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Measurement of the Inclusive ep Scattering Cross Section at Low and Medium Q^2 at HERA

Jan Kretzschmar[*†]
University of Liverpool
E-mail: jkretz@liverpool.ac.uk

New measurements of the inclusive DIS cross section $ep \rightarrow e'X$ using H1 data from the years 1999 and 2000 are obtained and combined with earlier publications. The combined data covers the region of $0.2\ \mathrm{GeV}^2 \leq Q^2 \leq 150\ \mathrm{GeV}^2$ at HERA with unprecedented accuracy. The structure Function F_2 is extracted and studied. In the transition region from DIS to photoproduction a few phenomenological models are tested. In the DIS regime the data are used for a QCD analysis, H1PDF 2009, to extract the proton PDFs using the new and published H1 inclusive measurements.

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*Speaker.
†For the H1 Collaboration.

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1. Introduction

The HERA collider facility in Hamburg, Germany, was a unique machine for lepton-proton scattering at highest energies. Here new analyses of data taken with the H1 detector in the years 1999 and 2000 are discussed [1, 2], when protons with an energy of 920 GeV were collided with positrons with an energy of 27.6 GeV, corresponding to a centre of mass energy of $\sqrt{s} = 320$ GeV.

Deep Inelastic Scattering (DIS) of leptons off nucleons continues to be the tool for high precision measurements of the quark and gluon content of the nucleons in the form of so called parton distribution functions (PDFs). The evolution of PDFs is a sensitive test of our understanding of QCD dynamics, which is expressed in the form of evolution equations. Furthermore a precise knowledge of PDFs is vital for measurements at hadron colliders, such as the LHC.

The kinematics of the scattering are described in terms of the Lorentz invariant quantities: the Bjorken scaling variable x, the inelasticity y, and the photon virtuality Q^2. The neutral current inclusive cross section for the reaction $ep \rightarrow e'X$ at low $Q^2 \ll M_Z^2$ can be expressed in the form

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)\right) \tag{1.1}$$

with $Y_+ = 1+(1-y)^2$ and the structure functions F_2 and F_L. At leading order, the structure function F_2 relates to the quark distribution functions simply as

$$F_2 = x\sum e_q^2(q(x)+\bar{q}(x))\,. \tag{1.2}$$

In higher orders the Bjorken scaling is violated and the derivative $\partial F_2(x,Q^2)/\partial \ln Q^2$ is related to the gluon distribution $xg(x,Q^2)$ and the value of the strong coupling constant α_s.

The longitudinal structure function vanishes at leading order. Its contribution to the cross section is $\propto y^2$ and thus can be studied at high $y \gtrsim 0.6$ only. Using assumptions on the low-x behaviour of F_2, it is possible to determine the F_L contribution to the cross section using data taken at a fixed centre of mass energy. However a direct F_L measurement needs to use data taken at different centre of mass energies, which has been presented elsewhere [3].

2. New Cross Section Measurements and Combination with Published Results

The new measurement of the DIS cross section is performed using data taken with the H1 apparatus in the years 1999 and 2000. The lower $0.2\,\mathrm{GeV}^2 \leq Q^2 \leq 12\,\mathrm{GeV}^2$ analyses are performed using two smaller samples with special detector conditions, where the lowest Q^2 values are reached with a shifted event vertex and slightly larger Q^2 values are accessed in nominal vertex running with a special trigger setup. The medium $12\ \mathrm{GeV}^2 \leq Q^2 \leq 150\ \mathrm{GeV}^2$ analysis employs data from the nominal running conditions.

In those analyses, the scattered positron is detected in the backward region of H1, where the SpaCal calorimeter is used to identify it and measure the energy E'_e. The determination of the positron scattering angle θ_e and further identification depends on the Q^2 range. In the low Q^2 analyses the silicon vertex detector BST is used, while at medium Q^2 the planar drift chamber BDC and Central Tracker are employed. The hadronic final state (HFS) is always reconstructed from a combination of tracks and calorimeter measurements, where the transverse momentum, P_T^h, and the total difference between energy and longitudinal momentum $E - p_z = \sum_i (E_i - P_{z,i}) + E'_e(1 - \cos\theta_e)$ are especially useful quantities. For the medium Q^2 analysis control distributions of these four basic variables characterising the scattered positron and the HFS are shown in figure 1, where an excellent agreement between data and simulation is observed. The good control of the relevant detector quantities expresses itself in small systematic uncertainties. For example, the positron energy scale is controlled to better than $0.2 - 1\%$ and the HFS energy to $\sim 2\%$. The relevant detector and reconstruction efficiencies are known to typically better than 0.5%.

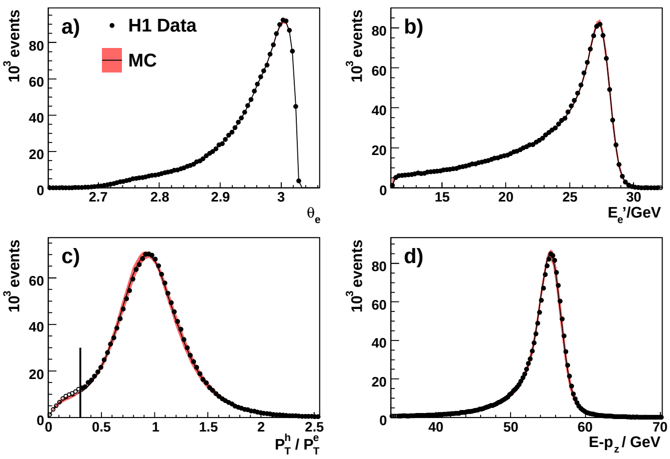

Figure 1: Control distributions of the polar angle θ_e a) and the energy E'_e b) of the scattered positron, the transverse momentum ratio $p_{t,HFS}/p_{t,e}$ c) and $E - p_z$ d).

The event kinematics is reconstructed using the Electron method at larger $y \gtrsim 0.1$ and the Σ method at lower y [1]. The Σ method can reconstruct events properly, in which the effective positron energy has been lowered by photon radiation. Those events are used to cover the lowest Q^2 region at high x with moderate precision.

The new measurements [1, 2] cover a similar kinematic domain as the previously best H1 measurement using data from 1995 and 1996/97 with a proton beam energy of 820 GeV [4]. While the total uncertainties are typically improved for newer data, the measurements benefit from a combination with the older results [4]. A new technique was introduced [1], which properly treats bin-to-bin correlated uncertainties. The cross sections are adjusted for the small difference in the centre of mass energies. Only small shifts of the central values of the correlated systematic uncertainty sources are required and a good consistency between the data sets is demonstrated with $\chi^2_{\text{tot}}/n_{\text{dof}}$ values of slightly less than 1. The combined data typically represent the most precise inclusive measurement in the covered kinematic domain to date with total uncertainties of $1.3 - 2.5\%$ in the bulk of the phase space.

3. Results on the Structure Function F_2

Starting from the double-differential DIS cross section, the structure function F_2 can be extracted using assumptions on F_L or equivalently the ratio $R = F_L/(F_2 - F_L)$. To keep the extrapolation small, F_2 is extracted only for $y < 0.6$. At larger Q^2 the value of R is taken from the NLO QCD fit H1PDF 2009 [2], while at lower Q^2 a fixed value of $R = 0.5$ is assumed.

Figure 3 shows a compilation of H1 data on F_2 at fixed Q^2 over the whole range covered by the new publications. As already observed in the early HERA data, F_2 rises towards low x and the steepness increases with Q^2.

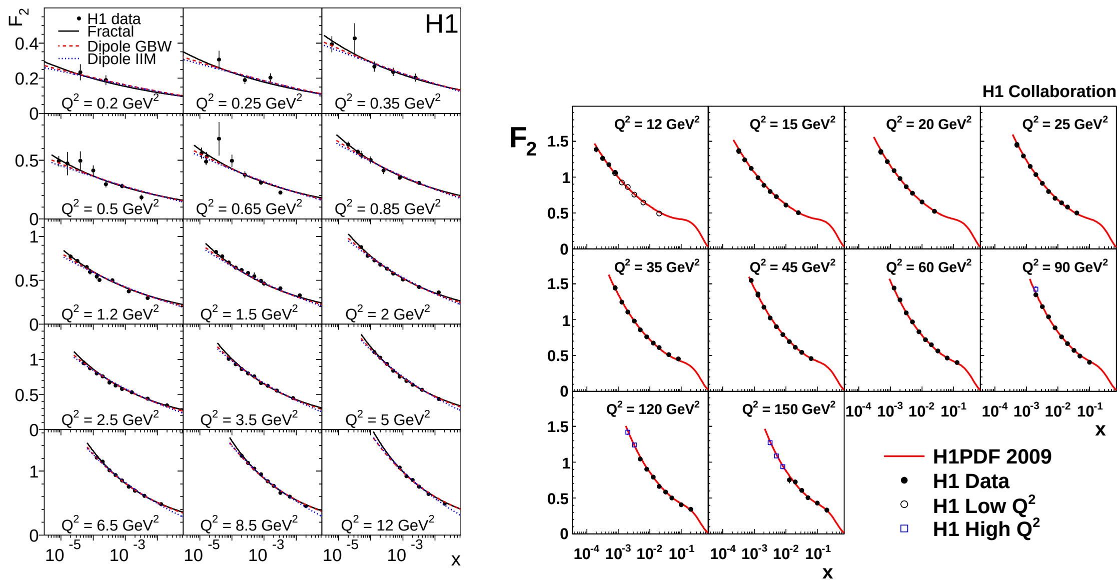

Figure 2: Measurements of the structure function F_2 at fixed Q^2 by the H1 collaboration at low x at low Q^2 (left) [1] and medium Q^2 (right) [2].

A number of models has been tested for their ability to describe the behaviour of F_2. In the transition region $Q^2 \to 0$ and very low x, where perturbative QCD calculations are not applicable, phenomenological models have been used. One interesting class are so-called colour dipole models, which describe both F_L and F_2 by a single characteristic dipole scattering cross section combined with transversely and longitudinally polarised photon wave functions. As an illustration, the data are compared to the original version by Golec-Biernat and Wüsthoff (GBW) [5] and a more recent model by Iancu, Itakura and Munier (IIM) [6]. Furthermore the fractal model [7] is used, which is based on self-similarity properties of the proton structure at low x. All models are seen to give a satisfactory description of the data, however they differ in the steepness of the rise of F_2 at low x.

At larger $Q^2 \geq 3.5\,\text{GeV}^2$ the data is used to perform the H1PDF2009 QCD fit, which is based on the DGLAP evolution equations at NLO. Only the H1 inclusive cross section data are used in the fit, which comprises the data presented here and higher Q^2 data [8]. The fit is able to describe the data very well.

Finally, figure 3 shows a compilation of new and published H1 data on F_2 at fixed x. Strong scaling violations are observed at low x, while at high $x \sim 0.1$ F_2 is nearly independent of Q^2. The evolution is compared to the H1PDF2009 fit, which describes the effects of the QCD dynamics well down to very low values of $Q^2 \sim 1.5\,\text{GeV}^2$.

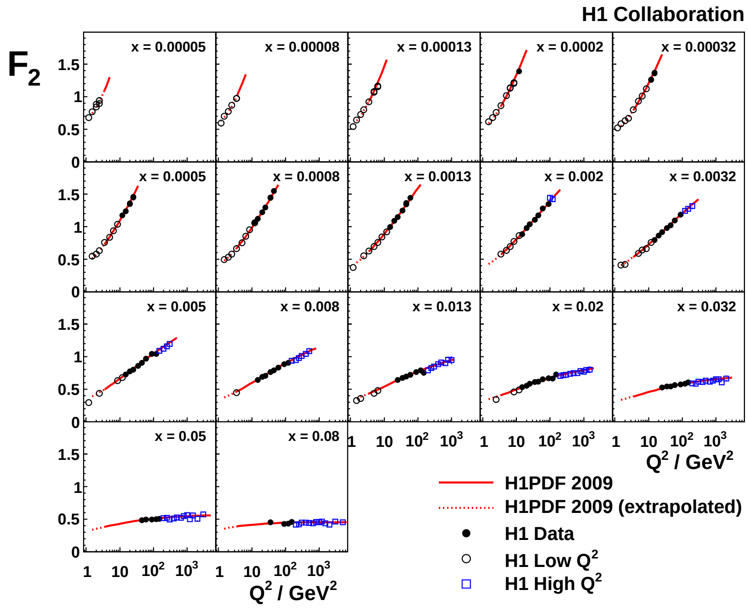

Figure 3: Measurements of the structure function F_2 by the H1 collaboration at constant x as a function of Q^2 together with the H1PDF2009 fit.

4. Conclusions

New measurements of the inclusive DIS cross section for 0.2 GeV$^2 \leq Q^2 \leq 150$ GeV^2 are performed using H1 data from the years 1999 and 2000. The new measurements are combined with published data, after correction of a small biases in the older result. The result is the most accurate measurement in this kinematic domain to date with typical total uncertainties of $1.3-2.5\%$ in the bulk of the analysis space. Phenomenological and QCD analyses are performed using the new data. Colour dipole and fractal models are able to describe the F_2 behaviour in the transition region to the photoproduction regime at very low x. The QCD fit H1PDF2009 is able to describe the data well at larger Q^2 in the range of applicability of perturbative calculations.

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