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Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.58.97

Observation of Scaling of the Photon Structure Function F_2^γ at Low Q^2

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(Received 3 September 1986)

The structure function F_2^γ for a quasireal photon has been measured in the reaction $ee \to eeX$ for Q^2 in the range $0.2 < Q^2 < 7\ \mathrm{GeV}^2$, by use of 9200 multihadron events obtained with the TPC/Two-Gamma detector at the SLAC storage ring PEP. The data have been corrected for detector effects by use of a regularized unfolding procedure and are presented as $F_2^\gamma(x,Q^2)$. The structure formation shows scaling in the region $0.3 < Q^2 < 1.6\ \mathrm{GeV}^2$, $x < 0.3$, and rises for higher Q^2 and $x > 0.1$. Below $Q^2 = 0.3\ \mathrm{GeV}^2$, scaling breaks down in accordance with the finite cross-section bound for real photons.

PACS numbers: 13.65.+i, 14.80.Am

Deep-inelastic electron-photon scattering[1] can be studied in e^+e^- storage rings via the two-photon process $e^+e^- \to e^+e^- +$hadrons, if either the electron or positron is detected at large angles. If the other electron is restricted to small scattering angles (single-tag condition), one can then measure the structure function $F_2^\gamma(x,Q^2)$ of the quasireal photon. Here $-Q^2$ is the square of the four-momentum transfer of the scattered electron and the scaling variable x is given by $x \equiv Q^2/(Q^2+W^2)$, where W is the invariant mass of the photon-photon system.

The photon structure function F_2^γ has been considered an excellent tool to test QCD because it contains a pointlike component, which is absolutely calculable[2] and which rises as $\ln Q^2$. There is, however, an additional piece of the photon structure function, arising from the hadronic matrix element of the photon, which cannot be calculated perturbatively. Previous experiments[3] could only make assumptions about the size and shape of this hadronic piece. A standard procedure[4] relates it to measurements of the pion structure function, under the assumption of vector-meson dominance. The parametrization which has been used in most experiments so far is given by[5]

$$F_2^{\mathrm{had}}(x,Q^2) = 0.2\alpha(1-x). \tag{1}$$

However, there are several problems with this procedure. First, there is some arbitrariness in the inclusion of the higher-mass vector mesons ω and ϕ. (If the ρ, ω, and ϕ contributions are added coherently, the result is a factor of 1.4 higher than the incoherent sum.) Second, it is not obvious that the pseudoscalar mesons should have the same quark distribution functions as the vector mesons and that the massless photon should have the same fraction of sea quarks as the pion. Finally, one has to assume scaling to relate the pion measurements in the timelike region at $Q^2=25$ GeV^2 to the photon in the spacelike region.

In this paper we present a measurement[6] of the photon structure function F_2^γ at low Q^2, where we expect the hadronic part of the photon to be substantial. If there exists a region of Q^2 in which F_2^γ scales, we can hope to obtain there an experimental estimate of $F_2^{\rm had}$. It is important to keep in mind, however, that at excessively low Q^2 ($\lesssim m_\rho^2$) one enters the soft-scattering regime in which the probing photon does not always directly couple to the quarks of the target photon, but sometimes converts into a vector meson first. Since $\rho\rho$ scattering is expected to dominate this soft process, its Q^2 dependence is approximately given by the ρ-pole form factor

$$F_2^{\rho\rho}=\frac{Q^2}{4\pi^2\alpha^2}\frac{\sigma_0}{(1+Q^2/m_\rho^2)^2}, \tag{2}$$

which should be quite distinguishable from the approximately scaling hadronic piece $F_2^{\rm had}$ and the rising pointlike piece.

The data were taken at 29-GeV center-of-mass energy by the TPC/Two-Gamma detector located at the PEP e^+e^- storage ring at SLAC. A description of the apparatus can be found elsewhere.[7] The trigger required a single energy deposition in one of the low-angle tagging devices coincident with a charged track in the cental detector. The data analyzed correspond to 50 pb^{-1} of integrated e^+e^- luminosity.

In the off-line analysis, events were selected which had a charged tag measured in the forward spectrometer with an energy greater than 8 GeV and $Q^2 \geq 0.2$ GeV^2. The square of the target photon's four-momentum, P^2, was restricted to values less than 0.1 GeV^2 by an antitag requirement of no energy deposition greater than 4 GeV in the arm opposite the tag. Hadronic events were selected by our requiring a minimum total detected multiplicity of three particles (excluding the tag), with at least two charged tracks. In addition, at least one track had to be identified as a hadron (or hadron/muon ambiguity), primarily by use of the dE/dx information from the time-projection chamber (TPC). Most radiative μ-pair events were identified in the muon detectors and rejected. In order to elminate any background from misidentified double-tag events and annihilation events, it was required that the total visible energy (including the tag) be less than 23 GeV and the total transverse momentum with respect to the beam axis be less than 2 GeV.

For the 9200 events passing the final selection requirements, the major source of background is from beam-gas events ($\approx 10\%$). This background was subtracted statistically by use of the sidebands of the event-vertex distribution. The background from $\gamma\gamma\rightarrow\tau\bar{\tau}$ production was estimated by Monte Carlo calculations to be less than 2% and was also subtracted from the data. The contribution to the background from the processes $\gamma\gamma\rightarrow ee,\mu\mu$ were found to be negligible. The resulting data sample covers the range $0.2<Q^2<7$ GeV^2 and $1<W_{\rm vis}<12$ GeV, where the visible invariant mass $W_{\rm vis}$ is generally lower than the true W.

We correct our data for the effects of resolution and particle losses by means of the unfolding technique developed by Blobel.[8] Like any other unfolding method, it requires the Monte Carlo simulation of the detector acceptance and resolution in order to determine the mapping from x to $x_{\rm vis}$, where $x_{\rm vis}$ is calculated with use of the visible variables $Q^2_{\rm vis}$ and $W_{\rm vis}$. Since the mapping as well as the overall detection efficiency for the final state depends on the details of the fragmentation of the $\gamma\gamma$ system into hadrons, a good framentation model is essential. Initial-state radiation has been put into the Monte Carlo generator according to the equivalent-photon approximation[9]; its effect was to increase the structure function by less than 5% compared to the case without radiation. The final state was generated as a superposition of two models, both based on the process $\gamma\gamma\rightarrow q\bar{q}$, but with different angular distributions in the $\gamma\gamma$ center-of-mass system. In the first model the quarks are given limited p_T with respect to the $\gamma\gamma^*$ axis, $\langle p_T\rangle \simeq 300$ MeV (typical of hadron interactions), while in the second model the quarks are given a typical lepton-pair angular distribution as in $\gamma\gamma\rightarrow\mu\mu$. In both models we use the usual quark masses ($m_u=m_d=325$ MeV; $m_s=500$ MeV; $m_c=1.6$ GeV) and the different flavors are selected according to the quark-parton model. The quarks are fragmented into hadrons according to the Lund[10] fragmentation model. At $W<5$ GeV, the fragmentation parameters were adjusted to fit the data distributions. These generated events were then processed through the simulation software for the TPC/Two-Gamma detector and passed through the same off-line analysis software as the data. The mapping from x to $x_{\rm vis}$ was then inverted in such a way that the enhancement of random fluctuations, which usually occurs in matrix inversions, was avoided. This was done by our weighting the Monte Carlo events by an x-dependent weight, $f(x)$, such that the distributions of the visible variables $x_{\rm vis}$, $Q^2_{\rm vis}$, and $W_{\rm vis}$ were matched. The data points are then obtained by integration over $f(x)$, where the binning is chosen such that the bin-to-bin correlations are minimized. The errors in each bin reflect both the statistics and the (small) correlation between data points. In addition,

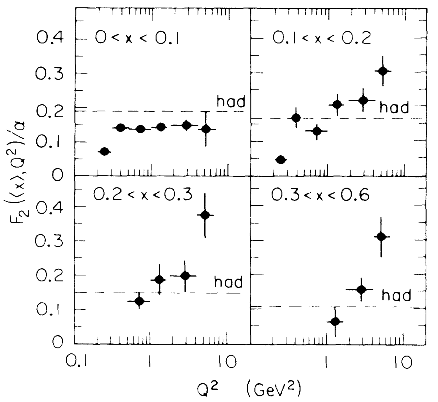

FIG. 1. The Q^2 dependence of the structure function F_2^γ in four bins of x. The dashed line represents the hadronic component of Eq. (1).

there are systematic errors of 11%–14%, which derive mainly from the choice of fragmentation model and its effect on the mapping and the detection efficiency. Other sources (detector simulation, background subtraction, radiative corrections, nonzero mass of the target photon, and luminosity calculation) were found to be of minor importance (typically 2%–3%).

The results are shown in Fig. 1 as $F_2^\gamma(Q^2)$ for four fixed bins of x. For low x the data are flat in Q^2 above 0.3 GeV^2 while for high x the data rise steeply, by about a factor of 3. This rise has been seen previously by other experiments[3] at larger values of Q^2 ($2.4 < Q^2 < 100$ GeV^2); in the region where we have overlapping acceptance ($2.4 < Q^2 < 7$ GeV^2), we find good agreement between our results and those of Berger *et al.*[3] In the intermediate-x range ($0.1 < x < 0.3$) the rise is less pronounced and becomes significant only above $Q^2=4$ GeV^2. However, the lowest-Q^2 point, which is accessible only in the first two x bins, is always low by a factor of 3 compared to the expected hadronic contribution. Qualitatively, this can be expected from quite general considerations. Since the relation between cross sections and structure functions contains a factor Q^2, a scaling structure function results in an infinite cross section as $Q^2 \rightarrow 0$. Thus scaling has to break down below some value of Q^2 and has to be replaced by a Q^2 dependence [as for instance in Eq. (2)] which results in a finite cross section for two real photons. The PLUTO Collaboration[11] measured the no-tag cross section at $Q^2 \approx 0$ to be near 300 nb. Taking 400 nb as an upper limit for all Q^2, we obtain an upper bound for the structure function. Figure 2 shows that for the $x < 0.1$ data this bound would be exceeded if F_2^γ were to scale to Q^2 values below 0.3 GeV^2. Also shown in this figure is the expectation from $\rho\rho$ scattering, if 300 nb is taken for σ_0 in Eq. (2). It is obvious that this part cannot account for the structure function; it would furthermore decrease by about a factor of 4 between $Q^2 = m_\rho^2$ and the largest accessible Q^2 value. Thus the fact that above $Q^2=0.3$ GeV^2 the structure function in all x bins is either flat or rising in Q^2 may indicate that we enter the deep-inelastic regime at relatively low values of Q^2.

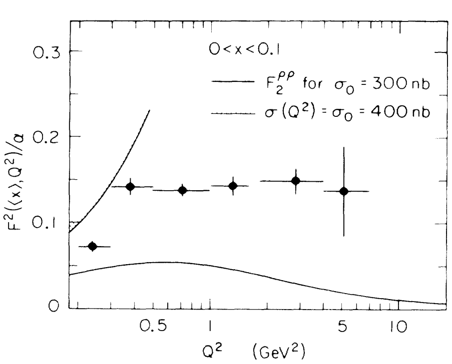

FIG. 2. The Q^2 dependence of the structure function F_2^γ at the lowest x bin compared to the expectation from meson-meson scattering [solid line, see Eq. (2)] and the upper bound as obtained from a constant cross section of 400 nb (shaded band).

Figure 3(a) shows a comparison oF $f_2^\gamma(x)$ in the three Q^2 bins between 0.3 and 1.6 GeV^2. The data show ap-

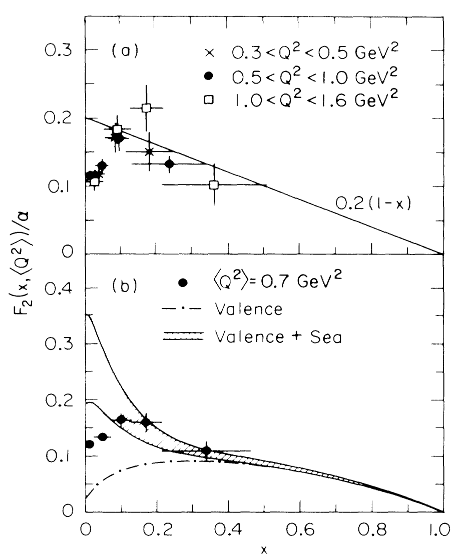

FIG. 3. (a) The x dependence of the structure function F_2^γ in three bins of Q^2. The solid line represents the hadronic component of Eq. (1). (b) The combined results of (a) interpolated to $Q^2=0.7$ GeV^2. The curves are obtained from fits by the pion structure function (Ref. 12), resulting in $0.22x^{0.41}(1-x)^{0.95}$ for the valence part and $(0.26 \pm 0.09)(1-x)^{8.4}$ for the sea part.

proximate scaling. At low x the measurements are quite precise, whereas at large x the test of scaling suffers from relatively large error bars as well as from limited overlap between the measurements at different values of Q^2. As we see no significant indications of scale breaking, in Fig. 3(b) we combine the data for $0.3 < Q^2 < 1.6$ GeV^2 and compare the result to the expectation of the hadronic component of F_2^γ as obtained from a recent measurement of the pion structure function.[12] The band was obtained with use of the same pion-photon conversion factor as in Ref. 5, which resulted in Eq. (1) based on older measurements of F^π.

The pion-structure-function data were fitted with a superposition of a valence and a sea contribution. For the pion the experimentally accessible range is restricted to $x > 0.1$, resulting in a large uncertainty in the sea contribution. The agreement in the overlap region $0.1 < x < 0.4$ is remarkable, especially if we keep in mind the assumptions needed to relate the (massive, charged, spin-0) pion in the timelike domain to the (massless, neutral, spin-1) photon in the spacelike domain (see above). For $x < 0.1$, where the extrapolation of the pion structure function is questionable, F_2^γ bends over and falls below the pion curve. Whether that can be taken as evidence that the photon has a smaller sea contribution than the pion has to await further confirmation, partly because the values of Q^2 are different (0.7 GeV^2 for the photon, 25 GeV^2 for the pion) and partly because no measurements of F^π exist for low x.

In conclusion, we have measured the photon structure function F_2^γ for the first time in the range $0.2 < Q^2 < 7$ GeV^2 in which the transition from soft scattering to hard scattering takes place. Above $Q^2 = 0.3$ GeV^2, the structure function is constant in Q^2 for low x ($x < 0.1$). In the range $0.3 < Q^2 < 1.6$ GeV^2, F_2^γ is consistent with scaling for all accessible x. We take both as evidence that we enter the deep-inelastic scattering regime quite early. The scaling photon structure function agrees with the measurements of the pion structure function in the overlap region $0.1 < x < 0.4$ and falls below an extrapolation of the pion data at low x. For $Q^2 > 2$ GeV^2 and $x > 0.1$, the structure function rises with Q^2, indicating the presence of a pointlike component of the photon.[6]

We acknowledge the efforts of the PEP staff and the engineers, programmers, and technicians of the collaborating institutions. This work was supported in part by the United States Department of Energy, the National Science Foundation, the Joint Japan–U.S. Collaboration in High Energy Physics, and the Foundation for Fundamental Research on Matter in The Netherlands.

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