MEASUREMENT OF DEEP INELASTIC ELECTRON SCATTERING OFF VIRTUAL PHOTONS

PLUTO Collaboration

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Deep inelastic electron scattering off virtual photons with an average invariant mass squared of -0.35 GeV^2 has been measured using photon–photon "double-tag" events taken with the PLUTO detector at PETRA. The data are expressed as a combination of the structure functions F_2 and F_L and are compared with expectations from the quark parton model and QCD.

The two-photon process $e^+e^- \to e^+e^- +$ hadrons has been extensively studied in the kinematic region where only one of the scattered electrons is detected (single tagging). The absence of a second tag means that the other scattered electron is constrained to a small angular region around the outgoing beam. The process is then usually interpreted as deep inelastic scattering from a (quasi-real) photon target and the data are analysed in terms of structure functions of a real photon [1]. If the second scattered electron is also detected (double tagging), the "target" photon is itself virtual, and the possibility arises of measuring the off-mass-shell behaviour of the photon structure functions. QCD predictions for these virtual photon structure functions are free from the unphysical singularities which arise in the real photon case [2,3].

The data described here were taken with the PLUTO detector at the e^+e^- colliding beam facility PETRA at DESY. The PLUTO detector has been described in detail elsewhere [4]. The good shower counter and drift-chamber coverage in the forward directions has allowed the accumulation of a sufficient number of double-tag events to make a first measurement of the virtual photon structure functions. Data were used from a total integrated luminosity of 30.1 pb^{-1}, accumulated at a beam energy of 17.3 GeV.

Double-tag events were selected in the kinematic region where one of the virtual photons, the probe, had a large (negative) invariant mass squared (Q^2) and the other, the target, a small (negative) invariant mass squared (P^2). Two shower signals (tags) at opposite ends of the detector were required with energy >6 GeV, one in the small angle tagger in the angular range $31 < \vartheta < 55$ mrad and one in the large angle tagger in the range $100 < \vartheta < 250$ mrad. Each large angle tagger is preceded by a set of five drift chambers. In the case of the large angle tag, an associated track through these chambers was required. Hadronic final states were selected by requiring at least three additional charged particles. The "visible" invariant mass of the events, W_{vis}, measured from the observed charged and neutral particles (excluding the two tags), was required to exceed 1.2 GeV. A total of 74 events fulfilled these criteria. For these events, the mean invariant mass squared of the target photon was -0.35 GeV^2 and that of the probe was -5.0 GeV^2.

Background levels were estimated by applying the same selection criteria to Monte Carlo events generated for various reactions. The largest sources of background were two-photon production of τ-pairs (~3 events) and single-tag two-photon events where an additional tag was faked by hadron showers or photons (~2.5 events). Other background processes considered were the reaction $e^+e^- \to$ hadrons (<1 event) and hadron production from inelastic Compton scattering (negligible). The beam–gas event background was also negligible. The data were uniformly scaled down to correct for these effects. A background subtraction was not practicable for statistical reasons.

For a quasi-real photon target, the cross section for the process $e\gamma \to e +$ hadrons can be expressed in terms of just two structure functions, $F_1(Q^2, x)$ and $F_2(Q^2, x)$:

$$d\sigma/dx\, dy = (16\pi\alpha^2 E E_\gamma/Q^4)[(1-y)F_2 + xy^2 F_1]\,, \quad (1)$$

where $F_2 = F_L + 2xF_1$ and x and y are the usual scaling variables ‡1 [5]. In practice the restrictions placed on the energy and angle of the tagged electron are such that the parameter y is small (~0.15) and the two-photon cross section is effectively saturated by the single structure function F_2.

Off-mass-shell extensions of the structure functions F_2 and F_L for a spin-averaged target photon can be defined [6,2,3]. They can be written in terms of virtual photon, $\gamma^*\gamma^*$, cross sections, using the notation

‡1 I.e. $x = Q^2/2p\cdot q$. This is the usual definition of the x scaling variable. At finite P^2 a modified version which extends over the whole range $0 \leqslant x \leqslant 1$ is often used (see for example ref. [3]). The difference is negligibly small for $P^2/Q^2 \ll 1$.

of Budnev et al. [7]

$$F_2/\alpha = (Q^2/4\pi^2\alpha^2)(1 - Q^2P^2/\nu^2)^{-1/2} \times (\sigma_{TT} + \sigma_{LT} - \tfrac{1}{2}\sigma_{TL} - \tfrac{1}{2}\sigma_{LL}) , \tag{2}$$

$$F_L/\alpha = (Q^2/4\pi^2\alpha^2)(1 - Q^2P^2/\nu^2)^{1/2} \times (\sigma_{LT} - \tfrac{1}{2}\sigma_{LL}) , \tag{3}$$

where $\nu = Q^2/2x$ and we adopt the convention that the first and second suffixes on the cross sections refer to the polarizations (in the $\gamma^*\gamma^*$ centre of mass system) of the probe and target photons respectively. For the quark parton model (QPM), the cross sections can be calculated from the corresponding QED Born diagram expressions [7] for $e^+e^- \to e^+e^-\mu^+\mu^-$ with quark charges and masses substituted. The above expressions reduce to the usual ones for F_2 and F_L in the limit $P^2 \to 0$, as those cross sections involving a longitudinally (L) polarized target photon vanish in this limit.

However, when $m^2 \ll P^2 \ll Q^2$, where m is the quark mass, the following relations hold [3]:

$$\sigma_{TL} \approx \sigma_{LT} , \tag{4}$$

$$\sigma_{LL} \approx 0 , \tag{5}$$

so that:

$$F_2/\alpha \approx (Q^2/4\pi^2\alpha^2)(\sigma_{TT} + \tfrac{1}{2}\sigma_{LT}) , \tag{6}$$

$$F_L/\alpha \approx (Q^2/4\pi^2\alpha^2)(\sigma_{LT}) . \tag{7}$$

The full $\gamma^*\gamma^*$ cross section is given by:

$$\sigma_{\gamma\gamma} = (\sigma_{TT} + \epsilon_1\sigma_{LT} + \epsilon_2\sigma_{TL} + \epsilon_1\epsilon_2\sigma_{LL}) , \tag{8}$$

where ϵ_1 and ϵ_2 are the ratios of longitudinal to transverse flux of the probe and target photons respectively. With both ϵ_1 and $\epsilon_2 \sim 1$ (the values of y for both photons are $\ll 1$), we find that the corresponding equation to eq. (1) for double-tagged events in our kinematic region is:

$$d\sigma/dx\, dy = (16\pi\alpha^2 E E_\gamma/Q^4) \times [(1-y)(F_2 + \tfrac{3}{2}F_L) + O(y^2)] , \tag{9a}$$

so that, again for small y, the combination of structure functions to which the experiment is sensitive is, to a good approximation,

$$F_{eff} \equiv F_2 + \tfrac{3}{2}F_L . \tag{9b}$$

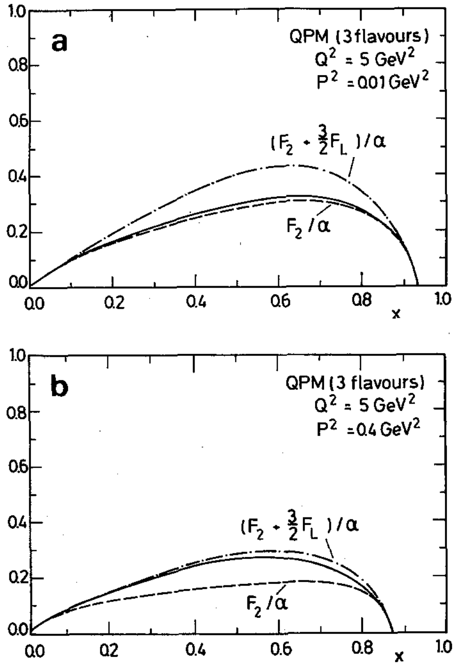

Fig. 1. Comparison of the quantity $(Q^2\sigma_{\gamma\gamma})/4\pi^2\alpha^2$ with F_2/α (dashed) and $(F_2 + \frac{3}{2}F_L)/\alpha$ (dash–dotted). (a) For Q^2 = 5 GeV^2 and P^2 = 0.01 GeV^2 assuming the QPM (3 flavour Born QED diagram with m_u, m_d = 0.3, m_s = 0.5 GeV), and (b) for the same Q^2 but with P^2 = 0.4 GeV^2. To a good approximation the quantity measured is the effective structure function $(F_2 + \frac{3}{2}F_L)/\alpha$.

Figs. 1a and 1b illustrate this change in the relationship between the structure functions and the $\gamma\gamma$ cross section in the QPM as the target photon moves off mass-shell. Our method of extracting the structure function will yield the quantity $(Q^2\sigma_{\gamma\gamma})/4\pi^2\alpha^2$. In fig. 1a, the expected value of this quantity, for the QPM (solid line) is compared with F_{eff}/α (dash–dotted line) and F_2/α (dashed line) for a typical single-tag configuration with Q^2 = 5 GeV^2 and small target mass (0.01 GeV^2). Fig. 1b shows the same quantities but with the target mass now raised to 0.4 GeV^2, typical of the events under study here. In each case the curves are for u, d and s quarks with masses of 0.3, 0.3 and 0.5 GeV/c^2 respectively. We conclude that the data can be compared with F_{eff}/α in the QPM with accuracy better than 10% over most of the x range.

The structure functions were extracted from the data using an unfolding procedure [8] which takes into account the resolution of the detector and corrects for systematic shifts of the measured variables. The scaling variable x was calculated from measured quantities using the relationship $x = Q^2/(Q^2 + P^2 + W^2)$ ‡1. The distortions in x arise mainly from mismeasurement of the hadronic invariant mass, W. The latter can be calculated either by summing the measured hadron 4-vectors or from the measured 4-vectors of the two tagged electrons. Monte Carlo studies indicate that the former method tends to underestimate the true value because of particle losses ($W_{vis}/W \sim 75\%$) whilst the latter suffers from poor resolution particularly at low W so that an unfolding is necessary whichever W measurement is used to determine x.

Simulated events were produced using a Monte Carlo program based on eq. (9) with a structure function of the form:

$$F(x)(1 + \alpha_1 \ln(Q^2/\langle Q^2\rangle)[1 + \alpha_2 \ln(P^2/\langle P^2\rangle)] . \quad (10)$$

The coefficients α_1 and α_2 allow for a possible Q^2 and P^2 dependence of the structure function. The simulation used parameters for fragmentation of the final state into pions determined from single-tag data [9]. The generated events were processed through a detector simulation and subjected to the same selection criteria as the data. $F(x)$, α_1 and α_2 were then adjusted to give the best simultaneous fit between the data and the simulated distributions of:

(a) x calculated from the hadrons,
(b) W measured from the tags,
(c) Q^2,
(d) P^2.

This procedure yielded the quantity $(Q^2\sigma_{\gamma\gamma})/4\pi^2\alpha^2 \approx F_{eff}/\alpha$ as a function of true x at a *fixed* Q^2 and P^2. A direct comparison between the data and theoretical expectations can therefore be made.

The extracted structure function F_{eff} is shown in fig. 2 for $Q^2 = 5$ GeV^2 and $P^2 = 0.35$ GeV^2. We compare the data with a QPM calculation (dash–dotted curve) using fractionally charged quarks and the following choice of constituent quark masses:

$$m_u = m_d = 0.3 \text{ GeV} ,$$

$$m_s = 0.5 \text{ GeV} ,$$

$$m_c = 1.6 \text{ GeV} . \quad (11)$$

A contribution from the "hadronic" component of the photon (see later) is also included.

Also in fig. 2 we compare the data with the higher

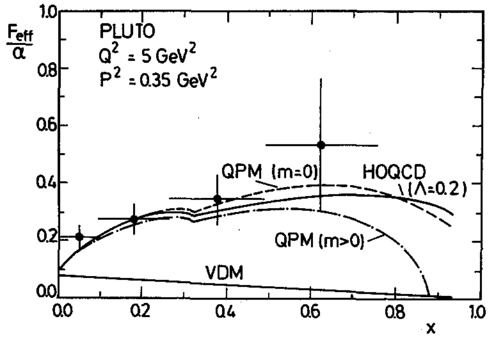

Fig. 2. The measured value of F_{eff}/α as a function of true x. The data are compared with QCD (solid curve), QPM with constituent quark masses (dash–dotted curve) and QPM with massless quarks (dashed curve). In each case a QPM c-quark contribution with constituent mass and a VDM contribution (see text) was added. The VDM contribution is shown separately as the lower diagonal line.

order QCD calculations of Rossi [3] for $\Lambda = 0.2$ GeV (upper solid curve) ‡2. Again a hadronic contribution has been added. To make the comparison we have assumed the same relationship between the $\gamma^*\gamma^*$ cross section and the structure functions F_2 and F_L as found for the QPM [eqs. (4)–(7), (9)], and have taken the QPM result for both F_L and the c-quark contribution.

It is well known that hadron production in $\gamma\gamma$ collisions is a sensitive test of the charges of quarks because any colour octet part of the photons can contribute to the colour singlet final state. For finite target masses, the sensitivity of the structure functions to the quark masses (in QPM) or the QCD scale parameter is reduced [2] and, in leading log, both the QPM and QCD structure functions F_2 have the form:

$$F_2 = \alpha \sum_{i=u,d,s,c} e_i^4 f(x) \ln \frac{Q^2}{P^2} . \quad (12)$$

Furthermore, the gluon emission corrections in the QCD predictions become small as the logarithmic interval $\ln(Q^2/P^2)$, measured in units of $\ln(P^2/\Lambda^2)$, is decreased [2,3], so that the QCD prediction for the x dependence of F_2, including next-to-leading terms,

‡2 The calculations in ref. [3] (fig. 12) are for $Q^2 = 5$ GeV^2 and $P^2 = 0.5$ GeV^2. The predictions were extrapolated to $P^2 = 0.35$ GeV^2 assuming the P^2 dependence of the QPM. These corrections are small (~5%).

also approaches that of the QPM (except at high x). That it does so is a consequence of asymptotic freedom in QCD. An absolute calculation of this x dependence can be made and, unlike that in the real photon case, it is free from singularities over the whole x range. As in the single-tag case, F_L is a function of x only, essentially unmodified by gluon radiation. With no other undetermined parameters then, the scale of the structure function is controlled solely by the sum of the fourth powers of the quark charges [10]. Included in fig. 2 is the QPM prediction for *massless* u, d and s quarks and massive c quark (upper dashed curve). The expectation from a naive integer charge quark model [11] would exceed this by a factor of ~3 and we can therefore exclude such a model. Gauge integer charge quark models cannot be excluded [12].

Although the QCD calculations include "hadron-like" terms [‡3], non-perturbative contributions, expected to be well described by vector meson dominance (VDM) models, are not included [3]. As in the case of the single-tag structure function [9], we find that the fit to data is improved by naively adding in such a VDM contribution. For the P^2 dependence of this contribution a ρ form factor, $F_\rho(P^2)$, has been assumed:

$$F^{\mathrm{VDM}}/\alpha = a(1-x)[F_\rho(P^2)]^2 \,. \qquad (13)$$

Here we have taken $a = 0.2$ [13,5]. A plot of this function is also shown in fig. 2 (lower solid curve) and it has been added to the other predictions. The data are consistent with this sum of a "target VDM" contribution and a point-like contribution given by either QCD or QPM. The possibility of "double-counting" remains if the VDM contribution is added. Furthermore, as pointed out by Rossi [3], since the inequalities $\Lambda^2 \ll P^2 \ll Q^2$ are not very strong for our values of P^2 and Q^2, the QCD calculations should, in any case, be treated with due caution. Data with target and probe photon masses such that the VDM contribution becomes negligible should yield an unambiguous check of the QCD prediction.

In fig. 3, the quantity $(Q^2\sigma_{\gamma\gamma})/4\pi^2\alpha^2$, $(\approx F_{\mathrm{eff}}/\alpha)$, averaged over both x and Q^2, is shown as a function of the measured P^2. The resolution in P^2 is sufficiently good that no unfolding was necessary. The point at $P^2 = 0$ was taken from PLUTO single-tag data [9]. The observed P^2 dependence is again consistent with a sum of target VDM and QPM. The sum is shown as the upper curve and the VDM contribution is shown separately in the lower curve. QCD predictions for the P^2 dependence in this range of P^2 are not yet available.

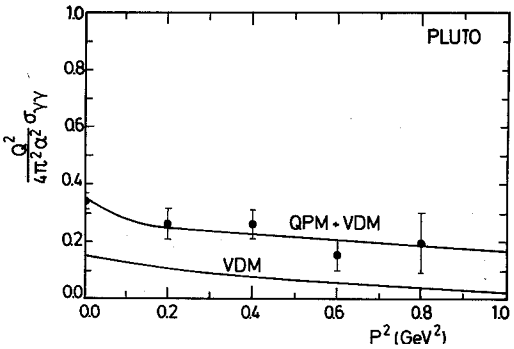

Fig. 3. The structure function F_{eff}/α as a function of target mass squared, P^2. The upper solid curve is the expectation from a sum of QPM and VDM. The lower curve is the VDM contribution.

In conclusion, we have measured a combination of virtual photon structure functions, which is well approximated by $F_{\mathrm{eff}} = F_2 + \frac{3}{2}F_L$ in the parton model, as a function of x at a $P^2 = 0.35$ GeV^2 and $Q^2 = 5.0$ GeV^2 and also as a function of P^2. The x dependence is consistent with a sum of contributions from QCD or QPM and a VDM contribution appropriate to the target photon. The P^2 dependence is consistent with a sum of QPM and VDM. The data imply that the sum of the fourth powers of the quark charges is consistent with fractionally charged quarks. Naive versions of integer charge quark models are excluded.

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‡3 It is precisely these terms which cancel the singularities in the point-like piece of the structure function.

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