STRUCTURE FUNCTIONS AND LARGE $Q^2$ CROSS SECTIONS AT HERA

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Abstract

The data collected with the H1 and ZEUS detectors during the running period 1994-99 are used to give an experimental review on the proton structure functions and the neutral current and charged current large $Q^2$ cross sections in $e^\pm p$ scattering at HERA.

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1 Foreword

With the advent of the HERA $e^\pm p$ collider at DESY, enormous progress in the measurement of the proton structure has been made. The large HERA $ep$ centre-of-mass energy $\sqrt{s} = 300 - 318$ GeV, obtained with a lepton-beam energy $E_e = 27.5$ GeV and proton-beam energies $E_p = 820$ GeV until 1997 and $E_p = 920$ GeV since 1998, allowed the two collider experiments H1 and ZEUS to measure $F_2$ up to virtualities of the exchanged boson $Q^2 \sim 10^5$ GeV$^2$ and down to Bjorken $x \sim 10^{-6}$. These measurements constitute an extension by more than two orders of magnitude of the $(x, Q^2)$ range in which we have knowledge of the proton structure (see Fig. 1). The study of $e^\pm p$ interactions is important throughout the above kinematic range,

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{kinematic_range.png}
\caption{The $(x, Q^2)$ kinematic plane, showing the range covered by the HERA and the fixed target measurements.}
\end{figure}

not only because of the structure functions, which allow a calculation of the expected rates at the LHC and an estimation of the $\nu N$ cross sections for ultra-high-energy neutrinos $^{[1]}$ ($E_\nu \sim 10^{12}$ GeV) from active galactic nuclei and $\gamma$-ray bursts, but also because of several theoretical issues still open in this field:
it is of primary importance to study the transition from the photoproduction ($Q^2 \sim 0$) to the deep inelastic scattering (DIS, $Q^2 \gtrsim \text{few GeV}^2$) regime to see at which value of $Q^2$ perturbative QCD (pQCD) begins to dominate;

the strong rise of $F_2$ measured in DIS at HERA for $x \to 0$ is a well established and important fact. However, it is imperative to measure $F_2$ with higher and higher precision over a wide kinematic range, in order to address the issues of parton saturation at very small $x$ and QCD evolution (the BFKL evolution), which ought to be important when terms in $\ln \frac{1}{x}$ become large, has yet to be observed experimentally;

as will be shown in the following, the study of electroweak (EW) physics at HERA is just beginning. Large luminosities both with electrons and positrons, as well as polarised beams, are needed to perform these studies, which have always been one of the main aims of HERA;

the exploration of new kinematic regimes may reveal new physics. The breakdown of the Standard Model may manifest itself as deviations of the measured cross sections from the predictions at very large $(x, Q^2)$.

In this document, an experimental review will be given of the knowledge of proton structure functions and $ep$ cross sections at large $Q^2$ using the H1 and ZEUS results, obtained with the $\sim 70 \text{ pb}^{-1}$ of $e^+p$ and $\sim 15 \text{ pb}^{-1}$ of $e^-p$ collisions that each experiment has collected until the end of 1999.

2 Kinematics

In inclusive deep inelastic scattering, $e(k) + p(P) \to e(k') + X$, the proton structure functions are expressed in terms of the negative of the four-momentum transfer squared:

$$Q^2 = -q^2 = -(k - k')^2$$

and of the Bjorken $x$:

$$x = \frac{Q^2}{2 P \cdot q}$$

where $k$ and $P$ are the four-momenta of the incoming particles and $k'$ is the four-momentum of the scattered lepton. The fraction of the lepton energy transferred to the proton in its rest frame is $y = Q^2/(sx)$. The ZEUS and H1 detectors measure the energies and angles of the scattered lepton and hadronic system. These four independent quantities over-constrain the kinematic variables $x$ and $Q^2$ (or, equivalently, $y$ and $Q^2$). In order to optimise the reconstruction of the kinematic variables,
the two collaborations use different methods, dictated by the characteristics of their detectors \(^2\).

3 The proton structure functions

In inclusive deep inelastic scattering the double differential cross section for the exchange of a neutral current (NC) is given by:

\[
\frac{d^2\sigma_{e^\pm p}^{NC}}{dx \, dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[ Y_+ F_2(x, Q^2) - y^2 F_L(x, Q^2) \mp y x F_3(x, Q^2) \right] \left( 1 + \delta_r(x, Q^2) \right) \tag{1}
\]

where \(Y_\pm = 1 \pm (1 - y)^2\), \(\alpha\) is the EW coupling constant and \(\delta_r\) is the EW radiative correction. In leading order QCD and for longitudinally unpolarized beams, the longitudinal structure function \(F_L = 0\), while the structure functions \(F_2\) and \(xF_3\) are expressed as sums over the quark flavor \(f\) of the product of the EW quark couplings, \(A_f\) and \(B_f\), and the quark momentum distributions in the proton \(q_f(x, Q^2)\):

\[
F_2 = x \sum_f A_f^2 \cdot (q_f(x, Q^2) + \bar{q}_f(x, Q^2))
\]

\[
xF_3 = x \sum_f B_f^2 \cdot (q_f(x, Q^2) - \bar{q}_f(x, Q^2))
\]

where, at low \(Q^2\), \(A_f\) reduces to the quark electric charge. The parity violating term \(xF_3\), due to \(Z^0\) exchange, becomes relevant only for \(Q^2 \simeq M_{Z^0}^2\), where \(M_{Z^0}\) is the mass of the \(Z^0\) boson. Beyond the leading order in QCD, the emission of gluons allows longitudinally polarised photons to be absorbed by spin \(1/2\) quarks. Therefore \(F_L\) becomes non-zero and can be written as a function of \(F_2\) and the gluon momentum distribution \(xg(x, Q^2)\):

\[
F_L = \frac{\alpha_s \alpha^2}{4\pi} x^2 \int \frac{dz}{z^3} \left[ \frac{16}{3} F_2 + 8 \sum_i e_i^2 \left( 1 - \frac{x}{z} \right) zg \right]. \tag{2}
\]

The effect of \(F_L\) on the cross section is negligible at small values of \(y\) and becomes substantial at large \(y\).

3.1 High precision \(F_2\) measurements at very small \((x, Q^2)\)

During 1997, the beam pipe tracker \(^3\) (BPT), a tracking device based on silicon microstrip technology, was installed in the ZEUS detector in front of the existing beam pipe calorimeter (BPC), a small electromagnetic sampling calorimeter positioned at small scattered-lepton angles to measure the energy of the scattered lepton in low-\(Q^2\) events. The installation of the BPT improved the measurement of the
scattered-lepton angle and allowed the fiducial range of the BPC to be increased, thus extending the kinematic range of the $F_2$ measurement at very small $(x, Q^2)$ to $0.045 < Q^2 < 0.65$ GeV$^2$ and $6 \cdot 10^{-7} < x < 1 \cdot 10^{-3}$. The measured $F_2$ as a function of $x$ for several $Q^2$ values, obtained with 3.9 $pb^{-1}$ of $e^+p$ collisions collected with the BPT, are shown in Fig. 2. The typical uncertainties are $\pm 2.6\%$ (stat.) and $\pm 3.3\%$ (syst.). The rise of $F_2$ for $x \to 0$ is measured to become slower as $Q^2$ decreases, and can be described by Regge theory with a constant logarithmic slope. The dependence of $F_2$ on $Q^2$ is stronger than at higher $Q^2$ values, approaching, at the lowest $Q^2$ of this measurement, a region where $F_2$ becomes nearly proportional to $Q^2$. 

Figure 2: The HERA measurement of $F_2$ at very small $x$ and $Q^2$. E665 data are also shown. The lines are the result of a fit to the data based on Regge phenomenology. 

ZEUS 1997
3.2 $F_2$, its derivatives and the QCD NLO fit at medium $Q^2$

3.2.1 $F_2$ measurements at medium $Q^2$ at HERA: precision data

The data samples collected during 1996-97 with the H1 and ZEUS detectors, each corresponding to approximately 40 pb$^{-1}$, made possible a precise measurement of $F_2$ at medium $Q^2$. This improvement was possible both because of the higher statistics and a better knowledge of the systematic uncertainties. The latter was partly due to the installation of new detector components, such as the H1 backward silicon detector. Typical uncertainties of approximately 1% statistical and 2 – 3% systematic were achieved, thus approaching the precision of the fixed-target experi-
The derivative $d\ln F_2/d\ln x = \lambda_{\text{eff}}$ as a function of $Q^2$ calculated by fitting $F_2 = Ax^{-\lambda_{\text{eff}}}$ to the E665 and ZEUS data with $x < 0.01$. The ZEUSREGGE and ZEUSQCD calculations are from the Regge and NLO QCD fits. The average $x$ values of the various points are reported on the top of the Figure.

3.2.2 Derivatives of $F_2$

As pointed out in the literature, the slopes $d\ln F_2/d\ln x$ and $dF_2/d\ln Q^2$ contain a lot of information. At fixed $Q^2$ and at small $x$ the behaviour of $F_2$ can be characterised by $F_2 \propto x^{-\lambda_{\text{eff}}}$, so that $\lambda_{\text{eff}} = d\ln F_2/d\ln x$. The value of $\lambda_{\text{eff}}$ as an observable at small $x$ has been discussed by Navelet et al. The E665 and ZEUS $F_2$ data at fixed $Q^2$ and $x < 0.01$ have been fitted to the form $A x^{-\lambda_{\text{eff}}}$. Fig. 4 shows the measured values of $\lambda_{\text{eff}}$ as a function of $Q^2$. Regge phenomenology
predicts $\lambda_{\text{eff}} = \alpha_P(0) - 1 \approx 0.1$ independent of $Q^2$, where $\alpha_P(0)$ is the intercept of the pomeron trajectory. Data for $Q^2 < 1$ GeV$^2$ are consistent with this prediction. For $Q^2 > 1$ GeV$^2$, $\lambda_{\text{eff}}$ is observed to rise, reaching approximately 0.3 at $Q^2 = 50$ GeV$^2$. The rise of $\lambda_{\text{eff}}$ with $Q^2$ is described by pQCD \cite{12}, in particular by the ZEUS pQCD NLO fit, based on DGLAP evolution equations, shown in Fig. 4. As was the case for the $F_2$ measurements, there is no need in the evolution equations for $(\ln \frac{1}{x})^n$ terms in order to to describe the logarithmic slope in $x$ of $F_2$.

Even more interesting is the study of $dF_2/d\ln Q^2$. At small $x$, this derivative is dominated by the convolution of the splitting function $P_{qg}$ and the gluon density, $dF_2/d\ln Q^2 \sim \alpha_S P_{qg} \otimes xg$. As a consequence, $xg$ can be directly related to the measured values of $dF_2/d\ln Q^2$ \cite{13}. The logarithmic slope $dF_2/d\ln Q^2$ has been calculated using the ZEUS data by fitting $F_2 = a + b \ln Q^2$ in bins of fixed $x$. The results \cite{13} are shown in Fig. 5. For values of $x$ down to $3 \times 10^{-4}$, the slopes increase as $x$ decreases, while at smaller values of $x$ and $Q^2$ the slopes decrease. It should be noted that each point in Fig. 5 corresponds to a different average value
Figure 6: The momentum distributions of partons as obtained by the H1 and ZEUS collaborations. Right: the gluon momentum distribution \(xg\) as a function of \(x\) at fixed values of \(Q^2 = 5, 20\) and 200 GeV\(^2\) from the H1 QCD fit. Left: the quark singlet momentum distribution, \(x\Sigma\) (shaded), and the gluon momentum distribution, \(xg\) (hatched), as functions of \(x\) at fixed values of \(Q^2 = 1, 7\) and 20 GeV\(^2\) from the ZEUS QCD fit.

of \(Q^2\), as indicated at the top of Fig. 5. As predicted by pQCD, the ‘turn over’ is not seen if \(dF_2/d\ln Q^2\) is plotted at a fixed value of \(Q^2\), neither in the fixed target data at \(Q^2 > 0.5\) GeV\(^2\) \cite{13} nor in the HERA data at \(Q^2 > 3\) GeV\(^2\) \cite{14}. Although the ‘turn over’ is partly a kinematic effect due to averaging over a \(Q^2\) range which is different for different \(x\) values, it reflects a smaller rise of the derivatives \cite{16} (i.e. of the gluon density) for \(x \to 0\) when \(Q^2\) decreases below few GeV\(^2\). We will return to this discussion in the next Section.

3.2.3 The pQCD NLO fits: the gluon and quark singlet momentum densities

In order to extract the parton momentum distributions in the proton, both the H1 and ZEUS collaborations performed a pQCD fit to the \(F_2\) data, solving the DGLAP evolution equations \cite{17} at NLO in the \(\overline{MS}\) renormalisation scheme. In both fits, \(\alpha_s(M_Z^0) = 0.118\), the momentum sum rule was applied and three light flavours were
considered, the $c$ and $b$ quarks being generated dynamically through boson-gluon fusion (BGF). The H1 fit\(^{[4]}\) used H1 and NMC data at $3.5 < Q^2 < 3000$ GeV\(^2\), while the ZEUS fit\(^{[13]}\) used ZEUS, NMC and BCDMS data at $1 < Q^2 < 5000$ GeV\(^2\). The results for the gluon momentum distribution $xg(x,Q^2)$ vs. $x$ are shown in Fig. 6 at fixed values of $Q^2$. Both collaborations measure a strong rise of $xg$ for $x \to 0$ for $Q^2 > \sim 5$ GeV\(^2\), with the rise increasing with increasing $Q^2$. In Fig. 6 right, the $xg$ obtained by ZEUS is compared to the quark singlet momentum distribution $x\Sigma(x,Q^2) = \sum_{f=u,d,s}[xq_f(x,Q^2) + x\bar{q}_f(x,Q^2)]$ obtained with the same fit. At $Q^2 = 1$ GeV\(^2\), the sea is still rising at the lowest $x$, while the gluon, within large uncertainties, is rising much less and is compatible with zero. These results are not compatible with the assumption that the rise of $F_2$ at $Q^2 \sim 1$ GeV\(^2\) is entirely driven by the increase of the gluon density at small $x$ due to parton splitting.

### 3.3 Determination of the longitudinal structure function $F_L$ at small $x$

The longitudinal structure function $F_L$ is predicted by pQCD to be a function of $F_2$ and $xg$ (see Eq.\(^2\)) and it is expected to give a sizable contribution to the cross section at large values of $y$. Therefore a measurement of $F_L$ constitutes an important constraint to the theory. In the measurements of $F_2$ described above, $F_L$ was assumed to be equal to the QCD prediction. A direct measurement\(^{[17]}\) of $F_L$ requires either running the HERA collider at different centre-of-mass energies or using events with initial state QED radiation. The H1 collaboration extracted $F_L$ from the NC cross section measurements using the “subtraction” method\(^{[18]}\). For $Q^2 \ll M_{Z^0}^2$ and neglecting radiative corrections, the NC cross section\(^{[11]}\) can be written:

$$\frac{d^2\sigma_{NC}^{ep}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \cdot \sigma_r$$

where the reduced cross section $\sigma_r = F_2 - (y^2/Y_+) \cdot F_L$. Therefore, at large $y$, $\sigma_r \simeq F_2 - F_L$ and $F_L$ may be approximated by $F_2 - \sigma_r$. The method used by H1 consists in the subtraction of $\sigma_r$ from $F_2^{QCD}$, i.e. the result of the NLO pQCD fit to the 1996-97 $F_2$ data at $y < 0.35$, for which $F_L \simeq 0$. The results\(^{[7]}\) obtained with this method for $Q^2 > 10$ GeV\(^2\) are shown in Fig. 7. They rely on the extrapolation of $F_2^{QCD}$ beyond $y = 0.35$. In the same Figure the results obtained with another method, which relies on assumptions on the behaviour of the derivative $dF_2/d\ln y$ for $Q^2 < 10$ GeV\(^2\), are also shown. The extracted $F_L$ is consistent with the QCD prediction.
3.4 Measurement of the charm structure function $F_{2}^{c\bar{c}}$

Charm production at HERA is expected to be dominated by BGF \(19\), i.e. by the gluon density. Therefore, given the large $xg$ measured at HERA for $x \to 0$ in most of the $Q^2$ range, we expect the charm contribution to $F_2$ to be large. In analogy with Eq. (1), for not too large $Q^2$ and $y$ and neglecting radiative corrections, the charm structure function $F_{2}^{c\bar{c}}$ is defined as:

$$\frac{d^2\sigma^{c\bar{c}}}{dx \, dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ F_{2}^{c\bar{c}}(x, Q^2).$$

Experimentally, the cross section for the production of a $c\bar{c}$ pair, $\sigma^{c\bar{c}}$, is extracted from the visible cross section for the production of $D^*$ mesons, $\sigma^{D^*}$, after correction for the $c \to D^*$ fragmentation and extrapolation to the full $(\eta, p_T)$ range. This measurement is a very effective test of QCD, since $F_{2}^{c\bar{c}}$ is also calculable from pQCD knowing $xg$ from the $F_2$ scaling violations and applying the BGF NLO calculations \(13\). The result of such a calculation can be compared to the direct measure-
Figure 8: Measurement of $F_{2c\bar{c}}$ (left) and $F_{2c\bar{c}}/F_2$ (right) vs. $x$ in bins of $Q^2$. The full lines are the result of the ZEUS pQCD NLO fit, while the dashed lines represent the uncertainty of the fit, dominated by the variation by 0.2 MeV of the charm mass around the central value $m_c = 1.4$ GeV.

The effect of the charm-mass threshold is negligible at the small $x$ values discussed here.\footnote{The effect of the charm-mass threshold is negligible at the small $x$ values discussed here.}
Figure 9: The $d\sigma_{NC}/dQ^2$ for $e^+p$ scattering at HERA. The line represents the Standard Model prediction described in the text.

4.1 Neutral currents

For $Q^2$ beyond a few thousand GeV$^2$, the parity violating structure function $xF_3$ becomes sizable and can no longer be neglected. In this case we will write the NC cross section:

$$\frac{d^2\sigma_{NC}^{e^+p}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[ Y_+\tilde{F}_2(x,Q^2) \mp Y_- x\tilde{F}_3(x,Q^2) \right]$$

(3)

having neglected radiative corrections and $F_L$. The structure functions themselves contain contributions from virtual photon and $Z^0$ exchange:

$$\tilde{F}_2 = F_2^{em} + \frac{Q^2}{(Q^2 + M_{Z^0}^2)} F_2^{int} + \frac{Q^4}{(Q^2 + M_{Z^0}^2)^2} F_2^{wk}$$

$$\tilde{F}_3 = \frac{Q^2}{(Q^2 + M_{Z^0}^2)} F_3^{int} + \frac{Q^4}{(Q^2 + M_{Z^0}^2)^2} F_3^{wk}$$

where the superscripts $em$, $wk$ and $int$ indicate the contributions due to photon exchange, $Z^0$ exchange and $\gamma Z^0$ interference. The measured $e^+p$ NC cross section vs. $Q^2$ is shown in Fig. 9. The fall of $d\sigma_{NC}^{e^+p}/dQ^2$ over seven orders of magnitude constitutes a great success for the Standard Model. The extrapolation to large $Q^2$ values of the NLO pQCD fit, including the EW propagator terms, obtained
Figure 10: The reduced cross section $\tilde{\sigma}_{NC}$ for $e^+p$ and $e^-p$ collisions. The effect of the $\gamma Z^0$ interference is evident at the largest $Q^2$ and is in agreement with the theory.

with the data at $Q^2 < 120 \text{ GeV}^2$ describes the data well, proving the validity of the theory in such a wide $Q^2$ range. Larger luminosities are needed to constrain the PDFs at the largest ($x, Q^2$) values.

The structure function $xF_3$ enters in Eq. (3) with a $-$ or $+$ sign depending if the lepton beam consists of positrons or electrons, respectively. Therefore the collection of both $e^-p$ and $e^+p$ data samples permit a measurement of $xF_3$. The reduced cross section:

$$\tilde{\sigma}_{NC} = Y_+ F_2(x, Q^2) \mp Y_- x F_3(x, Q^2)$$

is shown in Fig. 10 for both $e^+p$ and $e^-p$ data. For $Q^2 > 3000 \text{ GeV}^2$, the $e^-p$ cross sections are larger than the $e^+p$ ones, as expected from the Standard Model $\gamma Z^0$ interference.
4.2 Charged currents

The charged current (CC) double-differential cross section can be written:

\[
\frac{d^2\sigma_{CC}^{\pm}}{dx dQ^2} = \frac{G_F^2}{2\pi x} \left( \frac{M_W^2}{Q^2 + M_W^2} \right)^2 \cdot \Phi_{CC}^{\pm}(x, Q^2)
\]  

(4)

where \(G_F\) is the Fermi constant and \(M_W\) is the \(W^\pm\) boson mass. In the naive quark-parton model:

\[
\Phi_{CC}^{+}(x, Q^2) = \bar{u} + (1 - y)^2 \cdot (d + s)
\]

\[
\Phi_{CC}^{-}(x, Q^2) = u + (1 - y)^2 \cdot (\bar{d} + \bar{s}).
\]

It should be noticed that in the case of \(e^- p\) scattering the CC cross section is directly sensitive to quarks (whereas \(\sigma_{CC}^{e^+ p}\) is sensitive to antiquarks) and that in the case of \(e^+ p\) scattering the helicity factor \((1 - y)^2\) multiplies the quark densities. For both these reasons we expect \(\sigma_{CC}^{e^- p} > \sigma_{CC}^{e^+ p}\) at large \((x, Q^2)\), where valence quarks must dominate. Fig. 10 shows the HERA CC differential cross sections \[23, 24, 25, 26\] as

Figure 11: HERA CC differential cross sections vs. \(Q^2\) for \(e^+ p\) and \(e^- p\) scattering. The HERA 1994-97 data at \(\sqrt{s} = 300\,\text{GeV}\) and the 1998-99 data at \(\sqrt{s} = 318\,\text{GeV}\) are plotted. The lines represent the Standard Model predictions.
Figure 12: The HERA measurements of the CC cross section with respect to the Standard Model, $\sigma^0/\sigma^0(SM) \propto G_F$, and of the W-propagator mass. The one sigma contours are obtained using only the statistical uncertainties.

The difference between $\sigma^{e^-p}_{CC}$ and $\sigma^{e^+p}_{CC}$ increases with $Q^2$, reaching approximately one order of magnitude at $Q^2 \approx 10^4$ GeV$^2$. The Standard Model describes the data well.

4.2.1 Measurements of the W-propagator mass

Charged current reactions are mediated by the exchange of a virtual $W^{\pm}$. It is important to measure the $W$-propagator mass, i.e., the mass of a spacelike $W$, since a deviation from the timelike-$W$ mass measured in $e^+e^-$ and $pp$ collisions may reveal an anomalous spacelike EW sector. In Eq. (4) the absolute magnitude of the cross section is given by $G_F$ and the functions $\Phi^{\pm}$, while the cross-section shape is entirely contained in the propagator term. The H1 and ZEUS collaborations fitted the CC
cross section with two free parameters, the coupling $G_F$ and the propagator mass $M_W$. The results are shown in Fig. 11, where the H1 and ZEUS one sigma contour distributions, and the combined one, are given. Both collaborations find the $W$-propagator mass in agreement with the timelike-$W$ mass within a statistical uncertainty of approximately 5 GeV. This result proves the universality of the CC interactions over a wide range of $Q^2$. The fit has been repeated constraining the cross-section normalisation using the precise value $G_F = (1.16639 \pm 0.00001) \cdot 10^{-5}$ GeV$^2$, measured in muon decay. In this case, the results are in agreement with the timelike-$W$ mass within $\sim 3$ GeV (stat.) and $\sim 5$ GeV (stat. $\oplus$ syst.). Finally, to exploit the strong dependence of the cross-section normalisation ($G_F$) on the shape ($M_W$) in a model-dependent fit, ZEUS used the Standard Model relation:

$$G_F = \frac{\pi \alpha}{\sqrt{2}} \cdot \frac{M_{Z^0}^2}{M_W^2(M_{Z^0}^2 - M_W^2)} \cdot \frac{1}{1 - \Delta r(M_W)}$$

where $\Delta r(M_W)$ contains the radiative corrections to the lowest-order expression for $G_F$ and is a function of $\alpha$ and the masses of the fundamental bosons and fermions. Using this relation, the 3% cross-section uncertainty is cast in the uncertainty of a single EW parameter, and the uncertainty on the $W$-propagator mass is expected to reduce by a large factor. The result of this model-dependent fit is $25$:

$$M_W = 80.50^{+0.24}_{-0.25}(\text{stat.})^{+0.13}_{-0.16}(\text{syst.}) \pm 0.31(PDF)^{+0.03}_{-0.06}(\Delta M_t, \Delta M_H, \Delta M_Z)\text{GeV},$$

where the last uncertainty is obtained by varying the masses of the top quark, the Higgs and the $Z^0$ bosons.

### 4.3 Comparison of NC and CC cross sections

The Standard Model predicts that, with increasing $Q^2$, NC and CC should become of equal magnitude. This prediction can be verified at HERA, given the large range in $Q^2$. Fig. 13 shows the ZEUS and H1 measurements of the differential $e^-p$ NC and CC cross sections as a function of $Q^2$. At $Q^2 \simeq 10^4$ GeV$^2$ the $e^-p$ NC and CC cross sections reach similar values. The Standard Model predictions are in good agreement with the measurements. We conclude that the unification of charged currents and neutral currents has been verified at HERA.

### 5 Summary and outlook

The study of structure functions at HERA has reached a mature stage. The structure function $F_2$ has been measured in a very wide kinematic range, $10^{-1} < Q^2 < 10^5$.
Figure 13: The HERA measurements of NC and CC $e^-p$ cross sections, showing their unification at large $Q^2$, as predicted by the Standard Model.

GeV$^2$ and $x$ down to $10^{-6}$. Precisions of a few percent have been reached in a large fraction of the above range. At the lowest $Q^2$ measured, $F_2$ can be described by Regge phenomenology. For $Q^2$ above few GeV$^2$, the region where pQCD is expected to be applicable, the DGLAP evolution works well and no need is found for the BFKL $(\ln \frac{1}{x})^n$ correction terms. In this region $F_2$ rises strongly towards small $x$; hints have been found that at small $Q^2$ this rise may be driven by sea quarks, and not by gluons. The charm structure function $F_c\bar{c}$ is measured to be a substantial contribution to $F_2$, reaching 25% at small $x$ and large $Q^2$. Indirect determinations of the longitudinal structure function $F_L$ agree with the QCD expectation.

The first measurements of the NC and CC cross sections at very large $Q^2$ have been made in $e^\pm p$ scattering. The Standard Model predictions agree with the data. In NC interactions, $\gamma Z^0$ interference has been observed, while in CC interactions the $W$-propagator mass has been measured to be consistent with the timelike-$W$ mass within a few GeV. The unification of NC and CC interactions at very large $Q^2$ has been measured in $e^-p$ scattering.
Overall, the Standard Model is found to be in good agreement with the measurements based on approximately 100 $pb^{-1}$ of data collected at HERA by each collider experiment. The plans for the future are to increase the integrated luminosity by an order of magnitude. In Summer 2000 HERA will be shut down for nine months. During this period, superconducting magnets will be installed inside the H1 and ZEUS detectors to achieve stronger beam focusing at the interaction points and obtain an increase of a factor of five in specific luminosity. The plans are to run for at least five more years to integrate $\sim 1 \, fb^{-1}$ of data, which will give full access to the electroweak physics programme and to the search for physics beyond the Standard Model at HERA.

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