Physics at high Q^2 at HERA

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Abstract.
The neutral and charged currents deep inelastic ep scattering cross sections are measured by the H1 and ZEUS expermiments with longitudinally polarized lepton beams. The polarisation asymmetry as a function of Q^2 is measured with high precision, confirming the observation of parity violation. The total cross section of charged current process is measured for four independent data samples with electron and positron beams and different polarisation values. The lepton charge asymmetry of the unpolarised NC cross sections is used to extract the structure function $xF_3^{\gamma Z}$.

1. Introduction

In this paper, the measurements of inclusive charged and neutral current cross sections are presented using the complete HERA data set with an integrated luminosity of 500 pb^{-1} delived by each of the experiment, H1 and ZEUS.

The neutral current (NC) and charged current (CC) single differential cross section $\mathrm{d}\sigma/\mathrm{d}Q^2$ and the reduced cross section $\tilde{\sigma}(x, Q^2)$ are presented for e^+p and e^-p scatterings. The measured cross sections are combined with previously published HERA-I inclusive measurements to provide a single coherent set of cross sections. The neutral current data are also used to extract the structure function $xF_3^{\gamma Z}$. The polarisation asymmetry in NC cross section has been measured allowing a demonstration of the parity violation in NC interactions at a very small distance, down to about 10^{-18} m.

From fits to the data, parton distribution functions (PDFs) have been measured, especially the increased statistics in CC data has lead to a significant improved understanding of the valence quark distributions. The total CC cross section measured seperately for e^+p and e^-p, left- and right-handed data at $Q^2 > 400$ and $y < 0.9$ together with unpolarised total CC cross sections measured at HERA-I provide limits on right handed currents.

2. Deep Inelastic Scattering cross sections

2.1. Neutral current

At Born level, the NC double differential cross section can be expressed using proton structure functions [1]:

$$\frac{\mathrm{d}^2\sigma^{\pm}_{\mathrm{NC}}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{4\pi\alpha^2_{\mathrm{em}}}{Q^4}\left[Y_+\tilde{F}_2^{\pm} - y^2\tilde{F}_L^{\pm} \mp Y_- x\tilde{F}_3^{\pm}\right].(1+\Delta^{\mathrm{weak}}_{\mathrm{NC}}), \tag{1}$$

where $\alpha_{\rm em}^2$, $Y_\pm = 1 \pm (1-y)^2$, $\tilde{F}_i$ with $i = 2, L, 3$ and $\Delta_{\rm NC}^{\rm weak}$ are the electromagnetic coupling constant, the helicity functions, the generalized structure functions and the weak radiative corrections, respectively. The cross section is dominated by the contribution of the generalised structure function $\tilde{F}_2$ whereas sizeable effects from $\tilde{F}_L$ and $x\tilde{F}_3$ are only expected at large y and large Q^2, respectively. The weak radiative corrections [2] are small in the phase space of the presented analysis and are currently ingnored.

The generalised proton structure functions, $\tilde{F}_{2,3}$, maybe 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 on the EW couplings of the quarks to the neutral vector bosons. The function F_2 is associated to the pure photon exchange terms, $F_{2,3}^{\gamma Z}$ correspond to the photon-Z^0 interference terms and $F_{2,3}^{Z}$ describe the pure Z^0 exchange term. 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. Neglecting $\tilde{F}_L$, the linear combinations for arbitrarily polarized $e^\pm p$ scattering with lepton polarisation P_e are given by

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

$$x\tilde{F}_3^\pm = -(a_e \pm P_e v_e)\kappa \frac{Q^2}{Q^2+M_Z^2} xF_3^{\gamma Z} + (2a_e v_e \pm P_e[v_e^2 + a_e^2])\kappa^2 \left[\frac{Q^2}{Q^2+M_Z^2}\right]^2 xF_3^Z. \quad (3)$$

Here $\kappa^{-1} = 4M_W^2/M_Z^2(1-M_W^2/M_Z^2)$ in the on-mass-shell scheme [3] with M_W and M_Z the usual weak vector boson masses. The quantities v_e and a_e are the vector and axial-vector couplings of the electron (positron) to the Z^0.

The reduced NC cross section is defined by

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

2.2. Charged current

The double differential CC cross section for $e^\pm p$ scattering of polarised leptons with unpolarised protons, corrected for QED radiative effects, can be expressed as

$$\frac{{\rm d}\sigma_{\rm CC}^\pm}{{\rm d}x{\rm d}Q^2} = (1 \pm P_e)\frac{G_F^2}{4\pi x}\left[\frac{M_W^2}{M_W^2+Q^2}\right]^2 (Y_+ W_2^\pm - Y_\mp x W_3^\pm - y^2 W_L^\pm).(1+\Delta_{\rm CC}^{\rm weak}), \quad (5)$$

where G_F is the Fermi constant, $W_2^\pm$, $xW_3^\pm$ and $W_L^\pm$ are the charged current structure functions for $e^\pm p$ scattering, and $\Delta_{\rm CC}^{\rm weak}$ represents the weak radiative corrections for charged current interactions and has also not been applied to the measured cross sections.

The reduced CC cross section is defined as

$$\tilde{\sigma}_{\rm CC}^\pm(x,Q^2) \equiv \frac{2\pi x}{G_F^2}\left[\frac{M_W^2+Q^2}{M_W^2}\right]^2 \frac{{\rm d}\sigma_{\rm CC}^\pm}{{\rm d}x{\rm d}Q^2}. \quad (6)$$

3. HERA combined unpolarized cross section

The single differential cross sections ${\rm d}\sigma_{\rm NC}/{\rm d}Q^2$ and ${\rm d}\sigma_{\rm CC}/{\rm d}Q^2$ were measured at polarisation $P_e = 0$ and are found to be in good agreement with the standard model expectation determined by HERAPDF 1.0 fit [4], c.f. figure 1.

At low Q^2, the virtual photon exchange dominates the neutral current interactions, and CC events are suppressed by many orders of magnitude. With increasing Q^2, both cross sections approach each other, which means that electromagnetic and weak interaction strengths become comparable. At very high Q^2, the CC cross section for electron is higher than for positron. This is due to the W^- (W^+) boson exchange, which couples to up (down)-type quarks in the case of electrons (positrons). In addititon, for positron scattering, the helicity structure of the interaction leads to an additional suppression. In the highest Q^2 region also the NC cross section is larger for electron than for positrons. In this region, the interference between photon and Z exchange become relevant, which explains the observed asymmetry.

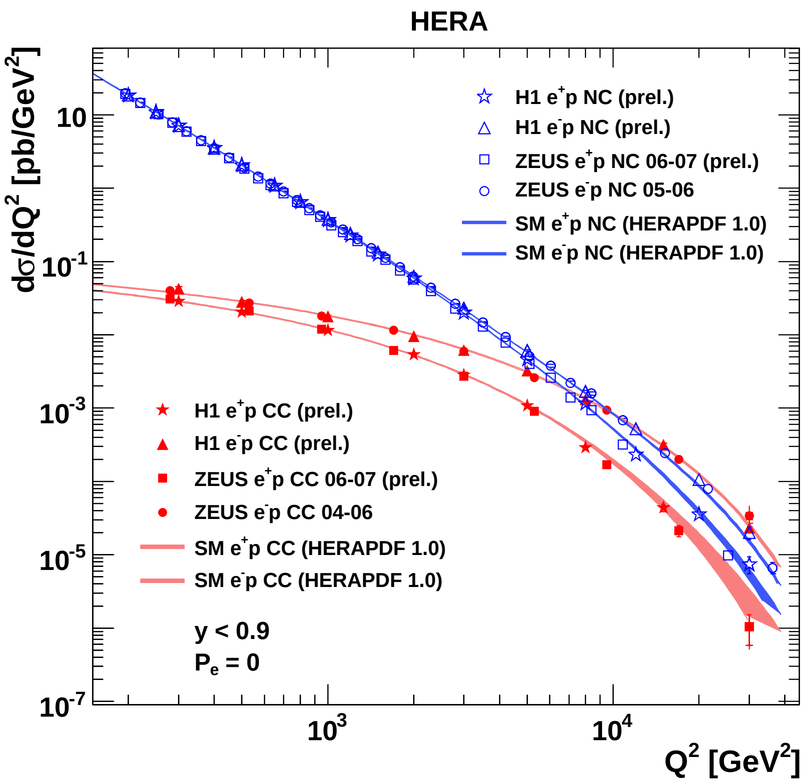

Figure 1. The Q^2 dependence of the unpolarised NC and CC cross sections measured by H1 and ZEUS based on the full HERA data. The results are compared to the corresponding standard model expectation determined using HERAPDF 1.0. The inner error bars represent the statistical uncertainties and the outer error bars represent the total errors.

4. Measurement of the structure function $x\tilde{F}_3^{\gamma Z}$

The dominant contribution to $x\tilde{F}_3$ arises from the $\gamma - Z$ interference and allows $xF_3^{\gamma Z}$ to be extracted according to $xF_3^{\gamma Z} \approx -x\tilde{F}_3(Q^2 + M_Z^2)/(\kappa a_e Q^2)$ (the pure Z exchange contribution is suppressed by the small vector coupling v_e). This structure function is non-singlet and has only little dependence on Q^2. The measured $xF_3^{\gamma Z}$ in Q^2 range from 1500 GeV^2 to 12000 GeV^2 can thus be converted to $Q^2 = 1500$ GeV^2 taking into account the small Q^2 dependence and is shown in figure 2.

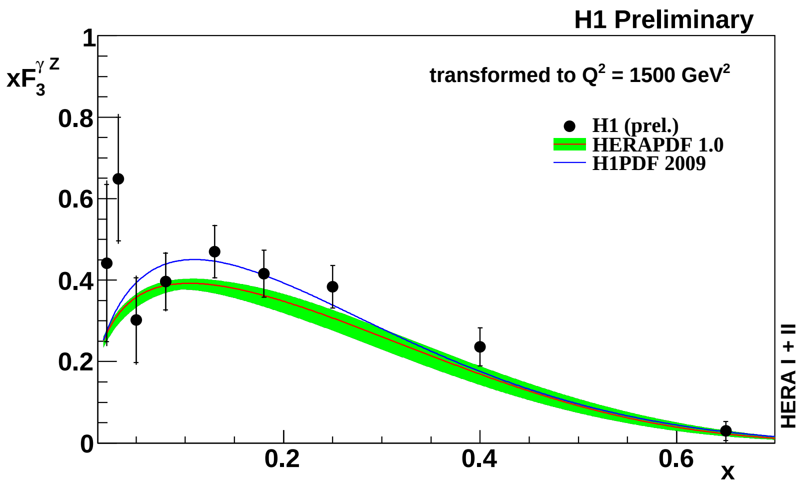

Figure 2. The averaged structure function $xF_3^{\gamma Z}$ fo $Q^2 = 1500$ GeV^2. The data are compared to the SM predictions using HERAPDF 1.0 and H1PDF 2009 [5]. The inner error bars represent the statistical uncertainties and the outer error bars represent the total errors.

5. Neutral current polarisation asymmetry

The SM predicts a difference in the cross sections for leptons with different helicity states arising from the chiral structure of the neutral electroweak exchange. The different longitudinal polarisations of the lepton beam in HERA-II allows the measurement of the polarisation asymmetry

$$A = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}, \tag{7}$$

where P_R and P_L denote the average values of the right-handed and left-handed polarisations, respectively. The asymmetry A can be approximated by the structure function ratio

$$A^{\pm} \approx \mp \kappa a_e \frac{F_2^{\gamma Z}}{F_2}, \tag{8}$$

which is proportional to combinations $a_e v_q$ and is thus a direct measure of parity violation. In positron scattering A is expected to be positive and about equal to $-A$ in electron scattering. At large x the asymmetry measures the d/u ratio of the valence quark distributions according to

$$A^{\pm} \approx \mp \kappa \frac{1 + d_v/u_v}{4 + d_v/uv}. \tag{9}$$

The polarised single differential cross sections $\mathrm{d}\sigma_{\mathrm{NC}/\mathrm{d}Q^2}$ are used to determine the asymmetry where it is assumed that the correlated uncertainties of each measurement cancel. The asymmetry is shown in figure 3 and compared to the SM expectations using the H1PDF 2009 fit. The magnitude of the asymmetry is observed to increase with increasing Q^2 and is negative in e^-p and positive in e^+p scattering. The data are in good agreement with the SM expectation using H1PDF 2009 and confirm the parity violation effects of electroweak interactions at large Q^2.

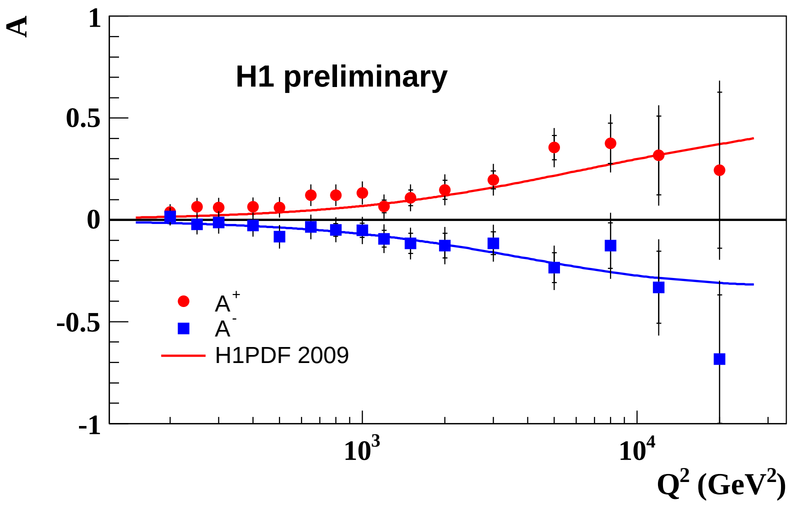

Figure 3. The Q^2 dependence of the polarisation asymmetry A, for e^+p (solid circles) and e^-p (solid squares) data. The data are compared to the SM predictions using H1PDF 2009 (lines). The inner error bars represent the statistical uncertainties and the outer error bars represent the total errors.

6. Charged current total cross section

The total CC cross sections have been measured in the region $Q^2 > 400$ GeV^2, $P_{T,h} > 12$ GeV and $0.03 < y < 0.85$. In figure 4 the cross section measurement from longitudinal polarized lepton beam data are shown together with the results from the unpolarized HERA-I data [1]. A clear linear polarisation dependence of the total cross section is observed which is maximal for left-handed e^-p scattering and right-handed e^+p scattering demonstrating the parity violation of purely weak charged current interactions.

7. Charged current reduced cross section

The reduced CC cross section was measured in the kinematic range $200 < Q^2 < 60000$ GeV^2 and $0.006 < x < 0.85$ and is shown as a function of x at fixed Q^2 in figure 5. The measured reduced cross sections are corrected to $P_e = 0$. The data are well described by the SM using different PDFs. The measurements show that the contribution of the down quark PDF dominates the e^+p cross section whereas the up quark PDF dominates e^-p cross section at high x.

8. Neutral current reduced cross section

The reduced NC cross section was measured in the kinematic range $200 < Q^2 < 60000$ GeV^2 and $0.003 < x < 1$ and is shown as a function of x at fixed Q^2 in figure 6. With the x reconstruction relying on jets, the measurements reached for the first time x values up to $x = 1$. The curves show the SM predictions evaluated with HERAPDF 1.5, which give an excellent agreement with the data.

9. Conclusions

The high Q^2 cross section measurements at HERA allowed precision tests of the Standard Model. In this paper, the most recent results of these studies have been shown. The neutral and charged current cross section at high Q^2 shows clearly the unification of the electroweak forces. At low Q^2, the NC cross section is comparable for e^-p and e^+p interactions which is explained by the

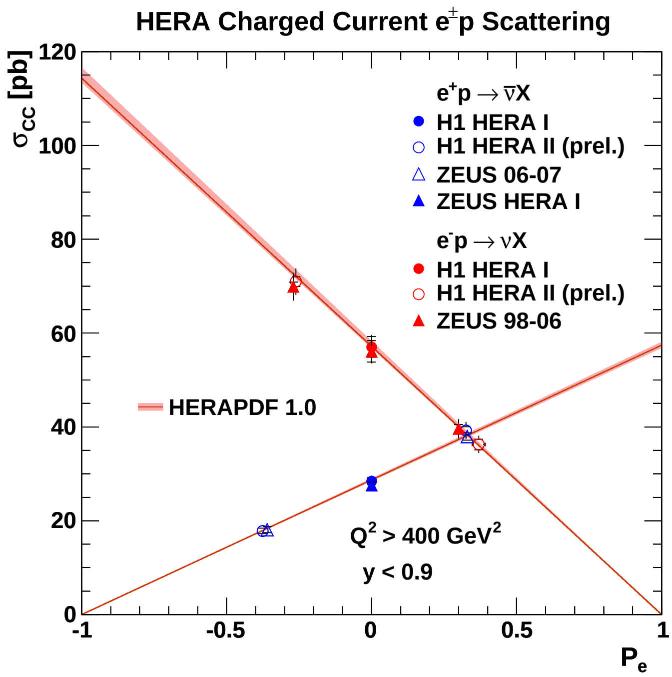

Figure 4. The dependence of the $e^{\pm}p$ CC cross section on the lepton beam polarisation P_e. The inner and outer error bars represent the statistical and total errors, respectively. The uncertainties on the polarisation measurement are shown in horizontal error bars which are in general smaller than the symbol size. The data are compared to the SM prediction based on the HERAPDF 1.0 parametrisation. The error bands represent the uncertainty on the SM expectation combining the uncertainties from experimental data used in the fit added in quadrature with model and parametrisation uncertainties. The data are consistent with the absence of right-handed currents as predicted in the SM.

exchange of the photon. The observation of a large structure function $xF_3^{\gamma Z}$ at HERA is a clear manifestation of the interference of the photon and the Z-boson. The polarisation asymmetry in both NC and CC interaction confirm the parity violation in weak interaction. The total CC cross section demonstrates the absence of the right-handed current.

References

[1] C. Adloff *et al.* [H1 Collaboration], Eur. Phys. J. **C 30** (2003), 1.

[2] A. Arbuzov *et al.*, *Hector 1.00: A program for the calculation of QED, QCD and electroweak corrections to ep and* lepton$^{\pm}$-N *deep inelastic neutral and charged current scattering*, Comput. Phys. Commun. **94** (1996), 128.

[3] K. Nakamura *et al.*, *Review of Particle Physics*, J. Phys. **G37** (2010), 075021.

[4] F.D. Aaron *et al.* [H1 and ZEUS Collaborations], *Combined measurement and QCD analysis of the inclusive ep scattering cross sections at HERA*, JHEP **01** (2010), 109.

[5] H1 Collaboration, H1prelim-09-042, H1prelim-09-043.

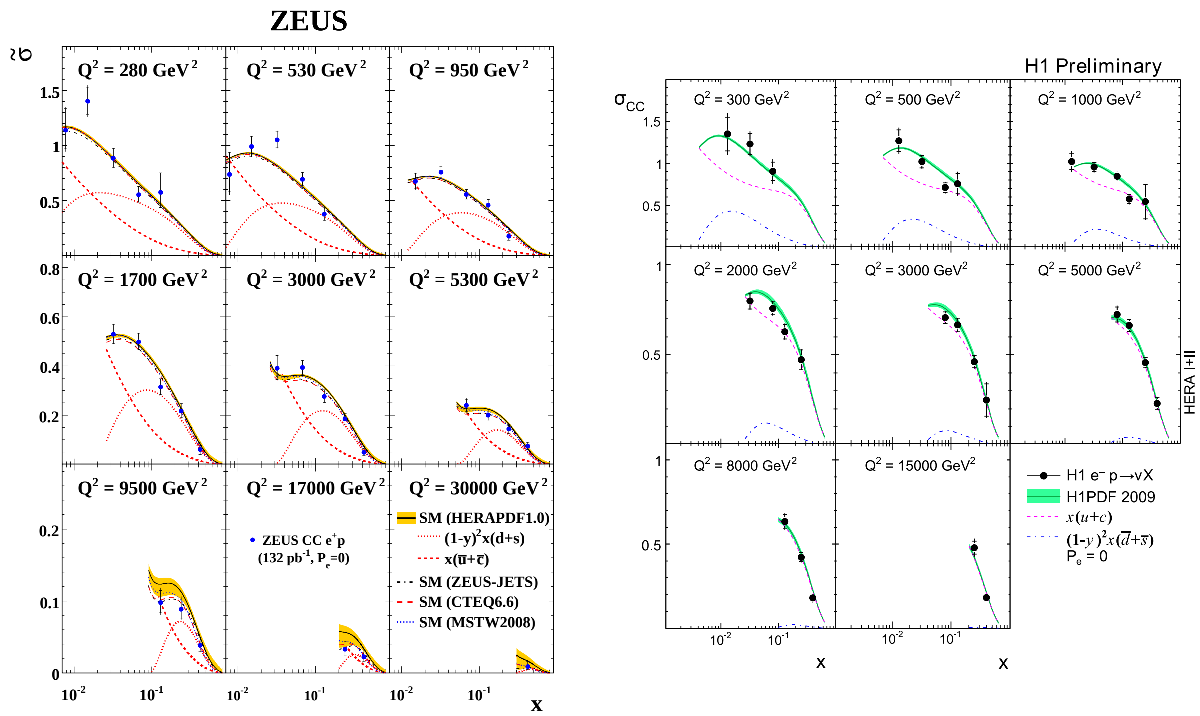

Figure 5. Left: The reduced e^+p CC cross section as a function of x for fixed Q^2 measured by the ZEUS Collaboration. The circles represent the data points and the curves show the prediction of the SM evaluated using HERAPDF 1.0, CTEQ 6.6 and MSTW 2008 PDFs. The dashed and dotted lines show the contributions of the PDF combinations $(1-y)^2x(d+s)$ and $x(\bar{y}+\bar{c})$, respectively. Right: The reduced e^-p CC cross section as a function of x for different values of Q^2 measured by the H1 Collaboration. Filled circles represents data points and the curves show the prediction of the SM evaluated using H1PDF 2009; the separate contributions from quarks and anti-quarks are shown as the dashed and dashed-dotted curves.

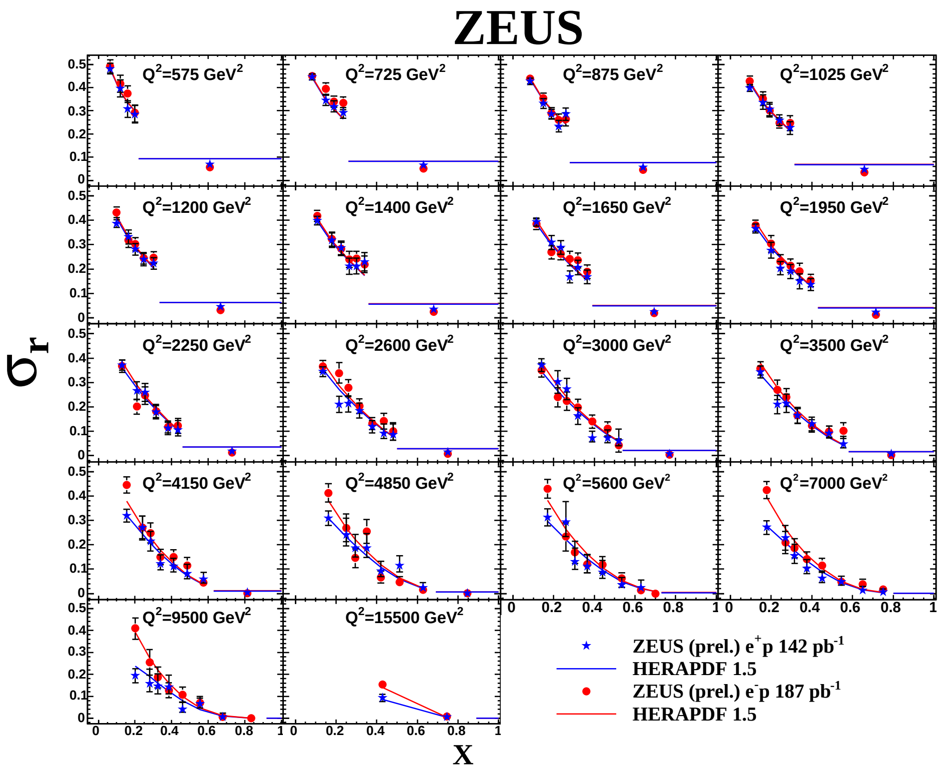

Figure 6. The NC reduced e^+p (filled circle) and e^-p (filled triangle) cross sections as a function of x for different values of Q^2 measured by the ZEUS collaboration. The curves show the prediction of the SM evaluated using HERAPDF 1.5.