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MEASUREMENT OF THE PHOTON STRUCTURE FUNCTION $F_2^\gamma(x, Q^2)$

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The structure function F_2^γ for a quasi-real photon has been measured in the Q^2 range 1.5 to 16 GeV^2 using 1417 multihadron events obtained with the PLUTO detector at PETRA. The x dependence of F_2^γ has been corrected for the effects of experimental resolution and incomplete acceptance. The result is compared with theoretical expectations. With weak theoretical assumptions, bounds of $65 < \Lambda_{\overline{\mathrm{MS}}} < 575$ MeV are obtained for the QCD scale parameter.

The structure of the photon can be studied in deep inelastic eγ scattering at e$^+$e$^-$ storage rings. If either the electron or positron is scattered at a large angle Θ_1 and the other one restricted to small angles $\Theta_2 \leqslant \Theta_2^{\mathrm{max}} \ll 1$ rad, the highly virtual photon emitted in the large-angle scatter probes the structure of the other quasi-real photon. In this asymmetric configuration the cross section for the reaction

$$\mathrm{ee} \to \mathrm{ee} + \mathrm{hadrons}\,, \qquad (1)$$

can be expressed in terms of the two structure functions $F_1^\gamma(x, Q^2)$ and $F_2^\gamma(x, Q^2)$ of the quasi-real photon as

$$\mathrm{d}\sigma/\mathrm{d}x\,\mathrm{d}Q^2 = (4\pi\alpha^2/Q^4)(1/x) \times [(1-y)F_2^\gamma(x, Q^2) + xy^2F_1^\gamma(x, Q^2)] \times N_\gamma(z, \Theta_2^{\mathrm{max}})\,\mathrm{d}z\,, \qquad (2)$$

where $-Q^2$ is the squared mass of the probing photon,

$$x = Q^2/(Q^2 + W^2)\,, \quad y = 1 - (E'/E)\cos^2(\Theta_1/2)\,, \qquad (3)$$

are the scaling variables, W is the invariant mass of the produced hadron system, and E' is the energy of the electron at Θ_1 which "tags" the probing photon ($E \equiv E_{\mathrm{beam}}$). The function

$$N_\gamma(z, \Theta_2^{\mathrm{max}}) = (\alpha/\pi)(1/z) \times \{(1 + (1-z)^2)\ln[E(1-z)\Theta_2^{\mathrm{max}}/m_\mathrm{e}z] - (1-z)\}\,, \qquad (4)$$

describes the energy spectrum of a beam of almost real "target" photons with squared mass $-P^2$ close to zero and fractional energy $z = E_\gamma/E$. The factorisation of the ee cross section into an eγ cross section and a target photon flux holds not only for small scattering angles [1], but also for arbitrary Q^2, provided $\Theta_2^{\mathrm{max}} \ll 1$ and $W^2 \gg P^2$ [2,3]. Because of the experimental cuts imposed on E' and Θ_1, y is small ($\langle y\rangle = 0.15$) so that the contribution from F_1^γ in eq. (2) is negligible, and the measurement yields F_2^γ directly.

The hadronic structure function of a photon F_2^γ is of interest for the following reasons [4]:

(1) It is expected to contain a point-like contribution from the direct $\gamma\gamma \to \mathrm{q\bar{q}}$ coupling [the Born diagram of the quark parton model (QPM)] which can be calculated in perturbative QCD [5] and which is expected to dominate at large Q^2. In leading order this point-like contribution factorises

$$F_2^{\mathrm{LO}}(x, Q^2) = \frac{3\alpha}{\pi}\sum e_\mathrm{q}^4 f^{\mathrm{LO}}(x)\ln(Q^2/\Lambda^2)\,, \qquad (5)$$

with $f^{\mathrm{LO}}(x)$ a rising function of the scaling variable x. Thus in leading order QCD (as well as in the QPM) F_2^γ increases with both x and Q^2 in contrast to all known structure functions of hadrons.

2. In higher order calculations (e.g. in the $\overline{\mathrm{MS}}$ scheme) the QCD scale is fixed so that $\Lambda_{\overline{\mathrm{MS}}}$ can in principle be determined from the magnitude of F_2^γ at any x and Q^2. The prediction can be written as

$$F_2^{\mathrm{HO}}(x, Q^2) = \frac{3\alpha}{\pi}\sum e_\mathrm{q}^4 \times [f(x)\ln(Q^2/\Lambda_{\overline{\mathrm{MS}}}^2) + g(x)\ln\ln(Q^2/\Lambda_{\overline{\mathrm{MS}}}^2) + h(x)]\,, \qquad (6)$$

where $f(x)$, $g(x)$, and $h(x)$ are known functions of x [6,7]. $F_2^{\mathrm{HO}}(x, Q^2)$ is regular and positive for $0.2 \lesssim x \lesssim 0.9$.

Such a determination of $\Lambda_{\overline{\mathrm{MS}}}$ is based on the measurement of the total eγ cross section and is therefore independent of the analysis of particular event topologies. Moreover this cross section has a more sensitive dependence on $\Lambda_{\overline{\mathrm{MS}}}$ than the total e$^+$e$^-$ annihilation cross section. However, besides the point-like contribution F_2^γ also contains a part from the hadronic (i.e. bound $\mathrm{q\bar{q}}$) photon coupling which is not calculable in perturbative QCD. At the currently available Q^2 this hadronic part is not negligible, but can be either separated by a study of the measured Q^2 evolution, which requires high statistics data, or inferred from measurements of the pion structure function.

Measurements of the photon structure function based on low statistics have been published by the PLUTO [8], JADE [9] and CELLO [10] experiments at PETRA. They demonstrate the existence of a point-like part in the $\gamma\gamma$ cross section in addition to a part due to the hadronic coupling of the photon. The present paper describes a detailed measurement of F_2^γ as a function of x and Q^2 based on 1417 hadronic events which were collected from an integrated luminosity of 34.2 pb^{-1} at the e^+e^- storage ring PETRA at DESY. In contrast to most of the previous investigations, the data presented here have been unfolded to correct for the resolution and acceptance of the experiment.

For these measurements the PLUTO detector [3, 11] was extended by the addition of two magnetic spectrometers covering the forward and backward region (4° to 15° and 165° to 176° with respect to the e^+e^- beam axis and 85% of the azimuthal angle), in which hadrons, photons, muons and electrons were detected. Each spectrometer included both drift chambers and shower counters, the latter called the "large angle taggers" (LAT). The electron or positron scattered at the larger angle was thereby reconstructed with a resolution $\sigma(Q^2)/Q^2 = 10\%$. The data were taken with a trigger which required only the deposition of shower energy >4 GeV in one of the LAT's, and no other condition. The resulting sample of "single tag" multihadron events is therefore free of trigger bias.

The following event selection criteria were defined so that a good compromise between large acceptance and low background contamination was achieved:

1. Tag definition. One isolated energy cluster in the LAT with $E > 8$ GeV was required to be associated with a reconstructed track in the forward spectrometer drift chambers. To avoid edge effects the position of the shower was restricted to a fiducial area corresponding to an angular range $5^\circ < \Theta_1 < 15^\circ$.

2. Antitag condition. To keep the mass of the target photons as small as possible, a veto against large P^2 (double tag) events was applied. No additional energy cluster of more than 4 GeV was allowed in the small angle tagger SAT, which covered the angular range 1.5°(178.5°) to 4°(176°), or in the LAT.

3. Hadronic final state. A multihadronic final state was required to have either 2 charged particles (tracks) and $\geqslant 2$ showers, or $\geqslant 3$ tracks. The visible invariant mass W_{vis}, reconstructed from the measured charged and neutral particles in the final state, was required to be between 1 and 12 GeV to maintain a good acceptance and to eliminate e^+e^- annihilation events.

4. QED rejection. To reduce the background from leptonic QED processes, all events with $\leqslant 3$ tracks and <3 showers were rejected in which one particle qualified as an electron by having a track with momentum $\geqslant 1$ GeV associated with a shower cluster of energy $\geqslant 1$ GeV.

To determine the background contamination in the selected event sample the following sources were considered:

(a) Beam–gas events.

(b) 1 γ annihilation events,
$e^+e^- \to$ hadrons,
$e^+e^- \to \tau\tau$.

(c) 2 γ QED events,
$\gamma\gamma^* \to ee$, (γ^* = tagged photon) ,
$\gamma\gamma^* \to \tau\tau$,
$\gamma\gamma \to \tau\tau$, one $\tau \to e\,\nu\nu$.

(d) $e^+e^- \to e^+e^-$ + hadrons via inelastic Compton scattering [12].

The beam–gas background was determined from the data using the side bands of the event vertex distribution along the beam ($|z| > 40$ mm), and found to be small (4%). The 1γ annihilation background is estimated to be less than 1% mainly because of the requirement of a high energy electron ("tag") identified by both a track and a shower in a forward spectrometer. The QED processes (c) were studied in detail in a Monte Carlo (MC) simulation. The most important one is $\tau\tau$ production in the single tag mode (5.9%). The Compton process (d), which is in principle indistinguishable from the genuine two photon process, was calculated with a MC program to be <1%. The sum of all background sources (a)–(d) was calculated to be 11% of the selected event sample and was subtracted from it.

The resulting data sample covers the Q^2 range $1.5 < Q^2 < 16$ GeV^2 with the average $Q^2 = 5.3$ GeV^2. The antitag condition (with $\Theta_2^{\max} \approx 30$ mrad) restricts the target photon mass $(-P^2)^{1/2}$ to be small. The good angular coverage of the detector for both charged and neutral particles gives rise to a good event acceptance: the fraction of the triggered events which are selected for the final analysis rises from 45% at $W = 2$ GeV to 70% at $W = 10$ GeV.

The evaluation of $F_2^\gamma(x, Q^2)$ is complicated for several reasons. Firstly, due to particle losses and the finite resolution of the detector the visible invariant mass W_{vis} is on average 24% lower than the true invariant mass W, with an r.m.s. resolution $\sigma_W/W_{\mathrm{vis}} = 27\%$. Fig. 1a shows the corresponding mapping from true x to x_{vis} determined from a MC simulation of the experiment (see below), where x_{vis} is calculated with W_{vis} in eq. (3). It demonstrates that both the resolution in x_{vis} is sufficiently small and the correlation between x and x_{vis} is sufficiently defined for a meaningful inversion of the mapping. Secondly, the accepted Q^2 range varies with x because the measurements are restricted to a fixed W interval. Thus in order to determine the x dependence of $F_2^\gamma(x, Q^2)$ in such a way that it can be compared easily with theoretical calculations, it is necessary to interpolate the data in Q^2, and to present $F_2^\gamma(x)$ at fixed Q^2 values which are independent of x. Thirdly, the multihadron acceptance after the data selection depends on the fragmentation of the $\gamma\gamma$ system into hadrons.

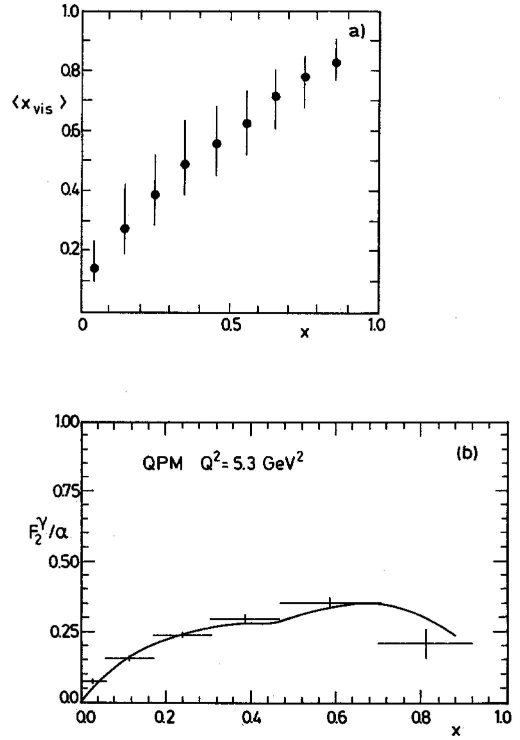

Fig. 1. (a) Mapping of the scaling variable x to the visible x_{vis} determined by a Monte Carlo simulation of the experiment (see text): the average x_{vis} and its r.m.s. scatter are shown as a function of the true x. (b) The result of a "Monte Carlo experiment" to investigate the overall validity of the unfolding technique for $F_2^\gamma(x, Q^2)$; the data points are the results of unfolding a sample of simulated Monte Carlo events which were generated assuming the QED Born term for $\gamma\gamma \to q\bar{q}$ (QPM). The curve is the expectation of the QPM at the value of Q^2 to which the unfolding procedure interpolates.

These complications were overcome by determining $F_2^\gamma(x, Q^2)$ from the data by means of an unfolding procedure. To this end a model for the fragmentation to hadrons of the $\gamma\gamma$ system was developed which, when included in a MC simulation of the experiment together with the extracted $F_2^\gamma(x, Q^2)$, gave a good overall description of all experimental distributions. A multipion final state was generated with mean charged and neutral multiplicities given by

$$\langle n^\pm \rangle = 2.0\sqrt{W}, \quad \langle n^0 \rangle = 1.3\sqrt{W} \quad (W \text{ in GeV}) .$$

For a given mean multiplicity the actual multiplicities were selected according to KNO [13] distributions similar to those found in e^+e^- annihilation [3]. The inverse relative dispersion $\chi = \langle n \rangle / D$ was fixed to be 2.7 for charged pions, and 2.4 for neutral pions. The distribution of the transverse momenta p_T of the pions relative to the $\gamma\gamma$ axis was best described by a mixture of isotropic phase space (IPS) and limited p_T phase space (LPS) [‡1], which changes with $w = (W/7\ \mathrm{GeV})^2$ like $e^{-w} \cdot \mathrm{IPS} + (1 - e^{-w}) \cdot \mathrm{LPS}$.

In the unfolding procedure the mapping from x to x_{vis} is determined by the MC simulation which includes both the $\gamma\gamma$ fragmentation and the detector response. This mapping is then inverted in such a way [14] as to avoid the enhancement of random fluctuations which usually occur in the matrix inversion in the procedure. The number of bins and the bin sizes in x are chosen to keep the correlations between the unfolded data points small. The x and Q^2 dependence of F_2^γ is represented by a factorising ansatz

$$F_2^\gamma(x, Q^2) = F_2^\gamma(x)[1 + b \ln(Q^2/\langle Q^2 \rangle)] ,$$

with $b = 0.17$. This ansatz improves the interpolation

[‡1] LPS events were generated like IPS events but with an additional weight factor $\exp(-5p_T^2)$ for each pion.

of the data in Q^2, and is not sensitive to the particular choice of b. Setting $b = 0$ changes the resulting $F_2^\gamma(x)$ of the full Q^2 range by 10%, and by only 2% in each of the three Q^2 sub-ranges (see below). A non-factorising form in which b depends on both x and Q^2 is not necessary to describe our data.

The reliability of the unfolding procedure for the PLUTO detector has been verified by simulating events with a model photon structure function (QPM with standard Field–Feynman quark fragmentation) and then extracting $F_2^\gamma(x)$ using the unfolding procedure described above. Fig. 1b demonstrates that the reconstructed $F_2^\gamma(x)$ agrees satisfactorily with the input $F_2^\gamma(x)$ and that the all-pion fragmentation model described above can describe the final state hadron distributions without introducing gross systematic errors into the result.

To adjust fragmentation parameters and to test the fragmentation model, various distributions of the data were compared with the MC simulation (which used the structure function obtained from the unfolding procedure). As examples in fig. 2 the inclusive p_T^2 distribution of charged particles and the neutral energy distribution demonstrate that the fragmentation model describes the data well; the x_{vis} and Q^2 distributions show that the solution achieved with the unfolding procedure is acceptable.

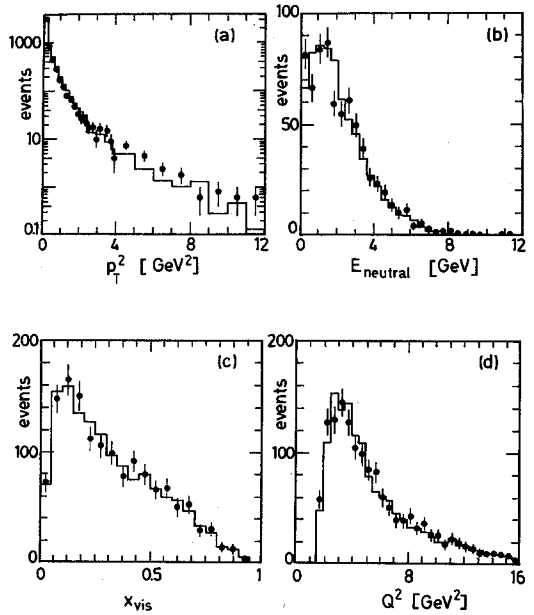

Fig. 2. Distributions of experimental variables (points) compared with the Monte Carlo calculation (histogram) obtained with the extracted structure function $F_2^\gamma(x, Q^2)$ and the fragmentation model described in the text. (a) Inclusive p_T (transverse momentum relative to the beam axis), (b) inclusive neutral energy, (c) x_{vis} and (d) Q^2.

The sensitivity of the unfolded $F_2^\gamma(x, Q^2)$ to the details of the hadron fragmentation was studied by varying the fragmentation parameters. With the constraints of the distributions of final state hadrons, the variety of possible fragmentation models is restricted, and the uncertainty in the acceptance is estimated to be $<10\%$ for $x > 0.1$ and $<20\%$ below [‡2]. A more detailed discussion of this source of systematic errors is given in ref. [16].

A small fraction of the data is expected to originate from the c-quark component of the photon for which the fragmentation model above and the factorisation ansatz for $F_2^\gamma(x, Q^2)$ are not appropriate. We therefore generated MC events for a c-quark mass of 1.6 GeV according to the QPM, with standard Field–Feynman fragmentation including strange particles, and subtracted them like a background (≈10%) before applying the unfolding procedure. The resulting F_2^γ was then finally adjusted by adding the QPM charm contribution calculated at the Q^2 to which the

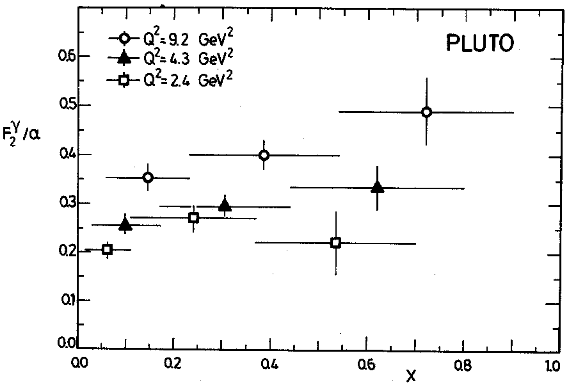

Fig. 3. The x dependence of the structure function F_2^γ measured using data from three separate ranges of Q^2 and interpolated in the unfolding procedure to the fixed values of 2.4, 4.3 and 9.2 GeV².

[‡2] If the same fragmentation model is used as in our analysis of jet production in $\gamma\gamma$ interactions [15] the result of the unfolding for F_2^γ agrees to well within the systematic errors quoted.

Table 1
x and Q^2 dependence of the photon structure function F_2.

Q^2 (GeV^2)	x	F_2/α	F_2/α – charm
2.4	0.016–0.110	0.204 ± 0.014	0.183 ± 0.014
(1.5–3)	0.110–0.370	0.272 ± 0.026	0.263 ± 0.026
	0.370–0.700	0.222 ± 0.064	0.222 ± 0.064
4.3	0.030–0.170	0.256 ± 0.014	0.218 ± 0.014
(3–6)	0.170–0.440	0.295 ± 0.020	0.273 ± 0.020
	0.440–0.800	0.336 ± 0.044	0.336 ± 0.044
9.2	0.060–0.230	0.354 ± 0.027	0.300 ± 0.027
(6–16)	0.230–0.540	0.402 ± 0.029	0.340 ± 0.029
	0.540–0.900	0.492 ± 0.069	0.492 ± 0.069
5.3	0.035–0.072	0.245 ± 0.015	0.216 ± 0.015
(1.5–16)	0.072–0.174	0.307 ± 0.010	0.258 ± 0.010
	0.174–0.319	0.277 ± 0.025	0.222 ± 0.025
	0.319–0.490	0.329 ± 0.037	0.329 ± 0.037
	0.490–0.650	0.439 ± 0.052	0.439 ± 0.052
	0.650–0.840	0.361 ± 0.076	0.361 ± 0.076

data had been interpolated in the unfolding. As the charm contribution is small, the final result depends only slightly on this treatment of charm production and the changes are negligible if we use the all-pion fragmentation model above for the entire data.

Fig. 3 shows the structure function $F_2^\gamma(x, \langle Q^2\rangle)$ unfolded in three separate Q^2 intervals:

(a) $1.5 < Q^2 < 3\ \mathrm{GeV}^2, \quad \langle Q^2\rangle = 2.4\ \mathrm{GeV}^2,$

(b) $3 < Q^2 < 6\ \mathrm{GeV}^2, \quad \langle Q^2\rangle = 4.3\ \mathrm{GeV}^2,$

(c) $6 < Q^2 < 16\ \mathrm{GeV}^2, \quad \langle Q^2\rangle = 9.2\ \mathrm{GeV}^2.$

The rise of F_2^γ with increasing x and Q^2, characteristic of the point-like γq coupling, is evident. In table 1 we also include F_2^γ values with the charm contribution subtracted by the method described above. Clearly the difference is small. The subtracted values can be compared directly to models using only u, d and s quarks.

The structure function determined from the full Q^2 range $1.5 < Q^2 < 16\ \mathrm{GeV}^2$ is shown in fig. 4. It is interpolated to $\langle Q^2\rangle = 5.3\ \mathrm{GeV}^2$ in the unfolding. In addition to the statistical errors shown in figs. 3 and 4 and in table 1, there are systematic errors, arising mainly from the sensitivity of the acceptance calculation to hadron fragmentation as discussed above. The systematic errors due to the (non zero) target photon mass squared $-P^2$ and to the radiative corrections have also been studied and found to be small (<5% in total). Including all contributions we estimate the systematic error of the data points to be 15% for $x > 0.2$, and 25% below. The systematic error of the average F_2^γ between $x = 0.3$ and $x = 0.8$ is 10%.

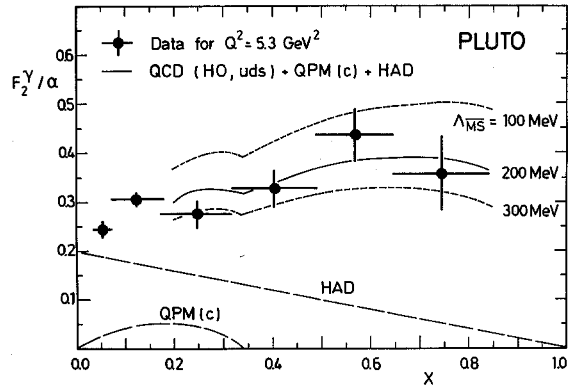

Fig. 4. The x dependence of the structure function F_2^γ measured using the data from the complete Q^2 range of the experiment, but interpolated to $Q^2 = 5.3\ \mathrm{GeV}^2$ in the unfolding procedure. The curves are for three values of $\Lambda_{\overline{\mathrm{MS}}}$ (100, 200 and 300 MeV) in a higher order QCD calculation with three quark flavours (u, d and s), QCD (HO, uds), to which is added the QPM contribution from c-quarks, QPM (c), and the estimate for the hadronic coupling of the photon, HAD, described in the text [eq. (7)].

A determination of the QCD parameter $\Lambda_{\overline{\mathrm{MS}}}$ from these results is not straightforward. A completely model-independent determination based only on the Q^2 evolution of perturbative QCD requires significantly higher statistics and a larger Q^2 range. To make use of the sensitivity of the magnitude of $F_2^\gamma(x)$ on $\Lambda_{\overline{\mathrm{MS}}}$ requires an assumed form for the non-perturbative QCD contributions.

One particular approach is to compare $F_2^\gamma(x)$ with the sum of a higher order perturbative QCD calculation and a part due to the hadronic photon coupling. The latter is estimated [12,17] from the pion structure function measured in the Drell-Yan process [18] to be

$$F_2^{\gamma\,\mathrm{had}}/\alpha = (0.20 \pm 0.05)(1-x)\,. \tag{7}$$

In fig. 4 the sum of this hadronic part, of the QCD next to leading order calculation [6,19] using only u, d and s quarks, and of the charm contribution from the QPM is shown for three different values of $\Lambda_{\overline{\mathrm{MS}}}$. For $x > 0.2$ both the x dependence and the absolute normalization of F_2^γ are well described if a value for $\Lambda_{\overline{\mathrm{MS}}}$ of about 200 MeV is used. Fig. 4 further demonstrates the sensitivity of the photon structure function $F_2^\gamma(x)$ to $\Lambda_{\overline{\mathrm{MS}}}$. A fit in the interval $0.3 < x < 0.8$ yields $\Lambda_{\overline{\mathrm{MS}}} = 190^{+50}{}_{-40}(\mathrm{stat.})^{+60}{}_{-50}(\mathrm{syst.})$ MeV.

Whether or not such a determination involves questionable theoretical assumptions is currently a source of much debate [20]. To minimise any sensitivity to details of the model for $F_2^{\gamma\,\mathrm{had}}$ we have derived limits for $\Lambda_{\overline{\mathrm{MS}}}$ from our results for $F_2^\gamma(x)$ at $Q^2 = 5.3\ \mathrm{GeV}^2$ making only weak theoretical assumptions. If we take as upper and lower limits $F_2^{\gamma\,\mathrm{had}}/\alpha \equiv 0.2$ (i.e. we assume there to be no decrease with increasing x of $F_2^{\gamma\,\mathrm{had}}$ from its value at small x) and $F_2^{\gamma\,\mathrm{had}}/\alpha \equiv 0$ (i.e. we consider F_2^γ to be already asymptotic at $Q^2 = 5.3\ \mathrm{GeV}^2$) we find the respective limits $65 < \Lambda_{\overline{\mathrm{MS}}} < 575$ MeV (90% confidence). They correspond to limits on α_s of $0.115 < \alpha_s < 0.170$ when extrapolated to $Q^2 = (35\ \mathrm{GeV})^2$, characteristic of e^+e^- annihilation at PETRA.

The Q^2 dependence of the data in table 1 and fig. 3 is consistent with the perturbative QCD expectation. A detailed QCD analysis of these and additional data extending up to $Q^2 = 100\ \mathrm{GeV}^2$ will be presented in a forthcoming paper.

To conclude, the photon structure function $F_2^\gamma(x, Q^2)$ has been measured for three Q^2 values in the range $1.5 < Q^2 < 16\ \mathrm{GeV}^2$. For $x > 0.2$ the results are well described by the sum of hadronic (VDM-like) and point-like coupling of the photon to hadrons, the latter calculated in next to leading order QCD. With weak theoretical assumptions we find bounds on the QCD scale parameter of $65 < \Lambda_{\overline{\mathrm{MS}}} < 575$ MeV (90% confidence).

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