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IS IT POSSIBLE TO MEASURE QCD COMPTON EFFECTS?

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ABSTRACT

The possibility of measuring QCD Compton effects is discussed in detail. We find that it is very difficult to measure by using calorimeters which do not distinguish a gluon jet from a quark jet.

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There are many clues, both experimentally and theoretically, that QCD is a good candidate for describing strong interactions. It has been conjectured by many authors that large transverse momentum phenomena can be treated in QCD perturbation theory, and that some of those phenomena might be suited for testing QCD theory. Fritzsche and Minkowski¹⁾ pointed out that there is a typical event in photon-hadron scattering at high energy, namely, the QCD Compton effect which is one of the simplest processes for testing QCD.

In the near future, some experimental groups are going to do some experiments to measure large p_T jets using both nuclear emulsion and calorimeters²⁾. Measuring the QCD Compton effect is one of their aims. But is it possible to measure it experimentally? In this short article we shall discuss it carefully in two cases: a stationary target and colliding beams.

1. The case with a stationary target in the lab system: The characteristic feature of the QCD Compton effect (Fig. 1) is that the incoming photon acts as a point-like particle and collides with a quark (or antiquark) inside a proton target (the proton is stationary in SPS experiments, moving in an e-p colliding machine³⁾). The incoming photon then transmits its entire energy to the outgoing quark (antiquark) gluon jets which can be at large p_T . In the γp centre-of-mass system there are no incoming photon fragments in the forward direction.

But there are some other processes which give similar experimental results to the QCD Compton effect.

First, when the incoming photon acts as a point-like particle and collides with a gluon instead of a quark (antiquark) inside the proton. The incoming photon then transmits its entire energy to the outgoing $q\bar{q}$ jets which also can be at large p_T (see Fig. 2). There is also no forward jet. If we cannot distinguish a gluon jet from a quark jet, experimentally this process gives the same results as the QCD Compton effect.

Secondly, in most cases the incoming photon behaves like a hadron, i.e., the photon is firstly hadronized and then interacts with the target. When the incoming photon transmits a large fraction, say, $\geq 80\%$, of its energy to the large p_T jets in the final states, there are only low-energy fragments of the projectile. So, there are no fragments detected experimentally in the forward direction. The corresponding Feynman diagrams are shown in Fig. 3, where because we only consider as an example the case in which more than 80% of the incoming photon energy is carried away by the interacting parton inside the photon, the Feynman variable y of the interacting parton is ≥ 0.8 . So, the gluon contribution inside the incoming photon can be neglected (see Fig. 4 in Ref. 4)).

As mentioned above, a photon has two components: the point-like component and the hadron-like one. For the hadron-like component the parton distribution functions $q_i^\gamma(x,t)$ and $G^\gamma(x,t)$ obey the following equations⁵⁾:

$$\frac{dq_i^\gamma(x,t)}{dt} = \epsilon_i^2 \frac{\alpha}{2\pi} a(x) + \frac{\alpha_s(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[P_{q_i} \left(\frac{x}{y} \right) q_i^\gamma(y,t) + P_{qG} \left(\frac{x}{y} \right) G^\gamma(y,t) \right] \quad (1)$$

$$\frac{dG^\gamma(x,t)}{dt} = \frac{\alpha_s(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[P_{Gq} \left(\frac{x}{y} \right) \sum_{j=1}^{2f} q_j^\gamma(y,t) + P_{GG} \left(\frac{x}{y} \right) G^\gamma(y,t) \right] \quad (2)$$

Here, α and $\alpha_s(t)$ are the coupling constants of the electromagnetic and the strong interactions respectively, $t = \ln Q^2/\Lambda^2$, $a(x) = x^2 + (1-x)^2$, ϵ_i is the fractional charge of the quark, i, j are flavour indices, f is the number of flavours, P_{qq} , P_{qG} , P_{Gq} , P_{GG} are probability functions (see Ref. 6)).

From Eq. (1) we can see that the quark distribution functions have two pieces, the "anomalous" part described by $\epsilon_i^2 (\alpha/2\pi) a(x)$ and the vector meson part described by the second term on the right-hand side of Eq. (1). The "anomalous" part has been calculated by several authors⁷⁾ in the leading logarithm. The vector meson part has also been estimated by using vector meson dominance⁸⁾. Unfortunately, there is no experimental information for ρ structure functions up to now but a rough estimate gives⁸⁾

$$\left[\int_0^1 dx F_2^\gamma(x) \right]_{\text{leading term}} / \left[\int_0^1 dx F_2^\gamma(x) \right]_{\text{vector meson part}} \sim 1.9 \alpha_s(t).$$

Thus it is reasonable to guess that at the SPS photon beam, the contribution of the vector meson part is of the same order as that of the "anomalous" part, and that at a very high-energy photon beam (for instance, an e-p colliding machine) the contribution of the "anomalous" part will dominate.

In order to estimate the background which competes with the QCD Compton effect, it is enough to calculate the contribution of the "anomalous" part. If we like, we may roughly include the contribution of the vector meson part by multiplying by a factor $2\alpha_s$.

Now we turn to the calculation of the differential cross-sections of all the processes mentioned above by using only the point-like component and the "anomalous" part of the incoming photon.

In the γp centre-of-mass system let k denote the incoming photon momentum carried by the interacting quark or antiquark from the photon, P the proton momentum, xP the interacting parton momentum inside the proton, and k', p' denote the two outgoing parton momenta (see Figs 1, 2 and 3).

Define

$$y_T = 2k'_T/\sqrt{S} = 2p'_T/\sqrt{S}, \quad y_L = 2k'_L/\sqrt{S}, \quad y_j = 2p'_j/\sqrt{S} \quad (3)$$

where $S = (p + k)^2$ is the total energy squared in the γp centre-of-mass system.

Then the double differential cross-section of the QCD Compton effect is

$$\begin{aligned} \frac{d^2\sigma}{dy_T dy_L} = & \frac{8\pi\alpha\alpha_s}{3S} \frac{y_T}{a_L(2-y_L-a_L)} \left(\frac{2}{y_L+a_L} + \frac{y_L+a_L}{2} \right) \cdot \frac{1}{x^2} \\ & \cdot \sum_i e_i^2 x \left(q_i^P(x, Q^2) + \bar{q}_i^P(x, Q^2) \right) \end{aligned} \quad (4)$$

where

$$x = \frac{a_L - y_L}{2 - y_L - a_L}, \quad a_L = \sqrt{y_T^2 + y_L^2}$$

e_q is the quark charge in units of e , $q^P(x, Q^2)$, $\bar{q}^P(x, Q^2)$ are quark and anti-quark distribution functions respectively. We can also express the differential cross-section by means of (y_T, y_j)

$$\begin{aligned} \frac{d^2\sigma}{dy_T dy_j} = & \frac{8\pi\alpha\alpha_s}{3S} \frac{y_T}{a_j(2-y_j-a_j)} \left(\frac{2}{2-y_j-a_j} + \frac{2-y_j-a_j}{2} \right) \frac{1}{x^2} \\ & \cdot \sum_i e_i^2 x \left(q_i^P(x, Q^2) + \bar{q}_i^P(x, Q^2) \right). \end{aligned} \quad (5)$$

where

$$x = \frac{q_j - y_j}{2 - y_j - q_j}, \quad q_j = \sqrt{y_T^2 + y_j^2}.$$

If we cannot distinguish a gluon jet from a quark jet, only the summation of the differential cross-sections (4) and (5) is the measured cross-section. So, we have

$$\begin{aligned} \left. \frac{d^2\sigma}{dy_T dy_L} \right|_{\substack{\text{QCD Compton} \\ 2 \text{ large } p_T \\ \text{jets}}} = & \frac{8\pi\alpha_s}{3S} \frac{y_T}{q_L(2-y_L-q_L)} \left[\left(\frac{2}{2-y_L-q_L} + \frac{2-y_L-q_L}{2} \right) \right. \\ & \left. + \left(\frac{2}{y_L+q_L} + \frac{y_L+q_L}{2} \right) \right] \frac{1}{x^2} \sum_i e_i^2 x \left(q^P(x, Q^2) + \bar{q}^P(x, Q^2) \right) \end{aligned} \quad (6)$$

where

$$x = \frac{q_L - y_L}{2 - y_L - q_L}, \quad q_L = \sqrt{y_T^2 + y_L^2}$$

and (y_T, y_L) denote jet variables no matter whether it is a gluon jet or a quark jet. For the contribution of Fig. 2, it is only necessary to give the two large p_T jet cross-sections without distinguishing a quark jet and an anti-quark jet

$$\begin{aligned} \left. \frac{d^2\sigma}{dy_T dy_L} \right|_{\substack{2 \text{ large } p_T \\ \text{jets}}} = & \frac{2\pi\alpha_s}{S} \sum_i e_i^2 \frac{y_T}{q_L(2-y_L-q_L)} \\ & \cdot \left(\frac{q_L+y_L}{2-y_L-q_L} + \frac{2-y_L-q_L}{q_L+y_L} \right) \frac{1}{x^2} x G^P(x, Q^2). \end{aligned} \quad (7)$$

where

$$x = \frac{q_L - y_L}{2 - y_L - q_L}$$

and (y_L, y_T) represent the quark jet variables or the antiquark jet variables.

For the contribution of diagrams (5), (6) and (7) in Fig. 3, similar to Eqs (4), (5) and (6) we have

$$\begin{aligned} \frac{d^2\sigma}{dy_T dy_L} = & \int_{-1}^1 dy_j \frac{\pi \alpha_s^2}{2S} \frac{y_T}{q_L q_j} \frac{1}{x^2 y^2} [y^2 (q_L - y_L)^2 + 4x^2 y^2] \\ & \cdot \left[\frac{2}{q x y^2 (q_L - y_L)} + \frac{1}{x^2 (q_L + y_L)^2} \right] \cdot x G^P(\alpha, Q^2) \sum_f y \left(q_f^x(y, Q^2) + \bar{q}_f^x(y, Q^2) \right) \end{aligned} \quad (8)$$

$$\begin{aligned} \frac{d^2\sigma}{dy_T dy_j} = & \int_{-1}^1 dy_L \frac{\pi \alpha_s^2}{2S} \frac{y_T}{q_L q_j} \frac{1}{x^2 y^2} [x^2 (q_j + y_j)^2 + 4x^2 y^2] \\ & \cdot \left[\frac{2}{q x^2 y (q_j + y_j)} + \frac{1}{y^2 (q_j - y_j)^2} \right] x G^P(\alpha, Q^2) \sum_f y \left(q_f^x(y, Q^2) + \bar{q}_f^x(y, Q^2) \right) \end{aligned} \quad (9)$$

$$\begin{aligned} \left. \frac{d^2\sigma}{dy_T dy_L} \right|_{2 \text{ large } p_T} = & \int_{-1}^1 dy_j \frac{\pi \alpha_s^2}{2S} \frac{y_T}{q_L q_j} \frac{1}{x^2 y^2} \left\{ [x^2 (q_L + y_L)^2 + 4x^2 y^2] \cdot \right. \\ & \cdot \left[\frac{2}{q x^2 y (q_L + y_L)} + \frac{1}{y^2 (q_L - y_L)^2} \right] + [y^2 (q_L - y_L)^2 + 4x^2 y^2] \cdot \left[\frac{2}{q x y^2 (q_L - y_L)} \right. \\ & \left. \left. + \frac{1}{x^2 (q_L + y_L)^2} \right] \right\} \cdot x G^P(\alpha, Q^2) \sum_f y \left(q_f^x(y, Q^2) + \bar{q}_f^x(y, Q^2) \right). \end{aligned} \quad (10)$$

where

$$x = \frac{1}{2} (q_L + q_j - y_L - y_j), \quad y = \frac{1}{2} (q_L + q_j + y_L + y_j), \quad q_L = \sqrt{y_T^2 + y_L^2}, \quad q_j = \sqrt{y_T^2 + y_j^2}.$$

$G^P(x, Q^2)$ is the gluon distribution function inside the proton; $q^Y(y, Q^2)$ and $\bar{q}^Y(y, Q^2)$ are the quark and antiquark distribution functions of the photon respectively.

Without distinguishing a quark (or antiquark) jet and a gluon jet, the cross-section of two large p_T jets in the final state contributed from all the diagrams in Fig. 3 is

$$\begin{aligned} \frac{d^2\sigma}{dy_T dy_L} \Big|_{\text{2 large } p_T \text{ jets}} &= \int_{-1}^1 dy_j \frac{2\pi\alpha_s^2}{9S} \frac{y_T}{q_L q_j} \frac{1}{x^2 y^2} \left[y q_{2/3}^Y(y, Q^2) \right] \cdot \\ &\left\{ \left[\frac{x^2}{y^2} \frac{(q_L + y_L)^2 + 4y^2}{(q_L - y_L)^2} + \frac{y^2}{x^2} \frac{(q_L - y_L)^2 + 4x^2}{(q_L + y_L)^2} \right] \cdot \left[x u_V^P(x, Q^2) + \frac{5}{2} x d_V^P(x, Q^2) \right. \right. \\ &+ 2 x S^P(x, Q^2) \Big] + \left[3 \frac{x^2}{y^2} \frac{(q_L + y_L)^2 + 4y^2}{(q_L - y_L)^2} + 3 \frac{y^2}{x^2} \frac{(q_L - y_L)^2 + 4x^2}{(q_L + y_L)^2} \right. \\ &- \frac{x^2(q_L + y_L)^2 + y^2(q_L - y_L)^2}{x^2 y^2} \left(2 - \frac{16}{3} \frac{xy}{y_T^2} \right) - 2 \left(1 + \frac{4}{3} \frac{xy}{y_T^2} \right) \Big] \\ &\cdot \left[x u_V^P(x, Q^2) + \frac{1}{4} x d_V^P(x, Q^2) + \frac{1}{2} x S^P(x, Q^2) \right] \\ &+ \left[\left(x^2(q_L + y_L)^2 + 4x^2 y^2 \right) \left(\frac{2}{9x^2 y (q_L + y_L)^2} + \frac{1}{y^2 (q_L - y_L)^2} \right) + \left(y^2(q_L - y_L)^2 + 4x^2 y^2 \right) \right. \\ &\cdot \left. \left(\frac{2}{9xy^2 (q_L - y_L)} + \frac{1}{x^2 (q_L + y_L)^2} \right) \right] \frac{27}{4} x G^P(x, Q^2) \end{aligned} \quad (11)$$

where $u_V^P(x, Q^2)$, $d_V^P(x, Q^2)$, $S^P(x, Q^2)$

are the valence up-quark, down-quark and the sea quark distribution functions of the proton, and we have neglected the charmed quark contributions. $q_{2/3}^Y(y, Q^2)$ is the up-quark distribution function of the photon.

For the numerical calculations we take $E_Y^{\text{lab}} \sim 150 \text{ GeV}$, $S \sim 300 \text{ GeV}^2$, $\alpha_s \sim 0.5$. We use the Buras and Gaemers⁹⁾ parametrization for proton structure functions and neglect the charmed quark contribution. We take $\Lambda \sim 0.5 \text{ GeV}$, $Q_0^2 \sim 1.8 \text{ GeV}^2$, $Q^2 \sim xyS$. For the photon structure functions we use the results given by Ref. 4), and neglect the charmed quark and gluon distributions.

The double differential cross-sections of Eqs. (6), (7) and (11) are presented in Figs 4, 5 and 6, where the figures on the curves denote the cross-sections in units of nanobarns. From Figs 4, 5 and 6 we can know the large p_T jet energy ($\sim \sqrt{y_T^2 + y_L^2} \cdot \sqrt{S}/2$), the scattering angle of the large p_T jet axis ($\tan \theta = y_T/y_L$) and the magnitude of the differential cross-sections. We can see clearly that the cross-section of $\gamma g \rightarrow q\bar{q}$ (Fig. 2) is relatively small in comparison with the QCD Compton effect and drops very rapidly when y_T increases. When $y_T \geq 0.4$,

$$\left[\frac{d^2\sigma}{dy_T dy_L} \Big|_{\gamma g \rightarrow q\bar{q}} \right] / \left[\frac{d^2\sigma}{dy_T dy_L} \right]_{\text{QCD Compton}} < 10\%$$

So, the process described by Fig. 2 is not a serious background. But the contribution from the "anomalous" part of the hadronized photon is of the same order as the QCD Compton effect in the whole range of y_T and y_L (see Figs 4 and 6). Thus, without distinguishing a gluon jet and a quark (antiquark) jet it is very difficult to pick up QCD Compton effects from so large a background.

If we can distinguish different types of jets, we should only consider the diagrams (5), (6) and (7) in Fig. 3, which give the same experimental results as QCD Compton effects when $y \geq 0.8$. Doing the integration in Eq. (10) under the condition of $0.8 \leq y \leq 1$. The results and the cross-sections of QCD Compton effects are shown in Figs 7 and 8. We see that when $y_T \geq 0.4$ the background is also very small. So, it is possible to measure the QCD Compton effect when one can distinguish a gluon jet from a quark (antiquark) jet.

2. The case with a moving target in the lab system: Now we discuss briefly the case of an e - p colliding machine. The fast electron radiates virtual photons. At $Q^2 \sim 0$ the bremsstrahlung photons are nearly real. Obviously the photon beam is not monochromatic. But by tagging the scattered electron we can acquire an almost monochromatic photon beam. For example, at 10 GeV we can have quite a nice photon flux¹⁰⁾. For simplicity, we concentrate on a 10 GeV photon beam colliding with a 270 GeV proton target.

In the colliding beam experiments we cannot measure both the forward and the backward jets due to the geometrical restrictions. That means that there is no hope in an $e-p$ colliding machine of measuring the QCD Compton effect without distinguishing a gluon jet from a quark (antiquark) jet. But if we can distinguish a gluon jet from a quark (antiquark) jet, it is possible to measure the QCD Compton effect. The reason is the following. In that case the only background to the QCD Compton effect comes from the processes described by diagrams (5), (6) and (7) in Fig. 3. In $e-p$ colliding experiments if we take the minimum angle relative to the beam pipe is about 10° both in the forward and backward direction, we get the restriction for the Feynman variable of partons inside the photon, namely, $y \gtrsim 0.1$ (see Fig. 2 in Ref. 11)). So we can also neglect the gluon contribution of the incoming photon and calculate the integration of Eq. (8) instead of (10) under the condition of $0.1 \leq y \leq 1$. The result is presented in Fig. 9. For comparison we also give the cross-section of the QCD Compton effect (Eq. (4)) in Fig. 10. From Figs 9 and 10 we can see that the background is very small when $y_T > 0.3$. So, it is possible to measure the QCD Compton effect as long as we make a p_T cut with $y_T \geq 0.3$ ($p_T \geq 15$ GeV) and distinguish between a gluon jet and a quark (antiquark) jet.

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Figure captions

- Fig. 1 : Feynman diagrams for the QCD Compton effect.
- Fig. 2 : Feynman diagram for the process $\gamma + p \rightarrow q + \bar{q} + X$.
- Fig. 3 : Feynman diagrams for the processes hadronized $\gamma + p \rightarrow 2 \text{ large } p_T \text{ jets} + X$.
- Fig. 4 : The double differential cross-section for the QCD Compton effect without distinguishing the type of jet, for the SPS photon beam.
- Fig. 5 : The double differential cross-section for the diagrams in Fig. 2 without distinguishing the type of jet for the SPS photon beam.
- Fig. 6 : The double differential cross-section for the diagrams in Fig. 3 without distinguishing the type of jet.
- Fig. 7 : The double differential cross-section for the QCD Compton effect for the SPS photon beam.
- Fig. 8 : The double differential cross-section for the diagrams (5), (6) and (7) in Fig. 3 for the SPS photon beam.
- Fig. 9 : The double differential cross-section for the diagrams (5), (6) and (7) in Fig. 3 for e-p colliding beams.
- Fig. 10 : The double differential cross-section for the QCD Compton effect for e-p colliding beams.

QCD Compton effect

FIG. 1

FIG. 2

FIG. 3

$\frac{d^2 \sigma}{dy_T dy_L} \Big|_{\text{QCD Compton (SPS)}}$

FIG. 4

$$\frac{d^2\sigma}{dy_T dy_L} \Big|_{\gamma g \rightarrow q\bar{q}} \text{ (SPS)}$$

FIG. 5

$\frac{d^2 \sigma}{dy_T dy_L} \mid 2 \text{ large } p_T \text{ jets (SPS)}$

FIG.6

$d^2\sigma/dy_T dy_L \big|_{\text{QCD Compton (SPS)}}$

FIG. 7

FIG. 8

FIG. 9

$\frac{d^2 \sigma}{dy_T dy_L} \Big|_{\text{QCD Compton (e-p)}}$

FIG. 10