FERMILAB-CONF-08-414-E

# Things decaying into top quarks, that are similar to top quarks, or that are produced with top quarks

J. Cammin on behalf of the CDF and D0 Collaborations
*University of Rochester, Rochester, NY 14627, USA*

Searches for new physics in the top-quark sector using data from proton-antiproton collisions at the Fermilab Tevatron are discussed. The large data sets collected by the D0 and CDF experiments allow for precision measurements of the standard model (SM) top-quark production rates and top quark properties so that deviations from the SM expectations can be interpreted as signs of new physics. The presented analyses exploit the fact that the new physics would reveal itself in final states that are similar or identical to those of SM top-antitop production.

arXiv:0809.4290v1 [hep-ex] 24 Sep 2008

## 1. INTRODUCTION

The production of top quark pairs at the Fermilab Tevatron provides us with an opportunity to perform a large variety of measurements related to the production and decay mechanisms of the top quark and many of its properties. Given the large integrated luminosity available at the Tevatron many of these measurements are no longer limited by statistical uncertainties. Consequently, it is possible to test the standard model (SM) in the top quark sector with high accuracy and to detect deviations that could be caused by new physics. New physics could reveal itself in many ways, by altering the production cross section, the top quark decay modes, the top quark mass distribution or the coupling constants, etc. The signature of new particles can be similar to or exactly the same as that of $t\bar{t}$ pairs. This motivates to look for signs of new physics using the same tools and analysis strategies developed for measurements in the top quark sector. In the following we will describe four examples: searches for particles decaying into $t\bar{t}$, searches for the supersymmetric partners of top quarks, a search for top-like objects $t'$, and a search for the production of a light SM Higgs boson in association with a pair of top quarks. The analyses are based on up to 3 fb$^{-1}$ of data collected by the CDF and DØ experiments.

## 2. $t\bar{t}$ RESONANCES

Several theories beyond the SM predict new $Z$-like particles that decay into a pair of top-quarks, causing a peak in the $t\bar{t}$ invariant mass distribution. Such resonances could occur as Kaluza-Klein states of the $Z$ or the gluon, in axigluon models or theories with top color. Both CDF and DØ have searched for narrow resonances $Z'$ assuming that the width is smaller than the detector mass resolution [1, 2]. Final states where one top quark decays hadronically ($t \to Wb \to q\bar{q}'b$) and the other one semileptonically ($t \to Wb \to \ell\nu b, \ell = e, \mu$) have been considered ("$\ell$ + jets" final state). The CDF analysis is based on approximately 1 fb$^{-1}$ of data and reconstructs the $M_{t\bar{t}}$ distribution in events with at least four jets from the jet-parton assignment that is most likely to come from $t\bar{t}$ events. The most consistent combination is found by minimizing a $\chi^2$ which is constructed from the reconstructed $W$ boson and top quark masses, and using additional information from $b$-tagged jets. No structure from a resonant signal is observed in the $t\bar{t}$ mass spectrum over the expected contributions from SM $t\bar{t}$ and non-$t\bar{t}$ backgrounds and limits are set on the production cross section times branching ratio $Z' \to t\bar{t}$ for $Z$-like resonances. For the specific case of topcolor leptophobic models a $Z'$ with a mass below 720 GeV is ruled out at the 95% CL. DØ's search is based on a data set of 2.1 fb$^{-1}$ in the $\ell$+jets final state requiring at least one $b$-tagged jet. No attempt is made to match partons to jets, and the invariant $t\bar{t}$ mass is calculated directly from the four-momenta of up to four leading jets, the charged lepton momentum and the neutrino momentum. The neutrino $p_z$ component is calculated from the $W$ mass constraint $m_W^2 = (p_\ell + p_\nu)^2$. The advantage of the direct reconstruction is that it allows to include events with only three jets. This recuperates sensitivity to events from a high mass $Z'$ where merging of two jets into a single jet due to the

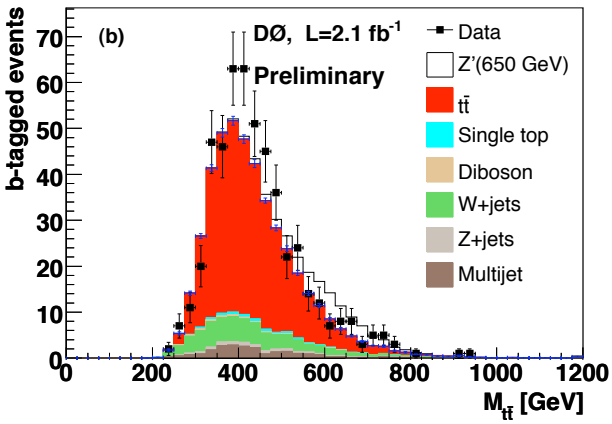


Figure 1: Distribution of the $t\bar{t}$ invariant mass in the $\ell + 4$ or more jets channel in data and in the expected signal plus background. The error bars indicate the statistical error on the data.

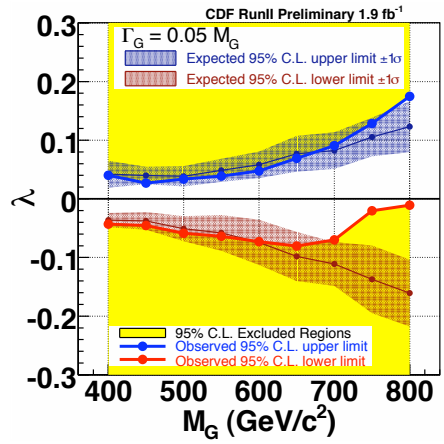


Figure 2: Expected and observed 95% CL excluded regions in the $\lambda - M_G$ parameters space in the CDF search for massive gluons. This example assumes $\Gamma_G = 0.05 \cdot M_G$.

relativistic boost occurs more often. With the data describing the mass shape expected from SM background only (Fig. 1), a $Z'$ mass below 760 GeV for topcolor-assisted technicolor models is excluded at the 95% CL.

CDF has also searched for new color-octet particles (massive gluons) that decay into $t\bar{t}$ in 1.9 fb$^{-1}$ of data [3]. The model introduces three new parameters, the coupling strength $\lambda$, the mass $M_G$ and the decay width $\Gamma_G$ of the heavy gluon. The $\ell +$ jets final state with at least one $b$-tagged jet is reconstructed using the *Dynamical Likelihood Method* [4] but omitting information from the matrix element of the process to avoid a bias towards specific model assumptions. Without an observed excess over the SM background, limits are set on the coupling $\lambda$ for massive gluon widths from $\Gamma_G = 0.05 \cdot M_G$ to $\Gamma_G = 0.5 \cdot M_G$ (see Fig. 2 for an example).

## 3. SUPERSYMMETRIC TOP QUARKS

The decays of the supersymmetric partners of the top quark, $\tilde{t}$ or stop quark, could lead to the same final state signature as that from SM top quarks. Some models like electroweak baryogenesis scenarios favor stop quarks that are lighter than the top quark. If the superymmetric parameter space is further constrained by assuming that $m_{\tilde{\chi}^\pm} < m_{\tilde{t}_1} - m_b$ so that the stop quark decays exclusively into $\tilde{t}_1 \to b\chi_1^+$ and assuming that $\tilde{\chi}_1^0$ is the LSP and that $\tilde{q}, \tilde{\ell}, \tilde{\nu}$ are heavy then the $\tilde{t}\bar{\tilde{t}}$ final states involving $b$ quarks, one or more leptons, missing transverse energy, and jets are identical to the SM top-pair decays in the $\ell$+jets or dilepton final states. Hence, contributions from stop pairs could be contained in the presumed top-quark pair data. CDF searched for signs of stop quarks using 2.7 fb$^{-1}$ of data [5] in the final state where both charginos decay into $\tilde{\chi}_1^0 + \ell + \nu$, mimicking the $t\bar{t}$ signature in the dilepton final state. Due to the undetected two neutralinos and two neutrinos, the stop quark mass cannot be reconstructed directly. Instead, the mass is estimated using the neutrino weighting method [6] and the reconstructed mass is used as a discriminant in the limit setting procedure. CDF sets limits on the $m_{\chi_1^0} - m_{\tilde{t}}$ parameter space for several values of the $m_{\chi_1^\pm}$ mass. An example for $m_{\chi_1^\pm} = 105.8$ GeV and various assumptions about the branching ratio $\chi_1^\pm \to \chi_1^0 \nu \ell$ is shown in Fig. 3. A similar search has been performed by DØ using 1 fb$^{-1}$ of data but in the $\ell$+jets final state [7]. The chargino and neutralino masses are fixed close to their experimental lower limits. Several input variables are combined into a likelihood discriminant whose distribution is used to extract the stop-pair signal. The 95% CL limits on the cross section are show in Fig. 4. The observed limits are a factor of 7–12 higher than the theoretical prediction.

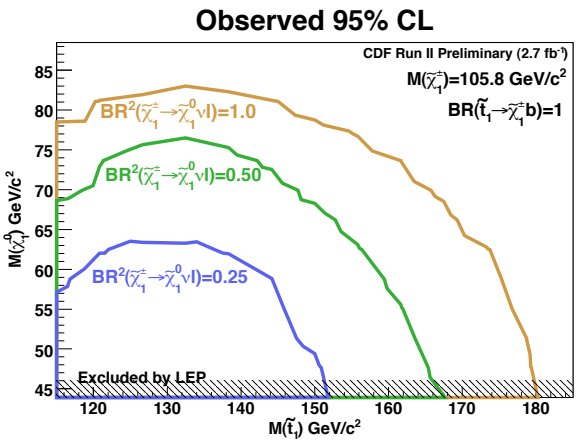


Figure 3: 95% CL exclusion regions in the $M(\chi_1^0) - M(\tilde{t}_1)$ parameter space for several values of the squared branching fraction $BR^2(\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 \nu\ell)$. In this example a chargino mass of $M(\tilde{\chi}_1^{\pm}) = 105.8$ GeV is assumed.

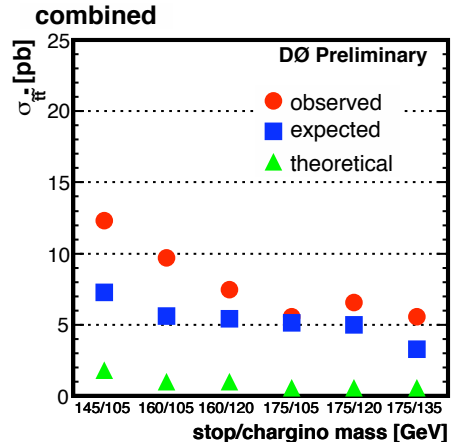


Figure 4: Expected and observed 95% CL cross section limits on the production of a pair of stop quarks as a function of the stop an chargino mass. Also shown is the theoretically predicted cross section.

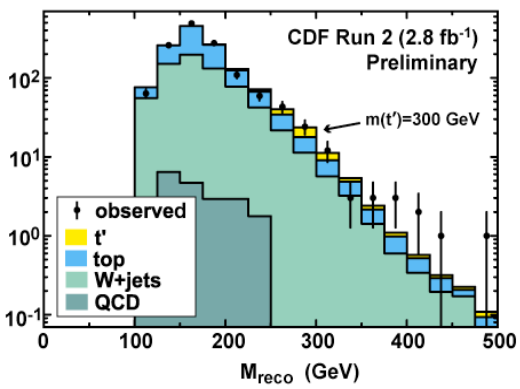


Figure 5: Fitted distribution of the reconstructed $t'$ mass in data and in the expected signal plus background. In this example a $t'$ mass of 300 GeV is assumed.

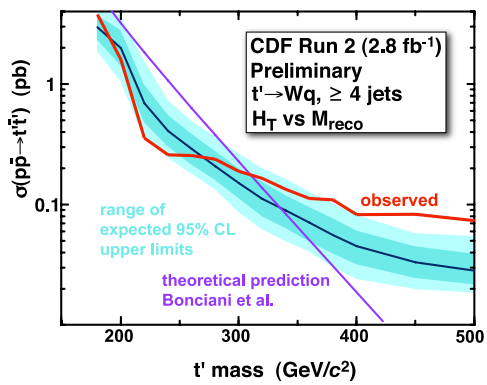


Figure 6: Expected and observed 95% CL cross section limits on $t'$ production as a function of the $t'$ mass.

## 4. FOURTH GENERATION, TOP-LIKE OBJECTS

The possibility of new top-like objects from a massive fourth generation of quarks has been studied by CDF based on 2.8 fb$^{-1}$ of data [8]. Such objects are predicted by various models, for example Little Higgs or Beautiful Mirrors scenarios. Assuming that the mass of the new $t'$ is larger than the top quark mass and that $m_{t'} - m_{b'} < m_W$ so that $t' \to qW$ exclusively, a template fit method based on a minimal $\chi^2$ to find the correct combination of parton-jets assignment is used to set limits on the $t'$ mass. No $b$-tagging is applied to avoid making assumptions about the coupling of the $t'$ to the SM quark sector. Both the reconstructed $t'$ mass (Fig. 5) and the scalar sum $H_T$ of the transverse momenta of all reconstructed objects in the event show good discrimination between the signal, the $t\bar{t}$ and other backgrounds. A two-dimensional likelihood fit to these variables is applied to extract the amount of signal that would be allowed by the data. Using this information, limits are set on the production rate $p\bar{p} \to t'\bar{t}'$ as a function of $m_{t'}$, see Fig 6. An analysis of the data in the high $H_T$ and reconstructed $m_{t'}$ tails of the 2D distribution show that no significant excess of data over the background predictions is observed. By comparing the observed cross section limit to the expected signal cross section, a $t'$ with a mass smaller than 311 GeV is excluded.

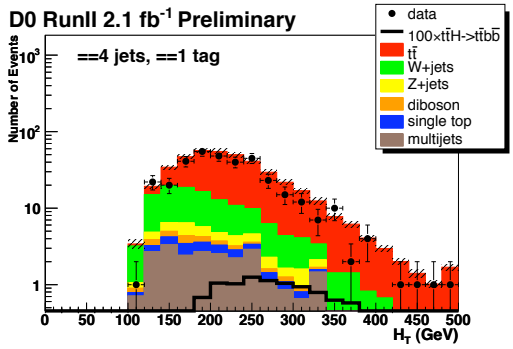


Figure 7: The $H_T$ distribution in data, expected backgrounds and the $t\bar{t}H$ signal (multiplied by a factor of 100) for events with four jets and one $b$-tagged jet.)

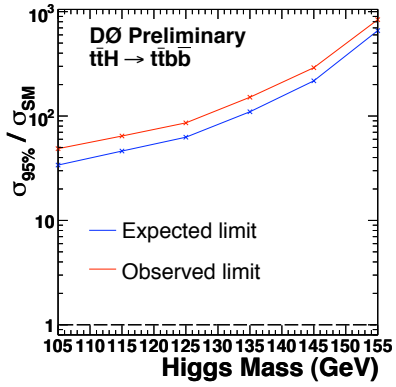


Figure 8: Expected and observed 95% CL cross section times branching ratio limits on the $t\bar{t}H$ process relative to the SM expectation as a function of the Higgs boson mass.

## 5. TOP-QUARK PAIRS AND THE HIGGS BOSON

The production of a SM Higgs boson in association with a top quark pair will be the only direct way to measure the top Yukawa coupling at the LHC. In the mass region $m_H \lesssim 135$ GeV the dominant Higgs boson decay mode is $H \to b\bar{b}$ which in the $\ell+$jets final state for the top quark pair leads to the challenging signature of one high $p_T$ lepton, large missing transverse energy and up to 6 jets of which four are $b$ jets. The $t\bar{t}H$ cross section at the Tevatron is very small (about 7 fb for $m_H = 115$ GeV) and observation of a Higgs boson in this channel alone is not possible. Nevertheless, the $t\bar{t}H$ channel can contribute to the total discovery or exclusion potential of the Tevatron. DØ has searched for $t\bar{t}H \to \ell\nu bjjbbb$ in 2.1 fb$^{-1}$ of data [9]. To increase the sensitivity, the analysis has been divided into events with four and at least five jets and with one, two, or three $b$-tagged jets. The distribution of the scalar sum of the transverse momentum of the up to five leading jets, $H_T$, shows good discrimination between the $t\bar{t}H$ signal and the backgrounds and is used in the limit setting procedure. The largest signal contribution is expected from events with five jets and at least three $b$-tagged jets. The combination of all channels leads to a limit on the cross section relative to the SM expectation as shown in Fig. 8. Additional tests show that the observed and expected cross section limits agree within one standard deviation. For $m_H = 115$ GeV a cross section greater than 64 times the SM value can be excluded.

## References


[1] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **77**, 051102 (2008) [arXiv:0710.5335 [hep-ex]].

[2] D0 Note 5600-CONF, `http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/TOP/T65/`.

[3] CDF Conference Note 9164, `http://www-cdf.fnal.gov/physics/new/top/confNotes/cdf9164_MG_DLM.pdf`.

[4] CDF DLM A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. D **73**, 092002 (2006) [arXiv:hep-ex/0512009].

[5] CDF Conference Note 9439, `http://www-cdf.fnal.gov/physics/new/top/2008/tprop/Stop/images2_7InvFb/stopDilCdfNote_2700InvPb.pdf`.

[6] A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. D **73**, 112006 (2006) [arXiv:hep-ex/0602008].

[7] D0 Note 5438-CONF, `http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/TOP/T52/`.

[8] CDF Conference Note 9446, `http://www-cdf.fnal.gov/physics/new/top/confNotes/cdf9446_tprime_public_2.8.pdf`.

[9] D0 Note 5739-CONF, `http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/HIGGS/H58/`.