PRAMANA
— journal of
physics

Vol. 61, No. 5
November 2003
pp. 819–826

Structure function measurements from HERA

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Abstract. In this paper recent measurements of structure functions from the HERA Collaborations are presented.

Keywords. Structure functions; HERA; F_2; F_3; F_L.

PACS No. 24.85

1. Introduction

In the years 1998–2000, HERA was operated in both e^+p and e^-p scattering modes at a centre of mass energy of $\sqrt{s} = 320$ GeV. The large data samples collected have allowed the determination of all the possible neutral current (NC, $ep \to eX$) structure functions F_2, F_L and xF_3 for the first time at HERA. The structure function F_2 is sensitive to all quark species and dominates the cross-section throughout the accessible phase space. The quantity xF_3 is sensitive to the valence quarks. Since the cross-section only becomes sensitive to xF_3 via the exchange of the Z^0 boson, its influence is limited to the very high Q^2 electroweak regime. Finally, F_L is sensitive to higher order gluon radiation processes providing valuable confirmation of the gluon content of the proton.

Like the neutral current cross-section, the charged current (CC , $ep \to \nu X$) cross-section is an important tool to measure the structure of the proton, particularly since the charged current process is sensitive to the quark flavour decomposition of the proton. Measurements of the e^+p and e^-p scattering cross-sections have allowed independent determination of the u quark and d densities.

The structure functions are usually presented in terms of the kinematic variables Bjorken x, the fraction of the proton's momentum carried by the struck quark and Q^2 the negative square of the four-momentum transfer of the exchanged boson. Q^2 may be interpreted as the resolving power of the exchange, with increasing Q^2 able to resolve smaller distances within the proton. They may be derived from the differential cross-sections as

$$\frac{\mathrm{d}\sigma_\mathrm{NC}(e^\pm p)}{\mathrm{d}x\mathrm{d}Q^2} \simeq \frac{2\pi\alpha^2}{xQ^4}[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_\mathrm{L}]. \tag{1}$$

Here α is the electromagnetic coupling constant and $Y_\pm = 1 \pm (1-y)^2$, where $y = Q^2/sx$. A similar relationship holds for CC interactions [1].

2. Proton structure at low *x*

The large integrated luminosity achieved by HERA in the last few years has provided large data samples of several million events for NC measurements at low x and low Q^2. This has allowed the determination of the proton structure function F_2 to an accuracy of $\simeq$2% [2,3]. Example measurements of F_2 from HERA and fixed target experiments are shown in figure 1. F_2, which is sensitive to the total quark density of the proton, is seen to rise steeply as x decreases. The data are compared to a next to leading order (NLO) quantum chromodynamics (QCD) fit, which describes all data for $Q^2 > 3$ GeV very well.

It may also be seen in figure 1 that the rise towards lower x becomes more pronounced as Q^2 increases. In order to explore this feature more quantitatively, F_2 is parametrized as $F_2 = c(Q^2)x^{-\lambda}$ and the slope parameter λ is plotted as a function of Q^2 in figure 2. For $Q^2 > 1$ GeV it can be seen that λ increases. This can be explained by the fact that as Q^2 increases the resolving power of the probe increases and more and more splitting processes of the form $g \to q\bar{q}$ are resolved. The components after the splitting carry less momentum and so are observed at lower x. At $Q^2 < 1$ GeV the data tend to reach a constant value for λ. In this region the data are difficult to describe using perturbative QCD although non-perturbative models do have some success [4].

It is also interesting to plot F_2 as a function of Q^2 at fixed x as shown in figure 3a. If the protons were made solely of three quarks, F_2 should remain constant or scale with Q^2. What is seen is negative scaling violations at large x, approximate scaling at $x \simeq 0.2$ and very large positive scaling violations at low x. In QCD these scaling violations are interpreted as gluon radiation. As Q^2 increases there is an increasing chance that a valence quark radiates a gluon and so decreases the quark density at higher x. Conversely at lower x there is an increased chance of a radiated gluon splitting into a quark pair so that the density increases.

NLO QCD theory shows that the gluon density is related to the differential of F_2: $\mathrm{d}F_2/\mathrm{d}Q^2 \propto xg$. Such a determination has been performed and the results are shown in figure 3b. Similar scaling violations are observed in the quark density of the proton.

3. Determination of the longitudinal structure function F_{L}

The structure function F_{L} has not been directly determined at HERA since a run taken at lower beam energies has not yet been performed. The data, however, are sensitive to F_{L} at high y as can be seen by examining eq. (1). H1 has used the approach that since F_2 is well-determined over a wide range of x and Q^2 it may be extrapolated into the region at high y using the QCD fit [5]. Thus, by subtracting a term that depends on F_2 and making a very small correction for xF_3 one may determine F_{L}. Such a determination is shown in figure 4 for different Q^2 and x for a fixed $y = 0.75$. Measurements from the e^+p data and the e^-p data are shown. It can be seen that the data are inconsistent with either $F_{\mathrm{L}} = 0$ or $F_{\mathrm{L}} = F_2$. The NLO QCD fit shows good agreement to the data. This is an important test of QCD since F_{L} only arises through higher order corrections. Measurements have also been made at lower Q^2 [2] which also show agreement to the theory.

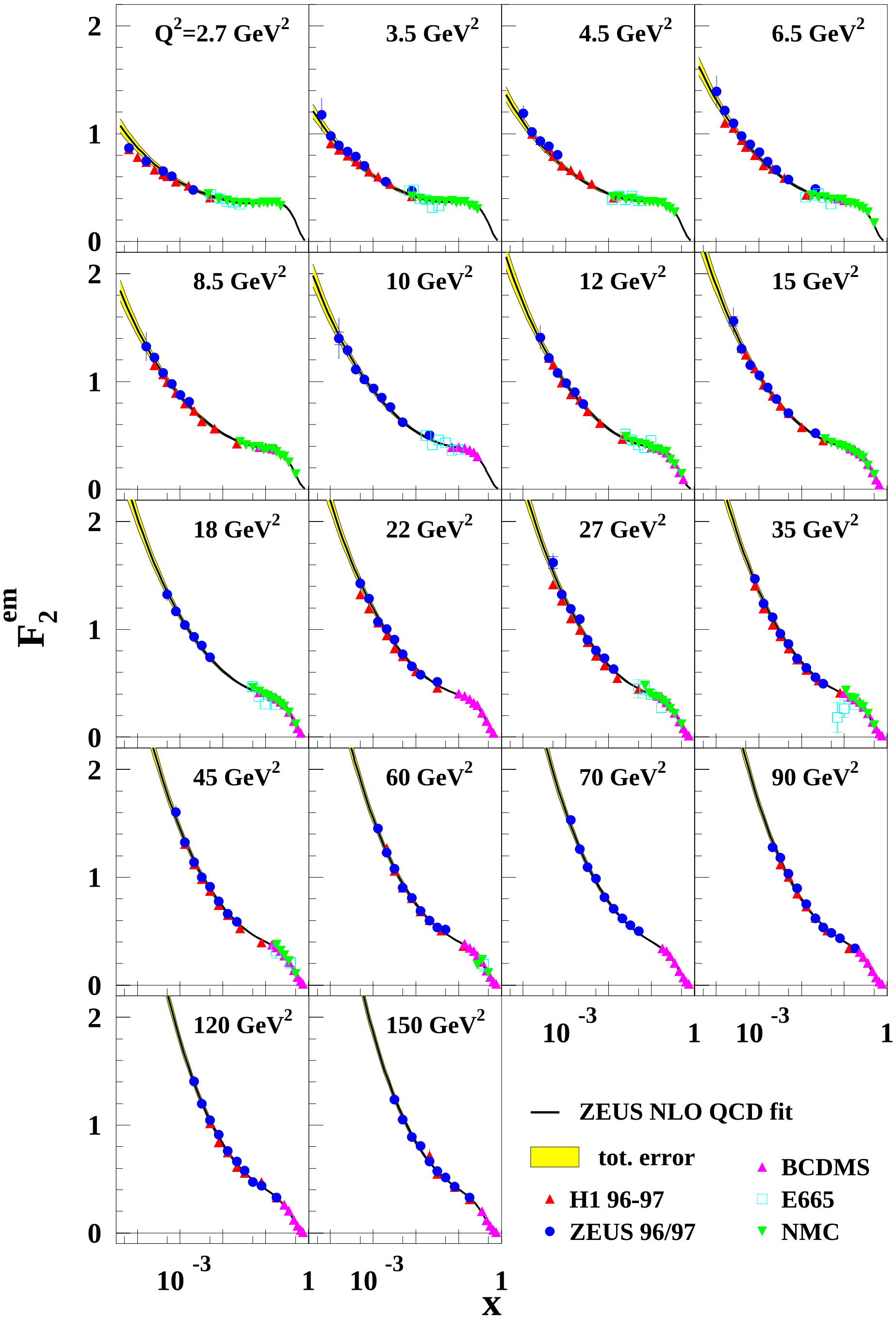

Figure 1. Measurements of the structure function F_2 from the HERA Collaborations and fixed target experiments. The data are plotted as a function of x for various fixed values of Q^2. Also included are the results of a NLO QCD fit to the data.

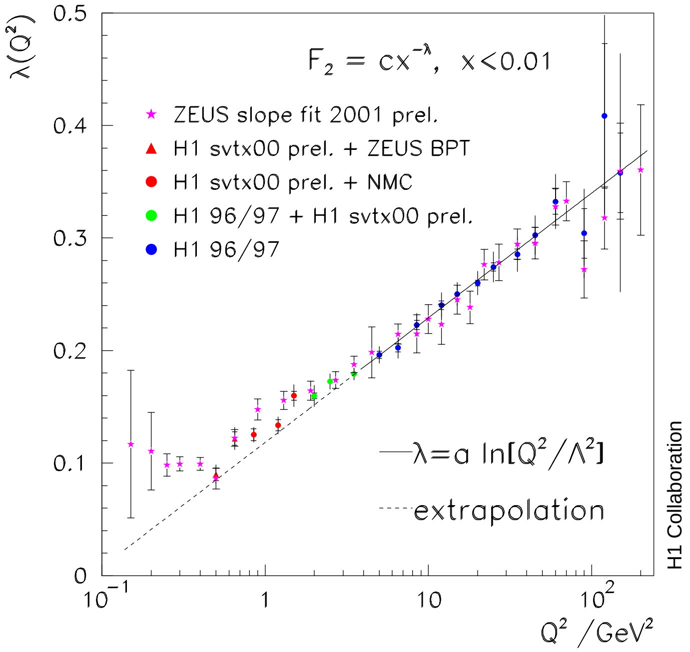

Figure 2. Measurements of the slope parameter λ where F_2 is parametrized as $F_2 = c(Q^2)x^{-\lambda}$.

4. Neutral and charged current cross-sections at high Q^2

The NC and CC single differential cross-sections $\mathrm{d}\sigma/\mathrm{d}Q^2$ at high Q^2 are shown in figure 5 for both e^+p and e^-p scattering [5–7]. The NC data are seen to fall with the typical $1/Q^4$ behaviour as expected for a photon propagator. The CC cross-section is suppressed at low Q^2 due to the large W boson mass. At $Q^2 > M_W^2$ the cross-sections become comparable as expected from the unification of the electroweak force. The measurements are compared to a NLO QCD fit which provides a good description of the data.

The combination of four cross-sections, NC and CC in both e^+p and e^-p scattering, allows the flavour separation of the proton to be achieved with minimal assumptions using HERA data alone for the first time. NLO QCD fits have been made by both collaborations to this data taking into account experimental and theoretical uncertainties [5,8]. The results of one of these fits are shown in figure 6 for the quark densities xU, $x\bar{U}$, xD, $x\bar{D}$, and xg where $U(D)$ is the sum of all up-type (down-type) quarks, and $\bar{U}(\bar{D})$ is the sum of all anti-up-type (anti-down-type) quarks. The error band shows the full uncertainty on each distribution.

The cross-section measurements have been improved through a reduction of the systematic uncertainties which dominate the NC measurement up to $Q^2 \simeq 1000$ GeV^2. The double differential NC cross-section now has a total systematic uncertainty of typically about 3% compared to 6% previously. This reduction in the systematic uncertainty has allowed the u density to be determined to a precision of typically 3%, and the d density with a precision of 10% at $x = 0.4$.

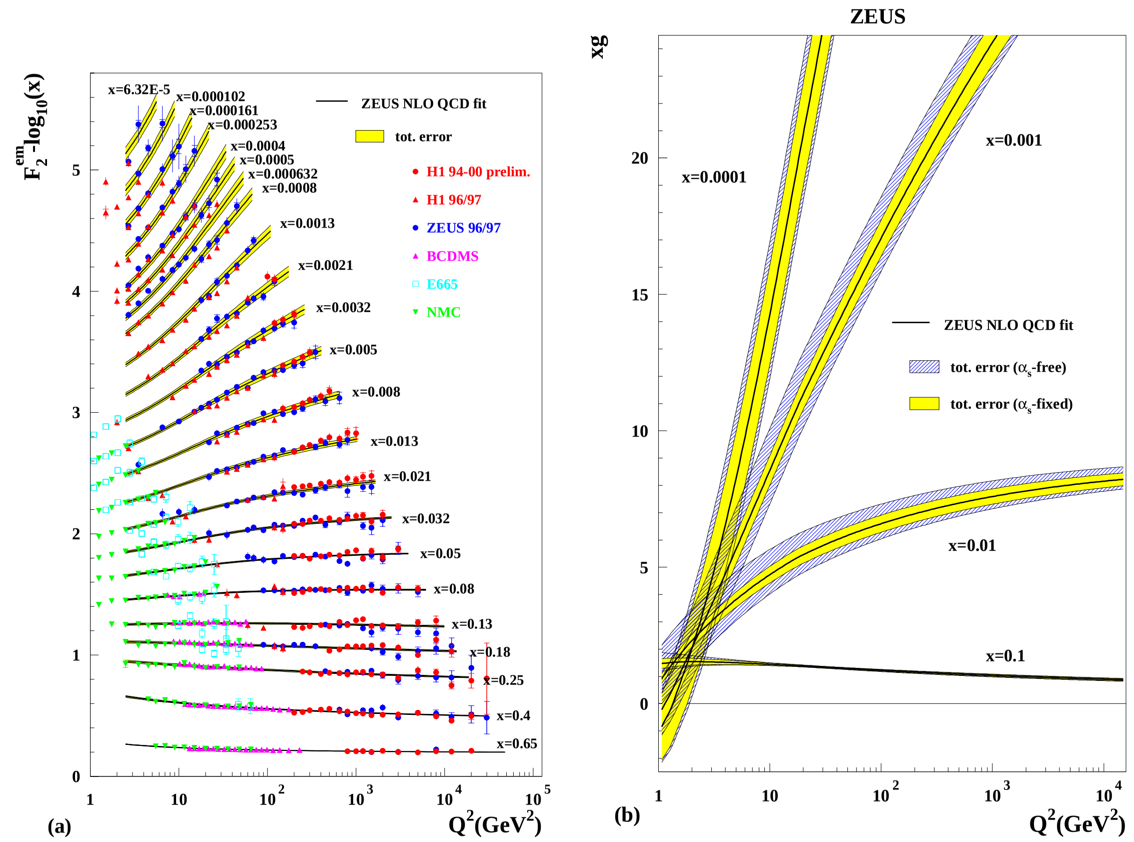

Figure 3. (**a**) Measurements of the structure function F_2 from the HERA Collaborations and fixed target experiments.The data are plotted as a function of Q^2 for various fixed values of x. Also included are the results of a NLO QCD fit to the data. (**b**) The gluon density derived from the NLO QCD fit, plotted as a function of Q^2 for various x.

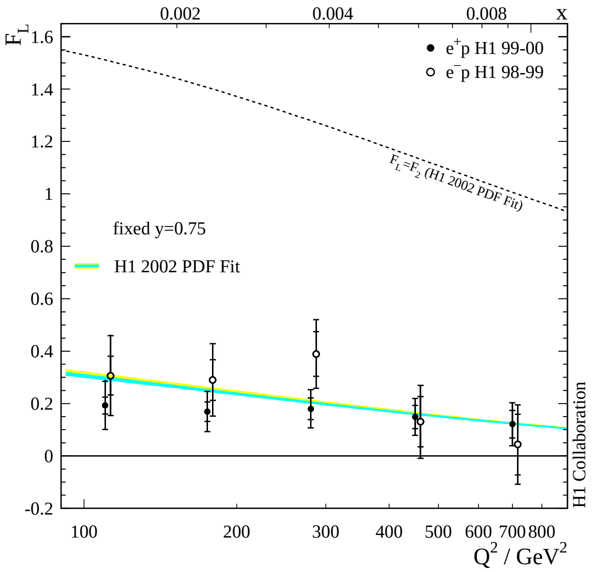

Figure 4. Determination of the structure function F_L. The data are plotted as a function of Q^2 and x for fixed values of y. Measurements from the e^+p data and the e^-p data are shown. The data are compared to the results of the NLO QCD fit. The two extreme possibilities $F_L = 0$ and $F_L = F_2$ are also shown.

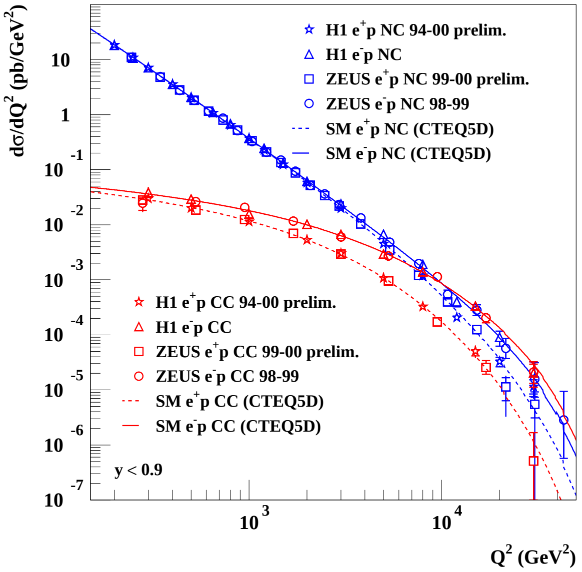

Figure 5. The Q^2 dependences of the NC (○) and CC (□) cross-sections $d\sigma/dQ^2$ are shown for the combined 94-00 e^+p and 98-99 e^-p measurements. The data are compared to the standard model expectations determined from a NLO QCD fit.

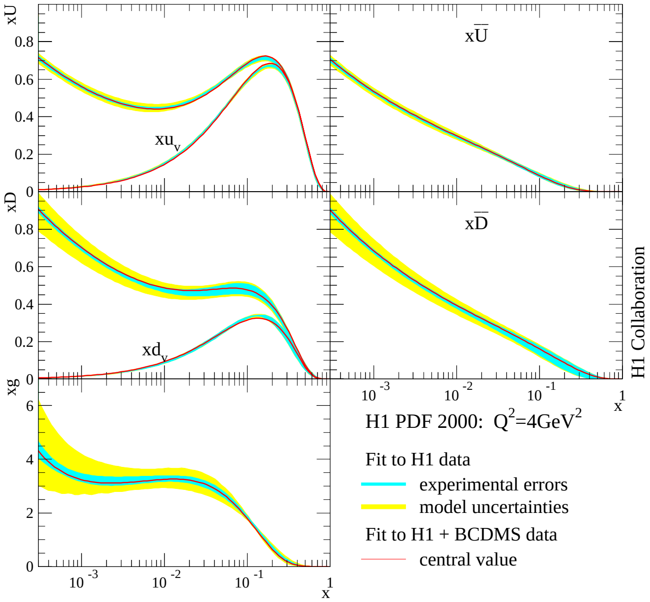

Figure 6. The parton distributions xU, $x\bar{U}$, xD, $x\bar{D}$, and xg as determined from the H1 PDF 2000 fit to H1 and data only. The distributions are shown at $Q^2 = 4$ GeV^2 with experimental and model uncertainties. The valence quark densities xu_v and xd_v are also shown. For comparison, the central values from the fit to H1 and BCDMS data are also shown as the full curves.

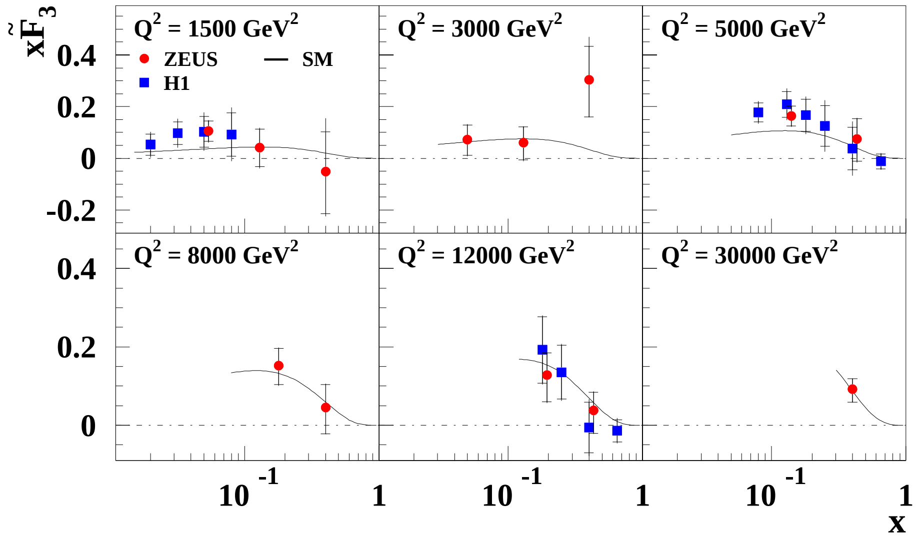

Figure 7. Measurements of the structure function xF_3. The data are plotted as a function of x for various fixed values of Q^2. Also included are the results of a NLO QCD fit to the data.

5. Measurement of the structure function xF_3

From eq. (1) it can be seen that the structure function xF_3 may be measured by subtracting the e^+p NC data from the e^-p data. Although xF_3 only becomes a non-negligible part of the cross-section at large Q^2 when $Q^2 \simeq M_Z^2$ there are now enough statistics for a first measurement from HERA. This is shown in figure 7. The structure function xF_3 is particularly important because it is only sensitive to the valence quarks. The measurements from HERA show good agreement to the NLO QCD fit. The excess seen at low x is not significant due to the relatively large errors on the data at the moment.

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