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MEASURING QCD COMPTON EFFECTS

H. Fritzsch

CERN - Geneva
and

Institute for Theoretical Physics
University of Wuppertal

and

P. Minkowski

Institute for Theoretical Physics
University of Bern

A B S T R A C T

We discuss QCD analogues of the Compton effect, where one of the photons in the Compton process is replaced by a gluon. "Gluon jets" are produced in photon-hadron scattering, "direct photons" in hadron-hadron scattering. The cross-sections for both processes are calculated in terms of the quark and gluon distribution functions of hadrons.

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1. - INTRODUCTION

There are good reasons to believe ¹⁾ that the strong interactions can be described by QCD, that hadrons are colour singlet bound states of quarks and gluons, and that the quark-gluon coupling constant is relatively small ($g^2/4\pi = \kappa \lesssim 0.5$) if a renormalization length of $\lesssim 1/10$ Fermi is chosen. In this case certain phenomena (e.g., scaling and its violation in leptonproduction) can be treated by QCD perturbation theory. Although the field theoretic methods which are used in the analysis of leptonproduction cannot be used in hadron-hadron scattering, it has been conjectured by many authors that in particular the large transverse momenta phenomena can be treated in perturbation theory, and that those phenomena are dominated by the large angle scattering of the hadronic constituents (quarks, gluons). In this case one expects the appearance of jets in those hadronic reactions where large transverse momenta occur [for a recent discussion, see Ref. 2].

In this paper we should like to point out another class of reactions which, we believe, are especially suited for testing QCD, namely the production of jets in γ hadron scattering, and the production of photons with large transverse momenta in hadron-hadron scattering.

2. - THE QCD COMPTON EFFECT

A typical event in photon-hadron scattering at high energies is similar to an event in hadron-hadron scattering ; in those events the incoming photon behaves like a hadron (vector meson). However, we expect that in some small fraction of all events the incoming photon acts like an elementary field and scatters off the quarks inside the hadronic target. If QCD is a correct description of hadron physics, the final product of such a photon-quark scattering will be (dominantly) a quark and a gluon both endowed eventually with high transverse momenta. Such a reaction is very similar to the conventional Compton effect discussed especially in Ref. 3), except the outgoing vector boson is not a photon, but a gluon, manifesting itself by a hadronic jet, and the process is not of order α^2 , but of order α ("QCD Compton effect"). The characteristic feature of such reactions is that the photon transmits its entire energy to the outgoing quark-gluon system. In the centre-of-mass system one should see events in which the incoming photon energy is carried away by two jets of high transverse momenta ; no

particles are scattered forward (see Fig. 1). Evidently such events are very different from those "hadron-like" events in photon-hadron scattering with two jets of hadrons carrying high transverse momenta which are presumed to arise from quark-quark scattering ; in such events typically only some fraction of the incoming photon energy is carried away by the jets, the remaining fraction being carried away by the fragments of the projectile (photon).

Let us calculate the cross-section for the reaction "photon + quark $\rightarrow$ gluon + quark". The cross-section for the Compton effect "photon + quark $\rightarrow$ photon + quark" is given by

$$\frac{d\sigma}{dt} = \frac{2\pi\alpha^2 e_q^4}{s^2} \left(1 + \frac{t}{s} + \frac{s}{s+t}\right) = - \frac{2\pi\alpha^2 e_q^4}{s^2} \left(\frac{s}{u} + \frac{u}{s}\right) \quad (1)$$

where $s = (k+p)^2$, $t = (k-k')^2$, $u = (p-k')^2$ (p : incoming quark momentum, e_q : quark charge in units of e , k : momentum of incoming photon, k' : momentum of outgoing photon). We note that the cross-section above is scale invariant, i.e., independent of external masses. Replacing the outgoing photon by a gluon we obtain after averaging over the incoming colours and summing over the outgoing colours :

$$\left(\frac{d\sigma}{dt}\right)_{\gamma \rightarrow \text{gluon}} / \left(\frac{d\sigma}{dt}\right)_{\gamma \rightarrow \gamma} = \frac{\alpha \kappa e_q^2}{3\alpha^2 e_q^4} \sum_{A,i,j} \left| \frac{\lambda_A^{ij}}{2} \right|^2 = \frac{4}{3} \frac{\kappa}{\alpha e_q^2}.$$

$$\left(\frac{d\sigma}{dt}\right)_{\gamma \rightarrow \text{gluon}} = - \frac{8\pi\alpha \kappa e_q^2}{3s^2} \left(\frac{s}{u} + \frac{u}{s}\right). \quad (2)$$

Here i, j denote the quark colours ($i, j = 1, 2, 3$), and A denotes the gluon colours ($A = 1, \dots, 8$). The normalization of the λ matrices is chosen such that $\text{tr}(\lambda_A^2) = 2$.

We calculate the cross-section for the reaction $\gamma + \text{nucleon} \rightarrow$ "gluon jet" + X. The four-momentum of the gluon jet is denoted by k' , the four-momentum of the outgoing "quark jet" by q' ; we also use the

variable $v = p \cdot (k - k')$. We are interested in the limit $s, -t \rightarrow \infty$, $(-t/s) = z$ fixed, and neglect all mass effects (nucleon mass, effective quark masses, effective gluon mass, transverse momenta of the quarks in the nucleon wave function). In the centre-of-mass system the incoming quark has the four-momentum $x \cdot p$. Due to the condition $p'^2 = (k + xp - k')^2 = 0$ one finds $x \cdot v = (-t/2)$. Thus the ratio $-t/2v$ measures directly the momentum fraction x of the quark in the target hadron. For the cross-section we obtain

$$\frac{d^2\sigma}{dt dv} \approx - \sum_q \int_0^1 dx e_q^2 q(x) \frac{8\pi\alpha\kappa}{3s^2 x^2} \left(\frac{u}{s} + \frac{s}{u} \right) \delta\left(v + \frac{t}{2x}\right). \quad (3)$$

Note that the function $\sum_q e_q^2 q(x)$ is measured in electroproduction: $F_2^e(x) = \sum_q e_q^2 q(x) \cdot x$, and we can rewrite Eq. (3) as follows:

$$\frac{d^2\sigma}{dt dv} \approx - \frac{16\pi\alpha\kappa}{3s^2 t} \left(\frac{u}{s} + \frac{s}{u} \right) \frac{F_2^e(x)}{x}. \quad (4)$$

In the centre-of-mass system, we use the following notation for the various kinematical parameters:

$$\begin{aligned} p &= (E, 0, 0, -E), \quad k = (E, 0, 0, E), \quad k' = (E', E' \sin \theta', 0, E' \cos \theta') \\ t &= 2EE'(\cos \theta' - 1), \quad s = 4E^2, \quad u = -2EE'(1 + \cos \theta') \\ v &= 2E^2 - EE'(1 + \cos \theta'). \end{aligned} \quad (5)$$

We find

$$E' \frac{d\sigma}{d\Omega dE'} = \frac{\alpha\kappa}{6E^2} \left(\frac{E'}{E} \right) \cot^2 \frac{\theta'}{2} \cdot \frac{F_2^e}{x} \left(\frac{E'(1 - \cos \theta')}{2E} + \frac{2E}{E'(1 - \cos \theta')} \right) \quad (6)$$

Let us estimate the cross-section for the special case $\theta' = 90^\circ$. We take as example $s \cong 400 \text{ GeV}^2$ ($E = 10 \text{ GeV}$, $E_{\text{lab}} \cong 200 \text{ GeV}$) and $E' = 4 \text{ GeV}$, which corresponds to $E'/E = 0.4$, $x = (E'/2E - E') = 0.25$. One finds

$$\left(E' \frac{d^2\sigma}{d\Omega dE'} \right)_{\theta'=90^\circ, E'=4 \text{ GeV}} = 12 \kappa \text{ nb}$$

(6 nb for $\kappa = 0.5$). Although the precise value of κ for this reaction is not known (typical estimates range between 0.2...1), one can say that the

cross-section for events due to the QCD Compton effect where a gluon and a quark jet of a few GeV momentum each emerge at large angles in the centre-of-mass system is $10^{-3} \dots 10^{-4}$ of the total photon-nucleon cross-section for $E_{\text{lab}} \approx 200$ GeV. Such events could be selected by a special trigger device which selects the special class of events where no particles are emitted in or very near to the forward direction. For example, a calorimeter system could be used, similar to the one proposed recently for the study of pure hadronic reactions ⁴⁾.

In the lab. system we can rewrite Eq. (4) as follows :

$$\frac{d^2\sigma}{d\Omega dk'_{\text{lab}}} = \frac{\alpha \pi}{6 k_{\text{lab}}^2 \sin^4 \frac{1}{2} \theta_{\text{lab}}} \cdot \frac{\nu}{k_{\text{lab}} \cdot k'_{\text{lab}}} \left(1 + \frac{\nu^2}{2 k_{\text{lab}} k'_{\text{lab}}} \right) F_2^e(x) \quad (7)$$

where θ_{lab} denotes the angle at which the gluon jet is emitted, k_{lab} is the incoming photon momentum, k'_{lab} the momentum of the outgoing gluon jet. Note that in the lab. system one has $t = -4kk' \sin^2 \frac{1}{2} \theta_{\text{lab}}$, $\nu = M(k_{\text{lab}} - k'_{\text{lab}})$. The angle θ_{lab} is required to be relatively large such that $|t|/s = 2k' \sin^2(\theta_{\text{lab}}/2)/M$ remains finite for large $|t|$ and s . It is useful to compare Eq. (7) with the cross-section for muon hadron scattering in the deep inelastic region, which is given by

$$\frac{d^2\sigma}{d\Omega dE'_r} = \frac{\alpha^2}{4 E_r^2 \nu \sin^4 \frac{1}{2} \theta} \left(1 + \frac{\nu^2}{2 E_r E'_r} \right) F_2^e(x) \quad (8)$$

$[E_\mu(E'_\mu)]$ is the energy of the incoming (outgoing) muon.] Comparing Eqs. (7) and (8) we deduce

$$\left(\frac{d^2\sigma}{d\Omega dk'} \right)_{g+N \rightarrow \text{gluon jet} + X} = \frac{2\pi}{3\alpha} \frac{\nu^2}{k_{\text{lab}} k'_{\text{lab}}} \left(\frac{d^2\sigma}{d\Omega dE'_r} \right)_{\mu^- + N \rightarrow \mu^- + X} \quad (9)$$

Equation (9) clearly exposes the similarity of the QCD Compton effect and deep inelastic scattering. The proportionality factor $2\pi/3\alpha$ is ~ 50 for $\alpha \approx 0.5$.

We emphasize that the effect discussed here is one of the very few processes where the properties of gluons and gluon jets can be tested by experiment ^{5),6)}. Gluon jets are expected to look different from the "quark jets" which are presumed to be produced in e^+e^- annihilation or in purely

hadronic reactions. On the average a gluon jet will have SU_3 singlet quantum numbers and zero baryon number [see also Ref. 6].

3. - THE INVERSE QCD COMPTON EFFECT

It is well known from the experimental results in lepton production that about 50% of the nucleon energy is carried by gluons. Thus we expect within the QCD approach that the gluons inside one of the incoming hadrons can react with the quarks inside the second incoming hadron to produce a photon and a quark jet, both endowed eventually with high transverse momenta ("inverse QCD Compton effect"). Averaging over the incoming and summing over the final colours, we obtain for the cross-section of the reaction "gluon + quark $\rightarrow \gamma$ + quark" (see Fig. 2) :

$$\frac{d\sigma}{d\tilde{t}} = \frac{\pi\alpha\kappa}{3\tilde{s}^2} \left(1 + \frac{\tilde{t}}{\tilde{s}} + \frac{\tilde{s}}{\tilde{s} + \tilde{t}} \right), \quad (10)$$

where $\tilde{s}, \tilde{t}$ are the s, t variables relevant for the quark gluon subsystem. The four-momenta of the two incoming hadrons are denoted by p, q respectively, the four-momenta of the outgoing photon and the outgoing quark-jet by k', ℓ' respectively. We introduce the variables $v_1 = p(k' + \ell')$, $v_2 = q(k' + \ell')$, $s = (p + q)^2 \simeq 2p \cdot q$, $t = (q - k')^2 = -2qk'$, $u = (p - k')^2 = -2pk'$. The four-momentum of the incoming gluon is denoted by $y \cdot q$, the four-momentum of the incoming quark by $x \cdot p$. Due to the relation $k' + \ell' = xp + yq$ we have $v_1 = p(xp + yq) \simeq y(p \cdot q) \simeq \frac{1}{2}ys$, $v_2 = q(xp + yq) \simeq \frac{1}{2}xs$. For the process $p + q \rightarrow \gamma + X$ we find

$$\begin{aligned} \frac{d^3\sigma}{dt dv_1 dv_2} &= -\frac{\pi\alpha\kappa}{3} \int_0^1 \int_0^1 dx dy \frac{y}{(xy s)^2} \left(\frac{ys}{u} + \frac{u}{ys} \right) \delta(v_1 - \frac{1}{2}ys) \delta(v_2 - \frac{1}{2}xs) \frac{F_2^{ep}}{x} G_q^q \\ &\quad + p \leftrightarrow q \\ &= -\frac{\pi\alpha\kappa}{3} \frac{4}{x^3 y^2 s^4} \left(\frac{ys}{u} + \frac{u}{ys} \right) F_2^{ep}(x) G_q^q(y) \cdot y \\ &\quad + p \leftrightarrow q, \end{aligned} \quad (11)$$

where $G_q^q(y)$ is the gluon distribution function of the hadron q .

We restrict ourselves to the special case of proton-proton scattering where both the photon and the "quark jet" emerge at 90° in the centre-of-mass system ($\theta_\gamma, \theta_{\text{jet}} = 90^\circ$). (This configuration is especially suited for experiments at the CERN-ISR). In this special case one has $x=y, t=u, v_1=v_2$, and one finds :

$$\left(E_\gamma \frac{d^3\sigma}{dE_\gamma d(\cos\theta_\gamma) d(\cos\theta_{\text{jet}})} \right)_{\theta_\gamma = \theta_{\text{jet}} = 90^\circ} = \frac{5\pi\alpha\kappa}{48} \frac{1}{E_\gamma^2} F_2^{\text{ep}}(x) G^P(x) \quad (12)$$

(E : energy of incoming proton, E_γ : energy of emerging photon, $x = E_\gamma/E$).

We estimate the cross-section for the inverse QCD Compton process for $E = 30$ GeV. We use the parametrization $G^P(x) = ((n+1)/2) \cdot ((1-x)^n/x)$, which is normalized such that $\int_0^1 G(x) dx = \frac{1}{2}$, as required by the leptonproduction data. In Fig. 3 we present the results for $\kappa = 0.5$ and $n = 4$ (the results depend only very little on n for $n = 2 \dots 10$).

Within the QCD framework the large angle scattering of quarks and gluons in high energy reactions leads to events with two hadronic jets, both having high (and opposite) transverse momenta. Eventually this will lead to a $p_\perp^{-4}$ behaviour of the various production cross-sections (apart from logarithmic corrections). It is well known that in the present experiments such a behaviour is not seen ; the data support a steeper fall-off consistent with $p_\perp^{-8}$. One expects the $p_\perp^{-4}$ behaviour to set in at energies and transverse momenta slightly higher than those reached by present experiments ⁷⁾. Assuming that this will be the case, we estimate the cross-section for producing a single γ and a quark jet at 90° in the centre-of-mass system relative to the cross-section for producing two quark jets with the same transverse momenta back-to-back at 90° in the centre-of-mass system. One finds :

$$\frac{d\sigma(p+p \rightarrow \gamma + \text{"quark jet"} + X)}{d\sigma(p+p \rightarrow \text{"quark jet"} + \text{"quark jet"} + X)} = \frac{45 \cdot \alpha}{4 \cdot 44 \cdot \kappa} \frac{G^P(x) \cdot x}{F_2^{\text{ep}}(x)} \quad (13)$$

where $x = E_\gamma/E \cong E(\text{quark jet})/E$. For $E = 30$ GeV, $\kappa = 0.5$, and $E_\gamma = 5 \dots 10$ GeV this ratio decreases from 2.6% to 0.5%. It is difficult to estimate the γ/π_0 ratio. Typically in a "quark jet" a pion carries only a small fraction of the total jet momentum, and one expects therefore the γ/π_0 ratio to be much

larger than the $\gamma/\text{"quark jet"}$ ratio given in Eq. (13) (above 10%). Note, however, that this large photon γ/π_0 ratio is only obtained in the region where the thus far hypothetical $p_{\perp}^{-4}$ behaviour, predicted by QCD, is valid. At energies explored thus far^{8),9)}, where the $p_{\perp}^{-4}$ term is supposed to be overshadowed by other terms, the γ/π_0 ratio is expected to be smaller (of the order of a few %).

Finally we should like to stress the importance to search for the two types of QCD Compton effects discussed here in high energy experiments. Besides the production of two back-to-back jets via, e.g., quark-quark scattering in high energy hadron collisions, those effects are important consequences of the QCD picture of hadrons. To establish those effects would be a central test of the QCD approach.

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FIGURE CAPTIONS

Figure 1 Description of the QCD Compton effect in the centre-of-mass system of the γ quark system. The incoming quark absorbs the incoming photon and decays into a gluon and a quark, both having high transverse momenta. Two "back-to-back" jets emerge. The quarks which are not hit by the photon continue to move to the left and generate the left-moving hadrons. No right-moving hadrons exist.

Figure 2 The inverse QCD Compton effect : an incoming gluon (dashed line) reacts with a quark to produce a quark jet and a γ ray. The figure describes this reaction in the gluon-quark centre-of-mass system.

Figure 3 The differential cross-section

$$E_\gamma \cdot \frac{d^2\sigma}{dE_\gamma d(\cos\theta)_\gamma d(\cos\theta_{jet})}$$

at $E = 30 \text{ GeV}$, $\theta_\gamma = \theta_{jet} = 90^\circ$ for $\kappa = 0.5$.

FIG.1

FIG.2

FIG.3