Volume 107B, number 1,2 PHYSICS LETTERS 3 December 1981

FIRST MEASUREMENT OF THE PHOTON STRUCTURE FUNCTION F_2

PLUTO Collaboration

Ch. BERGER, H. GENZEL, R. GRIGULL, W. LACKAS, F. RAUPACH and W. WAGNER
I. Physikalisches Institut der RWTH Aachen [1], *Germany*

A. KLOVNING, E. LILLESTÖL and J.A. SKARD [2]
University of Bergen [3], *Norway*

H. ACKERMANN, G. ALEXANDER [4], G. BELLA [4], J. BÜRGER, L. CRIEGEE, A. ESKREYS [5], G. FRANKE, W. GABRIEL [11], Ch. GERKE, G. KNIES, E. LEHMANN, H.D. MERTIENS, U. MICHELSEN, K.H. PAPE, H.D. REICH, J.M. SCARR [6], B. STELLA [7], U. TIMM, G.G. WINTER and W. ZIMMERMANN
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

O. ACHTERBERG, V. BLOBEL, L. BOESTEN, V. HEPP [8], H. KAPITZA, B. KOPPITZ, B. LEWENDEL, W. LÜHRSEN, R. van STAA and H. SPITZER
II. Institut für Experimentalphysik der Universität Hamburg [1], *Germany*

C.Y. CHANG, R.G. GLASSER, R.G. KELLOGG, K.H. LAU, R.O. POLVADO, B. SECHI-ZORN, A. SKUJA, G. WELCH and G.T. ZORN
University of Maryland [9], *USA*

A. BÄCKER, F. BARREIRO, S. BRANDT, K. DERIKUM, C. GRUPEN, H.J. MEYER, B. NEUMANN, M. ROST and G. ZECH
Universität – Gesamthochschule Siegen [1], *Germany*

and

H.J. DAUM, H. MEYER, O. MEYER, M. RÖSSLER [10] and D. SCHMIDT
Universität – Gesamthochschule Wuppertal [1], *Germany*

Received 14 September 1981

Using data taken at PETRA we present results on deep inelastic electron photon scattering at momentum transfers $1 < Q_2 < 15$ GeV^2. The results are expressed in terms of the photon structure function F_2 and are compared with QCD predictions and "hadronic" models of the photon. The pointlike component of the photon is found to be dominant.

---

[1] Supported by the BMFT, Germany.
[2] Now at University of Maryland, College Park, USA.
[3] Partially supported by the Norwegian Council for Science and Humanities, Norway.
[4] On leave from Tel Aviv University, Israel.
[5] Now at Institute of Nuclear Physics, Krakow, Poland.
[6] On leave from University of Glasgow, Scotland.
[7] Now at University of Rome, Italy; partially supported by INFN, Italy.
[8] Now at Heidelberg University, Germany.
[9] Partially supported by Department of Energy, USA.
[10] Now at Siemens AG, Munich, Germany.
[11] Now at Max Planck Institut für Limnologie, Plön, Germany.

0 031-9163/81/0000–0000/$ 02.75 © 1981 North-Holland

High-energy electron–positron storage rings offer the opportunity to measure the inclusive reaction

$$e^+e^- \to e^+e^- + \text{hadrons}\,. \qquad (1)$$

This reaction is usually interpreted as hadron production by two virtual photons which are radiated from the incoming leptons ($e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-$ + hadrons).

Experimentally, reaction (1) can be separated from the annihilation process ($e^+e^- \to \gamma^* \to$ hadrons) by detecting one of the outgoing leptons at moderately small scattering angles ("single tagging"). If the scattering angle of the other lepton is kept very small by excluding events with a scattering angle greater than 25 mrad ("antitagging"), the photon radiated from this lepton is practically on the mass shell ($\langle Q^2 \rangle \approx 0.07$ GeV^2) and purely transversely polarized. This set of conditions constrains the kinematics to that of *electron scattering off a real photon* beam. For a more detailed discussion of the kinematics and an explanation of the symbols used see ref. [1].

In a previous paper [2] we presented measurements of this reaction for invariant masses of the hadronic system in the range $1 < W < 10$ GeV and four-momemtum transfers squared of the scattered lepton $Q^2 < 0.7$ GeV^2. The results were interpreted in terms of a total photoabsorption cross section $\sigma_t(Q^2, W) + \epsilon\sigma_\ell(Q^2, W)$, where the indices t and ℓ refer to the transverse and longitudinal polarization of the virtual photon and ϵ determines the degree of polarization. It was found that the Q^2 dependence of the cross section has a typical "hadronic" behaviour

$$\sigma(Q^2, W) = \sigma(0, W) F_\rho^2\,, \qquad (2)$$

with the ρ-pole form factor given by $F_\rho = 1/(1 + Q^2/m_\rho^2)$. In this paper we present data covering an extended Q^2 range, up to 15 GeV^2. This allows to investigate the hadronic structure of the photon down to distances of 10^{-14} cm and in particular look for a hard quark component as expected from the quark parton model (QPM).

The large Q^2 were obtained by selecting events with a single tag in one of the large-angle taggers (LAT) of the PLUTO detector, which cover the polar angle region between 70 and 260 mrad with respect to the beams.

The energies of electrons and photons are determined with lead scintillator shower counters of 14.5 radiation length thickness. The positions of charged particles are determined by two planes (one horizontal, one vertical coordinate) of proportional tube chambers in front of the shower counter and by two planes inside the counter. The wire spacing of the tube chambers is 1 cm. The detection properties of this system have been extensively studied by using a high statistics data sample of small-angle Bhabha events. The reconstructed angular distribution agrees well with QED predictions and the luminosity determined in the LAT agrees to better than 10% with the luminosity monitor (SAT).

The single tag–antitag condition is given by requiring an energy deposition > 8 GeV in the LAT on one side and < 4 GeV in the SAT and LAT on the opposite side. Multihadron events ($n_\text{had} \geqslant 3$) in the central detector are defined by using the same criteria as in ref. [2].

In order to ensure uniform detection efficiency of the LAT we have applied a cut on the positron (electron) scattering angle of $100 < \theta_1 < 250$ mrad. The deep inelastic region in eγ scattering is expected to begin at rather small values of Q^2 and W [3]. For the analysis we have chosen $Q^2 > 1$ GeV^2 and $W_\text{vis} > 0.75$ GeV, W_vis being the measured invariant mass of the hadrons. This corresponds to an effective cut in W at 1 GeV. A total of 117 events survive these cuts, corresponding to an integrated luminosity of 2500 nb^{-1} at an average beam energy of 15.5 GeV.

We correct our data sample for three sources of background.

(a) The background from beam–gas scattering is measured from the vertex distribution of the tracks in the central detector to be 5 events.

(b) Annihilation processes can contribute in two ways. A forward jet or part of a forward jet can simulate a tag in the LAT. In addition a radiative annihilation event can simulate a deep inelastic eγ event, with the hadrons detected in the central detector and the high-energy radiated photon being detected in the LAT. Both contributions have been calculated by applying the two-photon analysis chain to Monte Carlo generated annihilation events. As a result only 1 event has to be subtracted from our data sample.

(c) Inelastic Compton scattering $e\gamma \to eX(C_X = -1$, see fig. 1b) can give events which are kinematically very similar to genuine two-photon events. This background has also been calculated in a Monte Carlo program using the cross section given in ref. [4]. Our cuts reduce this background to <0.3 events for our data sample.

Radiative corrections to the two-photon process have not been calculated explicitly. They are expected to be small [5] mainly because the hadronic mass W is *measured* in the central detector (quite in contrast to deep inelastic electron–nucleon scattering, where W is determined by the energy loss of the scattered electron).

From the subtracted sample of 111 events we have calculated $\sigma(Q^2, W_{\mathrm{vis}})$ using the same analysis procedure as described in ref. [2]. In fig. 2 we plot the result for the range $3.5 < W_{\mathrm{vis}} < 10$ GeV, where we found previously [2], that for small Q^2 values the cross section is practically constant w.r.t. W_{vis}. Fig. 2 also includes our earlier results [2] which are seen to follow the vector meson dominance (VMD) prediction [eq. (2)] very well. Above $Q^2 = 1\ \mathrm{GeV}^2$, however, the cross section deviates dramatically from this prediction. This deviation demonstrates that the photon has a structure which is much harder than expected from VMD.

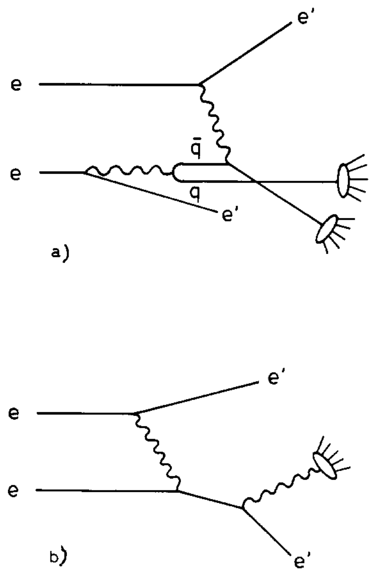

Fig. 1.(a) Feynman diagram for deep inelastic electron–photon scattering. (b) Feynman diagram for electron–photon Compton scattering.

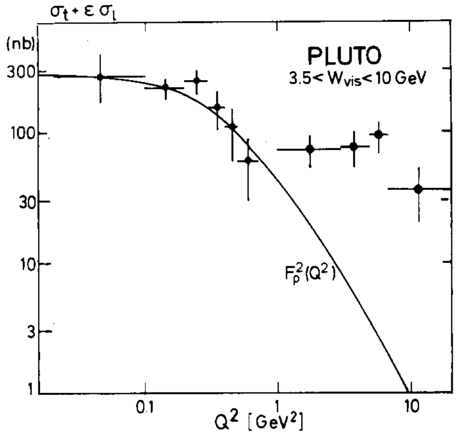

Fig. 2. Total $\gamma\gamma$-cross section as a function of Q^2. The data below 1 GeV^2 are published data (2), the solid line shows the VDM prediction $\approx F_\rho^2$.

In order to investigate this "pointlike" behaviour of the eγ scattering cross section more closely we discuss the data in terms of structure functions as in deep inelastic lepton–nucleon scattering. Defining

$$F_{\mathrm{t}} = (Q^2/8\pi^2\alpha x)\sigma_{\mathrm{t}}, \quad F_{\ell} = (Q^2/4\pi^2\alpha)\sigma_{\ell}\,, \tag{3}$$

the cross section for inelastic eγ scattering can be written as

$$\mathrm{d}\sigma/\mathrm{d}x\mathrm{d}y\,|_{\mathrm{e}\gamma\to\mathrm{eX}} = (16\pi\alpha^2 EE_\gamma/Q^4) \times [(1-y)F_2(x,Q^2) + xy^2F_1(x,Q^2)]\,, \tag{4}$$

with $F_1 = F_{\mathrm{t}}$ and $F_2 = 2xF_{\mathrm{t}} + F_{\ell}$ and the scaling variables x, y defined as

$$x = Q^2/(Q^2+W^2), \quad y = 1 - (E_1'/E)\cos^2\tfrac{1}{2}\theta_1\,. \tag{5}$$

Within our experimental acceptance xy^2 is small and eq. (4) is well approximated by

$$\mathrm{d}\sigma/\mathrm{d}x\mathrm{d}y\,|_{\mathrm{e}\gamma\to\mathrm{eX}} = (16\pi\alpha^2 EE_\gamma/Q^4)(1-y)F_2(x,Q^2). \tag{6}$$

In the quark model x is the relative momentum fraction of the quark and F_2 is a measure of the momentum-weighted quark content of the photon target (fig. 1a) $F_2 \sim \Sigma e_i^2 x \cdot q(x,Q^2)$.

We have evaluated $F_2(x,Q^2)$ in two steps [‡1]. First we compared the measured number of events in 5 bins of x_{vis} [‡2] with the expected number from a Monte Carlo

---

[‡1] A very preliminary account of this work has been given before [6].

[‡2] x_{vis} is determined by the measured values of Q^2 and W.

simulation averaging over the whole Q^2 range. The events were generated according to fig. 1a using formula (6) with a constant structure function F_2. For the decay of the hadronic system we used a limited p_T phase space model, where the transverse momenta of the hadrons were generated with a distribution $\exp(-5p_T^2)$, and p_T refers to the direction of flight of the $q\bar{q}$ pair in the $\gamma\gamma$ CMS. We have found that this ansatz reproduces the experimental distributions (Q^2, W_{vis}, x_{vis}) well enough to be used in a second step in which we unfold the data by converting the x_{vis} into a true x distribution. In fig. 3a the structure function F_2 (in units of α) is plotted versus x ($Q^2 > 1$ GeV^2, $W > 1$ GeV). Within errors F_2 is constant over the whole x range, with a mean $\langle F_2/\alpha\rangle \approx 0.35$. From a number of checks we conclude that the results are insensitive to details of the procedure. For example we determined the total $\gamma\gamma$ cross section with the method described in ref. [2], where we used a different event generator ($75\% \exp(-5p_T^2) + 25\% \exp(-p_T^2)$, p_T referring to the direction of flight of the *incoming photons*). We then converted this cross section into structure functions using formula (3) and obtained consistent results.

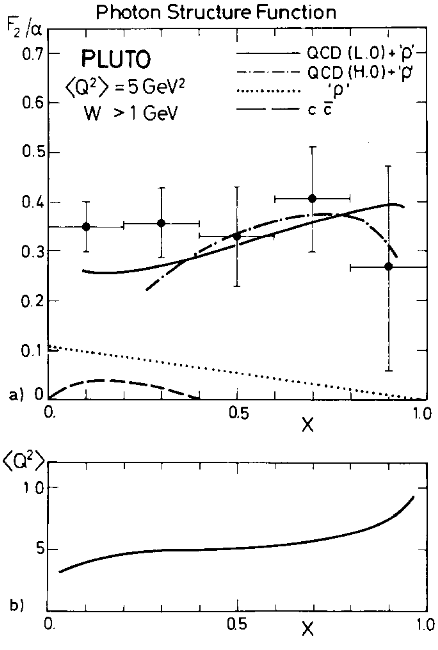

Fig. 3.(a) Photon structure function $F_2(x)/\alpha$. The data are averaged over $1 < Q^2 < 15$ GeV^2. ... Hadronic structure function $F_{2,\rho}$ (eq. 7). —: $F_{2,\text{QCD}} + F_{2,\rho}(\Lambda_{\text{LO}} = 0.2$ GeV, u, d, s quarks) in the leading order [eq. (9)]. —·—: $F_{2,\text{QCD}} + F_{2,\rho}(\Lambda_{\overline{\text{MS}}} = 0.2$ GeV, u, d, s quarks) including higher order corrections (from ref. [14]). – – –: $F_{2,\text{box}}$ for c quarks only ($m_q = 1.5$ GeV). (b) $\langle Q^2\rangle - x$ correlation for the kinematic range of this experiment.

In order to facilitate the comparison of data with theoretical models we have included in fig. 3b the correlation between Q^2 and x for this experiment, as calculated from the Monte Carlo model. For most of the x-range the average Q^2 does not vary very much, so that fig. 3a essentially gives the x dependence of F_2 at a constant $\langle Q^2\rangle \approx 5$ GeV.

The photon structure function is expected to have a "hadronic piece" accounting for the "vector-meson like" nature of the photon. This contribution has been estimated from the measured [7] structure function of the pion as [4]

$$F_{2,\rho} \approx \frac{\alpha}{f_\rho^2/4\pi}\,\frac{1}{4}(1-x) \tag{7}$$

and is shown in fig. 3a as the dotted line. It is clear, that the data are not described by $F_{2,\rho}$ alone.

In addition to the hadronic piece there is a point-like contribution arising from the fact, that the photon can create "free" $q\bar{q}$ pairs. This part can already be calculated in the quark model (quark box diagram, see for example ref. [4]).

$$F_{2,\text{box}} = \frac{\alpha}{\pi}\sum e_i^4 \times \{x[x^2 + (1-x)^2]\ln(W^2/m_q^2) + 4x^2(1-x)\}. \tag{8}$$

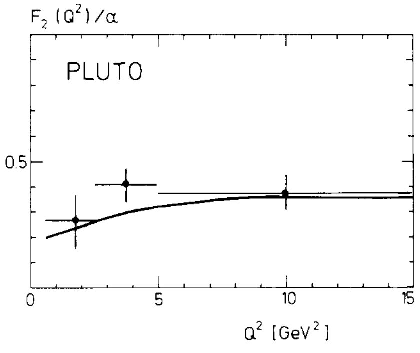

Fig. 4. Photon structure function $F_2(Q^2)/\alpha$. The data are averaged over $0.2 < x < 0.8$. The curve shows the QCD prediction in the leading order with $\Lambda_{\text{LO}} = 0.2$ GeV.

Gluon corrections to the quark box, summed in the leading log approximation of QCD, modify F_2 to

$$F_{2,\mathrm{QCD}} = h(x) \ln Q^2/\Lambda_{\mathrm{LO}}^2 , \qquad (9)$$

with Λ_{LO} being the QCD scale parameter. Several authors [4,8,9] have calculated $h(x)$ following the pioneering work of Witten [10]. For a comparison with our data we used $F_{2,\mathrm{QCD}}$ with $\Lambda_{\mathrm{LO}} = 0.2$ GeV (u, d, s quarks) from ref. [6] and calculated $F_{2,\mathrm{QCD}} + F_{2,\rho}$ (solid line in fig. 3a). This model describes the data very nicely for $x > 0.2$. Note, however, that the predictions of the standard quark model [eq. (8)] (with $m_\mathrm{q} = 300$ MeV, q = u, d, s) and also of the massive quark model [11] lead, within our acceptance, to a similarly good description.

A better agreement at small x between data and model can be achieved if one includes the charmed quark contribution. This contribution has been calculated in the quark model [formula (8)] using $m_\mathrm{q} = 1.5$ GeV (dashed line in fig. 3a). A coherent superposition of the ρ and ω contribution also helps by increasing the hadronic structure function by roughly a factor of 1.5 [12]. QCD corrections to the photon structure function have been calculated recently [13] beyond the leading order of asymptotic freedom. The main effect of higher order corrections is a suppression of the structure function at the highest x values. The dashed–dotted line in fig. 3a represents the result of a higher order calculation in the $\overline{\mathrm{MS}}$ scheme using $\Lambda_{\overline{\mathrm{MS}}} = 0.2$ GeV [14].

Finally, QCD predicts a Q^2 dependence of F_2 at fixed x, meaning a strong scale breaking [eq. (9)]. We have investigated this effect by plotting in fig. 4 F_2 versus Q^2, averaged over $0.2 < x_{\mathrm{vis}} < 0.8$. This restriction on x necessary in order to avoid Q^2–x correlations (see fig. 3b), which could also simulate a scale breaking. The data are clearly consistent with the QCD prediction in the leading order (solid line) but more data is needed for a detailed investigation.

In conclusion we have shown, that in deep inelastic eγ scattering the pointlike component of the photon is dominant and that the results are consistent with QCD calculations using a $\Lambda_{\overline{\mathrm{MS}}}$ value of 0.2 GeV.

The outside groups of the PLUTO-Collaboration want to express their gratitude to the DESY-Directorate, Professors V. Soergel, H. Schopper, G.A. Voss and E. Lohrmann, for the hospitality and for encouragement and support of the experiment. We appreciate illuminating discussions with Dr. A.J. Buras. We are indebted to the PETRA machine group and the DESY computer center for their excellent performance during the experiment. We gratefully acknowledge the efforts of all engineers and technicians of the collaborating institutes who have participated in the construction and maintenance of the apparatus.

References

[1] Ch. Berger, in: Lecture Notes in Physics, Vol. 134 (Springer, Berlin); PLUTO Collab., Ch. Berger et al., DESY 80/94.
[2] PLUTO Collab., Ch. Berger et al., Phys. Lett. 99B (1981) 287.
[3] H. Terazawa, Rev. Mod. Phys. 45 (1973) 615.
[4] C. Peterson, T.F. Walsh and P.M. Zerwas, Nucl. Phys. B174 (1980) 424.
[5] Y. Srivastava, Invited talk 4th Intern. Colloquium on $\gamma\gamma$ Interactions (Paris, April 1981), to be published in the Proceedings of the Conference.
[6] W. Wagner, Proc. XXth Intern. Conf. on High energy physics (Madison, 1980);
Ch. Berger, Proc. 4th Intern. Colloquium, on Photon–photon interactions (Paris, 1981).
[7] C.B. Newman et al., Phys. Rev. Lett. 42 (1979) 951.
[8] W.R. Frazer and J.F. Gunion, Phys. Rev. D20 (1979) 147.
[9] Ch. Llewellyn Smith, Phys. Lett. 79B (1978) 83.
[10] E. Witten, Nucl. Phys. B120 (1977) 189.
[11] P. Castorina, G. Nardulli and G. Preparata, Z. Phys. C8 (1981) 277.
[12] P. Zerwas, private communication.
[13] W.A. Bardeen and A.J. Buras, Phys. Rev. D20 (1979) 166;
D.W. Duke and J.F. Owens, Phys. Rev. D22 (1980) 2280.
[14] A.J. Buras and D.W. Duke, unpublished.