

## Top-quark decay via the anomalous coupling $\bar{t}c\gamma$ at hadron colliders

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We determine the constraints on the anomalous top-quark coupling associated with the flavor-changing neutral current vertex  $\bar{t}c\gamma$  from the limits on the  $b$ -quark rare decay  $b \rightarrow s\gamma$  and nonstandard top-quark decays. Based on these constraints, we discuss the experimental observability of the rare decay mode  $t \rightarrow c\gamma$ , both at the Fermilab Tevatron with a luminosity upgrade and at the CERN LHC. [S0556-2821(97)00411-6]

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### I. INTRODUCTION

The top quark has been experimentally observed at the Fermilab Tevatron by the CDF and D0 Collaborations [1] with a measured mass of around 175 GeV. Because it has a mass of the order of the Fermi scale, the top quark couples quite strongly to the electroweak symmetry-breaking sector. In the standard model (SM), the electroweak symmetry-breaking sector consists of a complex fundamental Higgs scalar, but ‘‘triviality’’ [2] and ‘‘naturalness’’ [3] of the scalar sector suggest that the Higgs sector may not be so simple. It is, therefore, plausible to assume that the mass generation mechanism is more complicated and the Higgs sector of the SM is just an effective theory, and that new physics phenomena may be manifested through effective interactions of the top quark [4].

An interesting set of top-quark interactions is composed of those given by the flavor-changing neutral vertices  $\bar{t}cZ$ ,  $\bar{t}cg$ , and  $\bar{t}c\gamma$ . The standard model predictions of the branching fractions for those rare top-quark decays ( $t \rightarrow cZ, cg, c\gamma$ ) are unobservably small [5]. Any experimental evidence for these types of couplings will therefore be an unequivocal indication of new physics beyond the standard model. On the other hand, it has been argued that those couplings may be enhanced significantly in many extensions of the standard model, such as supersymmetry (SUSY) or other models with multiple Higgs doublets [5,6], models with new dynamical interactions of the top quark [7], and models where the top quark has a composite [8] or soliton structure [9].

If anomalous top-quark couplings beyond the SM exist, they may affect certain low-energy quantities measured with high precision, such as the partial width ratio  $R_b = \Gamma(Z \rightarrow b\bar{b})/\Gamma(Z \rightarrow \text{hadrons})$  measured at the CERN  $e^+e^-$  collider LEP I [10] or the branching fraction for  $b \rightarrow s\gamma$  [11]. Furthermore, such couplings would also affect top-quark production and decay processes at hadron and  $e^+e^-$  colliders [12,13]. In Ref. [14], the experimental constraints on an anomalous top-quark coupling  $Z\bar{t}c$  and the experimental observability of the induced rare decay mode  $t \rightarrow Zc$ , at the Fermilab Tevatron and the CERN Large Hadron Collider (LHC), have been investigated in detail. The

observability of an anomalous coupling  $\bar{t}cg$  at the Tevatron energy is studied in Ref. [15]. In this paper, we examine the possible anomalous top-quark coupling  $\bar{t}c\gamma$  and its implications in both low- and high-energy processes. In our analysis we will also allow for the coexistence of a  $\bar{t}cg$  coupling for completeness, since it may have some similar effects.

This paper is organized as follows. In Sec. II, we examine the constraints on the anomalous  $\bar{t}c\gamma(g)$  couplings from  $b \rightarrow s\gamma$  and from the limit on nonstandard top-quark decays at the Tevatron. In Sec. III, we study the possibility of detecting the  $\bar{t}c\gamma$  coupling at the Tevatron and the LHC, paying particular attention to the kinematical characteristics to extract the signal from large backgrounds. The cuts are adjusted to the different physics requirements at the two accelerators. Finally, in Sec. IV, we summarize our results.

### II. CONSTRAINTS ON THE TOP-QUARK ANOMALOUS COUPLINGS

Following Ref. [4], we introduce an effective Lagrangian involving the anomalous top-quark couplings:

$$\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \Delta\mathcal{L}^{\text{eff}}, \quad (1)$$

where  $\mathcal{L}^{\text{SM}}$  is the standard model Lagrangian and  $\Delta\mathcal{L}^{\text{eff}}$  includes the anomalous top-quark couplings. For the purpose of this paper, we consider only the lowest dimension,  $CP$ -conserving operators which give rise to anomalous  $\bar{t}c\gamma(g)$  vertices. Then

$$\Delta\mathcal{L}^{\text{eff}} = \frac{1}{\Lambda} \left[ \kappa_\gamma e \bar{t} \sigma_{\mu\nu} c F^{\mu\nu} + \kappa_g g_s \bar{t} \sigma_{\mu\nu} \frac{\lambda^i}{2} c G^{i\mu\nu} \right] + \text{H.c.}, \quad (2)$$

where  $F^{\mu\nu}$  [ $G^{i\mu\nu}$ ] is the  $U_{\text{em}}(1)$  [ $SU_c(3)$ ] field strength tensor,  $e$  ( $g_s$ ) is the corresponding coupling constant, and  $\Lambda$  is the cutoff of the effective theory, which we take to be the order of 1 TeV. The parameters  $\kappa_\gamma$  and  $\kappa_g$  can be interpreted as the strengths of the anomalous interactions, or, alternatively,  $\Lambda/\kappa$  is the approximate scale at which new physics in the top-quark sector occurs.

The measurement of the inclusive branching ratio for the process  $b \rightarrow s\gamma$  [16] puts severe constraints on various exten-

sions of the standard model [11]. Here we study its constraints on anomalous top-quark couplings  $\bar{t}c\gamma$  and  $\bar{t}cg$ . Anomalous couplings of various types associated with the top quark and their constraints obtained from low-energy processes have been considered in the literature [17].

The effective Hamiltonian for  $b \rightarrow s\gamma$  is given by [18–20],

$$H_{\text{eff}} = -\frac{4}{\sqrt{2}} G_F V_{ts}^* V_{tb} \sum_i C_i(\mu) O_i(\mu), \quad (3)$$

where  $i$  runs from 1 to 8, and  $\mu$  denotes the energy scale at which  $H_{\text{eff}}$  is applied. The operator set  $O_i(\mu)$  consists of six four-quark operators  $O_{1-6}$ , the electromagnetic dipole operator  $O_7$ , and the chromomagnetic dipole operator  $O_8$ . At the weak scale, the only contributing operator is  $O_7$ . However, when evolving down to the low-energy scale  $\mu \sim m_b$ ,  $O_7$  will mix with operator  $O_8$  and others. Here,  $V_{ij}$  are the elements of the Cabbibo-Kobayashi-Maskawa mixing matrix.

The partial decay width for  $b \rightarrow s\gamma$  is, neglecting the strange-quark mass,

$$\Gamma(b \rightarrow s\gamma) = \frac{\alpha G_F^2 m_b^5}{32\pi^4} |V_{ts}^* V_{tb} C_7(m_b)|^2. \quad (4)$$

Normalized by the inclusive semileptonic branching ratio, the  $b \rightarrow s\gamma$  branching ratio can be written as

$$\frac{B(b \rightarrow s\gamma)}{B(b \rightarrow c\bar{\nu})} = \frac{|V_{ts}^* V_{tb}|^2}{|V_{cb}|^2} \frac{6\alpha}{\pi g(z)} |C_7(m_b)|^2, \quad (5)$$

where  $g(z) = 1 - 8z^2 + 8z^6 - z^8 - 24z^4 \ln z$ , with  $z = m_c/m_b$ . In the standard model, the complete leading logarithmic approximation gives [20]

$$C_7(m_b) = \eta^{16/23} C_7(M_W) + \frac{8}{3} (\eta^{14/23} - \eta^{16/23}) C_8(M_W) + C_2(M_W) \sum_{i=1}^8 h_i \eta^{p^i}, \quad (6)$$

with  $\eta = \alpha_s(M_W)/\alpha_s(m_b)$ . The coefficients  $C_2(M_W)$ ,  $h_i$ , and  $p^i$  can be found in [20].

The anomalous top-quark couplings  $\bar{t}c\gamma$  and  $\bar{t}cg$  modify the coefficients of operators  $O_7$  and  $O_8$ . The coefficients of these operators at the electroweak scale can be written as

$$C_7(M_W) = C_7^{\text{SM}}(M_W) - \frac{1}{2} \left( \frac{V_{cs}}{V_{ts}} \right)^* \frac{m_t}{\Lambda} \ln \left( \frac{\Lambda^2}{m_t^2} \right) \kappa_\gamma, \quad (7)$$

$$C_8(M_W) = C_8^{\text{SM}}(M_W) - \frac{1}{2} \left( \frac{V_{cs}}{V_{ts}} \right)^* \frac{m_t}{\Lambda} \ln \left( \frac{\Lambda^2}{m_t^2} \right) \kappa_g, \quad (8)$$

where  $C_7^{\text{SM}}(M_W)$  and  $C_8^{\text{SM}}(M_W)$  are the standard model contributions. The logarithmic terms are from the anomalous couplings, which contribute to  $b \rightarrow s\gamma$  and  $sg$  in one-loop order with top- and charm-quark intermediate states. The Feynman integrals are dimensionally regularized. The heaviest mass in the loop, i.e., the top-quark mass, is used to set the scale and the new physics cutoff serves as the cutoff of the integrals. More detailed procedures can be found in [21].

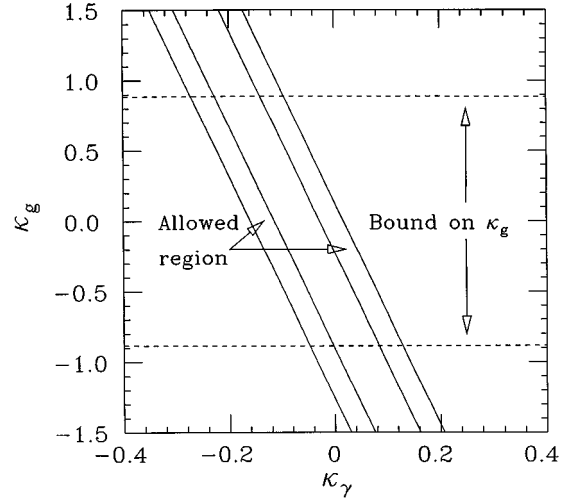


FIG. 1. Constraints on anomalous couplings  $\kappa_g$  and  $\kappa_\gamma$  from  $B(b \rightarrow s\gamma)$  (the two diagonal bands in solid lines) and  $B(t \rightarrow bW)$  (dashed horizontal lines).  $\Lambda = 1$  TeV is assumed throughout the paper.

Using  $B(b \rightarrow c\bar{\nu}) = 0.108$  and the recent CLEO measurement [16]

$$1 \times 10^{-4} < B(b \rightarrow s\gamma) < 4.2 \times 10^{-4}, \quad (9)$$

we plot the allowed region for  $\kappa_\gamma$  and  $\kappa_g$  in Fig. 1, for  $m_b = 5$  GeV,  $m_t = 175$  GeV,  $\alpha_s(M_Z) = 0.12$ , and  $|V_{ts}^* V_{tb}/V_{cb}|^2 = 0.95$  [20]. Throughout this paper, we take  $\Lambda = 1$  TeV. In the figure there are two allowed bands: The right band corresponds to a small anomalous correction to the SM  $C_7(m_b)$  coefficient which obeys the limit in Eq. (9), while the left band corresponds to a large correction which is approximately twice the magnitude of the SM contribution but of the opposite sign, so that the magnitude of  $C_7(m_b)$  is still consistent with Eq. (9).

A further restriction on  $\kappa_\gamma$  and  $\kappa_g$  can be obtained from the fact that  $t \rightarrow c\gamma$  and  $t \rightarrow c\gamma$  decays are not the most significant top-quark decay modes as shown by the recent CDF data [22]. A straightforward calculation of partial widths yields

$$\frac{\Gamma(t \rightarrow c\gamma)}{\Gamma(t \rightarrow bW)} = \frac{16\sqrt{2}\pi\alpha}{G_F(1 - M_W^2/m_t^2)^2(1 + 2M_W^2/m_t^2)} \left( \frac{\kappa_\gamma}{\Lambda} \right)^2, \quad (10)$$

where the masses of the  $c$  and  $b$  quarks have been ignored. For the case of  $\Gamma(t \rightarrow c\gamma)$ ,  $\alpha$  is replaced by  $4\alpha_s/3$  in the above equation.

The Collider Detector at Fermilab (CDF) data on the branching ratio of the top quark decaying to  $b$  [22],

$$B(t \rightarrow bW) = 0.87_{\pm 0.30}^{\pm 0.13 \pm 0.11}, \quad (11)$$

places the limit

$$B(t \rightarrow c\gamma) < 0.45 \quad (12)$$

at the one standard deviation level, where the insignificant contribution of  $t \rightarrow c\gamma$  has been ignored. This constraint gives the limit

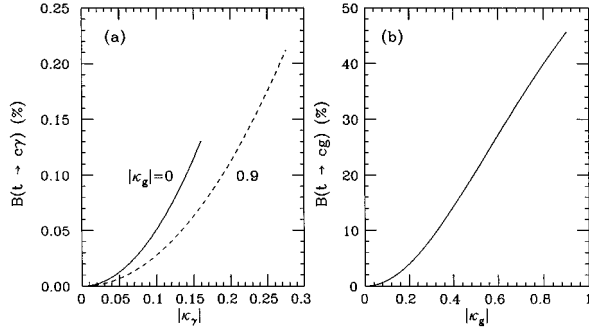


FIG. 2. (a) Branching ratios for (a)  $t \rightarrow c\gamma$  versus  $|\kappa_\gamma|$  for  $|\kappa_g|=0$  (solid line) and  $|\kappa_g|=0.9$  (dashed line), and (b)  $t \rightarrow cg$  versus  $|\kappa_g|$ . The curves stop at the maximum allowed value of the abscissa in each case.

$$|\kappa_g| < 0.9, \quad (13)$$

and is shown in Fig. 1 as the dashed lines.

One can see that  $B(b \rightarrow s\gamma)$  combined with  $B(t \rightarrow bW)$  has constrained  $\kappa_\gamma$  very strongly. The branching ratio for  $t \rightarrow c\gamma$  is shown in Fig. 2(a) versus  $\kappa_\gamma$  for the maximum and minimum allowed magnitudes of  $\kappa_g$ . Specifically, we find that, for  $\kappa_g=0$ ,

$$|\kappa_\gamma| < 0.16 \text{ and } B(t \rightarrow c\gamma) < 1.3 \times 10^{-3} \quad (14)$$

and, for  $|\kappa_g|=0.9$ ,

$$|\kappa_\gamma| < 0.28 \text{ and } B(t \rightarrow c\gamma) < 2.2 \times 10^{-3}, \quad (15)$$

when accounting for the contribution of the  $t \rightarrow cg$  decay to the total width. A similar constraint for the case with  $\kappa_g=0$  has been obtained in Ref. [23]. The branching ratio for  $t \rightarrow c\gamma$  is shown in Fig. 2(b) versus  $\kappa_g$ .

### III. TOP-QUARK DECAY VIA ANOMALOUS COUPLINGS AT HADRON COLLIDERS

At the Fermilab Tevatron, the cross section for  $t\bar{t}$  production is about 5 pb at  $\sqrt{s}=2$  TeV. A detailed study of top-quark decays is possible with the expected  $1 \text{ fb}^{-1}/\text{yr}$  integrated luminosity of the Main Injector or the  $10 \text{ fb}^{-1}/\text{yr}$  anticipated at the Tevatron Upgrade [24]. Top-quark production is much greater at the LHC, with a cross section of order 1000 pb, due to the larger center-of-mass energy (14 TeV) and higher integrated luminosity ( $100 \text{ fb}^{-1}/\text{yr}$ ). Therefore it is feasible to search for evidence of anomalous couplings such as  $\bar{t}c\gamma$  at hadron colliders.

The decay  $t \rightarrow c\gamma$  has already been discussed in the previous section. To obtain the signal event rate, we calculate the top-quark production via  $q\bar{q}, g\bar{g} \rightarrow t\bar{t}$  with the lowest order matrix elements, but normalize the total cross sections to values which include order- $\alpha_s^3$  corrections [25]. We thus find that the appropriate constant normalization factors ( $K$  factors) are

$$K=1.4 \text{ for Tevatron, } K=2.0 \text{ for LHC.}$$

For the parton distributions we use the recent parametrization Martin-Roberts-Sterling (MRS) set A [26]. Because of the enormous QCD backgrounds at hadron colliders, it is

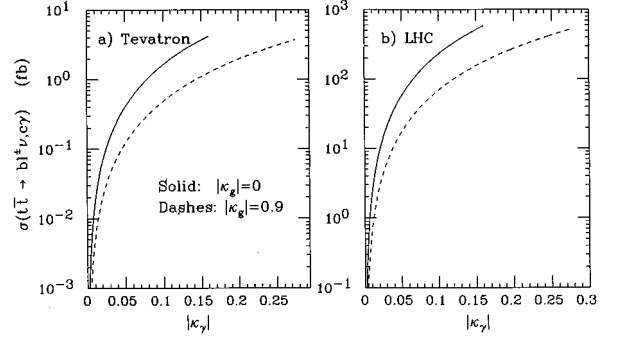


FIG. 3. Production cross section for  $t\bar{t} \rightarrow bWc\gamma \rightarrow b\ell\nu c\gamma$  at (a) the Tevatron ( $p\bar{p}$ ) with  $\sqrt{s}=2$  TeV and (b) the LHC ( $pp$ ) with  $\sqrt{s}=14$  TeV. The top-quark mass  $m_t=175$  GeV is used throughout the paper. The cross sections are plotted versus  $|\kappa_\gamma|$  for  $|\kappa_g|=0$  (solid line) and  $|\kappa_g|=0.9$  (dashed line). The curves stop at the maximum allowed value of  $|\kappa_\gamma|$  in each case.

very difficult, if not impossible, to search for the signal if both the top quark and top antiquark decay purely hadronically. We therefore look for events with one top quark decaying leptonically,  $t \rightarrow W^+b \rightarrow \ell^+\nu b$  (or  $\bar{t} \rightarrow W^-\bar{b} \rightarrow \ell^-\bar{\nu}\bar{b}$ ), where  $\ell=e, \mu$ . The cross section for such events is calculated using the exact matrix elements for an on-shell  $W$ . We have ignored the spin correlations for the decaying top quarks since the top-quark production mechanisms we consider give insignificant top-quark polarization [27].

Figure 3 shows the calculated total cross section plotted versus  $\kappa_\gamma$ , for two values of  $\kappa_g$ , for the process  $t\bar{t} \rightarrow bWc\gamma \rightarrow jj\ell^\pm\nu\gamma$ , where  $\ell=e, \mu$ , and  $j$  represents a jet from either a  $b$  or  $c$  quark. The curves stop at the maximum allowed value of  $\kappa_\gamma$  in each case. Figure 3(a) is for the Fermilab Tevatron ( $p\bar{p}$  collisions with  $\sqrt{s}=2$  TeV) and Fig. 3(b) for the LHC ( $pp$  collisions with  $\sqrt{s}=14$  TeV). We see that for the allowed values of  $\kappa_\gamma$ , the signal cross section at the Tevatron could be as large as 4 fb, which is rather small, but still might be observable at the Tevatron Upgrade. At the LHC, the maximal signal cross section is nearly 600 fb, which means that there could be a large number of events even for nonmaximal couplings. We should remark that the top-quark production cross section is somewhat sensitive to the top-quark mass. For  $m_t=200$  GeV, for example, the cross section is reduced by slightly more or less than 50% at the Tevatron and the LHC, respectively.

The only irreducible backgrounds to the signal are electroweak (EW)  $W^\pm\gamma$  production plus two QCD jets:

$$p\bar{p} \rightarrow W^\pm \gamma jj \rightarrow \ell^\pm \nu \gamma jj. \quad (16)$$

There are also possible ‘‘fake’’ events

$$p\bar{p} \rightarrow W^\pm jjj \rightarrow \ell^\pm \nu \gamma jj, \quad (17)$$

where one of the QCD jets fakes a photon. These backgrounds have substantial production rates. The signal is, however, distinctive: Besides the isolated charged lepton and large missing transverse energy ( $E_T^{\text{miss}}$ ) from  $W^\pm$  decay, there is a highly energetic photon, and two hard ( $b, c$ -quark) jets with which  $c\gamma$  and  $bW$  both reconstruct a top quark (or  $\bar{t}$ ). Without requiring  $b$  tagging, our signal

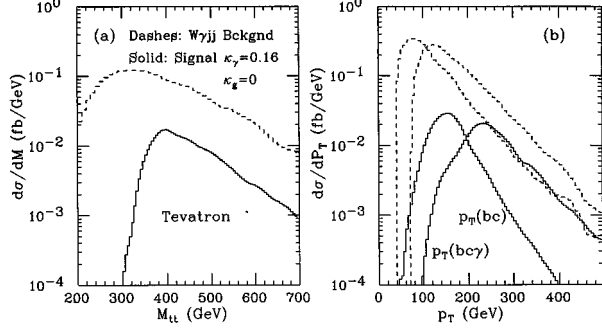


FIG. 4. (a) Top-quark-top-antiquark invariant mass distributions for the signal  $t\bar{t} \rightarrow Wbc\gamma$  (solid histogram) and background  $p\bar{p} \rightarrow Wjj\gamma$  (dashed histogram) at the Tevatron with  $\sqrt{s}=2$  TeV, assuming the basic acceptance cuts defined in Eq. (20) in the text. (b) Distributions for the transverse momenta scalar sums  $p_T(bc)$  and  $p_T(bc\gamma)$  for the signal (solid histograms) and background (dashed histograms). The signal histograms assume the maximal allowed value of  $\kappa_\gamma$  with  $\kappa_g=0$ .

selection procedure is as follows. We first examine the two values of the invariant mass  $M(\gamma j_1)$  and  $M(\gamma j_2)$  and identify the jet which gives an  $M(\gamma j)$  value closer to  $m_t$  as the  $c$ -quark jet. Naturally, the other jet will be identified as a  $b$ -quark jet. Because of the missing neutrino from the  $W$  decay, the  $W$  momentum cannot be reconstructed unambiguously due to the lack of knowledge of the parton c.m. frame. This is known as the twofold ambiguity in constructing the neutrino momentum along the beam direction [28]. Taking the  $W$  mass as an input and for massless leptons, using the measured charged lepton momentum ( $p^\ell$ ) and the *transverse* momentum (with respect to the beam direction) of the neutrino ( $p_T^\nu$ ), the two solutions for the *longitudinal* momentum of the neutrino can be expressed by

$$p_L^\nu = \frac{1}{2(p_T^\ell)^2} \{ p_L^\ell (M_W^2 + 2\mathbf{p}_T^\ell \cdot \mathbf{p}_T^\nu) \pm p^\ell [(M_W^2 + 2\mathbf{p}_T^\ell \cdot \mathbf{p}_T^\nu)^2 - 4(p_T^\ell)^2 (p_T^\nu)^2]^{1/2} \}. \quad (18)$$

There are therefore two solutions for  $p_W$ , correspondingly. We again take the one that gives an  $M(bW)$  value closer to  $m_t$ . With this procedure, both top-quark momenta are experimentally identifiable.

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:

$$\begin{aligned} \Delta E/E &= 30\%/\sqrt{E} \oplus 1\% \quad (\text{for lepton and photon}) \\ &= 80\%/\sqrt{E} \oplus 5\% \quad (\text{for jets}), \end{aligned} \quad (19)$$

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.

### A. Tevatron

To quantify the experimental sensitivity to the anomalous couplings, we first impose acceptance cuts on the transverse momentum ( $p_T$ ), pseudorapidity ( $\eta$ ), and the separation in

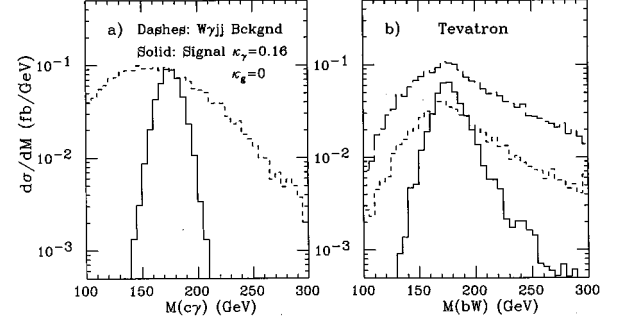


FIG. 5. Reconstructed top-quark mass distributions for (a)  $M(c\gamma)$  and (b)  $M(bW)$  at the Tevatron with  $\sqrt{s}=2$  TeV. In (a), the solid histogram shows the signal  $t\bar{t} \rightarrow Wbc\gamma$  and the short dashed histogram shows the background  $p\bar{p} \rightarrow Wjj\gamma$  after applying basic cuts and cuts on the top-quark-top-antiquark invariant mass and the transverse momenta scalar sums  $p_T(bc)$  and  $p_T(bc\gamma)$ , while in (b) the same curves are used to show the signal and background after making the further cut on  $M(c\gamma)$ . The long dashed histogram in (b) shows the  $M(bW)$  distribution of the background before  $M(c\gamma)$  cut is made [the effect of the  $M(c\gamma)$  cut on the signal is minimal]. The signal histograms assume the maximal allowed value of  $\kappa_\gamma$  with  $\kappa_g=0$ .

the azimuthal angle-pseudorapidity plane ( $\Delta R$ ) for the charged lepton and photon from the jets. We choose the ‘‘basic’’ acceptance cuts

$$p_T^\ell > 15 \text{ GeV}, \quad p_T^j > 20 \text{ GeV}, \quad p_T^\gamma > 30 \text{ GeV},$$

$$E_T^{\text{miss}} > 20 \text{ GeV},$$

$$|\eta^\ell|, |\eta^\gamma|, |\eta^j| < 2.5, \quad \Delta R_{\ell j}, \Delta R_{jj}, \Delta R_{j\gamma} > 0.4. \quad (20)$$

The high-transverse-momentum thresholds for the jets and the photon are motivated by the hard  $p_T$  spectrum from the heavy top-quark decay. With these basic cuts, the signal rate in Fig. 3(a) is reduced by about 40% (with a maximal value of about 2.7 fb), while the EW irreducible background of Eq. (16) is about 30 fb, and the QCD process for  $\ell^\pm \nu jjj$  production in Eq. (17) is about 3000 fb. It has been shown that the fake rate for a jet to a photon ( $j \rightarrow \gamma$ ) at the Tevatron experiments [29] can be controlled down to a level of  $10^{-4}$  for  $p_T^\gamma > 25$  GeV, making it insignificant. Therefore, the EW background dominates and we will consequently concentrate on that.

Figure 4(a) shows the reconstructed distributions for the top-quark-top-antiquark invariant mass. Obviously,  $M(t\bar{t})$  for the signal has a kinematical lower limit ( $2m_t$  if no energy smearing is applied), while the lower limit is significantly smaller for the background, near the  $Wjj\gamma$  threshold. If we only accept events with

$$M(t\bar{t}) > 2m_t = 350 \text{ GeV}, \quad (21)$$

we expect to improve the signal-to-background ratio ( $S/B$ ). Also, because of the nature of top-quark two-body decay, the final state jets and the photon have transverse momenta typically the order of  $\frac{1}{2}m_t \simeq 80$  GeV, while all the jets and photon in the background events tend to be soft. To further discrimi-

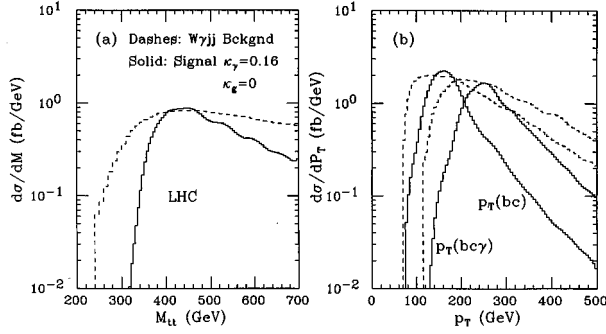


FIG. 6. (a) Top-quark–top-antiquark invariant mass distributions for the signal  $t\bar{t} \rightarrow Wbc\gamma$  (solid histogram) and background  $p\bar{p} \rightarrow Wjj\gamma$  (dashed histogram) at the LHC with  $\sqrt{s} = 14$  TeV, assuming the basic acceptance cuts defined in Eq. (25) in the text. (b) Distributions for the transverse momenta scalar sums  $p_T(bc)$  and  $p_T(bc\gamma)$  for the signal (solid histograms) and background (dashed histograms). The signal histograms assume the maximal allowed value of  $\kappa_\gamma$  with  $\kappa_g = 0$ .

nate the signal from the background, we define two scalar sums of the transverse momenta:

$$p_T(cb) \equiv |\vec{p}_T^c| + |\vec{p}_T^b|, \quad p_T(cb\gamma) \equiv p_T(cb) + |\vec{p}_T^\gamma|.$$

Figure 4(b) shows the distributions for these variables. We see indeed that the signal spectra are much harder at the low end. On the other hand, they are limited by the physical scale  $2m_t$  for the signal at the high end, while they extend further for the background. With these in mind, our choices of the cuts are

$$100 < p_T(cb) < 300 \text{ GeV}, \quad 150 < p_T(cb\gamma) < 450 \text{ GeV}. \quad (22)$$

With the additional cuts of Eqs. (21) and (22), the EW background is reduced to about 10 fb, while the signal may be as large as 2.4 fb.

In Fig. 5 we show the reconstructed top-quark mass distributions  $M(c\gamma)$  and  $M(bW)$ , after making the additional cuts in Eqs. (21) and (22). We see from Fig. 5(a) that, despite the improvement in  $S/B$ , the continuum background is still above the  $M(c\gamma)$  signal peak at  $m_t$ . Further improvement can be made if we only study the events with

$$|M(c\gamma) - m_t| < 20 \text{ GeV}. \quad (23)$$

TABLE I. Cross sections in units of fb for the  $t\bar{t} \rightarrow \ell^\pm vbc\gamma$  signal ( $\kappa_g = 0, \kappa_\gamma = 0.16$ ), and EW and QCD backgrounds at the Tevatron and the LHC. Comparison is made for the results with only the cuts of Eqs. (20) or (25) and (21), (22) and those plus  $b$  tagging. A 50% tagging efficiency and 1% impurity are assumed [31].

(a) Tevatron	Signal $t\bar{t} \rightarrow \ell^\pm vbc\gamma$	$W\gamma jj \rightarrow \ell^\pm v\gamma jj$	$Wjjj \rightarrow \ell^\pm v\gamma jj$
Cuts only	2.4	10	0.66
Plus $b$ tag	1.2	0.3	0.01
(b) LHC	Signal $t\bar{t} \rightarrow \ell^\pm vbc\gamma$	$W\gamma jj \rightarrow \ell^\pm v\gamma jj$	$Wjjj \rightarrow \ell^\pm v\gamma jj$
Cuts only	200	300	45
Plus $b$ tag	100	7	1

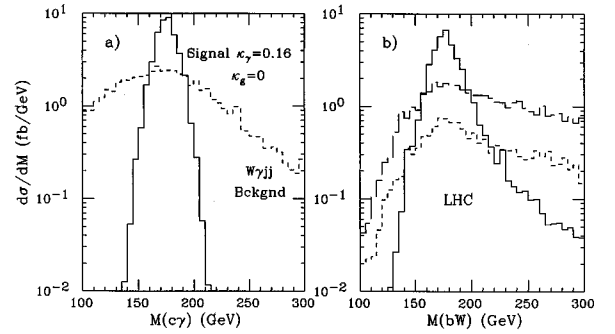


FIG. 7. Reconstructed top-quark mass distributions for (a)  $M(c\gamma)$  and (b)  $M(bW)$  at the LHC with  $\sqrt{s} = 14$  TeV. In (a), the solid histogram shows the signal  $t\bar{t} \rightarrow Wbc\gamma$  and the short dashed histogram shows the background  $p\bar{p} \rightarrow Wjj\gamma$  after applying basic cuts and cuts on the top-quark–top-antiquark invariant mass and the transverse momenta scalar sums  $p_T(bc)$  and  $p_T(bc\gamma)$ , while in (b) the same curves are used to show the signal and background after making the further cut on  $M(c\gamma)$ . The long dashed histogram in (b) shows the  $M(bW)$  distribution of the background before the  $M(c\gamma)$  cut is made [the effect of the  $M(c\gamma)$  cut on the signal is minimal]. The signal histograms assume the maximal allowed value of  $\kappa_\gamma$  with  $\kappa_g = 0$ .

The short-dashed histogram in Fig. 5(b) shows how the background in the  $M(bW)$  distribution is reduced by the cut Eq. (23). We find that the signal peak is nearly unaffected by this cut and is now above the background, so that statistically significant effects may be observed near  $m_t$  in the  $M(bW)$  spectrum. If we examine the events in the mass range

$$|M(bW) - m_t| < 30 \text{ GeV}, \quad (24)$$

the signal observability should be nearly optimized. After the cut in Eq. (24) we are left with a maximal signal of 2.0 fb and an EW background 1.8 fb.

## B. LHC

At the LHC energy, because of the more complicated hadronic backgrounds, we need to increase the transverse momentum thresholds, especially for jets, direct photons, and missing  $E_T$ . We adopt the “basic” acceptance cuts as

$$p_T^{\ell} > 20 \text{ GeV}, \quad p_T^j > 35 \text{ GeV}, \quad p_T^\gamma > 40 \text{ GeV},$$

$$E_T^{\text{miss}} > 30 \text{ GeV},$$

$$|\eta^i|, |\eta^j|, |\eta^k| < 3, \quad \Delta R_{\ell j}, \Delta R_{jj}, \Delta R_{\gamma j} > 0.4. \quad (25)$$

The signal rates given in Fig. 3(b) are reduced by about 60% with the cuts of Eq. (25) (with a maximal value of about 0.22 pb), while the EW background is about 0.5 pb, and the ‘‘faked’’ QCD background is about 70 pb. Assuming that we can effectively reject the QCD background by photon identification to a level of  $10^{-3}$  for  $j \rightarrow \gamma$  [30], then the dominant background is again the electroweak process. We see that after the basic cuts of Eq. (25) the  $S/B$  ratio is much closer to unity than in the Tevatron case.

Similar to the Tevatron study, we have constructed distributions for the top-quark–top-antiquark invariant mass and scalar sums of transverse momenta (see Fig. 6). We see that further background suppression can be achieved, without much loss of signal, by the cuts of Eqs. (21) and (22). The signal-integrated cross section after these cuts may be as large as 200 fb, while the EW background rate is about 300 fb.

As at the Tevatron, reconstructed top-quark mass distributions are also crucial to nonambiguously identify the signal. Figure 7 shows the top-quark mass distributions reconstructed from the  $c\gamma$  and  $bW$  final states after making the cuts in Eqs. (21) and (22). Once the final cuts in Eqs. (23) and (24) are made, the signal-integrated cross section has a maximal value of 175 fb and the EW background is 33 fb. We see that the  $S/B$  ratio is significantly better than at the Tevatron, primarily due to the huge enhancement for the  $t\bar{t}$  production at higher c.m. energies.

### C. $b$ -tagging effects

The CDF Collaboration was able to achieve about 50%  $b$ -tagging efficiency [31] and one hopes to reach about the same efficiency for the LHC experiments [30]. The impurity from the light quarks and gluons is assumed to be 1%. We therefore can naively expect to further suppress the backgrounds by a factor of  $1\% \times n_j$  (where  $n_j$  is the number of jets) at a cost of signal reduction of 50%.

One has to be cautious in making this statement since there is direct production of  $b\bar{b}$  among the other light quark-gluon jets in the background events. We have explicitly calculated the  $W\gamma b\bar{b}$  production rate and found the cross section to be about 0.12 fb at the Tevatron and 1.1 fb at the LHC with the basic cuts plus Eqs. (21) and (22). This implies that the misidentified  $b$  from light quarks and gluons is indeed the major background source. Consequently, we will not carry out the calculation for the  $b\bar{b}$  fraction in  $Wjj$  events, since this channel is always smaller to begin with.

Table I lists the signal rate (for  $\kappa_g=0, \kappa_\gamma=0.16$ ), EW, and QCD backgrounds at the Tevatron and the LHC. Comparison is made for the results with only cuts of Eq. (20) for Tevatron or Eq. (25) for LHC and Eqs. (21) and (22), and those plus  $b$  tagging. We indeed obtain significant improvement for the signal/background ratios, although the signal rate at the Tevatron is very limited.

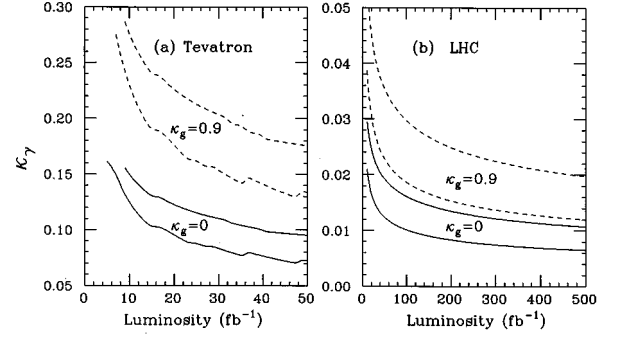


FIG. 8. 95% C.L. sensitivity to  $\kappa_\gamma$  vs integrated luminosity for (a) the Tevatron with  $\sqrt{s}=2$  TeV and (b) the LHC with  $\sqrt{s}=14$  TeV. We consider the limits for  $\kappa_g=0$  (solid lines) and  $|\kappa_g|=0.9$  (dashed lines). The upper curves in each case correspond to the limit obtained when comparing the signal and background after making all the cuts, while the lower curves correspond to the limits obtained when using  $b$  tagging with the cuts in Eqs. (20) or (25) and (21), (22). The curves cut off at the maximal allowed value of  $\kappa_\gamma$  in each case.

## IV. DISCUSSIONS AND SUMMARY

To estimate the sensitivity to the anomalous couplings for a given accumulated luminosity, we first establish the approximate cross section formula for the  $t \rightarrow c\gamma$  case in terms of the anomalous couplings:

$$\sigma = \frac{\kappa_\gamma^2}{(1 + 1.04\kappa_g^2)^2} \sigma(\kappa_\gamma=1, \kappa_g=0), \quad (26)$$

where  $\sigma(\kappa_\gamma=1, \kappa_g=0)$  is calculated for the appropriate set of cuts, and the couplings are subject to the constraints in Fig. 1. The cross section  $\sigma(\kappa_\gamma=1, \kappa_g=0)$  is 80 fb and 6.8 pb at the Tevatron and LHC, respectively, after the full set of cuts is made. We start with Poisson statistics since the signal rate is often small, especially at the Tevatron energy. Figure 8 presents the anomalous coupling  $\kappa_\gamma$  versus the luminosity needed to probe  $\kappa_\gamma$  at 95% confidence level<sup>1</sup> (C.L.). The solid curves presented in each panel are for  $\kappa_g=0$  and the dashed for  $|\kappa_g|=0.9$ . The upper curves for each case are those with kinematical cuts only, while the lower ones are those including  $b$ -tagging improvement. We see that at the Tevatron energy, minimal luminosity of about  $5 \text{ fb}^{-1}$  is needed in order to probe  $\kappa_\gamma$  near the current low-energy constraints at 95% C.L. At the LHC with  $100 \text{ fb}^{-1}$ , one expects to improve the sensitivity to  $\kappa_\gamma$  by more than one order of magnitude. For instance, for  $\kappa_g=0$  and with  $b$  tagging, the sensitivity at the Tevatron reaches, for  $5 \text{ fb}^{-1}$ ,

$$|\kappa_\gamma| \sim 0.16 \quad \text{and} \quad B(t \rightarrow c\gamma) \sim 1.3 \times 10^{-3},$$

for  $10 \text{ fb}^{-1}$ ,

$$|\kappa_\gamma| \sim 0.12 \quad \text{and} \quad B(t \rightarrow c\gamma) \sim 7 \times 10^{-4},$$

<sup>1</sup>In our approach, a 95% C.L. in Poisson statistics roughly corresponds to  $S/\sqrt{S+B}=3$  in Gaussian statistics when the number of events is large.

and, for  $30 \text{ fb}^{-1}$ ,

$$|\kappa_\gamma| \sim 0.08 \quad \text{and} \quad B(t \rightarrow c\gamma) \sim 3 \times 10^{-4}, \quad (27)$$

and at the LHC, for  $10 \text{ fb}^{-1}$ ,

$$|\kappa_\gamma| \sim 0.02 \quad \text{and} \quad B(t \rightarrow c\gamma) \sim 2 \times 10^{-5}$$

and, for  $100 \text{ fb}^{-1}$ ,

$$|\kappa_\gamma| \sim 0.01 \quad \text{and} \quad B(t \rightarrow c\gamma) \sim 5 \times 10^{-6}, \quad (28)$$

Alternatively, setting  $\kappa_\gamma = 1$  and letting  $\Lambda$  vary [see Eq. (2)], we can view this as a probe of the scale of new physics up to  $\Lambda/\kappa_\gamma \sim 10 \text{ TeV}$  at the Tevatron and about  $100 \text{ TeV}$  at the LHC.

If  $\kappa_g \neq 0$ , there of course is also the possibility of  $t \rightarrow c\gamma$  decay. It was found in Ref. [15] that with the existing Tevatron data of  $200 \text{ pb}^{-1}$ , one should be able to probe the  $\bar{t}c\gamma$  coupling [or  $B(t \rightarrow c\gamma)$ ] to a value of about 0.5 (20%). A data sample of  $1 \text{ fb}^{-1}$  at  $\sqrt{s} = 2 \text{ TeV}$  may probe this cou-

pling ( $B$ ) to a level of 0.15 (2%). There is also the possibility of single top-quark production in association with a charm quark [32]. A more detailed phenomenological exploration of this type at hadron colliders is currently under study [33].

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- [1] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **74**, 2626 (1995); D0 Collaboration, S. Abachi *et al.*, *ibid.* **74**, 2632 (1995).
- [2] For a recent review, see, e.g., H. Neuberger, in *Proceedings of the XXVI International Conference on High Energy Physics*, Dallas, Texas, 1992, edited by J. Sanford, AIP Conf. Proc. No. 272 (AIP, New York, 1992), Vol. II, p. 1360.
- [3] G. 't Hooft, in *Recent Developments in Gauge Theories*, Proceedings of the Cargese Summer Institute, Cargese, France, 1979, edited by G. 't Hooft *et al.*, Vol. 59 of NATO Advanced Study Institute Series B, Physics (Plenum, New York, 1980).
- [4] R.D. Peccei and X. Zhang, Nucl. Phys. **B337**, 269 (1990).
- [5] B. Grzadkowski, J.F. Gunion, and P. Krawczyk, Phys. Lett. B **268**, 106 (1991); G. Eilam, J.L. Hewett, and A. Soni, Phys. Rev. D **44**, 1473 (1991); M. Luke and M.J. Savage, Phys. Lett. B **307**, 387 (1993); G. Couture, C. Hamzaoui, and H. König, Phys. Rev. D **52**, 1713 (1995).
- [6] T.P. Cheng and M. Sher, Phys. Rev. D **35**, 3484 (1987); W.S. Hou, Phys. Lett. B **296**, 179 (1992); L.J. Hall and S. Weinberg, Phys. Rev. D **48**, R979 (1993); D. Atwood, L. Reina, and A. Soni, *ibid.* **53**, 1199 (1996).
- [7] C.T. Hill, Phys. Lett. B **266**, 419 (1991); **345**, 483 (1995); B. Holdom, *ibid.* **339**, 114 (1994); **351**, 279 (1995).
- [8] H. Georgi, L. Kaplan, D. Morin, and A. Schenk, Phys. Rev. D **51**, 3888 (1995). For a review of composite models, see, e.g., R.D. Peccei, in *Proceedings of The 1987 Lake Louise Winter Institute: Selected Topics in the Electroweak Interactions*, edited by J.M. Cameron *et al.* (World Scientific, Singapore, 1987).
- [9] X. Zhang, Phys. Rev. D **51**, 5039 (1995); J. Berger, A. Blotz, and K. Goetze, *ibid.* **54**, 3598 (1996).
- [10] R.S. Chivukula, E.H. Simmons, and J. Terning, Phys. Lett. B **331**, 383 (1994); C. T. Hill and X. Zhang, Phys. Rev. D **51**, 3563 (1995).
- [11] J.L. Hewett, in *Spin Structure in High Energy Processes*, Proceedings of the 21st SLAC Summer Institute, Stanford, California, 1993, edited by L. De Porcel and C. Dunwoodie (SLAC Report No. 444, Stanford, 1994).
- [12] See, e.g., D.O. Carlson, E. Malkawi, and C.-P. Yuan, Phys. Lett. B **337**, 145 (1994), and references therein.
- [13] See, e.g., D. Atwood, A. Kagan, and T. Rizzo, Phys. Rev. D **52**, 6264 (1995), and references therein.
- [14] T. Han, R.D. Peccei, and X. Zhang, Nucl. Phys. **B454**, 527 (1995).
- [15] T. Han, K. Whisnant, B.-L. Young, and X. Zhang, Phys. Lett. B **385**, 311 (1996).
- [16] CLEO Collaboration, M. Alam *et al.*, Phys. Rev. Lett. **74**, 2885 (1995).
- [17] J.L. Hewett and T. Rizzo, Phys. Rev. D **49**, 319 (1994); K. Fujikawa and A. Yamada, *ibid.* **49**, 5890 (1994).
- [18] B. Grinstein, R. Springer, and M. Wise, Nucl. Phys. **B339**, 269 (1990).
- [19] M. Ciuchini, E. Franco, G. Martinelli, L. Reina, and L. Silvestrini, Phys. Lett. B **316**, 127 (1993); M. Ciuchini, E. Franco, L. Reina, and L. Silvestrini, Nucl. Phys. **B421**, 41 (1994).
- [20] A.J. Buras, M. Misiak, M. Münz, and S. Pokorski, Nucl. Phys. **B424**, 374 (1994).
- [21] R.D. Peccei and X. Zhang, Nucl. Phys. **B349**, 305 (1991).
- [22] CDF Collaboration, J. Incandela, Nuovo Cimento A **109**, 741; (1996). In our calculation we use the branching ratio  $B(t \rightarrow bW) = 0.87_{\pm 0.32}^{+0.13}$ , where the two sets of errors are combined in quadrature, and interpret a  $1\sigma$  lower limit to be  $B(t \rightarrow bW) \geq 0.55$ .
- [23] R. Martinez, M.A. Perez, and J.J. Toscano, Phys. Lett. B **340**, 91 (1994).
- [24] S. Holmes, G. Dugan, and S. Peggs, in *Research Directions for the Decade*, Proceedings of the 1990 Summer Study on High Energy Physics, Snowmass, Colorado, 1990, edited by E.L. Berger (World Scientific, Singapore, 1994), p. 674.
- [25] R.K. Ellis, Phys. Lett. B **259**, 492 (1991); P. Nason, S. Dawson, and R.K. Ellis, Nucl. Phys. **B303**, 607 (1988); W. Beenakker *et al.*, *ibid.* **B351**, 507 (1991).
- [26] A.D. Martin, R.G. Roberts, and W.J. Stirling, Phys. Rev. D **50**, 6734 (1994).

- [27] V. Barger, J. Ohnemus, and R. Phillips, *Int. J. Mod. Phys. A* **4**, 617 (1989).
- [28] J. Stroughair and C. Bilchak, *Z. Phys. C* **26**, 415 (1984); J. Gunion, Z. Kunszt, and M. Soldate, *Phys. Lett.* **163B**, 389 (1985); J. Gunion and M. Soldate, *Phys. Rev. D* **34**, 826 (1986); W. J. Stirling *et al.*, *Phys. Lett.* **163B**, 261 (1985); J. Cortes, K. Hagiwara, and F. Herzog, *Nucl. Phys.* **B278**, 26 (1986).
- [29] See, e.g., H. Aihara, in *Proceedings of International Symposium on Vector Boson Self-Interactions*, edited by U. Baur *et al.*, Los Angeles, CA, 1995 (unpublished), p. 72.
- [30] CMS Collaboration, technical proposal, Report No. cern/lhcc94-38 (unpublished); ATLAS Collaboration, technical proposal, Report No. cern/lhcc94-43 (unpublished).
- [31] CDF Collaboration, F. Abe *et al.*, *Phys. Rev. D* **52**, 2605 (1995).
- [32] E. Malkawi and T. Tait, *Phys. Rev. D* **54**, 5758 (1996).
- [33] T. Han, M. Hosch, K. Whisnant, B.-L. Young, and X. Zhang (in preparation).