SUMMARY OF THE PHOTON STRUCTURE FUNCTIONS — MEASUREMENTS AT LEP*

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The present status of the photon structure functions measurements at LEP is discussed. The short introduction to the kinematics and theoretical framework of the structure functions measurements at LEP is given first. Then follow presentations of the most important measurements, ranging from the QED photon structure function, through the hadronic structure functions of real and virtual photons, and at the end the first measurement of the electron structure function is shown.

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1. Introduction

The photon as the gauge boson of the quantum electrodynamics (QED) mediates the electromagnetic interactions between charged objects. In these interactions it can be regarded as a structureless object, and is called *direct*. However due to the uncertainty principle, the photon can fluctuate into a pair of fermion–antifermion system carrying the same quantum numbers as the photon. If during such a fluctuation, one of the fermions interacts with another object, then the structure of the photon is revealed, and the photon is called *resolved*. The structure of resolved photons is further subdivided into a part which is perturbatively calculable (called *point-like*) and the part where the photon fluctuates into a hadronic system (called *hadron-like*).

At LEP, the structure of the photon is studied in the interactions of electrons and positrons[1] proceeding via the exchange of two photons, one of them being almost real and the other virtual. Such a process is schematically shown in Fig. 1(a). It can be regarded as deep inelastic scattering

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[1] For conciseness, positrons are also referred to as electrons.

of the electron off the quasi-real target photon, and is experimentally identified by tagging the scattered electron in the detector. The variables in parentheses are the four-vectors of the particles shown in the diagram. The usual kinematical variables are defined in the following. The virtualities of the probe and target photons are given by Q^2 and P^2, respectively: $Q^2 \equiv -q^2 = -(k-k^{'})^2 > 0$, and $P^2 \equiv -p^2 = -(l-l^{'})^2 \approx 0$. The center of mass energy of the e^+e^- system is given by $s=(k+l)^2$ and the invariant mass squared of the two photon system reads $W^2 = (q+p)^2$. The usual Bjorken variables are: $y_e = l\cdot q/l\cdot k,\ x = Q^2/2q\cdot p,\ z = Q^2/2q\cdot l$, where x is calculated with respect to the target photon. However, the same process can be also interpreted as a deep inelastic scattering of the electron off the target electron (see Fig. 1(b). In that case the Bjorken scaling variable is called z and calculated with respect to the target electron.

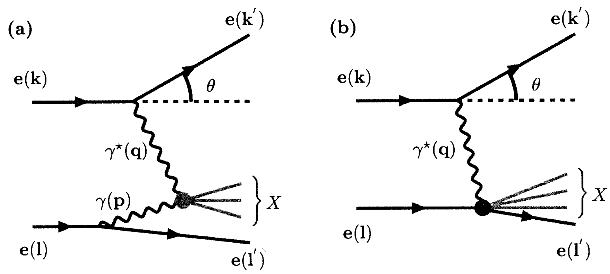

Fig. 1. Deep inelastic scattering of the electron off the quasi-real photon (a) and off the target electron (b).

The kinematic variables are experimentally measured using the energy, E, and the polar angle, θ, of the scattered electron. Only the measurement of x is based in addition on the measurement of W. As the significant part of the hadronic system is missing in the beam pipe, the measurement of W and consequently of x is much less precise than the measurement of z. Following formulas are used to calculate the kinematic variables:

$$Q^2 = 2EE_b(1-\cos\theta)\,, \quad y_e = 1 - \frac{E}{E_b}\cos^2\frac{\theta}{2}\,, \quad x = \frac{Q^2}{Q^2+W^2}\,, \quad z = \frac{Q^2}{y_e s}\,.$$

The cross section for the process shown in Fig. 1(a) can be expressed in terms of photon structure functions as follows:

$$\frac{d^4\sigma_{ee}}{dxdQ^2dzdP^2} = \frac{2\pi\alpha^2}{x^2Q^4}\left[\left(1+(1-y_e)^2\right)F_2^\gamma(x,Q^2) - y_e^2F_L^\gamma(x,Q^2)\right]\hat{f}^e_\gamma(z/x,P^2)\,,$$

where $\hat{f}^e_\gamma(y,P^2) = \frac{\alpha}{2\pi}\frac{1}{P^2}\left[\frac{1+(1-y)^2}{y} - 2y\frac{m_e^2}{P^2}\right]$ is the flux of quasi-real photons of transverse polarization in the electron and the P^2 dependence of the structure functions has been neglected. Treating the target photon as real is an approximation, because in fact it is always off-shell. Integrating the flux over P^2 and z we arrive at the standard DIS formula for $e\gamma$ scattering:

$$\frac{d^2\sigma_{e\gamma}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\left(1+(1-y_e)^2\right)F_2^\gamma(x,Q^2) - y_e^2 F_L^\gamma(x,Q^2)\right] .$$

On the other hand the cross section for the process shown in Fig. 1(b) can be immediately expressed in terms of the electron structure functions [1]:

$$\frac{d^2\sigma_{ee}}{dzdQ^2} = \frac{2\pi\alpha^2}{zQ^4}\left[\left(1+(1-y_e)^2\right)F_2^e(z,Q^2) - y_e^2 F_L^e(z,Q^2)\right] .$$

The photon structure function, $F_2^\gamma(x,Q^2)$, and the electron structure function, $F_2^e(x,Q^2)$, are related via the following integral equation:

$$F_2^e(z,Q^2) \equiv \int_z^1 dx \int_{P^2_{\mathrm{min}}(\frac{z}{x})}^{P^2_{\mathrm{max}}} dP^2\, \frac{z}{x^2} F_2^\gamma(x,Q^2,P^2)\hat{f}^e_\gamma(z/x,P^2) .$$

2. Measurements

A recent collection of results concerning the photon structure function measurements at LEP can be found *e.g.* in [2]. Here only a brief account of the newest results is presented.

The QED photon structure function, $F^\gamma_{2,\mathrm{QED}}$, has been measured at LEP in a broad range of photon virtualities $1.4 < \langle Q^2\rangle < 130$ GeV^2 using the $\mu^+\mu^-$ final state. A summary of the LEP measurements together with results from the previous experiments is shown in Fig. 2. In the plot the evolution of $F^\gamma_{2,\mathrm{QED}}$ as a function of Q^2 is shown for different average values of x. A very good agreement between predictions and the measurements is observed.

The measurements of the hadronic photon structure function F_2^γ have been recently extended to higher values of Q^2. In Fig. 3(a) the measurements of F_2^γ/α as a function of x performed by OPAL [3] and DELPHI [4] experiments are shown. The Q^2 evolution has been studied in a broad range of photon virtualities (Fig. 3(b)). As predicted by QCD, the data show positive scaling violations in F_2^γ with $F_2^\gamma/\alpha = (0.08 \pm 0.02^{+0.05}_{-0.03} + (0.13 \pm 0.01^{+0.01}_{-0.01}\ln Q^2$, where Q^2 is in GeV^2 and for the central x region 0.1–0.6.

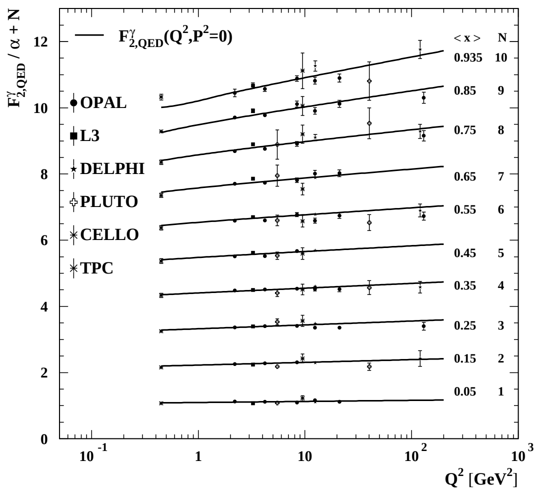

Fig. 2. Evolution of $F^{\gamma}_{2,\mathrm{QED}}$ as a function of Q^2. The curves are the QED predictions for $P^2 = 0$ and the data have been corrected for the non-zero P^2 effect.

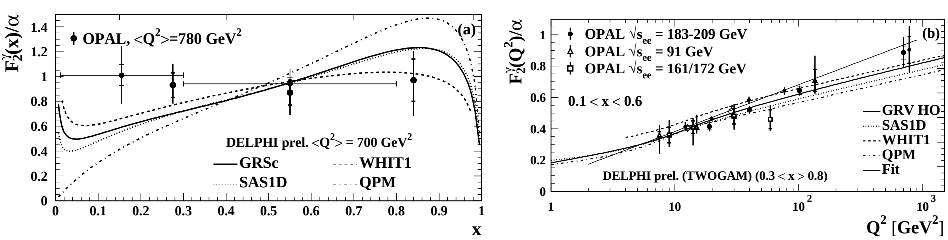

Fig. 3. (a) The measured F_2^{γ}/α in function of x for an average $\langle Q^2 \rangle = 780$ GeV^2 compared to LO predictions; (b) The evolution of F_2^{γ}/α as a function of Q^2 for the central region $0.1 < x < 0.6$.

The charm production cross section $\sigma(e^+e^- \to e^+e^-c\bar{c}X)$ shown in Fig. 4(a) and the charm structure function of the photon $F^{\gamma}_{2,\mathrm{c}}$ shown in Fig. 4(b) have been measured from the cross section for $D^{\star}$ production [5]. The data are compared to the LO and NLO calculations. The band for the NLO calculation indicates the theoretical error from uncertainties in the charm quark mass and renormalization and factorization scales. For $x > 0.1$ the perturbative QCD calculation at NLO order agrees perfectly with the measurement. For $x < 0.1$ the point-like component lies below the data. Subtracting the NLO point-like prediction a measured value for the hadron-like part of $0.154 \pm 0.059 \pm 0.029$ is obtained.

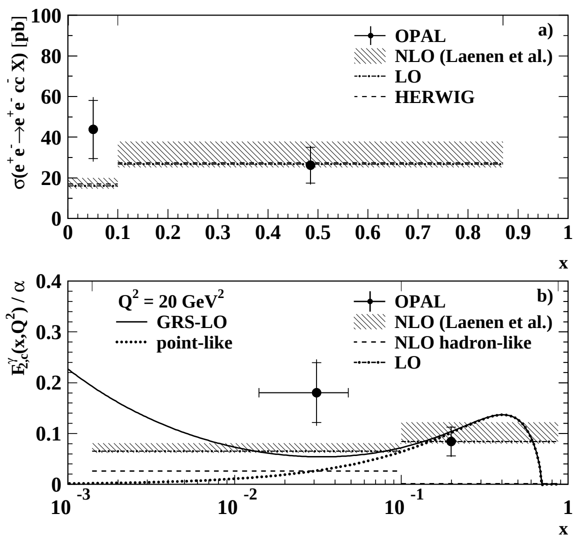

Fig. 4. (a) The cross section for $\sigma(e^+e^- \to e^+e^- c\bar{c}X)$ with $5 < Q^2 < 100$ GeV^2; (b) Charm structure function of the photon $F^{\gamma}_{2,c}(x,Q^2)/\alpha$ at $Q^2 = 20$ GeV^2.

The only result on the structure function of virtual photons comes from L3 [6]. The average virtualities of the measurement are $\langle Q^2 \rangle = 120$ GeV^2 and $\langle Q^2 \rangle = 3.7$ GeV^2. In Fig. 5(a),(b) the P^2 and Q^2 evolution of F^e_{eff} of the L3 result together with previous measurement from PLUTO are shown.

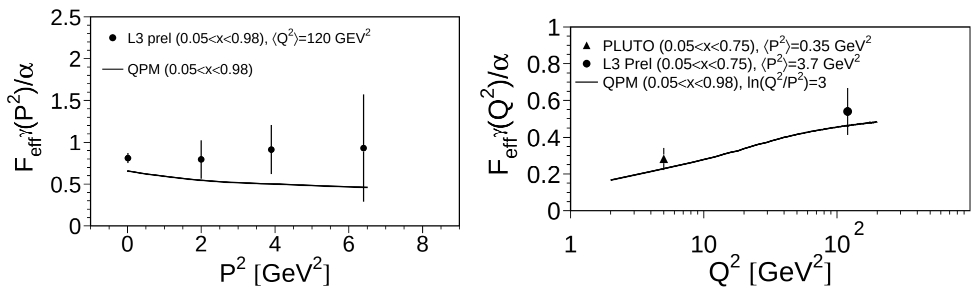

Fig. 5. Effective structure function ($F^{\gamma}_{\text{eff}} = F^{\gamma}_2 + \frac{2}{3}F^{\gamma}_L$) of virtual photons: (a) the P^2 dependence of F^{γ}_{eff} ; (b) the Q^2 dependence of F^{γ}_{eff} from PLUTO and L3. The QPM prediction is consistent in shape with the data, but its value is too low.

Recently the first measurement of the electron structure function F^e_2 has been presented by DELPHI Collaboration [7]. The preliminary results are shown in Fig. 6.

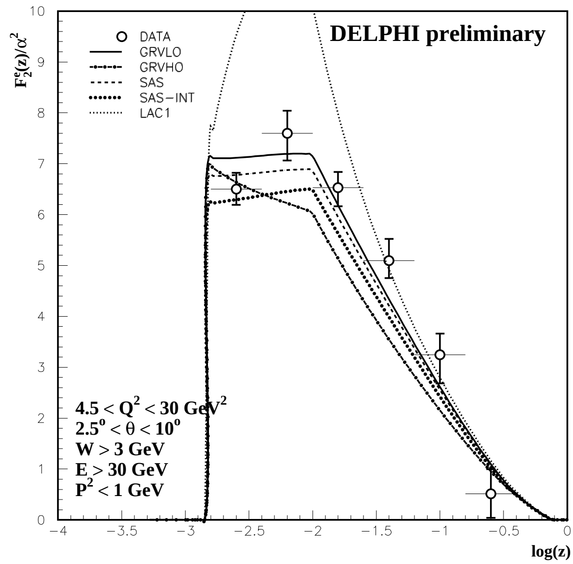

Fig. 6. The first measurement of F_2^e at LEP. The phase space of the measurement is the overlapping region of the cuts shown in the plot. That means that the average $\langle Q^2 \rangle$ is different in each bin of z. Out of all presented models the GRV LO, SaS and P^2 dependent SaS parameterizations follow the data, whereas GRV H0 and LAC1 are disfavored.

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