Electroweak physics at HERA

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Abstract. The HERA experiments have collected interesting luminosity samples with both polarized and unpolarized lepton beams. The polarized CC data are directly sensitive to right handed charged currents. The data are in agreement with the SM predicting their absence. Effects of Z-exchange have been seen in the lepton beam charge and polarization assymetries. A combined electroweak and QCD analysis allows one to measure electroweak parameters with world competitive accuracy.

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INTRODUCTION

HERA is the first and up to now the only electron-proton collider. It operates at a total center-of-mass energy $\sqrt{s} = 318$ GeV, enabling besides γ-exchange a large fraction of Z and W exchange. Thus HERA is a truly electroweak collider allowing to study weak interaction effects in the spacelike region. The data are collected by the two collider experiments, H1 and ZEUS.

Inclusive electron-proton scattering can be conveniently characterized by three invariant variables, the photon virtuality Q^2, Bjorken-x, and inelasticity y. At fixed center-of-mass energy only two of these are independent, as Q^2=sxy.

There are two distinct types of interactions observed at HERA. In the case of Neutral Current (NC) scattering, either a γ or Z-boson is exchanged. Experimentally such processes are characterized by a scattered electron and a hadronic jet (or jets) observed in a detector, balanced in transverse momentum. The NC cross section can be written in the following form:

$$\frac{d\sigma_{NC}^{e^{\pm}p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right], Y_{\pm} = 1 \pm (1-y)^2 \tag{1}$$

Here the unknown proton structure is expressed in terms of three generalized structure functions. The dominant contribution to the cross section is provided by $\tilde{F}_2$; in the quark-parton model (QPM) it is equal to the sum of parton density functions (pdfs) of quarks and antiquarks weighted by their charges squared.

At large momentum transfers $x\tilde{F}_3$ becomes sizable, in QPM it is proportional to the sum of pdfs of valence quarks weighted by their charges squared. The longitudinal structure function $\tilde{F}_L$ is visible only at high y and can be neglected in this article.

In the case of Charged Current (CC) scattering a W boson is exchanged and the electron is transformed to a neutrino. Such events are experimentally characterized by a hadronic jet (or jets) with missing transverse momentum. Expressing the structure

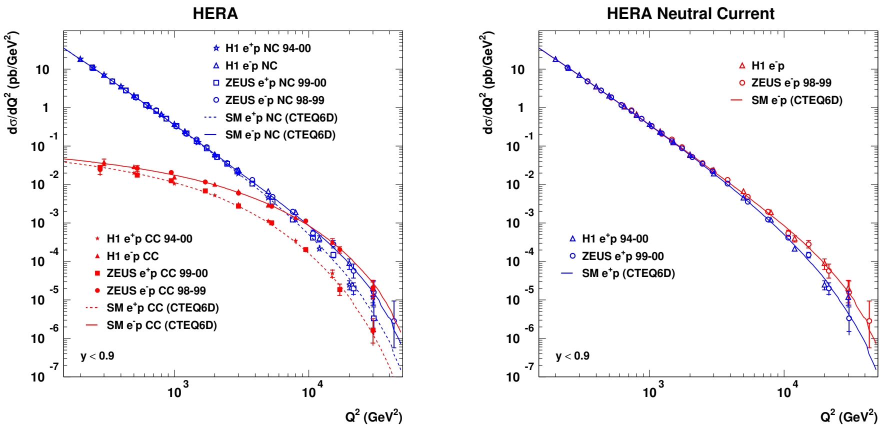

FIGURE 1. Differential cross sections of unpolarized NC and CC scattering as a function of Q^2 for NC and CC (left) and for $e^{\pm}p$ NC (right).

of the proton in terms of the functions W_2, xW_3 and W_L, the CC cross section can be parametrized as:

$$\frac{d\sigma_{CC}^{e^{\pm}p}}{dxdQ^2} = \frac{G_F^2}{4\pi x}\left[\frac{M_{\rm prop}^2}{M_{\rm prop}^2+Q^2}\right]^2\left[Y_+W_2 \mp Y_-xW_3 - y^2W_L\right] \qquad (2)$$

Here M_{prop} is the mass of the exchanged boson occuring in the propagator.

EW EFFECTS IN UNPOLARIZED NC/CC SCATTERING

The NC and CC differential cross sections as a function of Q^2 are shown on Fig. 1 left. While they differ by several orders of magnitude at low Q^2, due to different propagator terms, at Q^2 close to the W-mass squared they are of similar magnitude. The remaining differences are caused mainly by the fact, that NC and CC are sensitive to different combinations of pdf's.

On Fig. 1 right one can see the differential NC cross section as a function of Q^2 for e^+p and e^-p collisions. At high Q^2 the dependence on the lepton beam charge is visible. This effect is described by $x\tilde{F}_3$, its main contribution at HERA energies being the γZ interference.

POLARIZED NC/CC SCATTERING

Starting in 2000, the HERA collider was upgraded to deliver higher luminosities and longitudinally polarized lepton beams.

The transverse polarization in the HERA electron ring builds up naturally via emision of synchrotron radiation (Sokolov-Ternov effect). Spin rotators flip the transverse polar-

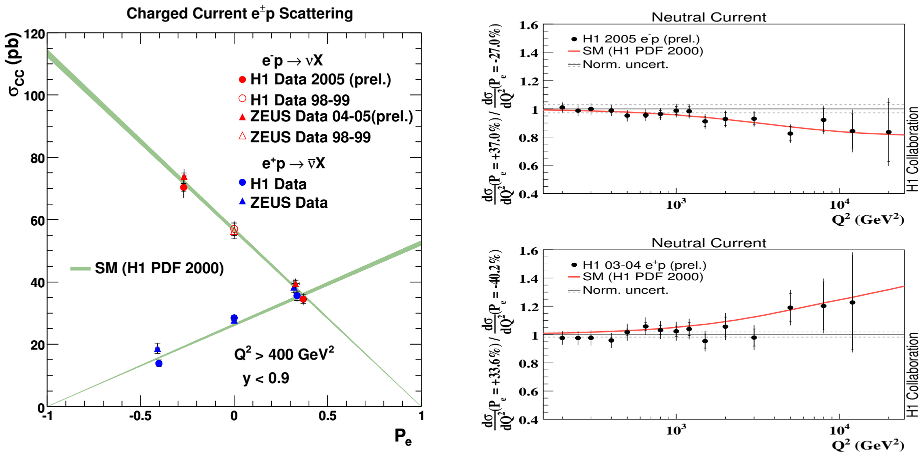

FIGURE 2. Differential cross sections of polarized CC as a function of pollarization (left) ad ratio between NC cross sections for two polarizations for electron an positron beam (right).

ization to longitudinal just before the interaction regions and vice versa behind it. The level of longitudinal polarization achieved up to now is 30-40 % .

The longitudinal polarization has a particularly strong effect on charged current cross sections. In the Standard Model (SM) only left handed particles (right handed antiparticles) interact via CC. Thus, defining the level of polarization as $P_e = (N_R - N_L)/(N_R + N_L)$, where N_L and N_R are numbers of left handed (right handed) leptons in the beam, a linear dependence of the cross section on P_e, giving zero cross section at $P_e = 1(-1)$ for electron (positron) beam is expected.

Indeed, the total CC cross section as a function of P_e, integrated over the visible phase space indicated on Fig. 2 left, is in good agreement with the SM prediction.

A contribution of a right-handed CC should change the slope and the intercept of the linear dependence of σ_{CC} on P_e. The cross sections were fitted by straight lines and extrapolated to $P_e = 1(-1)$ for electron (positron) beam. The H1 collaboration has presented data, for the visible phase space $Q^2 > 400$ GeV^2 and y< 0.9, leading to $\sigma_{CC}(e^+p, P_e = -1) = -3.9\ \pm 2.3(\text{stat}) \pm 0.7(\text{sys}) \pm 0.8(\text{pol})$pb and $\sigma_{CC}(e^-p, P_e = +1) = -0.9\ \pm 2.9(\text{stat}) \pm 1.9(\text{sys}) \pm 2.9(\text{pol})$pb. The ZEUS collaboration has shown results, for the visible phase space $Q^2 > 200$ GeV^2 leading to $\sigma_{CC}(e^+p, P_e = -1) = 7.4\ \pm 3.9(\text{stat}) \pm 1.2(\text{sys})$pb and $\sigma_{CC}(e^-p, P_e = +1) = 0.8\ \pm 3.1(\text{stat}) \pm 5(\text{sys})$pb. All results are compatible with zero, as predicted by the SM.

For NC scattering, both $\tilde{F}_2$ and $x\tilde{F}_3$ depend on the polarization due to pure Z exchange and γ-Z interference:

$$\tilde{F}_2 = F_2 - (\mathrm{v}_e \pm P_e \mathrm{a}_e)\,\chi_{\mathrm{Z}} F_2^{\gamma\mathrm{Z}} + \left(\mathrm{v}_e^2 + \mathrm{a}_e^2 \pm 2P_e \mathrm{v}_e \mathrm{a}_e\right) \chi_{\mathrm{Z}}^2 F_2^{\mathrm{Z}} \tag{3}$$

$$x\tilde{F}_3 = -\,(\mathrm{a}_e \pm P_e \mathrm{v}_e)\,\chi_{\mathrm{Z}} x F_3^{\gamma\mathrm{Z}} + \left(2\mathrm{v}_e \mathrm{a}_e \pm P_e(\mathrm{v}_e^2 + \mathrm{a}_e^2)\right) \chi_{\mathrm{Z}}^2 x F_3^{\mathrm{Z}} \tag{4}$$

where χ_{Z} is the ratio of two propagators, $\chi_{\mathrm{Z}} = 1/(\sin^2 2\theta_{\mathrm{W}}) Q^2/(M_{\mathrm{Z}}^2 + Q^2)$, and v_e and a_e are vector and axial couplings of Z to electron. At HERA energies, the contributions

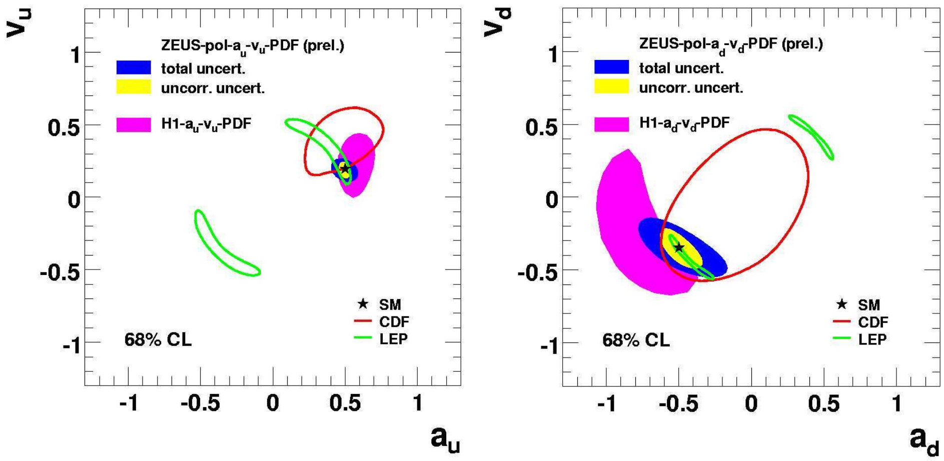

FIGURE 3. Measured axial and vector couplings of light quarks to Z-boson

of F_2^Z and xF_3^Z are suppressed by the propagator. As $\mathrm{v}_e << \mathrm{a}_e$, to first order $\tilde{F}_2 \approx F_2 \pm P_e \mathrm{a}_e \chi_Z F_2^{\gamma Z}$ and therefore one expects the polarization asymmetry to be of similar size but opposite sign for e^+p and e^-p interactions. This is indeed observed in the ratio of NC cross sections, taken with two slightly different polarizations, for e^+p and e^-p as shown on Fig. 2 right.

COMBINED EW AND QCD ANALYSIS OF NC/CC DATA

Good statistical precision and wide phase space coverage of HERA data allow one to perform a combined analysis, where the QCD and electroweak parameters are determined simultaneously from a fit to the data. The H1 analysis made use of HERA I unpolarized data, the preliminary ZEUS analysis included HERA II data.

The NC data are sensitive to the vector and axial coupling of light quarks to the Z-boson. In the QPM both $\tilde{F}_2$ and $x\tilde{F}_3$ can be expressed as: $F_2^{\gamma Z} = 2\sum e_q \mathrm{v}_q x[q+\overline{q}]$, $F_2^Z = \sum(\mathrm{v}_q^2 + \mathrm{a}_q^2)x[q+\overline{q}]$, $xF_3^{\gamma Z} = 2\sum e_q \mathrm{a}_q x[q-\overline{q}]$ and $xF_3^Z = 2\sum \mathrm{v}_q \mathrm{a}_q x[q-\overline{q}]$, where e_q is the quark electric charge.

Using ep data, it is possible to determine both axial and vector couplings simultaneously, as contributions from Z-exchange and the γZ-interference have different Q^2 dependence. Thanks to the interference terms, there is no sign ambiguity. Inclusion of the polarized data improves the determination of v_q.

The results are shown in Fig. 3. They are in good agreement with the Standard Model and competitive with measurements from LEP and CDF.

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