Using the radiative decay $b \to s\gamma$ to bound the chromomagnetic dipole moment of the top quark

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Using the CLEO data for $b \to s\gamma$, we constrain the chromomagnetic dipole moment of the top quark within the context of a decoupling effective Lagrangian approach. Our results are in agreement with the results obtained for the e^+e^- and hadron colliders.
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The standard model (SM) describes successfully all experimental data related with the strong and electroweak interactions. In particular, the electroweak radiative corrections at the one-loop level [1] agree consistently with the top quark mass measured by the Collider Detector at Fermilab (CDF) and D0 Collaborations [2]. However, the hierarchy mass problem suggests that new physics effects may lay beyond the SM.

Since the top quark mass is so heavy, it is expected that its physics may be different from the lighter fermions and that the top quark might couple quite strongly to the electroweak symmetry breaking sector. This suggests that the Higgs sector of the SM is just an effective theory and that the physics beyond the SM may be manifested through an effective Lagrangian involving the top quark [3].

The framework of effective theories, as a mean to parametrize physics beyond the SM in a model independent way, has been used recently. Two cases have been considered in the literature: the decoupling case, which includes the Higgs boson [4], and the nondecoupling case, where there is no Higgs boson. We shall consider only the first case, in which the SM is a low-energy limit of a renormalizable theory. In this approach, the effective theory parametrizes the effects at low energy of the full renormalizable theory by means of high-order-dimensional nonrenormalizable operators written in terms of the SM fields.

In the present work we are interested in studying possible deviations from the SM on the decay $b \to s\gamma$ within the context of the effective Lagrangian approach. Several authors have the CLEO results on radiative B decays to set bounds on the anomalous coupling of the t quark [5,6]. While in the first case [5] they used a parametrization which is only $SU(3)_C$ or $U(1)_Q$ gauge invariant to get bounds on the anomalous magnetic dipole moments, in the second case, Ref. [6], they used one which is SM gauge invariant. In the present Brief Report, we will use dimension-six operators which are full, strong, and electroweak gauge invariant and contribute to $b \to s\gamma$ in order to bound the chromomagnetic dipole moment of the top quark. Since this approach includes an effective Lagrangian respecting the full SM symmetry, we should expect some differences in the calculation of the $b \to s\gamma$ rate obtained from the mere use of $SU(3)_C$ gauge-invariant effective operators.

If an anomalous top quark coupling exists, it will modify the SM expectations for the top quark production and decay processes at hadron and e^+e^- colliders [7]. In Ref. [8] it was found that $-0.027 < \delta\kappa_g^t < 0.026$ for the process $e^+e^- \to t\bar{t}g$ at a 500 GeV Next Linear Collider (NLC) with an integrated luminosity of 100 fb^{-1} and a gluon spectrum above $E_g^{\rm min} = 25$ GeV. On the other hand, using the $t\bar{t}$ invariant mass and the p_t distribution of the top quark at the CERN Large Hadron Collider (LHC), the bound $|\delta\kappa_g^t| < 0.05$ was obtained with an 100 fb^{-1} integrated luminosity [9]. Similarly, the CDF data on the branching decay to b was used to get the limit $B(t \to cg) < 0.45$. This bound in turn gives the limit $|\kappa_g^{ct}| < 0.9$ for the neutral current flavor-changing transition moment [5]. It is important thus to consider different approaches to study the top quark anomalous couplings that may allow us to understand the physics beyond the SM. The prevailing differences of the SM results with respect to the experimental data for the partial width ratios $\Gamma(Z \to b\bar{b}(c\bar{c}))/\Gamma(Z \to \text{hadrons})$ suggest also to consider physics beyond the SM.

The effective Lagrangian involving the anomalous top quark couplings can be written as

$$\mathcal{L} = \mathcal{L}^{\rm SM} + \Delta\mathcal{L}^{\rm eff}, \tag{1}$$

where $\mathcal{L}^{\rm SM}$ is the SM Lagrangian and $\Delta\mathcal{L}^{\rm eff}$ includes the anomalous quark couplings. We consider the following dimension-six, CP-conserving operators, which are $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge invariant:

$$\mathcal{O}_{uG}^{ab} = \overline{Q_L^a} \sigma_{\mu\nu} G^{\mu\nu i} \frac{\lambda^i}{2} \tilde{\phi} u_R^b, \tag{2}$$

where $G^{\mu\nu i}$ is the gluon field strength tensor and a,b are the family indices. The above operator gives rise to the anomalous $t\bar{t}g$ vertex and its respective unknown coefficient ϵ_{ab}^{uG} is related to the anomalous chromomagnetic moment of the top quark by

$$\delta\kappa_g^t = \sqrt{2} \frac{g}{g_s} \frac{m_t}{M_W} \epsilon_{uG}^{33}. \tag{3}$$

The effective Hamiltonian used to compute the $b \to s$ transition is given by [10]

$$H_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{8} c_i(\mu) \mathcal{O}_i(\mu), \tag{4}$$

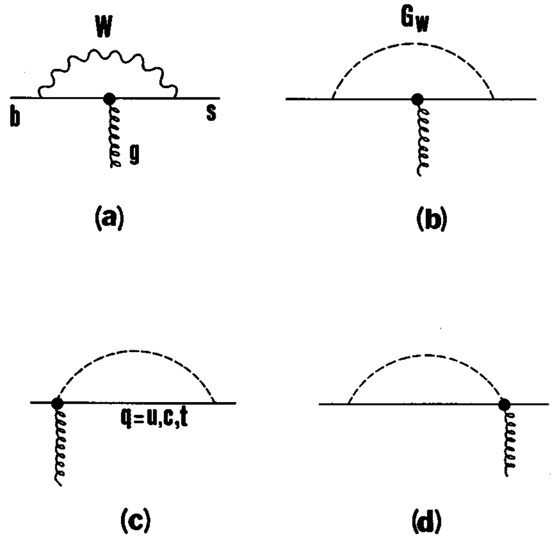

FIG. 1. Feynman diagrams contributing to the $b \to s\gamma$ transition. The heavy dots denote an effective vertex.

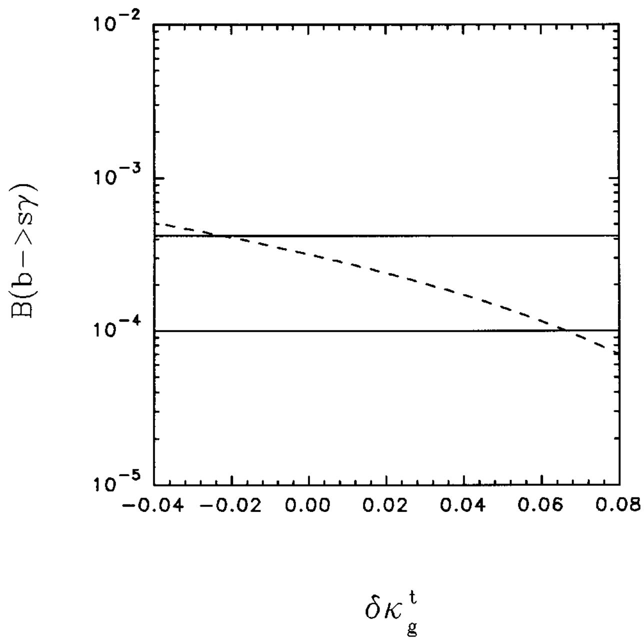

FIG. 2. The branching ratio $B(b \to s\gamma)$ as a function of $\delta\kappa_g^t$ for $m_t = 180$ GeV (dashed). The bounds of the CLEO Collaborations are explicitly indicated.

where μ is the energy scale at which $H_{\rm eff}$ is applied. For $i = 1-6$, $\mathcal{O}_i(\mu)$ correspond to four-quark operators, $\mathcal{O}_7(\mu)$ is the electromagnetic dipole moment, and $\mathcal{O}_8(\mu)$ is the chromomagnetic dipole operator. At low energy, $\mu \approx m_b$, the only operator that contributes to $b \to s$ transition is $\mathcal{O}_7(\mu)$ which results from a mixing among the $\mathcal{O}_2(M_W)$, $\mathcal{O}_7(M_W)$, and $\mathcal{O}_8(M_W)$ operators.

The six-dimensional operator (2) contributes to $\mathcal{O}_8$ by the diagrams shown in Fig. 1. The contribution of the diagrams 1(a), 1(b), and 1(c) are finite, while the diagram 1(d) has a logarithmic divergence. We replace the pole $1/\epsilon$ by $\ln(\Lambda^2)$, where Λ can be interpreted as the scale associated with the new physics. In the approaches used in Ref. [5], the contribution to $\delta\kappa_g^t$ comes from diagrams 1(a) and 1(b). On the other hand, the operator (2) gives additional contributions given by diagrams 1(c) and 1(d).

The total contribution of the effective operator (2) to the $\mathcal{O}_8(M_W)$ operator can be written as

$$c_8(M_W) = c_8(M_W)^{\rm SM} + \delta\kappa_g^t \Delta c_8(M_W), \qquad (5)$$

where

$$\Delta c_8(M_W) = \frac{1}{4V_{ts}} \ln\left(\frac{\Lambda^2}{M_W^2}\right) + \frac{1}{V_{ts}} \frac{x - x^2 + x(2-x)\ln(x)}{8(1-x)^2} + \frac{3x - 4x^2 + x^3 + 2x\,\ln(x)}{8(1-x)^3} \qquad (6)$$

and $x = m_t^2/M_W^2$.

In Fig. 2 we display the $b \to s\gamma$ branching fraction as a function of $\delta\kappa_g^t$ with $m_t = 180$ GeV (dashed line). The solid line is the result of the CLEO Collaboration on the inclusive quark level process, $1 \times 10^{-4} < B(b \to s\gamma) < 4.2 \times 10^{-4}$ [11]. We find that our bound $|\delta\kappa_g^t| < 0.066$ is consistent with analysis done in Refs. [8,9] for the process $e^+e^- \to t\bar{t}g$ and the pair production of the top quark at the LHC.

Using the effective Lagrangian approach, with a fully SM gauge-invariant operator, we have obtained the bound $|\delta\kappa_g^t| < 0.066$, which is consistent with the results obtained for the e^+e^- and hadron colliders.

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