Search for top-quark production via flavor-changing neutral currents in W+1 jet events at CDF

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(Dated: April 2, 2009)

Abstract

We report on a search for the non-standard-model process $u(c) + g \rightarrow t$ using $p\bar{p}$ collision data collected by the CDF II detector corresponding to $2.2\,\mathrm{fb}^{-1}$. The candidate events are classified as signal-like or background-like by an artificial neural network. The observed discriminant distribution yields no evidence for FCNC top-quark production, resulting in an upper limit on the production cross section $\sigma(u(c)+g \rightarrow t) < 1.8$ pb at the 95% C.L. Using theoretical predictions we convert the cross-section limit to upper limits on FCNC branching ratios: $\mathcal{B}(t \rightarrow u+g) < 3.9\times10^{-4}$ and $\mathcal{B}(t \rightarrow c+g) < 5.7 \times 10^{-3}$.

PACS numbers: 14.65.Ha, 13.85.Rm

In the standard model (SM) of particle physics the flavor quantum number of fermions can be changed by charged currents, i.e., weak interactions mediated by the exchange of a $W^{\pm}$ boson. Flavor-changing neutral-currents (FCNC) are absent at tree level, but do occur at higher order in perturbation theory through loop diagrams. These radiative corrections are further suppressed through the GIM mechanism [1]. In the bottom-quark sector the large top-quark mass alleviates the GIM suppression leading to FCNC decays with branching ratios at the level of 10^{-6}, while in the top-quark sector FCNC decays are more strongly suppressed and occur only at the order of $\mathcal{B} \approx 10^{-10}$ to 10^{-14} [2], way beyond the current experimental sensitivity. Therefore, any evidence for FCNC in the top-quark sector will be a signal of physics beyond the SM. Enhanced FCNC effects can be realized in extensions of the SM, such as models with multiple Higgs doublets [2, 3], supersymmetric models with R-parity violation [4], or topcolor-assisted technicolor theories [5]. In certain regions of parameter space of these models the branching ratio of FCNC decays can reach levels of 10^{-3} to 10^{-5}. But even with such an enhancement the detection of FCNC top-quark decays remains a very challenging task at the Tevatron: First, because one can only expect to reconstruct a few top quarks in these modes, and second, because the background for the most promising mode, $t \rightarrow cg$, is very difficult to discern from generic multijet production via quantum chromodynamics (QCD). It has therefore been suggested to search for FCNC couplings in top-quark production, rather than top-quark decay [6, 7].

In this Letter we present a search for the non-SM single top-quark production processes $u(c) + g \rightarrow t$. We do not consider a particular model, but perform a model-independent search based on an effective theory [6] that contains additional flavor-changing operators in the Lagrangian

$$g_s \frac{\kappa_{tug}}{\Lambda}\, \bar{u}\, \sigma^{\mu\nu} \frac{\lambda^a}{2} t\, G^a_{\mu\nu} + g_s \frac{\kappa_{tcg}}{\Lambda}\, \bar{c}\, \sigma^{\mu\nu} \frac{\lambda^a}{2} t\, G^a_{\mu\nu} + \; h.c. \tag{1}$$

Here κ_{tug} and κ_{tcg} are dimensionless parameters that relate the strength of the new, anomalous coupling to the strong coupling constant g_s and Λ is the new physics scale, related to the mass cutoff above which the effective theory breaks down. The gluon field tensor is denoted $G^a_{\mu\nu}$, the λ^a are the Gell-Mann matrices, and $\sigma^{\mu\nu} \equiv \frac{i}{2}[\gamma^{\mu}, \gamma^{\nu}]$ transforms as a tensor under the Lorentz group. The existence of FCNC operators allows the production of top quarks via $u(c) + g \rightarrow t$, but also non-SM decays $t \rightarrow u(c) + g$. In the allowed region of parameter space for κ_{tug} and κ_{tcg} an experimentally favorable situation occurs. While the FCNC production cross-section of top quarks is in the range of several picobarns, the branching ratio of FCNC decays is very small, and top quarks can thus be reconstructed in the SM decay mode $t \to Wb$. While u quarks are constituent quarks of the proton, c quarks, as needed for the process $c + g \to t$, occur as sea quarks originating from a gluon splitting into a $c\bar{c}$ pair. In the SM, top quarks are either produced as $t\bar{t}$ pairs by the strong interaction or singly via the exchange of a virtual W boson. The pair-production process is firmly established experimentally with a cross section of about 7 pb. Evidence for SM single top-quark production has been shown by CDF [8] and DØ [9], yielding a cross section around 3 pb.

Our analysis is the first one at the Tevatron searching for the $2 \to 1$ processes $u(c)+g \to t$, while a previous DØ analysis [10] has looked for $2 \to 2$ processes, such as $q\bar{q} \to t\bar{u}$, $ug \to tg$, or $gg \to t\bar{u}$, resulting in upper limits of $\kappa_{tug}/\Lambda < 0.037$ TeV^{-1} and $\kappa_{tcg}/\Lambda < 0.15$ TeV^{-1} at the 95% C.L. FCNC couplings to the top quark involving the photon or Z boson have been constrained by the analysis of top-quark decays at the Tevatron [11], the search for $e^+e^- \to t\bar{c}/t\bar{u}$ reactions at LEP, see e.g. [12], and the search for $ep \to e + t + X$ reactions at HERA [13, 14].

The analysis presented here uses $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV collected by the CDF II detector [15] at the Fermilab Tevatron between March 2002 and August 2007. The data set corresponds to an integrated luminosity of 2.2 fb^{-1}. We select a set of candidate events in the $t \to Wb \to \ell\nu b$ topology based on the event selection used for the measurement of SM single top-quark production [8]. We require exactly one isolated [18] electron with transverse energy [16] $E_T > 20\,\mathrm{GeV}$ or one isolated muon with $p_T > 20\,\mathrm{GeV}/c$, missing transverse energy $\not{E}_T > 25$ GeV, and exactly one jet with pseudorapidity [16] $|\eta| \leq 2.8$ and $E_T > 20\,\mathrm{GeV}$. The jet is further required to contain a reconstructed secondary vertex consistent with the decay of a b hadron [19]. After all selection cuts we observe 2472 candidate events.

Background yields from diboson processes WW, WZ, ZZ, and $t\bar{t}$ production are predicted using PYTHIA [21] Monte Carlo samples, normalized to next-to-leading order (NLO) cross sections [22, 23]. SM single top-quark rates are estimated with simulated events from the tree-level matrix-element generator MADEVENT [24], subsequent showering with PYTHIA, and normalization to NLO cross sections [25]. The processes with vector bosons (W or Z) plus jets are generated with ALPGEN [26], with parton showering and underlying event simulated with PYTHIA. Using a compound model [8] based on simulated events, theoretical cross

TABLE I: Predicted sample composition and observed number of W+1 jet events in 2.2 fb^{-1} of CDF Run II data.

Process	Expected events
$Wb\bar{b}$, $Wc\bar{c}$	750.9 ± 225.3
Wc	622.3 ± 186.7
$Wq\bar{q}$	769.9 ± 100.5
$t\bar{t}$	12.3 ± 1.8
QCD-multijet	43.0 ± 17.2
Diboson	19.9 ± 2.0
Z+jets	26.6 ± 4.2
SM single-top	24.4 ± 3.6
Total prediction	2269.3 ± 434.3
Observed	2472

sections, and normalizations in background-dominated regions we predict the composition of the W+1 jet data set as given in Table I. Top-quark events produced via the processes $u(c) + g \rightarrow t$ are simulated using the matrix-element generator TOPREX [27], followed by parton showering with PYTHIA. For the event generation, the coupling constants have been chosen to yield a cross section of 1 pb, which correponds to the approximate sensitivity to the process with the data set we analyzed. By investigating kinematic distributions at parton level, we verified that the event kinematics do not depend on that choice of parameters within the range relevant for our analysis. Under the assumption that $\kappa_{tug} = \kappa_{tcg}$ the tug coupling contributes 0.94 pb and the tcg coupling 0.06 pb. For a total FCNC top-quark cross section of 1 pb we expect a yield of 35.3 ± 5.3 events.

For an efficient background rejection, we employ the same neural-network technology as used in the search for SM single top-quark production [8, 28]. Neural networks (NN) have the advantage that correlations between the discriminating input variables are identified and utilized to optimize the separation power between signal and background processes. The networks are developed using the NEUROBAYES analysis package [29], which combines a three-layer feed-forward neural network with a complex and robust preprocessing of the input variables. The network infrastructure consists of one input node for each input variable plus one bias node, 15 hidden nodes, and one output node, which gives a continuous output in the interval $[-1, 1]$. We train the NN on the samples of simulated events listed above using a mixture of 50% signal events and 50% background events. The background composition is chosen in the proportions given in Table I, with SM single top-quark events included as background. In total, we use 14 variables that show significant discriminating power between signal and background. Variables derived directly from the four-vectors of reconstructed particles are the p_T and the η of the charged lepton, the p_T of the jet, the difference in azimuth angle between the jet and $\vec{\not{E}}_T$, and between the lepton and $\vec{\not{E}}_T$, as well as the ΔR between the charged lepton and the jet. The W-boson candidate is reconstructed in its leptonic decay mode from the charged lepton and $\vec{\not{E}}_T$ applying the kinematical constraint $M_{\ell\nu} = M_W = 80.4\,\mathrm{GeV}/c^2$. The two-fold ambiguity for the z-component of the neutrino momentum is resolved by choosing the smaller $|p_{z,\nu}|$ solution. Based on the W-boson reconstruction we define two input variables: the transverse mass $M_{T,\ell\nu}$ and $\eta_{\ell\nu}$. We further reconstruct top-quark candidates by adding the jet to the reconstructed W boson and thereby define the following input variables: $M_{\ell\nu j}$, $M_{T,\ell\nu j}$, the rapidity $y_{\ell\nu j}$, and $Q_\ell \cdot \eta_{\ell\nu j}$ where Q_ℓ is the charge of the lepton. An additional input variable is the output of an advanced jet-flavor separating tool mainly developed to increase the sensitivity of the SM single top-quark searches [28]. To describe the event shape in general, we use the aplanarity of the reconstructed top-quark decay system [30].

We apply the NN to the samples of simulated events and obtain template distributions of the network output for all physics processes considered. The template distributions of the most important background processes and the signal are shown in Fig. 1(a). As can be seen, the separation between FCNC top-quark events and SM single top-quark events is only marginal. The templates are weighted by their expected event yields and the resulting composite model is compared to the NN output distribution observed in collision data in Fig. 1(b).

To measure the potential content of FCNC-produced top quarks in the observed data set, we perform a binned maximum likelihood fit of the NN output distribution. The effect of systematic uncertainties is parameterized in the likelihood function including the correlation of rate normalization effects and shape distortions of the template distributions. Uncertainties in the jet energy scale, b-tagging efficiencies, lepton identification and trigger efficiencies, the amount of initial and final state radiation, parton distribution functions, factorization and renormalization scale dependence, and Monte Carlo modeling have been explored and incorporated in this analysis. We integrate over all parameters describing systematic uncertainties in the likelihood function using Gaussian priors. The rate of $Wb\bar{b}$ and $Wc\bar{c}$ events is required to be positive, but otherwise unconstrained. Applying a prior probability density, that is zero if the FCNC cross section is negative and one elsewhere, we obtain the posterior probability density. No significant rate of top quarks produced by FCNC is observed and we set an upper limit on the cross section of 1.8 pb at the 95% C.L., which is in good agreement with the expected upper limit of 1.3 pb obtained from ensemble tests. The probability to obtain an upper limit higher than the observed 1.8 pb under the assumption that FCNC top-quark production does not exist is 28%.

Using theoretical predictions of $\sigma(u(c) + g \to t)$, which include threshold resummation effects [31, 32], we convert the upper limit on the cross section into upper limits on the FCNC coupling constants at the 95% C.L. and find $\kappa_{tug}/\Lambda < 0.018\ \text{TeV}^{-1}$ assuming $\kappa_{tcg} = 0$, and $\kappa_{tcg}/\Lambda < 0.069\ \text{TeV}^{-1}$ assuming $\kappa_{tug} = 0$. Using predictions at NLO [33], we also express these limits on the coupling constants in terms of limits on the FCNC branching ratios and obtain: $\mathcal{B}(t \to u + g) < 3.9 \times 10^{-4}$ and $\mathcal{B}(t \to c + g) < 5.7 \times 10^{-3}$.

For the first time we have explored the W+1 jet data set in search for top quarks produced by gluon-induced FCNC via the processes $u(c) + g \to t$. No evidence for such processes is found, resulting in the most stringent limits on the branching fractions for FCNC top-quark decays.

The authors express their gratitude to Chong Sheng Li of Peking University for very useful communication and for providing a new calculation of FCNC top-quark branching ratios in a very timely fashion. We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique

Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

[1] S.L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D **2**, 1285 (1970).

[2] G. Eilam, J.L. Hewett, and A. Soni, Phys. Rev. D **44**, 1473 (1991); Erratum: Phys. Rev. D **59**, 039901(E) (1998).

[3] W.-S. Hou, Phys. Lett. B **296**, 179 (1992).

[4] J.M. Yang, B.-L. Young, and X. Zhang, Phys. Rev. D **58**, 055001 (1998).

[5] C. Yue *et al.*, Phys. Lett. B **508**, 290 (2001).

[6] M. Hosch, K. Whisnant, and B.-L. Young, Phys. Rev. D **56**, 5725 (1997).

[7] T.M.P. Tait and C.-P. Yuan, Phys. Rev. D **63**, 014018 (2000).

[8] T. Aaltonen *et al.* (CDF Collaboration), arXiv:0809.2581 [hep-ex], accepted by Phys. Rev. Lett.

[9] V.M. Abazov *et al.* (DØ Collaboration), Phys. Rev. Lett. **98**, 181802 (2007).

[10] V.M. Abazov *et al.* (DØ Collaboration), Phys. Rev. Lett. **99**, 191802 (2007).

[11] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **101**, 192002 (2008).

[12] P. Achard *et al.* (L3 Collaboration), Phys. Lett. B **549**, 290 (2002).

[13] S. Chekanov *et al.* (ZEUS Collaboration), Phys. Lett. B **559**, 153 (2003).

[14] A. Aktas *et al.* (H1 Collaboration), Eur. Phys. J. C **33**, 9 (2004).

[15] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).

[16] In the CDF geometry, θ is the polar angle with respect to the proton beam axis, and ϕ is the azimuthal angle. Pseudorapidity is defined by $\eta \equiv -\ln[\tan(\theta/2)]$. The transverse momentum p_T is the component of the momentum projected onto the plane transverse to the beam axis. The transverse energy of a shower or calorimeter tower is defined as $E_T \equiv E \sin\theta$, where E is the energy deposited.

[17] A. Bhatti *et al.*, Nucl. Instrum. Methods. A **566**, 2 (2006).

[18] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **72**, 052003 (2005).

[19] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 052003 (2005).

[20] T. Peiffer, diploma thesis, University of Karlsruhe, 2008, FERMILAB-MASTERS-2008-01.

[21] T. Sjöstrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).

[22] J.M. Campbell and R.K. Ellis, Phys. Rev. D **60**, 113006 (1999).

[23] M. Cacciari *et al.*, J. High Energy Phys. **0404**, 068 (2004).

[24] J. Alwall *et al.*, J. High Energy Phys. **0709**, 028 (2007).

[25] B.W. Harris, E. Laenen, L. Phaf, Z. Sullivan, S. Weinzierl, Phys. Rev. D **66**, 054024 (2002).

[26] M.L. Mangano *et al.*, J. High Energy Phys. **0307**, 001 (2003).

[27] S.R. Slabospitsky and L. Sonnenschein, Comput. Phys. Commun. **148**, 87 (2002).

[28] S. Richter, Ph.D. thesis, University of Karlsruhe, 2007, FERMILAB-THESIS-2007-35.

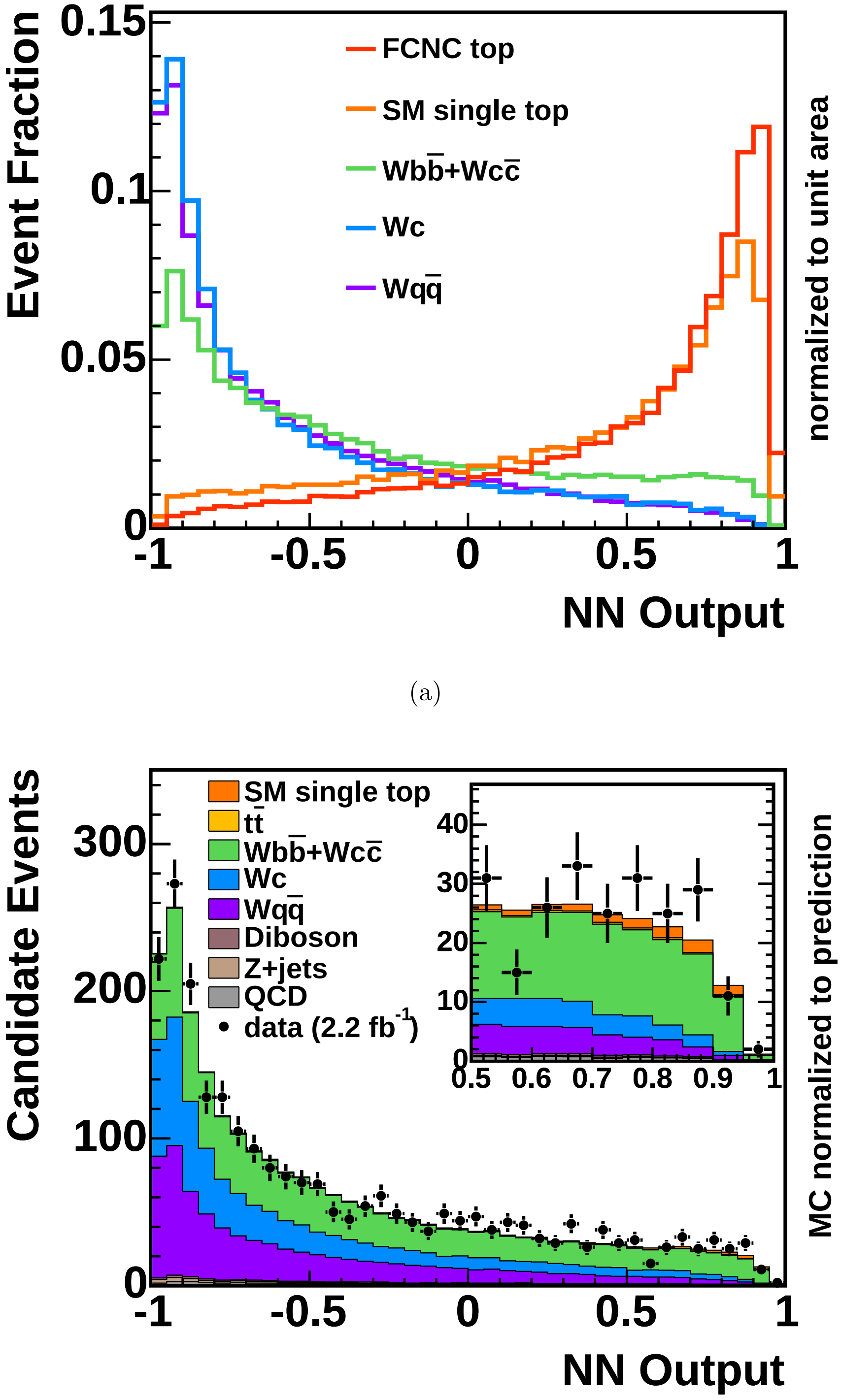
[29] M. Feindt and U. Kerzel, Nucl. Instrum. Methods A **559**, 190-194 (2006).

[30] Aplanarity is defined as $\frac{3}{2}$ of the smallest eigenvalue of the momentum tensor constructed from the jet, the charged lepton, and the reconstructed neutrino.

[31] L.L. Yang, C.S. Li, Y. Gao, and J.J. Liu, Phys. Rev. D **73**, 074017 (2006).

[32] J.J. Liu, C.S. Li, L.L. Yang, and L.G. Jin, Phys. Rev. D **72**, 074018 (2005).

[33] J.J. Zhang *et al.*, Phys. Rev. Lett. **102**, 072001 (2009).



(a)

(b)

FIG. 1: Distribution of the NN discriminant. (a) Discriminant shapes for the different physics processes normalized to unit area. (b) The composite model is compared to the distribution observed in collision data. The inset shows the high NN-output region, where top-quark events contribute the most.