Electroweak physics at HERA

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Precise tests of electroweak (EW) physics have been performed at the $e^{\pm}p$ collider HERA by making use of the longitudinally polarised lepton beams. In this paper, the parity violation in $e^{\pm}p$ neutral current interaction at distances down to 10^{-18} m, the charged current cross section as a function of the lepton beam polarisation, a QCD and EW parameter fit and cross sections for the single W production are presented.

1 Deep Inelastic Scattering at HERA

HERA was the first lepton-proton collider. It accelerated an electron (or positron) beam of energy 27.5 GeV and a proton beam of energy 920 GeV. The two beams collided at a centre-of-mass energy of 318 GeV. There were two experiments for the collision, H1 and ZEUS.

HERA underwent a major upgrade in the year 2000 (HERAII). In HERAII, high statistics data with longitudinally polarised lepton beam and the polarisation of typically $30 \sim 40$ % were provided to the experiments.

The ep scattering at a high invariant mass of a hadronic system and high four-momentum transfer, q, is known as deep inelastic scattering, DIS. There are two processes in DIS, neutral current (NC) and charged current (CC) interactions. NC and CC proceed via the γ/Z^0 and $W^{\pm}$ boson exchanges, respectively. The kinematics of DIS are usually described by Q^2 $(= -q^2)$, Bjorken-x and inelastisity, y.

CC cross sections at low Q^2 are suppressed due to the large mass of the W boson in the propagator term while NC cross sections are much larger at low Q^2, due to γ exchange dominance. However CC and NC cross sections become the same order for $Q^2 \sim M_W^2, M_Z^2$ where M_W and M_Z are the masses of the Z^0 and $W^{\pm}$ bosons, respectively. The measurements of the HERA experiments demonstrate the unification of electromagnetic and weak forces as shown in Fig. 1.

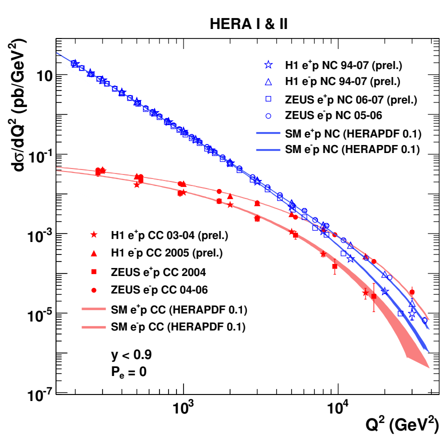

Figure 1: The Q^2 dependences of the NC and CC cross sections $d\sigma/dQ^2$ shown for the e^+p and e^-p data.

2 Electroweak effects in neutral current interactions

The unpolarised cross section for $e^{\pm}p$ NC interaction can be written as,

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^2}\left[Y_+F_2(x,Q^2) \mp Y_-xF_3(x,Q^2)\right], \tag{1}$$

where $Y_{\pm} = 1 \pm (1-y)^2$. F_2 and xF_3 are the proton structure functions. The xF_3 reflects distribution of valence quarks as follows,

$$xF_3 \simeq \sum_i -a_e\chi_Z[2e_ia_i] \times x(q_i - \bar{q}_i). \tag{2}$$

where, i runs over quark flavors and $q, \bar{q}$ are the quark, anti-quark density functions (PDFs) respectively. The quantity a_i (a_e) is the axial-vector coupling to the Z^0 boson of quark i (electron) [a]. The quantity χ_Z is the relative contribution of γ and Z^0 exchange, and $\chi_Z = \frac{1}{\sin^2 2\theta_W}\frac{Q^2}{M_Z^2+Q^2}$ where θ_W is the Weinberg mixing angle. The terms with χ_Z^2, which arose from the pure Z^0 exchange, are very small and have been ignored in Eq (2). The xF_3 structure function arises as a result of parity violation. It was measured from the difference between the e^-p and e^+p cross section [1] and it was found to be in agreement with the standard model (SM) prediction.

The parity violation effect with the longitudinally polarised beam is also seen in the structure function F_2 which is approximately given by,

$$F_2 \simeq \sum_i \left[e_i^2 + P_e(2\chi_Z a_e e_i v_i)\right] \times x(q_i + \bar{q}_i), \tag{3}$$

where v_i is the vector couplings to the Z^0 boson of quark i, and P_e is the electron/positron polarisation defined as,

$$P_e = \frac{N_R - N_L}{N_R + N_L}. \tag{4}$$

N_R and N_L are the number of leptons of right- and left- handed helicity, respectively. The polarisation asymmetry of the NC cross section, $A^{\pm}$, is defined as,

$$A^{\pm} = \frac{2}{P_R - P_L}\cdot\frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}, \tag{5}$$

for e^+p and e^-p scattering respectively, where P_R and P_L are the positive and negative polarisation. The asymmetry may be approximated as

$$A^{\pm} \simeq \chi_Z a_e \frac{2v_i}{e_i}, \tag{6}$$

so that it is sensitive to the quark vector couplings which are discussed in the next section. The measurement of the H1 and ZEUS data [2] are combined as shown in Fig. 2. The measured asymmetry shows a deviation of $A^{\pm}$ from zero at high Q^2 and it is well described by the SM prediction It demonstrates the parity violation at very small distances, down to about 10^{-18} m.

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[a] The vector coupling of electron, v_e, is small and terms containing it are ignored in Eqs. (2) and (3)

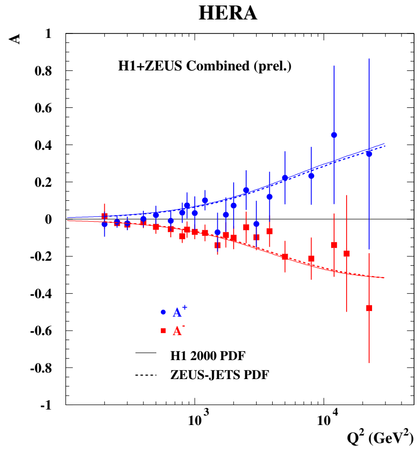

Figure 2: The measured polarisation asymmetries $A^{\pm}$ by the H1 and ZEUS combined analysis.The lines describe the theoretical predictions of NLO QCD evaluated with H12000 PDF and ZEUS-JETS PDF.

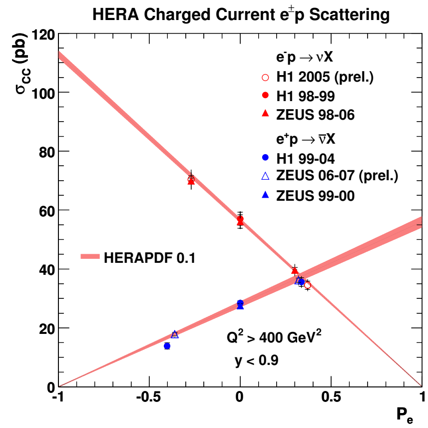

Figure 3: The total cross sections for e^-p and e^+p CC DIS as a function of the longitudinally polarisation of the lepton beam. The bands show SM predictions with HERAPDF0.1 NLO PDFs

3 Charged current cross sections

CC ep DIS is a pure weak process so that the parity is 100 % violated in the SM. The cross section for CC DIS is given as,

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 \left[Y_+ F_2^{CC}(x,Q^2) \mp Y_- xF_3^{CC}(x,Q^2)\right], \tag{7}$$

where F_2^{CC}, xF_3^{CC} are the structure functions and G_F is Fermi coupling constant.

As Eq. (7) shows, the CC cross section has a linear dependence on polarisation of incoming lepton. The measured CC total cross sections are shown as a function of the polarisation in Fig. 3, including previous measurements with unpolarised beams [3,4]. The data are compared to the SM predictions evaluated using HERAPDF0.1 [5] which are the NLO QCD PDFs extracted from fits to the combined H1 and ZEUS data. The SM prediction provides a reasonable description of the data.

Only left-handed particles and right-handed antiparticles take part in weak interactions. Lower limit on the mass of the W boson which couples to right-handed chirality can be set by extrapolating the e^+p and e^-p cross section to $P_e = -1, +1$, respectively. The limit by H1 e^+p data analysis is 208 GeV at 95 % CL [6].

4 Electroweak parameter and QCD fit

Precise measurement of structure functions at low Q^2 and hence precise determination of PDFs have been performed. Moreover high luminosity of HERAII data allows high statistics measurements up to higher Q^2 region. EW effects appear more clearly in high Q^2 DIS. Therefore PDFs and EW parameters can be fitted simultaneously.

As Eqs. (2) and (3) show, the NC DIS cross section has the sensitivity for quark couplings to the Z^0 boson. Fig. 4 show the 68 % CL contour plots from the determination of a_i and v_i for u and d-quarks. [7] The fit of HERA data is consistent with the SM and has significantly improved the determination of the u-quark coupling compared with the LEP and Tevatron results.

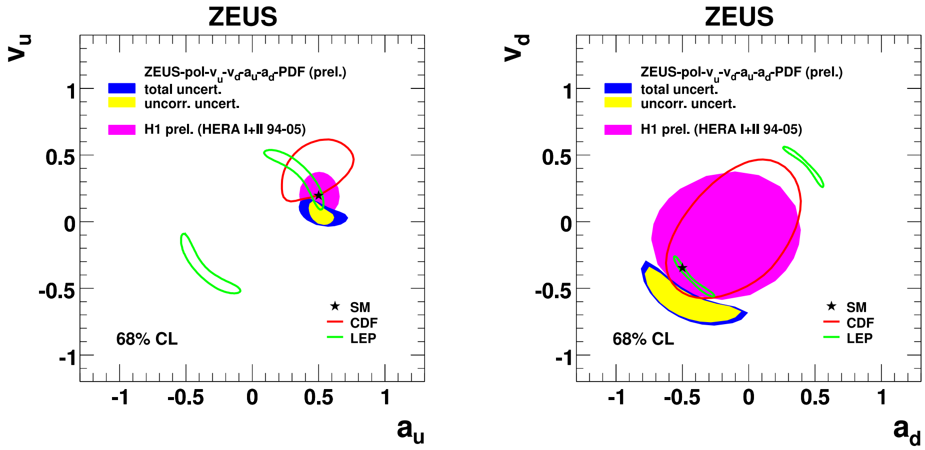

Figure 4: Contour plots of the 68 % limits on the electroweak couplings of the quarks to the Z^0 compared to those from CDF and LEP-II. Left side: a_u v.s v_u, right side: a_d v.s v_d.

5 Single W production

The single W production with a subsequent leptonic decay, $W \to l\nu$, has been studied at HERA. The signature of this process is a high transverse momentum (P_T) lepton and large missing P_T due to the decay neutrino. The cross section predicted by the SM is quite small. Therefore this channel is important in searches for the new physics which have a similar event topology as this process.

The cross section measured by H1 is,

$$\sigma_W = 1.14 \pm 0.25(stat.) \pm 0.14(syst.)\ pb,$$

with $\sigma_W^{SM} = 1.27 \pm 0.19$ of the SM expectation [8], ZEUS obtains,

$$\sigma_W = 0.89^{+0.25}_{-0.22}(stat.) \pm 0.10(syst.)\ pb,$$

with the SM prediction is $\sigma_W^{SM} = 1.2 \pm 0.18$. [9] The results from the both experiments, H1 and ZEUS have a good agreement with the SM.

6 Summary

Precise measurements for electroweak effects in the space-like scattering have been presented. The operation of HERA ended in June 2007 and the collected data corresponds to about 1 fb^{-1}, after combining the data of the two experiments. More analysis exploiting the full HERA data are expected to come, thus further improving the statistical precision.

References

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