THE STRUCTURE OF THE PHOTON IN HARD HADRONIC PROCESSES

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Abstract

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.

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 nor 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 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.

Quantum Electrodynamics (QED), the theory describing the interaction between electrons and photons, was introduced later on (years 1925-1927 by M. Born, W. Heisenberg, P. Jordan and P. Dirac [1b,c]); the photon plays here the 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 The "structure" of the photon

In quantum field theory, the electromagnetic field couples to all particles carrying the electromagnetic current, and thus a photon can fluctuate into virtual states of remarkable complexity. At high energies, the fluctuation of a photon into a Fock state of particles of total invariant mass $M$ can persist over a time of order $\tau = 2E_\gamma/M^2$ - until the virtual state is materialized by a collision or annihilation with another system, from Ref. [3g].

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

$$\gamma \rightarrow e^+e^-.$$ 

(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 $\alpha \sim 1/137$, from [2b].

The hadronic properties of the photon were observed first in soft processes like $\gamma p \rightarrow pp$ or $\gamma p \rightarrow \gamma p$, 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 "$\rho$- meson component" in the photon (also $\omega$ and $\phi$ components, or other vector mesons resonances in the Generalized VDM (GVDM)).

As $|t|$ 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 the game. This is expected since by similar reasoning as above, the transition

$$\gamma \rightarrow q\bar{q},$$

(2)

partly based on the D. R. Yennie talk given at the XVI Zakopane School [2a] and on [2b]
which may occur in a color field of hadronic constituents, should be treated as a signal of the quark constituent in the photon. The discussed above vector meson components of the photon arises when the $q\bar{q}$ system is confined.

### 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 hadrons, 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 in principle be calculated in QCD in a form of the asymptotic solutions, without the extra input at some scale, needed for hadrons. A singular behaviour is obtained in the NLL calculation of the asymptotic solution at small $x_{Bj}$, to be regularised by the nonperturbative (e.g. $\rho$) contribution. The structure function of a virtual photon, with virtuality $-p^2 = P^2$ in the region where $Q^2 \gg P^2 \gg \Lambda^2_{QCD}$, is free from such singular behaviour at small $x_{Bj}$. Therefore the measurement of the structure of virtual photon plays a special role as a unique test of perturbative QCD.

Similarly to the photon case, one can introduce the partonic “structure” of $W/Z$ bosons or leptons. 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 $e^+e^-$ collisions the dedicated 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 $p_T$ particle or jet production in $e^+e^-$ and $ep$ collisions (so called resolved photon processes) are suitable for this purpose as well, see e.g. [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]).

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3It may occur also due to a Coulomb field in the process: $\gamma\gamma \rightarrow q\bar{q}$
1.4 The structure of the photon AD 1997

During the last few years a significant progress has been made in measurements of the structure function $F_2^\gamma$ 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 the $ep$ 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 $F_2^\gamma$ 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 $F_2^\gamma$ 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 ones (as for example visible invariant mass of the hadronic system $W_{vis}$ 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 $\gamma p$ 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 $\alpha = e^2/4\pi$:

$$\sigma \sim \alpha + \alpha^2 + \ldots$$

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 the $\gamma$

Let us discuss the inclusive, pure electromagnetic process where the true expansion parameter is instead of $\alpha$ 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 a scale $Q^2$. 
We will study the following process, where a muon pair with a large invariant mass is produced together with an arbitrary electromagnetic state $X$:

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

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

$$\sigma_{\gamma e^+ \rightarrow \mu^+ \mu^- X}(s, M^2) = \int dx \gamma f_{e/\gamma}(x, Q^2) \hat{\sigma}_{e^+ e^- \rightarrow \mu^+ \mu^-}(M^2). \quad (5)$$

The function $f_{e/\gamma}(x, Q^2)$ describes the probability (within the LL accuracy in the LO approach) to find in the initial photon an electron with a fraction of momentum $x$, at the 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 as the scale for the large logarithms, $Q^2 = M^2$.

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

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

at a scale $Q^2 = -q^2 = -(k - k')^2$, usually greater than 1 GeV$^2$.

In the single tagged events at $e^+e^-$ colliders the initial (target) photon is almost real, i.e. $P^2 = -p^2 \ll 1$ GeV$^2$ (see Fig.1). To describe the DIS$_\gamma$ process (6) the following variables are being used:

$$x_{Bj} = \frac{Q^2}{2p \cdot q}, \quad y = \frac{p \cdot q}{p \cdot k}. \quad (7)$$

(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

\[\text{Figure 1: Deep Inelastic Scattering on a real photon, } p^2 = -P^2 \approx 0.\]
structure functions:

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

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

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

\[ \gamma^* \gamma \rightarrow \mu^+ \mu^- . \]

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

![Figure 2](image)

Figure 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 at \( Q^2 = 3.25 \) GeV\(^2\) [8b].

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

### 2.2 Hadronic (QCD) structure functions of the \( \gamma \)

Let us assume now that in the first step the photon decays with probability \( \alpha \) into a pair of quark antiquark (Eq.2). Then the subsequent radiation processes will be
rather governed by the strong coupling constant $\alpha_s$ than by the electromagnetic one. For the inclusive production of hadrons the true expansion parameter is expected to be $\alpha_s \log Q^2$, with the $Q^2$ scale parameter being, in order to apply the perturbative QCD, larger than $\Lambda_{QCD}^2$. 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:
\[ \gamma \bar{q} \rightarrow \mu^+ \mu^- X \text{hadrons}, \]  
(9)
with the LO formula for the cross section
\[ \sigma_{\gamma \bar{q} \rightarrow \mu^+ \mu^- X}(s, M^2) = \int dx \gamma f_{q/\gamma}(x \gamma, Q^2) \tilde{\sigma}_{q\bar{q} \rightarrow \mu^+ \mu^-}(M^2), \]  
(10)
where the function $f_{q/\gamma}(x \gamma, Q^2)$ describes the probability within the LL accuracy to find in the initial photon a quark with a fraction of momentum $x \gamma$, at the 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 Secs. 3.1 and 3.2, 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 of the photon $F_{1,2}^\gamma$, related to $f_q/\gamma$ are measured. Since only part of the final hadronic state is observed in practice, the proper estimation of $P^2$ 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 a real (or almost real) photon (with $P^2 \lesssim \Lambda_{QCD}^2$) and the case of a virtual photon, where $Q^2 \gg P^2 \gg \Lambda_{QCD}^2$.

### 2.2.1 Real photon

The unpolarized deep inelastic scattering on the real photon,
\[ e(k) \gamma(p) \rightarrow e(k') X \text{hadrons}, \]  
(11)
with a large momentum transfer between the electrons: $Q^2 = -q^2 = -(k - k')^2 \gg 1 \text{ GeV}^2$, can be described by two independent (hadronic) structure functions $F_1^\gamma$ and $F_2^\gamma$ or $F_L^\gamma$, according to Eq.8. The following formula which relates the structure function to the quark densities holds in LO approach (here $x_\gamma = x_{Bj}$):
\[ \frac{F_2^\gamma(x_{Bj}, Q^2)}{x_{Bj}} = \sum_{q}^{2N_f} e_q^2 f_{q/\gamma}(x_{Bj}, Q^2) = \frac{\alpha}{2\pi} N_c \sum_{q}^{2N_f} e_q^4 [x_{Bj}^2 + (1 - x_{Bj}^2)] \log \frac{Q^2}{\Lambda_{QCD}^2}. \]  
(12)
The existing results for $F_2^\gamma$ as a function of $x_{Bj}$ (from [7]) and of $Q^2$ are shown in Figs 3a and 3b), respectively. Note, that the low $x_{Bj}$ behaviour of $F_2^\gamma$ still has to be clarified, as parton parametrizations give different predictions here.
Figure 3: a) The $x_{Bj}$ dependence of $F_2^γ$ with the predictions of the GRV-NLO and Sas-1D(LO) parton parametrizations (from [7]); b) the $Q^2$ dependence of $F_2^γ$ 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].
2.2.2 Virtual photon

In the region where \( Q^2 \gg P^2 \gg \Lambda^2_{QCD} \), the structure of the virtual photon may be tested. The Parton Model (PM) formula for the corresponding structure function \( F_2^\gamma \) contains a \( \log \frac{Q^2}{P^2} \) term (instead \( \log \frac{Q^2}{\Lambda^2_{QCD}} \), see Eq. 12), and will disappear 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. Fig.4 shows the only existing (PLUTO) data and the comparison with the PM, VDM and QCD predictions.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{a) the \( x_{Bj} \) dependence, b) the dependence of the \( F_2^\gamma \) on \( P^2 \) for the virtual photon averaged \( Q^2 \) and \( x_{Bj} \) ranges, from [10]}
\end{figure}

3 Resolved photon processes

Large \( p_T \) particles production can be used to measure the partonic content of the photon. For a discussion on the newest results see e.g. [7]. Below we discuss the most important resolved photon processes, namely those involving jets (see also [6]).

3.1 Jet production with large \( p_T \)

Measurements of the production of jets with large transverse momentum in the (resolved) real or virtual photon processes give a complementary to the DIS, \( \gamma \) 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 at the \( ep \) HERA collider. 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 $\gamma p$ case only direct and single resolved ones. In Figs. 5a and 5b examples of resolved photon processes in $\gamma\gamma$ and $\gamma p$ collisions are presented. The relevant $x_\gamma$ distributions of the initial photons, with $x_\gamma \sim 1$ expected for the direct contribution, are shown in Figs. 6a and 6b. The gluon distribution in the real photon extracted from the jet production data for $Q^2 = 75$ GeV$^2$ at HERA is shown in Fig. 6c. The effective parton densities were also measured at HERA, the constructed from them the effective structure function $F_{2g}^e$ is plotted in Fig. 3b.

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 the 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. 4b).
3.2 Compton scattering $\gamma p \rightarrow \gamma X$

The large $p_T$ photon produced in the Deep Inelastic Compton (DIC) process may be used to study the content of the photon as well [13]. Note that recently this process, with almost real initial photon, was measured at HERA [14]. In papers [13b,c] we study the possibility of probing the structure of the virtual photon in DIC scattering at HERA. Fig. 8 shows the domination of the process $g_\gamma^*q_p \rightarrow \gamma q$ over the direct contribution: $\gamma^*q_p \rightarrow \gamma q$, for different virtualities of the initial photon. This result suggests a possibility to measure the gluonic content of the virtual photon in DIC process at HERA [13c].

4 Summary

An impressive progress was made in the 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 $F_2^\gamma$, to measure the polarized parton densities, and to test the structure
Figure 8: The rapidity distribution in the $\gamma p$ center of mass system 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].

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 an 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 "new physics", as due to the partonic content of photon a new production mechanisms may appear.

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References

[1] a) A. Zajonc, Catching the light, Oxford University Press, Oxford New York, 1995, Chapters 9 and 10; b) P. Jordan, talk at Neutrino Conference, Aachen 1976, in proc. p. 494; c) S. S. Schweber, QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga, Princeton University Press, Princeton, 1994.

[2] a) D. R. Yenni, Acta Physica Polonica B7, 897 (1976), b) T. H. Bauer et al., Rev.Mod.Phys. 50, 261 (1978); Erratum ibid 51, 407 (1979).
[3] a) V. M. Budnev et al., *Phys. Rep.* C15, 181 (1975); b) C. Peterson, T. F. Walsh, P. M. Zerwas, *Nucl. Phys.* B174, 424 (1980); c) H. Kolanoski, *Springer Tracts in Modern Physics* 84 - 85; d) Ch. Berger and W. Wagner, *Phys. Rep.* C146 (1987) 1; e) H. Abramowicz et al., *IJMP A* 8, 1005 (1993); f) M. Drees and R. M. Godbole, *Pramana - J. of Physics* 41, 83 (1993); M. Drees and R. M. Godbole, *Phys. Rev.* D50, 3124 (1994); *J. of Phys. G. Nucl. and Part. Phys.* 21, 1559 (1995); g) S. Brodsky and P. Zerwas, *Nucl. Instr. and Methods in Phys.Res.* A355, 19 (1995);

[4] W. Słomiński and J. Szwed, *Z. Phys.* C72, 87 (1996), *Phys. Rev.* D52, 1650 (1995), *Phys. Lett.* B323, 427 (1994).

[5] W. Słomiński and J. Szwed, *Acta Physica Polonica* B27, 1887 (1996), *Phys. Lett.* B387, 861 (1996); M. Drees and R. Godbole, *Phys. Rev.* D50, 3124 (1994).

[6] M. Krawczyk, M. Staszel and A. Zembrzuski, Survey on the photon structure functions and the resolved photon processes, preprint IFT 15/97, July 1997.

[7] S. Söndner-Rembold, Talk at XVIII International Symposium on Lepton-Photon Interaction, Hamburg, Germany, July 28-August 1, 1997.

[8] a) ALEPH Coll., C. A. Brew, S. Cartwright, M. Lehto, Proc. of PHOTON'97, Egmond aan Zee, The Netherlands, May, 1997; b) L3 Coll., submitted to EPS'97, Jerusalem, August 1997.

[9] K. Müller, talk at EPS'97, Jerusalem, August 1997, based on the H1 results, T. Ahmed at al., *Nucl. Phys.* B445, 195 (1997) and paper 270 submitted to EPS'97.

[10] PLUTO Coll., Ch. Berger et al., *Phys. Lett.* B142, 119 (1984).

[11] a) OPAL Coll., K. Ackerstaff et al., Z. Phys. C73, 433 (1997); b) ZEUS Coll., J. M. Butterworth et al., preprint 97-04 UCL/HEP, in Proc. of the Ringberg Workshop, Germany, May 1997.

[12] H1 Coll., C. Adloff at al., DESY 97-197 [hep-ex/9709017] .

[13] a) M. Krawczyk, *Acta Physica Polonica* B21, 999 (1990); A. Bawa, M. Krawczyk, W. J. Stirling, Z. Phys. C50, 293 (1991); P. Aurenche at al., HERA Workshop, Hamburg 1987, p.561 and Z. Phys. C56, 589 (1992); L. E. Gordon and J. K. Storrow, Z. Phys. C63, 581 (1994); b) M. Krawczyk, A. Zembrzuski, Physics at HERA Workshop, Hamburg 1991, vol.1, p. 617; c) M. Krawczyk, A. Zembrzuski *Phys. Rev.* D57 (1998)

[14] ZEUS Coll., paper 656 submitted to EPS'97, Jerusalem, August 1997.