

# Hadronic structure of the photon at LEP

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ABSTRACT: Recent improvements in the analysis techniques and Monte Carlo models used in the measurement of the hadronic structure function of the photon have led to much improved experimental results. Its low  $x$  behaviour was studied in various  $Q^2$  regions using LEP1 and LEP2 data, while its  $x$  dependence and  $Q^2$  evolution up to very high virtualities, as well as its charm component were studied using the high energy and luminosity data of LEP2. These recent results will be presented.

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## 1. Introduction

The photon is a unique particle in that it can act both as a fundamental field, the gauge boson of QED, and as an extended object with structure. The structure function of the photon differs from that of the proton and other hadrons, because the photon has a point-like coupling to quarks, calculable in perturbative QCD, as well as a non-perturbative hadron-like component, described by the vector meson dominance model (VDM) as a superposition of the light neutral vector mesons  $\rho^0$ ,  $\omega^0$  and  $\phi$ .

The classical way to study the structure of the photon [1] at  $e^+e^-$  colliders is through the deep inelastic scattering (DIS) of electrons (or positrons) on the quasi-real photons emitted by the other beam. The structure functions  $F_2^\gamma$  and  $F_L^\gamma$  can be extracted from the measured differential cross-section using the following formula:

$$\frac{d^2\sigma_{e\gamma\rightarrow eX}}{dx dQ^2} = \frac{2\pi\alpha^2}{x Q^4} [(1 + (1 - y)^2) F_2^\gamma(x, Q^2) - y^2 F_L^\gamma(x, Q^2)],$$

where  $\alpha$  is the fine structure constant,  $Q^2$  is the photon virtuality defined as the negative four-momentum squared of the virtual probe photon, while  $x$  and  $y$  are the dimensionless Bjorken variables. In the usual kinematic conditions at LEP  $y$  can be neglected, therefore the longitudinal component  $F_L^\gamma$  can not be measured.  $Q^2$  can be calculated from the

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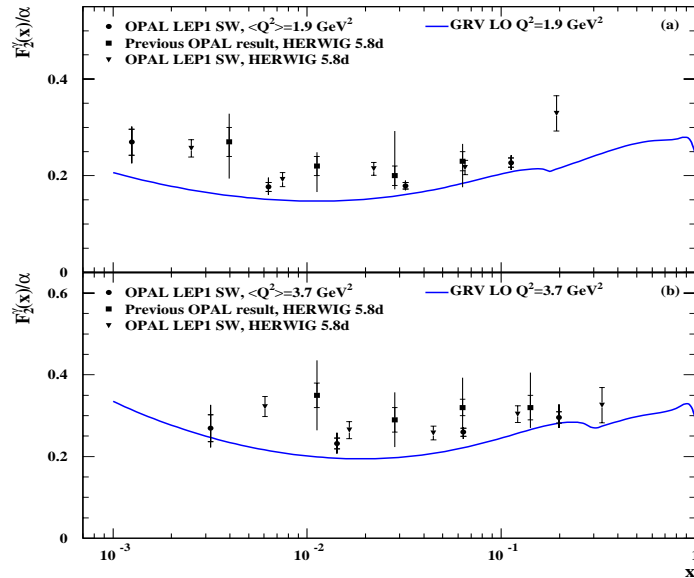
measured angle and energy of the scattered electron, but in contrast to electron-proton scattering, the target photon energy is not known, therefore  $x$  can only be obtained from the invariant mass of the hadronic system,  $W$ , as  $x \approx \frac{Q^2}{Q^2+W^2}$ , neglecting the virtuality of the target photon.

## 2. Photon structure at low $x$

The most important uncertainty in the measurement of the photon structure at low Bjorken  $x$  lies in the reliable modelling of the hadronic final state, which in most cases is only partially contained in the detector, leading to the need for a complicated unfolding procedure relying on Monte Carlo simulation.

The available Monte Carlo models have recently been critically compared to the combined data of several LEP experiments [2]. The differences between the experiments are used to estimate the systematic errors, usually smaller than the differences between the models, thus the comparison can serve as a constraint when developing new models.

OPAL recently published a measurement [3] of  $F_2^\gamma$  concentrating on its behaviour at low  $x$  in various regions of  $\langle Q^2 \rangle$  from 1.9 to 17.8 GeV<sup>2</sup>. This analysis improves the reconstruction of the hadronic final state by incorporating kinematic information from the scattered electron, measured more precisely than the hadrons, and uses a special treatment of the energy in the forward calorimeters, to make the detector response more uniform. In addition a two-variable unfolding in  $x_{\text{cor}}$ , the measured value of the Bjorken variable  $x$  using the above methods, and  $E_{\text{T}}^{\text{out}}/E_{\text{tot}}$ , the transverse energy out of the plane of the scattered electron scaled by the total observed energy, is used to further reduce the model



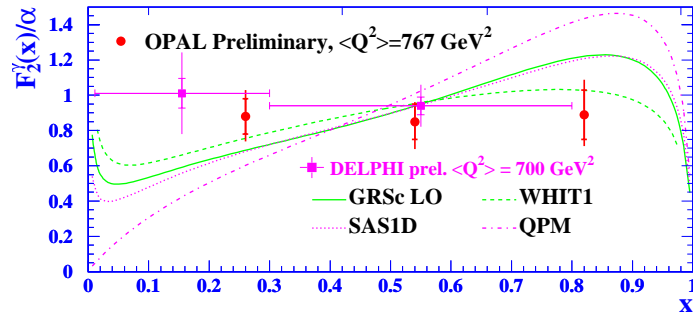
**Figure 1:** Photon structure function measured at the lowest  $x$  attainable at LEP. The inner error bars show the statistical error, while the outer error bars, where shown, correspond to the total error.

dependence of the results, leading to much reduced total systematic errors, as can be seen in Figure 1 for the two lowest  $Q^2$  regions.

The data are consistent with, but do not prove the presence of a rise in  $F_2^\gamma$  at low  $x$  predicted by QCD and observed for the proton at HERA. In general, the shape of the GRV and other leading order parametrisations is consistent with the data, but the predictions are too low for low  $\langle Q^2 \rangle$  values.

### 3. Photon structure at high $Q^2$

At high  $Q^2$  the point-like component of  $F_2^\gamma$  is expected to dominate. In this region the hadronic system has more transverse momentum and therefore it is better contained in the detector, leading to much better correlation between its true and measured invariant mass. This fact justifies the use of the traditional one-dimensional unfolding in the  $x_{\text{vis}}$  variable, the value of  $x$  calculated from the part of the hadronic final state that is visible in the detector. This approach was used in the new OPAL measurement [3] using the full LEP2 data set shown in Figure 2, an extension of the measurement discussed above to the  $Q^2$  range from 7.1 to 2323 GeV<sup>2</sup> by detecting the scattered electron in the electromagnetic endcap detectors.

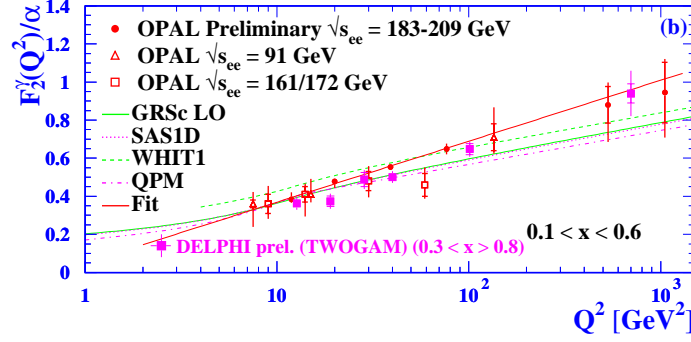


**Figure 2:** Measured values of the hadronic photon structure function  $F_2^\gamma$  at the highest  $\langle Q^2 \rangle$  measured so far, compared to various parametrisations.

A similar measurement [5] performed by DELPHI is also shown in Figure 2. This analysis uses a new approach with a multi-variable fit to the observed distributions to adjust the individual components of the hadronic structure function. This method results in larger uncertainties, but reduced model dependence.

### 4. $Q^2$ evolution of the photon structure function

Perturbative QCD can not predict the absolute normalisation of  $F_2^\gamma$ , which has to be extracted from data, but its evolution with  $Q^2$  is predicted to be logarithmic. Previous measurements of this evolution have been improved significantly by DELPHI and OPAL in [5] and [4] both in terms of the precision and in terms of the  $Q^2$  range covered, as shown in Figure 3 for medium values of  $x$ . The measured slope is noticeably higher than the existing leading order QCD parametrisations.

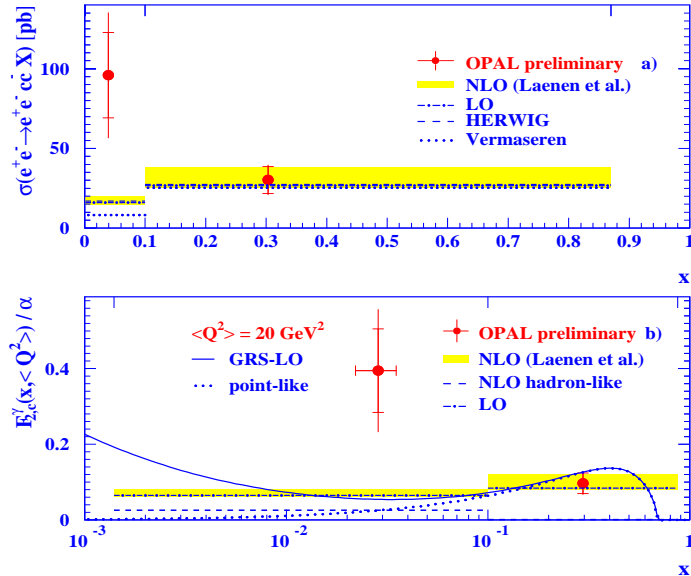


**Figure 3:** The evolution of  $F_2^\gamma$  with  $Q^2$  at medium values of  $x$ , compared to various parametrisations.

Instead of one wide range of  $x$ , the  $Q^2$  evolution of  $F_2^\gamma$  can also be measured in separate regions of  $x$  so that the scaling violations in each region can be examined. In contrast to the proton, the photon structure function shows positive scaling violations at all values of  $x$ , as expected from QCD due to the point-like coupling of the photon to quarks.

## 5. Charm structure function of the photon

An interesting question is the flavour composition of the photon structure function. Charm events can be recognised by reconstructing the  $D^* \rightarrow D^0\pi$  decay, where the small mass difference between the  $D^*$  and the  $D^0$  ensures that the phase space for random combinations faking this decay is small. Applying this well established charm identification method to deep inelastic  $e\gamma$  scattering one can measure the charm structure function of the photon separately.



**Figure 4:** The total cross section of charm production in  $e\gamma$  DIS and the charm structure function of the photon.

Figure 4 shows the recent update [6] of the first such measurement performed by OPAL, using improved Monte Carlo models and all the LEP2 data to obtain better precision. The data are divided in two bins of  $x$ ; the point-like component of the photon is expected to dominate for  $x > 0.1$ , while the hadron-like component is more significant for  $x < 0.1$ , according to the NLO calculation of [7].

While the OPAL data are well described by both the NLO calculation and the leading order Monte Carlo models for  $x$  above 0.1, the predictions are much lower than the data below 0.1, suggesting a significant hadron-like component of  $F_{2,c}^\gamma$ .

## 6. Conclusions

We have seen that the structure function of the photon has been investigated in a wide range of  $x$  and  $Q^2$  and its charm content has been studied separately. The introduction of new experimental methods and better Monte Carlo models coupled with the increased LEP energy and luminosity have opened up new regions of the phase-space and lead to more precise results. Further improvements both in the analysis techniques and in the Monte Carlo models, as well as the combination of the data of the LEP experiments can lead to more interesting results over the coming years.

## References

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