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Electroweak Neutral Currents at HERA

H1 and ZEUS Collaborations

Abstract

Measurements by the H1 and ZEUS Collaborations of the neutral current cross sections of deep inelastic polarised electron and positron-proton scattering are combined in order to investigate the interference of weak and electromagnetic interactions at high four-momentum transfer squared, Q^2. The data provide the most accurate measurements of the interference structure function $xF_3^{\gamma Z}$, which is sensitive to the valence quark distributions down to lower values of Bjorken x. The data on polarised cross section asymmetries, $A^{\pm}$, lead to the first observation of parity violation in neutral current $e^{\pm}p$ scattering at distances down to 10^{-18} m.

1 Introduction

Deep inelastic neutral current scattering $ep \to eX$ at very high squared momentum transfers Q^2 is sensitive to electroweak effects mainly due to the interference of photon and Z boson exchange which dominates over pure Z exchange effects in most of the kinematic range covered at HERA. The H1 and ZEUS experiments have recently accumulated large amounts of data in e^-p and e^+p inclusive deep inelastic scattering (DIS). A salient feature of the ongoing phase II of HERA's operation has been the longitudinal left and right handed polarisation of the $e^\pm$ beams at the level of 30 to 40% in collider mode. Thus the two collider experiments have now measured neutral current DIS cross sections in both charge and both helicity states which are combined here in a dedicated investigation of electroweak effects at HERA.

Access to electroweak effects is enabled by measuring charge and polarisation cross section differences by which the pure photon exchange part is removed. The charge asymmetry accesses the valence quark distributions at high Q^2 and lower x and is sensitive to the axial-vector weak quark couplings to the Z boson and to the sign of the electric quark charges. The polarisation asymmetry measures a product of vector and axial-vector couplings and at HERA is sensitive to parity violation at spatial dimensions down to 10^{-18} m. The first measurement of a charge asymmetry in deep inelastic scattering used a muon beam at CERN and extracted the interference structure function $xF_3^{\gamma Z}$ [1]. The first measurement of a neutral current polarisation asymmetry [2] , performed at $Q^2 \sim 1\,\mathrm{GeV}^2$, was crucial in establishing the standard GWS theory.

The ZEUS and H1 data used here cover a Q^2 range from 200 to 30000 GeV^2. The data have been published or presented in preliminary form at the ICHEP Conference at Moscow, both by the ZEUS [3] and the H1 Collaborations [4]. A summary of the luminosities and polarisation values of the data sets is presented in Tables 1,2. Since electroweak effects are increasing with Q^2, where the statistics become limited, it has been considered appropriate to make maximum use of the high Q^2 data available at HERA by performing a first combination of H1 and ZEUS measurements. The total amount of luminosity used in this analysis is 478.8 pb^{-1}.

2 Cross Section and Structure Functions

At high Q^2 the polarised neutral current deep inelastic scattering cross section in Born approximation can be written [5] in reduced form as

$$\tilde{\sigma}^\pm = \frac{d^2\sigma^\pm}{dxdQ^2}\frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2^\pm \mp \frac{Y_-}{Y_+} x\tilde{F}_3^\pm - \frac{y^2}{Y_+}\tilde{F}_L^\pm \tag{1}$$

with $Y_\pm = 1 \pm (1-y)^2$. The functions occuring in eq.(1) are generalised structure functions which receive contributions from pure photon exchange, the interference of photon and Z boson exchange and from pure Z exchange and thus depend on the lepton beam charge and polarisation (P) and on the electroweak parameters M_Z and $\sin^2\theta$ (or M_W)

$$\begin{aligned} \tilde{F}_2^\pm &= F_2 + k(-v_e \mp P a_e) F_2^{\gamma Z} + k^2(v_e^2 + a_e^2 \pm 2P v_e a_e) F_2^Z \\ x\tilde{F}_3^\pm &= k(-a_e \mp P v_e) xF_3^{\gamma Z} + k^2(2 v_e a_e \pm P(v_e^2 + a_e^2)) xF_3^Z \end{aligned} \tag{2}$$

and similarly for the longitudinal structure function $\tilde{F}_L$. Here $k(Q^2)$ determines the relative amount of Z to γ exchange, $k = \frac{1}{4\sin^2\theta\cos^2\theta}\frac{Q^2}{Q^2+M_Z^2}$, while $v_e = -1/2 + 2\sin^2\theta$ and $a_e = -1/2$ are the vector and axial-vector couplings of the electron to the Z boson and θ is the electroweak mixing angle.

At leading order in QCD the structure functions can be written in terms of quark and anti-quark density functions as

$$\begin{aligned}(F_2, F_2^{\gamma Z}, F_2^Z) &= x\sum(e_q^2, 2e_q v_q, v_q^2 + a_q^2)(q + \bar{q}) \\ (xF_3^{\gamma Z}, xF_3^Z) &= 2x\sum(e_q a_q, v_q a_q)(q - \bar{q})\end{aligned} \tag{3}$$

Here v_q and a_q are the vector and axial-vector couplings of the quark q to the Z boson.

3 Charge Asymmetry and xF_3

A variation of the lepton beam charge allows the structure function $x\tilde{F}_3$ to be measured. In order to remove charge dependent terms in the $\tilde{F}_2$ part of the cross section, all positron data and all electron data were added separately, using the unpolarised data from the first running period, HERA I, and the net unpolarised data from HERA II. In the latter period similar amounts of data with approximately equal polarisations have been collected. Thus with a very small correction for residual polarisation effects, one can consider the e^-p and e^+p data to be unpolarised, i.e. set $P = 0$ in eq. 2. The cross section difference between positron and electron data then determines the following combination of xF_3 structure functions as

$$\tilde{\sigma}^- - \tilde{\sigma}^+ = 2\frac{Y_-}{Y_+}(-a_e \cdot kxF_3^{\gamma Z} + 2v_e a_e \cdot k^2 xF_3^Z) \tag{4}$$

which are due to the γZ interference and due to pure Z exchange. Since the electron vector coupling, v_e, is small and $k < 1$, to a very good approximation the cross section difference is equal to $-2kY_- a_e xF_3^{\gamma Z}/Y_+$ which is a parity conserving quantity $\propto a_e a_q$. In leading order pQCD this "interference structure function" can be written as

$$xF_3^{\gamma Z} = 2x[e_u a_u(U - \overline{U}) + e_d a_d(D - \overline{D})], \tag{5}$$

with $U = u + c$ and $D = d + s$ for four flavours. The $xF_3^{\gamma Z}$ structure function thus provides information about the light quark axial vector couplings (a_u, a_d) and the sign of the electric quark charges (e_u, e_d). Equivalently one can write

$$xF_3^{\gamma Z} = 2x[e_u a_u(u_v + \Delta_u) + e_d a_d(d_v + \Delta_d)], \tag{6}$$

where in the naive parton model as in conventional perturbative QCD it is assumed that the differences $\Delta_u = (u_{sea} - \overline{u} + c - \overline{c})$ and $\Delta_d = (d_{sea} - \overline{d} + s - \overline{s})$ are zero. However, in non-perturbative QCD there may occur differences, for example between the strange and anti-strange quark distributions, for which there are some hints in DIS neutrino nucleon di-muon data [6]. Inserting the standard charge and axial coupling values one finds

$$xF_3^{\gamma Z} = \frac{x}{3}(2u_v + d_v + \Delta) \tag{7}$$

with $\Delta = 2\Delta_u + \Delta_d$. Neglect of Δ leads to a sum rule [7] which in leading order is

$$\int_0^1 xF_3^{\gamma Z}\frac{dx}{x} = \frac{1}{3}\int_0^1 (2u_v + d_v)dx = \frac{5}{3}. \tag{8}$$

The $xF_3^{\gamma Z}$ structure function thus is determined by the valence quark distributions and predicted to be only very weakly depending on Q^2.

H1 and ZEUS have measured this function at different Q^2 as a function of x [3, 4]. In order to study its x dependence more accurately, the H1 and ZEUS data have been adjusted to one fixed Q^2 value of $1500\,\mathrm{GeV}^2$ and a weighted average is determined using the full uncertainty of either measurement. The result is shown in Fig. 1. The two measurements agree within the quoted uncertainties. Taking into account the full uncertainties of the H1 and ZEUS measurements, an average result for the interference structure function $xF_3^{\gamma Z}$ is obtained as shown in Fig. 1. The measurement is well described by the ZEUS [8] and H1 NLO QCD fits [9] to previously published unpolarised HERA I data, dominated by e^+p, in which it is assumed that sea and antiquarks have the same distributions, $\Delta_u = \Delta_d = 0$, and the quark counting rule is applied. The predictions for $xF_3^{\gamma Z}$ are thus approaching zero at large x which is consistent with the measurement. The difference between the H1 and ZEUS fit results hints at the presence of only weak constraints on the behaviour of the valence quark densities at lower x.

In the range of acceptance the integral of $F_3^{\gamma Z}$ is measured to be

$$\int_{0.02}^{0.65} F_3^{\gamma Z} dx = 1.21 \pm 0.09(stat) \pm 0.08(syst) \tag{9}$$

which is consistent with the results of the H1 and ZEUS QCD fits, 1.12 ± 0.02 and 1.06 ± 0.02, respectively, for the same x interval at $Q^2 = 1500\,\mathrm{GeV}^2$. Using the H1 fit prediction to subtract the valence quark contribution to the sum rule, a constraint is obtained on the integrated difference term

$$\int_{0.02}^{0.65} \Delta dx = 0.09 \pm 0.09(stat) \pm 0.08(syst) \tag{10}$$

in the quoted kinematic range which is consistent with zero.

4 Polarisation Asymmetry

With HERA II longitudinal polarisation effects become accessible to the ep collider experiments. A direct measure for the electroweak effects are the charge dependent polarisation asymmetries of the neutral current cross sections. The cross section asymmetries defined as

$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)} \tag{11}$$

to a very good approximation measure the structure function ratio

$$A^{\pm} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2} \tag{12}$$

which is proportional to combinations $a_e v_q$ and thus a direct measure of parity violation. One also finds that A^+ is expected to be positive and about equal to $-A^-$ in the Standard Model. At large x the asymmetries measure the d/u ratio of the valence quark distributions according to

$$A^{\pm} \simeq \pm k \frac{1 + d_v/u_v}{4 + d_v/u_v}. \tag{13}$$

The data from ZEUS and H1 are shown in Fig. 2 where it is assumed that the correlated uncertainties of each experiment cancel. A combination of the H1 and ZEUS data is performed by first correcting the ZEUS data to $y < 0.9$ and then taking a weighted average in the common Q^2 intervals using the total uncorrelated errors. For a few Q^2 values no counterpart exists and then either the H1 or the ZEUS asymmetry value enters the combined asymmetry alone. The combined H1 and ZEUS data are shown in Fig. 2. The asymmetries are well described by the Standard Model predictions as obtained from the H1 and ZEUS QCD fits. By definition these are rather insensitive to the details of the parton distributions as in the ratio $F_2^{\gamma Z}/F_2$ the x dependences cancel to a large extent. The asymmetries $A^{\pm}$ are thus a direct measure of electroweak interaction effects.

The asymmetries $A^{\pm}$ are observed to be of opposite sign to a very good approximation. The difference $\delta A = A^+ - A^-$ can be seen to be significantly larger than zero. This is quantified by calculating the χ^2 for δA with respect to zero, based on the total uncorrelated uncertainty, and the corresponding probability of δA to be zero as a function of the minimum Q^2 considered. The behaviour of this function is as expected. At very large Q^2 the interference effects are large but hidden by the limited statistics. At low Q^2 they are small and not readily seen given the present uncertainties of the measurement. An optimum Q^2_{min} of about 5000 GeV^2 exhibits a χ^2/dof of 4.0 corresponding to a probability of $3.1 \cdot 10^{-3}$ for δA to be zero.

5 Conclusions

Inclusive cross section measurements performed by the HERA collider experiments H1 and ZEUS for different lepton beam charge and beam polarisation states are used in a dedicated investigation of electroweak interference effects in neutral current DIS. First results are presented based on nearly all data taken so far at HERA in unpolarised and in polarised $e^{\pm}p \rightarrow e^{\pm}X$ scattering. Beam charge and polarisation effects due to the interference of photon with Z boson exchange are observed and used to measure the interference structure function $xF_3^{\gamma Z}$ and the parity violation asymmetries $A^{\pm}$. The results are well described by the Standard Model. The $xF_3^{\gamma Z}$ data add to the knowledge of the valence quark distributions at lower Bjorken x. The polarisation asymmetry data demonstrate parity to be violated at very small distances, down to about 10^{-18} m.

References

[1] BCDMS Collaboration, A. Argento et al., Phys. Lett. B **140** (1984) 142.

[2] C.Y. Prescott *et al.*, Phys. Lett. B **77** (1978) 347 and Phys. Lett. B **84** (1979) 524.

[3] ZEUS Collaboration, "Measurement of high-Q^2 neutral current deep inelastic scattering cross sections with a longitudinally polarised electron beam at HERA", Paper contributed to the XXXIII International Conference on High Energy Physics, Moscow, Russia, July 2006 [ZEUS-prel-06-001].

[4] H1 Collaboration, "Neutral Current Interactions in $e^{\pm}p$ Scattering with Longitudinally Polarised Leptons", Paper contributed to the XXXIII International Conference on High Energy Physics, Moscow, Russia, July 2006 [H1prelim-06-042].

[5] M. Klein and T. Riemann, Z. f. Phys **24** (1984) 151.

[6] NuTeV Collaboration, D. Mason, "NuTeV strange / antistrange sea measurements from neutrino charm production", AIP Conf. Proc. **792** (2005) 851.

[7] E. Rizvi and T. Sloan, Eur. Phys. J. C **3**direct (2001) N2 [hep-ex/0101007].

[8] ZEUS Collaboration, S. Chekanov et al., Eur. Phys J. C **42** (2005) 1 [hep-ph/0503274].

[9] H1 Collaboration, C. Adloff et al., Eur. Phys J. C **30** (2003) 1 [hep-ex/0304003].

H1	R	L
e^+p	$\mathcal{L} = 26.9$ pb^{-1} $P = (+33.6 \pm 0.6)\%$	$\mathcal{L} = 20.7$ pb^{-1} $P = (-40.2 \pm 1.1)\%$
e^-p	$\mathcal{L} = 29.6$ pb^{-1} $P = (+37.0 \pm 1.8)\%$	$\mathcal{L} = 68.6$ pb^{-1} $P = (-27.0 \pm 1.3)\%$

Table 1: Table of luminosities, $\mathcal{L}$, and luminosity weighted longitudinal polarisations, $P = P_{L,R}$, for the H1 data sets collected in HERA II as used here. The extraction of xF_3 uses in addition the HERA I data in which the lepton beam was unpolarised, i.e. a set of 108.1 pb^{-1} for e^+p scattering and of 16.4 pb^{-1} for e^-p scattering. The total amount of integrated luminosity in the H1 analysis thus adds up to 270.3 pb^{-1}.

ZEUS	R	L
e^+p	$\mathcal{L} = 12.3$ pb^{-1} $P = (+32.0 \pm 1.1)\%$	$\mathcal{L} = 11.5$ pb^{-1} $P = (-41.0 \pm 0.9)\%$
e^-p	$\mathcal{L} = 42.7$ pb^{-1} $P = (+32.9 \pm 1.6)\%$	$\mathcal{L} = 78.8$ pb^{-1} $P = (-26.8 \pm 1.3)\%$

Table 2: Table of luminosities, $\mathcal{L}$, and luminosity weighted longitudinal polarisations, $P = P_{L,R}$, for the ZEUS data sets collected in HERA II used here. The extraction of xF_3 uses in addition HERA I data in which the lepton beam was unpolarised, i.e. a set of 63.2 pb^{-1} for e^+p scattering. The total amount of integrated luminosity in the ZEUS analysis thus adds up to 208.5 pb^{-1}.

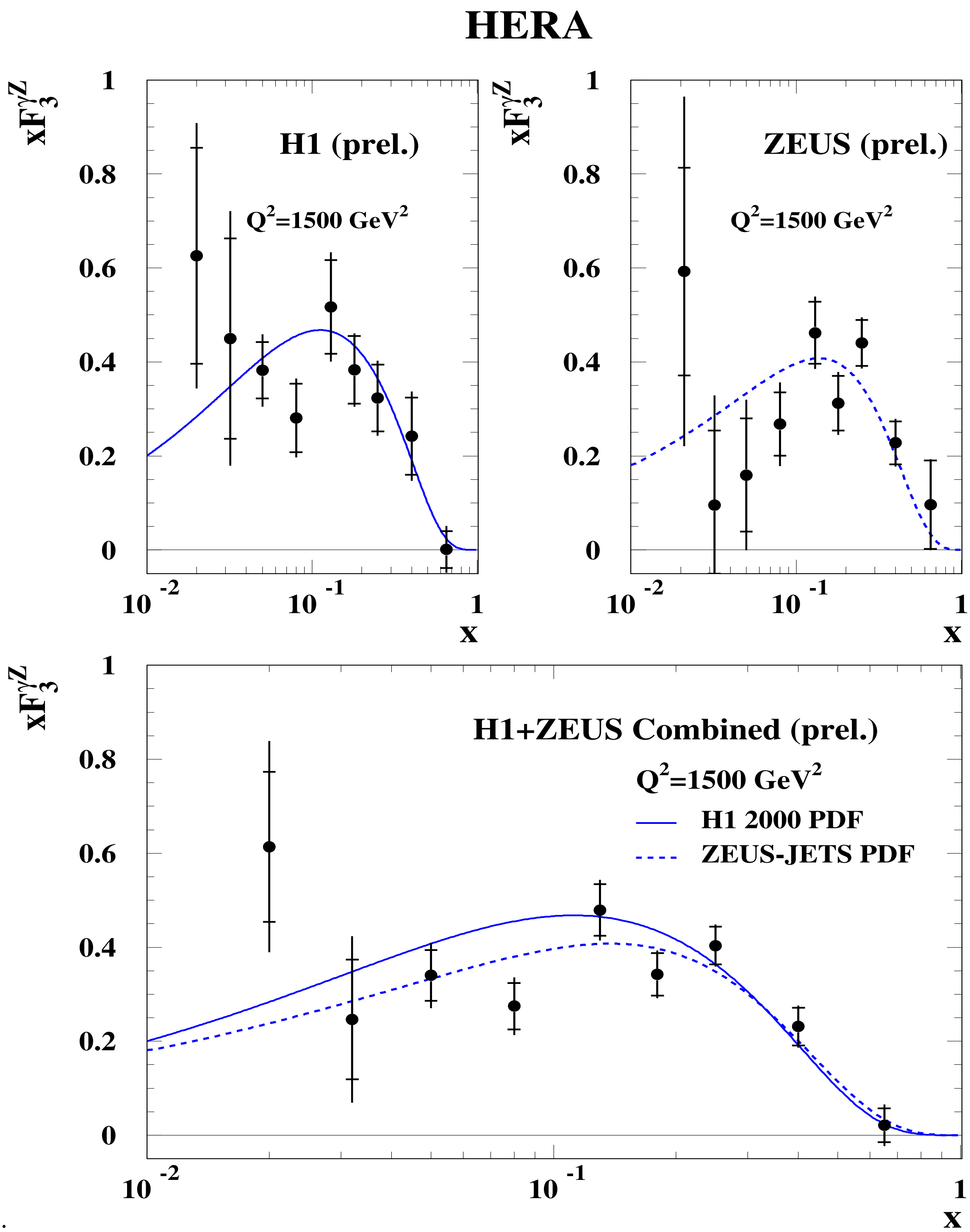

Figure 1: Measurements of the structure function $xF_3^{\gamma Z}$ by the H1 Collaboration (top left), the ZEUS Collaboration (top right) and combined (bottom). The inner error bars denote the statistical uncertainty while the full error bars comprise the statistical and systematic uncertainty added in quadrature. The curves describe the Standard Model predictions as obtained in NLO QCD fits to the H1 inclusive data and to the inclusive and jet ZEUS data, respectively. Both fits have been performed using the unpolarised HERA I data only and they differ in some detail concerning the parameterisations and treatment of the valence quark behaviour.

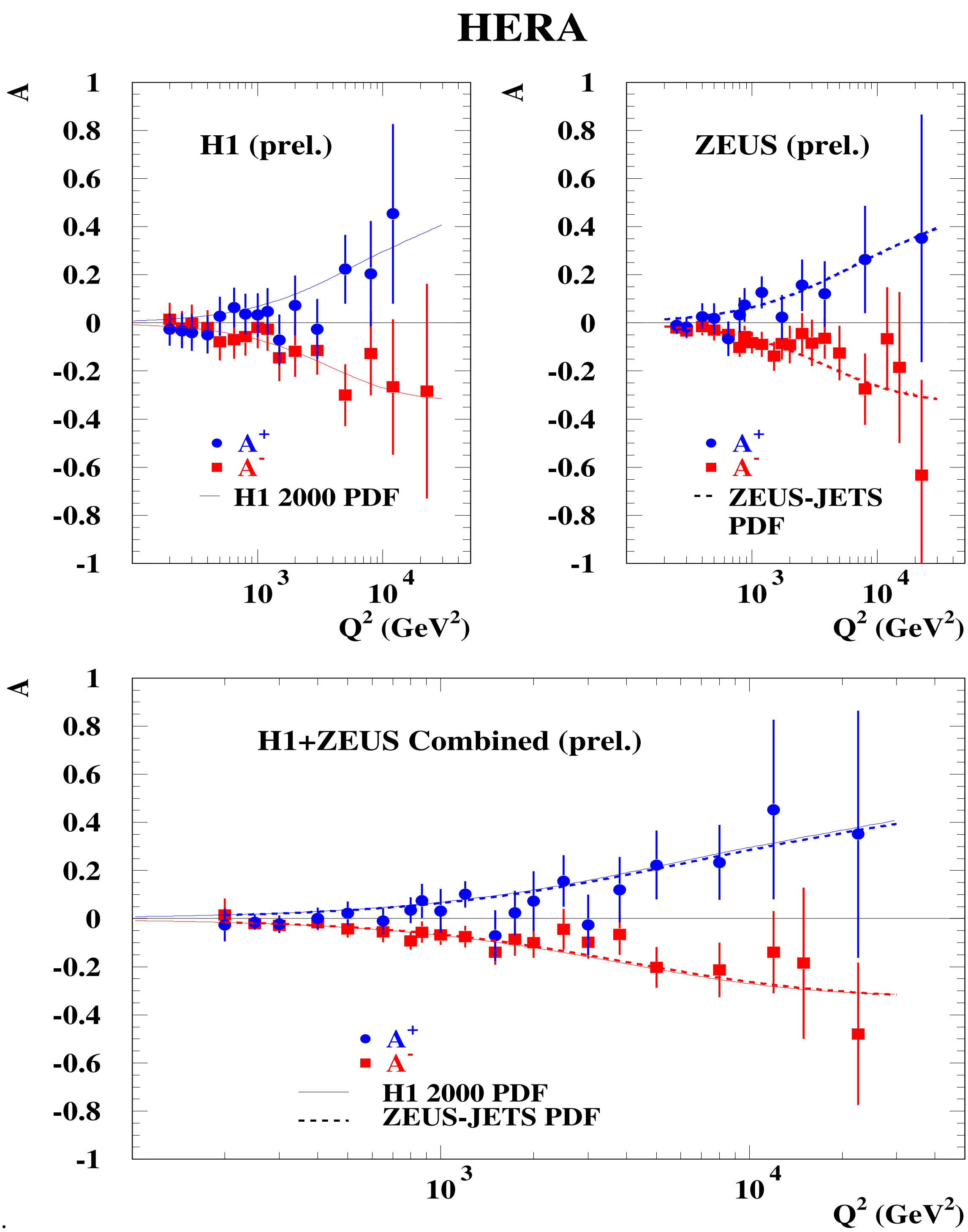

Figure 2: Measurements of the polarisation asymmetries $A^{\pm}$ by the H1 Collaboration (top left), the ZEUS Collaboration (top right) and combined (bottom). The error bars denote the total uncertainty which is dominated by the uncorrelated error contributions. The curves describe the theoretical predictions in NLO QCD as obtained in fits to the H1 inclusive data and to the inclusive and jet ZEUS data, respectively. Both fits have been performed using the unpolarised HERA I data.