NEUTRAL CURRENT DIS WITH POLARISED $e^{\pm}$ AT HERA

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The HERA experiments, H1 and ZEUS, have measured inclusive neutral current cross sections in $e^{\pm}p$ deep inelastic interactions with longitudinally polarised lepton beams. These data are used for investigation of the interference of weak and electromagnetic interactions at high four-momentum transfer squared, Q^2. Measurements of the interference structure function $xF_3^{\gamma Z}$, which is sensitive to the valence quark distributions, and of the polarised cross section asymmetries are presented. For the first time at HERA, the measurements of H1 and ZEUS are combined in order to improve the statistical precision at high Q^2. The combined data provide the most accurate measurement of $xF_3^{\gamma Z}$ at HERA and lead to the first observation of parity violation in neutral current $e^{\pm}p$ scattering at distances down to 10^{-18} m. The measurements are compared to predictions of the Standard Model which is able to provide a good description of the data.

Keywords: DIS; neutral current; polarisation; electroweak.

1. Introduction

In 2003 the HERA accelerator started operation of the second phase of its ep collider programme (HERA II). A new feature of this data taking period is the longitudinal polarisation of the lepton beam. The data collected by the H1 and ZEUS experiments since then were taken with positively and negatively polarised positron and electron beams. The amount of data collected at HERA II is already greater than that of HERA I (1992-2000). In particular, a significant increase of integrated luminosity is achieved in the e^-p mode, from ≈ 15 pb^{-1} at HERA I to more than 100 pb^{-1} in 2005. Both HERA experiments have reported neutral current (NC) deep inelastic scattering (DIS) cross sections measurements at high four-momentum transfer squared, Q^2, using HERA II data [1,2]. Profiting from the enlarged statistics and reduced systematic uncertainties, the previous measurements of xF_3, suffering from low statistics of the e^-p data taken in 1998-1999, are updated. In addition, the prediction of the Standard Model related to the difference in the cross section for leptons with different helicity states arising from the chiral structure of the neutral electroweak exchange is investigated. Furthermore, for the first time at HERA, the measurements of H1 and ZEUS are combined [3] in order to improve the statistical precision of the measurements at high Q^2.

2. NC cross sections with longitudinally polarised $e^{\pm}$ beams

The neutral current deep inelastic scattering cross section after correction for QED radiative effects can be written as

$$\frac{\mathrm{d}^2\sigma^{\pm}_{\mathrm{NC}}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L) \ , \quad (1)$$

and the reduced cross section is defined by

$$\tilde{\sigma}^{\pm}(x,Q^2) \equiv \frac{\mathrm{d}^2\sigma^{\pm}_{\mathrm{NC}}}{\mathrm{d}x\mathrm{d}Q^2}\frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+} \equiv \tilde{F}_2 \mp \frac{Y_-}{Y_+}x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L \ . \quad (2)$$

Here, x is the Bjorken scaling variable and y characterises the inelasticity of the interaction. The helicity dependences are contained in $Y_{\pm} = 1 \pm (1-y^2)$.

The generalised proton structure functions, $\tilde{F}_{2,3}$, occurring in eq.(1) may be written as linear combinations of the hadronic structure functions F_2, $F_{2,3}^{\gamma Z}$, and $F_{2,3}^{Z}$, containing information on the QCD parton dynamics as well as the electroweak couplings of the quarks to the neutral vector bosons. The function F_2 is associated to pure photon exchange terms, $F_{2,3}^{\gamma Z}$ correspond to photon-Z^0 interference and $F_{2,3}^{Z}$ correspond to pure Z^0 exchange terms. In addition, the longitudinal structure function $\tilde{F}_L$ may be similarly decomposed, however this is important only at high y and is expected to be negligible at large x and Q^2.

The generalised proton structure functions depend on the lepton beam charge, on the lepton beam polarisation, defined as $P = (N_R - N_L)/(N_R + N_L)$, where N_R (N_L) is the number of right (left) handed leptons in the beam, and on the electroweak parameters M_Z and $\sin^2\theta$ (or M_W):

$$\begin{aligned} \tilde{F}_2^{\pm} &= F_2 + k(-v_e \mp P a_e) F_2^{\gamma Z} + \\ &\quad k^2(v_e^2 + a_e^2 \pm 2 P v_e a_e) F_2^{Z}, \\ x\tilde{F}_3^{\pm} &= k(-a_e \mp P v_e) x F_3^{\gamma Z} + \\ &\quad k^2(2 v_e a_e \pm P(v_e^2 + a_e^2)) x F_3^{Z}. \quad (3) \end{aligned}$$

Here, $k(Q^2)$ determines the relative amount of Z to γ exchange, $k = \frac{1}{4\sin^2\theta\cos^2\theta}\frac{Q^2}{Q^2+M_Z^2}$, $v_e = -1/2 + 2\sin^2\theta$ 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 hadronic structure functions are related to linear combinations of sums and differences of the quark and anti-quark momentum distributions $xq(x,Q^2)$ and $x\bar{q}(x,Q^2)$ of the proton:

$$\begin{aligned} (F_2\ ,\ F_2^{\gamma Z}\ ,\ F_2^{Z}) &= \\ &\quad x\sum (e_q^2, 2e_q v_q, v_q^2 + a_q^2)(q + \bar{q}), \\ (xF_3^{\gamma Z}\ ,\ xF_3^{Z}) &= \\ &\quad 2x\sum (e_q a_q, v_q a_q)(q - \bar{q}), \qquad (4) \end{aligned}$$

where v_q and a_q are the vector and axial-vector couplings of the light quarks to the Z boson and e_q is the charge of the quark of flavour q.

3. Charge Asymmetry and xF_3

A variation of the lepton beam charge allows the structure function $x\tilde{F}_3$ to be measured. For this purpose H1 and ZEUS used the net unpolarised data from HERA II together with the unpolarised data from HERA I. The HERA II NC polarised data have been combined into an effective unpolarised $e^{\pm}p$ data sets after correcting for small residual polarisations.

The structure function $x\tilde{F}_3$ can be obtained from the cross section difference between electron and positron unpolarised data

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}\left[\tilde{\sigma}^-(x,Q^2) - \tilde{\sigma}^+(x,Q^2)\right]\ . \quad (5)$$

The dominant contribution to xF_3 arises from the γZ interference, which allows $xF_3^{\gamma Z}$ to be extracted according to $xF_3^{\gamma Z} \simeq -x\tilde{F}_3/ka_e$ by neglecting the pure Z exchange contribution, which is suppressed by the small vector coupling v_e. This structure function is non-singlet and has little dependence on Q^2. The measured $xF_3^{\gamma Z}$ at different Q^2 values can thus be averaged taking into account the small Q^2 dependence. The averaged $xF_3^{\gamma Z}$, determined by H1 and ZEUS for a Q^2 value of $1\,500\,\mathrm{GeV}^2$, are shown in Fig. 1 (top) and the combined H1 and ZEUS data are shown in Fig. 1 (bottom). The measurements are well described by the H1 and ZEUS NLO QCD fits[4,5] to previously published unpolarised HERA I data.

In leading order QCD the interference structure function $xF_3^{\gamma Z}$ can be written as

$$xF_3^{\gamma Z} = 2x[e_u a_u(U - \overline{U}) + e_d a_d(D - \overline{D})], \quad (6)$$

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). The conventional assumption that the differences $\Delta_u = (u_{sea} - \overline{u} + c - \overline{c})$ and $\Delta_d = (d_{sea} - \overline{d} + s - \overline{s})$ are zero leads to a sum rule [6] which in leading order QCD is

$$\int_0^1 x F_3^{\gamma Z} \frac{dx}{x} = \frac{1}{3} \int_0^1 (2u_v + d_v) dx = \frac{5}{3}. \quad (7)$$

Higher order corrections to this are expected to be of order α_s/π. In the range of acceptance, the integral of $F_3^{\gamma Z}$ is measured to be

$$\int_{0.02}^{0.65} F_3^{\gamma Z} dx = 1.21 \pm 0.09(stat) \pm 0.08(syst), \quad (8)$$

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 $Q^2 = 1500\,\mathrm{GeV}^2$.

In non-perturbative QCD differences may occur for example between the strange and anti-strange quark distributions, for which there are some hints in DIS neutrino nucleon di-muon data [7]. Inserting the standard charge and axial coupling values one can use the $xF_3^{\gamma Z}$ data to constrain the difference $\Delta = 2\Delta_u + \Delta_d$. Using the H1 fit prediction to subtract the valence quark contribution to the sum rule, a constraint is obtained on the integrated difference term

$$\int_{0.02}^{0.65} \Delta dx = 0.09 \pm 0.09(stat) \pm 0.08(syst) \quad (9)$$

which is consistent with zero.

4. Polarisation Asymmetry

The charge dependent longitudinal polarisation asymmetries of the neutral current cross sections, defined as

$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}, \quad (10)$$

measure to a very good approximation the structure function ratio

$$A^{\pm} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2}. \quad (11)$$

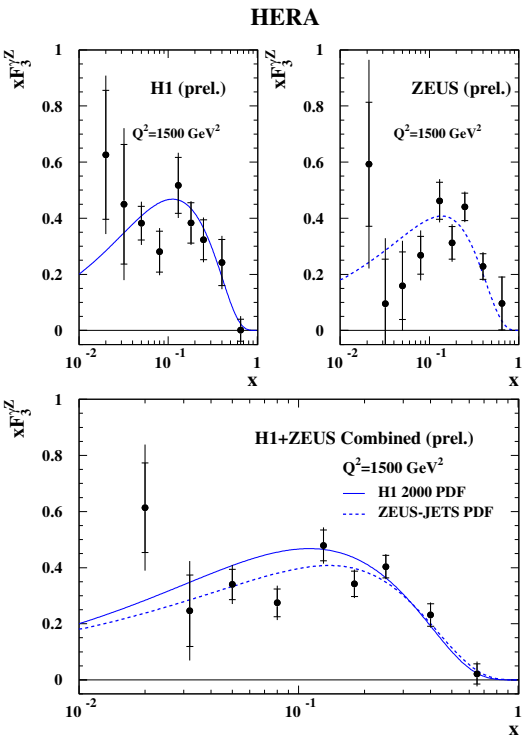

Fig. 1. Measurements of the structure function $xF_3^{\gamma Z}$ by the H1 Collaboration (top left), the ZEUS Collaboration (top right) and combined (bottom). The curves describe the Standard Model predictions as obtained in NLO QCD fits to the H1 inclusive data and to the inclusive and jet ZEUS data, respectively.

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

$$A^{\pm} \simeq \pm k \frac{1 + d_v/u_v}{4 + d_v/u_v}. \quad (12)$$

The data from ZEUS and H1 are shown in Fig. 1 (top) 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

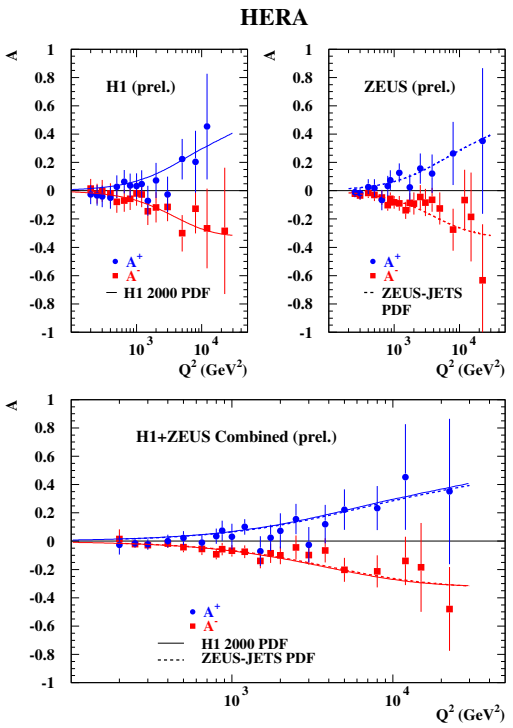

Fig. 2. Measurements of the polarisation asymmetries $A^{\pm}$ by the H1 Collaboration (top left), the ZEUS Collaboration (top right) and combined (bottom). The curves describe the Standard Model predictions as obtained in NLO QCD fits to the H1 inclusive data and to the inclusive and jet ZEUS data, respectively. Both fits have been performed using the unpolarised HERA I data.

then either the H1 or the ZEUS asymmetry value enters the combined asymmetry alone. The combined H1 and ZEUS data are shown in Fig. 1 (bottom). The asymmetries are well described by the Standard Model predictions as obtained from the H1 and ZEUS QCD fits [4,5].

The measured asymmetries $A^{\pm}$ are observed to be of opposite sign and 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. For optimal range of $Q^2 > 5000\,\mathrm{GeV}^2$, χ^2/dof is equal to 4.0, which corresponds to a probability of $3.1 \cdot 10^{-3}$ for δA to be zero.

5. Conclusions

The beam charge and polarisation effects due to the interference of photon with Z boson exchange are observed at HERA, and are 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 low Bjorken x. The polarisation asymmetry data demonstrate the parity violation at very small distances, down to about 10^{-18} m.

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