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INCLUSIVE EXPLORATION OF PROTON STRUCTURE AND QCD DYNAMICS AT HERA*

Uta Stösslein

DESY, Notkestrasse 85, 22607 Hamburg

On behalf of the H1 and ZEUS Collaborations

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This report highlights most recent results on the quark-gluon structure of the proton obtained in inclusive deep inelastic ep scattering with the collider experiments H1 and ZEUS at HERA.

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1. Introduction

Exploring proton structure with inclusive measurements in deep inelastic lepton–nucleon scattering (DIS) has been a successful tool for 40 years. Within the series of DIS facilities the Hadron–Electron-Ring Accelerator HERA at DESY in Hamburg is the most powerful ever built. The centre-of-mass energy of $\sqrt{s} = 320\,\mathrm{GeV}$ allows the HERA experiments to resolve the partonic structure of the proton down to distances as small as 10^{-18} m. Due to its large energy and the redundant kinematic reconstruction capabilities of the nearly 4π collider detectors H1 and ZEUS, HERA covers a range in Bjorken x from about 10^{-5} to 1 and negative momentum transfers squared, Q^2, from the photoproduction limit, $Q^2 = 0$, to close to the maximum of $Q^2_{\mathrm{max}} = s \simeq 10^5\,\mathrm{GeV}^2$. The x range corresponds to almost the full rapidity range of the Large Hadron Collider experiments now under construction at CERN. The quantum chromodynamics inside the proton as encoded in parton distribution functions (PDFs) and the strong coupling α_{s} are explored with high accuracy at HERA. PDFs can be extrapolated using evolution equations of perturbative QCD (DGLAP) at higher orders to the kinematic region of high masses at the LHC. The HERA measurements can therefore be used for understanding measurements at the LHC as could be required for a determination of parton luminosities in W and Z production and for

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an interpretation of new phenomena relying on a precise knowledge of the Standard Model (SM).

2. Cross sections and QCD dynamics from HERA I

The HERA collider experiments [1, 2] have measured the full set of unpolarised neutral (NC) and charged current (CC) double differential $e^{\pm}p$ inclusive scattering cross sections employing data taken in HERA's first phase (1994–2000), see Fig. 1 left. The Q^2 dependencies shown in Fig. 1 represent our knowledge of the electromagnetic (dominant at $Q^2 \lesssim 1000\,\mathrm{GeV}^2$) and electroweak structure of the proton. At a resolving power of the exchanged boson, Q^2, of about $Q^2 \approx M_Z^2 \approx 10^4\mathrm{GeV}^2$ the NC and CC cross sections become of equal size.

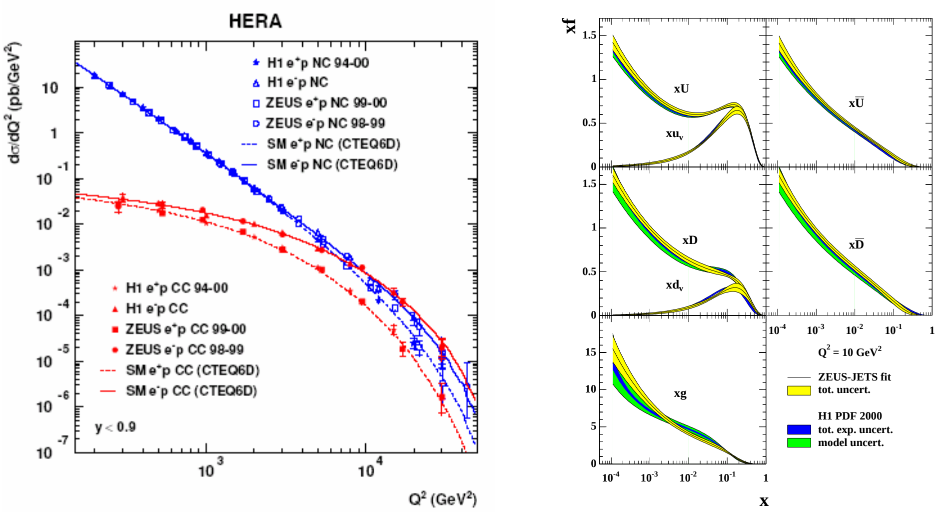

Fig. 1. Left: Single differential inclusive CC and NC cross sections $d\sigma/dQ^2$ as a function of Q^2 compared to SM predictions using modern PDFs. Right: Determinations of the quark and gluon distributions from NLO QCD fits to NC, CC and to inclusive jet data (ZEUS), at $Q^2 = 10\ \mathrm{GeV}^2$, as a function of Bjorken x.

In the Quark Parton Model, the inclusive ep cross sections are determined by structure functions and PDFs of the proton as follows:

$$\sigma^{\pm}_{\mathrm{NC}} \sim Y_+F_2 \mp Y_-xF_3, \tag{1}$$

$$F_2 \simeq e_u^2x(U+\bar{U}) + e_d^2x(D+\bar{D}), \tag{2}$$

$$xF_3 \simeq 2x[a_ue_u(U-\bar{U}) + a_de_d(D-\bar{D})], \tag{3}$$

$$\sigma^{+}_{\mathrm{CC}} \sim x\bar{U} + (1-y)^2xD, \tag{4}$$

$$\sigma^{-}_{\mathrm{CC}} \sim xU + (1-y)^2x\bar{D}. \tag{5}$$

Here $y = Q^2/sx$ is the inelasticity, $Y_\pm = 1 \pm (1-y)^2$, $U = u + c$ is the sum of the momentum distributions of the up-type quarks with charge $e_u = 2/3$ and axial vector coupling $a_u = 1/2$ while $D = d + s + b$ is the sum of the momentum distributions of the down-type quarks with charge $e_d = -1/3$, $a_d = -1/2$. Similar relationships hold for the anti-quark distributions $\bar{U}$ and $\bar{D}$. The differences $U - \bar{U}$ and $D - \bar{D}$ are used to determine the valence quark distributions u_v and d_v describing the proton structure at large $x > 0.1$.

In the kinematic range of HERA, the high statistic NC cross section is dominated by the one-photon exchange probing the electromagentic structure function F_2, Eq. (2). The γZ interference part is encoded in xF_3, Eq. (3), and also in F_2. The structure function xF_3 is a direct measure of the sum of the valence up and down quark distributions, $2u_v + d_v$, assuming symmetry between anti-quarks and sea-quarks. Similarly to neutrino–nucleon scattering experiments, the exchange of $W^\pm$ bosons in CC $e^\pm p$ scattering allows different quark flavour distributions to be unfolded. Thus valence quark distributions can be directly determined without any isospin assumption and free of nuclear corrections.

NC and CC scattering data, as measured by H1 and ZEUS, thus allow the complete set of parton distributions and the strength of the strong coupling α_s to be determined in a single experiment. NLO QCD results for the determinations by H1 and ZEUS of the quark and the gluon distributions are consistent, see Fig. 1 right. Adding inclusive ep jet data, as done by ZEUS, delivers constraints for the gluon distribution for moderate Bjorken x values and strongly constraints α_s. The experimental uncertainty of HERA α_s measurements is already about 2%. The precision of the HERA data calls for NNLO QCD analyses which for inclusive scattering have become available recently [3]. Testing the asymmetry of the light sea in the unexplored range of low x and to disentangle the non-singlet *versus* the singlet contributions to the QCD evolution would require data to be taken with a deuteron beam in HERA [4]. Precise inclusive NC and CC data allow a combined QCD and electroweak (EW) SM analysis. HERA results are complementary to determinations of EW parameters at LEP, the Tevatron and low energy experiments. Recently, H1 made a first measurement of the vector and axial-vector weak couplings of the light quarks to the Z^0 boson.

3. First results from HERA II and outlook

HERA started its second phase with a major upgrade [5] in 2000/2001. The focussing at the H1 and ZEUS interaction regions was improved to obtain higher luminosities. Each interaction region was complemented by a pair of spin rotators, allowing the transverse polarisation generated via synchrotron radiation in HERA-e to be converted to longitudinal polarisation.

HERA has been operating successfully since 2003, see Fig. 2 left for the delivered integrated luminosity. HERA II offers unique opportunities for testing the Standard Model and probing new physics areas, see for example [6] for an overview of beam polarisation effects.

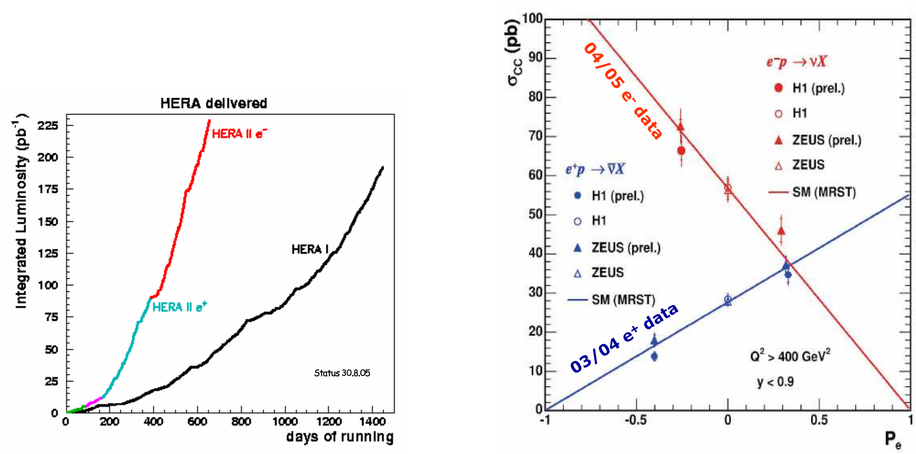

Fig. 2. Left: Development of the luminosity delivered by HERA. Right: Total cross sections for $e^{\pm}p$ CC DIS for different longitudinal polarisations P_e of the $e^{\pm}$ beam.

The chiral nature of the SM predicts the dependence of the NC and CC DIS cross sections on a longitudinal $e^{\pm}$ beam polarisation. In the CC case, the expected linear dependence is observed with the new polarised HERA data shown in Fig. 2 right. The CC DIS cross sections approach zero for right-handed (left-handed) electron (positron) beams. The measurements are well described by SM fits using recent proton PDFs. The first round of measurements and QCD analyses of NC and CC DIS data from HERA I at high Q^2 is essentially finished; the inclusion of the higher statistic polarised NC and CC HERA data into QCD fits will be an important next step.

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