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Measurement of the photon structure function at ALEPH

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The photon structure function F_2^γ has been measured with data taken by the ALEPH collaboration at LEP centre-of-mass energies $\sqrt{s} = 91\,\mathrm{GeV}$ with $\langle Q^2 \rangle$ of 9.9, 20.7 and $284\,\mathrm{GeV}^2$ and $\sqrt{s} = 183\,\mathrm{GeV}$ with $\langle Q^2 \rangle$ of 13.7 and $56.5\,\mathrm{GeV}^2$. For the data at $\sqrt{s} = 183\,\mathrm{GeV}$ a two-dimensional unfolding method employing the principle of maximum entropy is used, which reduces the errors compared to one-dimensional methods.

1. INTRODUCTION

The photon structure function F_2^γ in $\mathrm{e^+e^-}$ collisions is measured [1,2] where one of the incident beam leptons is scattered at sufficiently large angle to be detected. In these singly-tagged events the negative momentum transfer $Q^2 = -q^2$ of the photon emitted by the tagged lepton is $Q^2 = 2E_{\mathrm{tag}}E_{\mathrm{beam}}(1 - \cos\theta)$. The second lepton stays undetected so the momentum transfer is small.

The process then can be viewed as inelastic electron-photon scattering, where a quasi-real photon is probed by a virtual photon [3]:

$$\frac{\mathrm{d}^2\sigma_{\mathrm{e}\gamma\to\mathrm{eX}}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^2}\left[\left(1+(1-y)^2\right)F_2^\gamma(x,Q^2) - y^2F_L^\gamma(x,Q^2)\right] \quad (1)$$

with

$$x \approx \frac{Q^2}{Q^2+W^2} \quad (2)$$

$$y \approx 1 - \frac{E_{\mathrm{tag}}}{E}\cos^2(\theta_{\mathrm{tag}}) \quad (3)$$

The inelasticity, measured with y, is small and the term with F_L^γ may be neglected. Equation 1 can be used to relate the distribution in x and Q^2 to the structure function F_2^γ. A more elaborate introduction and discussion of F_2^γ you may find in Ref. [4].

In this article the recent measurements of F_2^γ with the ALEPH experiment are presented [1,2]. Measurements at two different centre-of-mass energies and various Q^2 have been performed. The data are used to test different model parameterizations of F_2^γ. Special emphasis has been put on a two-dimensional unfolding method to extract the true x distribution $\mathrm{d}N/\mathrm{d}x$ from the measured data.

2. DATA

The ALEPH detector and its performance have been described in detail elsewhere [5]. Charged tracks and neutral calorimeter energy as defined by the ALEPH energy flow package [6] are used in these analyses.

Single tag events are selected by the lepton detected in the electromagnetic calorimeters of ALEPH: ECAL and LCAL for $\sqrt{s} = 91\,\mathrm{GeV}$ (LCAL and SiCAL for $\sqrt{s} = 183\,\mathrm{GeV}$). The scattering angle is measured in the range of $-0.6 < \cos\theta_{\mathrm{tag}} < 0.95$ in ECAL and $65\,\mathrm{mrad} < \theta_{\mathrm{tag}} < 150\,\mathrm{mrad}$ in LCAL ($60\,\mathrm{mrad} < \theta_{\mathrm{tag}} < 155\,\mathrm{mrad}$ at 183 GeV). Further cuts on E_{tag} and a veto on a second tag are applied.

The visible hadronic final state has to consist of at least three charged tracks and has to have an invariant mass $W_{\mathrm{vis}} > 2\,\mathrm{GeV}$. Further cuts for rejection of beam-gas events are applied. Additional cuts are required for the data at $\sqrt{s} = 91\,\mathrm{GeV}$ rejecting background from Z decays.

We are left with clean data samples with a remaining background of a few percent. The samples are divided into three (two) subsamples; see Table 1.

The data are corrected for trigger efficiency

Table 1
Data samples with their statistics and Q^2

	# of events	Q^2 range GeV^2	$\langle Q^2\rangle$ GeV^2	$E_{\rm cms}$ GeV
ECAL	163	35 - 3000	284	91
LCAL	1647	13 - 44	20.67	91
LCAL	1543	6 - 13	9.93	91
SiCAL	1208	7 - 24	13.7	183
LCAL	861	17 - 200	56.5	183

(which is close to 100%), downscaling, and acceptance. For the correction it is important to note that the invariant mass W and therefore x is poorly measured only, see Fig. 1. This is especially due to the significant portion of the energy of the event which goes in the forward region where there is little or no tracking information. Therefore extraction of a measurement of the photon structure function from the data depends on the use of a model of the production of hadronic final states from $\gamma^*\gamma$ collisions. There is at present no complete theoretical description of this process, so a number of phenomenological models are used.

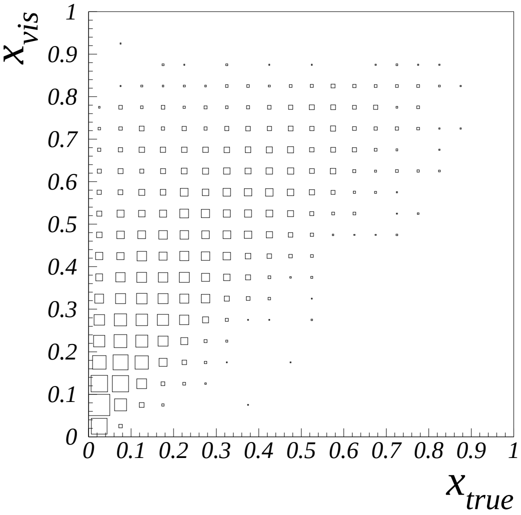

Figure 1. $x_{\rm vis}$ versus $x_{\rm true}$ for LCAL tagged events at $\sqrt{s} = 91\,$GeV

Models giving reasonable descriptions of global event variables are then used to correct the data using an unfolding method.

The models chosen at $\sqrt{s} = 91\,$GeV are firstly a combination of QPM and VDM [3,7], both with JETSET fragmentation [8], and secondly HERWIG [9] with GRV LO [10]. QPM and VDM are combined to form a single set, weighting each sample so as to give the best χ^2 between distributions (the number of energy flow objects, the transverse momentum of all energy flow objects with respect to the beam direction, and the thrust of the event) predicted by the combined simulation and the data. In the HERWIG program the defaults for version 5.9 are used, apart from the intrinsic transverse momentum $k_{\rm t}$ of the partons in the target photon. This was modified according to the scheme proposed by ZEUS and described in Ref. [11,12].

The models chosen at $\sqrt{s} = 183\,$GeV are firstly HERWIG [9] with GRV LO [10], secondly HERWIG [9] with SaS [13] and thirdly PHOJET [14] (only used for SiCAL data, because the description of the LCAL data is only moderate).

3. UNFOLDING AND EXTRACTION OF F_2^γ

As pointed out in the previous section, the invariant mass W is poorly measured by current detectors and an unfolding method has to be employed. Both at $\sqrt{s} = 91\,$GeV and at 183 GeV a regularization procedure is used to suppress oscillations in the result.

At $\sqrt{s} = 91\,$GeV the unfolding was performed using the procedure proposed by Blobel [15]. This procedure fits a sum of spline curves to the data after passing them through the $x_{\rm vis}$ versus $x_{\rm true}$ response matrix obtained from the simulated events (HERWIG and QPM+VDM), suppressing oscillations which have higher frequency. The structure function F_2^γ is then obtained using the GALUGA program [16], where F_L^γ is set to its theoretical value. With F_2^γ set to 1 the output is used as reference for the extraction of F_2^γ of the data.

At $\sqrt{s} = 183\,\mathrm{GeV}$ a new, recently proposed method [11] has been used for the unfolding (Ref. [2] and references therein). It uses the principle of maximum entropy. In addition, this method allows a two-dimensional unfolding to be applied. The regularization function $S(\vec{\mu})$ used is the Shannon entropy [17]:

$$S(\vec{\mu}) = -\sum_{j=1}^{M} \frac{\mu_j}{\mu_{\mathrm{tot}}} \log\left(\frac{\mu_j}{\mu_{\mathrm{tot}}}\right) \qquad (4)$$

when μ_j are the parameters to be estimated in bin j and μ_{tot} is their sum. This entropy-based regularization makes no reference to the relative locations of any of the bins. Therefore the principle of maximum entropy can be directly applied to multidimensional distributions. This method reduces the model dependence by including for each event not only x, but in addition some other variable characterizing the final state. For this, the variable E_{17} has been introduced, defined as the total energy of the particles having angles with respect to the beam line less than 17°. Here the x resolution degrades considerably for increasing E_{17}, see Fig. 2.

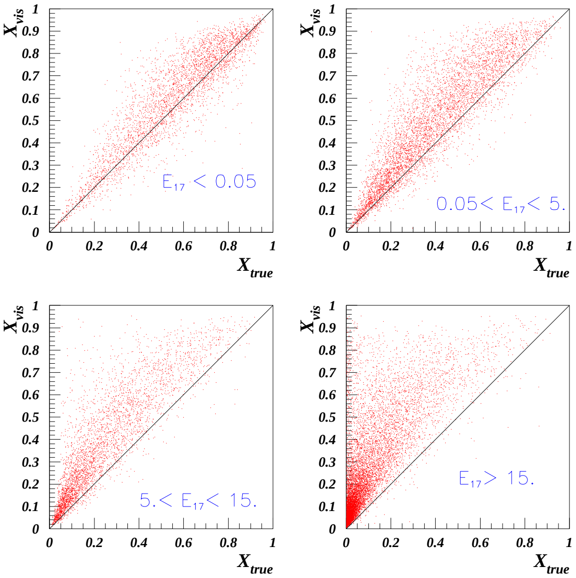

Figure 2. x_{vis} versus x_{true} for subsequent bins of the variable E_{17} using HERWIG simulation.

The two-dimensional unfolding leads to smaller statistical errors. This is because in the one-dimensional case, the effective weight of each event is determined by the average x resolution in the bin. With two-dimensional unfolding, those events with low E_{17} are given a higher weight in the final result. The improvements achievable by two-dimensional unfolding where investigated quantitatively in Ref. [11]. An example is shown in Fig. 3, where a toy-MC sample was used and two different response matrices to demonstrate the differences in one- and two-dimensional unfolding. Nevertheless the model dependence remains a significant source of systematic uncertainty, and several event generators are used in the presented analysis to account for this. After unfolding the structure function F_2^{γ} is obtained from the x distribution $\mathrm{d}N/\mathrm{d}x$ using the same MC simulation that was used for the determination of the response matrix. The measurement in data is taken as the average of the distributions obtained with the response matrices of the models used.

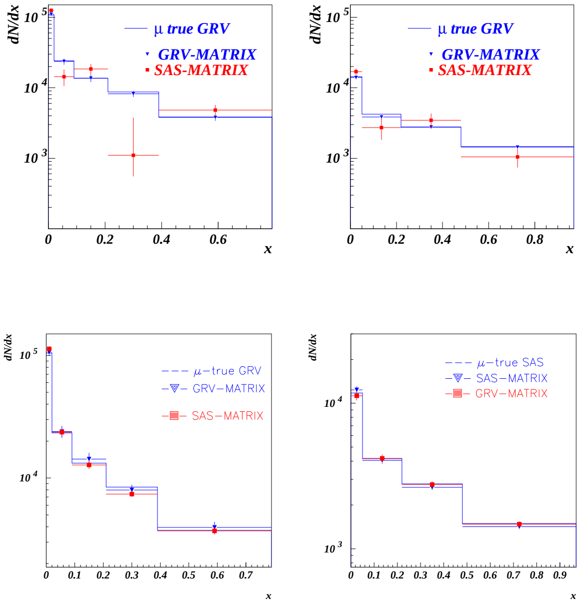

Figure 3. One- (upper) and two-dimensional (lower plots) test unfolding in SiCAL- (left) and LCAL- (right) tagged events using a sample of toy-MC.

4. RESULTS

4.1. Measurements for F_2^γ

The final results for F_2^γ are shown in Fig. 4 for $\sqrt{s} = 91\,\mathrm{GeV}$ and in Fig. 5 for $\sqrt{s} = 183\,\mathrm{GeV}$, resp. The inner error bars are statistical errors, the total error bars represent the quadratic sum of statistical and systematic errors. The systematic error comprise uncertainties from the unfolding (spread of the results based on the different models etc.), from detector efficiency and acceptance including trigger, selection criteria etc. The 91 GeV analysis includes a small theoretical error from the assumed form factor of the virtual photon as well as the dependence on the assumption of F_L^γ.

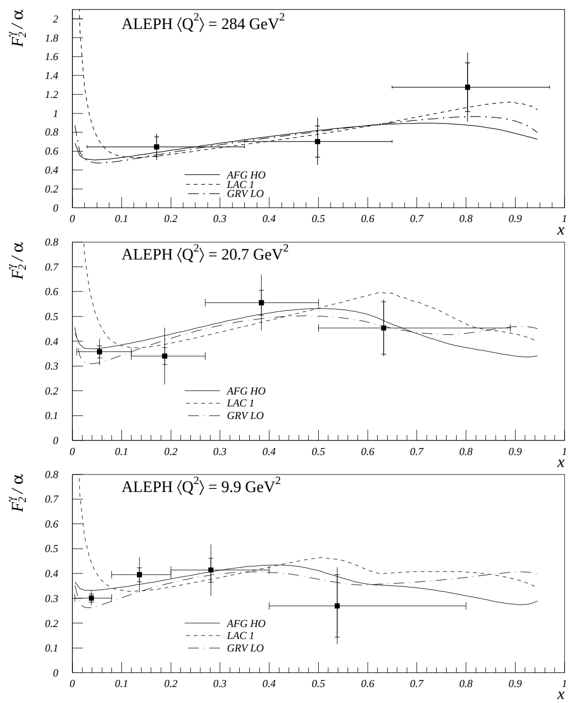

Figure 4. The values for F_2^γ/α at $\sqrt{s} = 91\,\mathrm{GeV}$ compared to three different parameterizations.

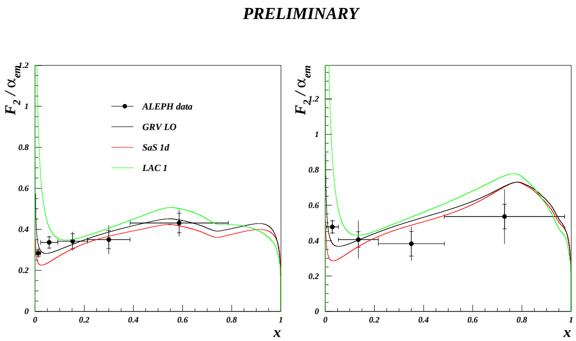

Figure 5. The values for F_2^γ/α at $\sqrt{s} = 183\,\mathrm{GeV}$ ($\langle Q^2\rangle$ =13.7 and 56.5 GeV^2) compared to three different parameterizations.

4.2. Comparison of F_2^γ to parameterizations

For both centre-of-mass energies and the different Q^2 ranges all of the parameterizations provide a good description of the data for $x > 0.1$. For lower x the LAC values are significantly too high. At $\sqrt{s} = 91\,\mathrm{GeV}$ a test has been made using event reweighting to ensure that the difference is not an artifact of the unfolding procedure; for more details see Ref. [1]. The low x region is sensitive to the gluon content of the photon. A χ^2 was calculated in the eleven bins in x to quantify the comparison to various sets of the parton density function of the photon, see Table 2. Those that show significantly large values of χ^2 such as LAC 1 and 2 and Whit 4,5, and 6, contain a large gluon content, resulting in a rapid rise in the structure function at low x.

4.3. Dependence of F_2^γ from $\langle Q^2\rangle$

The values of F_2^γ for the three Q^2 ranges at $\sqrt{s} = 91\,\mathrm{GeV}$ have been averaged over the region $0.1 < x < 0.6$. A logarithmic rise with $\langle Q^2\rangle$ is seen as expected from theoretical predictions using the parameterizations listed in Table 2.

Table 2
The values of χ^2 obtained data at to the more recently calculated photon parton density function, see [1] and references therein.

PDF	χ^2	PDF	χ^2
DG Set 1	4.3	DG Set 2	5.0
LAC 1	107.2	LAC 2	75.9
LAC 3	3.9	GS-96 HO	7.6
GS-96 LO	8.9	GRV HO	4.9
GRV LO	3.8	AFG HO	4.6
Whit 1	5.2	Whit 2	13.9
Whit 3	18.3	Whit 4	40.0
Whit 5	105.5	Whit 6	130.8
SaS Set 1D	10.0	SaS Set 1M	4.3
SaS Set 2D	3.6	SaS Set 2M	3.7

5. CONCLUSIONS

Single-tagged two-photon events recorded by the ALEPH detector at LEP I and LEP II have been studied in three and two bins of Q^2, which have a mean of 9.9, 20.7 and 284 GeV^2 and 13.7 and 56.5 GeV^2. The data have been used to measure the hadronic structure function F_2^γ as a function of x. The comparison with parameterizations show that those with parton density functions that contain a large gluon content are inconsistent with data. The rise of F_2^γ with $\langle Q^2 \rangle$ is found compatible with the available parameterizations.

A two-dimensional unfolding technique using the principle of maximum entropy has been successfully applied; with the second variable chosen as E_{17}, defined as the total energy of the particles having angles with respect to the beam line less than 17°. This unfolding method reduces the statistical errors and the model dependence of the extracted F_2^γ as compared to one-dimensional procedures.

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