MEASUREMENTS OF PROTON STRUCTURE AT HERA

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Measurements of proton structure functions in deep inelastic ep interactions are presented. The data were recorded with the H1 and ZEUS detectors at the HERA ep collider at DESY in the years 1994–2000 (HERA I) and 2003–2004 (HERA II) at the center-of-mass energy of $\sqrt{s} = 300$ GeV in 1994–1997 and 319 GeV in 1998 onwards. The HERA I data were used to extract quark and gluon parton distribution functions (PDFs) and to determine the strong coupling α_s. During the HERA II data taking period the lepton beam was longitudinally polarized.

1. Measurements of Structure Functions F_2 and xF_3

Deep inelastic scattering (DIS) is an ideal process with which to study the proton structure and to test Quantum Chromodynamics (QCD). Neutral current (NC) interactions are mediated by photons and Z^0 bosons. In NC ep events at HERA, the scattered lepton and the hadronic final state are measured in the H1 and ZEUS detectors with almost 4π solid angle coverage. The main contribution to the cross section for the dominant photon exchange is given in terms of the proton structure function $F_2(x, Q^2)$, which provides the total quark content of the proton at given values of the Bjorken scale variable x and of the modulus of the four-momentum transfer squared Q^2. Both experiments have shown that the Q^2 evolution of F_2 is well described by perturbative QCD (pQCD) throughout five orders of magnitude in x and Q^2, as illustrated in Fig. 1.[1,2,3,4,5]

While at low to medium Q^2 up to 3% precision is reached, the high Q^2 range is statistically limited. To improve the statistical significance at high Q^2, a luminosity upgrade of HERA in the H1 and ZEUS detector regions was performed in 2001. After initial background problems, the experiments are currently collecting data aiming roughly at an order of magnitude larger

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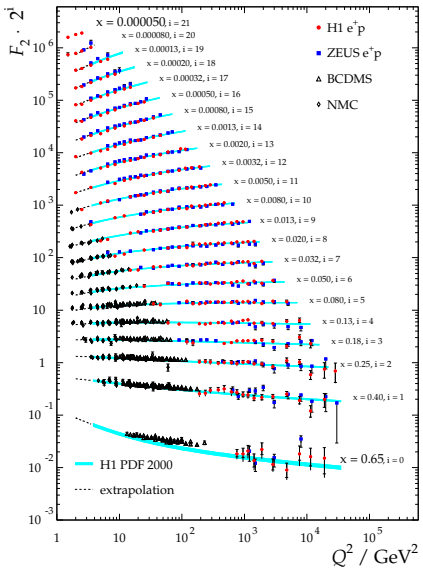

Figure 1. F_2 values measured by H1, ZEUS and fixed target experiments as functions of Q^2 at different x values. The bands represent the H1 PDF 2000 fit performed to the H1 NC and CC data with $Q^2 > 3.5$ GeV^2. The dashed lines depict the extrapolation of the fit towards lower Q^2 values.

integrated luminosity for the HERA II period than was collected during HERA I.

At $Q^2 \gtrsim M_Z^2$, the electroweak effects, especially the γZ interference, become significant leading to different NC cross-sections for e^+p and e^-p scattering (see Fig. 2a).[2,6,7] The difference is described in terms of the proton structure function $xF_3(x, Q^2)$. In pQCD, xF_3 is given by the difference between the quark and anti-quark density functions, and thus allows an extraction of the valence quark content of the proton. At present, the uncertainties are dominated by the limited statistics of the e^-p event samples. In order to increase the e^-p statistics, HERA has been operating in the e^-p mode since December 2004.

2. Comparison of Neutral Current and Charged Current Cross-Sections in e^+p and e^-p Scattering

In charged current (CC) interactions, mediated by $W^\pm$ bosons, the resulting neutrino escapes the detection. The CC events are thus recognized via imbalanced transverse momentum of the hadronic final state. At $Q^2 \gtrsim M_{Z,W}^2$, CC and NC cross-sections, driven by respective boson propagator terms, become of similar size, as shown in Fig. 2b. The measurements at HERA have confirmed the Standard Model predictions.[2,5,6,7]

As high Q^2 and high x ranges are kinematically correlated, the high Q^2

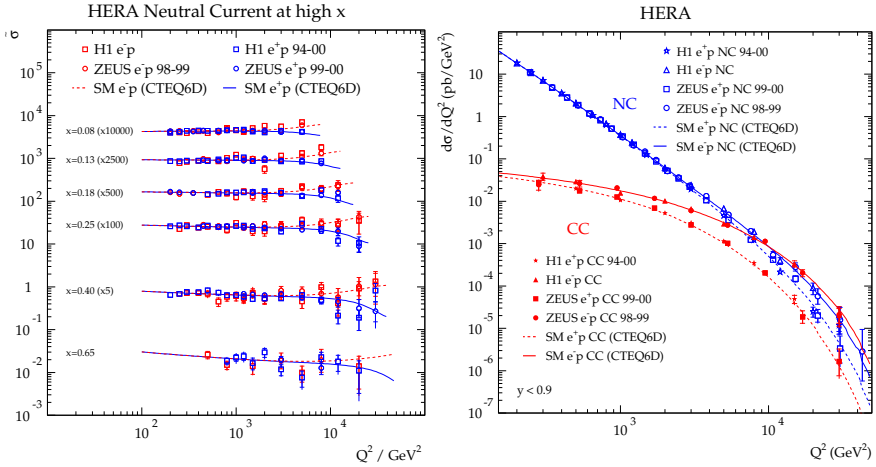

Figure 2. a) "Reduced" NC cross-sections (see definition *e.g.* in Ref. 2, eq. 11) at high Q^2 shown as functions of Q^2 for different x values in e^+p and e^-p scattering. b) Single differential NC and CC DIS cross-sections, measured as functions of Q^2 in e^+p and e^-p scattering. The results by H1 and ZEUS in both plots are compared to Standard Model predictions involving CTEQ6 parametrizations of parton densities in the proton.

measurements cover mainly the x region of valence quarks. At high x, the CC e^-p cross-section is dominated by the contribution of u quarks, while the CC e^+p is dominated by d quarks. Hence, the valence u and d PDFs are separated via the difference between e^+p and e^-p cross-sections.

3. Determination of Parton Densities and α_s

The quark and gluon PDFs are extracted via next-to-leading order (NLO) pQCD fits independently by H1 and ZEUS using somewhat different approaches.[2,4] The differences lie in the functional forms of the parametrizations, the densities parametrized, constraints imposed on the densities, the treatment of heavy quarks, phase space limits, Q^2 start scales, treatment of experimental uncertainties, the data sets used, etc. It is possible to extract PDFs from the HERA data only, without input from other experiments.[2,8]

Results of both collaborations agree broadly, as shown exemplary in Fig. 3 for $Q^2 = 10$ GeV^2. From the fits, the valence u quark distribution is best known (up to 3% precision), followed by the valence d distribution (typically $3-10\%$ precision) and the gluon distribution ($5-20\%$), which is obtained from the F_2 scaling violations.

A precise knowledge of proton PDFs in the kinematic range of HERA is

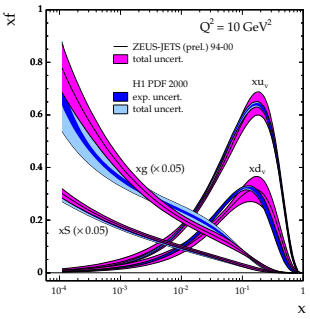

Figure 3. The valence u and d, the sea and the gluon PDFs from H1 2000 and ZEUS-JETS fits [2,8] are shown as functions of x for fixed $Q^2 = 10$ GeV^2. The sea and gluon PDFs are scaled down by a factor of 20.

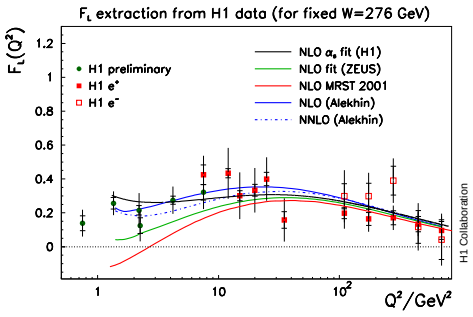

Figure 4. F_L measurements by H1 for $W = 276$ GeV and different Q^2 compared to the predictions of pQCD calculations.

of crucial importance for LHC data analyses, as the HERA data provide the only way to obtain PDF values in the LHC range via pQCD Q^2 evolution and thus to determine parton luminosities in pp reactions at the LHC.

The pQCD fits to the proton structure functions allow a precise determination of the running strong coupling, $\alpha_s(Q^2)$, reaching currently the experimental uncertainty of $2-3\%$. Recently, a new NLO QCD analysis was presented by ZEUS, in which α_s and the gluon PDF at high x were constrained using data on inclusive jet production in e^+p DIS and di-jet photoproduction.[8] This has allowed an improved determination of α_s.

4. Extraction of F_L

The contribution of longitudinally polarized photon exchange to the ep cross-section is described by the structure function $F_L(x, Q^2)$. In pQCD a non-zero value of F_L results from gluon emission. Measurements of F_L can thus provide constraints on the gluon PDF. This is especially important at low Q^2, where non-perturbative effects hamper the pQCD-based PDF extraction. The F_L dependent term in the DIS cross-section becomes significant only at very high values of the $\gamma^* p$ center-of-mass energy W. An overview of F_L values, obtained by H1 from the shape of the cross section at high W, is presented in Fig. 4 for fixed $W = 276$ GeV.[1,2,9] The measurements span over three orders of magnitude in Q^2. They are in agreement with NLO QCD fits. Non-zero F_L values are measured for the whole kinematic range down to the lowest Q^2 values.

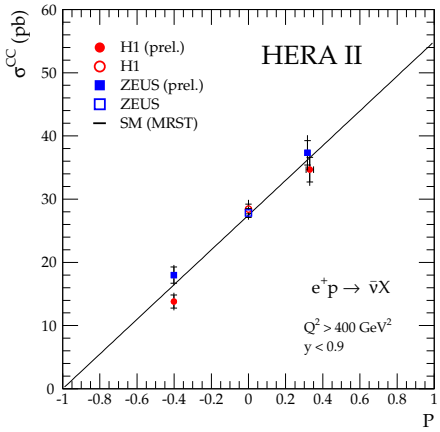

Figure 5. CC cross-sections of e^+p collisions measured by H1 and ZEUS during the years 2003–2004 of the HERA II data taking period for different e^+-beam polarizations. The solid line represents the Standard Model prediction involving proton PDF parametrizations by the MRST group.

5. First results with longitudinally polarized leptons

After the upgrade, HERA has provided longitudinally polarized leptons reaching currently up to 40% polarization. First results are obtained with polarized leptons for CC and NC inclusive cross-sections.

In the Standard Model only left-handed electrons and right-handed positrons take part in CC interactions, and the CC cross-section depends linearly on the polarization P: $\sigma^{CC}_{e^+p}(P) = (1+P)\sigma^{CC}_{e^+p}(0)$. A test of this assumption for three different values of the e^+ beam polarization is presented in Fig. 5. The results are well described by the predicted dependence on P and thus compatible with the absence of right-handed charged currents.[10,11]

NC reactions are also sensitive to the lepton polarization. When more statistics is collected, this can provide a new possibility to disentangle individual quark flavors at high Q^2.

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