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Nuclear Physics B Proceedings Supplement 00 (2012) 1–8

Nuclear Physics B
Proceedings
Supplement

High-Q^2 NC and CC cross sections at HERA and proton structure

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Abstract

A review of the recent HERA-II measurements from the H1 and ZEUS detectors on neutral-current and charged-current deep inelastic scattering of longitudinally polarized lepton beams with a proton up to a center-of-mass energy of 318 GeV are presented. Dependence of the cross sections on the polarization of the lepton beam is shown. The lepton charge asymmetry of the neutral current cross section is used to extract the structure function $x\tilde{F}_3$. Electroweak couplings of the u and d quarks are determined from a combined QCD and electroweak analysis of the data. Results on searches for physics beyond the Standard Model are presented. No deviations from the theory is seen, from which limits are derived on the presence of four fermion contact interactions, heavy leptoquarks and on the quark radius.

Keywords: DIS, HERA, H1, ZEUS, QCD, proton structure, PDF, CI, LQ

1. Introduction

In the first running period of HERA, from 1992 - 2000, each experiment H1 and ZEUS collected about 100 pb^{-1} of e^+p and 15 pb^{-1} of e^-p data. The data span about 6 orders in magnitude in negative four momentum transfer, Q^2 and Bjorken variable x. To increase the precision, H1 and ZEUS data were combined and the knowledge about the proton structure was embedded in what is called as HERAPDF1.0 [1]. After the shut down in 2000, HERA was upgraded to increase the luminosity and additional information on the polarization of the lepton beam was made accessible. Each detector, H1 and ZEUS collected and analyzed about 450 pb^{-1} of data.

The upgrade has made it possible to study the proton structure with better precision and various tests have been performed using the polarized beams to probe the electroweak sector of the Standard Model. Already published or preliminary results on the neutral current (NC) and charged current (CC) cross sections from the two collaborations [2, 3, 4, 5, 6, 7] in the high-Q^2 kinematic plane are reviewed. These results constrain the valence and sea quark parton distribution functions (PDFs). HERA data also provide a platform to study physics beyond the Standard Model [8, 9, 10, 11, 12]. HERA is an ideal place to search for new particles coupling to a lepton-quark pair (called leptoquarks) which appear in many extensions of the Standard Model (SM). Four-fermion eqeq contact interactions (CI) is another theory beyond the Standard Model at higher energy scales which can be studied using DIS ep interactions. Different CI possibilities are studied on the basis of helicity and flavour structure. Assuming the electron to be point-like, possible substructure of the quark is probed using HERA data. If the quark has a substructure the cross section would get modified from the Standard Model (SM) predictions. The recent results [13, 14] from the two collaborations on these topics are reviewed in the following sections.

2. DIS cross sections

Deep inelastic scattering (DIS) is the name given to a process in which the structure of a hadron is probed using a lepton beam at large momentum transfer. In DIS ep scattering, the process can be mediated by a neutral current boson (γ or Z^0) called neutral current scattering or by a charged current boson ($W^{\pm}$) called charged current scattering.

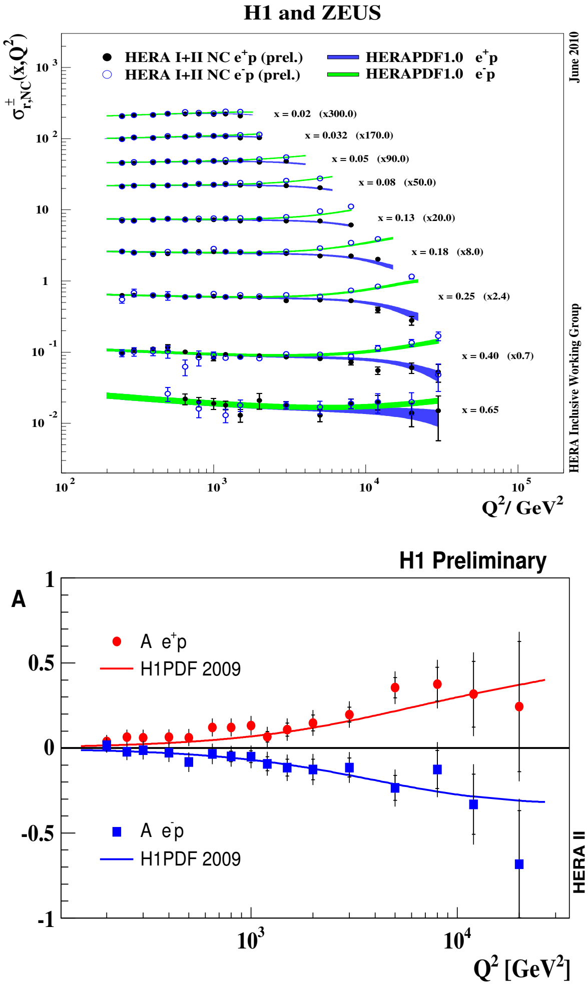

Figure 1: (Top) Neutral current H1 and ZEUS combined cross sections using HERA-I and II data for both lepton beams are compared to HERAPDF1.0 predictions. (Bottom) Measurement done by H1 on polarization asymmetry for both $e^- p$ and $e^+ p$ scattering are compared to an earlier H1 PDF set, H1PDF 2009.

2.1. Neutral current cross sections

The NC cross sections for the process, $e^{\pm} p \rightarrow e^{\pm} X$ is given by

$$\frac{d^2\sigma^{e^{\pm}p}_{Born}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\tilde{\sigma} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right],$$

where α is the fine structure constant and $\{\tilde{F}_2, \tilde{F}_3, \tilde{F}_L\}$ are generalized structure functions. The helicity dependence comes from $Y_{\pm} = 1 \pm (1-y)^2$ in the NC cross sections. Structure functions $\tilde{F}_2, \tilde{F}_3$ are given by

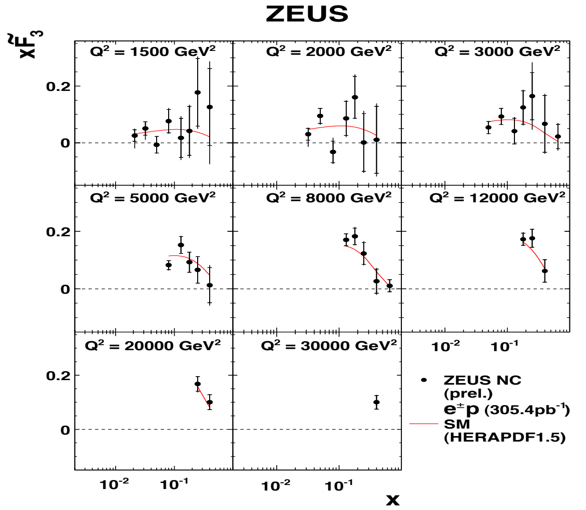

Figure 2: Measurement of xF_3 done by ZEUS using only HERA-II data with a luminosity ~ 300 pb^{-1}. The measurement is compared to the HERAPDF1.5 SM predictions.

$$\tilde{F}_2^{\pm} = \tilde{F}_2 + k(-\nu_e \mp Pa_e)\tilde{F}_2^{\gamma Z} + k^2(\nu_e^2 + a_e^2 \pm 2P\nu_e a_e)\tilde{F}_2^{Z},$$

$$x\tilde{F}_3 = k(-a_e \mp P\nu_e)x\tilde{F}_3^{\gamma Z} + k^2(2\nu_e a_e \pm P(\nu_e^2 + a_e^2))x\tilde{F}_3^{Z},$$

where k is

$$k(Q^2) = \frac{Q^2}{Q^2 + M_Z^2}\sin^2 2\theta_W$$

with θ_W being the electroweak mixing angle and M_Z the mass of the Z^0 boson.

The dependence on polarization enters the cross sections through P, where P is average longitudinal polarization of the lepton beam given as $P = (N_R - N_L)/(N_R + N_L)$, where $N_R(N_L)$ is the number of right-(left-) handed leptons in the beam. The quantities a_e and ν_e are the axial and vector couplings of the electron to the Z boson. The longitudinal structure function $\tilde{F}_L$ is negligible at high-Q^2. Figure 1 (top) shows the combined HERA-I and II H1 and ZEUS NC cross sections [15, 16] for both lepton beams compared to HERAPDF1.0 predictions. The cross sections for the electron and positron beams diverge at high Q^2 through the effect of the $\gamma - Z^0$interference term.

The polarization asymmetry of the NC cross section is defined as

$$A(e^{\pm}p) = \frac{2}{P_R - P_L}\frac{\sigma_R^{\pm} - \sigma_L^{\pm}}{\sigma_R^{\pm} + \sigma_L^{\pm}} = \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

and provides a direct measure of parity violation as it is proportional to the factor $a_e v_e$. In the SM one expects $A(e^+p)$ to be positive and to be equal to $A(e^-p)$ but opposite in sign. Asymmetry measurements from H1 [17] are shown in Fig. 1 (bottom) for both lepton beams. The asymmetry increases at high-Q^2 and is well described by the SM expectations.

As $x\tilde{F}_3$ is proportional to the parity violating Z^0 exchange, it is only sizeable at large Q^2, of the order of Z^0 mass. The structure function $x\tilde{F}_3$ is given by

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}\{\tilde{\sigma}^-_{NC}(x, Q^2) - \tilde{\sigma}^+_{NC}(x, Q^2)\}\,.$$

Figure 2 shows $x\tilde{F}_3$ measurements done by ZEUS [7] using HERA-II data with a total integrated luminosity of about 300 pb^{-1}.

2.2. *Charged current cross sections*

The polarized reduced CC cross section for the process, $ep \rightarrow \nu X$ is given as

$$\tilde{\sigma}^{e^\pm p}_{CC}(P) = (1 \pm P)\tilde{\sigma}^{e^\pm p}_{CC}(P = 0)\,,$$

where

$$\tilde{\sigma}^{e^-\{+\}p}_{CC}(P = 0) \propto x[(u\{\bar{u}\} + c\{\bar{c}\}) + (1 - y)^2(\bar{d}\{d\} + \bar{s}\{s\})]\,.$$

Here $q(x, Q^2)$ is a particular quark density inside the proton. The NC cross sections are sensitive to all quark densities, whereas the CC cross sections are sensitive to specific quark density. As for example, $e^-p\{e^+p\}$ is sensitive to $u\{d\}$ quark densities, respectively. The combined CC cross sections from ZEUS and H1 [15, 16] are shown in Fig. 3 in bins of Q^2 as a function of x. The combination of H1 and ZEUS data takes into account the correlations between systematic uncertainties and hence results in improved accuracy.

The polarization dependence of the CC cross sections is linear in the SM framework and it predicts that the cross sections for $e^-p\{e^+p\}$ should be zero for negative {positive} value of P equal to one. This dependence is studied and shown in Fig. 4 from the H1 and ZEUS experiments [3] and the data are consistent with the absence of right handed charged currents. Figure 4 shows the total CC cross sections with different values of the polarization of the lepton beam with negative four momentum transfer, Q^2 greater than 400 GeV^2 and inelasticity y less than 0.9 compared to the HERAPDF1.0 theoretical predictions.

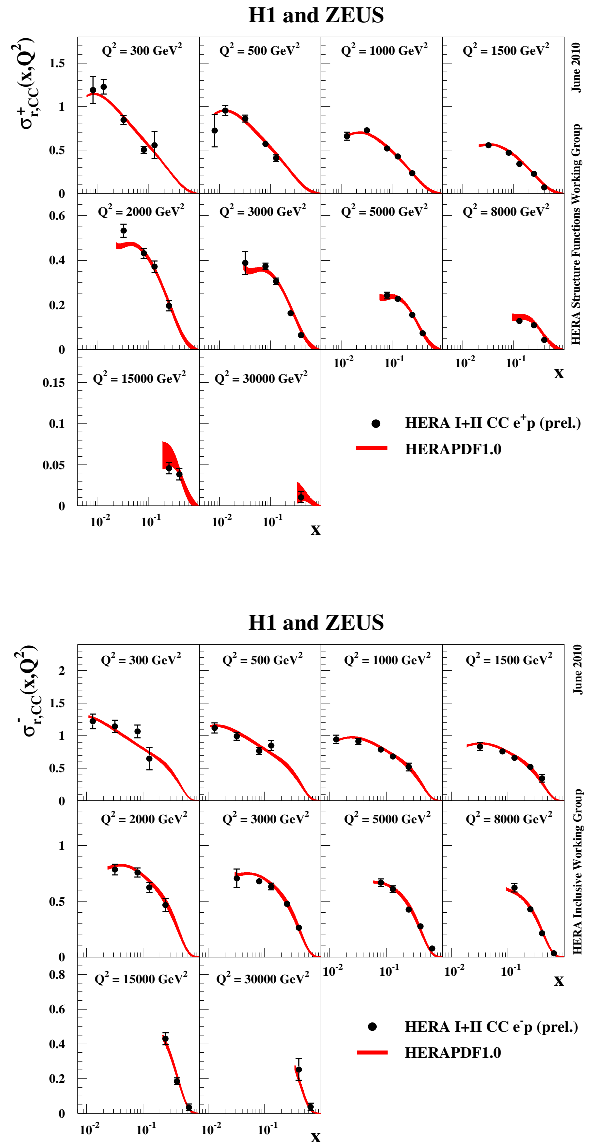

Figure 3: Double differential charged current cross sections for combined H1 and ZEUS HERA data for e^+p (top plot) and e^-p (bottom plot) DIS scattering. The data are compared to HERAPDF1.0 SM predictions.

2.3. *Electroweak QCD analysis*

The two experiments have used the full HERA-I and II data to perform an electroweak (EW) QCD analysis to determine the parameters of the EW theory [18, 19]. The axial and vector couplings to the Z^0 boson have been determined as shown in Fig. 5. The better precision for u quark comes from $x\tilde{F}_3$, the γZ interference term. The fit results are compared to the SM values and

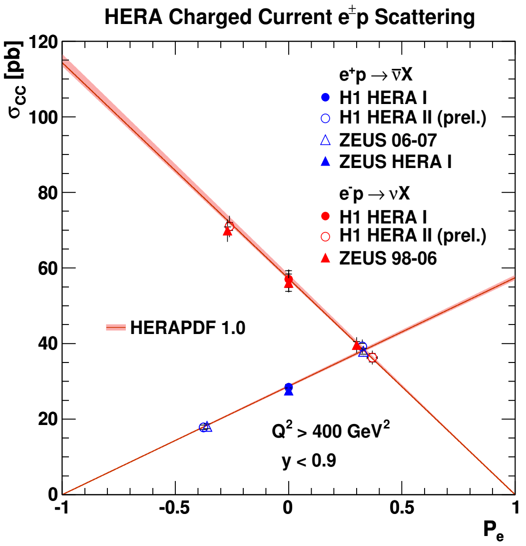

Figure 4: Dependence of the total charged current cross sections for $y < 0.9$ and $Q^2 > 400$ GeV^2 on the polarization of the lepton beam studied by the H1 and ZEUS experiments. The data are compared with the HERAPDF1.0 predictions.

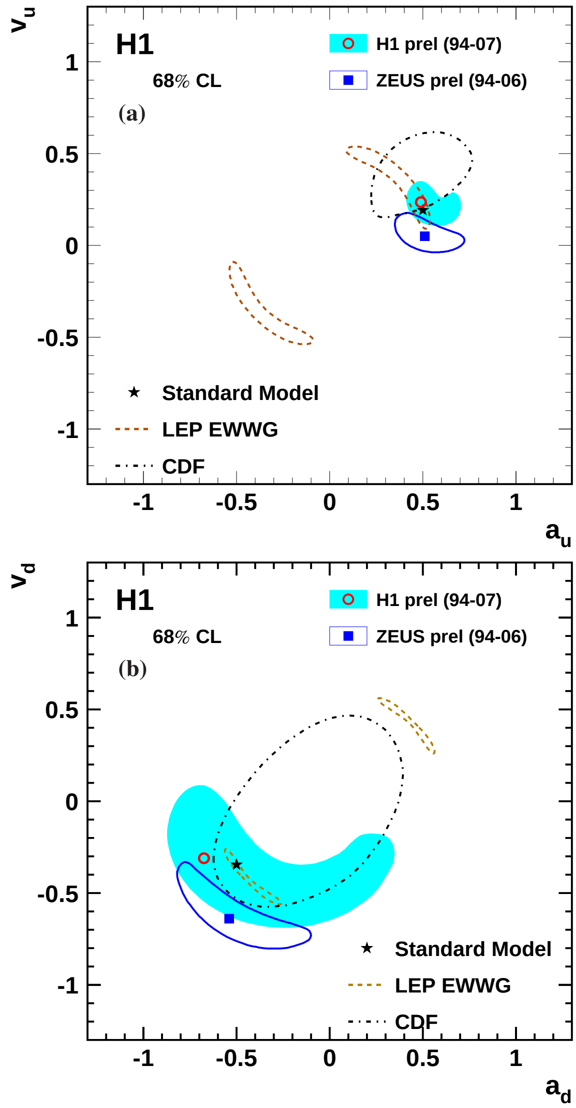

Figure 5: H1 and ZEUS results on axial and vector couplings of u (top plot) and d (bottom plot) quarks to the Z^0 boson. The results are compared to SM expectations and also to the results from LEP EWWG [20] and CDF [21].

the values from other collider experiments like LEP [20] and CDF [21], where the uncertainties from HERA are found to be competitive with these experiments.

2.4. High-Q^2 data in HERAPDF1.5

Data from phase I of the HERA running were the sole input to the NLO QCD analysis determining a new set of parton distribution functions (PDFs) HERAPDF1.0 including an estimate of the model and parametrization uncertainties of the fit results.

The results on NC and CC cross sections from phase II of HERA running are now included in the NLO QCD analysis, and the fit results were updated to the next version of PDFs called HERAPDF1.5 [22, 23]. Owing to the increased luminosity and further combination of the results from the two experiments the NC and CC cross sections are more precise than before and hence the PDFs have improved precision. This is evident from Fig. 6 where a comparison of the total uncertainty of HERAPDF1.0 and HERAPDF1.5 is shown. The HERAPDF1.5 PDFs are based on all HERA-II inclusive high-Q^2 NC and CC data.

What is still to be included at high-Q^2 kinematic are 135 pb^{-1} of NC e^+p data from ZEUS, which has been recently released as preliminary results as discussed in [7]. Figure 7 shows the NC cross sections from ZEUS with two different polarizations of the positron beam. With this last piece of results from ZEUS, the inclusive DIS measurements using HERA-II data are complete.

2.5. High-x NC cross sections from ZEUS

The valence quark PDFs fall sharply at high-x and have large uncertainties there. Studies have been done using the ZEUS experiment which focus on measuring x up to the kinematic limit. A first attempt was made using the HERA-I data to explore the high-x region with

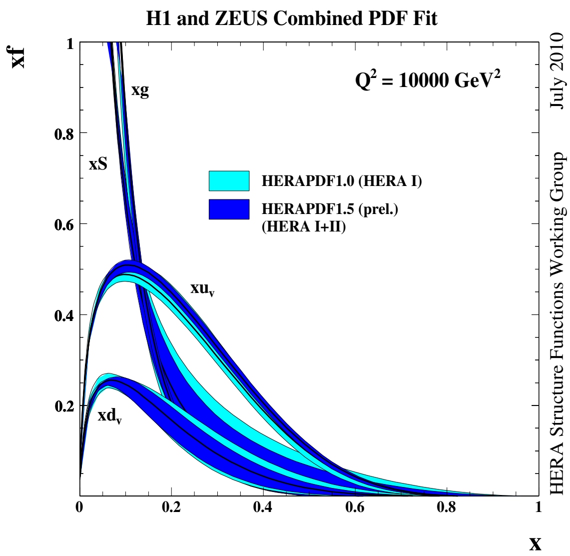

Figure 6: Total uncertainties from HERAPDF1.0 and HERAPDF1.5 are compared. HERAPDF1.5 has smaller uncertainties owing to the more precise data being included.

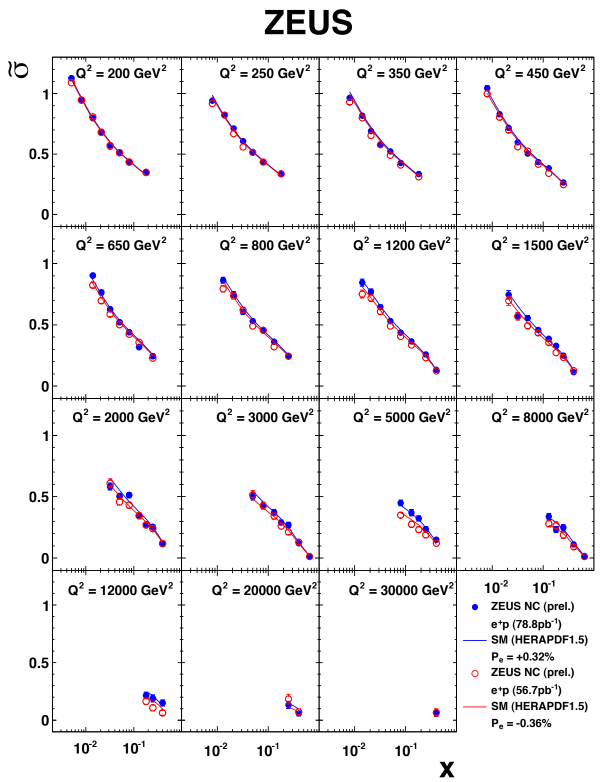

Figure 7: Double differential neutral current cross sections at high-Q^2 measured using the ZEUS detector for e^+p scattering for two different polarizations of the positron beam are shown. The results are compared to SM HERAPDF1.0 predictions.

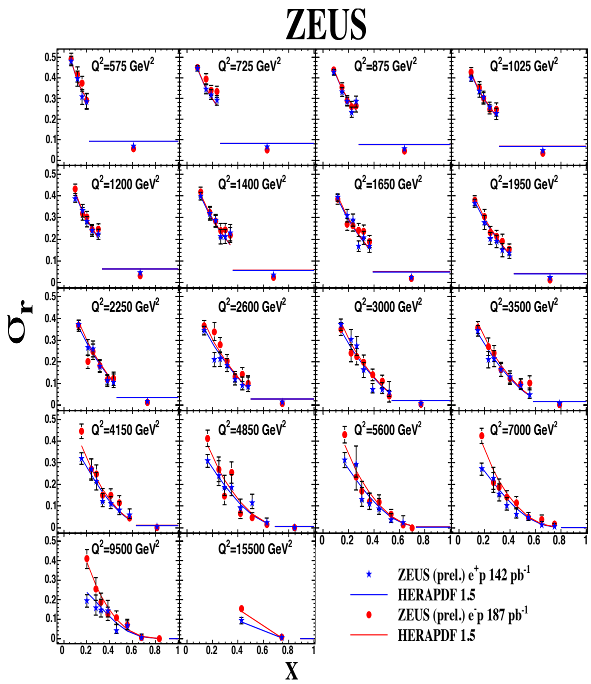

Figure 8: High-x double differential neutral current cross sections from ZEUS for HERA-II data for e^-p (dots) and e^+p (stars) compared to HERAPDF1.5 predictions.

$Q^2 > 200$ GeV^2 [24]. The full HERA-II data have been analyzed for $Q^2 > 450$ GeV^2 and $x \sim 1$ providing an improved precision to previous results. A new method has been employed to reconstruct x, which relies on the presence of jets within the detector acceptance up to a particular value of x, called x_{edge}, above which there are no jets, and the cross sections are integrated and averaged in x. Figure 8 shows the NC current high-x cross sections using 187 pb^{-1} of e^-p data [25] and 142 pb^{-1} of e^+p data [26] with $Q^2 > 450$ GeV^2. The measurements are generally well described by the HERAPDF1.5 except at the highest x.

3. Beyond standard model physics at HERA

3.1. Contact interactions

New types of interactions between electrons and protons at mass scales greater than the center-of-mass energy can modify the DIS cross sections predicted by the SM, thus providing a tool to study new physics. One such study is contact interactions with four fermion vertices of the type $eqeq$. The four fermion CI is an effective theory that describes low energy phenomena from

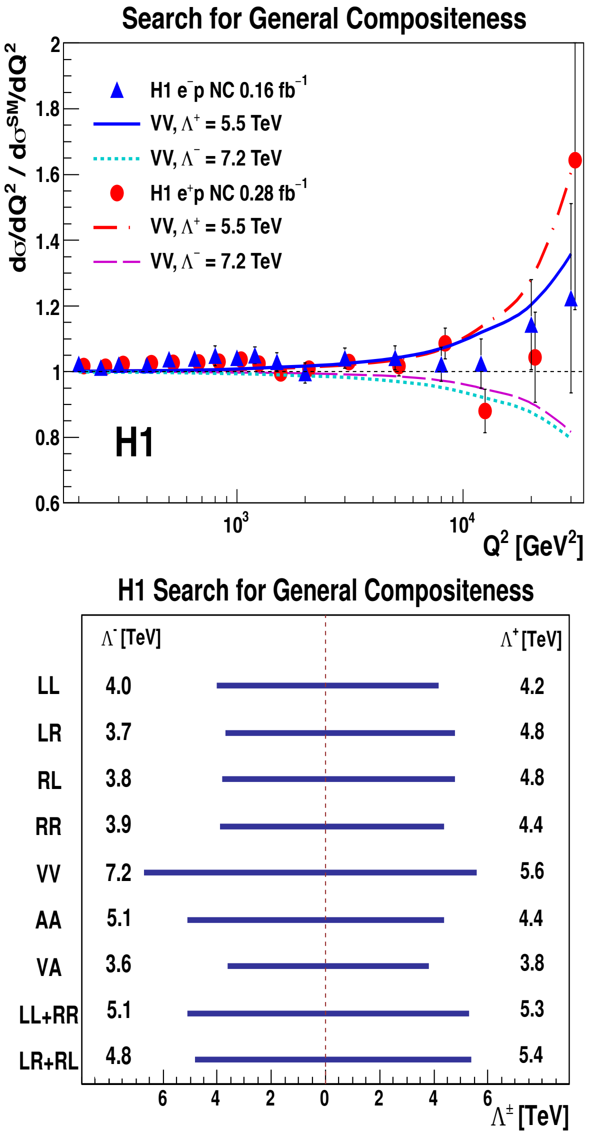

Figure 9: (Top) Comparison of 0.44 fb^{-1} H1 $e^{\pm}p$ data with the 95 % exclusion limits on the effective mass scale for VV contact interaction model. (Bottom) Confidence Limits from H1 on the compositeness scale Λ for different contact interaction models for negative and positive couplings.

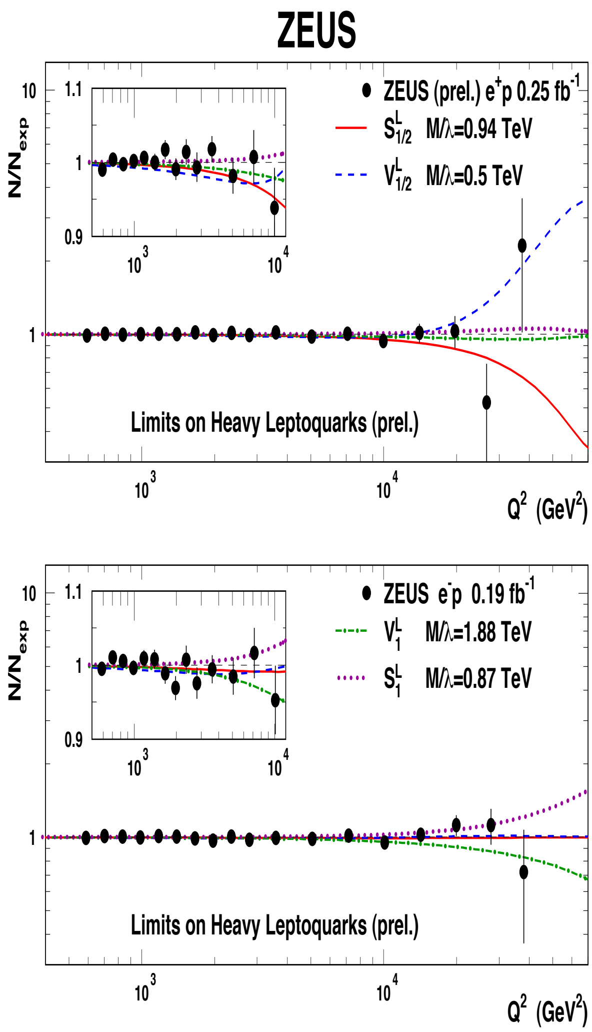

Figure 10: ZEUS $e^{+}p$ data (top plot) and $e^{-}p$ (bottom plot) data compared with 95 % CL exclusion limits for the ratio of mass of the leptoquark to the Yukawa coupling. The data are normalized to SM predictions using the CTEQ5D PDF.

physics at much high energy mass scales. The CI analysis involves comparisons of Q^2 distributions from the HERA data to the SM predictions. Figure 9 shows the results from the H1 collaboration on a CI search using 130 pb^{-1} of HERA I $e^{\pm}P$ data and 350 pb^{-1} of HERA-II $e^{\pm}P$ data.

Different chiral models have been studied and limits have been put on the compositeness scale for the presence of CI at 95% CL. The bottom plot in Fig. 9 compares the 95% CL on the compositeness scale Λ for various CI models studied using H1 data as discussed in detail in [13].

3.2. *Leptoquark search*

Leptoquarks (LQs) appear in extensions of the SM which connect electron and quarks [27]. In the limit of heavy LQs, these are equivalent to four fermion interactions. Figure 10 shows the results from ZEUS on heavy

LQs using the full HERA-I and HERA-II data. No deviations from the SM are observed, which again allows a limit to be placed on the ratio of the mass of the LQ to the Yukawa coupling [14].

3.3. Quark radius

Quark substructure can be studied using HERA data by measuring the spatial distribution of the quark charge [28]. Assuming that the electron is point-like, and that quarks have a root mean square radius R_q, the DIS cross sections predicted by the SM would get modified by a form factor as given below

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}(1 - \frac{R_q^2}{6}Q^2)^2$$

Figure 11 shows the comparison of about 0.44 fb^{-1} of HERA data from the H1 [13] and ZEUS [14] experiments to the SM predictions with the above form factor applied. No deviation from the SM is observed which leads to a limit on the quark radius. H1 puts a limit on the quark radius at 95 % CL

$$R_q < 0.65.10^{-18}m$$

and the limit from ZEUS corresponds to

$$R_q < 0.63.10^{-18}m.$$

4. Summary

The NC and CC $e^{\pm}p$ DIS cross sections are measured using longitudinally polarized lepton beams at HERA. These cross sections reduce the uncertainties on HERA PDFs. The polarization dependence of the CC cross sections expected from the SM is well established using HERA data and is consistent with the absence of right handed charged currents. The polarizations asymmetry of the NC cross sections is measured for both helicities of the lepton beams. HERA data are used to study the lepton charge asymmetry coming from the $\gamma - Z$ interference term in the cross sections. The $x\tilde{F}_3$ structure function is extracted yielding constraints on the valence quark distributions. An electroweak QCD analysis has been performed to calculate the coupling constants of u and d quarks to the Z bosons with improved precision. The ZEUS experiment has measured the NC cross sections up to the kinematic limit in x, thus providing a better understanding of the high-x region where PDFs fall sharply at large scales.

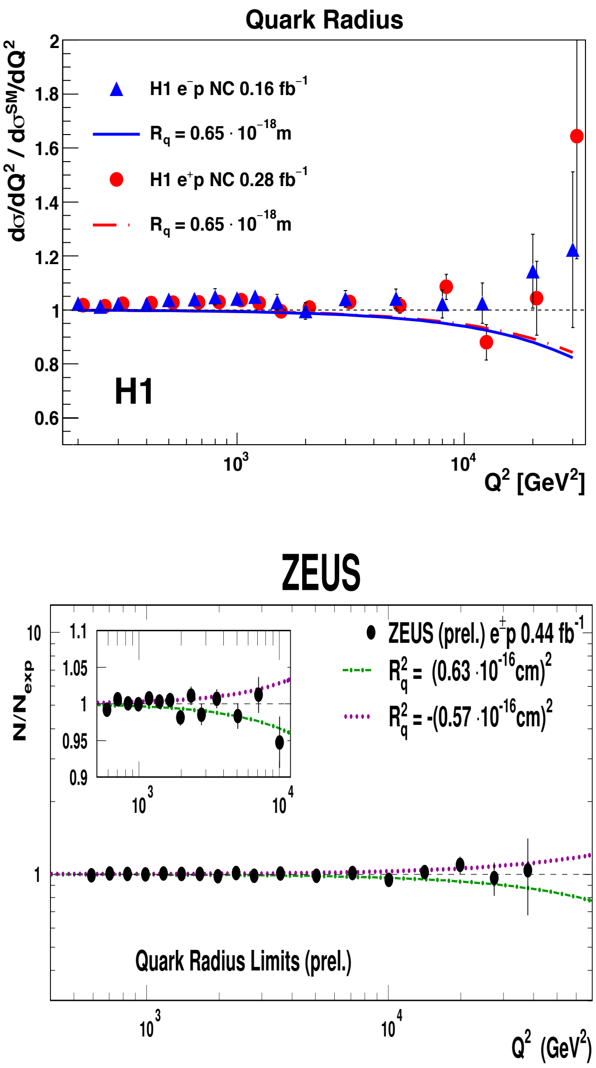

Figure 11: H1 (top plot) and ZEUS (bottom plot) results using HERA data compared with 95 % CL exclusion limits for the effective mean-square radius of the quark charge. The data are compared to SM predictions using the CTEQ5D PDFs. The model predictions are normalized to data.

A search for physics beyond SM has been performed using HERA data and no significant deviations from theory are found, and 95% CL limits have been placed on the theoretical parameters studied. For the contact interactions, limits have been obtained on the compositeness scale Λ for different models considered. For the presence of heavy leptoquarks, limits have been calculated on the ratio of the mass of the leptoquark to the Yukawa coupling. Quark substructure is probed and limits have been obtained for the effective mean square radius of the quark charge.

References

[1] F. Aaron, et al., Combined Measurement and QCD Analysis of the Inclusive *ep* Scattering Cross Sections at HERA, JHEP 01 (2010) 109. arXiv:0911.0884, doi:10.1007/JHEP01(2010)109.

[2] H1 Collab., High Q^2 Neutral Current in polarised ep collisions at HERA II, H1prelim-09-042, available at http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-09-042.long.html.

[3] H1 Collab., High Q^2 Charged Current in polarised ep collisions at HERA II, H1prelim-09-043, available at http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-09-043.long.html.

[4] H. Abramowicz, et al., Measurement of high-Q^2 charged current deep inelastic scattering cross sections with a longitudinally polarised positron beam at HERA, Eur. Phys. J. C70 (2010) 945–963. arXiv:1008.3493, doi:10.1140/epjc/s10052-010-1498-9.

[5] S. Chekanov, et al., Measurement of charged current deep inelastic scattering cross sections with a longitudinally polarised electron beam at HERA, Eur. Phys. J. C61 (2009) 223–235. arXiv:0812.4620, doi:10.1140/epjc/s10052-009-1015-1.

[6] S. Chekanov, et al., Measurement of high-Q^2 neutral current deep inelastic $e^- p$ scattering cross sections with a longitudinally polarised electron beam at HERA, Eur. Phys. J. C62 (2009) 625–658. arXiv:0901.2385, doi:10.1140/epjc/s10052-009-1055-6.

[7] ZEUS Collab., Measurement of High-Q^2 Neutral Current Deep Inelastic $e^+ p$ Scattering Cross Sections with a Longitudinally Polarised Positron Beam at HERA, ZEUS-prel-11-003.

[8] C. Adloff, et al., Search for new physics in $e^\pm q$ contact interactions at HERA, Phys. Lett. B568 (2003) 35–47. arXiv:hep-ex/0305015, doi:10.1016/j.physletb.2003.06.034.

[9] C. Adloff, et al., Search for compositeness, leptoquarks and large extra dimensions in *eq* contact interactions at HERA, Phys. Lett. B479 (2000) 358–370. arXiv:hep-ex/0003002, doi:10.1016/S0370-2693(00)00332-4.

[10] S. Aid, et al., Leptoquarks and compositeness scales from a contact interaction analysis of deep inelastic $e^\pm p$ scattering at HERA, Phys. Lett. B353 (1995) 578–588. arXiv:hep-ex/9504008, doi:10.1016/0370-2693(95)00611-N.

[11] S. Chekanov, et al., Search for contact interactions, large extra dimensions and finite quark radius in *ep* collisions at HERA, Phys. Lett. B591 (2004) 23–41. arXiv:hep-ex/0401009, doi:10.1016/j.physletb.2004.03.081.

[12] J. Breitweg, et al., Search for contact interactions in deep inelastic $e^+ p \to e^+ X$ scattering at HERA, Eur. Phys. J. C14 (2000) 239–254. arXiv:hep-ex/9905039.

[13] F. D. Aaron, et al., Search for Contact Interactions in $e^\pm p$ Collisions at HERA, Phys. Lett. B705 (2011) 52–58. arXiv:1107.2478, doi:10.1016/j.physletb.2011.09.109.

[14] ZEUS Collab., Search for contact interactions in *ep* collisions with ZEUS experiment at HERA, ZEUS-prel-09-013.

[15] H1 Collab., Combined Measurement of Neutral and Charged Current Cross Sections at HERA, H1prelim-10-141, available at http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-10-141.long.html.

[16] ZEUS Collab., Combined Measurement of Neutral and Charged Current Cross Sections at HERA, ZEUS-prel-10-017.

[17] H1 and ZEUS Collab., HERAPDF1.5 NNLO, H1prelim-10-042, ZEUS-prel-11-002, available at http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-10-042.long.html.

[18] ZEUS Collab., QCD and Electroweak analysis of the ZEUS NC and CC inclusive and jet cross sections, ZEUS-prel-06-003.

[19] A. Aktas, et al., A determination of electroweak parameters at HERA, Phys. Lett. B632 (2006) 35–42. arXiv:hep-ex/0507080, doi:10.1016/j.physletb.2005.10.035.

[20] J. Alcaraz, et al., A Combination of preliminary electroweak measurements and constraints on the standard model, LEP Electroweak Working Group, arXiv:hep-ex/0612034.

[21] D. Acosta, et al., Measurement of the forward-backward charge asymmetry of electron positron pairs in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV, Phys. Rev. D71 (2005) 052002. arXiv:hep-ex/0411059, doi:10.1103/PhysRevD.71.052002.

[22] H1 Collab., PDF fits including HERA-II high-Q^2 data (HERAPDF1.5), H1prelim-10-142, available at http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-10-142.long.html.

[23] ZEUS Collab., PDF fits including HERA-II high-Q^2 data (HERAPDF1.5), ZEUS-prel-10-018.

[24] S. Chekanov, et al., Measurement of neutral current cross sections at high Bjorken-x with the ZEUS detector at HERA, Eur. Phys. J. C49 (2007) 523–544. arXiv:hep-ex/0608014, doi:10.1140/epjc/s10052-006-0164-8.

[25] ZEUS Collab., Measurement of high-Q^2 charged current deep inelastic scattering cross sections with a longitudinally polarised positron beam at HERA, ZEUS-prel-10-004.

[26] ZEUS Collab., Measurement of positron-proton neutral current cross sections at high Bjorken-x with the ZEUS detector at HERA, ZEUS-prel-11-004.

[27] W. Büchmuller, R. Rückl, D. Wyler, Leptoquarks in lepton-quark collisions [Phys. Lett. B 191 (1987) 442], Phys. Lett. B448 (1999) 320–320. doi:10.1016/S0370-2693(99)00014-3.

[28] G. Kopp, D. Schaile, M. Spira, P. Zerwas, Bounds on radii and magnetic dipole moments of quarks and leptons from LEP, SLC and HERA, Z. Phys. C65 (1995) 545–550. arXiv:hep-ph/9409457, doi:10.1007/BF01556142.