

# Inclusive Deep Inelastic Scattering at High $Q^2$ with Longitudinally Polarised Lepton Beams at HERA and Determination of the Integrated Luminosity at HERA using Elastic QED Compton Events

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Inclusive  $e^\pm p$  single and double differential cross sections for neutral and charged current deep inelastic scattering processes are measured with the H1 detector at HERA. The data were taken at a centre-of-mass energy of  $\sqrt{s} \approx 319$  GeV with a total integrated luminosity of  $333.7 \text{ pb}^{-1}$  shared between two lepton beam charges and two longitudinal lepton polarisation modes. The luminosity was determined exploiting the elastic QED Compton process  $ep \rightarrow e\gamma p$  with a precision of 2.3%. The differential cross sections are measured in the range of negative four-momentum transfer squared,  $Q^2$ , between 60 and 50 000  $\text{GeV}^2$ , and Bjorken  $x$  between 0.0008 and 0.65. The measurements are combined with earlier published unpolarised H1 data to improve statistical precision and used to determine the structure function  $xF_3^{\gamma Z}$ . A measurement of the neutral current parity violating structure function  $F_2^{\gamma Z}$  is presented for the first time. The polarisation dependence of the charged current total cross section is also measured. The new measurements are well described by a next-to-leading order QCD fit based on all published H1 inclusive cross section data which are used to extract the parton distribution functions of the proton.

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## 1. Introduction

At HERA 27.6 GeV leptons (electrons and positrons) were collided with the 920 GeV protons, leading to an  $ep$  centre-of-mass energy of 320 GeV. During the second phase of the HERA program (HERA-II, 2003-2007), the machine provided longitudinal polarisation of the lepton beam. The polarisation was continuously measured using two independent polarimeters.

A measurement of the integrated luminosity has been done exploiting the elastic QED Compton process  $ep \rightarrow e\gamma p$  [1], where the scattered electron and the photon are detected in the backward calorimeter of the H1 experiment. The integrated luminosity of the data recorded during the whole HERA-II period is determined with a precision of 2.3%.

In this contribution measurements of the neutral current (NC) and charged current (CC) cross sections at high  $Q^2$  are reported for  $e^-p$  and  $e^+p$  for two values of longitudinal polarisation,  $P_e = (N_R - N_L)/(N_R + N_L)$ , with  $N_R$  ( $N_L$ ) being the number of the right (left) handed leptons in the beam. The investigation of electroweak (EW) effects in NC and CC reactions using polarised and unpolarised lepton beams are discussed.

To assess the impact of the H1 NC and CC cross sections at high  $Q^2$  on the determination of PDFs, a QCD analysis (H1PDF2012) of this data together with previously published H1 data [3, 4, 5, 6] is performed [2].

The cross sections from HERA-II are combined with the previous measurements from HERA-I to improve the statistical uncertainty of the unpolarised cross sections measurements.

## 2. Neutral Current Cross Section

The NC differential cross section for  $e^\pm p$  scattering can be expressed in terms of generalised proton structure functions  $\tilde{F}$  as

$$\frac{d^2\sigma_{\text{NC}}(e^\pm p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} (Y_+ \tilde{F}_2^\pm \mp Y_- x \tilde{F}_3^\pm - y^2 \tilde{F}_L^\pm) \equiv \frac{2\pi\alpha^2 Y_\pm}{xQ^4} \tilde{\sigma}_{\text{NC}}^\pm(x, Q^2), \quad (2.1)$$

where  $\alpha$  is the fine structure constant,  $x$  is the Bjorken  $x$  variable, and the functions  $Y_\pm = 1 \pm (1-y)^2$  describe the helicity dependence of the electroweak interactions with  $y$  characterises the inelasticity of the interaction. In Eq. (2.1) also the reduced NC cross section  $\tilde{\sigma}_{\text{NC}}^\pm(x, Q^2)$  is defined which is a combination of the generalised structure functions.

The generalised structure functions,  $\tilde{F}_{2,3}$ , may be written as linear combinations of the proton structure functions  $F_2$ ,  $F_{2,3}^{\gamma Z}$ , and  $F_{2,3}^Z$  associated to pure photon exchange term, photon-Z interference terms and pure Z exchange terms correspondingly. These functions are containing information on QCD parton dynamics as well as on the electroweak couplings of the quarks to the neutral vector bosons[7]. The linear combinations for  $\tilde{F}_2$  and  $x\tilde{F}_3$  in arbitrary polarised  $e^\pm p$  scattering are given by

$$\tilde{F}_2^\pm = F_2 - (v_e \pm P_e a_e) \kappa \frac{Q^2}{Q^2 + M_Z^2} F_2^{\gamma Z} + (a_e^2 + v_e^2 \pm P_e 2v_e a_e) \kappa^2 \left[ \frac{Q^2}{Q^2 + M_Z^2} \right]^2 F_2^Z, \quad (2.2)$$

$$x\tilde{F}_3^\pm = -(a_e \pm P_e v_e) \kappa \frac{Q^2}{Q^2 + M_Z^2} x F_3^{\gamma Z} + (2a_e v_e \pm P_e [v_e^2 + a_e^2]) \kappa^2 \left[ \frac{Q^2}{Q^2 + M_Z^2} \right]^2 x F_3^Z, \quad (2.3)$$

with  $\kappa^{-1} = 4M_W^2/M_Z^2(1 - M_W^2/M_Z^2)$  in the on-mass-shell scheme, where  $M_W$  and  $M_Z$  are the weak vector boson masses. The quantities  $v_e$  and  $a_e$  are the vector and axial-vector couplings of the electron to the  $Z$  boson.

In the quark parton model (QPM), the hadronic structure functions are related to linear combinations of the quark and anti-quark momentum distributions  $xq(x, Q^2)$  and  $x\bar{q}(x, Q^2)$  as

$$\left[ F_2, F_2^{\gamma Z}, F_2^Z \right] = x \sum_q \left[ e_q^2, 2e_q v_q, v_q^2 + a_q^2 \right] (q + \bar{q}), \quad \left[ xF_3^{\gamma Z}, xF_3^Z \right] = 2x \sum_q \left[ e_q a_q, v_q a_q \right] (q - \bar{q}), \quad (2.4)$$

where  $v_q$  and  $a_q$  are the vector and axial-vector couplings to the light quarks, and  $e_q$  is the charge of the quark of flavor  $q$ .

Longitudinally polarised lepton beams allow for the measurement of polarisation effects related to the chiral structure of the neutral electroweak exchange. The polarisation asymmetry,  $A^\pm$ , is defined as

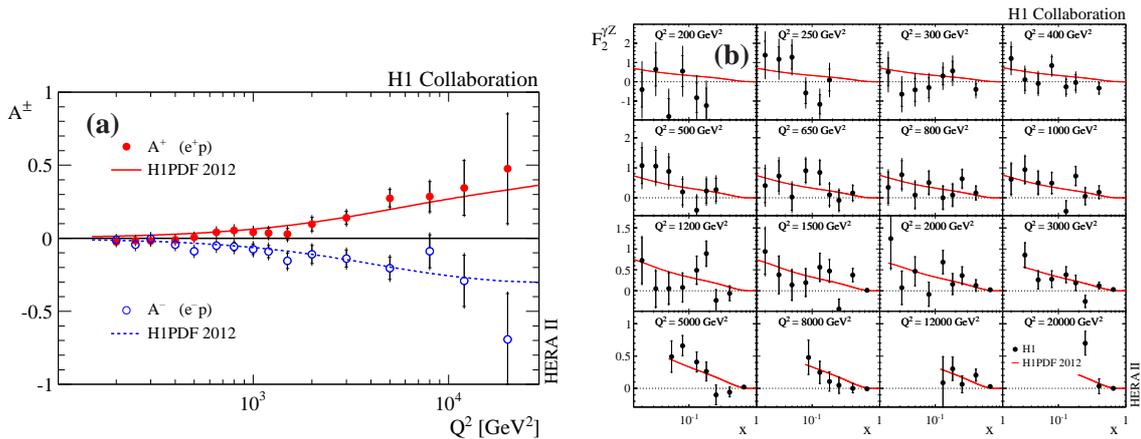
$$A^\pm \equiv A(e^\pm p) \equiv \frac{2}{P_R - P_L} \frac{\sigma_{NC}^\pm(P_R) - \sigma_{NC}^\pm(P_L)}{\sigma_{NC}^\pm(P_R) + \sigma_{NC}^\pm(P_L)} \approx \mp \kappa a_e \frac{F_2^{\gamma Z}}{F_2} \approx \pm \kappa \frac{1 + d_v/u_v}{4 + d_v/u_v}. \quad (2.5)$$

To a very good approximation  $A^\pm$  measures the structure function ratio  $F_2^{\gamma Z}/F_2$ . At large  $x$  the asymmetry is related to the  $d/u$  ratio of the valence quark distribution. The polarised single differential cross sections  $d\sigma_{NC}/dQ^2$  are used for the extraction of the asymmetry shown in Fig. 1a in comparison to the H1PDF2012 fit. The magnitude of the asymmetry rises with increasing  $Q^2$  and is positive (negative) in  $e^+p$  ( $e^-p$ ) scattering.

For a given lepton charge the difference in the left and right polarised NC cross section is sensitive to  $F_2^{\gamma Z}$  as well as  $xF_3^{\gamma Z}$  and  $xF_3^Z$  as given by

$$\frac{\sigma^\pm(P_L^\pm) - \sigma^\pm(P_R^\pm)}{P_L^\pm - P_R^\pm} = \frac{\kappa Q^2}{Q^2 + M_Z^2} \left[ \mp a_e F_2^{\gamma Z} + \frac{Y_-}{Y_+} v_e x F_3^{\gamma Z} - \frac{Y_-}{Y_+} \frac{\kappa Q^2}{Q^2 + M_Z^2} (v_e^2 + a_e^2) x F_3^Z \right] \quad (2.6)$$

By taking the difference of Eq. 2.6 for the  $e^+p$  and  $e^-p$  data,  $F_2^{\gamma Z}$  can be directly extracted from the measured cross sections. The measurement is performed for  $Q^2 > 200 \text{ GeV}^2$ . The result is shown in Fig. 1b in comparison to the H1PDF2012 fit.



**Figure 1:** (a) The  $Q^2$  dependence of the polarisation asymmetry  $A^\pm$ . (b) The structure function  $F_2^{\gamma Z}$  measurement. Both measurements are compared to the Standard Model predictions based on the H1PDF2012 parametrisation.

The polarised data sets from HERA-II were merged to obtain the unpolarised cross section after a small correction for a residual polarisation. The unpolarised cross sections from HERA-II were then combined with the HERA-I results to improve the precision of the measurement.

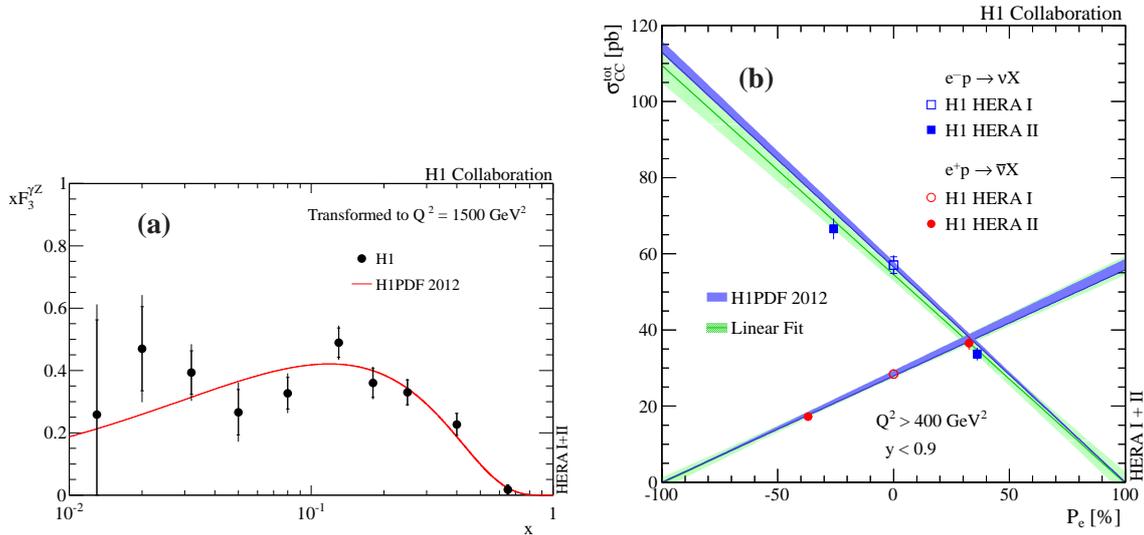
The combined HERA I+II NC unpolarised cross section measurements for  $e^+p$  and  $e^-p$  scattering are used for the  $xF_3^{\gamma Z}$  structure function measurement, which is obtained in a simultaneous fit with  $xF_3^{\gamma Z}$ ,  $\tilde{\sigma}_0^\pm \equiv \tilde{F}_2^\pm - y^2/Y_+ \tilde{F}_L^\pm$  and nuisance parameters for the systematics shifts being free minimisation parameters [2]. The non-singlet structure function exhibits only a weak dependence on  $Q^2$  and therefore the measurements are transformed to a common  $Q^2$  value of 1500 GeV<sup>2</sup> and averaged in each  $x$  bin as shown in Fig. 2a. The calculation from the H1PDF2012 fit gives a good description of the measurement. The structure function  $xF_3^{\gamma Z}$  determines both the shape and magnitude of the valence distribution  $2u_v + d_v$  assuming the quark and anti-quark sea distributions are the same. The integral of this structure function which is in LO predicted to be 5/3 after the extrapolation of the measurement to the full kinematic region in  $x$  is  $\int_0^1 F_3^{\gamma Z} dx = 1.69 \pm 0.12(\text{stat.}) \pm 0.10(\text{syst.})$ .

### 3. Charged Current Cross Section

The CC differential cross section may be expressed as

$$\frac{d^2 \sigma_{\text{CC}}(e^\pm p)}{dx dQ^2} = (1 \pm P_e) \frac{G_F^2}{2\pi x} \left[ \frac{M_W^2}{M_W^2 + Q^2} \right]^2 (Y_+ W_2^\pm - Y_\pm x W_3^\pm - y^2 W_L^\pm) \equiv \frac{G_F^2}{2\pi x} \left[ \frac{M_W^2}{Q^2 + M_W^2} \right] \tilde{\sigma}_{\text{CC}}(e^\pm p), \quad (3.1)$$

where  $G_F$  is Fermi constant,  $\tilde{W}_2^\pm$ ,  $x\tilde{W}_3^\pm$  and  $\tilde{W}_L^\pm$  are CC structure functions for  $e^\pm p$  scattering and  $\tilde{\sigma}_{\text{CC}}(e^\pm p)$  is the reduced cross section.



**Figure 2:** (a) The structure function  $xF_3^{\gamma Z}$  measured as a function of Bjorken  $x$ . (b) The dependence of the  $e^\pm p$  CC cross section on the lepton beam polarisation  $P_e$  in comparison with the SM prediction and the linear fit to the polarisation dependence. Both measurements are compared to the Standard Model predictions based on the H1PDF2012 parametrisation.

In the QPM, where  $W_L^\pm \equiv 0$ , the reduced cross section for the  $e^\pm p$  CC process may be expressed as the sum and difference of the quark and anti-quark momentum distributions,  $xq(x, Q^2)$  and  $x\bar{q}(x, Q^2)$ :

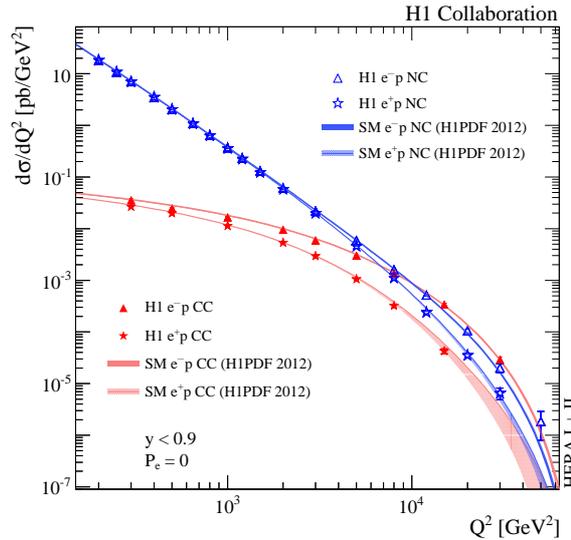
$$\tilde{\sigma}_{\text{CC}}(e^- p) = (xu + xc) + (1 - y)^2(x\bar{d} + x\bar{s}) \quad (3.2)$$

$$\tilde{\sigma}_{\text{CC}}(e^+ p) = (x\bar{u} + x\bar{c}) + (1 - y)^2(xd + xs) \quad (3.3)$$

The total CC cross section,  $\sigma_{\text{CC}}^{\text{tot}}$ , was measured as an integrated cross section in the kinematic region  $Q^2 > 400 \text{ GeV}^2$  and  $y < 0.9$  for the  $e^- p$  and  $e^+ p$  data and for different longitudinal lepton beam polarisations. The cross sections are shown in Fig. 2b together with the unpolarised data from HERA-I and the SM expectation using H1PDF2012 fit. A linear fit to the polarisation dependence of the measured cross sections simultaneously to  $e^- p$  and  $e^+ p$  data is performed and shown also. The extrapolation of the cross section with the fit to the point  $P_e = +1$  for  $e^- p$  ( $P_e = -1$  for  $e^+ p$ ) excludes the existence of a right-handed  $W^R$  boson of mass  $M_W^R$  [8] below 214 GeV (194 GeV) at 95% confidence level, assuming SM couplings and a light right handed  $\nu_e$ .

To obtain unpolarised cross section measurements, the left and right handed  $e^\pm p$  samples were combined into unpolarised data sets, correcting for small residual polarisation. The resulting  $e^\pm p$  cross sections were combined with the HERA-I measurement.

The single differential unpolarised cross section for CC together with the single differential NC cross section is shown in Fig 3. The measurements are compared with the theoretical expectation from H1PDF2012. At low  $Q^2$  the NC cross section is larger than the CC cross section by two orders of magnitude. Approaching the mass of the  $Z$  and  $W$  bosons, the NC and CC processes cross sections become of the same magnitude demonstrating an unification of the electroweak interactions.



**Figure 3:** The  $Q^2$  dependence of the unpolarised  $e^\pm p$  NC and CC cross sections compared to the SM expectation from H1PDF2012 fit.

#### 4. Summary

Measurements of the polarised NC and CC  $e^\pm p$  differential cross sections using the HERA-II data were presented. For the NC process the polarisation asymmetry  $A^\pm$ , sensitive to parity violation, is determined. The structure function  $F_2^{\gamma Z}$  is measured for the first time using the polarisation dependence of the  $e^\pm p$  NC cross sections. At high  $Q^2$  the structure function  $xF_3^{\gamma Z}$  is determined using unpolarised cross sections obtained from complete HERA-I and HERA-II data sets.

For the CC process the total polarised cross sections were measured and combined with the unpolarised measurements from HERA-I. The data exhibits a linear scaling of the cross section with  $P_e$  verifying the left handed structure of the weak interactions.

The results are in a good agreement with the Standard Model predictions.

#### References

- [1] F. D. Aaron *et al.* [H1 Collaboration], *Eur. Phys. J. C* **72** (2012) 2163
- [2] F. D. Aaron *et al.* [H1 Collaboration], *JHEP* **1209** (2012) 061
- [3] C. Adloff *et al.* [H1 Collaboration], *Eur. Phys. J.* **C13** (2000) 609
- [4] C. Adloff *et al.* [H1 Collaboration], *Eur. Phys. J.* **C19** (2001) 269
- [5] C. Adloff *et al.* [H1 Collaboration], *Eur. Phys. J.* **C30** (2003) 1
- [6] F. D. Aaron *et al.* [H1 Collaboration], *Eur. Phys. J.* **C71** (2010) 1579
- [7] M. Klein and T. Riemannm, *Z. Phys.* **C24** (1984) 151.
- [8] G. J. Feldman and R. D. Cousins, *Phys. Rev. D* **57** (1998) 3873