The chargino mass is set equal to 140 GeV, to prevent the possibility of 2-body decay. The samples are produced separately for the $W$ exchange and for the light sneutrino scenarios. In the light sneutrino scenario, the mass of the sneutrino is varied between 40 and 80 GeV for the 3-body decay, and is set to $m_{\tilde{t}} - m_b$ for the 4-body decay.

The expected cross-sections for the background processes and the numbers of events passing the final selection are given in Table 1, and compared to the expected 4-body decay stop signal for $m_{\tilde{t}}$ ($m_{\tilde{\chi}_1^0}$) = 120 (60) GeV in the light sneutrino and $W$ exchange scenarios. The efficiency for selecting the signal varies between 1% and 4% and is largest for high stop masses and low neutralino masses. The most significant sources of uncertainties on the number of signal events passing the selection criteria are given in Ref. [6] and combine to approximately 18%. The total 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 allows us to set cross-section upper limits on stop pair production. We make the assumption that all non-SM processes, except the ones specifically searched for, can be neglected. This translates to more conservative limits. The 95% confidence level (C.L.) limits are obtained using a Bayesian approach [20] that takes statistical and systematic uncertainties into account.

In the following we assume that the loop-induced stop decay, $\tilde{t} \to c\tilde{\chi}_1^0$, is negligible compared to the processes induced by $\tilde{t} \to b\tilde{\chi}_1^+$, where $\tilde{\chi}_1^+$ is virtual. This is true for a large variety of MSSM models in which the $\tilde{t}$ is the next-to-lightest supersymmetric particle and $\tan\beta \lesssim 5$ [12, 13], or when the 3-body decay $\tilde{t} \to b\ell\tilde{\nu}$ is kinematically allowed. The two main scenarios that we study are dependent on the sneutrino mass: if $m_{\tilde{\nu}}$ is large ($m_{\tilde{\nu}} \gtrsim 2m_W$) the decay $\tilde{\chi}_1^+ \to \ell\tilde{\nu}$ can be neglected, and only the decay $\tilde{\chi}_1^+ \to W\tilde{\chi}_1^0$ contributes significantly, leading to the so-called $W$ exchange scenario. Otherwise, the decay $\tilde{\chi}_1^+ \to \ell\tilde{\nu}$ plays a significant role, and is assumed to be dominant in the so-called light sneutrino scenario, as is the case for instance if $m_{\tilde{\nu}} \lesssim m_W$ [15]. The exact proportion of the two scenarios depends on the MSSM parameters; we treat them separately, assuming 100% branching ratio in each mode. Experimentally the light sneutrino scenario has an advantage since leptons are always present in the final state; this is the case for only about one-third of the stops decaying via $W$ exchange.

Cross-section limits in the $W$ exchange scenario are shown in Fig. 2 for three different neutralino masses, $m_{\tilde{\chi}_1^0} = 40,\ 50$ and 60 GeV. Even at low $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{t}}$, the limits are about a factor of two higher than the expected cross-section, so this 4-body decay scenario cannot be excluded with these data. The limits for the 3-body decay (*i.e.* when $m_{\tilde{t}} > m_W + m_b + m_{\tilde{\chi}_1^0}$) are also shown, but are about an order of magnitude larger than the expected cross-section. Our results are compared to those of the CDF collaboration [7] obtained assuming $\tilde{t} \to b\tilde{\chi}_1^+$ followed by $\tilde{\chi}_1^+ \to f\bar{f}'\tilde{\chi}_1^0$ via a virtual $W$ boson, with $m_{\tilde{\chi}_1^+}(m_{\tilde{\chi}_1^0}) = 90$ (40) GeV.

Cross-section upper limits in the light sneutrino scenario are shown in Fig. 3 assuming $m_{\tilde{\chi}_1^0} \leq m_{\tilde{\nu}} = 60, 80$ GeV ($m_{\tilde{\chi}_1^0} = 50, 60$ GeV, and $m_{\tilde{\nu}} = m_{\tilde{t}} - m_b$) for the 3- (4-) body decay. The limits are stronger than those obtained for the $W$ exchange scenario since two charged leptons are always present in the final state. The cross-section limits are below the expected cross-section for some part of the $(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$ plane: for instance, for $m_{\tilde{\chi}_1^0} = 50$ GeV the 4-body decay scenario is excluded for $90 \lesssim m_{\tilde{t}} \lesssim 120$ GeV. The limits for the 3-body decay are stronger, extending to $m_{\tilde{t}} = 140$ GeV for $m_{\tilde{\chi}_1^0} = 60$ GeV.

The resulting exclusion contours for the light sneutrino scenario are displayed in Fig. 4 in the $(m_{\tilde{t}},m_{\tilde{\chi}_1^0})$ plane assuming 3- or 4-body decay with a light sneutrino mass equal, respectively, to $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{t}} - m_b$. The results obtained by CDF [10] and at LEP [21] assuming 100% branching ratio for $\tilde{t} \to c\tilde{\chi}_1^0$ are also shown indicating that if the sneutrino is of comparable mass to the stop, or lighter, the intersection of the CDF exclusion contour and our 4-body light sneutrino exclusion contour provides a model-independent exclusion limit, *i.e.* up to stop (neutralino) masses approximately equal to 115 (50) GeV. However, without an assumption of the $m_{\tilde{\nu}}$ value, as we are not able to place exclusion limits in the $W$ exchange scenario, the current limit in the $(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$ plane is model dependent above approximately 90 GeV. While we were preparing this Letter, ALEPH has reported the first search at LEP for 4-body decays of the stop [22]. Their limit, when assuming 100% branching ratio for $\tilde{t} \to b\ell\nu\tilde{\chi}_1^0$, is about 95 GeV for $m_{\tilde{\chi}_1^0} \simeq 75$ GeV, and is also shown in Fig. 4. It is slightly lower when no assumptions on the branching ratio and on the $\tilde{t}\tilde{t}Z$ coupling are made.

In conclusion, our analysis places new cross-section limits as a function of the stop and neutralino masses by considering the 3- and 4-body decays of the stop, *i.e.* taking into account the possibility that the loop-induced $\tilde{t} \to c\tilde{\chi}_1^0$ decay is not dominant when the $b\tilde{\chi}_1^+$ decay is not kinematically allowed. If the sneutrino is of comparable mass to the stop or lighter, the existence of a stop with a mass smaller than approximately 115 GeV is excluded in the MSSM for $m_{\tilde{\chi}_1^0} \lesssim 50$ GeV. If the sneutrino mass is smaller than 60 GeV, the mass exclusion domain extends up to a stop mass of 140 GeV. Without any assumptions on the sneutrino mass, the present analysis emphasizes that there is no model-independent exclusion limit on the stop mass above approximately 90 GeV. We thus provide new cross-section upper limits in the $W$ exchange scenario up to $m_{\tilde{t}} = 140$ GeV.

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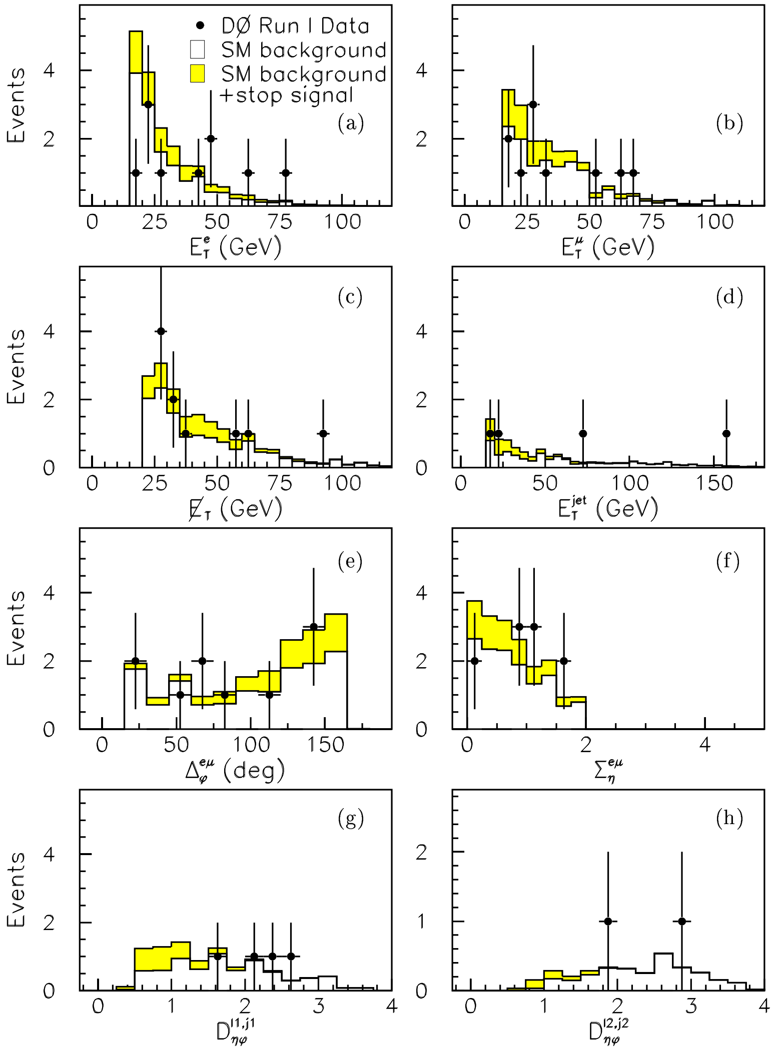

Figure 1: Distributions after initial selection cuts for the total background (open histogram), the sum of the total background and the expected 4-body decay stop signal for $m_{\tilde{t}}$ ($m_{\tilde{\chi}_1^0}$) = 120 (60) GeV in the light sneutrino scenario (shaded histogram), and the data (points) of (a) the transverse energy of the electron, (b) the transverse energy of the muon, (c) the missing transverse energy, (d) the transverse energy of any jets present, (e) the difference in azimuthal angle between the two leptons, (f) the absolute value of the sum in $\eta$ of the two leptons, and (g) the smallest lepton to jet distance in the event when at least one jet is reconstructed, (h) the distance between the lepton and jet that have not been used in (g), when two jets are reconstructed. For the final selection, all events having distances in (g) or (h) above 1.5 are rejected.

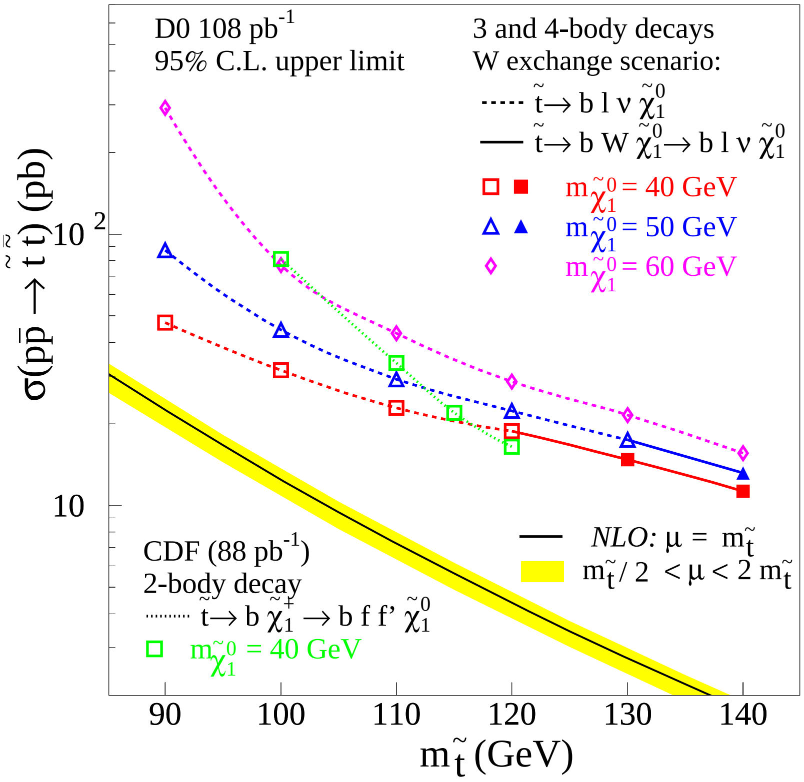

Figure 2: Cross-section upper limit as a function of $m_{\tilde{t}}$ for $m_{\tilde{\chi}_1^0} = 40, 50$ and 60 GeV, in the $W$ exchange scenario. The 3-body decay limits are shown as dashed lines, the 4-body decay limits as solid lines. The results of this analysis are compared to the CDF limit on the $\tilde{t} \rightarrow b\tilde{\chi}_1^+$ 2-body decay assuming a light $\tilde{\chi}_1^+$ ($m_{\tilde{\chi}_1^+} = 90$ GeV) and subsequent decay $\tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0$ with $m_{\tilde{\chi}_1^0} = 40$ GeV. The expected NLO cross-section is also shown (the error band is obtained by varying the factorization scale $\mu$). The renormalization scale is taken to be equal to $\mu$.

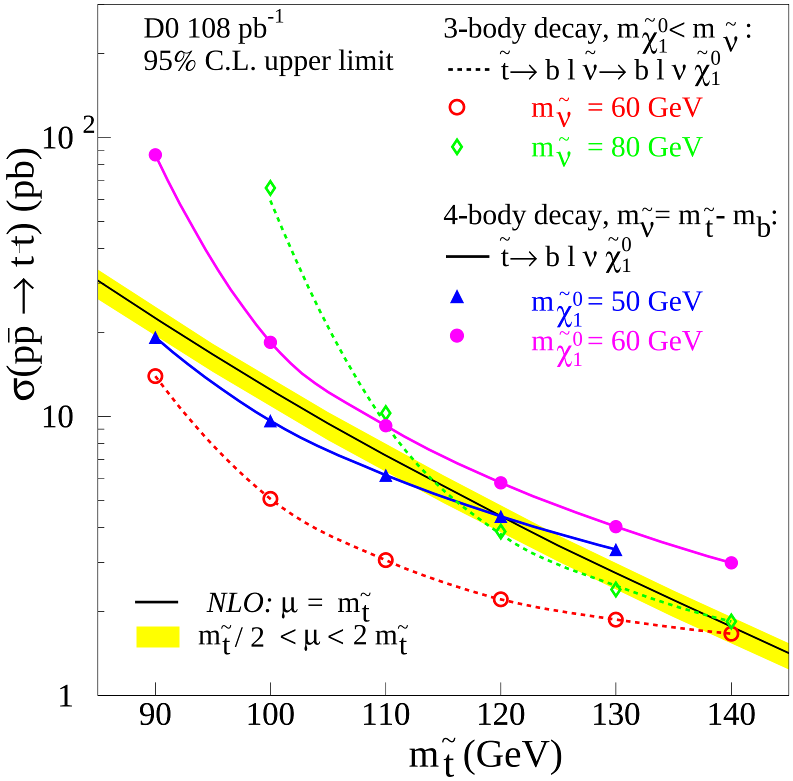

Figure 3: Cross-section upper limit in the light sneutrino scenario as a function of $m_{\tilde{t}}$, for the 3-body decay with $m_{\tilde{\chi}_1^0} < m_{\tilde{\nu}} = 60, 80$ GeV and for the 4-body decay with $m_{\tilde{\chi}_1^0} = 50, 60$ GeV and $m_{\tilde{\nu}} = m_{\tilde{t}} - m_b$. The 3-body decay limits are shown as dashed lines, the 4-body decay limits as solid lines. The expected NLO cross-section is also shown (the error band is obtained by varying the factorization scale $\mu$).

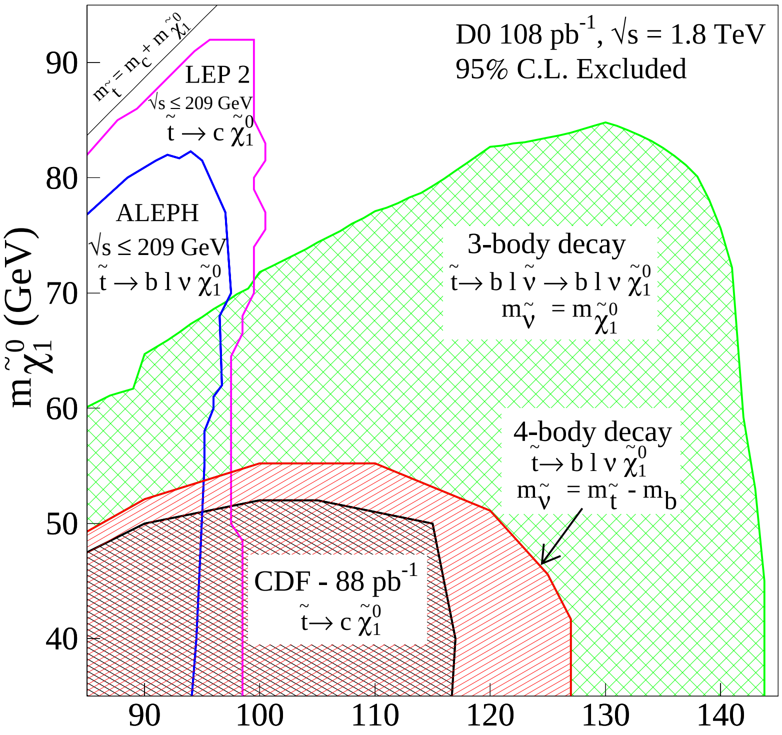

Figure 4: Excluded regions in the $(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$ plane for the $\tilde{t} \rightarrow b\ell\nu\tilde{\chi}_1^0$ decay channel in the MSSM, assuming 3- or 4-body decay with a light sneutrino mass equal, respectively, to $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{t}} - m_b$. The chargino mass is assumed to be $m_{\tilde{\chi}_1^+} = 140$ GeV. The results of this analysis (labeled DØ 108 $\mathrm{pb}^{-1}$) are compared to the exclusion limits obtained for the $\tilde{t} \rightarrow c\tilde{\chi}_1^0$ decay channel at LEP and at the Tevatron by the CDF collaboration, and in the $\tilde{t} \rightarrow b\ell\nu\tilde{\chi}_1^0$ decay channel at LEP by the ALEPH collaboration.

| Process | Cross-section (pb) | Number of events after selection |
|---|---|---|
| “QCD” | – | $4.3 \pm 0.3$ |
| $Z \rightarrow \tau\tau$ | 1.70 | $0.5 \pm 0.1$ |
| $WW$ | 0.69 | $2.8 \pm 0.3$ |
| $t\bar{t}$ | 0.40 | $0.4 \pm 0.1$ |
| Total background | – | $8.0 \pm 0.8$ |
| Data | – | 6 |
| $\tilde{t}\bar{\tilde{t}}$ (light sneutrino scenario with $m_{\tilde{\nu}} = m_{\tilde{t}} - m_b$) | 1.00 | $4.9 \pm 0.89$ |
| $\tilde{t}\bar{\tilde{t}}$ ($W$ exchange scenario) | 0.11 | $1.0 \pm 0.18$ |

Table 1: Cross-sections for the background processes, expected numbers of events surviving the final selection criteria for an integrated luminosity of 108.3 $\text{pb}^{-1}$, number of events selected in the $e\mu\not{E}_T$ data sample, and expected 4-body decay stop signal assuming $m_{\tilde{t}}$ ($m_{\tilde{\chi}_1^0}$) = 120 (60) GeV in the light sneutrino scenario and in the $W$ exchange scenario.