DEEP INELASTIC SCATTERING AT HERA*

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In the years 1992–2007, the H1 and ZEUS detectors at the HERA accelerator collected large-luminosity data samples. They provided a high precision and wide kinematic range in the photon virtuality Q^2 and Bjorken x scaling variable for studying Deep Inelastic Scattering (DIS) processes at HERA. The longitudinal lepton-beam polarisation of HERA II gave a unique opportunity to study the helicity structure of the electroweak interaction, proton content, as well as to test the Standard Model. Some of the newest and most precise results from both collaborations are presented here.

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1. Introduction

The study of deep inelastic scattering (DIS) of leptons off nucleons has contributed significantly to tests of the Standard Model (SM) of the electroweak and strong interactions. The structure of nucleons has mainly been determined from DIS experiments. The ep HERA collider has allowed an extension in the photon virtuality Q^2, and in Bjorken x by several orders of magnitude with respect to previous fixed-target experiments [1, 2]. The higher Q^2 reach of HERA has also allowed the exploration of the electroweak sector of the SM.

The ZEUS and H1 collaborations have both measured the e^-p and e^+p neutral (NC) and charged current (CC) DIS cross sections using accumulated integrated luminosity of ~ 0.5 fb^{-1} per experiment. This data offers a unique opportunity to study precise data sets in a wide kinematic plane, intersecting with the one of the Tevatron and the LHC. Checks of consistency of the Standard Model, detailed comparisons with electroweak and QCD predictions, as well as searches for physics Beyond Standard Model are presented below.

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2. Inclusive DIS cross sections at HERA

The inclusive DIS cross section for $e^{\pm}p$ interactions at a centre-of-mass energy of $\sqrt{s} = 319\,\mathrm{GeV}$ were measured by the H1 Collaboration using 333.7 pb^{-1} of integrated luminosity [1]. The operation of the HERA collider with left- and right-handed longitudinally polarised electron and positron beams allows measurements in the NC and CC channels with four distinct initial states. The NC and CC cross sections cover the region $Q^2 \geq 100\,\mathrm{GeV}^2$ and Bjorken $x \geq 10^{-3}$. The cross sections were measured differentially in Q^2 and double differentially in x and Q^2.

The Q^2 dependence of the combined HERA I+II NC and CC cross sections for the longitudinal polarization $P_e = 0$ is shown in Fig. 1 (left). The NC cross sections exceed the CC cross sections at $Q^2 \simeq 200\,\mathrm{GeV}^2$ by more than two orders of magnitude. The steep decrease of the NC cross section with increasing Q^2 is due to the dominating photon exchange cross section which is proportional to $1/Q^4$. The NC and CC cross sections are of comparable size at $Q^2 \simeq 104^2\,\mathrm{GeV}^2$, where the photon and Z exchange contributions to the NC process are of similar size to those of $W^{\pm}$ exchange to the CC process. These measurements, thus, illustrate the unified behaviour of the electromagnetic and the weak interactions in DIS.

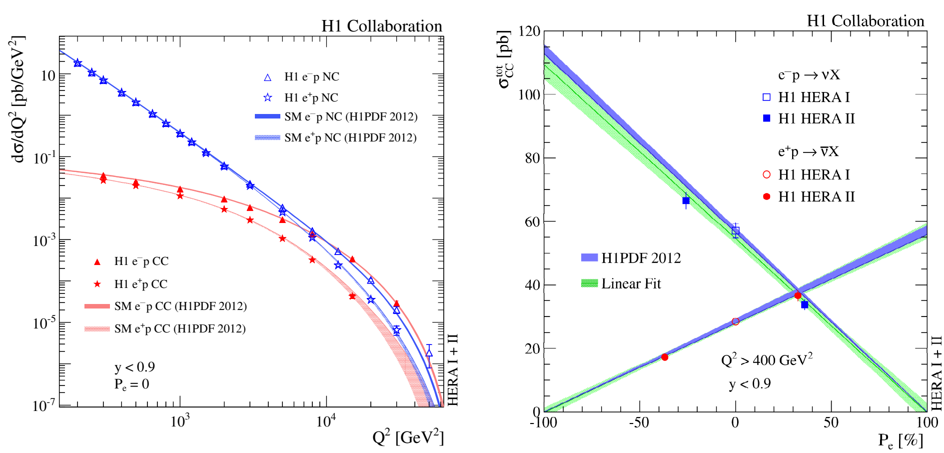

Fig. 1. Q^2 dependence of the NC and CC cross sections $d\sigma/dQ^2$ for the combined HERA I+II unpolarised e^-p and e^+p data (left) and dependence of the $e^{\pm}p$ CC cross sections on the longitudinal lepton beam polarisation P_e (right).

The total CC cross sections for $Q^2 > 400\ \mathrm{GeV}^2$ and elasticity $y < 0.9$ are shown in Fig. 1 (right) for the e^- and e^+ data and for different longitudinal lepton beam polarisations and compared to the SM expectations using the H1PDF 2012 fit. They agree within one standard deviation. A linear fit to the polarisation dependence of the measured cross sections is performed taking into account the correlated systematic uncertainties between the measurements and is also shown in Fig. 1 (right). This result excludes the existence of charged currents involving right-handed fermions mediated by a boson of mass M_W^{R} below 214 and 194 GeV at 95% C.L. respectively, assuming SM couplings and a light right-handed ν_e.

2.1. Parity violation in NC DIS

The SM predicts a difference in the NC cross section for leptons with different helicity states arising from the chiral structure of the neutral electroweak exchange. Parity-violating effects can be demonstrated via the difference between the cross sections involving negatively or positively polarised electron beams. The polarised single differential cross sections $d\sigma_{\mathrm{NC}}/dQ^2$ are used to construct the asymmetry $A^{\pm}$, which is proportional to the product of the electron axial (a_e) and quark vector (v_q) couplings to the Z boson. The asymmetry is shown in Fig. 2 compared to the H1PDF 2012 fit. The magnitude of the asymmetry is observed to increase with increasing Q^2 and is positive in e^+p and negative in e^-p scattering. The data are in good agreement with the SM using H1PDF 2012 and confirm the parity violation effects of electroweak interactions at large Q^2.

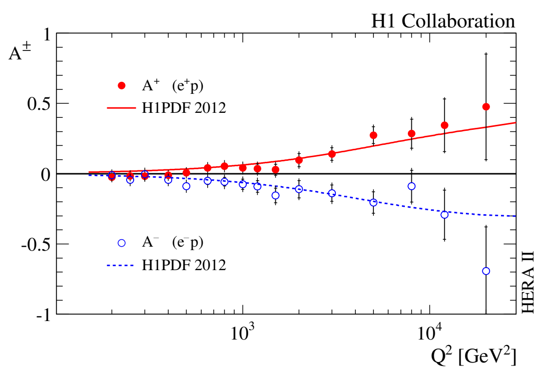

Fig. 2. Q^2 dependence of the polarisation asymmetry $A^{\pm}$, for e^+p (full circles) and e^-p (open circles). The data are compared to the Standard Model expectation.

2.2. Quark–antiquark and valence quark distributions

The DIS data extend to very high Q^2 which allows structure functions sensitive to the interference of photon and Z boson exchange to be measured. These "interference structure functions" access the difference of quark and antiquark distributions, with $xF_3^{Z\gamma}$, and a combination of their sums, with

$F_2^{Z\gamma}$. They were measured by using both the charge and polarisation dependence of the NC cross section, providing an improved determination of $xF_3^{Z\gamma}$ and a very first measurement of $F_2^{Z\gamma}$, by the H1 Collaboration. The results are shown in Fig. 3 as a function of x for $F_2^{Z\gamma}$ (left) in comparison to the H1PDF 2012 fit (left) and as a function of Q^2 for $xF_3^{Z\gamma}$ (right).

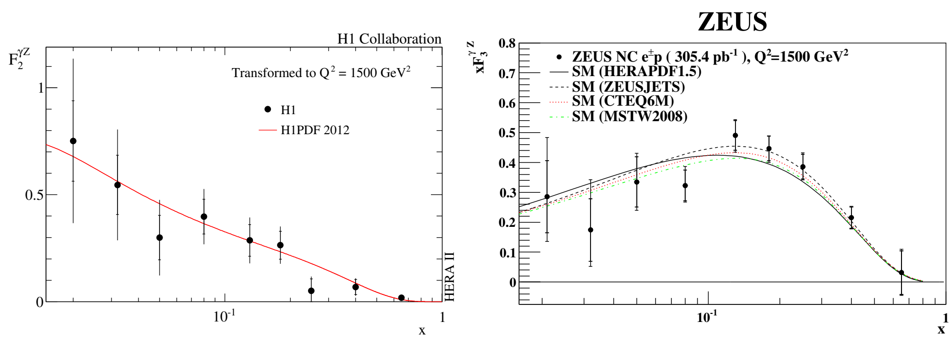

Fig. 3. Structure functions $F_2^{Z\gamma}$ (left) and $xF_3^{Z\gamma}$ (right) transformed to $Q^2 = 1500$ GeV^2.

2.3. Up- and down-type quark separation

The CC data can be used to separate the up- and down-type quark distributions in the proton. It is illustrated in Fig. 4 showing the CC reduced cross sections, where the quark contributions from $x(u+c)$ and $(1-y)^2x(d+s)$ are indicated for e^-p and e^+p data, respectively.

3. Leptoquarks at HERA

Many extensions of the Standard Model (SM) predict the existence of particles carrying both baryon and lepton number, such as leptoquarks (LQs) [5]. In *ep* collisions at HERA, such states could have been produced directly through electron[1]–quark fusion if their masses, $M_{\rm LQ}$, were lower than the HERA centre-of-mass energy, $\sqrt{s}$. The leptoquarks would have decayed into an electron and quark or an electron neutrino and quark, yielding peaks in the spectra of the final-state lepton-jets[2] invariant mass, $M_{\rm ljs}$. Leptoquarks with $M_{\rm LQ} > \sqrt{s}$ could not have been produced as resonances, but they would still have caused deviations from the SM prediction in the observed $M_{\rm ljs}$ spectrum due to virtual LQ exchange.

[1] Unless otherwise specified, 'electron' refers to both positron and electron and 'neutrino' refers to both neutrino and antineutrino.

[2] There can be more than one jet in the final state due to QCD initial- or final-state radiation.

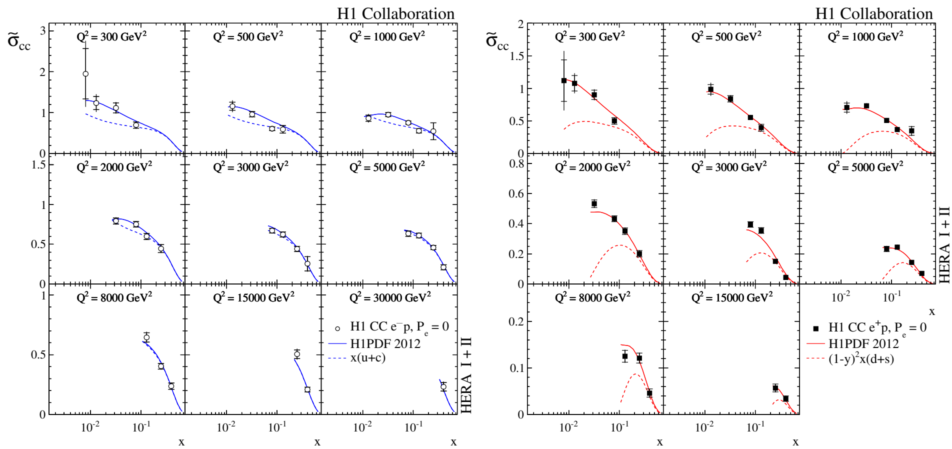

Fig. 4. Combined HERA I+II unpolarised CC reduced cross sections for e^-p (left) and e^+p (right) data shown for various fixed Q^2 values as a function of x in comparison with the expectation from H1PDF 2012.

The H1 and ZEUS collaborations published their final results on leptoquark search [3, 4], based on the data collected in the period 1994–2007, amounting to $\approx 0.5\,\mathrm{fb}^{-1}$ of integrated luminosity per experiment. No evidence for any leptoquark signal was found and, therefore, limits on the coupling λ were derived as a function of M_{LQ} for the different leptoquark states described by the Buchmüller–Rückl–Wyler model [5].

Figure 5 shows the limits on the $S^L_{1/2}$ LQ obtained by ZEUS compared to the limits from ATLAS [6], H1 [7], L3 [8] and OPAL [9]. In general, the limits from this analysis are significantly better than the LEP limits for $M_{\mathrm{LQ}} < \sqrt{s}$, and comparable for $M_{\mathrm{LQ}} > \sqrt{s}$. The limits obtained by ZEUS are similar to those obtained by H1.

4. Searches for contact interactions at HERA

A search for physics beyond the Standard Model in neutral current deep inelastic scattering at high negative four-momentum transfer squared Q^2 was performed in $e^{\pm}p$ collisions at HERA by the H1 Collaboration [10]. The differential cross section $d\sigma/dQ^2$, measured using the full H1 data sample corresponding to an integrated luminosity of $446\,\mathrm{pb}^{-1}$, was compared to the Standard Model prediction. No significant deviation was observed. Limits on various models predicting new phenomena at high Q^2 were derived. For general four-fermion *eeqq* contact interaction models, lower limits on the compositeness scale are set in the range of 3.6 TeV to 7.2 TeV. Leptoquarks with masses M_{LQ} and couplings λ are constrained to $M_{\mathrm{LQ}} = 0.41$–$1.86\,\mathrm{TeV}$

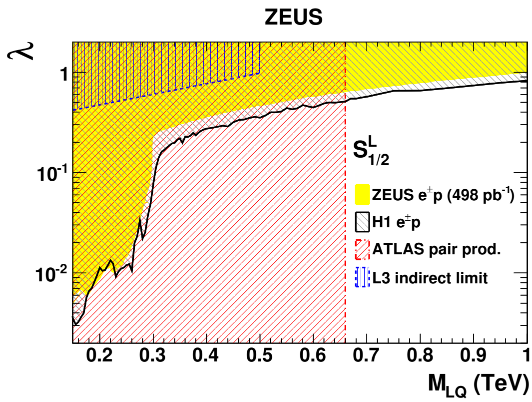

Fig. 5. Coupling limits as a function of LQ mass for the $S^L_{1/2}$ LQ from ATLAS, L3, H1 and ZEUS.

and limits on squarks in R-parity violating supersymmetric models are derived. A lower limit on the gravitational scale in $(4 + n)$ dimensions of $M_S > 0.9$ TeV is established for low-scale quantum gravity effects in models with large extra dimensions. For the light quark radius, an upper bound of $R_q < 0.65 \times 10^{-18}$ m is determined.

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