Charged and neutral current cross sections from HERA

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Abstract. The cross sections for inclusive neutral and charged current deep inelastic $e^\pm p$ scattering at high $Q^2$ with polarised lepton beams at HERA-II are presented. The electroweak effects in spacelike scattering are highlighted and compared to the Standard Model prediction.

1. Introduction
The operation of the HERA $ep$ collider came to an end in June 2007. A good understanding of QCD and the precise measurements of the proton parton density functions (PDFs) were made possible by intensive studies of two deep inelastic $e^\pm p$ scattering (DIS) processes: neutral current (NC) interactions, $e^\pm p \rightarrow e^\pm X$, and charged current (CC) interactions, $e^\pm p \rightarrow \bar{\nu_e}(\nu_e)X$. The NC (CC) processes are mediated by the exchange of a photon or $Z^0$ boson ($W^{\pm}$ boson) and they can be described by three invariant variables: the virtuality of the exchanged boson, $Q^2$, the Bjorken scaling variable, $x$, and the inelasticity, $y (Q^2 = sxy)$. In 2002, the collider was upgraded (HERA-II) to provide higher instantaneous luminosities and longitudinal polarisation of the lepton beam. This significantly improved the precision in the high-$Q^2$ region where $Z^0$ and $W^{\pm}$ exchange becomes significant and allowed tests to be made of the electroweak sector of the Standard Model (SM) in the spacelike scattering, complementary to LEP and Tevatron precision measurements. This paper reviews the recent electroweak measurements of the inclusive NC and CC cross sections at high $Q^2$ and high $x$, performed by H1 and ZEUS collaborations using part of the HERA-II data.

2. Unpolarised NC and CC cross sections and $xF_3$ structure function
The double differential cross section for $e^\pm p$ NC DIS may be written in terms of proton structure functions, $F_2$, $xF_3$ and $F_L$:

$$\frac{d\sigma^{e^\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+ F_2 + Y_- xF_3 - y^2 F_L], \quad (1)$$

where $\alpha$ is the fine-structure constant and $Y_\pm = 1 \pm (1 - y)^2$. The structure functions $F_2$ and $xF_3$ contain the sum and the difference of the quark and antiquark PDFs, the longitudinal structure function, $F_L$, is sizable only at high $y$ and can be neglected at high $Q^2$ and high $x$. The double differential cross section for $e^- p$ and $e^+ p$ CC DIS may be written as:

$$\frac{d\sigma^{e^- p}}{dxdQ^2} = \frac{G_F^2}{2\pi} \frac{M_W^4}{(Q^2 + M_W^2)^2}[(u + c) + (1 - y)^2(\bar{d} + \bar{s})] \quad (2)$$

$$\frac{d\sigma^{e^+ p}}{dxdQ^2} = \frac{G_F^2}{2\pi} \frac{M_W^4}{(Q^2 + M_W^2)^2}[(\bar{u} + \bar{c}) + (1 - y)^2(d + s)], \quad (3)$$
The longitudinal polarisation has a particularly strong effect on the CC cross sections, as they are predicted to be linearly dependent on the polarisation, independently of kinematic variables:

\[
\sigma_{CC}^{e^+p}(P_e) = (1 \pm P_e)\sigma_{CC}^{e^+p}(P_e = 0).
\]
Here, \( P_e \) is defined as \( P_e = (N_R - N_L)/(N_R + N_L) \), where \( N_R \) and \( N_L \) are the numbers of right and left-handed leptons in the beam. In the Standard Model only left-handed fermions and right-handed antifermions take part in weak interactions, hence the CC cross sections are expected to vanish at \( P_e = 1(-1) \) for \( e^{-}p(e^+p) \) scattering. Both H1[4, 7] and ZEUS[8, 9] have measured the total CC cross sections at different values of lepton polarisation, in the kinematic range \( Q^2 > 200 \) GeV\(^2 \) and \( Q^2 > 400 \) GeV\(^2 \) and \( y < 0.9 \), respectively. Figure 3 shows the total cross sections in the kinematic range of H1 data, together with unpolarised cross sections[11, 12, 13] and SM predictions. The linear dependence on \( P_e \) is clearly observed, in agreement with the chiral structure of the SM. The cross sections were fitted with the linear functions and from the extrapolation of fits to \( P_e = 1(-1) \) for \( e^{-}p(e^+p) \) scattering the limits on the mass of the right-handed \( W_R^\pm \) have been set by both experiments[10]. The ZEUS experiment has measured the \( e^{-}p \) single differential cross sections, \( d\sigma/dQ^2 \), \( d\sigma/dx \) and \( d\sigma/dy \), for two values of electron polarisation[8], shown in Figure 4. The results agree with the SM prediction and, as expected, the cross section dependence on the polarisation is independent of kinematic variables.

4. Polarsed NC cross sections

Since the contribution from \( Z^0 \) exchange becomes significant only at higher \( Q^2 \), the effect of the polarisation on the NC cross section is expected to depend on \( Q^2 \). This dependence can be seen by decomposing the generalised structure functions for \( e^{-}p \) scattering as follows:

\[
F_2^+ = F_2^\gamma - (v_e \pm P_e a_e) \chi_Z F_2^{\gamma - Z} + (v_e^2 + a_e^2 \pm a_e P_e) \chi_Z^2 F_2^Z, \tag{5}
\]

\[
x F_3^\pm = - (a_e \pm P_e v_e) \chi_Z x F_3^{\gamma - Z} + (2 v_e a_e \pm P_e (v_e^2 + a_e^2)) \chi_Z^2 x F_3^Z, \tag{6}
\]

where \( F_2^\gamma \) is associated with the pure photon exchange, \( F_2^{\gamma - Z} \) correspond to the \( \gamma - Z^0 \) interference and \( F_2^Z \) describe the pure \( Z^0 \) contribution. Here, \( \chi_Z = 1/\sin^2(2\theta_W)Q^2/(Q^2 + M_Z^2) \).
Figure 5. The ratio of the NC $d\sigma/dQ^2$ cross sections for the positive over negative lepton beam polarisation, for $e^+p$ (left) and $e^-p$ (right) scattering.

is the ratio of the $Z^0$ and photon propagators, $v_e \simeq 0$ and $a_e = -1/2$ are the vector and axial couplings of $Z^0$ to electron. Both collaborations have studied the polarisation effects on the NC cross sections [10]. Figure 5 shows the ratio of the differential $d\sigma/dQ^2$ cross sections for the positive over negative polarisation, measured by H1 for $e^+p$ and $e^-p$ scattering[5]. The observed polarisation asymmetry increases with $Q^2$, driven by the propagator ratio, $\chi_{Z\gamma}$, and it is positive (negative) for $e^+p$ ($e^-p$) data, due to the parity violating $F_{Z\gamma}^\gamma$ contribution to the cross section, which changes its sign with the lepton charge. This behaviour is in agreement with the SM expectation.

5. Summary
The high luminosities and polarised lepton beam available at HERA-II have allowed tests to be made of the electroweak sector of the SM in spacelike scattering at high $Q^2$. The dependence of the inclusive CC cross sections on the polarisation is in agreement with the chiral structure of the SM. The effect of the parity violation is seen in the NC cross sections at high $Q^2$. The high precision polarised inclusive CC and NC data also provide an important input to the combined NLO QCD and electroweak fits. The results presented here are based on part of HERA-II data and will be improved in the near future. In order to further increase precision, both H1 and ZEUS collaborations will combine the results, which will correspond to a total luminosity of about 1 fb$^{-1}$.

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