Inclusive Neutral Current and Charged Current Cross Sections at High Q^2

Claus C. Beier [a] [b]

[a]Institut für Hochenergiephysik (IHEP), Universität Heidelberg, Schröderstr. 90, D-69120 Heidelberg, Germany

[b]on behalf of the H1 and ZEUS collaborations, DESY, Notkestr. 85, D-22607 Hamburg, Germany

Abstract

The latest measurements of the HERA neutral and charged current cross sections of deep inelastic (DIS) *ep* scattering are presented and confronted with SM expectations. The positron proton results from the years 1994-1997 as well as preliminary electron proton measurements from the 1998-1999 period are summarized. No deviations from the SM predictions are seen in the single and double differential cross sections $d\sigma/dx, d\sigma/dQ^2$, and $d^2\sigma/dxdQ^2$. In the neutral current channel, the effect of the Z^0 exchange is visible for the first time in DIS *ep* scattering. In the charged current channel, the propagator mass of the W boson is shown to be consistent with the world average.

1. Introduction

Over the last years HERA, the world's first electron proton storage ring in operation since 1992, offered the possibility to study the stucture of the proton on a scale down to 10^{-18} m.

This paper summarizes the latest results of the H1 and ZEUS collaborations on the inclusive cross section measurements for both neutral current (NC) and charged current (CC) deep inelastic *ep* scattering reactions at very high momentum transfers. The results were gained from the 1994-1997 positron proton and the 1998-1999 electron proton data taking periods [1],[2],[3].

In the Standard Model, deep inelastic electron (positron) proton scattering in leading order in the NC ($ep \to eX$) channel is seen as the exchange of a photon or a Z^0 boson between the interacting particles, and the exchange of a W boson in the CC ($ep \to \nu X$) case[1].

The HERA cross section measurements at very high momentum transfers not only allow to measure the structure of the proton and thereby test QCD on the smallest accessible scale, but also render the possiblity to extract parameters of the weak interaction in the space-like region, and to search for physics beyond the Standard Model. The latter point raised particular interest after a higher than expected number of events at extremely high momentum transfers had been observed previously [4],[5].

[1] X refers to the hadronic final state irrespective of its components. The measured cross sections are called 'inclusive' as no event is rejected because of its hadronic signature.

2. Collected data

In the years 1994-1997, HERA was operated with protons of 820 GeV and **positrons** of 27.6 GeV colliding at a center of mass (CMS) energy of 300 GeV. In the years 1998-1999, the proton energy was increased to 920 GeV and **electrons** of 27.6 GeV were used for the collisions. The center of mass energy increased to roughly 319 GeV.

The *ep* scattering reactions were observed by the H1 and ZEUS experiments located at two of HERA's collision points. The H1 and ZEUS detectors are described in detail in [6], [7].

From 1994-1997, H1 collected 37 pb^{-1}, ZEUS 48 pb^{-1} of **positron** proton data, from 1998-1999, H1 analysed roughly 5 pb^{-1} and ZEUS about 6 pb^{-1} of **electron** proton data.

3. Standard model predictions

The kinematic quantities used to describe the deep inelastic scattering (DIS) processes are

- the four-momentum transfer squared Q^2
  $Q^2 = -(k-k')^2$,
- the Bjorken variable x
  $x = \frac{Q^2}{2 \cdot P \cdot (k-k')}$,
- and the inelasticity y
  $y = \frac{P \cdot (k-k')}{P \cdot k}$,

where k,k', and P are the four-momenta of the incoming lepton, the scattered lepton and the incoming proton, respectively.

The increase in luminosity of roughly an order of magnitude compared to earlier measurements, allowed the extension of the cross section measurements to higher values of both Q^2 and x.

The kinematic domain covered by the presented measurements ranges in x from $6.3 \cdot 10^{-3}$ to 1.0 and in Q^2 from 200 GeV^2 to 60,000 GeV^2 (ZEUS), respectively from $1.6 \cdot 10^{-3}$ to 1.0 in x and from 120 GeV^2 to 46,300 GeV^2 in Q^2 (H1).

3.1. Neutral current

The **Born level cross sections** for the NC DIS ep reaction is given by

$$\frac{d^2\sigma_{NC}(e^\pm)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \cdot [\quad Y_+ \cdot F_2(x,Q^2) \mp Y_- \cdot xF_3(x,Q^2)] \quad (1)$$

where $(Y_\pm = 1 \pm (1-y)^2)$.

The **reduced cross section**

$$\begin{aligned} \frac{d^2\sigma^{red}_{NC}(e^\pm)}{dxdQ^2} &= \frac{1}{Y_+}\frac{xQ^4}{2\pi\alpha^2} \cdot \frac{d^2\sigma(e^\pm)}{dxdQ^2} \\ &= F_2(x,Q^2) \mp \frac{Y_-}{Y_+} \cdot xF_3(x,Q^2) \quad (2) \end{aligned}$$

directly relates to the proton structure functions $F_2(x,Q^2)$ and $xF_3(x,Q^2)$, which in the quark parton model (QPM) are interpreted as the incoherent sums $((F_2))$, respectively differences (xF_3) of the quark momentum densities within the proton [8]. The measurement of the reduced cross section therefore yields a direct picture of the quark distributions inside the proton.

The generalized structure function $F_2(x,Q^2)$ comprises contributions not only due to the photon exchange, but also due to the Z^0 exchange and the photon-Z^0 interference. The structure function $xF_3(x,Q^2)$ takes into account the parity violation of the weak interaction:

$$F_2 = F_2^\gamma + \frac{Q^2}{Q^2+M_Z^2} F_2^{\gamma/Z^0} + \left(\frac{Q^2}{Q^2+M_Z^2}\right)^2 F_2^{Z^0} \quad (3)$$

$$xF_3 = \frac{Q^2}{Q^2+M_Z^2} xF_3^{\gamma/Z^0} + \left(\frac{Q^2}{Q^2+M_Z^2}\right)^2 xF_3^{Z^0} \quad (4)$$

The Z^0 exchange is suppressed due to the propagator term $Q^2/(Q^2+M_Z^2)$. Only at very high values for Q^2, i.e. when Q^2 is of the order of M_Z^2, the Z^0 exchange plays a notable role[2].

Note that the cross sections for electron and positron scattering differ by the sign of the xF_3 term. In fact, at equal CMS energy the following relation holds:

$$xF_3(x,Q^2) = \frac{Y_+}{Y_-}\left(\frac{d^2\sigma^{red}_{NC}(e^-)}{dxdQ^2} - \frac{d^2\sigma^{red}_{NC}(e^+)}{dxdQ^2}\right). \quad (5)$$

3.2. Charged current

The Born cross section for positron and electron CC deep inelastic ep scattering is respectively given by $Y_-^{CC} = (1-y)^2$:

$$\frac{d^2\sigma_{CC}(e^+)}{dxdQ^2} = P_W \cdot \left(\bar{u} + \bar{c} + Y_-^{CC}(d+s)\right) \quad (6)$$

$$\frac{d^2\sigma_{CC}(e^-)}{dxdQ^2} = P_W \cdot \left(u + c + Y_-^{CC}(\bar{d}+\bar{s})\right) \quad (7)$$

with $P_W = G_F^2/(2\pi(1+Q^2/M_W^2)^2)$, G_F being the Fermi constant, and u, d, c, s $(\bar{u}, \bar{d}, \bar{c}, \bar{s})$ denoting the respective (anti-)quark flavors[3].

Electrons and positrons couple to different quark flavors. The positron proton cross section is dominated by the d valence quark and the anti-quark distributions while the electron proton cross section is dominated by the u valence quark distribution[4].

Again, the reduced Born cross section

$$\frac{d^2\sigma^{red}_{CC}(e^\pm)}{dxdQ^2} = \frac{2\pi}{G_F^2} \cdot (1+Q^2/M_W^2)^2 \cdot \frac{d^2\sigma_{CC}(e^\pm)}{dxdQ^2} \quad (8)$$

directly relates to the quark densities.

[2] For $Q^2 \approx 5{,}000$ GeV^2, the Z^0 contribution to the cross section is about 10 %.
[3] b, t quark contributions are neglected.
[4] Note the helicity dependent kinematic factor $Y_-^{CC} = (1-y)^2$ by which the quark flavor densities are multiplied.

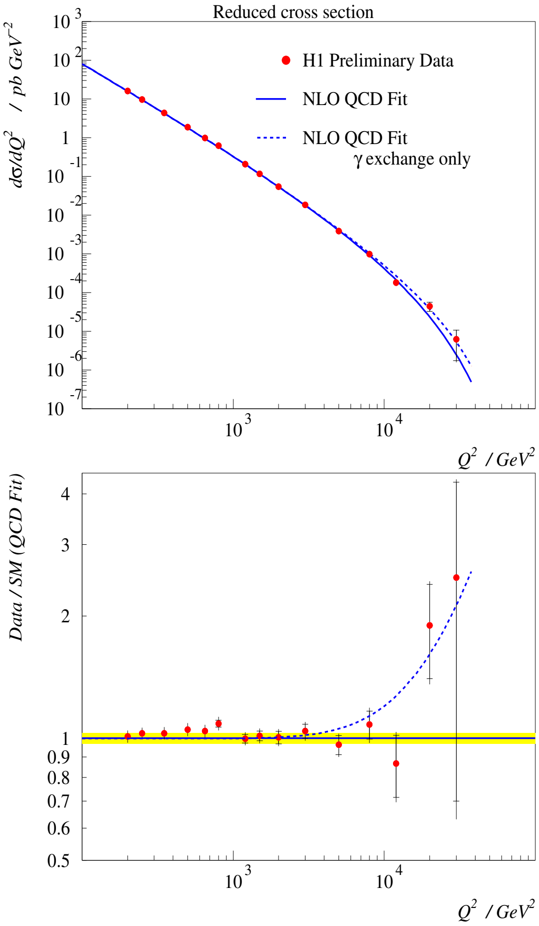

Figure 1. H1 NC cross section $d\sigma/dQ^2$.

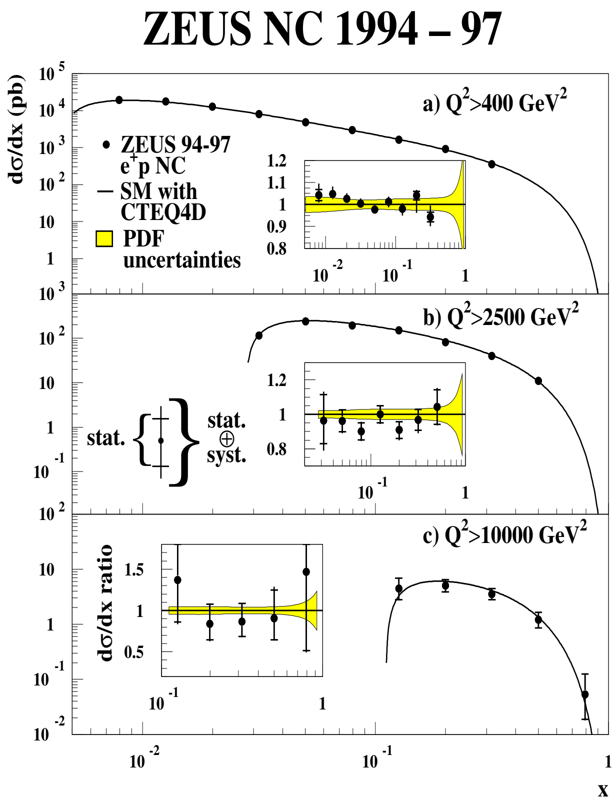

Figure 2. ZEUS NC cross section $d\sigma/dx$.

4. Results of HERA measurements

In the following subsections the H1 and ZEUS measurements of the inclusive DIS ep cross sections are presented and confronted with their SM expectations.

4.1. Neutral currents

4.1.1. Cross section measurements

The differential cross section with respect to Q^2, $d\sigma/dQ^2$, as measured by the H1 collaboration is shown in figure 1.

The cross section's steep fall as a function of Q^2 over about 7 orders of magnitude as predicted by the SM is well described by the data (top of figure 1). The bottom plot in figure 1 shows the ratio of the measured cross section with respect to the SM expectation, which in this case assumes parton density functions gained from a NLO QCD fit that was performed on the double differential NC and CC cross sections as well as results from fixed target experiments[5]. Within the uncertainties good agreement is found[6].

Only for the extreme high Q^2 values a higher than expected cross section is observed. This is consistent with the observation of an excess of events in this kinematic domain [4],[5]. However, the quoted errors are large.

The ZEUS result for the differential cross sec-

[5]The H1 QCD fit is based on the DGLAP evolution of the quark densities and is described in detail in [1], for the results of the double differential cross section measurement, see below.

[6]The error band around the SM expectation does not reflect the uncertainty on the parton densities, but represents the normalization uncertainty on the measured cross section.

tion with respect to x, $d\sigma/dx$, is depicted in figure 2 for different ranges in Q^2. The ZEUS results are compared to the SM expectation which were calculated assuming the CTEQ 4D parton density parameterization[7][9]. Very good agreement is found. The insert shows in more detail the ratio of the measured cross sections over the SM expectation.

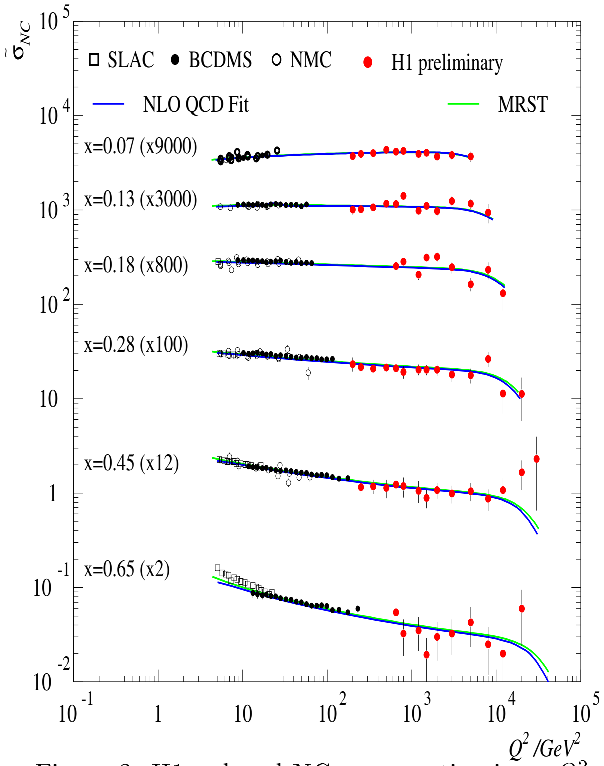

Figure 3. H1 reduced NC cross section in x, Q^2.

The double differential reduced Born cross section in x and Q^2, $d^2\sigma/dxdQ^2$, which is directly related to the proton structure functions (cf. section 3.1), is shown in figure 3. Again good agreement between measurement and SM expectation is found over the whole kinematic range. In addition, the H1 data nicely extend the measurements gained by the fixed target experiments BCDMS and NMC.

4.1.2. Effects of Z^0 in NC DIS *ep* reactions

As noted in section 3.1, the effect of the Z^0 exchange becomes notable only at very high values of the momentum transfer Q^2 (i.e. for Q^2 comparable to M_Z^2).

For the first time in DIS *ep* scattering, the effect of the Z^0 exchange is visible as shown in figure 4. The data appear to be in good agreement

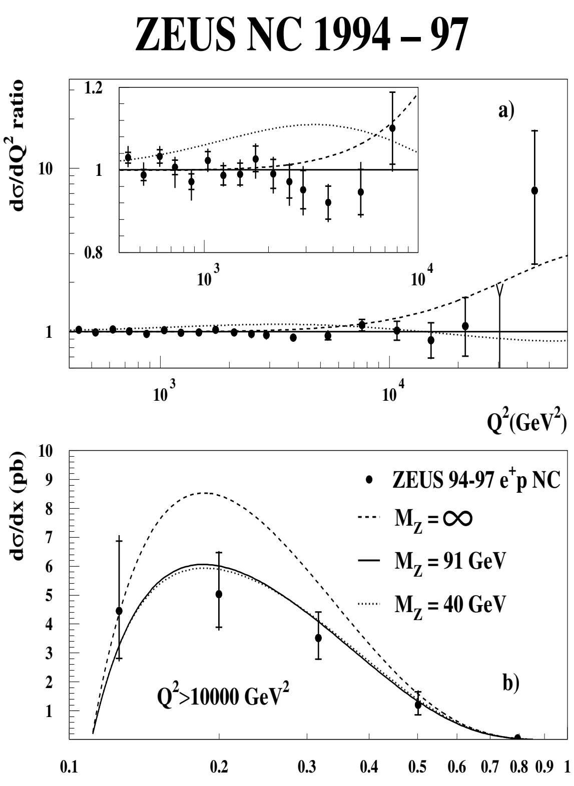

Figure 4. ZEUS NC single differential cross sections compared to predictions with $M_Z = 40$ GeV and with photon-only exchange.

with the SM expectation assuming the propagator mass[8] $M_Z = 91$ GeV, whereas smaller values

[7]Here the error band reflects the parton density uncertainty.

[8]The term "propagator mass" refers to the mass parameter by which the virtual Z (or W boson, cf. section 4.2.2)

for M_Z result in expectations incompatible with the data (insert at top of figure 4, the dashed line was calculated setting $M_Z = 40$ GeV). On the other hand, neglecting the Z^0 exchange[9] as in figure 4 bottom) is disfavored by the experimental results.

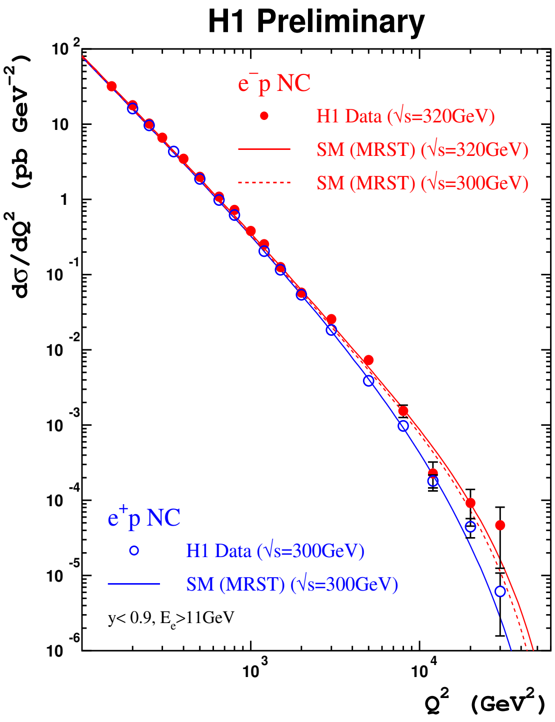

Figure 5. H1 preliminary NC cross section $d\sigma/Q^2$ for e^-p and $e+p$ reactions.

4.1.3. Comparison of electron and positron data

Comparing the preliminary H1 e^-p cross section measurements of the years 1998 and 1999 with the e^+p cross section measurements of 1994-1997 in figure 5 demonstrates that the electron cross section is consistently greater than the positron cross section. This behaviour is expected due to the parity violating structure function xF_3 (cf. section 3.1)[10].

4.2. Charged current

4.2.1. Cross section measurements

The measured CC single differential cross section with respect to Q^2, $d\sigma/dQ^2$, demonstrates good agreement with the SM expectation as the ZEUS result in figure 6 shows. Here, the CTEQ 4D parton density distributions were assumed for the SM prediction.

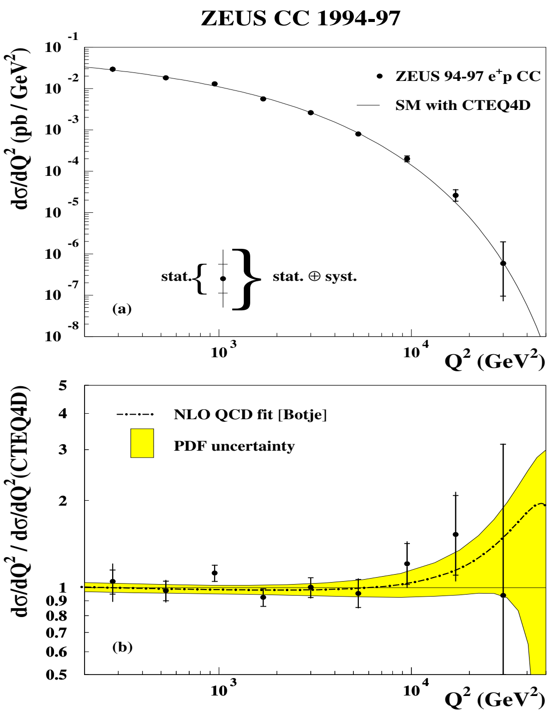

Figure 6. ZEUS CC cross section $d\sigma/Q^2$.

is represented in the expression for the Born cross section: it is the mass of the boson in the space-like region. The SM assumes this mass to be equal to the the mass of a Z (W) boson produced in the s-channel.

[9]This is equivalent to setting $M_Z = \infty$.

[10]Note that the CMS energy was increased to 319 GeV in the 1998-1999 electron data taking period compared to the CMS energy of 300 GeV in the 1994-1997 positron data taking period. The dashed line gives the SM expectation for the electron cross section at 300 GeV. The shift due the different CMS energy is significantly smaller than the observed difference in electron and positron data.

For the first time the data of the years 1994-1997 allowed to measure the charged current cross section in DIS ep scattering at HERA double differentially with respect to both x and Q^2. Figure 7 shows the H1 result of the reduced Born cross section,$(d^2\sigma_{red}^{CC}(e^+)/dxdQ^2)$ (which is directly related to the quark density functions inside the proton, cf. section 3.2).

Again, very good agreement of data with SM expectation is observed. The SM prediction was calculated using the MRS T parton density distributions for comparison [10]. The dashed line represents the predicted d valence quark contribution. Noticeably, at high x the CC DIS ep reactions can be viewed as the scattering of electrons off d valence quarks.

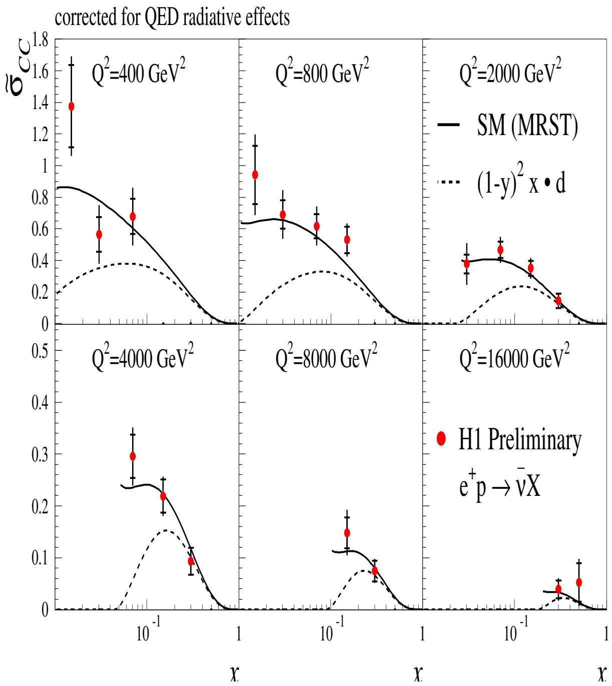

Figure 7. H1 CC reduced cross section $(d\sigma_{red}^{CC}(e^+)/dxdQ^2)$.

4.2.2. Extraction of W boson propagator mass

With the CC cross section directly related to the propagator mass of the exchanged W boson by equation (6), the CC cross section measurements allow the extraction of the propagator mass M_W.

Constraining the value for G_F, H1 and ZEUS find comparable results [1],[2]:

$$\begin{aligned} M_W^{ZEUS} &= 81.4^{+2.7}_{-2.6}(\text{stat})^{+3.3}_{-3.0}(\text{syst}) \\ &\quad ^{+3.3}_{-3.0}(\text{pdf})\text{GeV}, \\ M_W^{H1} &= 80.9 \pm 3.3(\text{stat}) \pm 1.7(\text{syst}) \\ &\quad \pm 3.7(\text{theo.}) \end{aligned}$$

In addition, ZEUS performed two more fits: an unconstrained fit yielding values for both G_F and M_W:

$$\begin{aligned} G_F &= (1.171 \pm 0.034(\text{stat})^{+0.026}_{-0.032}(\text{syst}) \\ &\quad ^{+0.016}_{-0.015}(\text{pdf})) \cdot 10^{-5}\text{GeV},^{-2} \\ M_W &= 80.8^{+4.9}_{-4.5}(\text{stat})^{+5.0}_{-4.3}(\text{syst})^{1.4}_{-1.3}(\text{pdf})\text{GeV}, \end{aligned}$$

and a model dependent fit by constraining the electroweak parameters to SM relations

$$\begin{aligned} M_W &= 80.5^{+0.24}_{-0.25}(\text{stat})^{+0.13}_{-0.16}(\text{syst}) \\ &\quad ^{+0.3}_{-0.31}(\text{pdf})^{+0.03}_{-0.03}(M_T)^{+0}_{-0.05}(M_H)\text{ GeV} \end{aligned}$$

with M_T, M_H masses of the top quark and the Higgs boson, respectively. The additional constraints result in smaller errors on M_W, it should be kept in mind, though, that the latter result rather represents a model dependent fit than a measurement[11].

All values for the propagator mass M_W are well compatible with the world average of 80.41 GeV [11].

4.2.3. Comparison of electron and positron data

The preliminary measurements for the CC single differential electron proton cross sections with respect to Q^2, $d\sigma/dQ^2$, are found to be in good agreement with the SM expectation.

Comparing the ZEUS results for electrons and positrons - depicted in figure 8 - shows that the

[11] For details see [2].

electron cross sections are consistently greater than the positron cross sections over the whole kinematic range in Q^2 [12].

This behaviour reflects the different abundance of quark flavors inside the proton as the incoming electron couples to different quark flavors than the incoming positron (cf. section 3.2). The increasing ratio of the electron with respect to the positron cross section (bottom of figure 8) is due to the helicity dependence of the cross sections.

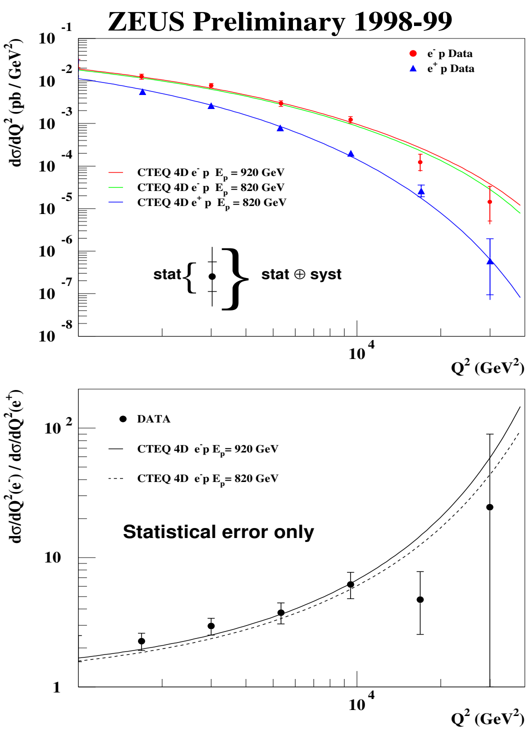

Figure 8. ZEUS CC cross sections $d\sigma/dQ^2$ for e^+p and e^-p reactions.

[12]The dashed line gives the expectation for the electron cross section at a CMS energy of 300 GeV. The difference to the CMS energy of 319 GeV is noticeable, but small when comparing electron and positron cross sections.

5. Summary

The inclusive cross sections for deep inelastic ep scattering were measured by the H1 and ZEUS collaborations in the space-like regime in both the neutral current ($ep \to eX$) and the charged current channel ($ep \to \nu X$) at very high values for the momentum transfer Q^2.

For the 1994-1997 **positron proton** reactions, the differential cross sections $d\sigma/dx$,$d\sigma/dQ^2$, and the reduced cross section $(d^2\sigma/dxdQ^2)_{red}$ were measured and confronted with the SM expectations.

Overall, the SM prediction is in good agreement with the data. In addition, a NLO QCD fit performed by H1 describes the data accurately. The effect of the Z^0 boson is visible for the first time in neutral current DIS ep scattering. The charged current cross sections were used to fit the propagator mass of the W boson. Both the H1 and ZEUS results are compatible with the world average.

For the 1998-1999 **electron proton** reactions, preliminary H1 and ZEUS measurements of the differential cross section $d\sigma/dQ^2$ are presented for neutral and charged currents. No deviation from the SM prediction is seen. The cross section for electrons is consistently greater than for positrons in both channels. While this behavior in neutral currents results from the parity violating structure function $xF_3(x, Q^2)$, in charged currents, beside kinematic factors, it is due to the different abundance of quark flavors inside the proton.

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