MEASUREMENTS OF HADRONIC STRUCTURE FUNCTIONS OF THE PHOTON AT LEP

R. J. TAYLOR

Department of Physics and Astronomy, University College London,
Gower Street, London WC1E 6BT, United Kingdom
E-mail: rjt@hep.ucl.ac.uk

The present status of the measurements of hadronic structure functions of the photon, investigated in deep inelastic electron-photon scattering at LEP, is presented. This article covers the hadronic structure function F_2^γ of quasi-real photons as well as the structure function F_{eff}^γ of virtual photons. Special emphasis is given to new developments in the analysis and to the most recent measurements.

1   Introduction

The photon is unique in that it can act both as a fundamental particle - the gauge boson of QED - or as an extended object with structure. The structure function of the photon differs from that of the proton because the photon has a point-like coupling to quark charges - which is calculable in perturbative QCD - as well as a non-perturbative hadron-like part.

The classic way to investigate the structure of the photon is via the deep inelastic scattering of electrons (or positrons) on the quasi-real photons which accompany the beams at e^+e^- colliders. The structure function F_2^γ, which in leading order is proportional to the sum over the parton densities of the photon weighted by the square of the parton's charge, can be extracted by measuring the differential cross section for this process and through recourse to the following relation:

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

where $Q^2 = -q^2$ is the negative value of the four-momentum squared of the virtual probe photon, α is the fine structure constant and x and y are the usual dimensionless deep inelastic scattering variables. In the kinematic region explored at LEP, $y^2 \ll 1$ and the term proportional to F_L^γ in Equation 1 can be neglected.

This article concentrates on the most recent results on photon structure from the LEP collaborations. A recent, comprehensive review can be found in Reference 1, which also contains the references to all LEP results in addition to those explicitly referenced here.

2   Recent improvements in the analysis

Because the electron which emits the quasi-real photon is not seen in the detector, x needs to be determined by measuring the invariant mass, W, of the hadronic final state. The hadrons tend to be boosted in the forward direction and thus poorly contained in the detector, so a central component of structure function analyses at LEP is the use of an unfolding procedure to relate the visible distributions to the underlying ones.

The unfolding requires the input of a reference Monte Carlo model and this leads to a dependence of the F_2^γ measurement on the modelling of the hadronic final state. As a consequence, past LEP measurements of F_2^γ have suffered from large model dependent errors, and significant effort has been invested in exploring techniques to reduce these.

In order to stimulate improvements in the available Monte Carlo models, ALEPH, L3 and OPAL have combined their data and produced corrected distributions of variables related to the hadronic final state [2]. The differences between experiments are used to estimate the systematic errors, and these errors are usually smaller than the significant differences between models. This result thus serves as a useful constraint on the development of the models.

ALEPH and OPAL have employed the method of two-dimensional unfolding [3] to reduce the sensitivity of the result to the large differences observed in the modelling of the hadronic final state. This relies on the fact that discrepancies between data and Monte Carlo in the variable in which you unfold are not important. There is information in every event about the angular distribution of the hadrons, but this information is not exploited if only x is used in the unfolding. If a variable that characterises the final state hadrons is chosen and used as a second unfolding variable, the result will be independent of the differences between Monte Carlo models in that variable as well as in x, thus reducing the overall model dependence.

Improving the reconstruction of W will also reduce the uncertainties due to the models, and several techniques have been employed to do this. Both OPAL and L3 have used a method which uses information from the tagged electron together with transverse momentum conservation [4]. This improves the reconstruction because the resolution on electromagnetic energy measurements is generally better than those on hadronic energy. OPAL have also introduced a special treatment of the energy in the forward region to make the detector response more uniform [5]. For their analysis of F_2^γ at high Q^2, L3 have made use of a kinematic fit, and showed this to give a good correlation between the generated and measured W [6].

In the past, QED radiative corrections have been neglected in measure-

ments of F_2^γ. However, the most recent OPAL analyses [5,7] have corrected for the effects of initial state radiation and the Compton scattering process using the RADEG program [8]. The radiative corrections are x-dependent and largest at small values of x, such that the shape of F_2^γ is changed when the corrections are applied.

3   Recent results

The rise in F_2^p at low x seen at HERA has precipitated intensive investigation to try and establish whether such a rise is also present in F_2^γ, and LEP is able to extend the reach at low x relative to measurements at previous e^+e^- colliders. OPAL has recently published measurements [5] concentrating on the behaviour of F_2^γ at low x for $\langle Q^2 \rangle$ between 1.9 and 17.8 GeV^2, examples of which are shown in Figure 1 along with a number of earlier measurements. The systematic uncertainties have been considerably reduced compared to previous
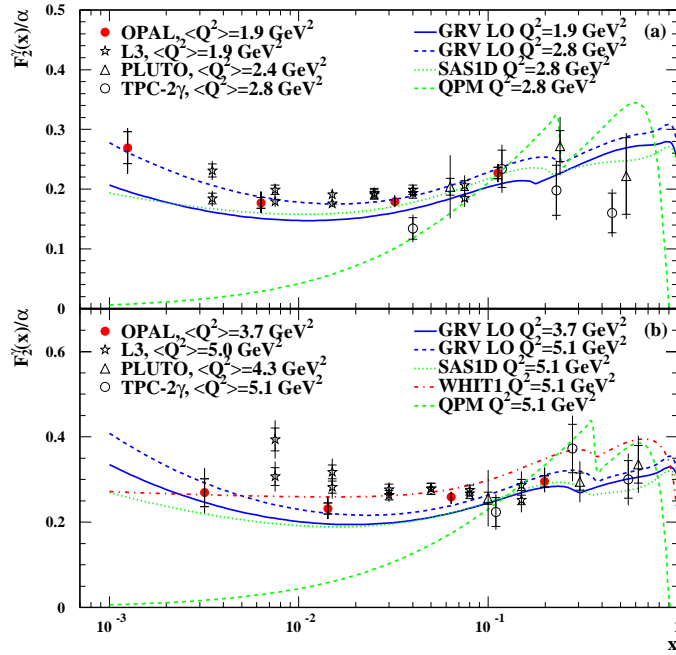

Figure 1. The measurements of F_2^γ at low x

analyses, through the use of the techniques described in the previous section, along with improved Monte Carlo models. In addition, account has been taken of the fact that when systematic errors are evaluated by modifying parameters in the analysis a significant statistical component can be introduced if, for example, events are added to or removed from bins. A procedure has been used to evaluate the size of this component, which is then subtracted from the systematic error.

The shapes of the GRV LO and SaS1D parameterisations are generally consistent with the OPAL and L3 data. The data are consistent with, but do not conclusively prove, the presence of a rise in F_2^γ at low x. They do, however, demonstrate that the photon must contain a significant hadron-like component at low x.

At high Q^2 the point-like part of F_2^γ is expected to dominate. A new OPAL measurement of F_2^γ at the highest $\langle Q^2 \rangle$ thus far [7] is shown in Figure 2. At large Q^2 the hadronic system has more transverse momentum and as a consequence there is much better correlation between the true and measured invariant mass. This leads to a much smaller dependence of the result on the unfolding and the input Monte Carlo model. The present measurement suffers from large statistical and systematic uncertainties, which should be reduced once the final analysis - which will include the full LEP2 data sample - is published.
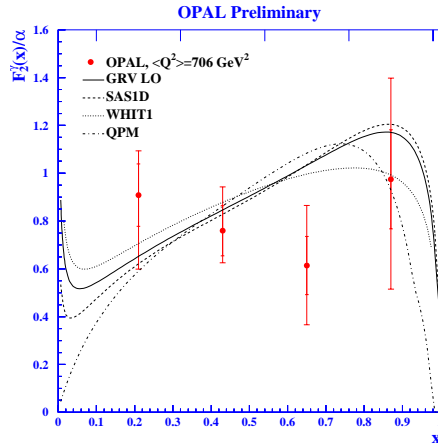

Figure 2. New OPAL measurement of F_2^γ at high Q^2.

4   Virtual photon structure

A suppression of F_2^γ is expected with increasing virtuality of the target photon, P^2, although the various theoretical predictions show a large spread in the magnitude of this suppression. For real photons only transverse helicity states of the target photon contribute. For $P^2 \gg 0$, though, longitudinal helicities must in addition be taken into account, and Equation 1 is not valid. However, if the condition $Q^2 \gg P^2 \gg \Lambda_{\mathrm{QCD}}^2$ is satisfied, an effective structure function F_{eff}^γ can be defined.

Only L3 have measured F_{eff}^γ at LEP [6] and their result is shown in Figure 3. Both theoretical predictions undershoot the data - something that is to be expected since the QPM does not include the hadron-like contribution and the GRS parameterisation takes account only of transverse virtual photons. The measured P^2 dependence is consistent in shape with the QPM prediction, but the statistics are severely limited and the full LEP2 data need to be exploited to shed further light on this aspect of the photon's structure.
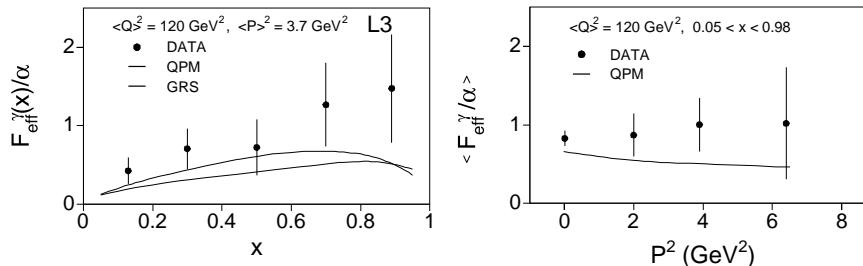
Figure 3. L3 measurement of F_{eff}^γ.

5   Summary and Conclusions

LEP has considerably improved our understanding of the hadronic structure of the photon. Recently, it has been demonstrated that the systematic uncertainties can be reduced through methods such as two dimensional unfolding. The current status is shown in Figure 4, which shows the evolution of F_2^γ with Q^2. One can see the positive scaling violations for all values of x which result from the point-like coupling.

Despite recent advances, however, further improvements, in particular in the available Monte Carlo models, are desirable. Also, many results are still statistically limited and the exploitation of the full LEP2 data will enhance our understanding of the hadronic structure of the photon.
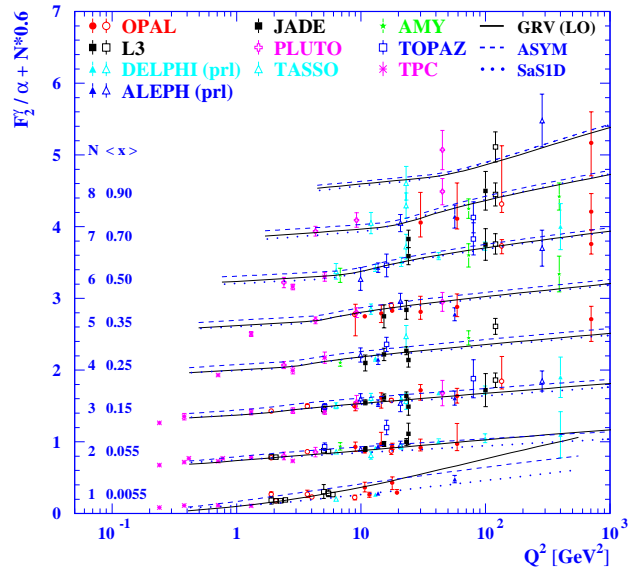
Figure 4. Summary of the measurements of the Q^2 evolution of F_2^γ in bins of x (taken from Reference 1).

References

1. R. Nisius, *Phys. Rep.* **332**, 165 (2000).
2. The LEP Working Group for Two-Photon Physics, ALEPH, L3 and OPAL Collaborations, CERN-EP/2000-109, Submitted to *Eur. Phys. J.* **C**, hep-ex/0010041.
3. S. Cartwright, M.H. Seymour *et al., J. Phys.* **G24**, 457 (1998).
4. L. Lönnblad *et al.*, CERN 96-01, Physics at LEP2, eds G. Altarelli, T. Sjöstrand and F. Zwirner (1996) Vol. 2, p. 201.
5. OPAL Collaboration, G. Abbiendi *et al., Eur. Phys. J.* **C18** 15 (2000).
6. L3 Collaboration, M. Acciarri *et al., Phys. Lett.* B**483** 373 (2000).
7. R.J. Taylor, in *Photon 2000*, ed. A.J. Finch (AIP 2001), hep-ex/0010010.
8. E. Laenen and G.A. Schuler, in *Photon 97*, eds. A. Buijs and F.C. Erné, 57 (World Scientific 1998).