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Future *ep* Physics: *The Outlook for HERA*

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Abstract

The luminosity of the electron-proton collider, HERA, will be increased by a factor of five during the long shutdown in the year 2000. At the same time longitudinal lepton beam polarisation will be provided for the collider experiments H1 and ZEUS. These far reaching upgrades to the machine will be matched by upgrades to the detectors. The result will be a unique facility for the study of the structure of the proton and the nature of the strong and electroweak interactions. The physics potential of the upgraded accelerator is discussed here together with a brief description of the HERA machine and collider detector upgrades.

1 Introduction

The electron-proton collider HERA started operation in the summer of 1992. The proton beam energy was 820 GeV while the electron beam energy was 27.5 GeV. The $\sim$25 nb^{-1} of data collected by the experiments ZEUS and H1 in the first running period extended the kinematic range covered by deep inelastic scattering, DIS, measurements by two orders of magnitude in both Q^2, the four-momentum transfer squared, and x, the fraction of the proton four-momentum carried by the struck quark. The proton structure function was extracted from the data and observed to rise rapidly with decreasing x [1, 2]; a dramatic result, not expected by many.

In the years 1992-1997 H1 and ZEUS have each collected a luminosity of $\sim$1 pb^{-1} using electron beams and $\sim$50 pb^{-1} using positron beams. These data have been used to make measurements which test the electroweak Standard Model, SM, and the theory of the strong interactions, QCD, in both neutral current, NC, and charged current, CC, DIS. Jet analyses in DIS and photoproduction have been used to address fundamental issues in QCD. The observation of diffraction in DIS has led to a careful investigation of the transition from the kinematic region in which perturbative QCD is valid to the region where phenomenological models based on Regge theory must be applied (see for example [3] and [4] and references therein).

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During the running period August 1998 to April 1999 ∼20 pb^{-1} of e^-p data were delivered with a proton beam energy of 920 GeV. The data collected by H1 and ZEUS will be used to study the dependence of the NC and CC DIS cross sections on the charge of the lepton beam.

The HERA experiments will continue to take data until May 2000 when a long, 9 month, shutdown is scheduled. The shutdown will be used to upgrade the HERA accelerator and the collider detectors. The HERA luminosity will be increased by a factor of five and longitudinal lepton beam polarisation will be provided for ZEUS and H1. The physics motivation for this major upgrade programme is discussed in detail in reference [5]. Reference [5] also contains a discussion of the physics potential of HERA were polarised proton beams and beams of heavy nuclei to be provided. These interesting possibilities will not be discussed further here.

This report is organised as follows: section 2 contains a selection of current results from H1 and ZEUS which will benefit from more data or from improvements in the quality of the data expected to come from the detector upgrades; the HERA machine and the collider detector upgrades are reviewed in section 3; section 4 contains a selection of key physics topics which will be addressed after the upgrade; finally, section 5 contains a summary.

2 A Selection of Open Questions

The wealth of data provided by the successful operation of HERA over the past seven years has allowed a set of open questions to be clearly defined. Since a discussion of each open question can not be attempted here, the case for the upgrade of the accelerator and of the collider detectors will be made using three key examples.

2.1 Determination of the Gluon Density of the Proton

The double differential cross section for $e^{\pm}p$ NC DIS may be written in the form

$$\frac{d\sigma^{\rm NC}_{e^{\pm}p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+F_2^{\rm NC} \mp Y_-xF_3^{\rm NC} - Y^2F_L^{\rm NC}] = \frac{2\pi\alpha^2}{xQ^4}Y_+\tilde{\sigma}^{\rm NC}_{e^{\pm}p} \quad (1)$$

where $Y_{\pm} = 1 \pm (1-y)^2$ with $y = Q^2/xs$, $\sqrt{s}$ is the $e^{\pm}p$ centre of mass energy, α is the fine structure constant and $\tilde{\sigma}^{\rm NC}_{e^{\pm}p}$ is referred to as the reduced cross section. The structure functions $F_2^{\rm NC}$ and $xF_3^{\rm NC}$ contain parton density functions, PDFs, and electromagnetic and weak couplings [6]. The longitudinal structure function $F_L^{\rm NC}$ arises from QCD corrections to the naive quark parton model and makes a significant contribution to the NC cross section only at low Q^2. The structure function $F_2^{\rm NC}$ can be written as the sum of two terms $F_2^{\rm NC} = F_2^{\rm em} + F_2^{\gamma/Z}$. $F_2^{\rm em}$ contains the purely electromagnetic contribution, while $F_2^{\gamma/Z}$ receives contributions from the parity conserving terms which arise from Z exchange and photon-Z interference. ZEUS and H1 have measured the structure function $F_2^{\rm NC}$ over the kinematic range $3.6 \times 10^{-5} < x < 0.65$ and $0.14 < Q^2 < 2 \times 10^4\,{\rm GeV}^2$ and extracted $F_2^{\rm em}$ from these measurements [7, 8]. The error in $F_2^{\rm em}$ is now dominated by systematic uncertainties over a large part of the this range. Fits to the data using next to leading order, NLO, QCD have been used to extract the gluon density, xg, with a precision varying from 20% at $x \approx 3 \times 10^{-5}$, $Q^2 = 20\,{\rm GeV}^2$ to 15% at $x \approx 4 \times 10^{-4}$, $Q^2 = 7\,{\rm GeV}^2$ [9]. This is an indirect determination of xg since the positron scatters from a quark. A quantity more directly sensitive to the gluon density is the charm production cross section. This may be measured using a sample of events which contain a D^* meson reconstructed using the decay chain $D^* \to D^0\pi \to K\pi\pi$. Both H1 and ZEUS have performed such a measurement in DIS and in photoproduction [10, 11]. A sensitive test of QCD can be made by comparing the measured charm cross sections to the cross sections obtained from the scaling violations of $F_2^{\rm em}$. At present the data are not sufficiently precise to allow a quantitative comparison to be made.

In order to investigate the extent to which the gluon distribution extracted from the scaling violation of $F_2^{\rm em}$ agrees with that inferred from the charm production cross sections it is necessary to extend the range of x and Q^2 over which $F_2^{\rm em}$ is measured to high precision so increasing the precision with which xg can be extracted. At the same time a much larger charm data set is required to reduce the errors on the charm cross sections. The HERA luminosity upgrade combined with the improved charm tagging efficiency to be provided by the detector upgrades will make it possible to address the issue of whether the gluon distribution extracted from $F_2^{\rm em}$ is also that required to describe the charm production cross sections.

2.2 Neutral Current DIS Cross Section Measurement at High Q^2

The effect of Z exchange on the NC DIS cross section has been observed at high Q^2. This is demonstrated in figure 1 where the single differential cross sections $d\sigma^{\rm NC}_{e^+p}/dQ^2$ and $d\sigma^{\rm NC}_{e^+p}/dx$ are compared with the expectations of the SM [12]. The SM, including the Z exchange contribution, describes the data while a calculation in which the Z exchange contribution is ignored is in clear conflict with the data. The SM predicts that the $\gamma - Z$ interference contribution to NC e^+p scattering is destructive while in e^-p scattering it is constructive. The measured single differential cross sections $d\sigma^{\rm NC}_{e^+p}/dQ^2$ and $d\sigma^{\rm NC}_{e^-p}/dQ^2$, shown in figure 2, are consistent with this expectation [14]. It will be possible to extract the structure function $xF_3^{\rm NC}$ by combining the e^-p and e^+p data, however, with the luminosities currently available the precision of the measurement will be dominated by the statistical uncertainty. To improve the measurement will require a significant increase in luminosity and some improvements in the detection of the scattered lepton at high x and at high Q^2.

A second motivation for significantly improving the NC data set at high x and high Q^2 is indicated in figure 3 where $\tilde{\sigma}^{\rm NC}_{e^+p}$ is plotted as a function of Q^2 for various fixed values of x [16]. For $x = 0.45$ the data points at the highest Q^2 lie above the SM expectation. In order to establish this effect as something other than a statistical fluctuation requires a significant increase in the size of the NC data set.

2.3 Searches for Physics Beyond the Standard Model

It is in the nature of searches for physics beyond the SM to push to the edges of phase space. Hence, such analyses are always in need of a large increase in data. Searches for physics beyond the SM at HERA are reviewed elsewhere in these proceedings [17]. The limits presented in reference [17] indicate that HERA plays a crucial role in exploring the full panorama of new physics precisely because it is the worlds only *ep* collider. As such the HERA collider experiments have the potential to make decisive contributions in the search for R-parity violating SUSY, leptoquarks, contact interactions and much more besides.

3 The Upgrades to the HERA Machine and the Collider Detectors

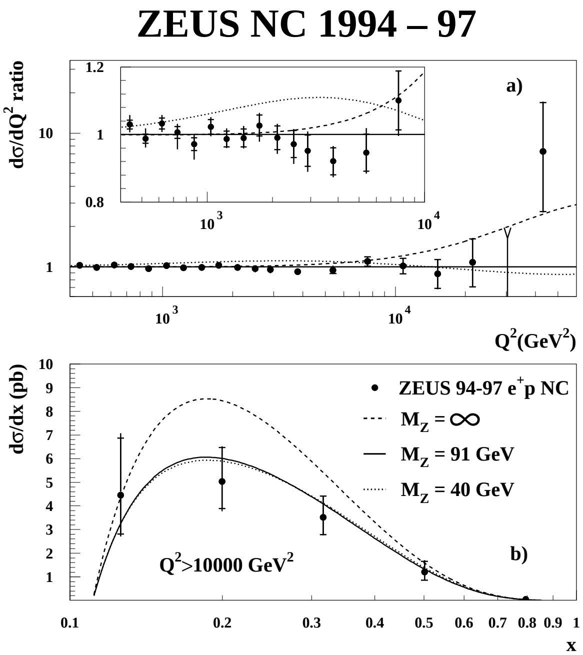

Figure 1: (a) The points with error bars give the ratio of the measured cross sections, $d\sigma^{\rm NC}_{e^+p}/dQ^2$, to the SM prediction using the CTEQ4D [13] parton densities and fixing the Z mass, M_Z, at its nominal value of 91.175 GeV. (b) $d\sigma^{\rm NC}_{e^+p}/dx$ for $Q^2 > 10000\,{\rm GeV}^2$. The three lines show the predictions of the SM for $M_Z = 91.175\,{\rm GeV}$, for $M_Z = 40\,{\rm GeV}$ (dotted line) and for no Z contribution (dashed line) [12].

3.1 The HERA Accelerator Upgrade

The goals of the HERA upgrade programme are to provide an increase of a factor of five in luminosity and to provide longitudinal lepton beam polarisation for ZEUS and H1. Over a six year running period it is anticipated that a total luminosity of 1000 $\rm pb^{-1}$ will be delivered [18].

The key parameters of the upgraded machine are summarised in table 1 [18]. The five fold increase in luminosity is to be achieved by stronger focusing of the lepton and proton beams. In order to achieve the strong focusing required superconducting magnets must be installed close to the interaction region inside the H1 and ZEUS detectors. In order to calculate the synchrotron radiation background a maximum lepton beam energy, E_e, of 30 GeV was used. In operation E_e will be reduced somewhat to ensure that the RF system performs reliably at high current. HERA has been operating reliably with a proton beam energy of 920 GeV since 1998 so that it is likely that the proton beam energy will remain 920 GeV after the upgrade.

The second major goal of the HERA upgrade, the provision of longitudinal lepton beam polarisation for the collider experiments, will be achieved by the provision of spin rotators for ZEUS and H1. Figure 4 shows the build up of polarisation during HERA running in 1998 [19]. The asymptotic value of $\sim$60% is routinely obtained in HERA. Spin rotators have been operating at the HERMES interaction point for several years and are routinely providing 60% longitudinal polarisation. The present performance falls only slightly short of the design goal of 70% lepton beam polarisation at HERA after the upgrade.

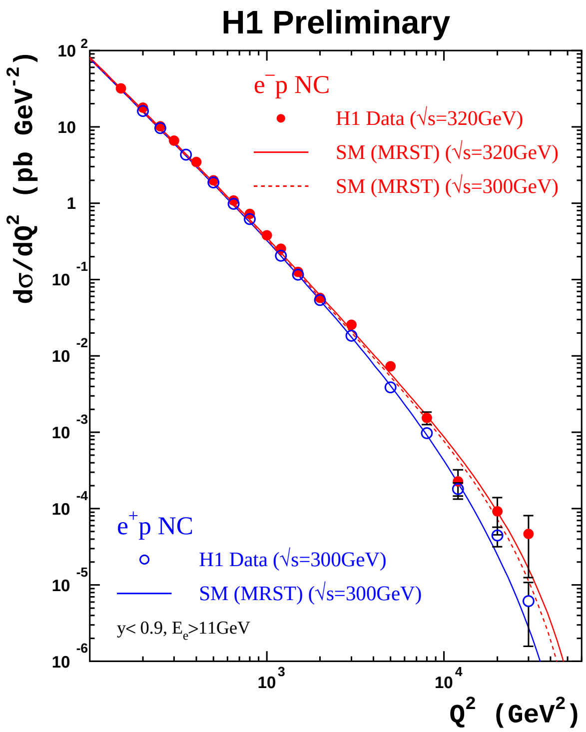

Figure 2: Preliminary inclusive neutral current cross sections as a function of Q^2 for H1 e^-p data from 1998-99 (solid points) and for H1 e^+p data from 1994-97 (open points) [14]. The SM curves were evaluated using the MRST PDFs [15].

HERA Parameters		
	1997	Upgrade
p beam energy (GeV)	820	820
e beam energy (GeV)	27.5	30
Number of bunches	180/189	180/189
Number of protons/bunch	7.7×10^{10}	10×10^{10}
Number of electrons/bunch	2.9×10^{10}	4.2×10^{10}
Proton current (mA)	105	140
Electron current (mA)	43	58
Hor. proton emittance (nm rad)	5.5	5.7
Hor. electron emittance (nm rad)	40	22
Proton beta function x/y (m)	7/0.5	2.45/0.18
Electron beta function x/y (m)	1/0.7	0.63/0.26
beam size $\sigma_x \times \sigma_y (\mu m)$	200×54	118×32
Synchrotron Rad. at IP (kW)	6.9	25
Specific luminosity (cm^{-2} s^{-1} mA^{-2})	7.6×10^{29}	1.4×10^{30}
Luminosity (cm^{-2} s^{-1})	1.5×10^{31}	7×10^{31}

Table 1: HERA parameters achieved in 1997 compared to the specifications of the luminosity upgrade programme [18].

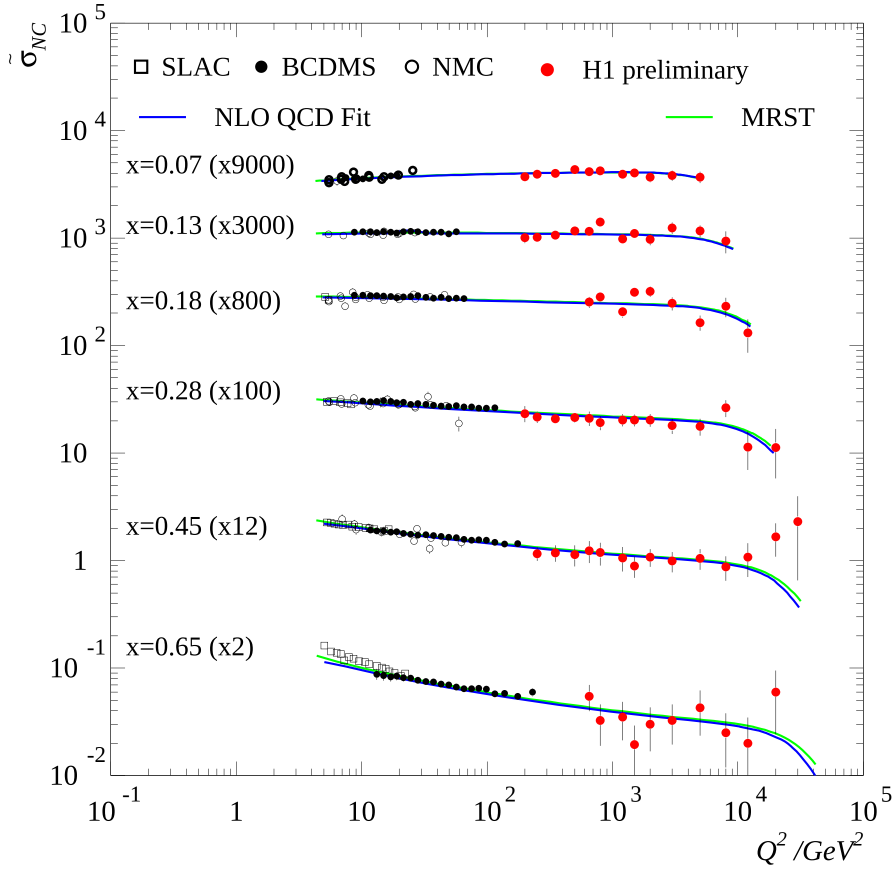

Figure 3: The reduced cross section, as defined in equation 1, compared with the expectations of the Standard Model evaluated using the MRST [15] PDFs and the result of the H1 NLO QCD fit. The error bars represent the total error of the measurements [16].

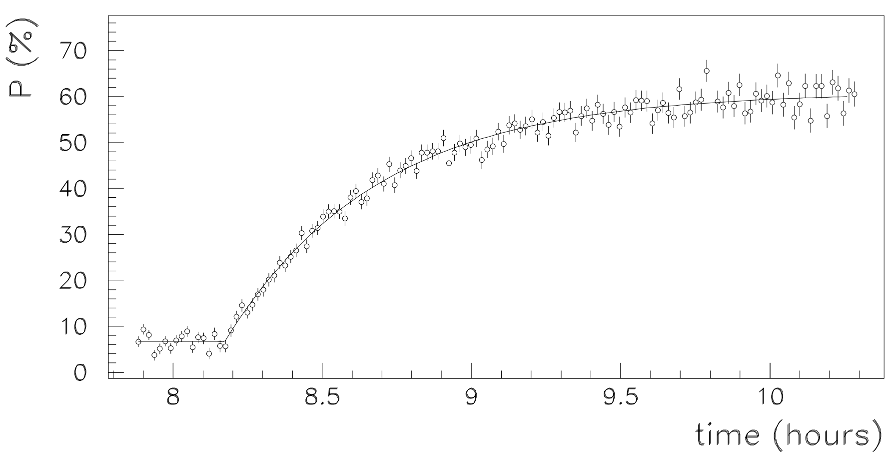

Figure 4: A measurement of the build up of polarisation as a function of the time after the beam has been depolarised. The solid line shows the result of a fit to the data [19].

3.2 The Collider Detector Upgrades

The collider detector upgrades focus on providing optimal performance for charm and beauty tagging and for the reconstruction of the scattered lepton at high x and high Q^2 [20, 21]. Charm tagging is strongly enhanced by the ability to identify displaced vertices. Hence ZEUS will install a silicon micro-vertex detector. The boost of the lepton-quark centre of mass system throws the decay products of charmed particles preferentially into the forward direction. Hence the ZEUS micro-vertex detector will be equipped with a set of 'wheels' to cover the forward region. H1 already operates a micro-vertex detector. In order to enhance the charm tagging efficiency a forward silicon tracker will be installed and a set of 'wheels' will be added to the backward silicon tracker in order to measure the azimuthal coordinate so complementing the existing 'wheels' which measure the radial coordinate. To further enhance track reconstruction in the forward direction both collaborations will upgrade the forward tracking system [22, 23]. H1 will install a system of planar drift chambers while ZEUS is building a set of planar straw tube trackers. These detectors will significantly enhance track reconstruction in the forward direction and so lead to improved charm tagging and enhanced reconstruction of the scattered lepton particularly at high x and at high Q^2 .

In view of the redesigned lepton and proton beams both experiments are planning upgrades to the luminosity measurement systems and H1 plans to upgrade the system of roman pots used to detect elastically scattered protons. Both collaborations plan trigger upgrades in order to increase flexibility and selectivity, particularly for events containing charmed particles.

4 Physics at HERA after the Upgrade

Following the HERA upgrade the proton will be probed using each of the four possible combinations of lepton beam charge and polarisation. The combination of high luminosity and polarisation will lead to a rich and diverse programme of measurements which can only be sketched below using a few examples. A detailed description of the physics opportunities afforded by the upgrade is to be found in reference [5].

4.1 Proton Structure

The large data volume will allow F_2^{NC} to be extracted with an accuracy of $\sim$3% over the kinematic range $2 \times 10^{-5} < x < 0.7$ and $2 \times 10^{-5} < Q^2 < 5 \times 10^4\,\mathrm{GeV}^2$ [24]. This estimate is based on an assumed luminosity of 1000 pb^{-1} and reasonable assumptions for systematic uncertainties. Such a measurement will represent a significant improvement over current results. If QCD evolution codes which go beyond next to leading order become available and a careful study of the dependence of the systematic errors on the kinematic variables is made it will be possible to determine α_{S} from the scaling violations of F_2^{NC} with a precision of ≤ 0.003. The gluon distribution will also be extracted from such a fit. The result of a fit in which systematic errors are handled in an optimal way and assuming a luminosity of 1000 pb^{-1} is shown in figure 5. The gluon distribution will be determined with a precision of $\sim$ 3% for $x = 10^{-4}$ and $Q^2 = 20\,\mathrm{GeV}^2$

The combination of high luminosity and high charm tagging efficiency transforms the measurement of the charm contribution to F_2^{NC}, F_2^{cc} [25]. For example, figure 6 shows the precision on F_2^{cc} expected from a luminosity of 500 pb^{-1}. The precision will be sufficient to allow a detailed study of the charm production cross section to be made. The lifetime tag provided by

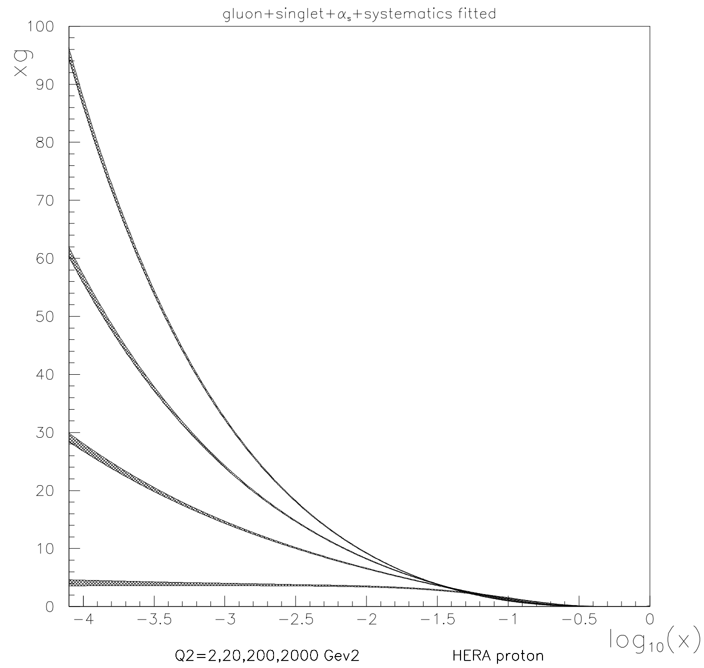

Figure 5: Anticipated precision of a determination of the gluon density using a luminosity of 1000 pb^{-1}. Reasonable estimates of systematic uncertainties have been included in the fit [24].

the silicon micro-vertex detector allows the tagging of b-quarks. Figure 7 shows the anticipated result of a measurement of the ratio of the beauty contribution to $F_2^{\rm NC}$, F_2^{bb}, to F_2^{cc} assuming a luminosity of 500 pb^{-1} [25]. The figure indicates that H1 and ZEUS will be sensitive to the beauty content of the proton as well as the charm content.

In the quark parton model CC DIS is sensitive to specific quark flavours. The e^+p CC DIS cross section is sensitive to the d- and s-quark parton densities and the $\bar{u}$- and $\bar{c}$-anti-quark densities, while the e^-p CC DIS cross section is sensitive to the $u, c, \bar{d}$ and $\bar{s}$ parton density functions. With the large CC data sets expected following the upgrade it will be possible to use $e^{\pm}p$ CC data to determine the u- and d- quark densities. Further, by identifying charm in CC DIS it will be possible to determine the strange quark contribution to the proton structure function $F_2^{\rm NC}$ with an accuracy of between 15% and 30% [28].

In summary, following the upgrade the HERA collider experiments will make a complete survey of the parton content of the proton.

4.2 Tests of the Electroweak Standard Model

The high luminosity provided by the upgrade will allow access to low cross section phenomena such as the production of real W-bosons. The SM cross section for the process $ep \rightarrow eWX$ is ~ 1 pb [29] which, combined with an acceptance of $\sim 30\%$, gives a sizeable data sample for a luminosity of 1000 pb^{-1}. The production of the W-boson at HERA is sensitive to the non-abelian coupling $WW\gamma$ [30]. The sensitivity of HERA to non-SM couplings is comparable to the sensitivities obtained at LEP and at the Tevatron and complementary in that at HERA the $WW\gamma$ vertex is probed in the space-like regime.

The full potential of electroweak tests at HERA will be realised through measurements using polarised lepton beams [31]. Two types of electroweak test have been considered. The first

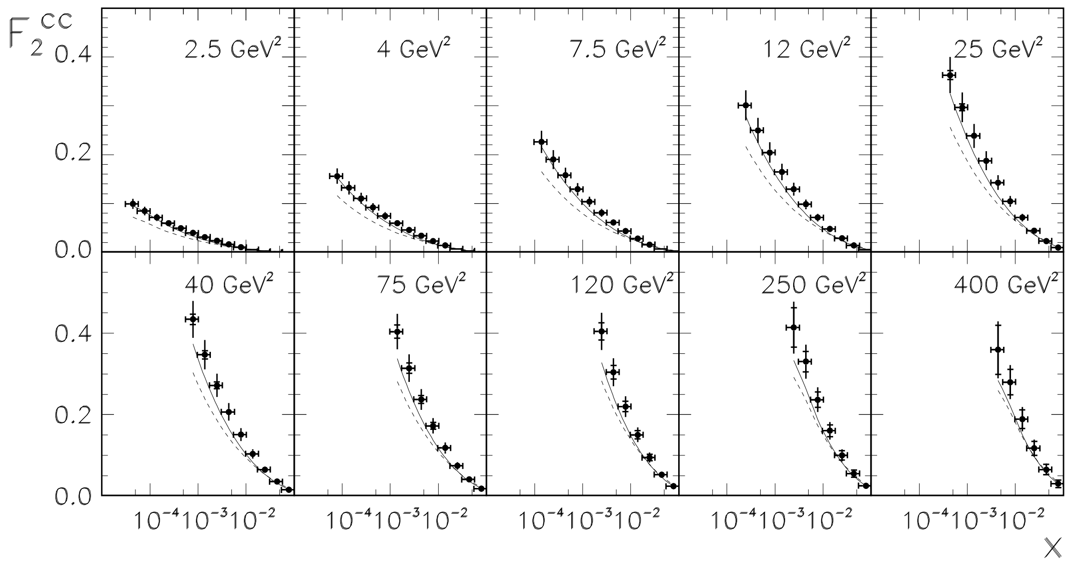

Figure 6: Expected F_2^{cc} for a luminosity of 500 pb^{-1}. The inner (outer) error bars show the statistical (full) error of the anticipated measurement. The full (dashed) line gives the expectation from the NLO calculations based on GRV-HO [26] (MRSH [27]) parton distributions taking a charm quark mass of 1.5 GeV [25].

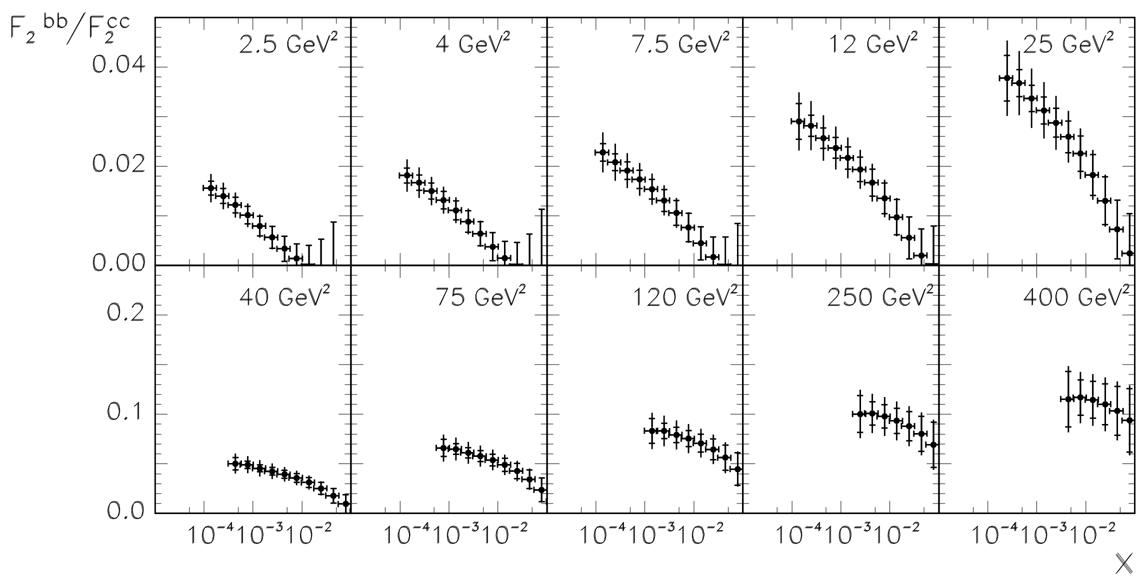

Figure 7: Expected ratio of F_2^{bb} to F_2^{cc} for a luminosity of 500 pb^{-1}. The inner (outer) error bars bars show the statistical (full) error of the anticipated measurement [25].

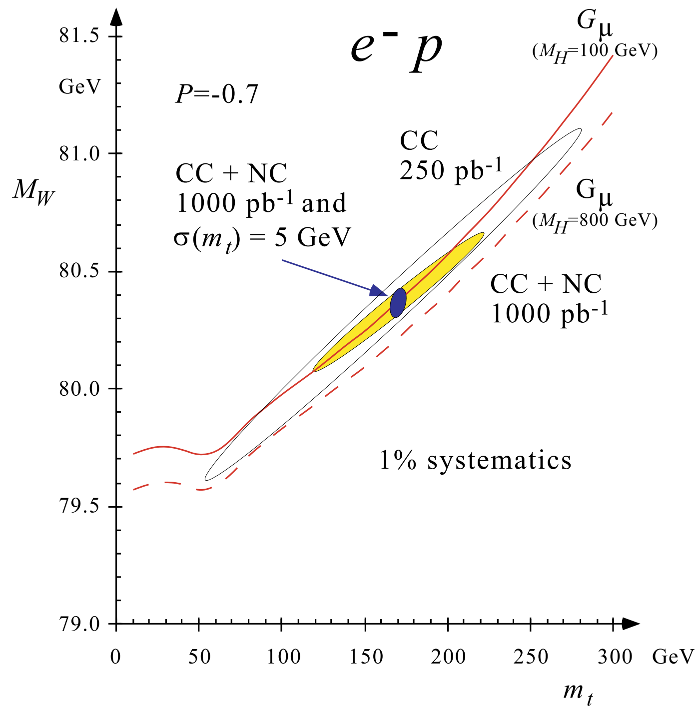

Figure 8: One standard deviation contours in the M_W, m_t plane from polarised electron scattering ($P = -70\%$), utilising CC scattering at HERA alone with a luminosity of 250 pb^{-1} (large ellipse), NC and CC scattering at HERA with 1000 pb^{-1} (shaded ellipse), and the combination of the latter HERA measurements with a direct top mass measurement with a precision of 5 GeV (full ellipse). The M_W - m_t relation following from the G_μ constraint is shown for two values of M_H (full and dashed curves) [32].

involves the interpretation of NC and CC cross section measurements in terms of parameters of the SM such as the mass of the W boson, M_W, and the mass of the top quark, m_t. The consistency of the SM requires that the values extracted must be in agreement with those obtained in measurements of the same parameters in other experiments. The second form of SM test involves the determination of parameters, such as the light quark NC couplings, which are not free parameters in the SM. In this case a deviation from the SM prediction would be a signal for new physics.

Within the SM NC and CC DIS cross sections may be written in terms of α, M_W and m_t together with the mass of the Z boson, M_Z, and the mass of the Higgs boson, M_H. In order to test the consistency of the theory we may fix the values of α and M_Z to those obtained at LEP or elsewhere and use measurements of the NC and CC DIS cross sections to place constraints in the M_W, m_t plane for fixed values of M_H. The SM is consistent if the values of the parameters M_W and m_t obtained agree with the values determined in other experiments. The result of such an analysis is shown in figure 8 where one standard deviation contours in the M_W, m_t plane have been derived from anticipated measurements of NC and CC DIS in e^-p scattering with an electron polarisation of -70% [32]. Combining NC and CC data corresponding to a luminosity of 1000 pb^{-1} with a top mass measurement from the Tevatron with a precision of $\sim \pm 5$ GeV yields a measurement of M_W with an error of ~ 60 MeV.

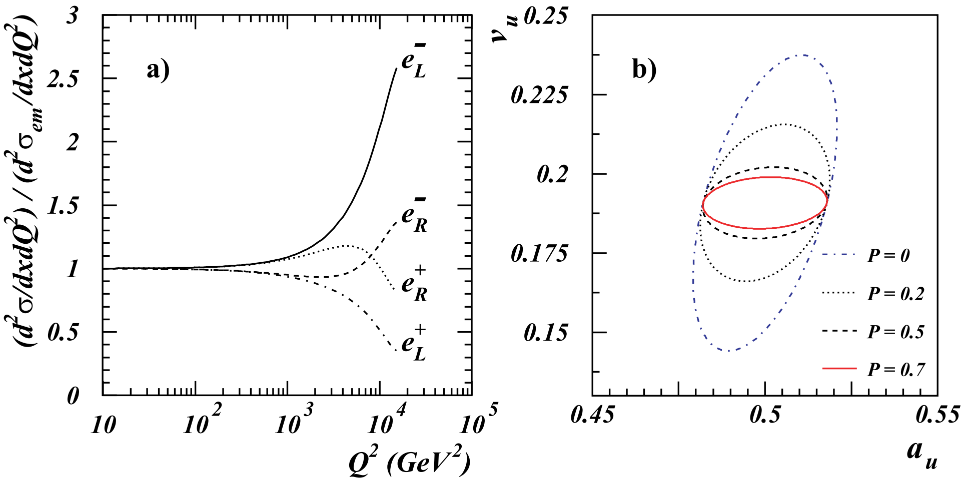

Figure 9: (a) Ratio of the NC DIS cross section to the cross section obtained when only single photon exchange is included as a function of Q^2 at $x = 0.2$. (b) Sensitivity of the errors on the u-quark coupling to the Z to the lepton beam polarisation P. One standard deviation contours are shown for fits in which the u-quark couplings are allowed to vary while the d-quark couplings are held fixed at their SM values [33].

The sensitivity of NC DIS to lepton beam polarisation is shown in figure 9(a). The figure shows the ratio

$$R = \left(\frac{d^2\sigma^{\rm NC}}{dxdQ^2}\right) / \left(\frac{d^2\sigma^{\rm em}}{dxdQ^2}\right) \tag{2}$$

where $d^2\sigma^{\rm em}/dxdQ^2$ is the differential cross section obtained if only photon exchange is taken into account. The strong polarisation dependence of the NC cross section can be used to extract the NC couplings of the light quarks. In such an analysis the CC cross section may be used to reduce the sensitivity of the results to uncertainties in the PDFs [33]. The precision of the results obtained depend strongly on the degree of polarisation of the lepton beam as shown in figure 9(b). The figure shows the anticipated error on the vector and axial-vector couplings of the u-quark, v_u and a_u respectively, obtained in a fit in which v_u and a_u are allowed to vary while all other couplings are fixed at their SM values. With a luminosity of 250 pb^{-1} per charge, polarisation combination and taking the vector and axial-vector couplings of the u- and d-quarks as free parameters gives a precision of 13%, 6%, 17% and 17% for v_u, a_u, v_d and a_d respectively. By comparing these results with the NC couplings of the c- and b-quarks obtained at LEP a stringent test of the universality of the NC couplings of the quarks will be made.

5 Summary

Deep inelastic scattering has played, and continues to play, a central role in the development of the understanding of the interactions among the fundamental particles. The HERA upgrade programme provides exciting opportunities which are both qualitatively and quantitatively new. The measurements to be performed in the years following the HERA upgrade will impinge directly on the description of the structure of the proton, the nature of the strong interaction and the electroweak sector of the Standard Model.

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