Measurement of photon structure functions with the PLUTO detector

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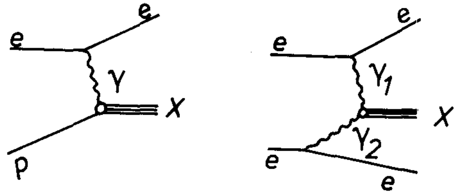
Abstract

Photon structure functions have been measured in photon photon interactions at the e^+e^- collider PETRA. Results are presented for the leptonic structure function $F_2(x,Q^2)$ measured in the process $\gamma\gamma \to \mu^+\mu^-$. The hadronic structure function $F_2(x,Q^2)$ of a real photon has been determined for momentum transfers Q^2 up to 100 GeV^2. First results on the hadronic structure function of a virtual photon are presented.

1.INTRODUCTION

In a similar way as in measurements of the nucleon structure the internal structure of the photon can be determined in deep inelastic lepton scattering processes.



Electron positron colliders provide the possibility to measure photon photon scattering processes ($\gamma_1\gamma_2 \to X$) by observing reactions of the type $e^+e^- \to e^+e^-X$. Since both photons (γ_1,γ_2) are in general off mass shell the measured cross section $\sigma(e^+e^- \to e^+e^-\ X)$ depends on four photon photon cross sections $\sigma_{TT},\sigma_{TL},\sigma_{LT},\sigma_{LL}$,where the first index describes the helicity state of γ_1 and the second one that of γ_2 (T=transverse , L=longitudinal). The $\gamma\gamma$ cross sections depend on the mass Q^2 of the probe photon ,the mass P^2 of the target photon and the mass W of the final state X.
In the special case of deep inelastic electron scattering on a real target photon (P^2=o) the cross section reduces to $\sigma(e\gamma \to eX)=f(\sigma_{TT},\sigma_{LT})$. In this case one prefers to parametrize the cross section $\sigma(e\gamma \to eX)$ by the photon structure functions F_1 and F_2 . The relations between the structure functions F_1 , F_2 and σ_{TT} , σ_{LT} are given by

$$F_2=(Q^2/4\alpha\pi^2)(\sigma_{TT}+\sigma_{LT})$$

$$2xF_1=(Q^2/4\alpha\pi^2)\sigma_{TT}$$

The scaling variables are $x=Q^2/(Q^2+W^2)$ and $y=1-E'/E\cdot\cos^2(\Theta/2))$ where E' and Θ are the energy and scattering angle of the detected electron respectively and E the beam energy. The cross section for deep inelastic electron photon scattering then reads

$$[d\sigma/dxdy]\ (e\gamma \to eX)= 16\pi\alpha^2EE_\gamma/Q^4[(1-y)F_2(x,Q^2)\ +xy^2F_1(x,Q^2)]$$

with E_γ beeing the target photon energy.

2. EXPERIMENTAL PROCEDURE

The experiment was performed at the e^+e^- collider PETRA by the PLUTO collaboration. The detector is specially designed for a measurement of $\gamma\gamma$ interactions. To determine the structure function F_2 (x,Q^2,P^2=o) one has to measure one electron (tag),restrict the other electron to small angles (antitag ,$P^2\approx$o) and reconstruct the final state X.

Three electromagnetic shower counter systems covering small, medium and large polar angles for the tagged electrons were used (SAT:28-60mr,LAT:87-284mr,EC:16°-50°). The average values for Q^2 are 0.4, 5.5, 40 GeV^2 respectively. The requirement of E_{tag}> 8 GeV resulted in an average inelasticity of the events <y> =0.15. In this condition the sensitivity to F_1 is small and $\sigma(e\gamma \rightarrow e\ X)$ is to good approximation proportional to F_2. Events in which also the second electron was registered in the shower counter system were rejected (antitag).

In $\gamma\gamma$ interactions the final state X is in general not at rest in the laboratory system, but boosted along the beam direction. A forward spectrometer system specifically designed for $\gamma\gamma$ physics studies provided a good acceptance down to polar angles of 5°. The overall acceptance of the PLUTO detector is 93% of 4π for charged particles and 97% of 4π for neutral particles.

3. LEPTONIC STRUCTURE FUNCTION OF REAL PHOTONS

To determine the leptonic structure function of the photon deep inelastic electron scattering on a quasireal photon producing a dimuon final state ($e\gamma \rightarrow e\mu^+\mu^-$) was measured (fig.1). After a cut of $W\mu^+\mu^-$ >1.2GeV the accepted rates were 372±19 events in the SAT, 283± 17 events in the LAT and 42±7 events in the EC tagging systems. QED calculations predict the leptonic structure function to be of the form

$$F_2(x,Q^2)=\alpha/\pi\left[x(x^2+(1-x)^2)\ln\,(W^2/m_\mu{}^2)+8x^2(1-x)-x\right]$$

This expression shows that

a) F_2 rises with x

b) F_2 rises like ln Q^2 for fixed x since $W^2=Q^2(1/x-1)$

In fig.2a and fig.2b the measured structure function F_2 is shown as a function of x for <Q^2> =5.5 GeV^2 and <Q^2> =40 GeV^2 respectively. The data show the explicit scale breaking and are in perfect agreement with the QED prediction,which is shown also in fig.2.

4. HADRONIC STRUCTURE FUNCTION OF REAL PHOTONS

Theoretical expectations

Different model expectations for the hadronic photon structure function can be summarized as follows:

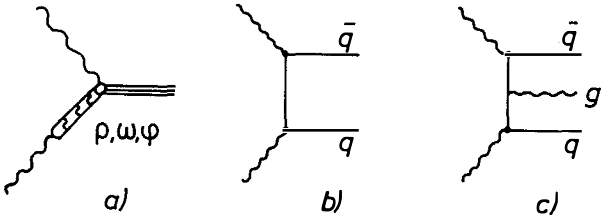
- a) The photon behaves hadronlike (VDM)
  The structure function F_2 falls with x like the protron structure functions. The hadronic part of the photon structure function has been estimated[1)] from the pion structure function measured in Drell Yan processes[2)] to be $F_2(x)=\alpha$ (0.2+-0.05)(1-x)
- b) The photon couples directly to quarks (QPM)

Within the naive quark parton model (QPM) one expects F_2 to be similar to the leptonic structure function with modifications due to the quark charges and colours.

$F_2(x,Q^2) = 3\sum e_q^4\, f(x)\, \ln(Q^2/m_q^2)$ summing over all quark flavours.

c) Gluon corrections to QPM (QCD)

In leading order QCD the explicit scale breaking of F_2 is set by the QCD scale Λ resulting in $F_2(x,Q^2)=f(x)\ln Q^2/\Lambda^2$



In summary it can be stated that F_2 is sensitive to pointlike photon quark couplings because of the characteristic x dependence (rising with x) and explicit scale breaking expected for this case.

Experimental procedure

In contrast to the reaction $e\gamma \to e\mu^+\mu^-$ one does in general not measure the full final state in the process $e\gamma \to e$ hadrons. This in turn means that due to selection criteria imposed on the data sample, some events are lost, and the accepted events are in general not measured completely. The visible invariant mass W_{vis} of the hadronic system is smaller than its true mass W_{true}, which results in $x_{vis} > x_{true}$.

The aim of this experiment is to measure the hadronic structure function F_2 as a function of the true x for fixed Q^2 values. An unfolding procedure[3] has been applied to the data to correct for the x_{vis} to x_{true} distortion and to take into account detector acceptances. In this procedure that structure function $F_2(x,Q^2)$ is determined which best describes the observed event distributions dN/dQ^2dW_{vis}. A test of the method has been performed by generating simulated data according to a test structure function and applying the unfolding procedure on these data to determine the underlying structure function. Fig.3 shows that the results are satisfactory.

Results on the hadronic structure function F_2

Hadronic $\gamma\gamma$ events tagged in the LAT shower detector were selected in the ranges $1.5<Q^2<16\,\mathrm{GeV}^2$ and $1<W_{vis}<12\,\mathrm{GeV}$. After background subtraction (10%) a sample of 1452 events was obtained. In fig.4 the structure function $F_2(x)$ is shown at a fixed value of $Q^2=5.3\,\mathrm{GeV}^2$. The data points shown include only statistical errors. Systematic errors due to radiative corrections,target mass effects and fragmentation scheme dependences of the unfolding procedure are smaller than 15% for $x > 0.2$. The data are compared in fig.4 to a VDM type structure function $F_2=0.2(1-x)$ and are clearly incompatible with this ansatz (HAD). Good agreement is achieved by adding to the VDM part a higher order QCD calculation [4] for u,d and s quarks and a QPM based calculation for the contribution of charmed quarks. The data are found to be in good agreement with this ansatz for a value of $\Lambda_{\overline{MS}}$ around 200 Mev. Fig.5 shows the Q^2 evolution of the structure function as measured at three fixed values of Q^2 =2.4, 4.3, 9.2 GeV^2. The fact that F_2 rises with Q^2 is clearly visible. The data are in all three cases compatible with a value of $\Lambda_{\overline{MS}}$ =200 MeV. Since the simple ansatz of adding to a VDM part a QCD based calculation is currently a source of much debate[5] we prefer to consider a possible hadronic contribution of $0 < F_2 < 0.2$ as a systematic error in a determination of $\Lambda_{\overline{MS}}$. Doing so , we derive from the absolute normalization of F_2 for the QCD cut off parameter the limits $65 < \Lambda_{\overline{MS}} < 575$ MeV (90% confidence level).

For the determination of $\Lambda_{\overline{MS}}$ from the Q^2 evolution of F_2 one needs a bigger Q^2 range than that covered by the LAT tagging system. A preliminary analysis of deep inelastic electron photon scattering using data where the tag is recorded in the end cap tagging system yielded 89 events with Q^2 extending up to 100 GeV^2. Fig.6 shows the measured structure function $F_2(x,Q^2=45\text{GeV}^2)$ compared to VDM+QCD. The contribution of charmed quarks has been subtracted from the data according to a QPM calculation and is not included in the curves shown in fig.6.. Analysis is in progress to combine LAT and EC data for a more precise determination of $\Lambda_{\overline{MS}}$.

5. HADRONIC STRUCTURE FUNCTION OF VIRTUAL PHOTONS

When both final state electrons are detected also the invariant mass P^2 of the target photon can be determined. Since the target photon has in this case ($P^2 \neq 0$) also longitudinal components, in principle all four $\gamma\gamma$ cross sections $\sigma_{TT},\sigma_{TL},\sigma_{LT},\sigma_{LL}$ contribute to $\sigma_{\gamma\gamma}(P^2,Q^2,x)$. It can be shown [6] in the QPM model that for $m_q{}^2 \ll P^2 \ll Q^2$ the correlation between the measured $\sigma_{\gamma\gamma}$ and the structure functions is given by

$$\sigma_{\gamma\gamma}(P^2,Q^2,x)=4\pi\alpha^2/Q^2 \cdot \left[F_2+3/2F_L\right]$$

Using this relation one determines from the measured cross section $\sigma_{\gamma\gamma}$ an effective structure function of the virtual photon $F_{eff} = F_2 + 3/2\, F_L$.
QCD based theoretical predictions for the structure function are for $P^2 \neq 0$ less problematic[7] than in the real photon case ,since no unphysical negative values are predicted at low x. But on the other hand it turns out that the sensitivity to quark masses in the QPM model or to Λ in QCD models is very much reduced since the scaling violations go essentially like $\ln Q^2/P^2$ in both cases.

The structure function $F_{eff}(x)$ has been measured selecting events where one electron is detected in the LAT ($<Q^2>=5$ GeV^2) and the other in the SAT ($<Q^2>=0.35$ GeV^2) yielding a sample of 74 events. The analysis procedure is identical to that described for single tagged events. Fig.7 shows the measured structure function F_{eff} determined at the values Q^2 = 5 GeV^2 and P^2 = 0.35 GeV^2. A VDM type of structure function $F_2 = 0.2(1-x)F_\rho(P^2)$ does not describe the data ,whereas an addition of a QPM calculation with either zero quark masses or constituent quark masses describes the data well. Good agreement is also achieved by a sum of a VDM contribution and a higher order QCD calculation with a $\Lambda_{\overline{MS}}$= 200 MeV.

A naive integer charge quark parton model can be ruled out since this would result in predictions three times higher than those shown in fig.7 for fractionally charged quarks.

6. CONCLUSIONS

The leptonic structure function of the real photon is in perfect agreement with the QED prediction. The hadronic structure function F_2 of a real photon has been measured in a range $1 < Q^2 < 100$ GeV^2 as a function of the true value of the scaling variable x. The x dependence of F_2 is found to be flat or slowly rising with x in sharp contrast to a VDM dominated photon structure function. For fixed x the structure function is rising with Q^2 showing in this way explicit scaling violations as expected for pointlike photon couplings. The shape and normalization of F_2 is consistent with a QCD calculation for a value of $\Lambda_{\overline{MS}}$ around 200 MeV. The structure function of a virtual photon has been measured for the first time and found to be in good agreement with QPM or QCD based calculations.

References:

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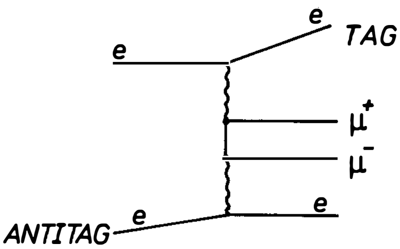

Fig. 1 Dimuon production in $\gamma\gamma$ scattering

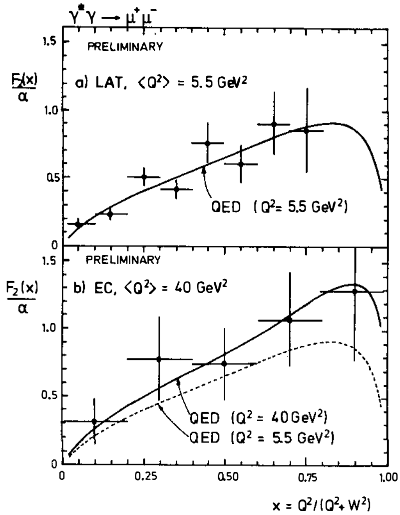

Fig. 2 Leptonic structure function $F_2(x)$ measured in $\gamma\gamma \to \mu\mu$ compared to QED

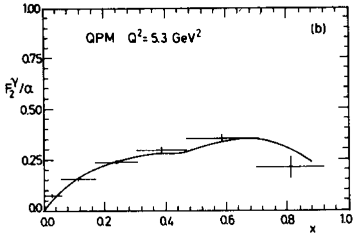

Fig. 3 The curve shows the input F_2, the points the unfolding result

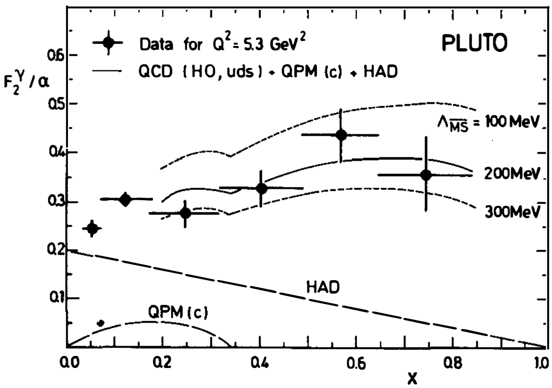

Fig. 4 The x dependence of the hadronic structure function F_2 at $Q^2 = 5.3$ GeV^2

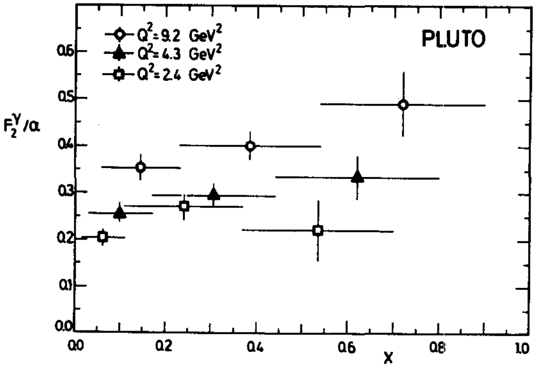

Fig. 5 The x dependence of F_2 at Q^2=2.4, 4.3 end 9.2 GeV^2

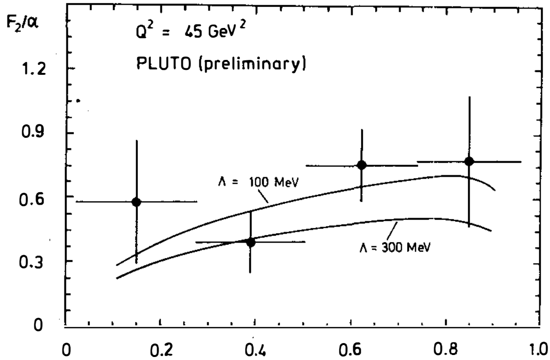

Fig. 6 The x dependence of F_2 at Q^2= 45 GeV^2

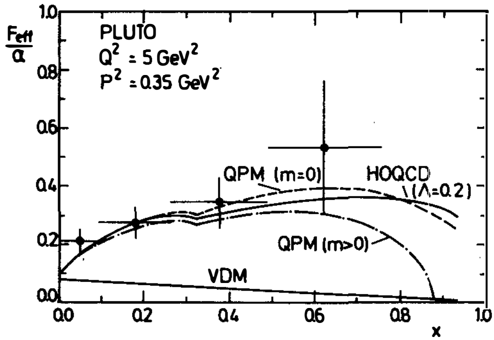

Fig. 7 The x dependence of the virtual photon structure function F_{eff}