Limits on Anomalous Couplings of Quarks From Prompt Photon Data *

Kingman Cheung
Center for Particle Physics, University of Texas, Austin, Texas 78712
Dennis Silverman
Department of Physics & Astronomy, University of California, Irvine, CA 92697-4575

ABSTRACT

Prompt photon production has been known to be a sensitive probe to the gluon luminosity inside a hadron because it is mainly produced by quark-gluon scattering. For the same reason prompt photon production should also be sensitive to the anomalous couplings of gluons to quarks. We will examine the effects of two specific anomalous couplings – chromoelectric and chromomagnetic dipole moments of quarks – on the prompt photon production. Using the data collected by CDF and D0 at the Tevatron we put a bound on the these anomalous couplings.

I. INTRODUCTION

The Standard Model (SM) has been very successful for more than thirty years. Only recently have some deviations from the SM surfaced in the R_b and R_c measurements at LEP [1] and in the high E_T inclusive jet production recorded by CDF [2]. Since we have no true knowledge of the structure or even the symmetry of the correct high energy theory, we use the effective Lagrangian approach to study low energy phenomena. Deviations from the SM can be studied systematically by means of an effective Lagrangian, which is made up of the SM fields and obeys the symmetry of the low energy theory. The leading terms are simply given by the SM and consist of dimension-4 operators while the higher order terms consist of higher-dimension operators and are suppressed by powers of the scale Λ of the new physics. In other words, if the scale Λ is much larger than the present scale the theory is essentially the same as the SM.

Among all the dimension-5 operators, the most interesting ones involving quarks and gluons are the chromomagnetic (CMDM) and chromoelectric (CEDM) dipole moment couplings of quarks. They are given by $\sigma^{\mu\nu}G^a_{\mu\nu}$ and $i\sigma^{\mu\nu}\gamma^5 G^a_{\mu\nu}$, respectively. Although these couplings are zero at tree level within the SM, they can be induced in loop levels. In many extensions of the SM, they are easily nonzero in one-loop level or even in tree-level, e.g., the multi-Higgs doublet model [3]. These dipole moment couplings are important not only because they are only suppressed by one power of Λ but also because a nonzero value for the CEDM moment is a clean signal for CP violation. The effects of these anomalous couplings have been studied quite extensively, e.g., in $t\bar{t}$ production [4, 5, 6], in $b\bar{b}$ production [5], and in inclusive jet production [7].

The purpose of this paper is to study the effects of the anomalous CMDM and CEDM dipole moments of quarks on prompt photon production. Prompt photon production has been known to be a useful probe to the gluon luminosity inside a hadron because they are mainly produced by quark-gluon scattering. The fact that the production depends on the quark-gluon vertex also makes the process sensitive to the anomalous couplings of quarks to gluons. Not only is the total cross section affected but also the differential distributions, e.g., transverse momentum distribution. Both CDF[8] and D0[9] have measurements on prompt photon production. We can therefore use the data to constrain these CMDM and CEDM couplings. Thus, the bounds obtained will be the main result of the paper. The organization is as follows. In the next section, we shall write down the effective Lagrangian and all the formulas for the calculation. In Sec. III we study the effects on the transverse momentum distribution, and obtain the results.

II. EFFECTIVE LAGRANGIAN

The effective Lagrangian for the interactions between a quark and a gluon that include the CEDM and CMDM form factors is

$$\mathcal{L}_{\rm eff} = g_s \bar{q} T^a \left[-\gamma^\mu G^a_\mu + \frac{\kappa}{4m_q}\sigma^{\mu\nu}G^a_{\mu\nu} - \frac{i\tilde{\kappa}}{4m_q}\sigma^{\mu\nu}\gamma^5 G^a_{\mu\nu} \right] q \; . \tag{1}$$

where $\kappa/2m_q$ ($\tilde{\kappa}/2m_q$) is the CMDM (CEDM) of the quark q. The Feynman rules for the interactions of quarks and gluons can be written down:

$$\mathcal{L}_{q_i q_j g} = -g_s \bar{q}_j T^a_{ji} \left[\gamma^\mu + \frac{i}{2m_q}\sigma^{\mu\nu}p_\nu(\kappa - i\tilde{\kappa}\gamma^5) \right] q_i \; G^a_\mu \; , \tag{2}$$

where $q_i(q_j)$ is the incoming (outgoing) quark and p_ν is the 4-momentum of the outgoing gluon. The Lagrangian in Eq. (1) also induces a $qqgg$ interaction given by

$$\mathcal{L}_{q_i q_j gg} = \frac{i g_s^2}{4m_q}\bar{q}_j (T^b T^c - T^c T^b)_{ji}\sigma^{\mu\nu}(\kappa - i\tilde{\kappa}\gamma^5) q_i G^b_\mu G^c_\nu \; , \tag{3}$$

which is absent in the SM. In the following, we write

$$\kappa' = \frac{\kappa}{2m_q} \; , \tilde{\kappa}' = \frac{\tilde{\kappa}}{2m_q} \tag{4}$$

which are given in units of (GeV)$^{-1}$.

A. Prompt Photon Production

The contributing processes are:

$$q(\bar{q})g \to \gamma q(\bar{q}) \; , \quad q\bar{q} \to \gamma g \; .$$

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The contributing Feynman diagrams are shown in Fig. 1. The spin- and color-averaged amplitude for $q(p_1)g(p_2) \to \gamma(k_1)q(k_2)$ is given by

$$\overline{\sum}|\mathcal{M}|^2 = \frac{16\pi^2\alpha_s\alpha_{\rm em}Q_q^2}{3}\left[-\frac{s^2+t^2}{st} - 2u(\kappa'^2+\tilde{\kappa}'^2)\right] \quad (5)$$

where

$$s = (p_1+p_2)^2\,,\;\; t = (p_1-k_1)^2\,,\;\; u = (p_1-k_2)^2\,, \quad (6)$$

and Q_q is the electric charge of the quark q in units of proton charge. Similarly, the spin- and color-averaged amplitude for $q(p_1)\bar{q}(p_2) \to \gamma(k_1)g(k_2)$ is given by

$$\overline{\sum}|\mathcal{M}|^2 = \frac{128\pi^2\alpha_s\alpha_{\rm em}Q_q^2}{9}\left[\frac{t^2+u^2}{ut} + 2s(\kappa'^2+\tilde{\kappa}'^2)\right]\,. \quad (7)$$

The subprocess cross section is then given by

$$d\hat{\sigma} = \frac{1}{(2\pi)^2 2s}\overline{\sum}|\mathcal{M}|^2\,\delta^4(p_1+p_2-k_1-k_2)\frac{d^3k_1}{2k_1^0}\frac{d^3k_2}{2k_2^0} \quad (8)$$

which is then folded with the appropriate parton distribution functions. We use the CTEQ2M parton distribution functions[10] and the two-loop formula for the strong coupling constant. Although the NLO calculation to prompt photon production exists, there is no NLO calculation that includes CMDM and CEDM couplings, however. Therefore, throughout the paper we employ only the LO calculation. But in calculating the fractional difference from the pure QCD cross section we shall use a K-factor to multiply the LO QCD cross sections by. The procedures will be illustrated in the next section.

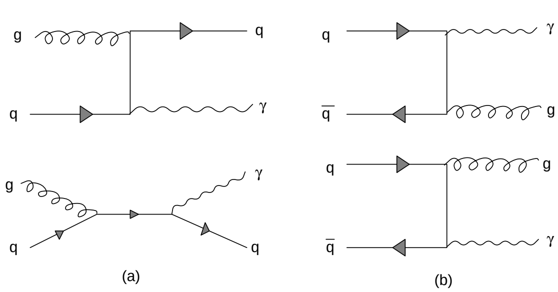

Figure 1: Contributing Feynman diagrams for the processes: (a) $qg \to \gamma q$, and (b) $q\bar{q} \to \gamma g$

III. RESULTS

We first study the effects of nonzero CMDM and CEDM on the transverse momentum spectrum of the photon. In order to compare with experimental data we have to impose a similar set of acceptance cuts as CDF and D0 did. For both CDF and D0 data we use

$$|\eta(\gamma)| < 0.9\,,\;\; \Delta R(\gamma, j) > 0.7\,, \quad (9)$$

where the $\Delta R(\gamma, j)$ cut is used to imitate the complicated experimental isolation procedures. In our LO calculation, the value of this $\Delta R(\gamma, j)$ cut is not crucial to our analysis. We have included the quark flavors: u, d, s, c in our calculation and assume that their anomalous couplings are the same. In Fig. 2, we show the differential cross sections of the prompt photon production versus the transverse momentum spectrum of the photon. The LO QCD curve has to be multiplied by a factor of about 1.3 to best fit the CDF data. Therefore, we shall use a K-factor $K = 1.3$ for the LO QCD cross section. Figure 2 also shows curves with nonzero values of CMDM. We can see that nonzero κ' will increase the total and the differential cross sections, especially, at the large $p_T(\gamma)$ region. Thus, the transverse momentum spectrum becomes harder with nonzero CMDM. The effects due to nonzero CEDM will be the same because the increase in cross sections is proportional to $(\kappa'^2+\tilde{\kappa}'^2)$. This is different from the case of $t\bar{t}$ production [4], in which the increase has a term proportional to the first power of κ.

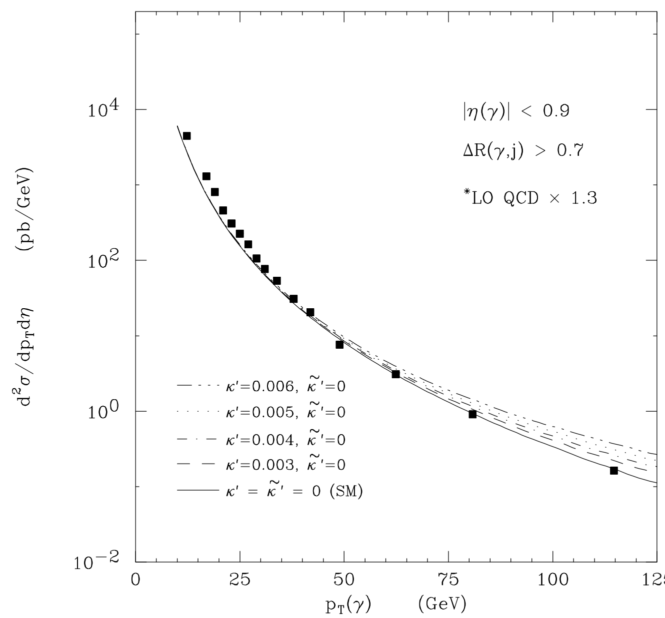

Figure 2: Differential cross sections for prompt photon production versus the transverse momentum of the photon for pure QCD and nonzero values of CMDM of quarks. The data points are from CDF.

Figure 3 shows the fractional differences from pure QCD for nonzero CMDM. The data are from CDF and D0. The anomalous behavior at the low $p_T(\gamma)$ has already been resolved by including initial and final state shower radiation. For our case we are only interested in the large $p_T(\gamma)$ region. Since in Eqs. (5) and (7) the role of κ' and $\tilde{\kappa}'$ are the same, we can put one of them to be zero when we obtain bounds on the other. We show a few curves with different values of κ'. From these curves we can see that the CDF and D0 data would be inconsistent with $\kappa' > 0.0045$, therefore, giving a bound of

$$\kappa' \le 0.0045\;\; {\rm GeV}^{-1} \quad (10)$$

on the CMDM of quarks. Similarly, we put a bound of

$$\tilde{\kappa}' \leq 0.0045 \ \ \mathrm{GeV}^{-1} \tag{11}$$

on the CEDM of quarks. Furthermore, this bound is also valid for the case that the photon-quark coupling is anomalous instead of the gluon-quark coupling. We also found that the normalized angular distribution in $\cos\theta^*$ (θ^* is the angle of the outgoing photon in the CM frame of the incoming partons) is not affected appreciably by the presence of the anomalous dipole moments. It would be interesting to compare with the results obtained in Ref.[7]. The value of κ' obtained in fitting to the CDF[2] transverse energy distribution of the inclusive jet production is[7]

$$\kappa' = (1.0 \pm 0.3) \times 10^{-3} \ \ \mathrm{GeV}^{-1} \tag{12}$$

which is consistent with the bound obtained in this paper.

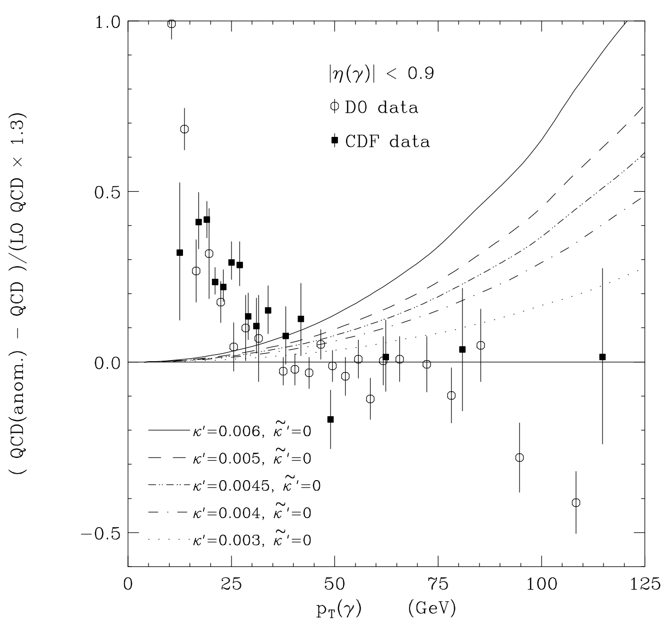

Figure 3: Fractional difference from QCD for various values of κ' and $\tilde{\kappa}'$. Both D0 and CDF data are shown. The errors on D0 data are statistical only.

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IV. REFERENCES

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