Low $Q^2$ and High $y$ Inclusive Cross Section Measurements from the HERA Experiments ZEUS and H1

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Abstract
An overview of inclusive cross section measurements from the HERA experiments covering the low $Q^2$ domain, $0.2 \text{ GeV}^2 < Q^2 < 150 \text{ GeV}^2$, is presented. The emphasis is put on new experimental results obtained at lowest values of $Q^2 < 10 \text{ GeV}^2$ and high $y > 0.6$. Furthermore future prospects for measurements of the structure functions $F_2$ and $F_L$ are shortly discussed.

1 Introduction
The HERA collider facility in Hamburg, Germany, is a unique tool for lepton-proton scattering at highest energies. It consists of two accelerators: one for protons, which are accelerated up to 920 GeV beam energy, and one for electrons or positrons, which are accelerated to 27.6 GeV. For the two colliding beam experiments H1 and ZEUS this is equivalent to a maximal centre of mass energy of $\sqrt{s} = 320$ GeV. At the end of June 2007 the data taking has finished after a final period of running at lowered proton beam energies of $E_p = 460$ GeV and $E_p = 575$ GeV.

In Deep Inelastic Scattering (DIS) of leptons off nucleons the substructure of the nucleons was discovered and DIS continues to be the tool for exploring the substructure of the nucleons with high precision. The kinematics of the scattering are described in terms of the Lorentz invariant quantities: the Bjorken scaling variable $x$, the inelasticity $y$, and the virtuality $Q^2$, which are related by $Q^2 = xys$. Figure 1 shows the kinematic $(x, Q^2)$-plane, where the HERA experiments and the fixed target experiments have made measurements of the proton structure. $Q^2$ values of up to 50000 GeV$^2$ and $x$ values down to $10^{-6}$ are reached at HERA.

One of the most fundamental measurements to be performed is that of the inclusive cross section for the reaction $ep \rightarrow e' X$, which can be expressed at low $Q^2$ in the form

$$\frac{d^2\sigma_{NC}}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4} \left( F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \right) = \frac{2\pi\alpha^2 Y_+}{xQ^4} \cdot \sigma_r ,$$

with $Y_+ = 1 + (1 - y)^2$ and the structure functions $F_2$ and $F_L$. Usually the data are presented in the form of the reduced cross section $\sigma_r$, which is defined to exclude the kinematic factor.

In the following, three parts of the phase space are discussed in more detail, which are as well marked in figure 1

- In the Bulk Low $Q^2$ domain, defined as $10 \text{ GeV}^2 < Q^2 < 150 \text{ GeV}^2$, the cross section is dominated by the contribution of the structure function $F_2$. Here also the highest precision
is reached. In QCD fits, also including data at larger $Q^2$ and $x$, the Parton Distribution functions (PDFs) and the strong coupling constant $\alpha_s$ can be determined. The evolution of the PDFs with $Q^2$ can be described using the DGLAP equations.

- In the very low $Q^2$ domain, $0.2 \text{GeV}^2 < Q^2 < 10 \text{GeV}^2$, the transition to the non-perturbative regime is covered. Here the strong coupling $\alpha_s$ becomes large and perturbative QCD calculations are not applicable.
- The high $y > 0.6$ domain is sensitive to the influence of the longitudinal structure function $F_L$, which provides an independent access to the gluon density.

For data taken at different centre of mass energies the kinematic plane is shifted allowing the direct measurement of $F_L$.

2 The Low $Q^2$ Bulk Domain

The domain $10 \text{GeV}^2 < Q^2 < 150 \text{GeV}^2$ is interesting because the experimental precision is high and a hard scale is present, so perturbative QCD calculations are applicable. The structure function $F_2(x, Q^2)$ has been measured with very high accuracy by both H1 [1] and ZEUS [2]. Figure 2 gives an example of the progress made with the HERA collider: from the very first data and the discovery of the strong rise of $F_2$ towards low $x$ to the currently reached $2 - 3\%$ precision. QCD fits using this data have been performed by the HERA collaborations [3] as well as other authors to exploit this data.

For the future a new measurement by H1 is expected with reduced systematic uncertainties. A further improvement may be achieved by combining data from ZEUS and H1 to obtain a final word of the HERA experiments on the structure function $F_2$ with best precision. First preliminary results have been presented [4].
3 The Lowest $Q^2$ Region

As the virtuality of the exchanged photon becomes smaller, $Q^2 \rightarrow 0$, the transition is made to the non-perturbative QCD regime. From a theoretical and experimental point of view this is both interesting and challenging. Experimentally specialised techniques have to be employed to detect scattered leptons at very small angles:

- Both H1 and ZEUS have used events with tagged Initial State Radiation [5], which extends the accessible phase space to lower $Q^2$. Recent H1 measurements are using untagged ISR events for the same purpose [6].
- The lowest values of $Q^2$, down to 0.045 GeV$^2$, were reached by ZEUS using a special low angle calorimeter and tracker called BPT [7].
- Recently H1 has presented new results which are based on data using a minimum bias trigger setup and an improved tracking of the scattered lepton using the Backward Silicon Tracker (BST). A part of the data was taken with a shifted vertex position to enhance the acceptance for lower $Q^2$ values down to 0.2 GeV$^2$ [6].

The new H1 analysis achieves a very good control of the energy of the scattered lepton. The reconstruction of the event kinematics is done mostly independent of the hadronic final state using the BST. The precision is further improved by combining three data sets.

Including these new results, the HERA measurement in this kinematic domain is completed with very good precision of typically a few %. The results, expressed as the effective photon-proton cross section $\sigma^{eff}_{\gamma p} = 4\pi^2\alpha/(Q^2(1 - x)) \cdot \sigma_{r,}$, are given in figure 3.

4 The High $y$ Region

The analysis in the high $y > 0.6$ region is experimentally especially difficult, as the energy of the scattered lepton $E'_e$ is small. Therefore the scattered lepton is difficult to identify and the background posed by photoproduction ($\gamma p$) events is high. On the other hand, the results are
particularly interesting, as the cross section at high $y$ is influenced by both structure functions $F_2$ and $F_L$. The experimental problems are similar to the ones posed by a direct measurement of $F_L$.

Both ZEUS and H1 have released new preliminary cross section measurements at high $y$. The techniques used to cope with the large background are different:

- ZEUS can study the $\gamma p$ background in detail using events with the scattered lepton tagged in a special calorimeter. The measurement uses a Monte Carlo model for the subtraction. The preliminary analysis reaches down to $E'_e = 5$ GeV and up to $y = 0.8$ [8].

- In the H1 analysis the background is determined directly from data using the charge of the scattered lepton track. This enables a cross section measurement without the use of $\gamma p$ Monte Carlo models. The analysis can go to very low energies of $E'_e = 3.3$ GeV, which corresponds to $y = 0.9$ [9].

The H1 measurement makes use of a large data set of $96 \text{ pb}^{-1}$ and improves the uncertainty by a factor of 2 w.r.t. the previous publication. The cross section together with measurements at lower $y$ is shown in figure 4. The results of the ZEUS measurements are shown there as well. For ZEUS it represents the first measurement at high $y$ and the full accessible $Q^2$ range is covered. An extension to higher values of $Q^2$ was meanwhile presented by H1 [10].

Fig. 3: ZEUS and H1 measurements in the transition region $Q^2 \sim 1 \text{ GeV}^2$. 
5 The Direct $F_L$ Measurement

The program of HERA structure function measurements would not be complete without a direct measurement of the longitudinal structure function $F_L$. To disentangle the contributions to the inclusive cross section, measurements at different centre of mass energies $\sqrt{s}$ are needed. Therefore, for the last 3 months of its operation time HERA was operated at reduced proton beam energies $E_p = 460$ GeV and $E_p = 575$ GeV. The luminosity accumulated was approximately $L_{460} \approx 13$ pb$^{-1}$ and $L_{575} \approx 7$ pb$^{-1}$, respectively, see also figure 5.

The measurement principle with the systematical and statistical uncertainties, as expected for the H1 measurement, is also illustrated in figure 5. It is performed using the inclusive cross sections at a fixed set of $(x, Q^2)$ for all three centre of mass energies, which lie according to equation 1 on a straight line as a function of $y^2/Y$. The extrapolation to $y \to 0$ gives $F_2$, while the slope determines $F_L$.

6 Conclusion

While the experimental phase of the HERA experiments is over, the data still has a lot of potential for precise inclusive cross section measurements at low $Q^2$. Recently new and improved results were presented for lowest $Q^2$ and in the high $y$ domain.

For the future, improved determinations of the structure function $F_2$ can expected due to new analyses and the combination of available H1 and ZEUS data. The longitudinal structure
Fig. 5: On the left: illustration of the $F_L$ measurements using cross section measurements from three centre of mass energies. On the right: Luminosities of the data sample collected during the low and medium $E_p$ runs in 2007.

function will be measured for the first time directly using the data from the successful HERA running at lowered centre of mass energy.

With extended and more precise measurements at hand, we will be able to test the theory of strong interaction QCD and improve our knowledge about the structure of the proton. Eventually this also will lead to precise input for measurements at the upcoming Large Hadron Collider.

References