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QCD PREDICTIONS FOR γp COLLISIONS WITH A LARGE
 p_T REAL PHOTON IN THE FINAL STATE

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ABSTRACT

The processes $\gamma p \rightarrow \gamma + \text{jet} + X$ and $\gamma p \rightarrow \pi^0 + \text{jet} + X$ are discussed in detail using perturbative QCD. The possibilities of experimental tests are also discussed.

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1. INTRODUCTION

General QCD predictions for processes involving real photons have recently been discussed¹⁾. In processes involving hard scattering QCD perturbative techniques are applicable. Fritzsche and Minkowski²⁾ suggested an experimentally interesting QCD Compton effect, namely, the incoming photon transmits its entire energy to the outgoing quark-jet and gluon-jet. In the centre-of-mass system there are no incoming photon fragments in the forward direction.

We would like to recall that the QED Compton effect is also experimentally interesting³⁾. In this process (see Fig. 1) the incoming photon acts as an elementary field and collides with a proton stationary in the lab system. The incoming photon then transmits its entire energy to the final photon and a hadronic jet which can be at large p_T . In the γp centre-of-mass system there are still no incoming photon fragments in the forward direction. The dependence of the differential cross-section for this QED Compton effect is expected to be given by the proton structure function $F_2(x, Q^2)$ whose evolution at large Q^2 can be calculated using perturbative QCD. In the old-fashioned parton model the proton structure functions are only functions of x and independent of Q^2 . In the scheme of QCD, F_2 depends on Q^2 which usually is taken to be approximately equal to p_T^2 of the final photon or jet. The process is theoretically interesting because the magnitude of the cross-section will determine whether the quark charge is fractional or not⁴⁾.

But in most cases the incoming photon behaves like a hadron, i.e., the photon is firstly hadronized and then interacts with the target⁵⁾. In Fig. 2 the corresponding Feynman diagrams are shown. When the incoming photon transmits a large fraction, say 80%-100%⁶⁾, of its energy to the final state large p_T particles, there are only low-energy fragments of the projectile (photon). The low-energy fragments are not experimentally distinguishable. Thus, these processes described by Fig. 2 give the same experimental results as the QED Compton effect. The cross-sections of these processes can also be calculated by QCD.

There are other processes which give similar experimental results to the QED Compton effect. We show diagrams for some of them in Fig. 3. From Fig. 3 we can see that if the emitted photon or π^0 carries away a large fraction of the parton's momentum, the remaining fragments of the parton ($q, \bar{q}, g$) will have very low energy. They are also undetectable. In final states only a single γ and a counter-balancing large p_T jet are observed.

It is interesting to calculate the cross-sections of all the processes described by Figs 2 and 3 and to compare them with the QED Compton effect. This we do in the next Section.

2. THE DIFFERENTIAL CROSS-SECTIONS

Because we are interested in the case in which the interacting parton inside the incoming photon carries away more than about 80% of its energy, the gluon contribution in the photon structure functions is negligible. For a similar reason, the fragmentation function of $g \rightarrow \gamma$ is also negligibly small.

In the γp centre-of-mass system let k denote the incoming photon momentum, k' the outgoing photon momentum, P the momentum of the target (proton), xP the interacting parton momentum inside the proton and p' the outgoing parton momentum. Define

$$x_T = \frac{k'_T}{E} = \frac{p'_T}{E}, \quad x_L = \frac{k'_L}{E}, \quad x_j = \frac{p'_j}{E} \quad (1)$$

where $E = \sqrt{s}/2$, $s = (p+k)^2$

then

$$\left. \frac{d^2\sigma}{dx_T dx_L} \right|_{\text{QED Compton}} = \frac{\pi\alpha^2}{2E^2} \frac{x_T}{a_L(a_L - x_L)} \left[\frac{2}{a_L + x_L} + \frac{a_L + x_L}{2} \right] \cdot \frac{1}{x} \sum_q e_q^4 x [q^P(x, Q^2) + \bar{q}^P(x, Q^2)] \quad (2)$$

where $a_L = \sqrt{x_T^2 + x_L^2}$, $x = \frac{a_L - x_L}{2 - x_L - a_L}$,

and $q^P(x, Q^2)$, $\bar{q}^P(x, Q^2)$

are the quark and antiquark distribution functions inside a proton.

The contribution of diagrams (1)-(4) in Fig. 2 is

$$\left. \frac{d^2\sigma}{dx_T dx_L} \right|_{\gamma\gamma \rightarrow \gamma g} = \int_{-1}^1 dx_j \frac{\pi\alpha_s}{qE^2} \frac{x_T}{a_L a_j} \left[\frac{a_j - x_j}{a_L - x_L} + \frac{a_L - x_L}{a_j - x_j} \right] \frac{1}{x^2 y^2} \sum_q e_q^2 y q^j(y, Q^2) x [q^P(x, Q^2) + \bar{q}^P(x, Q^2)] \quad (3)$$

where y_k is the momentum carried by the interacting q or $\bar{q}$ from the incoming photon, and $q^Y(y, Q^2)$ is the quark (or antiquark) distribution function inside the photon, and

$$\begin{aligned} a_L &= \sqrt{x_T^2 + x_L^2}, \quad a_j = \sqrt{x_T^2 + x_j^2} \\ x &= \frac{1}{2} [a_L + a_j - x_L - x_j] \\ y &= \frac{1}{2} [a_L + a_j + x_L + x_j] \end{aligned} \quad (4)$$

The integration with respect to x_j in (3) will be carried out under the constraint $0.8 \leq y \leq 1$ ⁷⁾, corresponding to the experimental sensitivity to low-energy fragments of the incoming photon.

The contribution of diagrams (5)-(8) in Fig. 2 is

$$\begin{aligned} \frac{d^2\sigma}{dx_T dx_L} \Big|_{\substack{qg \rightarrow q\gamma \\ \bar{q}g \rightarrow \bar{q}\gamma}} &= \int_{-1}^1 dx_j \frac{2\pi\alpha_s}{3E^2} \frac{x_T}{a_L a_j} \left[\frac{2x}{a_L - x_L} + \frac{a_L - x_L}{2x} \right] \frac{1}{16x^2 y^2} \\ &\quad x G^P(x, Q^2) \sum_q e_q^2 y [q^Y(y, Q^2) + \bar{q}^Y(y, Q^2)] \end{aligned} \quad (5)$$

where $x, y, a_L, a_j, q^Y(y, Q^2)$ are the same as in (4), and $G^P(x, Q^2)$ is the gluon distribution function inside a proton. For the reasons mentioned above, we neglect the contribution of diagrams (9)-(12) in Fig. 2.

The contribution of diagrams (1)-(4) in Fig. 3 for γ emission is

$$\begin{aligned} \frac{d^2\sigma}{dx_T dx_L} \Big|_{\substack{\gamma q \rightarrow gq \\ \gamma \bar{q} \rightarrow g\bar{q}}} &= \int_{0.8}^1 dz \frac{2\pi\alpha_s}{3E^2} \frac{x_T}{z a_L (2z - x_L - a_L)} \left[\frac{2z}{2z - x_L - a_L} + \frac{2z - x_L - a_L}{2z} \right] \\ &\quad \cdot \frac{1}{x^2} \sum_q e_q^2 x [q^P(x, Q^2) + \bar{q}^P(x, Q^2)] D_q^\gamma(z, Q^2) \end{aligned} \quad (6)$$

where

$$x = \frac{a_L - x_L}{2z - x_L - a_L}, \quad a_L = \sqrt{x_T^2 + x_L^2}$$

x_T, x_L are the final photon variables defined as before, and $D_q^Y(z, Q^2) = D_q^Y(z, Q^2)$ is the fragmentation function of $q \rightarrow \gamma$ or $\bar{q} \rightarrow \gamma$ ¹⁾.

The contribution of diagrams (5)-(8) in Fig. 3 is

$$\left. \frac{d^2\sigma}{dx_T dx_L} \right|_{\substack{\gamma q \rightarrow \bar{q} q \rightarrow \gamma \\ \gamma q \rightarrow q \bar{q} \rightarrow \gamma}} = \int_{0.8}^1 dz \frac{\pi \alpha_s}{4E^2} \frac{x_T}{z q_L (2z - x_L - q_L)} \left[\frac{q_L + x_L}{2z - x_L - q_L} + \frac{2z - x_L - q_L}{q_L + x_L} \right] \cdot \frac{1}{x^2} \times G^P(x, Q^2) \sum_f e_f^2 [D_f^Y(z, Q^2) + D_{\bar{f}}^Y(z, Q^2)] \quad (7)$$

where $x = \frac{q_L - x_L}{2z - x_L - q_L}$, $q_L = \sqrt{x_T^2 + x_L^2}$

For π^0 emission, the contribution of diagrams (9)-(12) in Fig. 3 is

$$\left. \frac{d^2\sigma}{dx_T dx_L} \right|_{\substack{\gamma q \rightarrow q q \rightarrow \pi^0 \\ \gamma \bar{q} \rightarrow q \bar{q} \rightarrow \pi^0}} = \int_{0.8}^1 dz \frac{2\pi \alpha_s}{3E^2} \frac{x_T}{z q_L (2z - x_L - q_L)} \left[\frac{2z}{2z - x_L - q_L} + \frac{2z - x_L - q_L}{2z} \right] \frac{1}{x^2} \sum_f e_f^2 x [q_f^P(x, Q^2) + \bar{q}_f^P(x, Q^2)] D_f^{\pi^0}(z, Q^2) \quad (8)$$

where $x = \frac{q_L - x_L}{2z - x_L - q_L}$, $q_L = \sqrt{x_T^2 + x_L^2}$

x_T, x_L are the final π^0 variables defined as before, and $D_q^{\pi^0}(z, Q^2)$ is the fragmentation function of $q \rightarrow \pi^0$ or $\bar{q} \rightarrow \pi^0$.

The contribution of diagrams (13)-(16) is

$$\left. \frac{d^2\sigma}{dx_T dx_L} \right|_{\substack{\gamma q \rightarrow q g \\ \gamma \bar{q} \rightarrow \bar{q} g \\ \rightarrow \pi^0}} = \int_0^1 dz \frac{2\pi\alpha_s}{3E^2} \frac{x_T}{z q_L (2z - x_L - q_L)} \left[\frac{2z}{q_L + x_L} + \frac{q_L + x_L}{2z} \right] D_u^{\pi^0}(z, Q^2) \frac{1}{x^2} \sum_i e_i^2 x [q^p(x, Q^2) + \bar{q}^p(x, Q^2)] \quad (9)$$

where we have assumed that $D_g^{\pi^0}(z, Q^2) \sim D_u^{\pi^0}(z, Q^2)$. Experimentally, there is a preliminary result from BEBC⁸⁾ which indicates that $D_g^{\pi^0}(z, Q^2) \sim D_q^{\pi^0}(z, Q^2)$ at $Q^2 \sim 10 \text{ GeV}^2$ (even at $Q^2 \sim 100 \text{ GeV}^2$).

The contribution of diagrams (17)-(20) in Fig. 3 is

$$\left. \frac{d^2\sigma}{dx_T dx_L} \right|_{\substack{\gamma g \rightarrow q \bar{q} \\ \gamma g \rightarrow \bar{q} q \\ \rightarrow \pi^0}} = \int_0^1 dz \frac{\pi\alpha_s}{4E^2} \frac{x_T}{z q_L (2z - x_L - q_L)} \left[\frac{q_L + x_L}{2z - x_L - q_L} + \frac{2z - x_L - q_L}{q_L + x_L} \right] \cdot \frac{1}{x^2} x G^p(x, Q^2) \sum_i e_i^2 [D_q^{\pi^0}(z, Q^2) + D_{\bar{q}}^{\pi^0}(z, Q^2)] \quad (10)$$

where $D_q^{\pi^0} = D_{\bar{q}}^{\pi^0}$.

For numerical calculations we take $E_Y^{\text{lab}} \sim 150 \text{ GeV}$, $S \sim 300 \text{ GeV}^2$, $\alpha_s \sim 0.5$, $\Lambda \sim 0.5 \text{ GeV}$, $Q_0^2 \sim 1.8 \text{ GeV}^2$, $Q^2 \sim S \sim 300 \text{ GeV}^2$. In principle $Q^2 \sim xyS$. In our case $y \sim 1$. If we consider the region $0.2 \leq x \leq 1$ (for reasons given in the last section) then the Q^2 varies from $\sim 300 \text{ GeV}^2$ to $\sim 50 \text{ GeV}^2$. It turns out that the change of cross-sections for $Q^2 \sim 300 \text{ GeV}^2$ to $Q^2 \sim 50 \text{ GeV}^2$ is only $\sim 10\%$.

We use the Buras and Gaemers parametrization for proton structure functions⁹⁾, and neglect the charmed quark contribution.

For photon structure functions we use the result given by Llewellyn Smith¹⁾. We did not use the new higher-order result for photon structure functions¹⁰⁾. The main difference between these two results is that at large y the former is larger than the latter, and we are mainly interested in these processes as backgrounds for our fundamental concern, the QED Compton process.

For the fragmentation function we use the Field-Feynman results¹¹⁾ and neglect the Q^2 dependence because the Q^2 involved in our case is not very large:

$$D_u^{\pi^0}(z, Q^2) \sim D_d^{\pi^0}(z, Q^2) \sim 0.0057 z^2 - 1.37 z + 5.03 z^{0.46} \\ - 0.0089 \ln z + 1.02 z^{-1} - 4.66$$

$$D_s^{\pi^0}(z, Q^2) \sim -0.024 z^2 - 1.71 z + 5.02 z^{0.46} + 0.35 \ln z + 1.02 z^{-1} - 4.31$$

All the numerical results of double differential cross-sections (2), (3), (5)-(10) are presented in Figs 4-11, respectively. The figures by the curves are the numerical values of the cross-sections in units of nanobarns.

In Fig. 12 we also give the ratio $\gamma_{\text{emitted}}/\gamma_{\text{QED}}$ which is equal to the summation of the cross-sections (6) and (7) divided by the QED Compton differential cross-section. In Fig. 13 we give the ratio $\pi_{\text{emitted}}^0/\gamma_{\text{QED}}$ which is equal to the summation of the cross-sections (8), (9) and (10) divided by QED Compton cross-section.

3. DISCUSSION

For the different processes the kinematically allowed areas in $x_T - x_L$ plots are different.

For the QED Compton effect

$$x = \frac{a_L - x_L}{2 - x_L - a_L} \quad x_T = x_T(x, x_L) \quad (11)$$

For hadronized incoming γ processes,

$$x = \frac{1}{2} [a_L + a_j - x_L - x_j], \quad x_T = x_T(x, x_j, x_L) \quad (12)$$

$$y = \frac{1}{2} [a_L + a_j + x_L + x_j], \quad x_T = x_T(y, x_j, x_L) \quad (13)$$

For γ, π^0 emission processes,

$$X = \frac{a_L - x_L}{2z - x_L - a_L}, \quad x_T = x_T(z, x, x_L) \quad (14)$$

In Figs 14-18 we plot x_T against x_L with x, z, x_j, y as parameters and constraints $0.8 \leq y, z \leq 1$.

From the plots we can see that the kinematically allowed areas of (12)-(14) are almost contained within the allowed areas of (11). So, we can use the kinematically allowed areas of the QED Compton process as a reference to find out which area is favourable to experiments.

Comparing Figs 5 and 6 with Fig. 4 we can see that when $X \sim 0.1$ the contributions of hadronized incoming photon processes are about 1/10 of that of the QED Compton process, and decrease very rapidly with increasing X . So, they are not a serious background.

From Fig. 12 we can see that the ratio $\pi^0_{\text{emitted}}/\gamma_{\text{QED}} \sim 0.1$ when $X \sim 0.1$. So, the background of γ emission is also not serious.

For π^0 emission, from Fig. 13 we can see that when $X \sim 0.1$ the ratio $\pi^0_{\text{emitted}}/\gamma_{\text{QED}} \sim 5$, $\sim 2-3$ when $X \sim 0.2$. Although the background of π^0 emission is relatively large, experimentally it can be eliminated with a large efficiency $\sim 80\%$ ¹²⁾. So, if one does experiments in the region $X \geq 0.2$ the background problem would be not so hard.

For $x \ll 0.1$, $Q^2 \ll 10 \text{ GeV}^2$, the QCD predictions are probably not reliable because perturbative QCD is only meaningful at relatively large Q^2 .

We conclude that within the framework of QCD the deep inelastic QED Compton process is expected to be observable, and clearly visible above expected background reactions.

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REFERENCES AND FOOTNOTES

- 1) C.H. Llewellyn Smith, Phys. Letters 79B (1978) 83;
E. Witten, Nuclear Phys. B120 (1977) 189.
- 2) H. Fritzsch and P. Minkowski, Phys. Letters 69B (1977) 316.
- 3) J.D. Bjorken and E.A. Paschos, Phys. Rev. 185 (1969) 1975.
- 4) M.S. Chanowitz mentioned about that point, see preprint LBL-5312 (1976).
- 5) Many authors pointed out that there are two parts of a photon which contribute in photoproduction processes: the point-like and hadronic parts. See Ref. 1).
- 6) This is an experimental cut suggested by D. Treille.
- 7) See Ref. 6) and if changed to $0.9 \leq y \leq 1$, the cross-section will decrease by a factor 2.
- 8) D.H. Perkins, "Lepton Scattering and QCD", Oxford Univ. preprint 2/79 (1979).
- 9) A.J. Buras and K.J.F. Gaemers, Nuclear Phys. B132 (1978) 249.
- 10) W.A. Bardeen and A.J. Buras, Fermilab PUB 78-91 THY (1978).
- 11) R.D. Field and R.P. Feynman, Nuclear Phys. B136 (1978) 1.
- 12) Private communication from D. Treille and P. Weilhammer.

Figure captions

- Fig. 1 : Feynman diagrams for the QED Compton effect.
- Fig. 2 : The lowest order Feynman diagrams of the hadronized incoming photon colliding with a proton.
- Fig. 3 : The lowest order Feynman diagrams which give important contributions to γ or π^0 emission.
- Fig. 4 : The double differential cross-section of QED Compton scattering. The figures by the curves are the numerical values of the cross-sections in units of nanobarns.

- Fig. 5 : The double differential cross-section

$$\frac{d^2\sigma}{dx_T dx_L} \Big|_{\gamma\gamma \rightarrow \gamma\gamma}$$

which comes from the diagrams (1)-(4) in Fig. 2.

- Fig. 6 : The contribution of the diagrams (5)-(8) in Fig. 2.
- Fig. 7 : The contribution of the diagrams (1)-(4) in Fig. 3.
- Fig. 8 : The contribution of the diagrams (5)-(8) in Fig. 3.
- Fig. 9 : The contribution of the diagrams (9)-(12) in Fig. 3.
- Fig. 10 : The contribution of the diagrams (13)-(16) in Fig. 3.
- Fig. 11 : The contribution of the diagrams (17)-(20) in Fig. 3.
- Fig. 12 : The ratio of the contribution of the diagrams (1)-(8) in Fig. 3 to that of QED Compton scattering.
- Fig. 13 : The ratio of the contribution of the diagrams (9)-(20) in Fig. 3 to that of QED Compton scattering.
- Fig. 14a : The kinematics of QED Compton scattering. For convenience of comparison, they are given in different scales.
- Fig. 14b :

Figs 15-17 : The kinematics of the hadronized incoming photon processes with different X_j .

Fig. 18 : The kinematics of the γ or π^0 emission processes for $z = 0.9$.

Feynman diagrams for QED Compton scattering

FIG.1

FIG.2

(1)

(2)

(3)

(4)

(5)

(6)

(7)

(8)

(9)

(10)

(11)

(12)

(13)

(14)

(15)

(16)

(17)

(18)

(19)

(20)

FIG.3

FIG.4

FIG.5

FIG. 6

FIG.7

FIG.8

FIG.9

FIG.10

FIG.11

FIG.12

FIG.13

$x_T(x, x_L)$ for QED Compton kinematics

FIG.14

(a)

$x_T(x, x_L)$ for QED Compton process

FIG.14

(b)

$x_T (x, x_j, x_L)$ for hadronized incoming γ kinematics

FIG.15

$x_T = x_T(x, x_j, x_L)$ for hadronized incoming γ kinematics

FIG.16

$x=0.1$ coincide with x_L axes
 $x_T = x_T(x, x_j, x_L)$ for hadronized incoming γ kinematics

FIG.17

$x_T = x_T(x, z, x_L)$ for γ, π^0 emission kinematics

FIG.18