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Measurements at high Q^2 and searches at the ep energy frontier

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Abstract

A brief overview is given on most recent, preliminary results obtained by the HERA experiments H1 and ZEUS on the measurements of the neutral current ($ep \to eX$) and charged current ($ep \to \nu X$) deep inelastic scattering (DIS) cross sections at high values of negative four-momentum transfer squared, Q^2. Such processes provide the possibility to study the structure of the proton, the dynamics of strong interactions, to test quantum chromodynamics (QCD) and also provide complementary information on the QCD and electroweak parts of the Standard Model (SM). In addition, a short report is given on indirect searches for new phenomena in which no evidence for the new physics has been found. The results presented in this paper are based on the full statistics of data collected at HERA, the only $e^{\pm}p$ collider, operated in the years 1992-2007 at centre-of-mass energies 300-320 GeV.

Keywords: deep inelastic scattering, neutral current, charged current, polarisation, multileptons, isolated leptons

1. Introduction

At HERA about 100 (20) pb^{-1} of e^+p (e^-p) data were collected until the year 2000 (HERA-I). Afterwords, HERA underwent a major upgrade (HERA-II) aiming for higher luminosity, and until March 2007, HERA provided in total about 500 pb^{-1} of $e^{\pm}p$ collisions per experiment to H1 and ZEUS. After the upgrade, longitudinally polarised lepton beams have been provided to the H1 and ZEUS experiments with an average polarisation, P_e, from 35 to 40%. DIS measurements with polarised leptons on protons allow the parton distribution functions (PDFs) of the proton to be further constrained through polarisation asymmetries and specific tests of the electroweak part of the SM to be performed. In particular, by measuring the polarisation dependence of the charged current cross section, the V-A structure of charged current interactions can be tested.

The total luminosity collected at HERA of about 1 fb^{-1} provides access to rare processes with cross sections of the order of 0.1 pb, giving a solid ground for testing of the SM which is complementary to the tests performed in e^+e^- and $p\overline{p}$ scattering. Searches for new physics often compare the data to the predictions of specific models. Recent H1 and ZEUS analysis searched for single top production, excited quarks, supersymmetric particles or lepton flavor violation [1–5]. A complementary approach is followed in signature based searches by looking for differences between data and SM expectation in various event topologies. Therefore, such model independent analysis do not rely on any a priori definition of expected signatures for new phenomena. Combinations of the H1 and ZEUS results based on model-independent searches which exploit the complete $e^{\pm}p$ data samples of both experiments have been published [6, 7] and will be discussed in this paper.

The kinematics of inclusive deep inelastic electron[1]-proton scattering is described in terms of the variables Q^2, the four-momentum transfer squared of the exchanged vector boson, Bjorken x, the fraction of the momentum of the incoming nucleon carried by the struck quark, and inelasticity $y = Q^2/sx$, which is a measure of the energy transfered between the electron and the proton. The centre of mass energy squared, s, is given by the electron and the proton beam energies, $s = 4E_eE_p$.

The neutral current (NC) cross section can be expressed by three generalised proton structure functions,

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[1]The term electron is used to denote both electrons and positrons.

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$\tilde{F}_2$, $\tilde{F}_L$ and $x\tilde{F}_3$ as

$$\frac{d^2\sigma(e^\pm p \to e^\pm X)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ (\tilde{F}_2^\pm \mp \frac{Y_-}{Y_+} x\tilde{F}_3^\pm - \frac{y^2}{Y_+}\tilde{F}_L^\pm),$$

with $Y_\pm = 1 \pm (1-y^2)$ and

$$\tilde{F}_2^\pm = F_2 + k_z(-v_e \mp P_e a_e)F_2^{\gamma Z} + k_z^2(v_e^2 + a_e^2 \pm 2P_e v_e a_e)F_2^Z,$$
$$x\tilde{F}_3^\pm = k_z(-a_e \mp P_e v_e)xF_3^{\gamma Z} + k_z^2(2v_e a_e \pm P_e(v_e^2 + a_e^2))xF_3^Z.$$

F_2 describes pure photon exchange, F_2^Z and xF_3^Z describe pure Z exchange and $F_2^{\gamma Z}$ and $xF_3^{\gamma Z}$ γZ interference. v_e is the weak vector coupling and a_e the weak axial-vector coupling of the electron to the Z. The quantity k_z is defined via Weinberg angle θ_w, the four-momentum transfer squared Q^2 and mass of the Z boson, $k_z = \frac{Q^2}{Q^2+M_Z^2}\frac{1}{4cos^2\theta_W sin^2\theta_W}$. The longitudinal structure function $\tilde{F}_L$ gives sizable contribution only at high y. The terms from the generalised structure functions are given by the following expressions,

$$[F_2, F_2^{\gamma Z}, F_2^Z] = x\sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2](q + \overline{q}),$$
$$[xF_3^{\gamma Z}, xF_3^Z] = 2x\sum_q [e_q a_q, v_q a_q](q - \overline{q}).$$

v_q and a_q are the vector and axial-vector coupling constants of the quarks to the Z^0 respectively. xq and $x\overline{q}$ are quark and antiquark PDFs. e_q is quark charge.

In the SM the cross sections of the charged current (CC) DIS interaction has a linear dependence on polarisation, P_e, and can be written as,

$$\frac{d^2\sigma_{CC}^{e^+p}}{dxdQ^2} = (1 \pm P_e)\frac{{G_F}^2}{2\pi x}\frac{{M_W}^4}{(Q^2 + {M_W}^2)^2}\overline{\sigma}_{CC}^{e^\pm p},$$

where the reduced CC cross section $\overline{\sigma}_{CC}^{e^\pm p}$ is related to the quark and antiquark densities in $e^\pm p$ scattering via

$$\overline{\sigma}_{CC}^{e^+p} = x[\overline{u} + \overline{c} + (1-y)^2(d+s)],$$
$$\overline{\sigma}_{CC}^{e^-p} = x[u + c + (1-y)^2(\overline{d} + \overline{s})],$$

thus bringing flavor sensitivity of the valence quark PDFs at large x.

2. High Q^2 measurements and electroweak physics

Unpolarised neutral and charged current cross sections measured at HERA as function of Q^2 are shown in Fig. 1. NC and CC cross sections become about equal in magnitude for $Q^2 \geq M_{Z,(W)}^2$. In this region also the influence of $x\tilde{F}_3$ in the e^+p and e^-p NC cross sections is visible. At low Q^2 the NC cross section, driven by the electromagnetic interaction, is two orders of magnitude

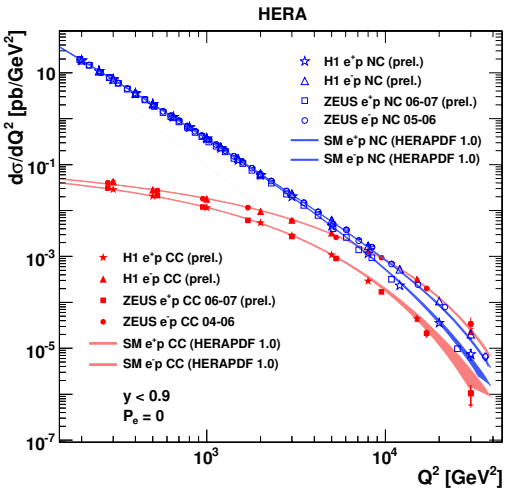

Figure 1: The Q^2 dependence of the unpolarised NC and CC cross sections shown for e^+p (open points) and e^-p (solid points) scattering data from the H1 and ZEUS collaborations. The inner and outer error bars represent respectively the statistical and total errors. The results are compared with the corresponding SM expectations determined from the HERAPDF 1.0 fit.

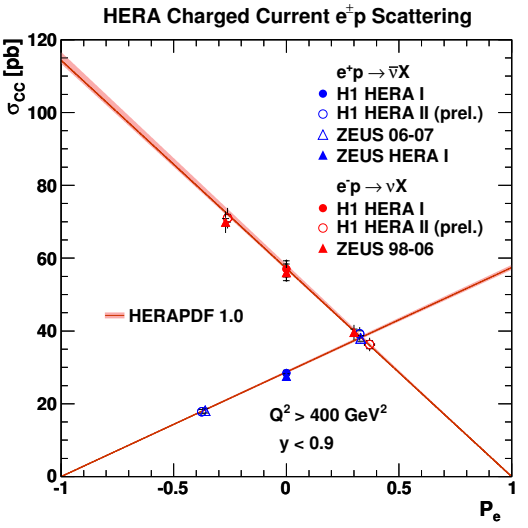

Figure 2: The dependence of the $e^\pm p$ CC cross section on the lepton beam polarisation P_e. The inner and outer error bars represent respectively the statistical and total errors. The data are compared to the SM prediction based on the HERAPDF 1.0 parametrisation.

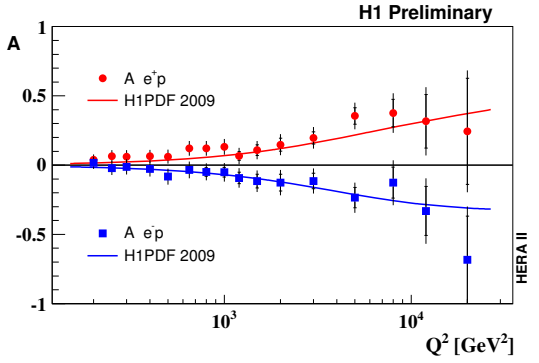

Figure 3: The Q^2 dependence of the polarisation asymmetry for e^+p (circles) and e^-p (squares). The data (solid points) are compared to the SM prediction (full lines) from the H1PDF 2009 fit. The inner error bars represent the statistical uncertainties and the outer error bars represent the total errors.

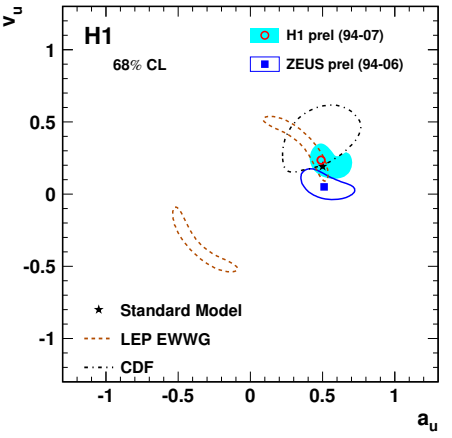

Figure 4: H1 and ZEUS results at 68% confidence level (CL) on the couplings of the u quark to the Z^0 boson obtained using the full HERA data. The results obtained by the LEP EWWG [8] and the CDF experiment [9] are also shown. The stars show the expected SM values.

larger than the CC cross section and corresponds to a pure weak interaction.

The dependence of the $e^\pm p$ CC cross section on the lepton beam polarisation is shown in Fig. 2. The obtained measurements show a linear dependence on P_e which is consistent with the absence of right handed charged currents as predicted by the SM.

The SM predicts a difference in the cross section for leptons with different helicity states arising from the chiral structure of the neutral electroweak exchange. With longitudinally polarised lepton beams in HERA-II such polarisation effects can be tested, providing a direct measure of electroweak effects in the neutral current cross sections. The polarisation asymmetry, A, is defined as

$$A = \frac{2}{P_R - P_L} \cdot \frac{\sigma^\pm(P_R) - \sigma^\pm(P_L)}{\sigma^\pm(P_R) + \sigma^\pm(P_L)} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2}.$$

A recent preliminary result on the Q^2 dependence of the polarisation asymmetry, obtained by the H1 Collaboration using the complete HERA II data, is shown in Fig. 3.

Using the $e^\pm p$ NC and CC cross sections, a combined EW and QCD analysis is performed to determine the vector and axial-vector couplings v_q and a_q of the light quarks u and d to the Z^0 boson, accounting for their correlation with parton distributions. The preliminary results on the vector and axial-vector couplings of the u quark to the Z^0 boson obtained by the H1 and ZEUS experiments are shown in Fig. 4 and compared with those from LEP and Tevatron.

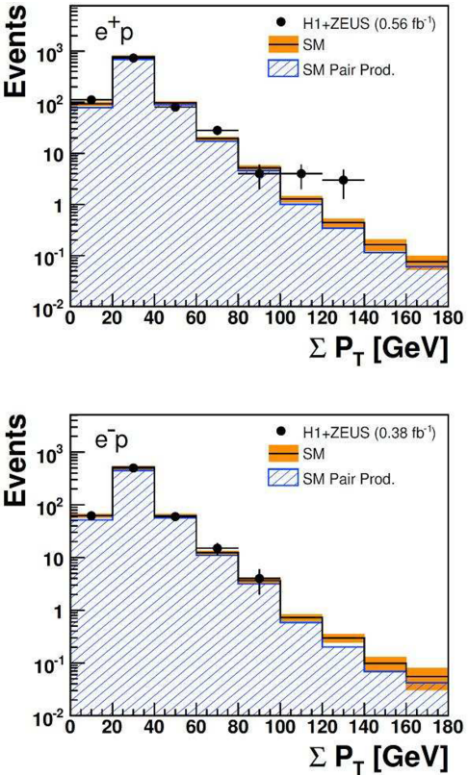

Figure 5: The distribution of the scalar sum of the transverse momenta ΣP_T for combined di-lepton and tri-lepton event topologies for e^+p (top) and e^-p (bottom) data. The points correspond to the observed data events and the histogram to the SM expectation. The total uncertainty on the SM expectation is given by the shaded band. The hatched histogram corresponds to the SM expectation arising from lepton pair production.

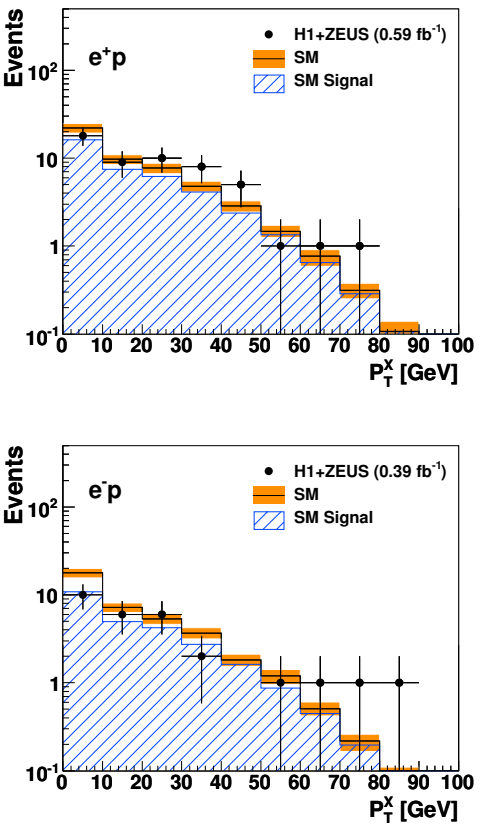

Figure 6: The distribution of the hadronic transverse momentum P_T^X of events with an isolated electron or muon and missing transverse momentum for the e^+p (top) and e^-p (bottom) data. The points correspond to the observed data events and the histogram to the SM expectation. The total uncertainty on the SM expectation is given by the shaded band. The hatched histogram corresponds to the signal component of the SM expectation dominated by single W production.

3. Model-independent searches at HERA

Combined analyses of events with multi-leptons with high transverse momentum [6] and of an isolated lepton and missing transverse momentum [7] are performed using H1 and ZEUS data in a common phase space. The analyses make use of the full data samples available to both experiments allowing more precise measurements.

According to predictions of the SM the production of multi-lepton final states in ep collisions proceeds mainly via photon-photon interactions. The clean experimental signature of leptons with high transverse momenta, P_T, together with the precisely calculable small SM cross section provides high sensitivity to possible contributions of physics beyond the SM. The production of multi-lepton (electron and muon) events at high transverse momenta was studied using the full $e^\pm p$ data sample collected by the H1 and ZEUS experiments with a total integrated luminosity of 0.94 fb^{-1}. The yields of di-lepton and tri-lepton events are in good agreement with the SM predictions. Both experiments observe events at high values of the sum of the lepton transverse momenta, ΣP_T, in e^+p collisions. Seven events have a $\Sigma P_T > 100$ GeV, wheres the corresponding SM expectation for e^+p collisions is 1.94 ± 0.17. For comparable SM expectations, none are observed in e^-p collisions. Distributions of the ΣP_T are in good overall agreement with the SM expectations as can be seen in Fig. 5.

A search for events containing an isolated electron or muon and missing transverse momentum is performed using data collected with the H1 and ZEUS detectors which correspond to an integrated luminosity of 0.98 fb^{-1}. As can be seen from Fig. 6, the observed event yields are in good overall agreement with the SM prediction, which is dominated by single W production. A total of 81 events are observed in the data, compared to a SM prediction of 87.8 ± 11.0. In the e^+p data, at large hadronic transverse momentum $P_T^X > 25$ GeV, a total of 23 data events are observed compared to a SM prediction of 14.0 ± 1.9.

In this analysis the total single W boson production cross section is measured as 1.06 ± 0.16(stat.) ± 0.07(sys.) pb, in agreement with an SM expectation of 1.26 ± 0.19 pb.

There is also final result from the H1 Collaboration [10] on a general analysis of all high transverse momentum final state configurations involving electrons, muons, jets, photons or neutrinos in $e^\pm p$ collisions. The total integrated luminosity of the data is 463 pb^{-1}. Data events are found in 27 different final states and events with up to five high P_T particles are observed. A good agreement with the SM expectation is observed in the phase space covered by this analysis demonstrating the good understanding of high P_T SM phenomena at HERA.

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