Very energetic photons at HERA ☆

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We show that very energetic photons in the backward direction can be produced in deep inelastic Compton scattering at HERA. Assuming a fixed energy of 9 GeV for the initial photons and 820 GeV for the protons a high rate is found for the production of final photons with a transverse momentum equal to 5 GeV/c and energy between 40 GeV and 300 GeV. These energetic photons arise mainly from the scattering of the soft gluonic constituents of the initial photon with quarks from the proton. They are produced in the backward direction in coincidence with a photon beam jet of energy ~9 GeV in the forward direction.

The deep inelastic Compton (DIC) process

$$\gamma p \to \gamma X\ , \qquad (1)$$

with the transverse momentum of the final-state photon larger than say 5 GeV/c, is the simplest type of photoproduction which can be measured at the ep collider HERA. Several effects arising from the hadronic interaction of photons in this process have been studied in the literature. The contributions containing the structure and fragmentation functions of the photon have been included in analyses based on the order α_s calculation [1–4] as a background to the basic subprocess

$$\gamma q \to \gamma q \qquad (2)$$

(see fig. 1). In ref. [5] these leading-logarithmic contributions have been considered with respect to a study of the structure of the photon at HERA. A more detailed investigation which incorporates a study of the fragmentation of the final-state partons into photons is presented in our recent papers [6,7]. The cross section for the DIC process (1) at the ep collider HERA has been calculated [6,7] with the simplifying assumption that the initial photon has a fixed energy of 9 GeV and this leads to a γp centre-of-mass energy squared of $S_{\gamma p} = 30\,000$ GeV^2. In addition, ref. [7] provides some estimates of the production rate for the DIC process in the ep collision based on a more realistic treatment of initial photons, based on the equivalent photon approximation. We studied the Born contribution (eq. (2)), the $O(\alpha_s)$ corrections to the process and the $\alpha\alpha_s$ and α_s^2 leading-logarithmic subprocesses which arise if one of the initial or final photons or both photons in process (1) interact with the constituents of the proton not directly but via their constituents, i.e. like hadrons. The two most important subprocesses of this type are shown in figs. 2 and 3. The hadronic interaction of photons with the protons dominate at low and medium p_T^γ; that is for $5 < p_T^\gamma < 15$ GeV/c [6,7]. This is due to the fact that in this range of p_T^γ the photon can be probed to very small x_γ, down to ~0.003 at $p_T^\gamma = 5$ GeV/c and ~0.03 at $p_T^\gamma = 15$ GeV/c. Note that the proton is probed similarly in this region of p_T^γ.

In this note we would like to discuss a particular feature of the DIC process at HERA, namely the possibility of the production of very energetic photons

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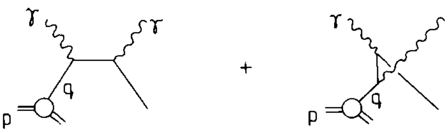

Fig. 1. The Feynman diagram for the γq→γq Born subprocess.

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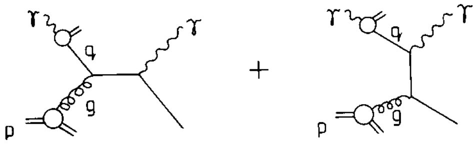

Fig. 2. The Feynman diagram for the $q^{\gamma}g^{p} \to \gamma q$ subprocess.

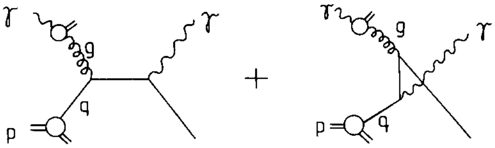

Fig. 3. The Feynman diagram for the $g^{\gamma}q^{p} \to \gamma q$ subprocess.

in the backward direction with respect to the incident photon (or electron). The energy of final photons may be more than one order of magnitude larger than the energy of the initial photons. In fig. 4 we show the maximum of the final-state photon energies E'_{γ} which can be acquired at a particular scattering angle in the ep laboratory frame. At an angle of 30° with respect to the electron direction the photon energy is ~10 GeV, at 90° it is 5 GeV and at about 177° it is ~110 GeV. The invariant cross section for the DIC process is large for backward scattering at these angles and energies; for example, for $E'_{\gamma} \sim 110$ GeV, it is approximately 2 pb/GeV ^{2}.

In order to understand better this effect which is due to the boost in the ep collider HERA we discuss the features of the simple QED Compton process. It is well known that the elementary Compton process

$$\gamma e \to \gamma e \tag{3}$$

is dominated at high energies by the backward (with respect to the incident photon) scattering. The relevant matrix element squared is

$$\overline{|\mathcal{M}|}^2 = -2e^4(u/s+s/u) , \tag{4}$$

where $s=(p_{\gamma}+p_e)^2$ and $u=(p_{\gamma}-p'_{\gamma})^2$ are the usual Mandelstam variables. It is obvious that backward

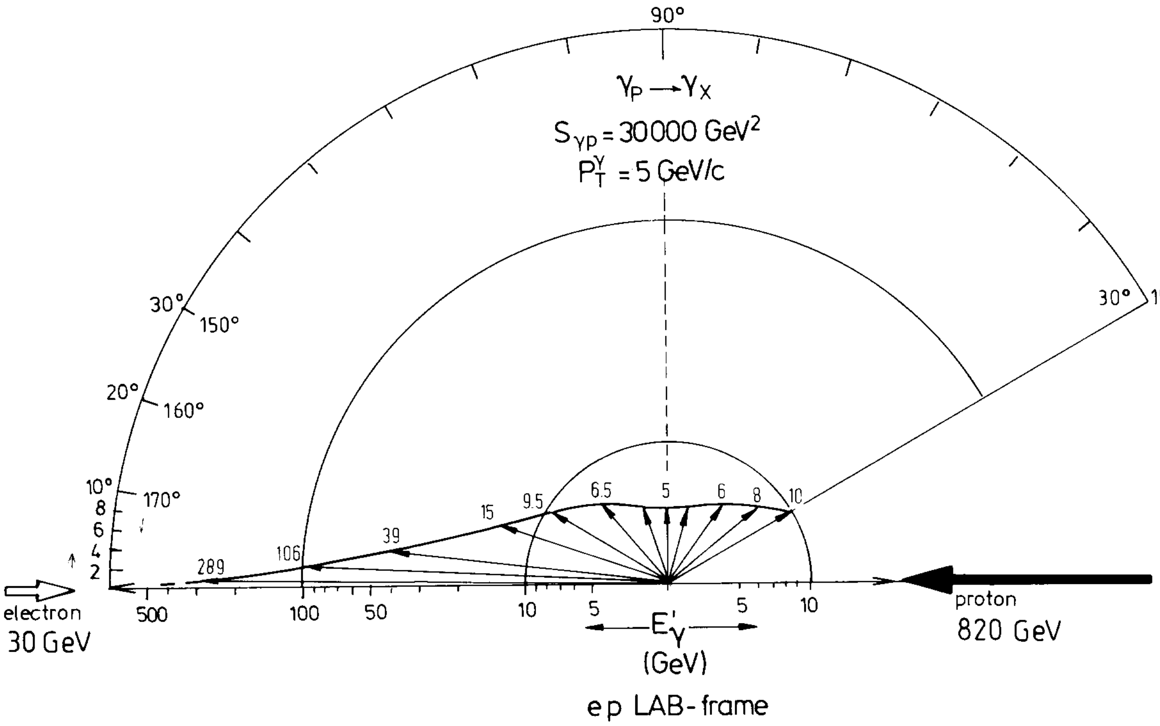

Fig. 4. A polar plot for the DIC process in the ep laboratory system indicating the relationship between the maximum energies of the final-state photons E'_{γ} and the angle at which they are emitted for $S_{\gamma p} = 30\,000$ GeV^2 and $p_T^{\gamma} = 5$ GeV/c.

Compton scattering, which corresponds to $\theta \sim 180°$ (or $u \sim 0$), gives the largest contribution to the cross section for the eγ scattering. The other interesting feature of the backward scattering in process (3) is that at high energies the photon and the electron interchange their energies during the collision. This is especially important if the initial electron possesses an energy much larger than the initial photon. In this case photons with energies much higher than the initial photon energy can be produced in the backward, or in other words, the inverse Compton process. This fact has been used to produce e.g. 20 GeV photons in the scattering of ultraviolet photons off 30 GeV electrons [8]. It has been proposed also [9] that by scattering 1 eV laser photons off 1 TeV electrons will produce an ~1 TeV photon beam by the inverse Compton scattering. The maximum energy is obviously obtained at $\theta = 180°$. In this case [10]

$$E_\gamma = 1\ \text{eV}, \quad E_e = 1\ \text{TeV}, \quad E'_\gamma = 0.95\ \text{TeV} \gg E_\gamma . \qquad (5)$$

The Compton process (2), where photons scatter off quarks is also dominated by backward scattering. The relevant matrix element squared is the same as in (4) with the charge of the electron being replaced by the charge of the quark but where $s = (p_\gamma + p_q)^2$ and $u = (p'_\gamma - p_\gamma)^2$ are now the partonic Mandelstam variables. However, this subprocess, unlike the $\gamma e \to \gamma e$ process, cannot proceed independently. It constitutes one of the many subprocesses of an inclusive hadronic process of the type of deep inelastic Compton scattering (1).

Now we will discuss the DIC process with the production of the photons with transverse momentum of 5 GeV/c, at the kinematics relevant to HERA (defined above) where the elementary as well as nonelementary aspects of photon interaction may be studied. By elementary interaction we understand here the case where the photon directly participates in the hard subprocess, like for example in the subprocess (2), which we are going to consider now.

The asymmetric nature of HERA's kinematics (9 GeV photons and 820 GeV protons) seems to suggest that the final state photons arising from subprocess (2) would exhibit some of the characteristics of the γe collision described above. However, in this case the situation is very different. The QED hard cross section for the process (2) must be convoluted with the quark distributions in the proton which are peaked at small x_p. This prefers the scattering of (9 GeV) photons on quarks with lowest kinematically allowed energy ($x_p \sim 10^{-3}$). At the partonic level (in the γq centre-of-mass system) this corresponds to 90° scattering and not 180° scattering as we would expect from the matrix element alone (eq. (4)). As a result the production of forward photons in the γp centre-of-mass system dominates in the DIC process (1). In the ep laboratory frame (see fig. 1) we find that the photons are still produced in the forward direction although at larger angles (~50°–80°) with only a moderate energy

$$E'_\gamma = 6\text{–}7\ \text{GeV}, \quad \sim E_\gamma = 9\ \text{GeV} . \qquad (6)$$

As has already been mentioned the process (1) may also occur via the nonelementary interaction of the photons. In this case photons interact indirectly through their constituents. The contributions arising from the nonelementary photon interactions are particularly large for the production of final photons in the direction opposite to the incident photons [6,7]. Two important contributions to the DIC cross section are due to the following subprocesses (see figs. 2 and 3):

$$q^\gamma g^p \to \gamma q \qquad (7)$$

and

$$g^\gamma q^p \to \gamma q , \qquad (8)$$

where for convenience we add the superscripts which indicate the parent particles. The first one has very similar features to the subprocess (2) since the quarks are rather hard in the photons while the gluons in the proton are very soft. Photons coming from this subprocess are mainly produced in the forward hemisphere in the ep laboratory frame ($\theta \sim 50°$–$80°$). On the contrary the second subprocess (eq. (8)) may lead to very energetic photons in the final state and in this respect may be regarded as a hadronic analogue of the inverse Compton process (eq. (3)) described above. The matrix element for the process (8) is given by eq. (3) but with the change of the coupling constant and the charge. Again, we would expect the backward scattering of the photon, i.e. small $|u|$, to dominate at the parton level. However, the contribution of this subprocess to the hadronic cross section for the DIC process, given by

$$E\,\mathrm{d}\sigma = \int \mathrm{d}x\, q^{p}(x, Q^2) \int \mathrm{d}x_\gamma\, g^{\gamma}(x_\gamma, Q^2) E\,\mathrm{d}\sigma\,, \quad (9)$$

is affected strongly by the fact that the gluons in the photon have a very soft distribution while the number of quarks in the proton at large x_p is small. The competition of these opposite tendencies results in the most preferred configuration corresponding to approximately $30°\,^{+40°}_{-20°}$ scattering at the parton level (in the partonic centre-of-mass system). In the γp centre-of-mass system this corresponds to backward scattering of the photons, $\theta \sim 10°–70°$. In the ep laboratory frame these photons are boosted further in the backward direction (see fig. 4). Their energies range from 40 GeV at 173° to 300 GeV at approximately 179° relative to the electron direction. The contribution of these events to the invariant cross section for the DIC process is large, of the order of a few pb/GeV^2 [7].

The largest angle at which photons may realistically be measured at HERA is about 176° and in this case we may expect about 2000–3000 events per year with

$$E'_\gamma \sim 110\ \mathrm{GeV} \gg E_\gamma = 9\ \mathrm{GeV}\,. \quad (10)$$

In obtaining this number of events we assumed that the luminosity for the γp collision is one tenth of the nominal luminosity for HERA.

Note that at $p_T^\gamma = 5$ GeV/c the invariant cross section for the production of photons in the backward direction in process (1) that results from the direct coupling of photons to the constituents of the proton, i.e. from eq. (2), is two orders of magnitude smaller than that due to the interaction of the nonelementary photons with the protons [6,7].

In fig. 5 we compare the contributions to the cross

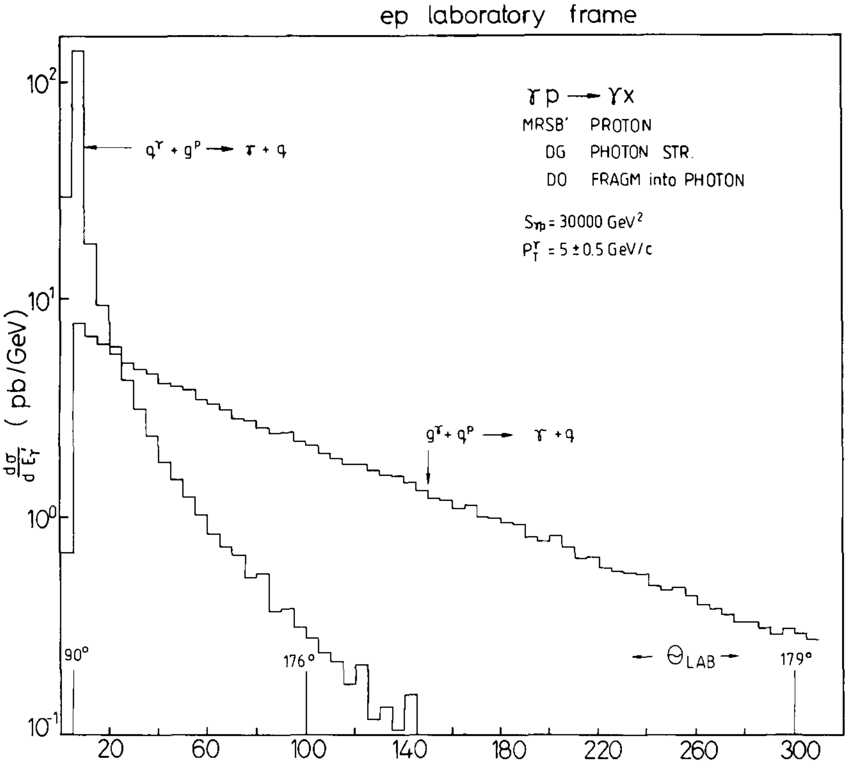

Fig. 5. The cross sections $\mathrm{d}\sigma/\mathrm{d}E'_\gamma$ for the DIC process due to the sub-processes $g^\gamma + q^p \to \gamma + q$ and $q^\gamma + g^p \to \gamma + q$ as a function of the final-state photon energy E'_γ in the ep laboratory frame. $S_{\gamma p} = 30\,000$ GeV^2 and $p_T^\gamma = 5$ GeV/c. In the calculation we used the MRSB′ proton structure function [11], the Drees and Grassie photon structure function [12] and finally the Duke and Owens fragmentation [1] for the quark-to-photon fragmentation. The corresponding scattering angles are also indicated.

section $d\sigma/dE'_\gamma$ for the DIC process from the two subprocesses described above in the ep laboratory frame. At the lower energies of final photons it is (7) that dominates while at higher energies (8) does, as expected. In this calculation we used the MRSB′ proton structure function [11], the Drees and Grassie photon structure function [12] and finally the Duke and Owens fragmentation [1] for the quark-to-photon fragmentation. In refs. [6,7] we found that the broad peak in the invariant cross section for the subprocess in (8) occurred at $y^\gamma = -1.5$ in the γp centre-of-mass system which corresponds to an energy in the ep laboratory frame of ~110 GeV.

In conclusion we note that at HERA in a tagged experiment corresponding to the fixed energy of photon–proton scattering we can expect a significant number of very high energy photons produced in the backward DIC process due to a certain subprocess which results from the nonelementary behaviour of the initial-state photons. Simultaneously in the forward direction we expect to find the initial photon beam jet with an energy almost equal to 9 GeV, i.e. full energy of incident photons. Other subprocesses which lead also to the backward production of energetic photons have a photon which results from the fragmentation of a final-state parton and presumably these will be found accompanied by a jet (see ref. [7]). Among them π^0's decaying into photons are expected.

For a realistic estimate of the flux of high energy photons in the final-state in untagged experiments at the ep collider HERA we convolute the γp calculation with the equivalent photon approximation. Some results obtained in this manner can be found in refs. [4,5,7]. They indicate that when integrated over the γ spectrum in the ep collision the relevant cross sections are still large enough to be observed at HERA. Using this approach we calculate the energy distributions $d\sigma/dE'_\gamma$ from subprocesses (7) and (8) contributing to the process ep→eγX. As can be seen in fig. 6 also in these circumstances high energy photons are produced in the backward direction although with a somewhat lower rate than in the previous case with the fixed energy of the γp collision.

To summarize, the observation of energetic photons produced in the direction of the incoming proton at HERA would be a clean signal of the nonelementary structure of photons in high energy interactions with hadrons.

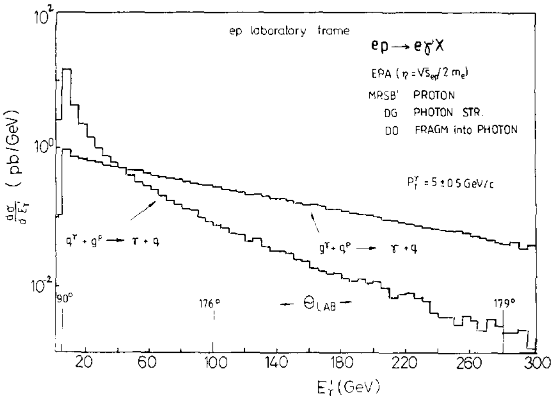

Fig. 6. The same as in fig. 5 for the process ep→eγX at the collider HERA ($E_e = 30$ GeV, $E_p = 820$ GeV). The energy spectrum of the initial-state photons is based on the equivalent photon approximation (EPA): $f(x) = (\alpha/2\pi)\{[1+(1-x)^2]/x\}\ln\eta$, where $x = E_\gamma/E_e$ and $\eta = \sqrt{S_{\gamma p}}/2m_e$.

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