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J.H. Field

Deutsches Elektronen-Synchrotron DESY, Hamburg

F. Kapusta, L. Poggioli

Laboratoire de Physique Nucléaire et des Hautes Energies,
Université de Paris VI and VII, Paris

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THE F_2 PHOTON STRUCTURE FUNCTION AND Λ_{QCD}

J.H. Field*, F. Kapusta† and L. Poggioli†

* Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

† Laboratoire de Physique Nucléaire et des Hautes Energies Université de Paris VI and VII, Paris, France

(Presented by J.H. Field)

The real photon structure function F_2^γ is discussed in the QPM and QCD taking into account the signature of hadronic or point-like parts provided by the final state jet structure. A re-derivation of Witten's result for the non singlet part of F_2^γ indicates that hadronic and point-like terms have been mis-identified in recent calculations that have been widely compared to experiment, leading to overly optimistic estimations of the sensitivity of F_2^γ to Λ_{QCD}.

1. INTRODUCTION

For several years now there has been a controversy over whether measurements of F_2^γ for almost real photons can/cannot precisely determine Λ_{QCD}. It was stated many years ago /1,2/ that modifications to the Quark Parton Model (QPM) predictions /3/ are expected to be small at experimentally accessible Q^2 values and that unavoidable non-perturbative effects would largely obscure sensitivity to Λ. More recently this conclusion has been re-stated by other authors /4,5/ who stressed the importance of retaining non leading-log terms in the LO /6/ and HO /7/ QCD solutions at non-asymptotic Q^2 values.

This point of view has not however gained universal acceptance /8/ and in particular it has been claimed /9-12/ that except for very small x-values ($\lesssim 0.15$) F_2^γ is indeed $\simeq \ln(\frac{Q^2}{\Lambda^2})$ even for Q^2 as low as 5 $(GeV/c)^2$, so that existing F_2^γ measurements /13/ can determine Λ with good precision /14/.
In recent work /15,16/ we have found that the resolution of the controversy rests on a correct definition, in QCD, of the 'hadronic' (HAD) and 'point-like' (PL) parts of F_2^γ. For clarity we first discuss F_2^{HAD} and F_2^{PL} in the QPM.

2. F_2 IN THE QUARK PARTON MODEL

The transverse momentum of final state particles or jets relative to the $\gamma\gamma^*$ axis gives a signature of F_2^{HAD} and F_2^{PL} /17/.
F_2^{HAD} is characterised by a steep exponential distribution ($\approx \exp(-6\,p_T)$ for light hadrons) whereas F_2^{PL} gives a flatter (p_T^{-4}) power law behaviour. These two components in the p_T distribution have now been seen in many different experiments /13/.
F_2^{HAD} and F_2^{PL} can then be separated, in an approximate way, by a cut (p_T°) in the parton (or jet) p_T:

$$F_2 = \int_0^{p_T^\circ} dF_2^{HAD} + \int_{p_T^\circ}^{\frac{w}{4}} dF_2^{PL} \qquad (1)$$

Such a description gives a good fit to the PLUTO measurement of F_2^γ /18/ with $\langle Q^2 \rangle$ = 5.3 $(GeV/c)^2$. Using p_T° = 1 GeV/c for w>6 GeV/c^2 and $p_T^\circ \propto$ w for w<6 GeV/c ^{2} gives the solid line in Fig. 1. Setting p_T = 0,

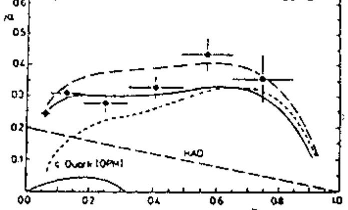

Fig. 1: Comparison of QPM predictions with PLUTO data for F_2 (see text for curve definitions)

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$m_u = m_d = 300$, $m_s = 500$, $m_c = 1700$ MeV/c² (Fig. 1 broad dashed line) overestimates the data near x = 0.3 (F_2^{HAD} is 'double counted'), while neglecting $F_2^{HAD} = 0.2\alpha(1-x)$ (Fig. 1 fine dashed line) under the same conditions fails to fit the data at small x values (F_2^{HAD} must be included). In /15/ the $O(\alpha_s)$ QCD correction for $\langle Q^2\rangle = 5.3$ (GeV/c)² is found to be small, so the fit given by the solid line in Fig. 1 is little changed by this correction. The choice $p_T^o \approx$ 1 GeV/c agrees well with the exponential-power law transition region observed in the final state jet structure /13/.

3. QCD CORRECTIONS TO F_2

The LO QCD solution for F_2 factorises:

$$F_2 = \left[P_{q\gamma}^{HAD} + P_{q\gamma}^{PL}\right] \sigma(\gamma^* q \to X) \quad (2)$$

$P_{q\gamma}^{HAD,PL}$ are photon-quark splitting functions and $\sigma(\gamma^* q \to X)$ is the cross section for the probe photon and a virtual quark from the target photon to scatter into the state X:

$$\sigma(\gamma^* q \to X) = \sigma(\gamma^* q \to q) + \sigma(\gamma^* q \to gq) + \ldots (3)$$

The first term on the RHS of (3) gives the QPM prediction, the other terms QCD corrections.
In terms of quark densities $q, \bar{q}$:

$$F_2 = \sum e_q^2 x \left[q + \bar{q}\right] \quad (4)$$

the non-singlet (NS) contribution to F_2 where N real gluons are radiated comes from $q_N^{HAD,NS} + q_N^{PL,NS}$ where:

$$q_N^{HAD,NS}(Q^2,x) = \int_{y_2}^{1} q^{HAD,NS}(t_o,y_1) \frac{dy_1}{y_1} C_N^{NS} \quad (5a)$$

$$q_N^{PL,NS}(Q^2,x) = \frac{3\alpha e_q^2}{2\pi} \int_{y_2}^{1} \left[y_1^2 + (1-y_1)^2\right] \frac{dy_1}{y_1} \int_{t_o}^{t_1^{MAX}} \frac{dt_1}{t_1} C_N^{NS} \quad (5b)$$

The convolution integral C_N^{NS} and all variable definitions are given in Ref. /15,16/.

t_o is related to the (space-like) virtuality of the off-shell quark at the target photon vertex at the boundary of hadronic and point-like phase space:

$$t_o = y_1 P^2 + \left[m_q^2 + (p_T^o)^2\right]/(1-y_1)$$

If P^2 /19/ or m_q /1/ are large F_2^{HAD} vanishes, but t_o still defines the lower limit of the (now purely point-like) phase space. In this case $p_T^o = 0$. Eqn (5) refers to light quarks ($m_q \ll p_T^o$) and a real photon target ($P^2=0$).

The LO solution is derived from (4) by performing the t integrals in ordered phase-space ($t_i < t_{i+1}$), and taking moments:

$$f(n) = \int_0^1 f(x) x^{n-1} dx$$

to decouple the convolution integral in the energy fraction variables y_1 /16/:

$$q_N^{HAD,NS}(Q^2,n) = q^{HAD,NS}(t_o,n) \frac{\left[-B \ln R\right]^N}{N!} \quad (6a)$$

$$q_N^{PL,NS}(Q^2,n) = a(n) B^N \left\{ \ln\left(\frac{Q^2}{t_o}\right) - \ln\left(\frac{t_o}{\Lambda^2}\right) \sum_{M=1}^{N} \frac{(\ln R)^M}{M!} \right\} \quad (6b)$$

where:

$$R = \ln(t_o/\Lambda^2)/\ln(Q^2/\Lambda^2) = \alpha_s(Q^2)/\alpha_s(t_o),$$

$$B = d_{NS}^n < 0$$

d_{NS}^n are proportional to the non singlet elements of the anomalous dimension matrix.

(6b) implies that the <u>leading log term at any order in α_s is independent of Λ /15/.</u>

The complete LO, NS solution /6/ is given by summing (5) from N = 0 to infinity:

$$q^{HAD,NS}(Q^2,n) = q^{HAD,NS}(t_o,n)\ (R)^{-d_{NS}^n} \quad (7a)$$

$$q^{PL,NS}(Q^2,n) = \frac{a(n)}{1-d_{NS}^n} \ln\left(\frac{Q^2}{\Lambda^2}\right) \left[1 - R^{1-d_{NS}^n}\right] \quad (7b)$$

The leading log term in the complete solution, as is well known, depends on Λ. It is the sum of two terms, $a(n)\ln\left(\frac{Q^2}{t_o}\right)/(1-d_{NS}^n)$ coming from the sum of the leading log terms at each order in α_s, and $a(n)\ln\left(\frac{t_o}{\Lambda^2}\right)/(1-d_{NS}^n)$ coming from the sum of loglog terms. <u>The non leading-log (NLL) point-like terms (proportional to $R^{1-d_{NS}^n}$ in (7b))</u>

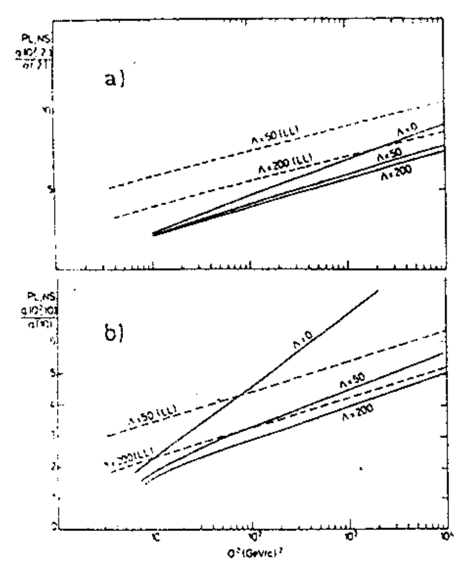

Fig. 2: Non singlet moments
a) n=2, b) n=10
Solid line LO solution,
dashed line LL term only

<u>are never negligible for any value of Q^2 or n.</u> This is illustrated in Fig. 2a,b where $q(Q^2,n)/a(n)$ for n = 2,10 (with t_o = 1 $(GeV/c)^2$ and Λ = 0, 50, 200 MeV/c) is compared (as a function of Q^2) with the leading log (LL) solution given by setting R = 0 in (7). The much reduced sensitivity to Λ of the full solution (7) as compared to the LL solution is evident.

In Fig. 3a,b $q^{PL,NS}(Q^2,n)/a(n)$ for n = 2,10 (with t_o = 1 $(GeV/c)^2$ and Λ = 100 MeV/c) is compared with solutions given by truncating the perturbation series in (6b) at N = 1 (fine dashed line) and N = 2 (broad dashed line). The $O(\alpha_s)$ solution is seen to give a good approximation to the all orders solution for $Q^2 \lesssim 100$ $(GeV/c)^2$.

The LO singlet contributions to F_2 have the same form as (7) with different anomalous dimension parameters (d_+^n, d_-^n) and a(n) coefficients. Here also the NLL terms are large for all experimentally relevant Q^2 values and all n.

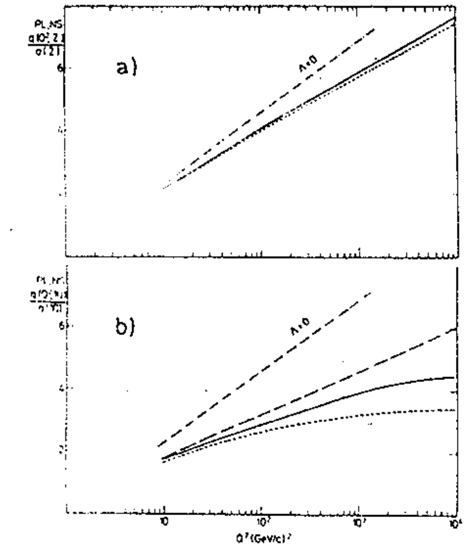

Fig. 3: Non singlet moments with
Λ = 100 MeV/c
a) n=2, b) n=10
Solid line all orders.
Fine, broad dashed lines
$O(\alpha_s)$, $O(\alpha_s^2)$ solutions

4. COMPARISON WITH THE SCHEME OF ANTONIADIS, GRUNBERG AND MARLEAU

The solution (7) can be re-written as:

$$q^{NS}=q^{HAD,NS}+q^{PL,NS}=A(t_o,n)(R)^{-d^n_{NS}} + \frac{a(n)}{1-d^n_{NS}}\ \ln\left(\frac{Q^2}{\Lambda^2}\right) \qquad (8)$$

where:

$$A(t_o,n)=q^{HAD,NS}(t_o,n)+\frac{a(n)}{1-d^n_{NS}}\ \ln\left(\frac{t_o}{\Lambda^2}\right) \qquad (9)$$

Comparing the first term on the RHS of (8) with (7a) it can be seen that <u>$A(t_o,n)$ has the same Q^2 evolution as the hadronic part of F_2.</u> This led Antoniadis, Grunberg and Marleau /9-12/, following Bardeen /22/, to identify $A(t_o,n)$ with q^{HAD}_o and to assume that the point-like contribution is given solely by the LL term in (8).

However, as is clear from our derivation of (7) $A(t_o,n)$ contains both hadronic and point-like parts. The second term on the RHS of (9) is purely point-like, coming from the region of phase space where $t_1>t_o$.

As already pointed out by Glück and Reya /4/ the much discussed /9-12, 20-22/ problem of singularities related to the zeros of $1-d_i^n$ in the LO solution and of d_i^n in the HO solution for certain n values (i=NS,+,-) goes away when the numerically important (see Fig. 2) NLL terms are retained in both the LO and HO solutions.

Our analysis shows that the hadronic (7a) and point-like (7b) terms are <u>separately</u> singularity free, the NLL terms coming entirely from the point-like phase space region $t_1 > t_0$.

Many published QCD analyses based on Ref. /9,10/ have given plausible /14/ but actually incorrect 'measurements' of Λ. In these analyses the NLL point-like terms are set to zero except for values of n where a singularity occurs in the LL term or the HO correction terms, in which case arbitrary parameters are introduced by hand to 'regularise' these singularities. Such a procedure has no physical justification, and the additional parameters are quite unrelated to F_2^{HAD}, which has now been directly measured at low Q^2 /13/.

An $O(\alpha_s)$ calculation of the QCD correction to the QPM, assuming factorisation, but using exact kinematics in the final state phase space integrations is given in Ref. /15/. The QCD correction is found to be less sensitive to Λ than to the poorly known phenomenological cut-off p_T^c.

Further progress in the comparison of theory and experiment for F_2^{γ} can perhaps be achieved by exact Feynman diagram calculations at $O(\alpha_s)$ or $O(\alpha_s^2)$, since the LO QCD solution suggests small corrections at $O(\alpha_s^3)$ and higher (Fig. 3) where in any case confinement effects limit the validity of perturbative calculations. In this way tests of the many approximations /16/ which underlie the derivation of the existing LO, HO calculations can be done allowing more quantitative comparisons of theory and experiment for F_2^{γ}.

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