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Parametrization of parton distributions in the photon

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A new parametrization for parton distributions in the real photon is obtained by solving the inhomogeneous leading order Altarelli–Parisi equations for the photon case. All the presently available data on the photon structure function are used to fit the quark and gluon distributions. The dependence of the results on the initial conditions for the evolution, the starting value of Q^2, Q_0^2, and the shape of the gluon distributions in particular, is investigated. Expectations in the HERA kinematical limit are discussed.

1. Introduction

The interactions of the photon with matter can proceed in two ways. The photon may couple directly to the charged constituents of the target, in which case the interaction is referred to as due to a direct photon. It may also happen that the photon fragments into its own constituents before interacting with the target – those reactions are referred to as due to a resolved photon [1]. This last property of photon interactions is the reason for introducing the notion of a photon structure function, in analogy to the proton structure function, and to talk about parton distributions in the photon. The structure of the resolved photon is induced by two possible contributions: a point-like contribution, where the photon has a point like coupling to a q$\bar{\text{q}}$ pair, and a hadron-like contribution, where the photon turns into a bound q$\bar{\text{q}}$ state through an effective coupling to a vector meson like state.

The two-component picture of the resolved photon led [2] to the decomposition of the photon structure function into a point-like part (F_2^{PL}) and hadron-like part (F_2^{HAD}):

$$F_2^\gamma = F_2^{\mathrm{PL}} + F_2^{\mathrm{HAD}} , \tag{1}$$

where the point-like part is calculable in perturbative QCD and depends only on the QCD mass scale Λ, and the hadron-like part, of nonperturbative origin, cannot be calculated and thus is model dependent. This two-part decomposition of the photon structure function has its reflection in the quark and gluon distributions:

$$q^\gamma(x, Q^2) = q^{\mathrm{PL}}(x, Q^2) + q^{\mathrm{HAD}}(x, Q^2) ,$$
$$G^\gamma(x, Q^2) = G^{\mathrm{PL}}(x, Q^2) + G^{\mathrm{HAD}}(x, Q^2) , \tag{2}$$

where Q^2 is the scale at which the structure of the photon is being probed and the 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 point-like part was shown to dominate at high Q^2 [2], the hadron-like part cannot be neglected even at high Q^2 because it is needed in order to cancel the singularity coming from the point-like part at $x = 0$ by its own singularity [3]. Thus there is no absolute prediction for the structure function of the photon since the hadron like part cannot be neglected and has to be inferred from phenomenological considerations or from the data themselves.

The PL parton distributions were calculated in perturbative QCD and parametrized in a convenient analytical form by Duke and Owens [4]. Thus one possible approach to the description of F_2^γ is to use this parametrization and add to it the hadronic part. The parametrization of the hadronic part is model

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dependent, and usually is based on such models as the vector dominance model (VDM) [5].

A different approach, in which one avoids the ambiguous two-component decomposition, was used by Drees and Grassie (DG) [6]. They gave up the controversial possibility to determine the QCD scale Λ and performed a QCD analysis of the photon case in the same way as is done for the photon. In order to get the Q^2 dependence of the parton distributions, they solved the leading order Altarelli–Parisi evolution equations for the photon, with initial conditions derived from experimental data. The difference between the evolution equations for the proton and the photon is due to the contribution of the point-like coupling of the photon, which makes these equations inhomogeneous in the photon case.

In this approach one has to assume a parametrization of quark and gluon distributions at a chosen initial Q_0^2 and determine the free parameters by fitting the evolved distributions to the measured structure function data. Unfortunately, when Drees and Grassie performed their fit, only seven data points were available and only at one Q^2 value [7] – a poor constraint to the assumed 13 parameters.

The purpose of the present study is to apply the approach of Drees and Grassie and to determine more up-to-date distribution functions of the partons in the photon by using all available measurements on the photon structure function.

2. The parametrization

In order to determine our parametrization, we have used the evolution equations with four flavors, neglecting possible contributions from b and t quarks. Although the evolution was carried out for four flavors, the charm contribution to the photon structure function was taken into account only if $W^2 > 4m_c^2$, where m_c is the mass of the charm quark and was assumed to be 1.5 GeV.

The solution of the inhomogeneous evolution equations for the parton distributions in the photon consists of a superposition of a general solution of the homogeneous equations (a solution similar to that for hadrons) and a particular solution of the inhomogeneous equations (the PL type of solution). This is reflected in our assumption on the x-dependence of the input quark distributions at Q_0^2:

u, d:

$$xq(x) = Ae_q^2 x \frac{x^2 + (1-x)^2}{1 - B\ln(1-x)} + Cx^D(1-x)^E, \quad (3)$$

s:

$$xq(x) = Ae_q^2 x \frac{x^2 + (1-x)^2}{1 - B\ln(1-x)} + C_s x^{D_s}(1-x)^{E_s}, \quad (4)$$

c:

$$xq(x) = Ae_q^2 x \frac{x^2 + (1-x)^2}{1 - B\ln(1-x)} + C_c x^{D_s}(1-x)^{E_s}. \quad (5)$$

The first term on the right hand side is suggested by the PL contribution, while the second term reflects the properties expected for a hadron. Note that in spite of the apparent identical form used for the u and d quarks, their distribution is different because of the e_q^2 factor which multiplies the first term. The s and c quarks are assumed to have the same functional form, however, with different coefficients (C_s and C_c, respectively).

For the gluon distribution we have assumed the form

$$xG(x) = C_g x^{D_g}(1-x)^{E_g}. \quad (6)$$

We did not try to fit the value of the QCD scale parameter Λ which enters into the evolution equations. We have assumed the value of $\Lambda = 0.2$ GeV, compatible with the results obtained in the QCD analyses of the nucleon data [8]. We have checked that for $\Lambda = 0.4$ GeV the results of our parametrization remain the same within errors. We thus end up with 12 parameters to be determined by fitting to the experimental data. Note that this is the first time an attempt is performed to determine the gluon distribution in the photon by using data. It is more difficult than in the proton case because there are no momentum sum rules for the photon and the structure function is sensitive to the gluon distribution only in an indirect way.

3. The data

The photon structure function has been measured so far mainly with two e^+e^- machines: at PETRA and at PEP. Recently a measurement from TRISTAN has become available [9].

Three experiments have published the results of their measurements at PETRA:PLUTO [10], for average Q^2 values of 2.4, 4.3, 5.3, 9.2, and 45 GeV^2, TASSO [11], at $\langle Q^2 \rangle = 23$ GeV^2, and JADE [12] for $\langle Q^2 \rangle = 24$ and 100 GeV^2. Preliminary results exist for the CELLO detector for Q^2 values of 7, 13.1 and 28.8 GeV^2 [13]. At PEP, the TPC/2γ [14] group measured F_2^γ at $\langle Q^2 \rangle = 0.24$, 0.38, 0.71, 1.31, 2.83, 5.09, and 20 GeV^2. At TRISTAN the photon structure function has been measured by the AMY [9] group for $\langle Q^2 \rangle = 73$ GeV^2.

In the fitting procedure we have used all data available above the Q_0^2 value assumed for the initial conditions. In estimating the measurement errors we have added the statistical errors and the quoted systematic errors in quadrature. They are in the range of 10–25% and are x dependent.

4. Results

We have tried to fit the data for $Q_0^2 = 1$, 2, 3 and 4 GeV^2. Above 2 GeV^2 the results depend very slightly

Table 1
Results of the fit for the three sets of the parametrization of the parton distributions in the photon (see the text for details).

Parameters	Set I $Q_0^2 = 4$ GeV^2	Set II $Q_0^2 = 4$ GeV^2	Set III $Q_0^2 = 1$ GeV^2
A	0.54±0.09	0.41± 0.21	1.18±0.12
B	0.12±0.21	0.01± 0.85	0.20±0.13
C	0.93±0.05	0.61± 0.09	1.53±0.12
D	1.19±0.06	0.77± 0.1	0.89±0.02
E	0.73±0.08	0.49± 0.08	7.67±0.86
C_s	1.0 ±0.4	1.3 ± 1.3	0.9 ±0.3
C_c	0.4 ±0.1	0.4 ± 0.3	–
D_s	0.35±0.05	0.32± 0.2	0.63±0.11
E_s	5.8 ±0.8	6.2 ± 2.8	7.1 ±2.5
C_g	9.6 ±2.3	35.5 ±13.3	82.8 ±8.9
D_g	−0.34±0.1	0.0 (fixed)	5.9 ±0.5
E_g	12.5 ±2.3	17.4± 1.6	0.56±0.05
χ^2/DF	0.88	0.87	1.04

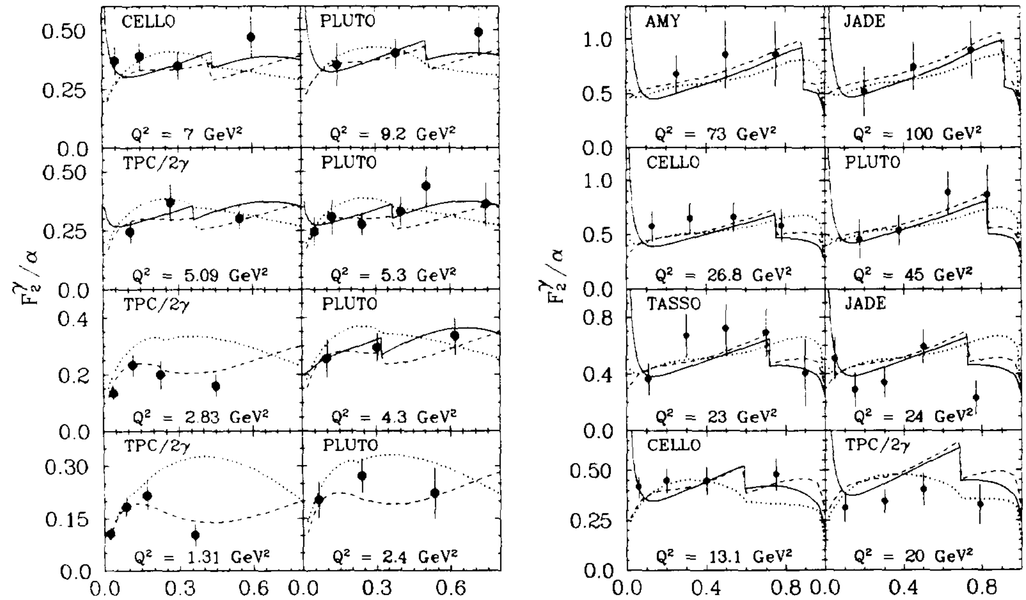

Fig. 1. Comparison of the predictions of the new parametrizations with $Q_0^2 = 1$ GeV^2 (dashed line), with $Q_0^2 = 4$ GeV^2 (full line) and the DG parametrization (dotted line) with the measurements of F_2^γ as a function of x in bins of Q^2.

on the initial conditions. The results at 1 GeV^2 are substantially different, and we performed this fit partly in order to compare with the Drees and Grassie parametrization. For most of the applications, the photon structure function is needed only in the region of large Q^2. Recent studies [15] indeed suggest that the value of Q_0^2 should be closer to 4 than to 1 GeV^2. Here we report the results obtained at the two extreme values of Q_0^2. We have used 62 (51) data points to determine the parameters for the fit starting at $Q_0^2=1$ (4) GeV^2.

Fig. 1 shows the measured photon structure function data together with the calculated one using our best-fit parameters, as a function of x, for different Q^2 values. Although the evolution was done for four flavors in the whole kinematical range, the charm contribution to the photon structure function was included only for $W>3$ GeV, W being the mass of the $\gamma\gamma$ system. For comparison we show also the ones obtained with the parametrization of Drees and Grassie. We obtain a $\chi^2/DF=1.0$ starting from $Q_0^2=1$ GeV^2 (set III) and a $\chi^2/DF=0.9$ for $Q_0^2=4$ GeV^2

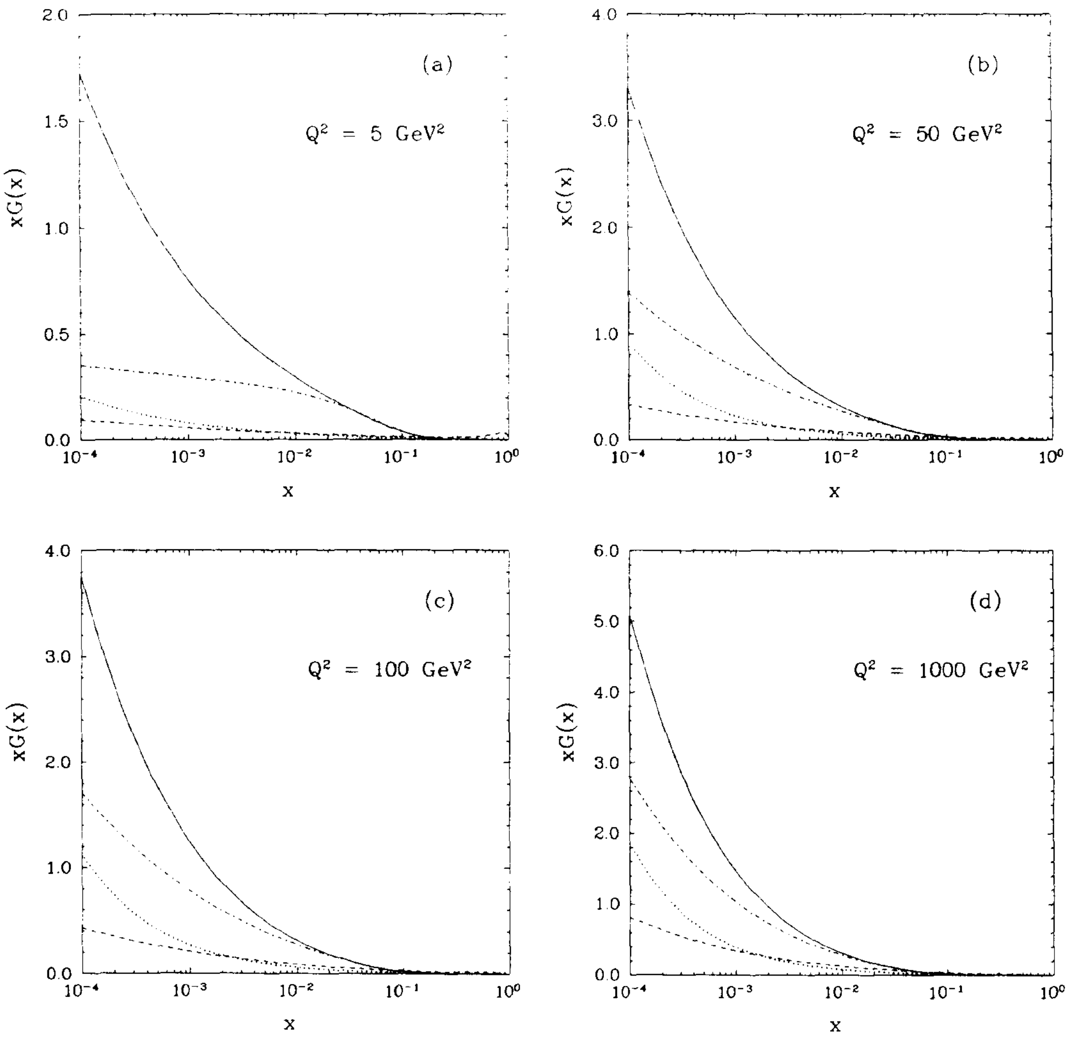

Fig. 2. Comparison between gluon distributions obtained for the set I, set II, set III parametrizations (full, dash-dotted and dashed lines, respectively) and the gluon distribution of the DG parametrization (dotted) evolved to (a) $Q^2=5$ GeV^2, (b) $Q^2=50$ GeV^2, (c) $Q^2=100$ GeV^2, and (d) $Q^2=1000$ GeV^2.

(set I). The values of the fitted parameters for the two Q_0^2 values are listed in table 1. For $Q_0^2=4$ GeV ^{2} we show also results of a fit in which B_g was fixed to 0 (set II). This was done in order to get some estimate on the spread of the gluon distribution in the small x region. The distributions have been tabulated for the range $10^{-4}<x<1$ and $Q_0^2<Q^2<10^5$ GeV^2, and are available in a subroutine form which interpolates the distributions for any given x and Q^2 within that range [#1].

[#1] The program can be obtained upon request from F1PCHA@DHHDESY3.

In fig. 2 we present a comparison of $xG(x)$ for our new three parametrizations set I, set II, and set III together with the one of DG at Q^2 values of 5, 50, 100 and 1000 GeV^2. For the very small x region one can see that while in the gluon contribution of the set III parametrization is smaller than the DG one, both set II and set I have a larger contribution than the DG gluons. Fig. 3 presents the same comparison on a linear scale. Above an x of 0.05, set I and set II are practically equal to each other and above an x of 0.2 coincide with the DG one. The set III gluon distributions are higher than DG already for $x>0.005$ and higher than set I and set II for $x>0.15$–0.2.

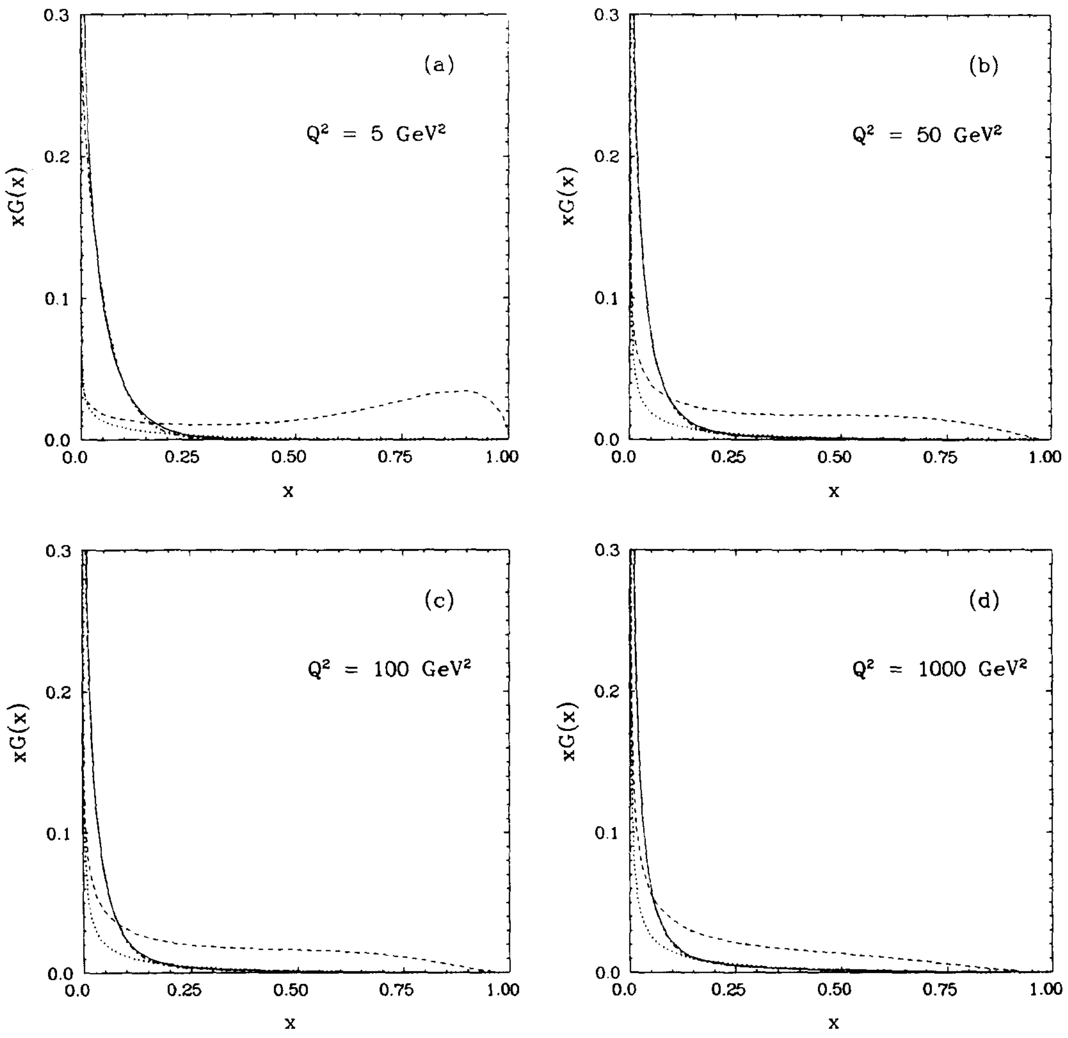

Fig 3. Same as fig. 2, in linear scale.

Table 2
Predictions for the deep inelastic Compton process obtained for various parametrizations of the parton distributions in the photon.

Process	Cross section (pb) ($\hat{p}_T > 5$ GeV/c)			
	set I	set II	set III	DG
$q^\gamma(\bar{q}^\gamma)+\bar{q}^p(q^p)\to g+\gamma$	15.6	15.4	16.4	11.8
$q^\gamma(\bar{q}^\gamma)+g^p\to q(\bar{q})+\gamma$ and $g^\gamma+q^p(\bar{q}^p)\to q(\bar{q})+\gamma$	122.8	117.5	107.0	69.2
sum	138.4	122.9	123.4	81.0

In order to check how the different parametrizations influence the cross sections of processes which involve the resolved photon, we have calculated the cross sections of the resolved part for the deep inelastic Compton process (DIC) [16] at HERA using the parametrizations mentioned above for the parton distribution of the photon and the EHLQ1 [17] one for the proton, together with the event generator PYTHIA [18] (see table 2). The transverse momentum in the hard subprocess ($\hat{p}_T$) was larger than 5 GeV/c. The cross sections obtained using the new parametrizations are by (50–70)% bigger than that of the DG one. Therefore the experiments at HERA will be able to constrain the parton distributions of the photon.

5. Conclusions

A new parametrization of the parton distributions in the resolved photon has been obtained. The available data on the photon structure function have been used to fit the quark and gluon distributions at a starting value of Q_0^2. The evolution was carried out for four flavors with a Λ value of 0.2 GeV. The charm contribution to the photon structure function was taken into account only above the threshold for charm production. The parameters were fitted for different starting values of Q_0^2, ranging from 1 to 4 GeV^2. The results do not depend on the value of Q_0^2 for $Q_0^2>2$ GeV^2. The data are well reproduced for all starting values of Q_0^2.

A comparison of the gluon distributions obtained with the new parametrizations to that assumed by DG shows that although the data seem to be able to accommodate more gluons than was assumed by DG, there is quite some freedom in the choice of the gluon distribution in the photon. It should be noted that the gluon distribution obtained for the set III parametrization ($Q_0^2=1$ GeV^2) has an unusual shape which peaks at high x and which is difficult to understand. It is hoped that better data on the photon structure function, or analyses using parton distributions of the photon like the one used recently by the AMY Collaboration [19], will help to restrict the choice of the gluon distribution in the photon.

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