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Effects of anomalous couplings of quarks on prompt photon production

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Prompt photon production is sensitive to the anomalous couplings of gluons to quarks, because it is mainly produced by quark-gluon scattering. We will examine the effects of the anomalous chromoelectric and chromomagnetic dipole moment couplings of quarks on prompt photon production. Using the data collected by CDF and D0 at the Fermilab Tevatron we put a bound on these anomalous couplings. We also estimate the sensitivity of various future high energy collider experiments to these anomalous couplings. [S0556-2821(97)03005-1]

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I. INTRODUCTION

The standard model (SM) has been very successful for more than 30 years. Only recently have some deviations from the SM surfaced in the R_b measurement at the CERN e^+e^- collider LEP [1] and in the high E_T inclusive jet production recorded by the Collider Detector at Fermilab (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-four 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-five operators, the most interesting ones involving quarks and gluons are the chromomagnetic dipole moment (CMDM) and chromoelectric dipole moment (CEDM) couplings of quarks. They are given by $\sigma^{\mu\nu}T^aG^a_{\mu\nu}$ and $i\sigma^{\mu\nu}\gamma^5T^aG^a_{\mu\nu}$, respectively. Although these couplings are zero at the tree level within the SM, they can be induced in loop levels. In many extensions of the SM, they are easily nonzero at one loop level or even the 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 [4–6], 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 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 this 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., the 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 of the paper is as follows. In the next section, we shall write down the effective Lagrangian and the formulas for the calculation. In Sec. III we study the effects on the transverse momentum distribution, and obtain the results. In Sec. IV we estimate the limits of these anomalous couplings that can be probed in the future collider experiments. We conclude in Sec. V.

II. EFFECTIVE LAGRANGIAN

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

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

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:

$$\mathcal{L}_{q_iq_jg}=-g_s\bar{q}_jT^a_{ji}\left[\gamma^\mu+\frac{i}{2m_q}\sigma^{\mu\nu}p_\nu(\kappa-i\tilde{\kappa}\gamma^5)\right]q_iG^a_\mu\,, \tag{2}$$

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

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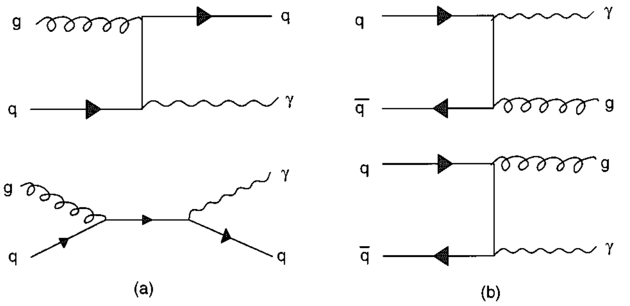

FIG. 1. Contributing Feynman diagrams for the processes: (a) $qg \to \gamma q$ and (b) $q\overline{q} \to \gamma g$.

$$\mathcal{L}_{q_i q_j g g} = \frac{i g_s^2}{4 m_q} \overline{q_j} (T^b T^c - T^c T^b)_{ji} \sigma^{\mu\nu} (\kappa - i \widetilde{\kappa} \gamma^5) q_i G_\mu^b G_\nu^c , \tag{3}$$

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

$$\kappa' = \frac{\kappa}{2 m_q}, \quad \widetilde{\kappa}' = \frac{\widetilde{\kappa}}{2 m_q}, \tag{4}$$

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

The contributing processes for prompt photon production are

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

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

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

where

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

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

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

The subprocess cross section is then given by

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

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 next-to-leading order (NLO) calculation to prompt photon production exists, there is, however, no NLO calculation that includes CMDM and CEDM couplings. Therefore, throughout the paper we employ only the leading order (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. The procedures will be illustrated in the next section.

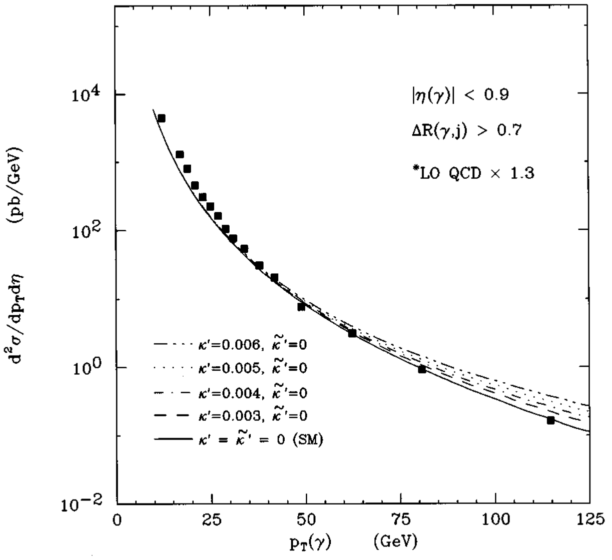

FIG. 2. Differential cross sections for prompt photon production versus the transverse momentum of the photon for pure QCD and nonzero values of CMDM of quarks. The data points are from CDF.

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

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

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 assumed that their anomalous couplings are the same. In Fig. 2, we show the differential cross sections of prompt photon production versus the transverse momentum 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 in 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 $(\kappa'^2 + \widetilde{\kappa}'^2)$. This is different from the case of $t\overline{t}$ production [4], in which the increase has a term proportional to the first power of κ.

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 [11]. For our case we are only interested in the large $p_T(\gamma)$

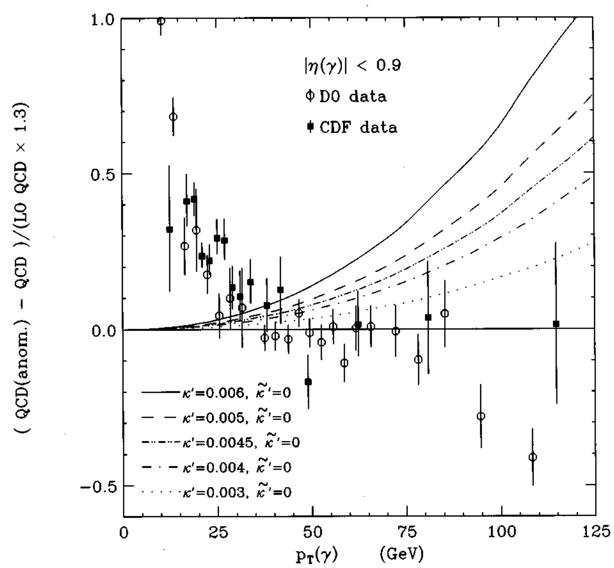

FIG. 3. Fractional difference from QCD for various values of κ' and $\tilde{\kappa}'$. Both D0 and CDF data are shown. The errors on D0 data are statistical only.

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

$$\kappa' \leqslant 0.0045 \ \text{GeV}^{-1} \tag{10}$$

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

$$\tilde{\kappa}' \leqslant 0.0045 \ \text{GeV}^{-1} \tag{11}$$

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.[1] 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. We compare these 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 without adjusting the gluon parton distribution function is [7]

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

which is consistent with the bound obtained in this paper.

IV. SENSITIVITY AT FUTURE HIGH ENERGY COLLIDER EXPERIMENTS

The next run (run II) at the Fermilab Tevatron will be at $\sqrt{s} = 2$ TeV with an integrated luminosity of 2 fb^{-1}. If the run II is stretched to a longer run it could accumulate a luminosity of about 10 fb^{-1} [12]. There is also a plan called TeV33 [12] after run II, in which the luminosity gets a further boost to about 30 fb^{-1}. At about the same time scale the CERN Large Hadron Collider (LHC) will operate at $\sqrt{s} = 14$ TeV with an initial yearly luminosity of 10 fb^{-1}, which will later increase to the designed luminosity of 100 fb^{-1}. In this section, we shall estimate the sensitivities of $\kappa' \equiv 1/\Lambda$ or the limits on Λ that can be probed in these future experiments. We shall use a simple approach to calculate the limits.

Without a full Monte Carlo study of the detector including energy determination errors, we treat here only the statistical sensitivity of the various experiments. Our criteria [13] are to take bins of appropriate size for the energy range being examined, and find the p_T called p_T^* at which the SM cross section statistical error bars are 10%. These will be the bins with 100 SM events. We then explore the cross section due to the SM plus the anomalous chromomagnetic moment contribution, and find the value of $\kappa' \equiv 1/\Lambda$ or Λ where the excess over the SM is 10% at this p_T^*. In Table I we show the p_T^* and $\Lambda \equiv 1/\kappa'$ for various experiments [14]. We have used only the leading order cross sections without a K factor to determine p_T^* and Λ. Since the p_T distribution is steeply falling, so with or without a K factor would not affect significantly the values for p_T^* and Λ. Actually, the experimental determination of p_T might be the largest systematic errors among all [2,8,9]. We have also imposed cuts on the isolated photon by $|\eta| < 0.9$ and $\Delta R(\gamma, j) > 0.7$ at the Tevatron energies, while $|\eta| < 1$ and $\Delta R(\gamma, j) > 0.7$ for the LHC. We can

TABLE I. Table of high $p_T(\gamma)$ bins at 10% statistical error and 1-σ sensitivity for Λ in that bin.

Accelerator	$E_{\text{c.m.}}$ TeV	Integrated luminosity fb^{-1}	Bin width GeV	Photons p_T^* GeV	Photons Λ TeV
Tevatron:					
Run I	1.8	0.1	10	140	0.7
Run II	2.0	2	20	260	1.5
Stretch	2.0	10	20	325	1.9
TeV33	2.0	30	20	370	2.1
LHC	14	10	100	1000	4.5
LHC	14	100	100	1400	6.3

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[1] Taking a value for the light quark mass $m_q \approx 0.3$ GeV, $\kappa = 2 m_q \kappa' \leqslant 0.0027$. Therefore, only affects the magnetic moment of the light quark by an amount of order 10^{-3}. Thus, it has a negligible effect on baryon magnetic moments.

see from the table that Λ sensitivity scales roughly with the machine energy, but scales roughly with the eighth root of the luminosity.

V. CONCLUSIONS

We have studied the effects of anomalous chromomagnetic and chromoelectric dipole moment couplings of light quarks on prompt photon production. The increase in cross sections is proportional to $\kappa'^2 + \tilde{\kappa}'^2$. These couplings increase the total cross section and the transverse momentum spectrum, especially at the large $p_T(\gamma)$ region. Using the CDF and D0 data we found a bound κ' or $\tilde{\kappa}' \leqslant 0.0045\ \text{GeV}^{-1}$ on the chromomagnetic or chromoelectric dipole moment of light quarks, which is the main result of the paper. In addition, we have also estimated the sensitivity of $\kappa' \equiv 1/\Lambda$ in the future collider experiments at the Tevatron and LHC. The sensitivity is shown to be scaled roughly with the machine energy, but roughly with the eighth root of the luminosity. For example, the run II at the Tevatron can probe $\Lambda \equiv 1/\kappa'$ in the range 1.5–2 TeV for integrated luminosities of 2–30 fb^{-1}, while the LHC can probe up to 6 TeV with a 100 fb^{-1} luminosity.

ACKNOWLEDGMENTS

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[1] In the summer of 1996, the reported value of R_b was reduced to only 2σ away from the SM and R_c agrees with the SM, see, e.g., P. Langacker, invited talk given at the DPF96 meeting, American Physical Society, University of Minnesota, Minneapolis, Minnesota, 1996 (unpublished).

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