THE STRUCTURE OF THE PHOTON IN HARD HADRONIC PROCESSES *,**

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The concept of the structure of the photon is discussed and the progress in the measurement of various structure functions of the photon as well of parton distributions in the photon is shortly reviewed.

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1. The photon and its structure

1.1. The notion of the photon

The concept of the photon originated in 1900 in the description of the black body radiation when M. Planck assumed that the emission and the absorption of energy should appear in the form of quanta of energy. The Einstein suggestion presented in 1905, that light be considered a collection of independent particles of energy, or particles of light was not easily accepted neither by Planck nor by other physicists. R.A. Millikan, experimentalist working on the photo-emission from metal surfaces, *even in the face of his own data (*supporting the Einstein's view*) called it a "bold, not to say reckless, hypothesis"*. For twenty years also Bohr resisted the concept of light quanta, *he, again like Planck, argued that the locus of the problem was not light, but matter* (from [1a]). In 1922 a convincing evidence for light quanta appeared in the scattering of X rays on electrons (A. Compton's experiment). The current name: the photon was given by the American chemist G.N. Lewis in 1926.

The Quantum Electrodynamics (QED), the theory describing the interaction between electrons and photons, was introduced later on (years 1925–1927 by Born, Heisenberg, Jordan and Dirac [1b, c]); photon plays

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here a role of a gauge boson, mediating the electromagnetic interaction. It is assumed to be a massless and chargeless object with a pointlike coupling to elementary, charged particles. Its role is not changed in the Standard Model. No doubt, it is the oldest and the best known boson.

1.2. "Structure" of the photon[1]

In quantum field theory a photon can fluctuate into virtual states of remarkable complexity (Ref. [3g]). Such a state may materialized by a collision with another system.

At first, the photon was regarded as structureless ... As the scale of available energies increased, it was found that through an interaction with a Coulomb field the photon could materialize as pairs of electrons

$$\gamma \rightarrow e^+e^-. \quad (1)$$

Although not usually thought of in these terms, this phenomenon was the earliest manifestation of photon structure. So, one can say that *the physical photon has an electron-positron pair constituent.*

... The photon (real or virtual) was for purpose of hadronic interactions again regarded as structureless, ... in reality the photon has an internal structure which is very similar to that of hadrons, except that it occurs with a probability only of order $\alpha \sim 1/137$.

The hadronic properties of photon were observed first in the soft processes like $\gamma p \rightarrow \rho p$ or in $\gamma p \rightarrow \gamma p$, where the typical for pure hadronic elastic processes falloff with the square of the momentum transfer t was present. Such *soft* hadronic processes involving photons can be described in the so called Vector Dominance Model(VDM), assuming the "ρ-meson component" in the photon (also ω and ϕ components, or other vector mesons resonances in the Generalized VDM (GVDM)).

As the $|t|$ increases it is very unlikely that the process remains elastic. The inelastic production starts to dominate, nevertheless one can still find in the photon–hadron scattering a similarity to the pure hadron–hadron collision. In both cases, for example, in the *hard* inclusive processes the quark and gluon degrees of freedom.come into game. This is expected since by similar reasoning as above, the transition

$$\gamma \rightarrow q\bar{q}, \quad (2)$$

which may occur in a color field of hadronic constituents [2], should be treated as a signal of the quark constituent in the photon. The discussed above ρ component of the photon arises when the $q\bar{q}$ system is confined.

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[1] Based partly on the D.R. Yennie talk given at the XVI Zakopane School [2a] and on review [2b]; citation from [2b].

[2] it may occur also due to a Coulomb field in the process: $\gamma\gamma \rightarrow q\bar{q}$

1.3. Parton content of the photon in QCD

Hard hadronic processes involving partonic constituents of the photon can be described in Quantum Chromodynamics (QCD) due to smallness of the corresponding coupling constant $\alpha_s(Q^2)$, with Q^2 being the hard scale. Presently such results exist up to next-to-leading $\log Q^2$ terms (NLL). Contrary to the structure of hadron, the structure functions for the photon can be calculated in the Parton Model and already at this (Born) level the scaling violation appears. The all order logarithmic Q^2 dependence of the partonic densities in the photon can be in principle calculated in QCD in a form of the asymptotic solutions, without the extra input at some scale, needed for hadrons. The singular behaviour is obtained in the NLL calculation of the asymptotic solution at small x_{Bj}, to be regularized by the nonperturbative (*e.g.* ρ) contribution. The structure function of *virtual photon*, with virtuality $-p^2 = P^2$ in the region where $Q^2 \gg P^2 \gg \Lambda^2_{\rm QCD}$, is free from such a singular behaviour at small x_{Bj}. Therefore the measurement of the structure of virtual photon plays a special role as a unique test of the perturbative QCD [3].

Similarly to the photon case, one can introduce the partonic "structure" of W/Z bosons [4] or leptons [5]. Note, that the structure of the virtual photon and the structure of the electron are closely related to each other in the e^+e^- or ep collisions. This new area for theoretical investigations has been opened in the last few years, leading to interesting results.

In the e^+e^- collision the dedicated $\rm DIS_\gamma$ experiments are performed in order to measure the photon structure functions. Here the photon-probe with the high virtuality tests the partonic structure of the photonic target. The large $p_{\rm T}$ particle or jet production in the e^+e^- and ep collisions (so called resolved photon processes) are suitable for this purpose as well [3,6,7].

The existing data allow to construct the parton parametrizations for both real and the virtual photon using the appropriate for the photon evolution equations (inhomogeneous ones, due to the direct coupling to quarks (Eq. (2)). So far only the parametrizations for unpolarized parton densities are available (the review of parton parametrizations can be found in [6]).

1.4. Structure of the photon AD 1997

During last few years a significant progress has been made in measurements of the structure function F_2^γ and of the individual parton distributions in the resolved photon processes due to LEP and KEK e^+e^- experiments, as well as due to photoproduction measurements at ep collider HERA (recent results are discussed in *e.g.* [6, 7]).

In the single tagged e^+e^- experiments with an arbitrary hadronic final state the structure function F_2^γ is measured in the Q^2 range between 0.24

and 390 GeV^2 and x_{Bj} from 0.002 to 0.98. Although the general behaviour of F_2^γ both as a function of the Q^2 and x_{Bj} agrees with the theoretical predictions, the situation is not satisfactory. The uncertainties of the data are large because of still small statistics, and because of difficulties with the unfolding of the true variables from the visible one (as for example visible invariant mass of the hadronic system $W_{\rm vis}$ instead of the full W needed to extract the quantity x_{Bj}).

Note also, that serious discrepancies were found recently in the description by the existing MC generators of some details of the final hadronic systems in the DIS$_\gamma$ experiments and also in the jet production in resolved photon processes, both in $\gamma\gamma$ collisions at LEP and in the γp collisions at HERA.

2. Structure functions of the photon

Following the line of reasoning from Sec. 1.2 we discuss now the structure functions of the photon. The cross section for the process involving the interaction of the photon with elementary, charged particles can be presented symbolically as a series in the coupling constant $\alpha = e^2/4\pi$:

$$\sigma \sim \alpha + \alpha^2 + \dots . \tag{3}$$

For small coupling constant, one can approximate the cross section by the first, or by first few terms in the above expansion. However for some inclusive processes involving a large energy scale, the expansion parameter may be different — there may appear large logarithms which should then be summed up to all orders.

2.1. Leptonic structure functions of γ

Let us discuss the inclusive, pure electromagnetic process where the true expansion parameter is, instead of α, rather $\alpha \log Q^2$ (the Leading Logarithms (LL) expansion), and the cascade process starting from the initial photon Eq. (1) may be factorized (separated) from the basic hard subprocess which occurs at scale Q^2.

We will study the following process, where a muon pair with the large invariant mass is produced together with the arbitrary electromagnetic state X:

$$\gamma e^+ \to \mu^+\mu^- X \text{ (leptons and photons)}. \tag{4}$$

The leading order (LO) cross section for the process (4) is given by:

$$\sigma_{\gamma e^+ \to \mu^+\mu^- X}(s, M^2) = \int dx_\gamma f_{e/\gamma}(x_\gamma, Q^2)\hat{\sigma}_{e^+e^- \to \mu^+\mu^-}(M^2). \tag{5}$$

The function $f_{e/\gamma}(x_\gamma, Q^2)$ describes the probability (within the LL accuracy in the LO approach) to find in the initial photon the electron with the fraction of the momentum x_γ, at scale Q^2. $\hat{\sigma}$ is here the lowest order cross section for the muon pair production ($\sim \alpha^2$) with large invariant mass M^2, which serves here the scale for the large logarithms, $Q^2{=}M^2$.

The electromagnetic structure functions of photon related to the introduced above function f are being measured presently in the following Deep Inelastic Scattering on photon (DIS_γ):

$$e(k)\gamma(p) \to e(k')X \text{ (leptons)}, \tag{6}$$

at the scale $Q^2 = -q^2 = -(k-k')^2$, usually greater that 1 GeV^2. [3]

In the single tagged events at e^+e^- colliders the initial (target) photon is almost real, *i.e.* $P^2 = -p^2 \ll 1\ \mathrm{GeV}^2$ (see Fig. 1).

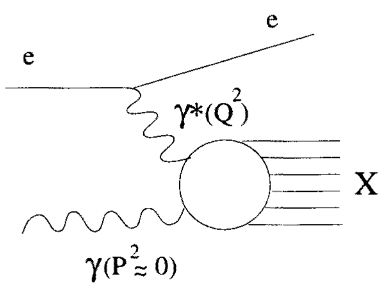


Fig. 1. Deep Inelastic Scattering on the real photon, $p^2 = -P^2 \approx 0$.

To describe the DIS_γ process (6) the following variables are being used:

$$x_{Bj} = \frac{Q^2}{2p\,q}, \qquad y = \frac{p\,q}{p\,k}. \tag{7}$$

(Note that in the LO approach $x_{Bj} = x_\gamma$). The differential cross section for process (6), for unpolarized initial particles, is given by the following QED or leptonic structure functions:

$$\frac{d\sigma}{dx_{Bj}dy} = \frac{4\pi\alpha^2}{Q^4} 2p\,k[(1-y)F_2^{\gamma(\mathrm{QED})}(x_{Bj}, Q^2) + x_{Bj}y^2 F_1^{\gamma(\mathrm{QED})}(x_{Bj}, Q^2)]. \tag{8}$$

Note that function $F_1^{\gamma(\mathrm{QED})}$(equal to the transverse $F_\mathrm{T}^{\gamma(\mathrm{QED})}$) or the longitudinal function $F_\mathrm{L}^{\gamma(\mathrm{QED})}$ ($F_\mathrm{L}^{\gamma(\mathrm{QED})} = F_2^{\gamma(\mathrm{QED})} - 2x_{Bj}F_\mathrm{T}^{\gamma(\mathrm{QED})}$) are not easily accessible, due to small y range probed in present experiments.

[3] the limit 1 GeV^2 arises since the discussed measurement is in practice correlated to the one, where the QCD structure functions are probed (see below for details)

Some of the recent data for the $F_2^{\gamma(\mathrm{QED})}$, obtained for the muonic final state, are presented in Fig. 2 together with the QED prediction, based on the first order process:

$$\gamma^*\gamma \to \mu^+\mu^- .$$

(Other structure functions (azimuthal correlations), which arise when final state particles are observed were measured as well, see discussion in [6, 7].)

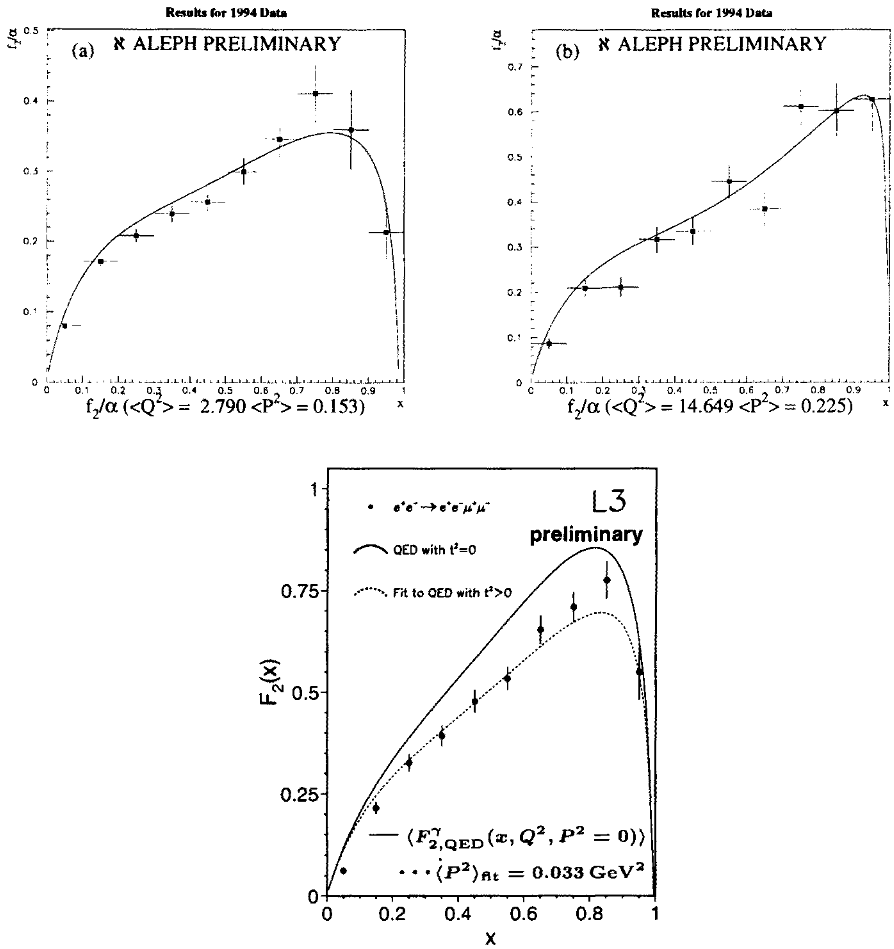


Fig. 2. The leptonic structure function of the photon for the different P^2 values, a) and b) ALEPH data at $Q^2 = 2.790$ and 14.649 GeV^2 [8a]; c) L3 data [8b]

The important additional results from these measurements is the estimate of the averaged virtuality of the initial photon needed for the extraction of hadronic structure functions, see below.

2.2. Hadronic (QCD) structure function of γ

Let us assume now that in the first step with the probability α the photon decays into quark and antiquark Eq. (2). Then the subsequent radiation processes will be rather governed by the strong coupling constant α_s than the electromagnetic one. For the inclusive production of hadrons the true expansion parameter is expected to be $\alpha_s \log Q^2$, with Q^2 scale parameter being, in order to apply the perturbative QCD, larger than $\Lambda^2_{\rm QCD}$. Then the cascade process originated from the initial photon can be described in the perturbative QCD in terms of the parton distribution in the photon. The analogue of the process (4) may be now the process:

$$\gamma\bar{q} \to \mu^+\mu^- X(\text{hadrons})\,, \tag{9}$$

with the LO formula for the cross section

$$\sigma_{\gamma\bar{q}\to\mu^+\mu^- X}(s, M^2) = \int dx_\gamma f_{q/\gamma}(x_\gamma, Q^2)\hat{\sigma}_{q\bar{q}\to\mu^+\mu^-}(M^2)\,, \tag{10}$$

where the function $f_{q/\gamma}(x_\gamma, Q^2)$ describes the probability within the LL accuracy to find in the initial photon the quark with the fraction of the momentum x_γ, at scale Q^2. The hard process here is the Drell–Yan process for muon pair production with large invariant mass M^2, and $Q^2 = M^2$. (See the Section 3, where other hard processes "resolving" the photon are discussed.)

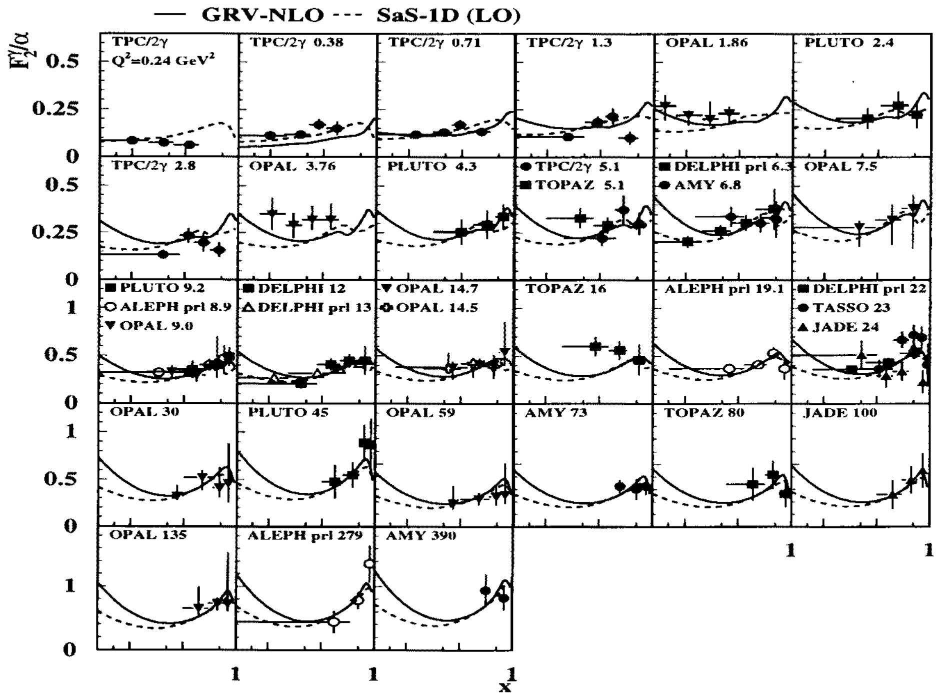
When in the final state only hadrons are produced in the DIS$_\gamma$ experiment at e^+e^- colliders, the (hadronic) structure functions for the photon $F^\gamma_{1,2...}$ related to $f_{q/\gamma}$ are measured. Since only part of the final hadronic state is observed in practice, the proper estimation of the P^2 and also the proper unfolding of the true variables, *e.g.* $x_{Bj} = Q^2/(Q^2 + W^2 + P^2)$, is crucial. Below we discuss separately the case of real (or almost real) photon (with $P^2 \lesssim \Lambda^2_{\rm QCD}$) and the case of the virtual photon, where $Q^2 \gg P^2 \gg \Lambda^2_{\rm QCD}$.

2.2.1. Real photon

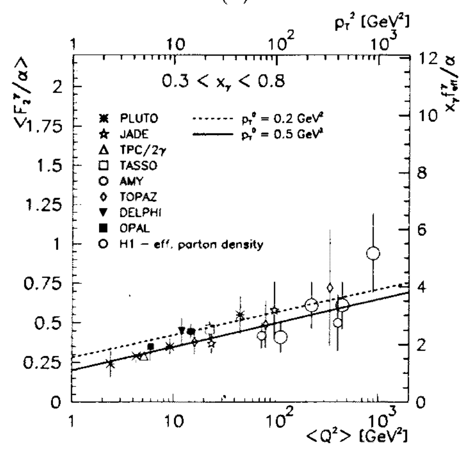
The unpolarized deep inelastic scattering off the real photon,

$$e(k)\ \ \gamma(p) \to e(k')\ \ X(\text{hadrons})\,, \tag{11}$$

with a large momentum transfer between electrons: $Q^2 = -q^2 = -(k - k')^2 \gg 1$ GeV^2, can be described by two independent (hadronic) structure functions F^γ_1 and F^γ_2 or F^γ_L, according to Eg. (8). The following formula which relates the structure function to the quark densities holds in LO ap-



(a)



(b)

Fig. 3. (a) The x_{Bj} dependence of F_2^γ with the prediction of the GRV-NLO and Sas-1D(LO) parton parametrizations (from [7]); (b) the Q^2 dependence of the F_2^γ averaged on the x_{Bj} range between 0.3 and 0.8, together with data from HERA (H1), based on the effective parton density, from [9].

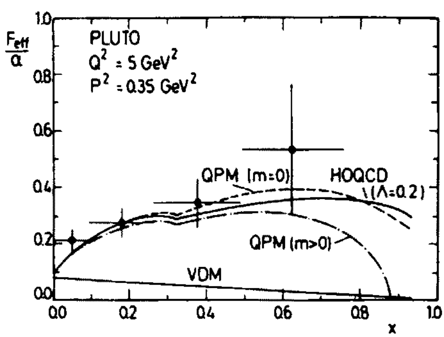
proach (here $x_\gamma = x_{Bj}$):

$$\frac{F_2^\gamma(x_{Bj},Q^2)}{x_{Bj}} = \sum_q^{2N_f} e_q^2 f_{q/\gamma}(x_{Bj},Q^2) = \frac{\alpha}{2\pi} N_c \sum_q^{2N_f} e_q^4 [x_{Bj}^2 + (1-x_{Bj}^2)] \log \frac{Q^2}{\Lambda_{\rm QCD}^2} . \tag{12}$$

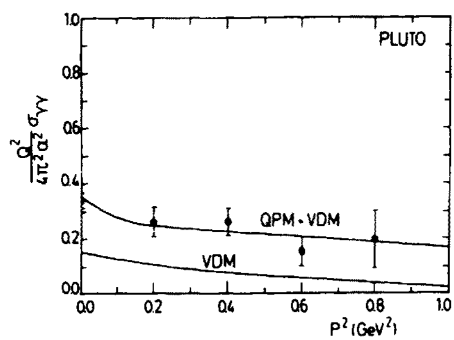
The existing results for F_2^γ as a function of the x_{Bj} (from [7]) and of the Q^2 are shown in Figs 3(a) and 3(b), respectively. Note, that the low x_{Bj} behaviour of F_2^γ still has to be clarified, as parton parametrizations give different predictions here.

2.2.2. Virtual photon

In the region where $Q^2 \gg P^2 \gg \Lambda_{\rm QCD}^2$, the structure of the virtual photon may be tested. The Parton Model formula for the corresponding structure function F_2^γ contains the $\log Q^2/P^2$ (instead $\log Q^2/(\Lambda_{\rm QCD}^2)$, see Eq. (12)), and will disappears when both scales approach each other. The higher order QCD corrections will not change this behaviour. There are no new data on the structure function of the virtual photon, see Fig. 4 for the only existing (PLUTO) data and the comparison with the PM, VDM and QCD predictions.



(a)



(b)

Fig. 4. (a) the x_{Bj} dependence, (b) the dependence on the P^2 for the F_2^γ for the virtual photon averaged Q^2 and x_{Bj} ranges, from [10]

3. Resolved photon processes

3.1. Jet production with large $p_{\rm T}$

Measurements of the production of jets with large transverse momentum in the (resolved) real or virtual photon processes give a complementary to the DIS_γ experiments information on the parton density in the photon, being *e.g.* much more sensitive to the gluon density. Such analyses are performed now in e^+e^- experiments as well as in the ep HERA collider [6, 7]. In case of the $\gamma\gamma$ processes direct photon (*i.e.* without the partonic "agent"), single and double resolved photon processes are studied, whereas in the γp case only direct and single resolved ones. In Figs 5(a) and 5(b) examples of resolved photon processes in $\gamma\gamma$ and γp collisions are presented. The relevant x_γ distributions of the initial photons, with the $x_\gamma \sim 1$ expected for the direct contribution, are shown in Figs 6(a) and 6(b).

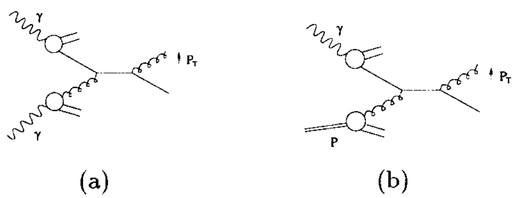


Fig. 5. Resolved photon processes in (a) $\gamma\gamma$ and (b) γp collisions.

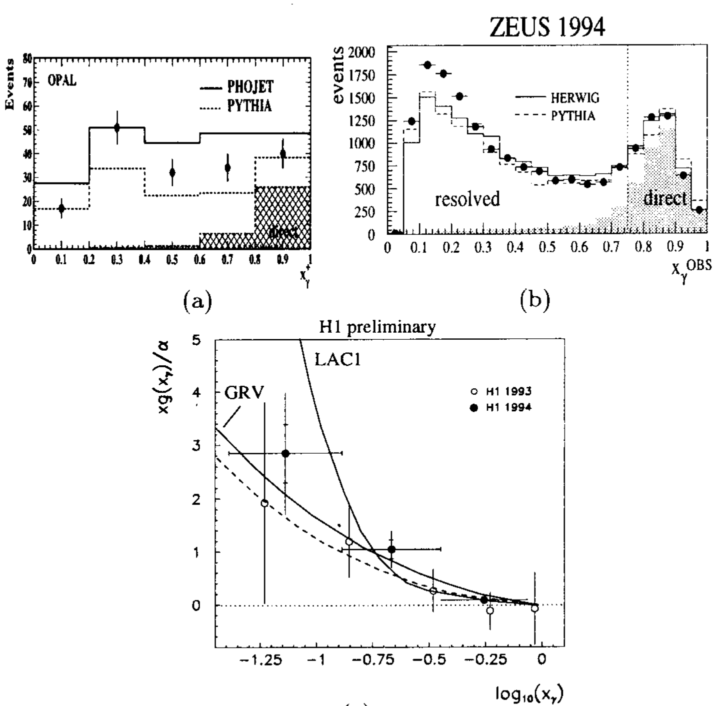


Fig. 6. The x_γ distribution from (a) OPAL [11a], (b) ZEUS [11b]; (c) the gluon density at Q^2 =75 GeV^2 from H1 [9] compared to LAC1 and GRV-LO parametrizations.

The gluon distribution in the real photon extracted from the jet production data for $Q^2 = p_T^2 = 75$ GeV^2 at HERA is shown in Fig. 6(c). The effective parton densities were also measured at HERA, the constructed from them effective structure function F_2^γ is plotted in Fig. 3(b).

In the resolved photon processes the content of the virtual photon can be studied as well. The cross section measurement for the different virtualities of the photon was performed at HERA collider. The hard Q^2 scale corresponds here to the transverse energy of jets, E_T^2. Only if E_T^2 is bigger than the virtuality squared for the initial photon the interpretation in terms of the structure function (parton distributions) of the virtual photon is appropriate (see Fig. 7 for results, to be compared with Fig. 4(b)).

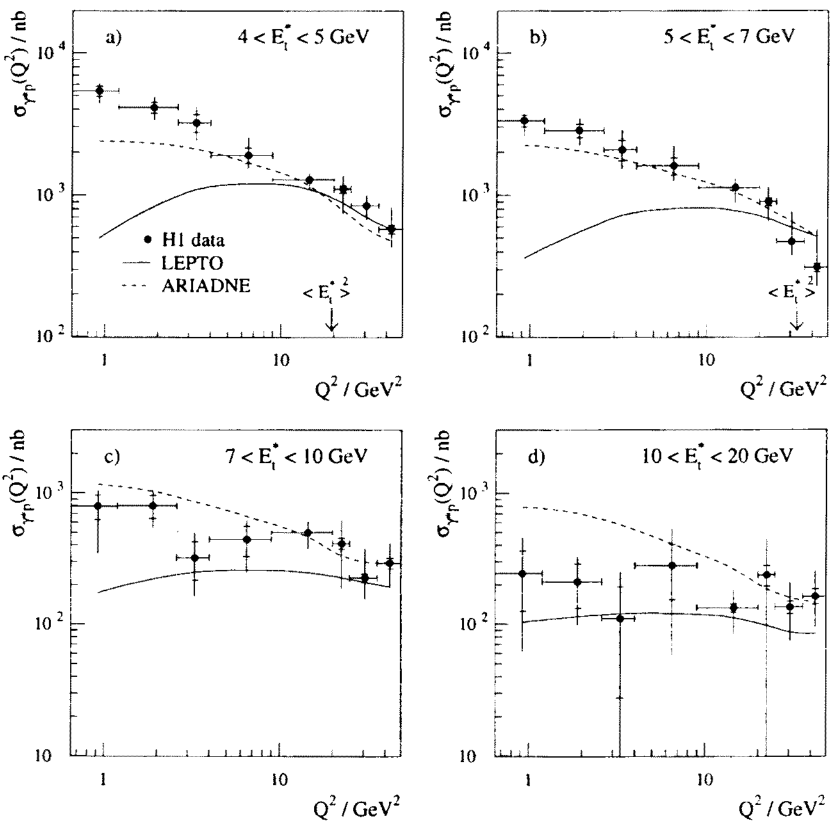


Fig. 7. The dependence on the squared virtuality of the initial photon of the cross section $\sigma_{\gamma^* p}$ measured at HERA (H1), from [12].

3.2. Compton scattering $\gamma p \to \gamma X$

Not only jet but also large p_T particles production can be used to measure partonic content of the photon. For the discussion on the newest results see *e.g.* [7]. Here I would like to mention that the large p_T photon produced in the Deep Inelastic Compton (DIC) process may be used for this purpose as well [13, 14]. Fig. 8 shows the domination of the process $g_{\gamma^*} q_p \to \gamma q$ over the direct contribution: $\gamma^* q_p \to \gamma q$, for the different virtuality of the initial photon. This result suggests a possibility to measure the gluonic content of the virtual photon in DIC at HERA [13c].

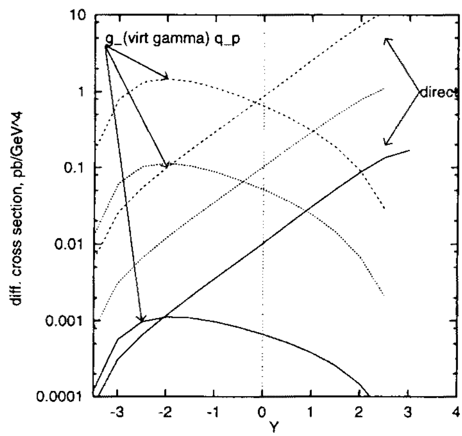


Fig. 8. The rapidity distribution in the γp CM at HERA for the photon produced with p_T=5 GeV for initial photon virtualities: P^2=0.03, 0.25 and 2.5 GeV^2(upper, middle and lower lines) [13c].

4. Summary

The impressive progress was made in last few years in the measurements of the structure functions and individual parton distributions in the photon, both in e^+e^- and ep experiments. Still more data are needed in order to clarify the small x_{Bj} behaviour of F_2^γ, to measure the polarized parton densities, and to test the structure of the virtual photon. The interplay between the structure of the electron and of the virtual photon may also be important in future analyses.

Being important test of QCD, the structure of the photon may be also a useful tool in the high energy physics in studying the effects of the "new physics", as due to the partonic content of photon the new production mechanisms may appear.

I wish to thank organizers of this excellent School and of all previous Zakopane Schools I was happy to attend. I am indebted to Peter Zerwas for the important comment on the early developments of QED and pointing to me the Ref. [1b]. I am grateful to Aaron Levy for a critical reading of the manuscript and to Andrzej Zembrzuski for his help in preparing this contribution. I wish to thank Stefan Söldner-Rembold for sending his newest compilation on F_2^γ data.

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