EFFECTS OF THE STRUCTURE OF PHOTON IN DEEP INELASTIC COMPTON PROCESS AT HERA

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We investigate the deep inelastic Compton process $\gamma p \Rightarrow \gamma X$ at the forthcoming ep collider HERA ($\sqrt{s_{\gamma p}} \sim 170$ GeV). We perform the consistent, order $\alpha^2\alpha_s$ calculation of the DIC cross section paying particular attention to the contributions which appear due to the hadron-like interaction of photon. In addition we include new important higher order contributions, $\sim\alpha^2\alpha_s^2$, which arise due to the hadronic nature of initial *and* final photons. We find that the production of photons with transverse momenta p_T up to ~ 15 GeV/c is dominated by events involving hadron-like interaction of photon, with a significant contribution from the new subprocesses. In this region of p_T there appears an interesting possibility to probe separately the content of gluons in photon and in proton as they contribute to the different domains of rapidity.

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1. Introduction

The first aim of the planned ep collider HERA is to consider the fine structure of proton through the collision of proton with highly virtual photons in a new region of very large Q^2 — up to $\sim 10^5$ GeV^2 [1].

However, at HERA there is also a large chance for the hard interaction of proton with almost real photons ($Q^2 \approx 0$). In this case we deal with the photoproduction processes which also can be used to probe structure of proton at very small distance. The average photon-proton center-of-mass energy expected for these events ($s_{\gamma p} \sim 30000$–50000 GeV^2, see e.g. [1]) is high enough to allows for hard collision of real photon with proton constituents. Individual particles or jets with large transverse momenta produced in such hard scattering can then be used to determine structure functions of proton at energy scale $Q^2 \sim p_T^2$ similarly as in high energy hadron-hadron processes.

The simplest inclusive photoproduction process which can be measured at HERA is the deep inelastic Compton (DIC) scattering $\gamma p \Rightarrow \gamma X$. In this paper we discuss this process in the region of large transverse momenta of final photons, $p_T \gg \Lambda_{QCD}$, where the perturbative QCD can be applied.

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Various aspects of QCD can be tested in the DIC process depending on the magnitude of the transverse momentum of produced γ's.

The production of photons with largest p_T ($p_T \sim p_T^{max} \sim \sqrt{s_{\gamma p}}$) is dominated by the direct quark-photon interaction. In these events both initial and final photons act as elementary fields. The photons with relatively low p_T are produced mainly in higher order subprocesses which occur due to hadronic structure of photons.

In the region where the point-like coupling of the photon to the constituents of the proton dominates (events with large p_T photons) one can study the Compton scattering on quarks $\gamma q \Rightarrow \gamma q$ (the Born level) and the structure of higher order QCD corrections to this process [2–6]. At the HERA collider this can be done in a new kinematic range of the photon transverse momentum up to 80 GeV/c. Presently the data on the deep inelastic Compton scattering coming from the fixed target experiment (NA14 collaboration) exist at much lower energy, $\sqrt{s_{\gamma N}} \sim 13$ GeV, with the highest transverse momentum of final photons about 4 GeV/c [7].

In this large p_T region both initial and final photons probe directly the parton distributions in the proton by pure electromagnetic forces. Therefore the DIC process at large p_T can be used for the measurement of the proton structure functions in a way complementary to the usual deep inelastic scattering structure function method [4, 8]. Typically the large Q^2 ($\sim p_T^2$) and large x, $x \geqslant 0.1$, can be reached here. It is important that higher order QCD corrections are found to be small for these events [2–6].

The DIC process at low p_T has more complicated structure. In the region where p_T is small but nevertheless large enough to justify the perturbative calculation there may appear large QCD corrections typical for the processes characterized by two large but very different scales, $\sqrt{s_{\gamma p}} \gg p_T \gg \Lambda_{QCD}$ [9].

The other new aspect which shows up at low p_T is related to the nonelementary, hadronic-type interaction of photons with hadrons [10, 11, 2, 3]. This feature of high energy photons can be described in a convenient way by introducing the concept of the structure of photon.

The point-like or perturbative component describing the parton content of photon and the parton fragmentation into photon is, in principle, exactly calculable in the QCD [10]. Unfortunately the next-to-leading order calculation leads to unphysical results in small x region [12].

The nonperturbative contribution to the photon structure function is usually taken from the vector dominance model. There is no unique way for adding in a consistent way these two components, the perturbative and nonperturbative one, especially in the analysis performed beyond the leading order. Recently there was proposed an interesting leading order approach based on solving Altarelli-Parisi equations for photon with the experimental input at some Q_0^2 [13]. This is probably the most consistent treatment of the structure of photon, even if it has some limitations, e.g. it leads to discontinuities in parton distributions.

Unfortunately, in our analysis we need to know not only the parton distributions in the photon but also the functions describing parton fragmentation into photon. These are not known experimentally and at the moment only the "pure" theoretical parametrizations of fragmentation functions based on parton model [10] or on leading order analysis, as proposed by Duke and Owens [12], exist.

Therefore we prefer here to use the simple description of the effects of the nonelementary structure of photon taking into account only the point-like component of quark densities and quark decays functions basing on the parton model predictions or asymptotic leading order parametrization [10, 12]. The other parametrizations we will discuss in the forthcoming publication [14].

In the DIC process there exists the region of relatively low p_T where the effects of the structure of photon dominate over the higher order QCD corrections and even over the Born contribution i.e. that due to the subprocess $\gamma q \Rightarrow \gamma q$. In this case the DIC process looks like ordinary hadron-hadron collision. At HERA collider this is expected to happen for $p_T \sim 5 \div 15$ GeV/c. In this kinematic region one can consider hadronic structure of photon, especially, as we will see later, the gluon content of photon. Of course in these same events simultaneously the structure of proton is probed. Comparing to the previous case of large p_T photons, lower Q^2 and wider range of x, down to very small value $\sim 10^{-3}$, might be involved here. The similar effect has been found by Drees and Godbole [15] in the photoproduction of jets at the HERA collider.

In this note we study the deep inelastic Compton scattering at HERA energies. Our main aim is to investigate the effects of hadronic structure of photon connected with its point-like constituents: quarks and gluons. We discuss the importance of $\alpha\alpha_s$ subprocesses which correspond to the hadronic-type interaction of initial *or* final photon. Next we calculate the contributions to the DIC cross section due to order α_s^2 subprocesses arising when both initial *and* final photons interact through their constituents. These terms were neglected in all previous analyses of the DIC process at HERA (see however the comment in Ref. [3]).

We are primarily interested in the main features of Compton events and for this purpose we make simplifying assumption of the fixed energy of photon-proton scattering. Following [1] we assume that the (real) photon energy in the laboratory frame for the HERA collider is equal to 9 GeV which, taking into account that the proton energy is 830 GeV, corresponds to $S \equiv s_{\gamma p} = 30000$ GeV^2. The more appropriate treatment should include a spread in the initial photon momentum spectrum using the equivalent photon approximation or full ep kinematics. This will be done later when the final results for cross section will be presented [14].

2. *Basic subprocesses*

The deep inelastic Compton (DIC) process

$$\gamma p \to \gamma X \tag{1}$$

occurs at the lowest order of the perturbative expansion in α and α_s, i.e. in the Born approximation, due to the photon-quark scattering ($\sim\alpha^2$)

$$\gamma q \to \gamma q. \tag{2}$$

This leads to the α^2 terms in the inclusive cross section for the process (1). The corresponding diagrams for processes (1) and (2) are shown in Fig. 1 and Fig. 2, respectively.

The simple photon-gluon elastic process

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

contributes also to (1) via the box diagram (Fig. 3). It gives however higher order terms $\sim\alpha^2\alpha_s^2$ in the cross section for the process (1). The process (3) plays a minor role at the kinematical regime expected for the collider HERA and we will not consider it in detail. The discussion of some features of this interesting process can be found in Refs [16] and [2, 3].

Taking into account the α_s corrections to the lowest order basic subprocess (2) we have to include the virtual diagrams (Fig. 4a) as well the real gluon production (Fig. 4b)

$$\gamma q \to \gamma q g \tag{4a}$$

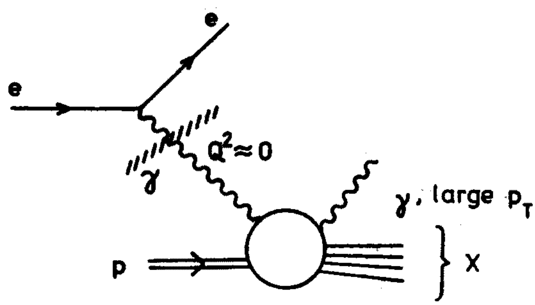

Fig. 1. The deep inelastic Compton process $\gamma p \Rightarrow \gamma X$ with almost real initial photons coming from the bremsstrahlung radiation from the electron at the ep collider HERA

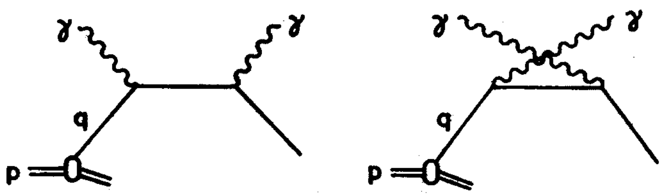

Fig. 2. The Born contribution to the Compton process :$\gamma q \Rightarrow \gamma q$

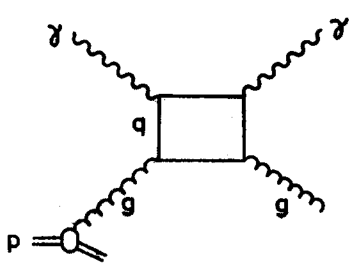

Fig. 3. The box contribution to the Compton process :$\gamma g \Rightarrow \gamma g$

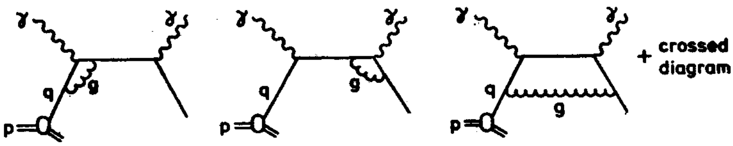

Fig. 4a

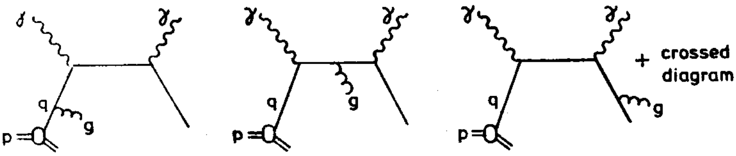

Fig. 4b

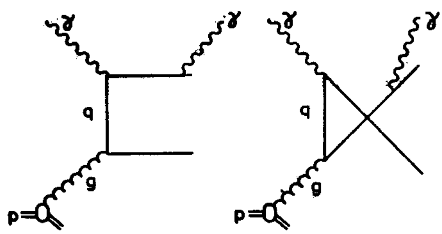

Fig. 4c

Fig. 4. The Feynman diagrams representing α_s order QCD corrections: a) virtual gluon corrections to the Born term; b) real emission of gluons : $\gamma q \Rightarrow \gamma q\, g$; c) subprocess with initial gluons: $\gamma g \Rightarrow \gamma q\, \bar{q}$, which contribute at the same order

and the process (Fig. 4c)

$$\gamma g \to \gamma q \bar{q}. \tag{4b}$$

These corrections leads to the order $\alpha^2\alpha_s$ terms in the cross section for (1).

To the DIC process (1) contribute also some subprocesses involving the interactions of partonic constituents of photon. We will consider the following order $\alpha\alpha_s$ subprocesses (see Figs 5–6) involving one elementary photon:

$$q\bar{q} \to \gamma g, \tag{5a}$$

$$qg \to \gamma q, \tag{5b}$$

$$gq \to \gamma q, \tag{5c}$$

$$\gamma q \to qg, \tag{6a}$$

$$\gamma g \to q\bar{q}. \tag{6b}$$

The above formulae have the general form of the 2-body subprocesses ab ⇒ cd, where a(c) stands for the initial γ or its constituent (the final γ or its parent parton), b — for the constituent of proton. The related processes corresponding to the change $q \Leftrightarrow \bar{q}$ are not explicitly written. Note that some of cross diagrams are omitted in Figs. 5–6.

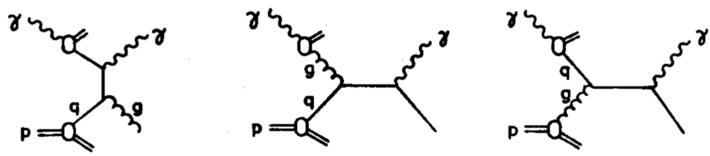

Fig. 5a

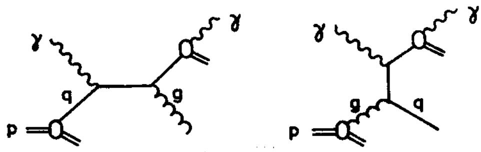

Fig. 5b

Fig. 5. Initial *or* final photons interacting through their partonic constituents. The most important $\alpha\alpha_s$ subprocesses: a) the decay of initial photon into quark or gluon; b) the fragmentation into photon. Only quark and antiquark fragmentation is taken into account

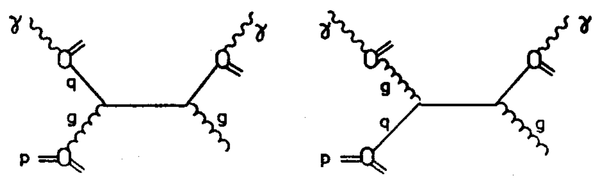

Fig. 6. Initial *and* final photons interacting through their partonic constituents. The most important α_s^2 subprocesses with gluons qg ⇒ qg and gq ⇒ qg. The gluon fragmentation into γ and gg collisions are neglected

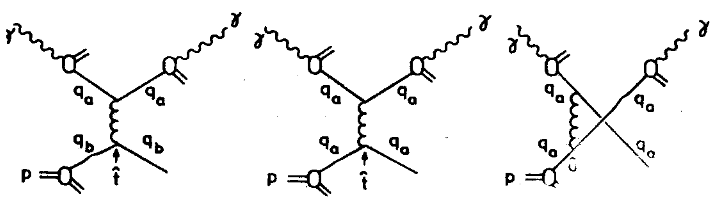

Fig. 7. Initial *and* final photons interacting through their partonic constituents. The α_s^2 quark-antiquark subprocesses $q_aq_b \Rightarrow q_aq_b$ and $q_aq_a \Rightarrow q_aq_a$

When both photons in (1) act as hadrons there appear the order α_s^2 subprocesses involving quarks and gluons. We take into account the following α_s^2 subprocesses (see Figs 7–8)

$$gq \to qg, \tag{7a}$$

$$qg \to qg, \tag{7b}$$

$$q_aq_b \to q_aq_b, \tag{8a}$$

$$q_a q_a \to q_a q_a, \tag{8b}$$

$$q_a \bar{q}_a \to q_a \bar{q}_a, \tag{9a}$$

$$q_a \bar{q}_a \to q_b \bar{q}_b, \tag{9b}$$

and the corresponding ones obtained by the substitution $q \Leftrightarrow \bar{q}$. Subscripts denote flavour states.

As can be seen from the above formulas, Eqs (5)–(9), we neglect in the calculation the gluon fragmentation into photon, and we do not take into account gluon-gluon scattering. These contributions due to the softness of the structure and the fragmentation functions of gluon are expected to be negligibly small in the considered p_T range even at the lowest transverse momentum which we will consider, $p_T \sim 5$ GeV/c. We will discuss these contributions in future [14].

Taking into account that the structure and fragmentation functions for photon are proportional to α we see that the subprocesses (5–6) lead to the $\alpha^2\alpha_s$ terms in the cross sections for (1) whereas subprocesses (7–9) contribute at order $\alpha^2\alpha_s^2$. They are the higher order (in α_s) corrections as compared to the previous ones. Nevertheless they happen to be large, as we will see later. In some papers there is introduced a different notation (see for example Ref. [2]) based on the fact that the structure and fragmentation functions for the photon contain the factor $\log Q^2/\Lambda^2 \sim 1/\alpha_s$. In this approach both sets of subprocesses give the contributions to the cross section for the DIC process (1) of the same order which moreover is equal to the lowest order (Born) term, namely α^2. We prefer to use the notation which shows the close relation of the $\alpha\alpha_s$ subprocesses with the α_s corrections which appear simultaneously in the analysis of the DIC process performed beyond the leading logarithmic approximation.

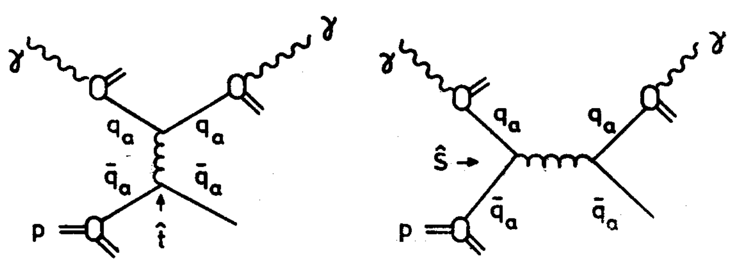

Fig. 8a

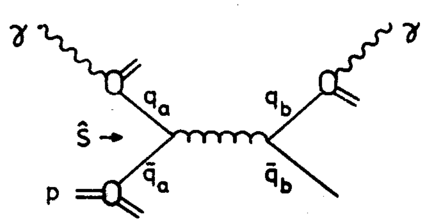

Fig. 8b

Fig. 8. As in Fig. 7 for a) $q_a\bar{q}_a \Rightarrow q_a\bar{q}_a$; b) $q_a\bar{q}_a \Rightarrow q_b\bar{q}_b$

3. *The Born contribution*

For the deep inelastic Compton process (1) we consider the inclusive distribution of the final hard photons. The naive parton model predicts the invariant cross section for the photon production in the following form:

$$2E_\gamma \frac{d\sigma}{d^3p_\gamma} = \sum_{q,\bar{q}} \int_0^1 dx f(x) 2E_\gamma \frac{d\hat{\sigma}^{\text{Born}}}{d^3p_\gamma}, \tag{10}$$

where

$$2E_\gamma \frac{d\hat{\sigma}^{\text{Born}}}{d^3p_\gamma} = \frac{1}{8\pi^2 s} |\overline{M}|^2_{\text{Born}} \delta(s+t+u) \tag{11}$$

is the differential cross section for the $\gamma q \Rightarrow \gamma q$ scattering calculated in the Born approximation (Fig. 2). The squared matrix element averaged (summed) over spin, polarization and colour in the initial (final) states is equal in this approximation to

$$|\overline{M}|^2_{\text{Born}} = -2e_q^4 \left(\frac{u}{s} + \frac{s}{u}\right). \tag{12}$$

We use the Mandelstam variables s, t, u describing the kinematics of the partonic Compton process $\gamma q \Rightarrow \gamma q$ and assume that quarks are massless. The energy-momentum conservation for the Compton process at the parton level leads to the delta function in Eq. (11). Introducing the corresponding hadronic variables S, T, U:

$$s = xS, \quad t = T, \quad u = xU, \tag{13}$$

one can find that only quarks (antiquarks) carrying the momentum fraction $x = x_0$, where

$$x_0 = \frac{-T}{S+U}, \tag{14}$$

contribute to the hadronic cross section (10).

Finally we give the QCD improved parton model formula for the DIC process (1) with scale dependent quark distributions in the proton

$$2E_\gamma \frac{d\sigma}{d^3p_\gamma} = \frac{\alpha^2}{S(-T)} \sum_{q,\bar{q}} e_q^4 f_q(x_0, Q^2)\, \Sigma^{\gamma q \Rightarrow \gamma q}, \tag{15}$$

with the modified matrix element

$$\Sigma^{\gamma q \Rightarrow \gamma q} = -2\left(\frac{u}{s} + \frac{s}{u}\right). \tag{16}$$

We see (Eqs (12), (16)) that the matrix element is large for the backward scattering (small u) but for the hadronic cross section (15) the situation is quite opposite — here the large enhancement for the forward direction is predicted due to the structure function behaviour.

4. The order α_s corrections

Taking into account the α_s corrections to the basic subprocess (Figs 4a–c) we get for the inclusive production of photon in the DIC process the following expression (symbolically)

$$2E_\gamma \frac{d\sigma}{d^3p_\gamma} = \int_0^1 dx f(x, Q^2)\left[2E_\gamma \frac{d\hat{\sigma}^{\text{Born}}}{d^3p_\gamma} + \alpha_s \Delta\right]$$

$$+ \int_0^1 dx \int_0^1 d(xp) f(x, Q^2) f_\gamma(xp, Q^2) d\hat{\sigma}_1 + \int_0^1 dx \int_0^1 \frac{dz}{z^2} f(x, Q^2) D_\gamma(z, Q^2) d\hat{\sigma}_2, \tag{17}$$

where $f(x, Q^2)$ is the parton distribution in proton, $f_\gamma(xp, Q^2)$ and $D_\gamma(z, Q^2)$ describe parton distribution in photon and parton fragmentation into γ, respectively; xp is the momentum fraction carried by the partonic constituents of photon (parton in γ), z is the fraction of the parton momentum carried by final photon (γ in parton). The invariant partonic cross sections with nonelementary initial (final) photon are denoted by $d\hat{\sigma}_1 (d\hat{\sigma}_2)$:

$$d\hat{\sigma}_j = 2E_\gamma \frac{d\hat{\sigma}_j}{d^3p_\gamma}, \quad j = 1, 2. \tag{18}$$

For simplicity we have omitted in the above formula, Eq. (17), the sum over different species of partons. The subprocesses described by Eqs (5a–c) contribute to the $d\hat{\sigma}_1$; these from Eqs (6a, b) to $d\hat{\sigma}_2$. The invariant cross sections for the individual subprocesses can be calculated using the relevant formulae from Ref. [2].

In the equation (17) the first two terms constitute the QCD improved parton model contribution or the Born term (Eq. (15)) and the first order correction, respectively. The others terms are due to structure or the fragmentation function of the photon. The formula has the next-to-leading order structure, that means that all ingredients e.g. distribution and fragmentation functions (also the running coupling constant α_s) should have a proper accuracy.

In this next-to-leading order approach the size of the α_s correction (function Δ) depends on the scheme used for the definition of the structure and fragmentation functions and there is an interplay between the various terms in (17). It would be inconsistent to compare the Born contribution (with elementary photons) with the hadron-like photon contributions omitting the Δ term in the next-to-leading analysis.

We will discuss the contributions due to the structure fragmentation of the photon (Eq. (17)) separately in the next Section.

It can be easily found that in the Eq. (17) the following range of x:

$$x_0 \leqslant x \leqslant 1,$$

where x_0 is given by Eq. (14), is relevant.

5. *Hadron-like photon contributions*

5.1. The order $\alpha\alpha_s$ subprocesses

As we already discussed, the contributions due to the order $\alpha\alpha_s$ subprocesses appear necessarily in the consistent QCD calculation of the cross section for the process (1) with the $\alpha^2\alpha_s$ accuracy (see Eq. (17)).

The contribution involving the structure function of photon due to the particular subprocess (i) from Eq. (5) can be written in the following form

$$2E_\gamma \frac{d\tilde{\sigma}^i_{st}}{d^3p_\gamma} = \frac{\alpha\alpha_s}{S(-U)} \int_{x_0}^{1} dx f(x, Q^2) f_\gamma(\overline{xp}_0, Q^2) \frac{1}{x^2} \tilde{\Sigma}_i, \tag{19}$$

with

$$\overline{xp}_0 = \frac{-xU}{xS+T}, \tag{20}$$

whereas for the fragmentation into photon we have (for subprocess (i) from Eq. (6))

$$2E_\gamma \frac{d\tilde{\sigma}^i_{fr}}{d^3p_\gamma} = \frac{\alpha\alpha_s}{S(-T)} \int_{x_0}^{1} dx f(x, Q^2) D_\gamma(\bar{z}_0, Q^2) \frac{1}{x(1+xU/T)} \tilde{\Sigma}_i, \tag{21}$$

with

$$\bar{z}_0 = \frac{-(T+xU)}{xS}. \tag{22}$$

In Eqs (19) and (21), for each subprocess (i), there appears the modified matrix element $\tilde{\Sigma}_i$, which is equal to the standard matrix element without the corresponding coupling constant.

5.2. The α_s^2 subprocesses

Taking into account the possibility that in the DIC process (1) both initial and final photons interact through their constituents we have to include the contributions due to the α_s^2 subprocesses. The individual subprocesses (i) of this type (Eqs (7–9)) contributes

$$2E_\gamma \frac{d\tilde{\tilde{\sigma}}_i}{d^3p_\gamma} = \int_0^1 dx \int_0^1 d(xp) \int_0^1 \frac{dz}{z^2} f(x, Q^2) f_\gamma(xp, Q^2) D(z, Q^2) [\hat{d\sigma}]_i, \tag{23}$$

where the partonic cross section

$$[d\hat{\sigma}]_i = 2E_\gamma \frac{d\hat{\sigma}_i}{d^3p_\gamma}$$

can be found in Ref. [17].

The expression (23) can be written in the simpler form

$$2E_\gamma \frac{d\tilde{\tilde{\sigma}}_i}{d^3 p_\gamma} = \frac{\alpha_s^2}{S(-T)} \int\limits_{x_0}^{1} dx \int\limits_{xp_0}^{1} d(xp) f(x, Q^2) f_\gamma(xp, Q^2) D_\gamma(\zeta_0, Q^2) \frac{1}{x(xp)(xp+xU/T)} \tilde{\tilde{\Sigma}}_i, \quad (24)$$

where, as above, we have introduced the corresponding modified matrix elements and

$$\zeta_0 = \frac{-(xpT+xU)}{(x(xp)S)}. \quad (25)$$

6. *Results*

We have studied the DIC process (1) at the future HERA collider. Assuming the fixed energy of the γp scattering with real photon $S = 30000$ GeV^2 we first calculated the kinematical range of x, xp and z, corresponding to the structure of proton, photon and for the quark fragmentation into photon, as well Q^2 which can be probed in this process by observing the final photon with the particular transverse momentum and rapidity. Next we performed the numerical calculations of the cross sections for the DIC process.

6.1. Kinematics

It is very convenient to describe the production of final photons in the DIC process (1) in terms of following variables (the γp center of mass system is assumed):

$$x_T = \frac{2p_T}{\sqrt{S}} \quad \text{and} \quad y = -\ln \mathrm{tg}\frac{\theta}{2} = -\tfrac{1}{2}\ln\frac{T}{U}. \quad (26)$$

The forward (backward) scattering is described by large positive (negative) y, with initial photons pointing in the positive rapidity direction.

In the Born approximation (Eqs (10)–(16)) we have obtained the simple result that only quarks carrying the momentum fraction x_0 (Eq. (14)) contribute to the hadronic cross section for the DIC process. In terms of the variables (26) we find for x_0 the following expression

$$x_0 = \frac{x_T e^{-y}}{2 - x_T e^{y}}. \quad (27)$$

At fixed x_T the minimum value of x_0 is reached in the forward hemisphere, namely we have

$$x_0^{\min} = x_T^2 \quad \text{at} \quad y = -\ln x_T. \quad (28)$$

The range of the rapidity of final photons is given by

$$y_{\min} < y < y_{\max}, \quad (29)$$

where

$$y_{\max} = -\ln \mathrm{tg}\frac{\arcsin x_T}{2} \quad \text{and} \quad y_{\min} = -y_{\max}.$$

The kinematics based on the lowest order subprocess (2) is shown in Fig. 9. Here the value of x_0 as a function of the rapidity oι the final photon at few values of p_T (5, 20 and 60 GeV/c) is presented. If higher order subprocesses are included the whole range of x, between x_0 and 1, contributed to the DIC scattering. From the Fig. 9 it is easy to read out what proton constituents participate in the production of final photons with particular values of p_T and of y. We see that at $p_T = 5$ GeV/c for the forward direction we enter very small x_0, with the minimum value $x_0 \sim 3 \cdot 10^{-3}$ at the rapidity $y_m \sim 2.8$. The minimal value of x_0 grows with the p_T, at $p_T = 20$ GeV/c it is ~0.055. Very characteristic shape of x_0, with rapid growth in the forward direction, will influence the behaviour of the cross section as we will see later.

The similar analysis one can perform for the contributions due to the structure of photon and due to fragmentation into photon. The minimal values of xp and z can be obtained from Eqs (20), (22) by putting x equal to 1. In terms of x_T and y they can be written as follows

$$xp_0 = \frac{x_T e^y}{2-x_T e^{-y}}, \tag{30}$$

$$z_0 = \frac{x_T(e^y+e^{-y})}{2}. \tag{31}$$

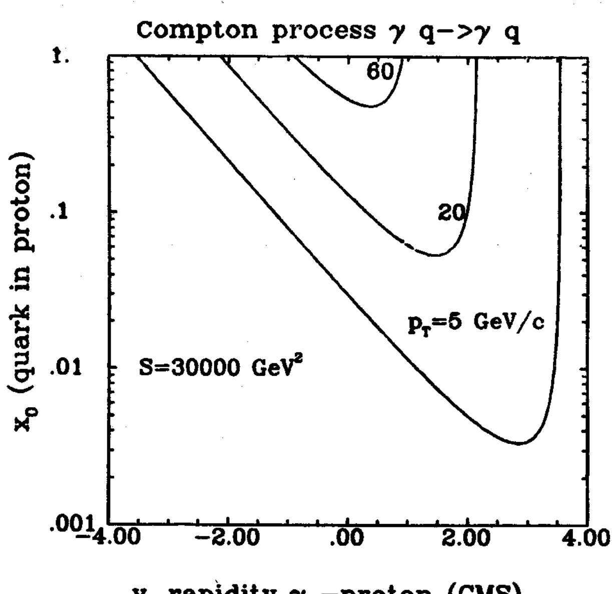

Fig. 9. The kinematics of the DIC process at $S = 30000$ GeV^2 corresponding to the Born subprocess $\gamma q \Rightarrow \gamma q$ (with elementary γ's). The values of x_0 (Eq. (27)) probed in the DIC scattering at the different transverse momenta of final photon (p_T = 5, 20 and 50 GeV/c) are shown as a function of its rapidity y (in the γ-proton center of mass system with the initial γ going to the right)

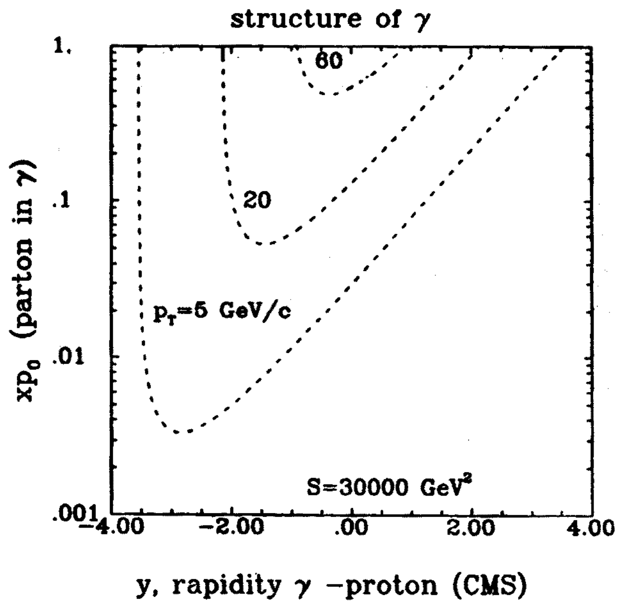

Fig. 10. The kinematics of the DIC process at $S = 30000\ \mathrm{GeV}^2$ for the contribution due to the structure function of photon. The values of xp_0 (Eq. (30)), i.e. the minimal fraction of the initial photon momentum carried by its constituents as can be probed in the DIC events with different transverse momentum of final photons ($p_T = 5$, 20 and 50 GeV/c) are shown as a function of the rapidity of the photon y

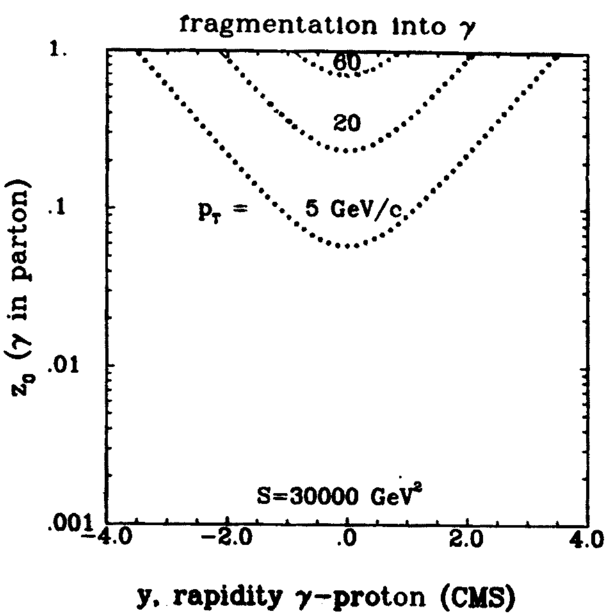

Fig. 11. The kinematics of the DIC process at $S = 30000\ \mathrm{GeV}^2$ for the contribution due to the parton fragmentation into photon. Here we present the values of z_0 (Eq. (31)), i.e. the minimal fraction of the final parton momentum which should carry the final photon in order to be observed with the particular transverse momentum ($p_T = 5$, 20 and 60 GeV/c) and the rapidity y

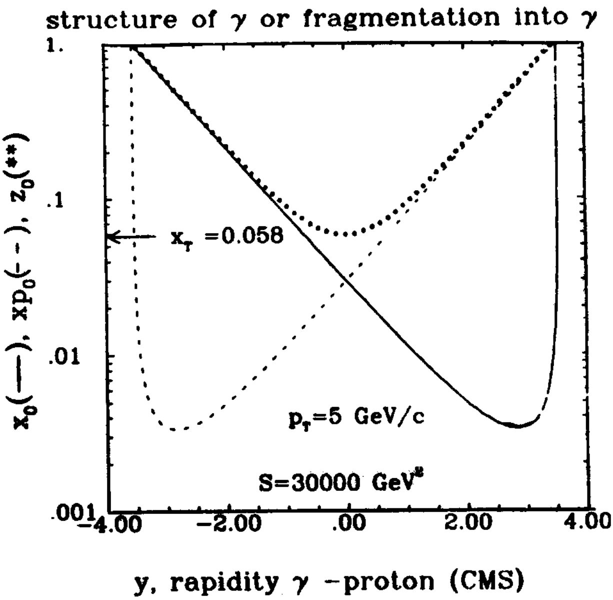

Fig. 12. The momentum fractions x_0, xp_0, and z_0 as functions of the final photon rapidity for the DIC process at S = 30000 GeV² and p_T = 5 GeV/c. At fixed value of the rapidity the allowed ranges of fractions x, xp and z lie between the corresponding curves and 1

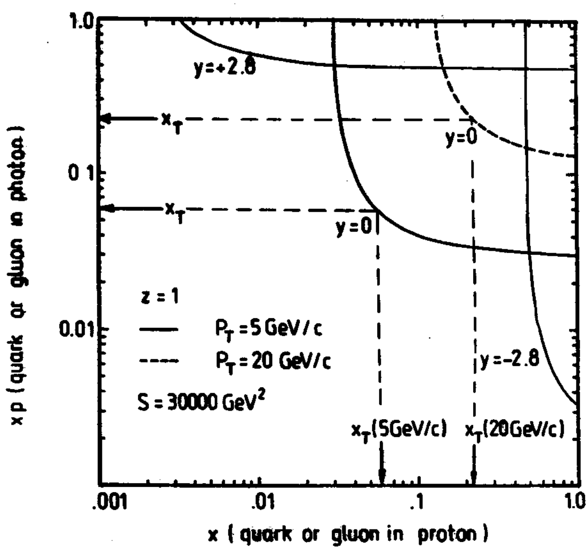

Fig. 13. The relation between x and xp for the photon structure function contributions (z = 1) to the DIC process at S = 30000 GeV². The transverse momentum of the final photon are equal to 5 GeV/c (———) and 20 GeV/c (- - - -). The corresponding rapidities are y = 0, ±2.8 for p_T = 5 GeV/c and y = 0 for p_T = 20 GeV/c

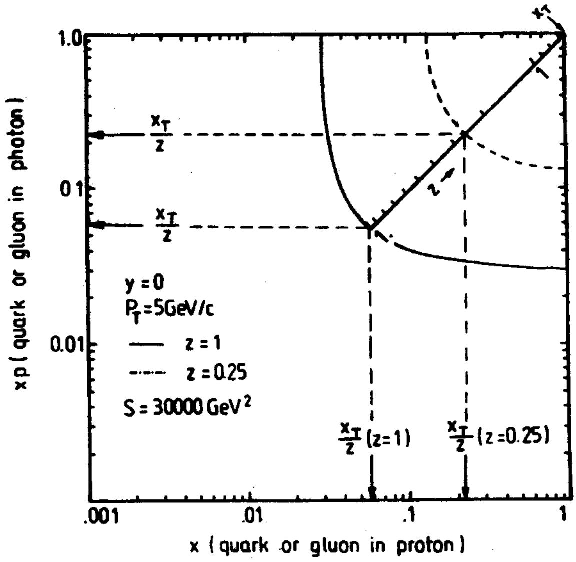

Fig. 14. The same as in Fig. 13 but for the case where the photon structure and the fragmentation into photon contribute to the DIC process. Now the transverse momentum and the rapidity of final photon are fixed, $p_T = 5$ GeV/c and $y = 0$. The relation between x and xp is presented for two values of z, $z = 1$ (———) and $z = 0.25$ (– – – –)

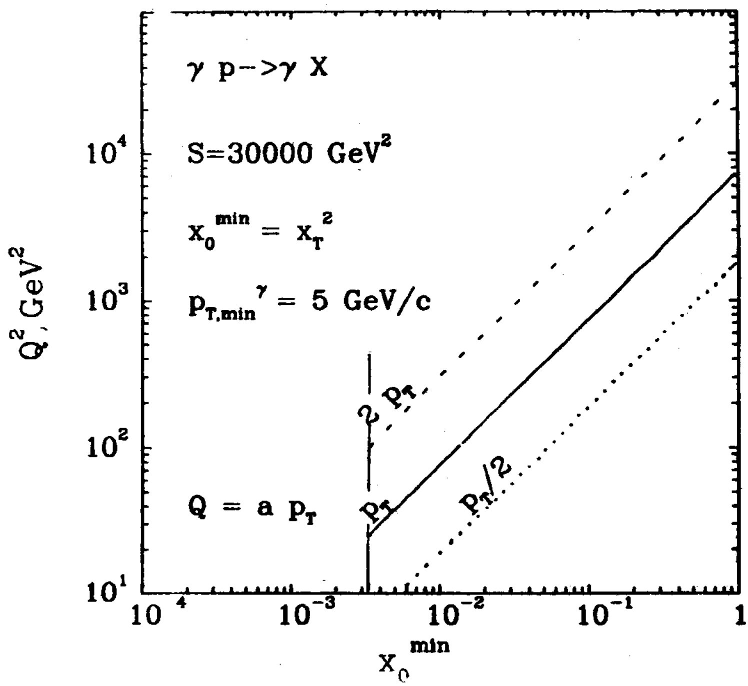

Fig. 15. The range of x and Q^2 as can be measured in the DIC process at $S = 30000$ GeV². The full line corresponds to the widely used definition of the Q^2, namely $Q^2 = p_T^2$. The allowed area (Q^2, x) lies to the right of the line. The comparison with two other definitions, $Q = 2p_T$ and $Q = p_T/2$, is presented

The values of xp_0 and z_0 as functions of y at fixed transverse momentum of photon, $p_T = 5$, 20 and 60 GeV/c, are shown in Fig. 10 and Fig. 11, respectively. Note that, whereas the xp_0 follows the pattern of x_0 from Fig. 9 with the interchange of the forward and the backward direction, the shape of z_0 is different. It is symmetric under the change $y \Leftrightarrow -y$. Note that the fragmentation is rather hard for the DIC process in the considered range of transverse momentum. The minimum value of z_0 is $\sim$0.06 at $p_T = 5$ GeV/c and $\sim$0.3 at $p_T = 20$ GeV/c. But even in the case of lower p_T we will see that effectively the fragmentation will be much harder, since the most important contribution arises from $y \sim \pm y_m$ where the corresponding z_0 is around 0.6. This fact may help in the detection of final photons.

In Fig. 12 the comparison of x_0, xp_0 and z_0 as function of y is presented for $p_T = 5$ GeV/c. In Figs 13 and 14 we show in more detail the kinematics of the DIC events with the nonelementary photons.

In Fig. 15 the allowed range of (Q^2, x_0) is presented for the DIC scattering. It seems that it may fill the gap between the present day DIS experiments and the DIS at HERA collider [1]. Of course one has to remember that in the DIC process there is a freedom in the definition of the scale Q^2. Besides, x is not fixed as we discussed above.

6.2. Cross sections

We have performed numerical calculations of the invariant cross section for the deep inelastic Compton process at $S = 30000$ GeV^2. For the parton densities in proton we use the Martin-Roberts-Stirling parametrization (MRS1 set [18]). The Duke-Owens [12] and parton model [10, 3] parametrization of quark distribution in the photon and of the quark fragmentation into the photon were used. For the gluon distribution in the photon only the Duke-Owens parametrization was taken. The other parameters are as follows: energy scale $Q = p_T$, $\Lambda_{QCD} = 0.197$ GeV, $n_f = 4$. We used the results of Ref. [6] for the contribution Δ (Eq. (17)) using the universal conventions for the structure and fragmentation functions. Two loop coupling constant α_s was introduced.

In Fig. 16 we present the contribution to $Ed\sigma/d^3p$ for the DIC process due to hadron--like γ's — the $\alpha\alpha_s$ subprocesses (Eqs (5)–(6)) — at the transverse momentum of the final photon equal to 5 GeV/c. In Fig. 17 the same for the α_s^2 subprocesses (Eqs (7)–(9)) are shown. In both cases the gluon content of the photon and gluon content of the proton dominate the corresponding cross sections. Their domination occurs in the separated regions of the phase space — "gluons in γ" dominate in the photon production in the backward direction whereas "gluons in proton" are responsible for the large cross section in the forward direction. This can be easily understood since in these regions very small xp_0 and x_0 are probed in photon and in proton, respectively. As it is well known, small x regions are highly populated by gluons in proton and in photon. In addition in these interesting for us domains of rapidities, $y \sim \pm y_m$, produced photons are taking large fractions of their parent parton energy ($z > 0.6$).

In Fig. 18 we compare the elementary γ and hadron-like γ contributions to the invariant cross section $E\,d\sigma/d^3p$ for the DIC process at $S = 30000$ GeV^2 and $p_T = 5$ GeV/c. The

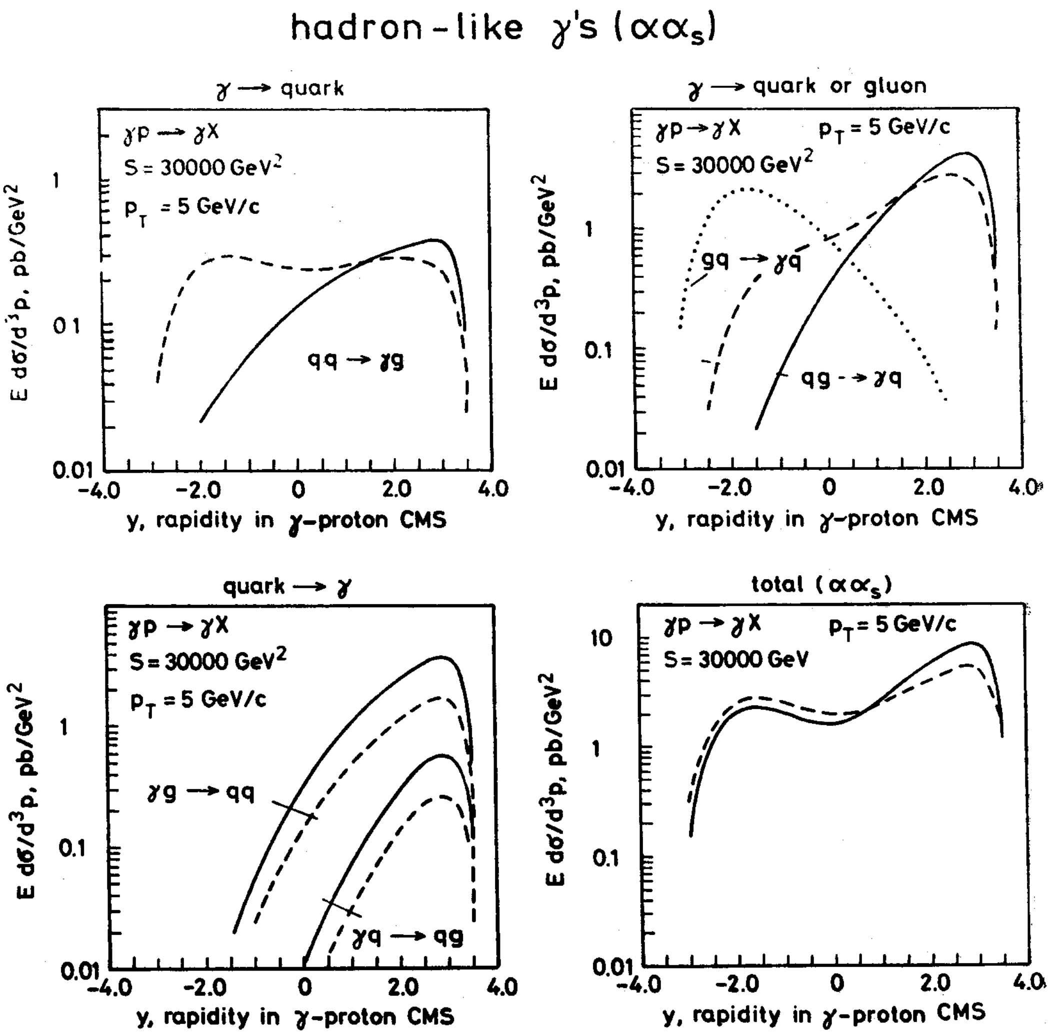

Fig. 16. The contribution to the invariant cross section $E\, d\sigma/d^3p$ for the DIC process due to hadron-like γ's — the $\alpha\alpha_s$ subprocesses. The energy $S = 30000\ \mathrm{GeV}^2$, the transverse momentum of the final photon is equal to 5 GeV/c. For the proton we use the Martin-Roberts-Stirling parametrization (MRS1) set [18]. The Duke-Owens [12] (DO - - - -) and parton model [10, 3] (parton ———) parametrization of quark distribution in the photon and of the quark fragmentation into the photon were used. For the gluon distribution in the photon (.........) the Duke-Owens parametrization was taken. The other parameters: energy scale $Q = p_T$, $\Lambda_{QCD} = 0.107$ GeV, $n_f = 4$

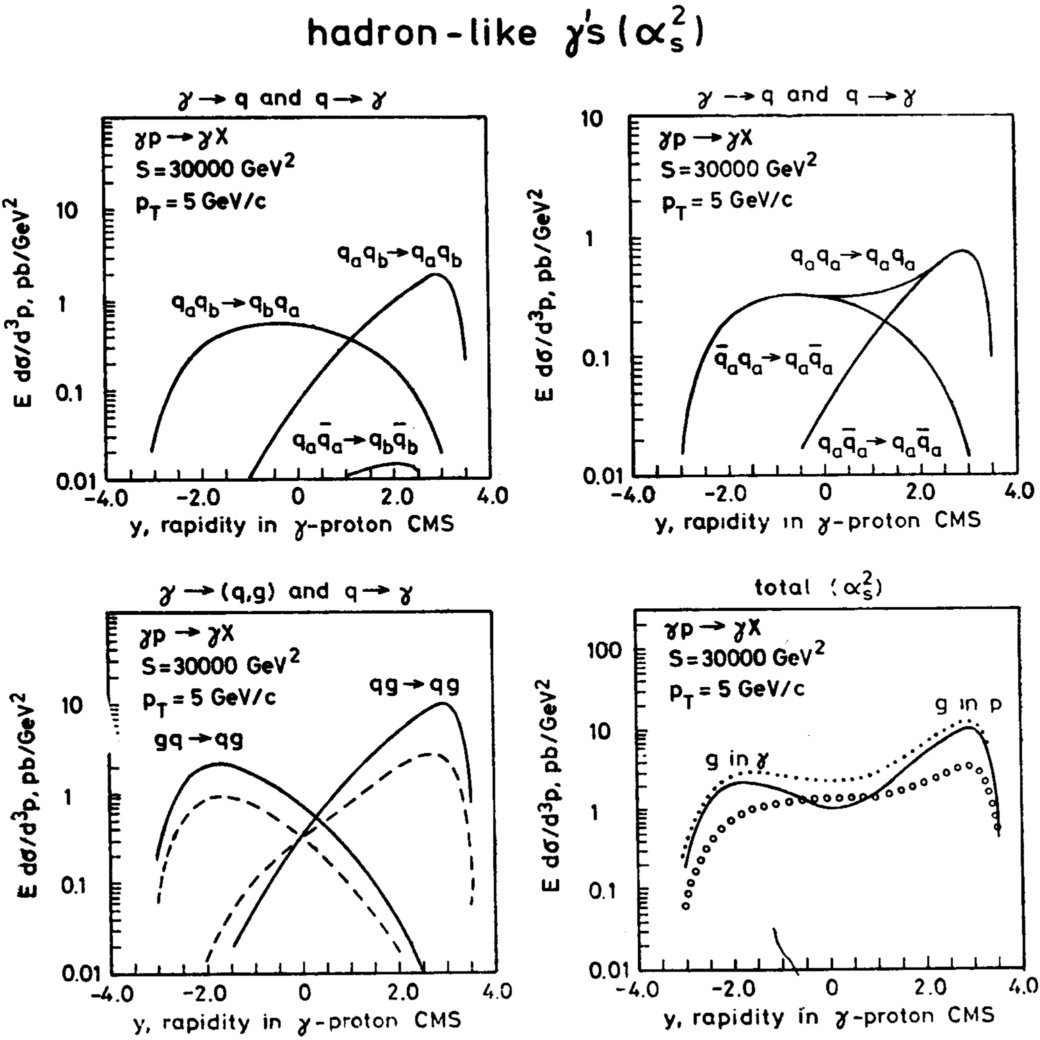

Fig. 17. The contribution to the invariant cross section $E\,d\sigma/d^3p$ for the DIC process due to hadron-like γ's — the α_s^2 subprocesses. The parton model (parton ———) parametrization of quark distribution in the photon and of the quark fragmentation into the photon were used. For the most important contribution due to qg ⇒ qg and gq ⇒ qg processes also the Duke-Owens (– – – –) parametrization were introduced: energy scale $Q = p_T$, $\Lambda_{QCD} = 0.107$ GeV, $n_f = 4$. On the down-right diagram a curve (· · · ·) is a sum of (o o o o) qq processes and (———) gq+qg processes

elementary photons lead to the Born term and the "Born + (α_s)" contribution (see Eq. (17)) and also to the box term (Eq. (3)) due to the diagram from Fig. 3.

The hadron-like γ's contribute to the cross section due to $\alpha\alpha_s$ and α_s^2 subprocesses. Their sum is presented by the highest curve in the figure. We see that the hadron-like γ's dominate over the elementary ones especially in the backward scattering where the effect is on level of two orders of magnitude. The most interesting is the fact that the $\alpha\alpha_s$ and α_s^2 subprocesses are giving similar contributions both in shape and in magnitude.

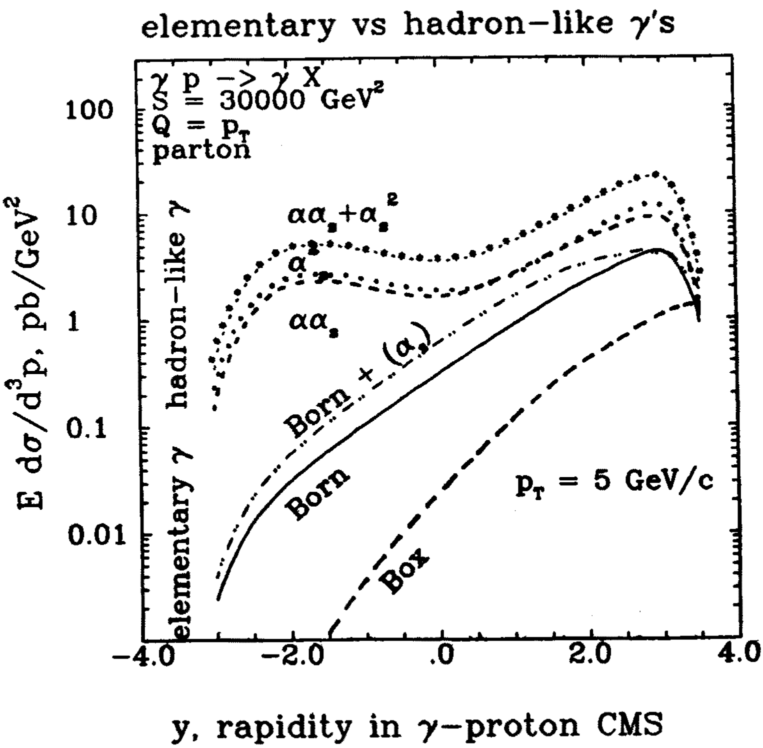

Fig. 18. The elementary versus hadron-like γ's contribution to the invariant cross section $E\, d\sigma/d^3p$ for the DIC process at $S = 30000$ GeV^2 and $p_T = 5$ GeV/c. The scale Q is equal p_T. The MRS1 parametrization for proton and the parton parametrization for photon were used. Only for the gluon content in the photon the DO parametrization was introduced. The elementary photons leads to the Born term (———) and the "Born + (α_s)" (– · · · –) contribution (see Eq. (17)). The hadron-like γ's contribute to the cross section due to $\alpha\alpha_s$ (– – – –) and α_s^2 subprocesses (.........). Their sum is presented by the highest curve (· ∗ · ∗ ·). For comparison also the box contribution (– – – –) (see Eq. (3)) is shown. Other details as in Fig. 16

The box contribution (Eq. (3)), which gives contributions of the same order $(\alpha^2\alpha_s^2)$ to the cross section for the DIC process (1) as the α_s^2 subprocesses, can be neglected here but in the very forward direction (see also Ref. [6]).

The results for $p_T = 30$ and 60 GeV/c are presented in Fig. 19. Only the Born contribution (Eq. (19)) and the full hadron-like γ's contribution (the sum of the $\alpha\alpha_s$ and α_s^2 subprocesses) are shown here. The elementary photon interaction dominates already at $p_T = 30$ GeV/c. As before the box diagram plays negligible role and we do not present the corresponding curves.

Finally we show the p_T distribution for final γ's produced in the DIC process at $S = 30000$ GeV^2. The comparison of contributions from elementary (only the Born term) and hadron-like γ's are presented. In the range 5 GeV/$c \lesssim p_T \lesssim 15$ GeV/c one can expect to observe the effect due to structure of photons.

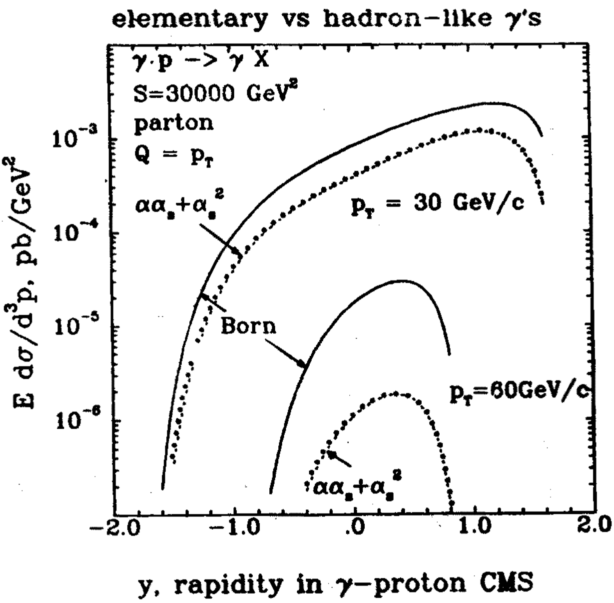

Fig. 19. The same as in Fig. 18 for $p_T = 30$ and 60 GeV/c. Only the Born contribution (Eq. (19)) (———) and the full hadron-like γ's contribution (the sum of the $\alpha\alpha_s$ and α_s^2 subprocesses) (– • – •) are shown

7. *Conclusions*

We have discussed the deep inelastic Compton process at the ep collider HERA, assuming according to the existing estimation that the fixed initial energy of γp collision would be, in the center of mass system, around 170 GeV ($S = 30000$ GeV^2). At this energy we discuss production of the photons with the transverse momentum p_T between 5 GeV/c and the maximum $p_T \sim 80$ GeV/c. We present predictions for the invariant cross section and p_T distribution of hard photons based on consistent order $\alpha^2\alpha_s$ calculations. In this approach there appear large contributions from the hadronic structure of initial or final photons. The effect is very large for the production of photons with $p_T = 5$ GeV/c especially in the backward direction. In this region subprocesses connected with the structure of photon give contributions to the invariant cross section almost two orders of magnitude larger than elementary basic Compton process $\gamma q \Rightarrow \gamma q$ (the Born term). The α_s corrections are well under control, not exceeding 100% of the lowest order contribution. Summing large double logarithmic terms we can obtain the factor of 3–4 but no more [7]. This will not change the domination of the hadronic structure of photon over the elementary γ's interaction at least in the backward direction. Having this in mind we then include in the analysis the α_s^2 subprocesses which arise when two γ's involved in the DIC process behave as hadrons. These contributions formally should be neglected as terms of higher order in the small parameter α_s. However, numerically they are found to be large, comparable to those which are due to order $\alpha\alpha_s$ subprocesses. At larger p_T the contributions due to α_s^2 subprocesses decrease faster than these due to $\alpha\alpha_s$ subprocesses as can be seen in Fig. 20, where the p_T distribution is shown.

Results obtained in this paper show that we should expect the large effect due to hadronic structure of initial or/and final photons in DIC at HERA for the p_T between 5 and 15 GeV/c. However some words of caution are needed here.

First, in the consistent analysis of the DIC process with the $\alpha^2\alpha_s$ accuracy one should use the parton distributions in the photon as well the parton fragmentation function into photon calculated in the next-to-leading order approach. Unfortunately they do not exist yet.

Second, in performing the consistent $\alpha^2\alpha_s^2$ calculation one should include beside the considered by us contributions due to hadron-like γ's also the α_s^2 corrections to the basic Compton process (Eq. (2)) and the α_s corrections to the $\alpha\alpha_s$ subprocesses. We expect that the first type of terms should not influence the effect, as we have discussed above. Similarly we do not expect that the second type of new contributions i.e. α_s corrections to the $\alpha\alpha_s$ subprocesses may be larger that 100%.

Finally, the high energy photons interact with proton not only elementarily or via their partonic constituents. There is an important nonperturbative component as given by the vector meson dominance model. It should be included in the full analysis of the DIC process at HERA, especially at region of low p_T. There does not exist the accepted, consistent approach which would allow to separate and extract the nonperturbative component of photon from the data. However one expects that considered effect of non-elementary γ's would be stronger due to these additional contributions.

Nevertheless we believe that our results give reliable estimations of the particular

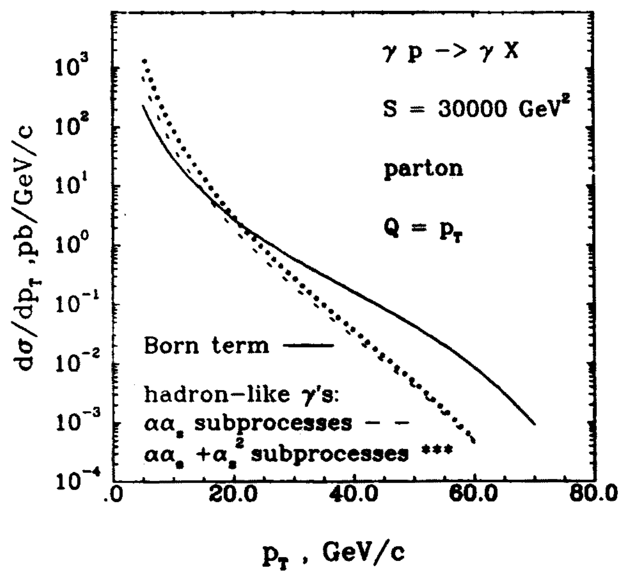

Fig. 20. The p_T distribution for final γ's produced in the DIC process at $S = 30000$ GeV^2. The contributions from elementary and hadron-like γ's are presented: the photon-quark scattering $\gamma q \Rightarrow \gamma q$ (Born term ———), order $\alpha\alpha_s$ subprocesses (- - - -) and the sum of the $\alpha\alpha_s$ and α_s^2 subprocesses (* * * *). The other details as in the Fig. 16

contributions to the cross section for the DIC process at HERA. If we take integrated luminosity of 100 pb^{-1} per year, we see the photon distribution is measurable out to about $p_T \sim 60$ GeV/c [4]. This means that HERA enlarges enormously the range of p_T as compared to with previous experiment on DIC. It is interesting that in the DIC process at HERA the proton structure functions can be measured in the range of x, and Q^2 which may fill the gap between the present day DIS experiments and the deep inelastic scattering planned at HERA.

For p_T larger than 20 GeV/c the Born contribution dominates. At lower p_T the higher order subprocesses involving the constituents of photon are more important than the ones with elementary photons. The events with photons carrying the transverse momentum $p_T \sim 5$–10 GeV/c and going in the backward direction may be used to measure the gluon content of photon with xp down to 10^{-3}. The same can be done for gluon content of proton by observing photons with the same p_T but going in the forward direction.

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