Search for Production of Single Top Quarks Via *tcg* and *tug* Flavor-Changing-Neutral-Current Couplings

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We search for the production of single top quarks via flavor-changing-neutral-current couplings of a gluon to the top quark and a charm (c) or up (u) quark. We analyze 230 pb^{-1} of lepton + jets data from $p\bar{p}$ collisions at a center of mass energy of 1.96 TeV collected by the D0 detector at the Fermilab Tevatron Collider. We observe no significant deviation from standard model predictions, and hence set upper limits on the anomalous coupling parameters κ_g^c/Λ and κ_g^u/Λ, where κ_g define the strength of tcg and tug couplings, and Λ defines the scale of new physics. The limits at 95% C.L. are $\kappa_g^c/\Lambda < 0.15$ TeV^{-1} and $\kappa_g^u/\Lambda < 0.037$ TeV^{-1}.

Top quarks were discovered in 1995 by the CDF and D0 collaborations [1] at the Fermilab Tevatron Collider in $t\bar{t}$ pair production involving strong interactions. The standard model (SM) also predicts the production of single top quarks via electroweak exchange of a W boson with cross sections of 0.88 pb in the s channel (tb) and 1.98 pb in the t channel (tqb) [2]. At the 95% C.L., limits set by D0 are 6.4 pb on the s channel cross section and 5.0 pb on the t channel cross section [3], and those set by CDF are 13.6 pb and 10.1 pb, respectively [4]. D0 recently reported evidence for the production of single top quarks at significance of 3.4 standard deviations [5].

Since the top quark's discovery, several precision measurements have been made of its properties. Its large mass close to the electroweak symmetry-breaking scale suggests that any anomalous coupling could possibly be first observed in the top quark sector. One form of anomalous couplings can give rise to a single top quark in the final state through flavor-changing-neutral-current (FCNC) interactions with a charm or an up quark, involving the exchange of a photon, a Z boson, or a gluon [6,7]. Although such interactions can be produced by higher-order radiative corrections in the SM, the effect is too small to be observed [8]. Any observable signal indicating the presence of such couplings would be evidence of physics beyond the SM and would shed additional light on flavor physics in the top quark sector.

At present, strong constraints exist for FCNC processes via a photon or a Z boson exchange [9–11] from studies of both the production and decay of top quarks. In this Letter, we present a search for the production of single top quarks via FCNC couplings of a gluon to the top quark in data collected from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using the D0 detector. This is the first search of its kind at hadron colliders. We consider top quark production rather than decay, since the former is more sensitive to the anomalous couplings (κ_g) involving the gluon [12]. To date, the best constraints on these processes are from the DESY ep Collider (HERA): $\kappa_g/\Lambda < 0.4$ TeV^{-1}, at 95% C.L. [13], where Λ is the new physics cutoff scale.

We consider events where the top quark decays into a b quark and a W boson, and the latter subsequently decays leptonically ($W \to \ell\nu$, where $\ell = e$, μ or τ, with the τ decaying to either an electron or a muon, and two neutrinos). This gives rise to an event with a charged lepton of high transverse momentum (p_T), significant missing trans-verse energy ($\not{E}_T$) from the neutrinos, and at least two jets, one that is a b-quark jet (from the top quark decay), and the other from a c quark, u quark, or a gluon. Displaced secondary vertices are used to identify b jets [3]. The largest physics backgrounds to these events are from SM production of W + jets and $t\bar{t}$, along with smaller contributions from SM production of single top quarks (tb and tqb) and dibosons (WW and WZ). An additional source of background is from multijet events in which a jet is incorrectly identified as an electron or in which a muon from a heavy flavor decay appears isolated.

The D0 detector is described elsewhere [14]. We use the same data set, basic event selections and background modeling as in our SM single top quark search [3]; however, since the FCNC signal processes have only one b quark in the final state, we consider here events with only one b-tagged jet. In addition, we include here the SM single top quark processes (tb and tqb) in the background model. The data were recorded between August 2002 and March 2004 with a total integrated luminosity of 230 ± 15 pb^{-1} [15] and were collected using a trigger that required a reconstructed jet and an electromagnetic energy cluster in the electron channel, or a jet and a muon in the muon channel.

We model the FCNC signal kinematics using a parton-level leading order (LO) matrix element event generator COMPHEP [16]. All vertices involving the top quark, a charm or an up quark, and the gluon are taken into account. Representative $2 \to 2$ Feynman diagrams are shown in Fig. 1. Decays of the top quark and W boson are done in
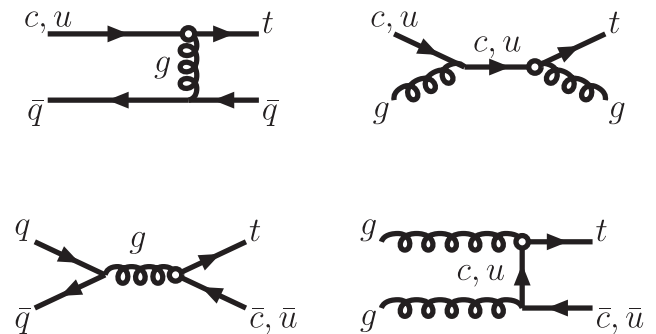

FIG. 1. Representative $2 \to 2$ Feynman diagrams for single top quark production through flavor-changing neutral currents involving the gluon.

TABLE I.   The production cross sections of single top quarks through a gluon exchange in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV for different values of κ_g/Λ, as obtained from COMPHEP and scaled to NLO by a K factor of 1.6.

κ_g/Λ [TeV^{-1}]	$\sigma(t)$ [pb]	
	tcg ($\kappa_g^u = 0$)	tug ($\kappa_g^c = 0$)
0.01	0.05	0.88
0.03	0.45	7.92
0.07	2.40	42.61
0.11	5.86	104.78

COMPHEP to take into account all spin-dependent effects. The effects of FCNC couplings are parametrized in a model-independent way via an effective Lagrangian [12] that is a linear function of the factor κ_g/Λ. The production cross section of single top quarks thus depends quadratically on κ_g/Λ, and for certain values of κ_g/Λ can be significantly larger than that in the SM, as shown in Table I. The cross sections are evaluated at a top quark mass of $m_t = 175$ GeV, with the factorization and renormalization scales set to $Q^2 = m_t^2$. The LO cross sections are scaled to next-to-leading (NLO) order by a K factor (NLO/LO cross section ratio) of 1.6 [17].

The effect of FCNC couplings on the top quark decay is negligible for $\kappa_g/\Lambda \lesssim 0.2$ TeV^{-1} [12]. In this range of κ_g/Λ, it is therefore safe to assume that the top quark decays into a W boson and a b quark with a branching fraction close to unity, as in the standard model, and hence, the cross section $\sigma(t)$ multiplied by the branching fraction for the process $t \to Wb \to \ell\nu b$ would also depend quadratically on κ_g/Λ. We may therefore model the shapes of the signal kinematic variables at any one value of κ_g/Λ and scale the distributions appropriately to obtain them at any other value. We choose that value of κ_g/Λ to be 0.03 TeV^{-1} in COMPHEP and generate two sets of signal events: one for the tcg process only, in which κ_g^u is set to zero, and the other for the tug process only, in which κ_g^c is set to zero.

The parton-level samples from COMPHEP are processed with PYTHIA [18] for fragmentation, hadronization, and modeling of the underlying event, using the CTEQ5L [19] parton distribution functions. We use TAUOLA [20] for the

TABLE II.   Summary of event selections.

	Electron channel	Muon channel
Lepton	$E_T > 15$ GeV $\|\eta\| < 1.1$	$p_T > 15$ GeV $\|\eta\| < 2.0$
$\not{E}_T$	$15 < \not{E}_T < 200$ GeV	
Jets	2, 3 or 4 jets, $E_T > 15$ GeV, $\|\eta\| < 3.4$	
	$E_T(\text{jet1}) > 25$ GeV, $\|\eta(\text{jet1})\| < 2.5$	
	Exactly one b-tagged jet	

TABLE III.   Event yields after all selections for the electron and muon channels. The signal yields are evaluated at $\kappa_g/\Lambda = 0.03$ TeV^{-1}. The yields for $t\bar{t}$ include both lepton + jets and dilepton final states, and those from W + jets also include the diboson backgrounds.

Source	Electron channel	Muon channel
tcg	0.6 ± 0.2	0.6 ± 0.2
tug	8.4 ± 2.1	9.8 ± 2.7
SM single top ($tb + tqb$)	6.4 ± 1.4	6.1 ± 1.4
$t\bar{t}$	31.8 ± 6.9	31.4 ± 7.0
W + jets	84.6 ± 10.2	76.8 ± 8.5
Multijets	13.7 ± 4.3	17.2 ± 1.5
Total SM background	136.5 ± 13.4	131.5 ± 12.7
Observed no. of events	134	118

tau lepton decays and EVTGEN [21] for the b-hadron decays. The generated events are processed through a GEANT-based [22] simulation of the D0 detector, and normalized to the NLO cross sections for $\kappa_g/\Lambda = 0.03$ TeV^{-1}. For the backgrounds, the Monte Carlo (MC) simulated samples are generated and normalized as described in Ref. [3].

The event selections [3] applied to the simulated signals and backgrounds and to the D0 data are summarized in Table II. The resulting numbers of events from all samples, along with their systematic uncertainties described later, are shown in Table III. We find that the observed numbers of events agree with the predicted numbers for the SM backgrounds within uncertainties in both the electron and muon channels, and that the FCNC signals are a tiny fraction. We therefore construct multivariate discriminants using neural networks to separate the expected signal from the background and enhance the sensitivity.

TABLE IV.   Input variables used in the neural network analysis.

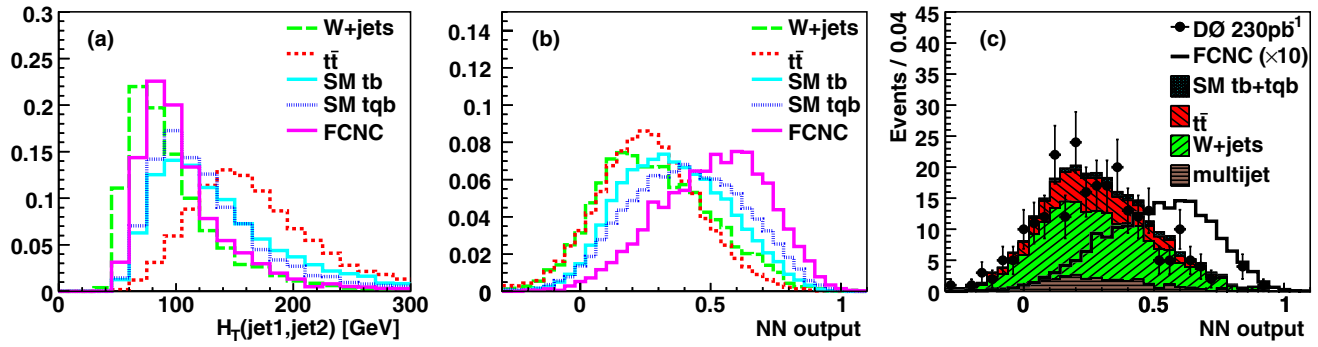|	
$p_T(\text{jet1})$	Transverse momentum of the leading jet
$p_T(\text{jet1}_{\text{tagged}})$	Transverse momentum of the b-tagged jet
$\eta(\text{lepton})$	Pseudorapidity [24] of the lepton
$\not{E}_T$	Missing transverse energy
$p_T(\text{jet1, jet2})$	Transverse momentum of the two leading jets
$H_T(\text{jet1, jet2})$	Scalar sum of the transverse momenta of the two leading jets
$p_T(W)$	Transverse momentum of the reconstructed W boson
$M(W, \text{jet1}_{\text{tagged}})$	Invariant mass of the reconstructed top quark using the W boson [25] and the b-tagged jet
$M(\text{all jets})$	Invariant mass of all jets
$\cos(\text{jet1, lepton})_{\text{lab}}$	Cosine of the angle between the leading jet and lepton in the laboratory frame of reference

FIG. 2 (color online).   Distributions of (a) an input variable to neural networks, and outputs normalized to (b) unity, and (c) 230 pb^{-1} of data with backgrounds summed. The FCNC signal is for the summed tcg and tug processes, each evaluated at $\kappa_g/\Lambda = 0.03$ TeV^{-1}.

We use MLPfit implementation [23] of neural networks with ten input variables representing individual object kinematics, global event kinematics, and angular correlations. These are listed in Table IV, with the distribution of one representative variable shown in Fig. 2(a). The combination of several variables in this manner allows us to separate the FCNC signals not only from the dominant backgrounds ($W +$ jets and $t\bar{t}$) but also from the SM single top quark processes as can be seen in Fig. 2(b) where the neural network outputs for the combined electron and muon channels are shown from different sources normalized to unity. Here the FCNC signal is for the summed tcg and tug processes, each evaluated at $\kappa_g/\Lambda = 0.03$ TeV^{-1}. Figure 2(c) shows the output distributions normalized to D0 data with backgrounds summed. Since the observed spectrum agrees with the predicted SM background, we set upper limits on the FCNC coupling parameters κ_g^c/Λ and κ_g^u/Λ.

To estimate systematic uncertainties, we consider effects that alter the overall normalization of the distributions and those that also change their shapes. The dominant normalization effects are from lepton identification (4%), integrated luminosity measurement (6.5%), and cross section estimates. The uncertainties on cross sections vary from 9% for diboson production to 16% for SM single top quark production and 18% for $t\bar{t}$ samples [26]. The latter two include the uncertainty due to the top quark mass. For the FCNC signal, we factor out the parameter $(\kappa_g/\Lambda)^2$ from the cross section, and assume an uncertainty of 15% on the remaining quantity based on a discussion in Ref. [17] on how the theoretical predictions depend on the particular choice of factorization scale. The $W +$ jets and multijets samples have an overall uncertainty of 4% from their normalization to data [3]. This includes an uncertainty of 25% on the heavy flavor fraction of the $W +$ jets sample.

The shape effects are modeled by shifting each source of uncertainty by plus or minus 1 standard deviation with respect to its nominal value before any event selections. The resulting uncertainties are (i) (1–16)% due to jet energy scale, (ii) (2–8)% from trigger modeling, (iii) (1–

5)% due to jet energy resolution, (iv) (1–9)% due to jet identification, and (v) (5–13)% from b-tag modeling. Since the $W +$ jets MC yield is normalized to data before b-tag parametrization, we take into account the uncertainty from b-tag modeling for this sample.

We use a Bayesian approach to set upper limits [27] on the FCNC coupling parameters. Given N observed events, we define a Bayesian posterior probability density in a two-dimensional plane of $(\kappa_g^c/\Lambda)^2$ and $(\kappa_g^u/\Lambda)^2$ as:

$$p([\kappa_g^c/\Lambda]^2, [\kappa_g^u/\Lambda]^2 | N) \propto \iiint L(N|n)p_1(f_c, f_u, b)$$
$$\times p_2([\kappa_g^c/\Lambda]^2)p_3([\kappa_g^u/\Lambda]^2)$$
$$\times df_c df_u db, \qquad (1)$$

where L is a Poisson likelihood with mean n, and $p_i(i = 1, 2, 3)$ are prior probability densities of the respective parameters. The likelihood L is a product of the likelihoods over all bins of the neural network output distributions, n is the predicted number of events, equal to the sum of signal
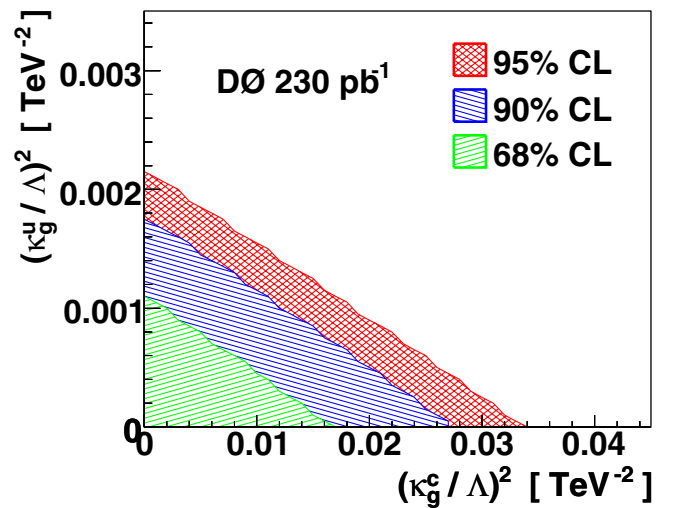

FIG. 3 (color online).   Exclusion contours at various levels of confidence using 230 pb^{-1} of D0 data in both the electron and muon channels.

TABLE V. Upper limits on κ_g^c/Λ and κ_g^u/Λ, at 95% C.L.

| | Observed (expected) limits [TeV^{-1}] | |
	κ_g^c/Λ	κ_g^u/Λ
Electron channel	0.16 (0.19)	0.046 (0.052)
Muon channel	0.21 (0.21)	0.049 (0.050)
Combined	**0.15(0.16)**	**0.037(0.041)**

(s) and background (b) yields:

$$n = s + b = f_c(\kappa_g^c/\Lambda)^2 + f_u(\kappa_g^u/\Lambda)^2 + b, \qquad (2)$$

where the constant factors f_c and f_u are obtained from the simulated signal samples at $\kappa_g/\Lambda = 0.03$ TeV^{-1}. The prior probability density p_1, is a multivariate Gaussian, with the mean and standard deviation defined by the estimated yields and their uncertainties, to take into account correlations among the different samples and bins. Since the signal cross sections depend quadratically on κ_g/Λ, for p_2 and p_3 we choose priors flat in $(\kappa_g^c/\Lambda)^2$ and $(\kappa_g^u/\Lambda)^2$ respectively, which imply priors flat in the corresponding cross sections.

From the two-dimensional posterior probability density, exclusion contours at different levels of confidence (k) are defined as contours of equal probability that enclose a volume k around the peak of the posterior density. These contours are shown in Fig. 3, using data from both electron and muon channels. The one-dimensional posterior probability density over any dimension is obtained by integrating the two-dimensional posterior over the other dimension. The resulting limits, translated to κ_g/Λ, using data (observed limits) as well as the expected limits for which the observed count is set to the predicted background yield in any bin, are summarized in Table V.

To conclude, we analyzed 230 pb^{-1} of lepton + jets data collected at D0 from $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV, and searched for presence of non-SM production of single top quarks. We found no deviation from SM predictions, and therefore set limits on anomalous coupling parameters, κ_g^c/Λ and κ_g^u/Λ, using multivariate neural network discriminants. The 95% C.L. observed (expected) limits are 0.15(0.16) TeV^{-1} on κ_g^c/Λ, and 0.037(0.041) TeV^{-1} on κ_g^u/Λ. These are first limits from hadron colliders on FCNC couplings of a gluon to the top quark and a charm or up quark, and a factor 3–11 better than those from HERA.

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