Searching for $t \rightarrow cg$ at the Fermilab Tevatron

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Abstract

We examine the experimental observability of the decay mode $t \rightarrow cg$ at the Fermilab Tevatron via the flavor-changing neutral current vertex $t\bar{c}g$. We find that with the existing data, one should be able to probe the $t\bar{c}g$ coupling to a value smaller than indirect limits previously obtained from $b \rightarrow s\gamma$ and the measured branching fraction for $t \rightarrow bW$, reaching $BF(t \rightarrow cg) \sim 15\% - 28\%$. A data sample of 1 fb$^{-1}$ (10 fb$^{-1}$) at $\sqrt{s} = 2$ TeV may probe the $t \rightarrow cg$ branching fraction to a level of 2\% (0.5\%).
I. INTRODUCTION

With the discovery of the top quark [1] the long anticipated completion of the fermion sector of the standard model has been achieved. Its unexpected large mass in comparison with the other known fermions suggests that the top quark will play a unique role in probing new physics, and has prompted both theorists and experimentalists alike to search for anomalous couplings involving the top quark. On the experimental side, the CDF [2,3] and D0 [4] collaborations have begun to explore the physics of top quark rare decays, and interesting bounds on flavor-changing decays to electroweak gauge bosons have been reported [3]. On the theoretical side, a systematic examination of anomalous top quark interactions is being actively undertaken [5,6].

An interesting set of anomalous interactions are those given by the flavor-changing chromo- and electro-magnetic operators

\[ \frac{\kappa_g}{\Lambda} g_s \sigma^{\mu\nu} \frac{\chi^a}{2} tG^a_{\mu\nu} + h.c. \]  

and

\[ \frac{\kappa_{\gamma}}{\Lambda} e \sigma^{\mu\nu} tF_{\mu\nu} + h.c., \]  

where \( \Lambda \) is the new physics cutoff, \( \kappa_g \) and \( \kappa_{\gamma} \) define the strengths of the couplings, and \( G_{\mu\nu} \) and \( F_{\mu\nu} \) are the gauge field tensors. The investigation of these couplings is well motivated. Although these operators can be induced in the standard model by high order loops, their effects are too small to be observable [6]. However, it has been argued that they may be enhanced significantly in many extensions of the standard model, such as SUSY or other models with multiple Higgs doublets [7,8], models with new dynamical interactions of the top quark [9], and models where the top quark has a composite [10] or soliton [11] structure. Therefore, any observed signal indicating these types of couplings is direct evidence for non-standard physics and will improve our understanding of flavor dynamics.

In this letter we propose an optimized procedure to search for the coupling \( t\bar{c}g \) via the decay \( t \rightarrow c\bar{g} \) at the Tevatron energies. We find that an improved limit on \( \kappa_g \), better than
that obtained before from indirect constraints [5], is possible even based on the existing 200 pb$^{-1}$ Tevatron data in the $W + 3$-jet mode of $t\bar{t}$ pair production.

II. EXISTING LIMITS ON FLAVOR-CHANGING TOP QUARK COUPLINGS

The strategy of searching for anomalous top quark couplings consists of two complementary approaches: (i) obtain indirect bounds from low energy processes in which top quark anomalous couplings can enter via loop processes, or from the bound on $t \to bW$ which puts limits on other decay modes of the top, and (ii) direct searches at high energies for the effects of the anomalous couplings in top quark production and decay. We have found earlier [5] that the experimental lower limit on $BF(t \to bW)$ from CDF [2] implies an upper bound of $BF(t \to cg) < 0.45$ at one standard deviation, which gives the limit $|\kappa_g| < 0.95$ for $\Lambda = 1$ TeV. Then from data on $b \to s + \gamma$ [12], we found correlated bounds on $\kappa_g$ and $\kappa_\gamma$, with $|\kappa_\gamma| < 0.3$ for $|\kappa_g| < 0.95$ and $\Lambda = 1$ TeV. More recently the CDF data [3] gives the bound

$$BF(t \to c\gamma) + BF(t \to u\gamma) < 2.9\%$$

(3)

at 95% Confidence Level (CL), which translates to $\kappa_\gamma/\Lambda < 0.73/\sqrt{BF(t \to bW)}$, where $\Lambda$ is in units of TeV. Reference [3] also gives the bound

$$BF(t \to cZ) + BF(t \to uZ) < 90\%$$

(4)

at 90% CL, which puts limits on the flavor-changing neutral current couplings $tcZ^0$ and $tuZ^0$. Using the anomalous coupling $\kappa_{tc}$ defined in Ref. [13], which denotes the combined effect of $V + A$ and $V - A$ $Zt\bar{c}$ couplings, we obtain a rather loose limit of $\kappa_{tc} < 1.3/\sqrt{BF(t \to bW)}$. The low energy data give $\kappa_{tc} < 0.29$ [13]. Hence for the anomalous couplings $\kappa_\gamma$ and $\kappa_{tc}$ the low energy data still provide tighter bounds than the direct limits from top quark decay.

The situation for the anomalous coupling $\kappa_g$ is different. Because the indirect constraint $|\kappa_g| < 0.95$ is relatively weak, and since the interaction in Eq. (1) involves the strong coupling
constant, there is the possibility that it can contribute significantly to top quark production and decay in hadron colliders.

III. TOP QUARK DECAY TO CHARM-GLUON AT THE TEVATRON

At the Fermilab Tevatron, the cross section for \( t\bar{t} \) production is about 5 pb at \( \sqrt{s} = 1.8 \) TeV. The CDF and D0 experiments have each collected about 100 pb\(^{-1}\) of data. Since a significant branching fraction for \( t \rightarrow cg \) is still allowed, the current data sample should be sufficient to put improved limits on \( \kappa_g \). Because QCD backgrounds are very large at hadron colliders, it is best to look for events where one top quark decays semi-leptonically

\[
t \rightarrow W^+b \rightarrow \ell^+\nu b \quad (\text{or} \quad \bar{t} \rightarrow W^-\bar{b} \rightarrow \ell^-\bar{\nu}\bar{b}) \quad (\ell = e \text{ or } \mu)
\]

and the other decays \( \bar{t} \rightarrow \bar{c}g \) (or \( t \rightarrow cg \)), i.e.,

\[
p\bar{p} \rightarrow t\bar{t} \rightarrow \ell^+\nu b\bar{c}g \quad \text{or} \quad \ell^-\bar{\nu}b\bar{c}g.
\]

The signature is then \( W(\rightarrow \ell^\pm\nu) + 3 \) jets, where two jets \((cg)\) reconstruct to the top mass, and so do the other jet \((b)\) and the \( W \).

To obtain the signal event rate, we calculate the top-quark pair production via \( q\bar{q} \rightarrow t\bar{t} \) and \( gg \rightarrow t\bar{t} \) using the lowest order matrix elements, and normalize the total cross section to theoretical results which include order \( \alpha_3^s \) corrections [14] by including a \( K \)-factor of 1.4. For the parton distributions we use the recent parametrization MRS Set-A [15]. The top decays are calculated using exact matrix elements for each decay, assuming an on-shell \( W \).

We have ignored the top quark spin correlations since the top-quark production mechanisms we consider give insignificant top-quark polarization [16]. The top-quark branching fractions may be obtained from the partial width ratio [3]

\[
\frac{\Gamma(t \rightarrow cg)}{\Gamma(t \rightarrow bW)} = \frac{64\sqrt{2}\pi\alpha_s}{3G_F \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right)} \left(\kappa_g^2\Lambda\right)^2 = 0.91\kappa_g^2,
\]

and thus, assuming that only \( t \rightarrow bW \) and \( t \rightarrow cg \) contribute dominantly to top decays,

\[
BR(t \rightarrow cg) = \frac{0.91\kappa_g^2}{1 + 0.91\kappa_g^2},
\]

(7)
where we have taken $m_t = 175$ GeV, $\alpha_s(2m_t) = 0.099$, $\Lambda = 1$ TeV, and the masses of the $b$ and $c$ quarks have been ignored. The signal cross section for the reaction given in Eq. (3) can then be written as

$$\sigma = \sigma_{max} \left(1.82 \right)^2 \left(\kappa_g / 0.95 \right)^2 \left[1 + 0.82 \left(\kappa_g / 0.95 \right)^2 \right]^2,$$

where $\sigma_{max}$ is the signal cross section for the maximum allowed value of the $\kappa_g$ (=0.95).

Without requiring $b$-tagging to begin with, we can identify the jet which goes with the $W$ as follows: the pair of jets which best reconstructs the top mass is assumed to come from the $t \to cg$ decay, and the other jet is then identified as the $b$-quark jet. Although the transverse momentum of the neutrino can be taken as the missing $p_T$, there is a two-fold ambiguity in determining the neutrino momentum along the beam direction [17]. We choose the solution which best reconstructs the top mass using the momenta of the jet previously identified as the $b$ jet, the charged lepton, and the neutrino.

To make the calculation more realistic, we simulate the detector effects by assuming a Gaussian energy smearing for the electromagnetic and hadronic calorimetry as follows:

$$\Delta E/E = 30\%/\sqrt{E} \oplus 1\%, \text{ for leptons}$$
$$= 80\%/\sqrt{E} \oplus 5\%, \text{ for jets},$$

where the $\oplus$ indicates that the $E$-dependent and $E$-independent errors are to be added in quadrature, and $E$ is to be measured in GeV.

The dominant background is from $W$ production plus three QCD jets [18],

$$p\bar{p} \to W^{\pm}jjj \to \ell^\pm\nu jjj.$$ (10)

Although the production rate of the background process is significantly larger than that of $t\bar{t}$ production at Tevatron energies, the kinematics for those processes is quite different, especially after imposing the top-quark mass constraint.

To simulate the detector coverage and help reduce the background, we first impose the following “basic” acceptance cuts on the transverse momentum ($p_T$), pseudo-rapidity ($\eta$),
and the separation in the azimuthal angle-rapidity plane ($\Delta R$) of the charged lepton, jets and missing transverse momentum

$$p_T^\ell, p_T^{\text{miss}} > 15 \text{ GeV}, \quad p_T^j > 20 \text{ GeV}, \quad |\eta^\ell|, |\eta^j| < 2.5, \quad \Delta R_{\ell j} > 0.4, \quad \Delta R_{jj} > 0.8. \quad (11)$$

The higher transverse momentum and $\Delta R$ cuts for the jets is motivated by the hard nature of the heavy top decay. The signal cross section for the maximal allowed value of $\kappa_g$ is reduced from about 550 fb with no cuts to around 322 fb with these basic cuts, while the $W + 3$ jets background is about 10.7 pb after the cuts.

To improve the relative strength of the signal, we make use of the following facts:

- the top-antitop invariant mass $M(t\bar{t})$ has a kinematical lower limit ($2m_t$ before energy smearing is applied), while the lower limit is significantly smaller for the background, near the $Wjjj$ threshold;

- the final state jets in the signal have transverse momenta typically the order of $\frac{1}{2}m_t \simeq 80$ GeV due to the nature of top-quark two-body decay, while all the jets in the background events tend to be soft. We can define two scalar sums of the transverse momenta:

$$p_T(j_1j_2) \equiv |\vec{p}_T^{j_1}| + |\vec{p}_T^{j_2}|, \quad p_T(jjj) \equiv p_T(j_1j_2) + |\vec{p}_T^{j_3}|, \quad (12)$$

where the jet transverse momenta are ordered such that $|\vec{p}_T^{j_1}| > |\vec{p}_T^{j_2}| > |\vec{p}_T^{j_3}|$. In fact, the signal spectra are much harder than the background at the low end, but they are limited by the physical scale $2m_t$, so that the background tends to extend relatively further at the high end.

With these points in mind, we therefore accept events with

$$M(t\bar{t}) > 2m_t = 350 \text{ GeV}, \quad 100 < p_T(j_1j_2) < 300 \text{ GeV}, \quad 150 < p_T(jjj) < 400 \text{ GeV}. \quad (13)$$
If we define our Level-II cuts as those given in Eq. (13), then the maximal signal is reduced only moderately to about 275 fb, while the background is reduced by about a factor of six to around 1870 fb.

In Fig. 1 we show the reconstructed top-quark mass distributions $M(cg)$ and $M(bW)$ after making both the basic and Level-II cuts, where the $W$ momentum is obtained from the momenta of the charged lepton and the reconstructed neutrino. We see from Fig. 1(a) that the continuum background is still above the $M(cg)$ signal peak in the region around $m_t$. A further improvement can be made if we impose the cut

$$|M(cg) - m_t| < 20 \text{ GeV}. \quad (14)$$

In Fig. 1(b) the dashed histograms show how the background in the $M(bW)$ distribution is reduced by the cut in Eq. (14). The signal distribution is reduced only moderately by this cut (see the dotted and the solid curves) and is now within a factor of two of the background when $\kappa_g$ is at its maximal value. The signal observability can be maximized if we consider the events in the mass range

$$|M(bW) - m_t| < 30 \text{ GeV}. \quad (15)$$

After the final cut in Eq. (15), the maximal signal cross section is

$$\sigma_{\text{max}} = 195 \text{ fb} \quad (16)$$

and the background is about 400 fb. Therefore up to 40 signal events would be expected for the current integrated luminosity, with a background of about 80 events, which would correspond to nearly a $4\sigma$ signal near the $M(bW)$ peak. Table I summarizes the effect of the various cuts on the maximal signal and the background. The signal rate for non-maximal $\kappa_g$ is easily computed using Eqs. (8) and (16).

We have so far optimized $S/B$ only based on kinematical variables. If we further require a $b$-tagging on the jet that satisfies Eq. (13) in top-quark mass reconstruction, and assume a 50% $b$-tagging efficiency and 1% impurity [19], one expects to improve the $S/B$ ratio by a factor of 50.
To estimate the sensitivity to $\kappa_g$ for a given integrated luminosity, we can take the cross section given in Eq. (8), using the value of $\sigma_{\text{max}}$ in Eq. (10), and compare it to the background rate. With Gaussian statistics, a measurement is sensitive to the signal at 99% CL when

$$S/\sqrt{S + B} = 3.$$  \hspace{1cm} (17)

The solid line in Fig. 2 presents the anomalous coupling $\kappa_g$ versus the integrated luminosity required at the Tevatron with $\sqrt{s} = 1.8$ TeV. The dashed curve in Fig. 2 shows the improvement in sensitivity if $b$-tagging is employed. We see that with 200 pb$^{-1}$ integrated luminosity as accumulated by CDF and D0 collaborations, one should be able to probe this anomalous coupling to $\kappa_g \sim 0.43 - 0.65$ with or without $b$-tagging, corresponding to a branching fraction $BR(t \to cg) \sim 15\% - 28\%$. In other words, if we assume the anomalous coupling $\kappa_g$ is naturally of order unity and allow the new physics cutoff scale ($\Lambda$) to change, then the current Tevatron data should be sensitive to $\Lambda \sim 2$ TeV.

In the future, with $\sqrt{s} = 2$ TeV and the expected 1 fb$^{-1}$/yr integrated luminosity of the Main Injector, or 10 fb$^{-1}$/yr at the Tevatron Upgrade, further dramatic improvements in the limits on $\kappa_g$ should be possible. Potential results for the 2 TeV Tevatron are also shown in Table I (in parentheses) and Fig. 2 (dotted and dash-dotted curves). We see that a branching fraction of order 2% (0.5%) would be reached for 1 fb$^{-1}$ (10 fb$^{-1}$) integrated luminosity, corresponding to a probe of the coupling down to $\kappa_g = 0.15(0.07)$.

IV. DISCUSSION AND SUMMARY

Before concluding, a few remarks are in order. First, the top-quark events with the SM hadronic decay $t \to bW \to bjj$ may pose a background to our signal as well if one of the jets escapes detection. However, our requirement in Eq. (12) for $m_t$ reconstruction by two non-$b$ jets would hopefully remove this background. Second, if such a coupling exists at an observable level, there might also be a possibility of significant single top production via the anomalous vertex. A study of $q\bar{q} \to t\bar{c}$ has recently appeared \cite{20}. Given the fact that the
signal from the decay \( t \rightarrow cg \) is more kinematically characteristic, our results here should be more promising. More detailed studies with all contributing processes which involve the \( t\bar{c}g \) coupling, including calculations at LHC energies, will be presented elsewhere [21].

In summary, we have found that the current Tevatron data sample can already be used to improve the current limit on (or detect the existence of) an anomalous flavor-changing magnetic \( t\bar{c}g \) coupling via a direct search for \( t \rightarrow cg \) decay in top-antitop pair production. The upgraded Tevatron will allow a probe of the \( t \rightarrow cg \) branching fraction to the order of 1%.

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TABLES

TABLE I. Cross sections in units of fb for the $t\bar{t} \to \ell^\pm \nu bcg$ signal (with maximal coupling $\kappa_g = 0.95$), and the $Wjjj$ background at the Tevatron with $\sqrt{s} = 1.8$ TeV (2 TeV). The results are shown at various stages of the analysis: for the basic acceptance cuts of Eq. (11), after the Level-II cuts of Eq. (13), after the cuts on $M(cg)$ and $M(bW)$, and finally after including $b$-tagging. A 50% $b$-tagging efficiency and 1% impurity are assumed [19].

| Cuts                      | Signal: $\sigma_{max}(t\bar{t} \to \ell^\pm \nu bcg)$ (fb) | Background: $\sigma(W^{\pm}jjj \to \ell^\pm \nu jjj)$ (fb) |
|---------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| Basic Cuts                | 322 (447)                                                   | 7920 (10700)                                               |
| Level-II                  | 276 (380)                                                   | 1870 (2850)                                               |
| $|M(cg) - m_t| < 20$ GeV          | 239 (329)                                                   | 767 (1150)                                               |
| $|M(bW) - m_t| < 30$ GeV          | 195 (268)                                                   | 399 (585)                                               |
| plus $b$-tagging          | 98 (134)                                                     | 4 (6)                                                     |

FIGURE CAPTIONS

FIG. 1 Invariant mass distributions after basic and Level-II cuts at the Tevatron with $\sqrt{s} = 1.8$ TeV for (a) $M(cg)$ and (b) $M(bW)$ with the additional cut $|M(cg) - m_t| < 20$ GeV. The solid curves are the signal and the dashed curves represent the $W + 3$ jet background. In the $M(bW)$ distribution, also shown are the background (upper dashed) and signal (dotted) curves before the $M(cg)$ cut (the signal is about 20% lower with this cut).

FIG. 2 Sensitivity to $\kappa_g$ vs. integrated luminosity at the Tevatron at 99% CL. The solid (dashed) curves represent the sensitivity at $\sqrt{s} = 1.8$ TeV without (with) $b$-tagging, and the dotted (dot-dashed) curves represent the sensitivity at $\sqrt{s} = 2$ TeV without (with) $b$-tagging.
Figure 1

(a) Dashes: Wjjj Bckgnd
Solid: Signal $\kappa_g=0.95$

(b) Tevatron 1.8 TeV
Figure 2

Fermilab Tevatron