Neutral and charged current at high- x and high- Q^2 at HERA

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The results of neutral and charged current deep inelastic scattering at high- x and high- Q^2 from H1 and ZEUS are presented. F_2 , xF_3 , neutral and charge current cross section measurements are covered. The first measurements on neutral and charge current cross sections in $e^\pm p$ collisions with longitudinally polarised lepton beam at HERA II are also presented. The dependences on the polarisations of charged and neutral current cross sections are found to be consistent with the Standard Model expectations.

1. Introduction

In Quantum-Chromo-Dynamics (QCD), the understanding of proton structure is of fundamental interest, but also of great practical importance for the present and future hadron hadron scattering experiments like those at the forthcoming LHC. Deep inelastic scattering (DIS) of leptons off nucleons is a key tool in the understanding of proton structure and the form of the Standard Model (SM). The fully inclusive neutral current (NC) and charged current (CC) reactions are particularly suited to unveil the parton structure of the proton due to the comparatively simple and well understood theoretical description of these reactions.

Since its beginning in 1992, the HERA accelerator has been a major source of information on proton structure. The electrons (positrons) with 27.5 GeV energy collide with 920 GeV protons. H1 and ZEUS are the two general purpose detectors operating on the HERA ring.

2. Cross sections and structure functions

In $e^\pm p$ scattering, the proton structure can be probed by NC and CC interactions. The NC interactions are mediated by γ and Z boson, and the double differential cross section can be expressed in terms of three structure functions, $\tilde{F}_2$, $x\tilde{F}_3$ and $\tilde{F}_L$:

$$\begin{aligned} \frac{d^2\sigma_{NC}(e^\pm p)}{dx dQ^2} &= \frac{2\pi\alpha^2}{xQ^4} Y_+ \left[\tilde{F}_2 - \frac{y^2}{Y_+} \tilde{F}_L \mp \frac{Y_- x}{Y_+} \tilde{F}_3 \right] \\ &= \frac{2\pi\alpha^2}{xQ^4} Y_+ \tilde{\sigma}_{NC}(e^\pm p) \end{aligned} \quad (1)$$

where $Y_\pm = 1 \pm (1-y)^2$. Here, $Q^2 = -q^2$, with q being the four-momentum of exchanged gauge boson. Bjorken $x = Q^2/2(P \cdot q)$, the momentum fraction of the proton carried by the parton participating in the interaction, and $y = (P \cdot q)/(P \cdot k)$, the inelasticity, where $k(P)$ is the four-momentum of the incoming lepton (proton). The term $\tilde{\sigma}_{NC}(e^\pm p)$ is called “reduced cross section”, which is a combination of structure functions and directly related to the differential cross section. The structure function $\tilde{F}_2$ is the dominant contribution in most of the phase space, in leading order (LO) QCD, it can be written in terms of the quark densities $\tilde{F}_2 \propto \sum (xq_i + x\bar{q}_i)$. The term $x\tilde{F}_3$, contributes significantly only at high Q^2 , and can be written in terms of the valence quarks densities $x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$.

The CC interactions are mediated by $W^\pm$ boson. Like NC interactions, the double differential cross section can be written:

$$\frac{d^2\sigma_{CC}(e^\pm p)}{dx dQ^2} = \frac{G_F^2}{2\pi x} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 \cdot \tilde{\sigma}_{CC}^\pm \quad (2)$$

where G_F is the Fermi coupling constant. In LO:

$$\tilde{\sigma}_{CC}^+ = [x(\bar{u} + \bar{c}) + (1-y)^2 x(d + s)] \quad (3)$$

$$\tilde{\sigma}_{CC}^- = [x(u + c) + (1-y)^2 x(\bar{d} + \bar{s})] \quad (4)$$

The positron proton scattering is therefore sensitive to d -quark density, while electron proton scattering is sensitive to u -quark density.

The SM predicts that the cross sections for $e^\pm p$ NC and CC DIS should exhibit dependence on the polarisation of the incoming lepton beam due to the parity violating nature of weak interactions. For the NC, the proton structure functions $\tilde{F}_2$ and $x\tilde{F}_3$ may be written as linear combinations of the hadronic structure function F_2 , $F_{2,3}^{\gamma Z}$ and $F_{2,3}^Z$,

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associated to pure γ exchange, γZ interference and to pure Z exchange:

$$\begin{aligned}\tilde{F}_2 &= F_2 - (\nu_e \pm P_e a_e) \eta_Z F_2^{\gamma Z} \\ &\quad + (\nu_e^2 + a_e^2 \pm 2P_e \nu_e a_e) \eta_Z^2 F_2^Z \quad (5) \\ x\tilde{F}_3 &= - (a_e \pm P_e \nu_e) \eta_Z x F_3^{\gamma Z} \\ &\quad + (2\nu_e a_e \pm P_e (\nu_e^2 + a_e^2)) \eta_Z^2 x F_3^Z \quad (6)\end{aligned}$$

with $\eta_Z = \frac{\kappa Q^2}{(Q^2 + M_Z^2)}$, $\kappa^{-1} = 4 \frac{M_W^2}{M_Z^2} (1 - \frac{M_W^2}{M_Z^2})$, where ν_e and a_e are the vector and axial-vector couplings of the electron to the Z boson and P_e is the longitudinal polarisation defined as $P_e = \frac{N_R - N_L}{N_R + N_L}$ with $N_R(N_L)$ being the number of right (left) handed polarised leptons in the beam. For the CC, the double cross section has a linear dependence on the polarisation of the lepton beam:

$$\frac{d^2 \sigma_{CC}(e^\pm)}{dx dQ^2} = (1 \pm P_e) \frac{G_F^2}{2\pi x} \left(\frac{M_W^2}{Q^2 + M_W^2} \right) \tilde{\sigma}_{CC}^\pm(7)$$

For positrons (electrons) with positive (negative) polarisation, the cross section is enlarged, whilst the cross section for negative (positive) polarised positrons (electrons) vanishes.

3. F_2 and $x F_3$ measurements

Figure 1. F_2 values as functions of Q^2 at different x values. The bands represent the H1 PDF 2000 fit. The dashed lines depict the extrapolation of the fit towards lower Q^2 values.

The HERA NC F_2 data is illustrated in Fig.1 [1–5]. Both H1 and ZEUS measurements show that the Q^2 evolution of F_2 is well described by NLO pQCD throughout five order of magnitude in both x and Q^2 . The scaling violation is clearly seen, which provides indirectly constraint on gluon density. At low to medium Q^2 up to 3% precision is reached, while at high Q^2 range, the statistic is limited, and will be improved with HERAII data.

At $Q^2 \geq M_Z^2$, the electronweak effects, especially the γZ interference become significant leading to different NC cross sections for e^+p and e^-p scattering (Fig.2) [2,6,7]. The difference is described by the proton structure function $x F_3$, and allows an extraction of the valence quarks content of the proton.

Figure 2. The reduced NC cross sections at high Q^2 show as functions of Q^2 for different x values.

Figure 3. The averaged structure function $x F_3$ for $Q^2 = 1500 \text{ GeV}^2$, the solid line shows the SM prediction from the H1 PDF 2000 fit, the dashed line shows the SM prediction evaluated using the ZEUS-JETS PDFs.

The uncertainties of $x F_3$ are dominated by the limited statistics of the HERAI e^-p data sample. Using already about ten times more e^-p data on HERAII, the unpolarised e^-p NC reduced cross sections are measured by combining the positive and negative polarisation data samples, and correcting for the small residual polarisation [8,9]. The structure function $x F_3$ is extracted with higher precision (Fig.3) by combining HERAI and HERAII data. The measurements of the H1 and ZEUS are in good agreement, the expectations of the SM give a good description of data.

4. High- x NC measurement

Due to the detection acceptance and the low cross section, the highest value of x of the mea-

sured cross section so far is limited to $x = 0.65$. This leads the ZEUS collaboration [10] to apply a new technique, which exploits the fact, that at very high x , where Q^2 can still be well measured using the scattered electron alone with the hadronic jet escaping in the beam pipe at small forward angle. If this happens, the events are collected in the highest bin with $x_{odg} < x < 1$, where x_{odg} depends on Q^2 .

Figure 4. The Born level cross sections for e^+p NC scattering (solid squares) and the integral of the Born level cross sections divided by the width (open squares) compared to the SM expectations evaluated using CTEQ6D PDFs (lines).

Fig.4 shows Born level cross sections for e^+p compared to the SM expectations using the CTEQ6D PDFs. Similar results were obtained for the e^-p data. The double differential cross sections generally agree well to the SM expectations. For the highest x bins, there are a tendency to lie above the expectations. These data may provide significant contributions at high x in pQCD analysis.

5. CC measurement

The e^+p and e^-p CC reduced cross sections measured by H1 [2,6] and ZEUS [11] are compared to the SM predictions evaluated using CTEQ6D in Fig.5. Contrary to the NC data, the CC e^-p data are everywhere different with e^+p data. At low Q^2 , the difference is less pronounced because the sea quark contribution is relatively important, whereas at high Q^2 and high x , the difference can mostly be attributed to underlying quark flavors difference between xu and $(1-y)^2xd$ as indicated respectively with the dashed and dash-pointed lines in figure. Therefore the $e^\pm p$

CC cross sections at high Q^2 and high x can be used to constrain the u and d valence quarks respectively.

Figure 5. The reduced CC cross sections as function of x and Q^2 compared with predictions based on CTEQ6D (solid line).

The expectations from the SM evaluated using CTEQ6D PDFs are found to give a good description of the measured CC cross sections.

6. NC and CC with longitudinally polarised lepton beams

Since 2003, HERA began the second phase of data taking (HERAII). An increase of the specific luminosity after upgrade has been achieved. A major additional feature of HERAII is the ability to collide longitudinally polarised electrons (positrons) with unpolarised protons, the 40% polarisation of leptons is reached. The first results for CC and NC inclusive cross sections are obtained.

Figure 6. The total CC cross sections for different lepton beams and lepton polarisations compared with SM predictions based on H1 PDF 2000 fit.

The integrated e^+p and e^-p CC cross sections with positive and negative longitudinal polarisations of lepton beams have been measured by

HERAII and are presented in figure Fig.6 [12–15]. The results are consistent with each other between H1 and ZEUS. Together with the HERAI unpolarised data, the linear dependence on polarisation of CC cross sections is well established for both electrons and positrons beams, the cross sections vanish at $P_e = \pm 1$ for electrons and positrons respectively. The results are consistent with the absence of right handed charged currents as predicted by the SM.

Figure 7. The H1 NC differential cross section ratio between positive and negative longitudinal polarisations for electrons and positrons beams.

From Eqs.(5,6), the dependence of the NC cross section on the polarisation arises mainly from the γZ interference terms. The cross sections at low Q^2 region is dominated by γ exchange and thus is independent of P_e . But at high Q^2 , the NC cross sections depend on both the helicity and electric charge of the lepton due to the interference between γ and Z exchange which becomes significant. The differential cross sections with different polarisation are measured for electrons and positrons beams at HERAII by both H1 and ZEUS [8,9,14], the results are consistent between the H1 and ZEUS collaborations. Fig.7 shows the H1 measurements of the differential cross sections ratios between positive and negative longitudinal polarisations for electrons and positrons beams respectively. A clear indication of parity violation is seen as the cross sections ratios deviate from unity. The ratio rises for e^+p and falls for e^-p scattering due to different sign in Eqs.(5,6). The measurements are consistent with the SM predictions

7. Conclusion

Both H1 and ZEUS measure the proton structure functions in a wide range of x and Q^2 , and

play an important role in testing of the SM. The measurement of inclusive NC and CC processes provide important contributions to the knowledge of the proton structure and QCD. The dependences on the lepton beams polarisations of the NC and CC cross sections have been measured, and the results are consistent with the SM predictions. The forthcoming HERAII data will improve the measurements to a new level and enhance the potentials in testing of the SM.

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