# Measurements of Proton Structure at Low $Q^2$ at HERA

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**Abstract.** Inclusive *ep* scattering measurements at low virtualities of the exchanged boson, $Q^2$, allow precision tests of perturbative QCD at high gluon densities, as well as studies of the transition from the perturbative to non-perturbative QCD domain. Measurements in the transition region require special experimental approaches due to the limited detector acceptance. The current status and results of low $Q^2$ measurements at HERA are summarised.

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## INTRODUCTION

Inclusive measurements of lepton–proton scattering are the main source for our knowledge of proton structure. Over several decades, they have played a decisive role in the development of Quantum Chromodynamics (QCD). So far the greatest kinematic coverage, over five magnitudes in the Bjorken scale variable $x$ and in the modulus of the four-momentum transfer squared $Q^2$, is reached by the H1 and ZEUS experiments at HERA. Their inclusive deep-inelastic (DIS) scattering data [1–5] have shown that the $Q^2$ evolution of the proton structure function $F_2(x,Q^2)$ is well described by perturbative QCD (pQCD) in the range of $Q^2 \gtrsim 2-3\,\mathrm{GeV}^2$. The data reach $2-3\%$ precision for $Q^2$ values up to $\sim 100\,\mathrm{GeV}^2$.

At $Q^2 \lesssim 2-3\,\mathrm{GeV}^2$ the transition takes place into a domain in which non-perturbative effects dominate and the assumption of asymptotic freedom is no longer valid. A proper treatment of the transition from soft to hard QCD regime can thus improve our understanding of quark confinement. The description of the transition region remains a challenge for the theory and a field for phenomenological models.

The measurements performed at $Q^2 \lesssim 2-3\,\mathrm{GeV}^2$ at HERA are presented in the next section, followed by the studies of the $F_2$ behaviour and comparisons to models. In the last section, extractions of the longitudinal structure function $F_L$ are described.

## MEASUREMENTS IN THE TRANSITION REGION

The acceptance of the main H1 and ZEUS detectors is limited to $Q^2 \gtrsim 2\,\mathrm{GeV}^2$, therefore special experimental techniques are necessary to access the transition region. One way is to use special low $Q^2$ devices [6] mounted close to the outgoing lepton beam directon. However, the region $0.8 \lesssim Q^2 \lesssim 2\,\mathrm{GeV}^2$ is not reached via these devices since the respective angular range of the scattered lepton is complicated by the instrumentation of the main calorimeters.

This region is covered by data collected in special runs with the interaction vertex shifted in the direction of the proton beam [7–9]. In such an experimental configuration the scattered lepton is detected at lower scattering angles in the main detector, thus gathering events at lower $Q^2$ values.

The low $Q^2$ measurements are further extended towards higher $x$ values making use of events with hard photon radiation. The cross section for radiative processes becomes sufficiently large for distinct experimental configurations, in which the photon is emitted either nearly collinear with the electron beam (Initial State Radiation, ISR) or nearly collinear with the scattered lepton (Final State Radiation, FSR), or both the lepton and the photon are detected under finite polar angles nearly back-to-back in azimuth (QED Compton process, QEDC). Two of these topologies, ISR [10–13] and QEDC [14], are used for measurements at HERA.

In Fig. 1 the reduced cross section

$$\sigma_r = \frac{Q^4 x}{2\pi\alpha^2}\frac{d^2\sigma}{dxdQ^2} = F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)\ , \qquad (1)$$

with the inelasticity $y = Q^2/(xs)$ and $Y_+ = 1+(1-y)^2$, is shown. The ZEUS Beam Pipe Tracker (BPT) measurements [6], the H1 measurement using QED Compton events [14], the preliminary H1 results of running with the standard vertex position [15] and with the vertex shifted by 70 cm [9,13] are shown together with the fixed target data from NMC [16]. In the shifted vertex data sample both inclusive [9] and ISR [13] events are analysed. The HERA inclusive data in the transition domain reach $3-4\%$ precision. The predictions of the extrapolated Fractal model fit [17] and the ALLM97 parametrisation [18] are also displayed. All predictions are in a good agreement with the data.

## INTERPRETATION OF THE DATA

A principal feature of the HERA data is the dramatic rise of $F_2$ at low $x$ driven by the gluon evolution. This rise questions the validity of the DGLAP [19] approach, on which the current pQCD fits to the data are based, in the region of high parton densities. While in the DGLAP formalism only the $\ln Q^2$ terms are summed, the subleading terms involving powers of $\alpha_s \ln(1/x)$ may become large as $x$ decreases. This may require a different summation scheme, such as BFKL [20] or CCFM [21], or non-linear corrections to the pQCD expansion [22]. The non-linear effects may lead to gluon-gluon absorption which would tame the growth of $F_2$ at low $x$.

High precision $F_2$ data at very low $x$ are necessary in order to search for deviations from the DGLAP evolution and signs of saturation. As low $x$ can only be reached at low $Q^2$ due to kinematical correlation, it is the low $Q^2$ data which are used for these studies.

In the double asymptotic limit, the DGLAP equations can be solved analytically and $F_2$ is expected to rise approximately as a power of $x$ towards low $x$. A damping of this rise would indicate the presence of novel QCD effects. A relevant observable for the investigation of the dynamics of this growth is the derivative $\lambda = -\partial F_2(x,Q^2)/\partial \ln x|_{Q^2}$.

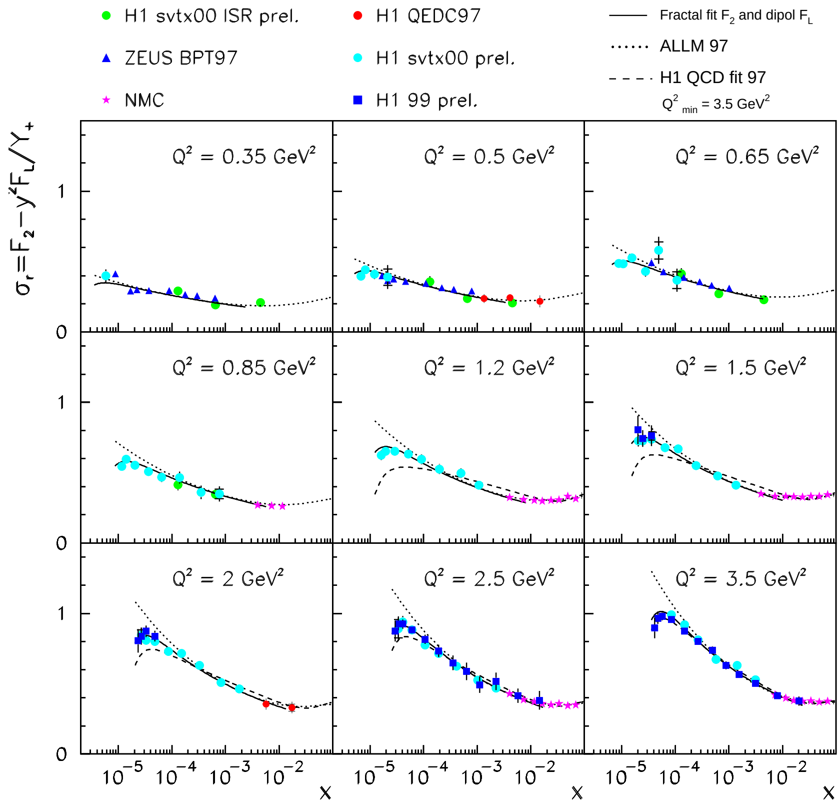


**FIGURE 1.** Reduced cross section measurements at $Q^2 \lesssim 3\,\mathrm{GeV}^2$ by H1, ZEUS and NMC compared with phenomenological and QCD fits.

The high precision of the present $F_2$ data allowed H1 to measure this quantity locally [9,23]. The measurements are consistent with no dependence of $\lambda$ on $x$ for $x < 0.01$. The monotonic rise of $F_2$ persists down to the lowest $x$ measured at HERA, and no evidence for a change of this behaviour is found. This suggested that $F_2$ can be parameterised by $F_2 = c(Q^2) \cdot x^{-\lambda(Q^2)}$. The results, obtained by fitting the present data at fixed $Q^2$ values are shown in Fig. 2. The left plot presents $\lambda(Q^2)$ values obtained separately from the H1 and ZEUS data. The extension of the $x$ range of the H1 shifted vertex data achieved by including the ISR data allowed an improved extraction of $\lambda$. The highest precision can probably be reached by combining H1, ZEUS and fixed target data, as shown in the right plot.

The coefficient $c(Q^2) \approx 0.18$ and the logarithmic dependence of $\lambda$ on $Q^2$ for $Q^2 \gtrsim 2-3\,\mathrm{GeV}^2$ are in accord with pQCD predictions. In contrast, at lower $Q^2$ the behaviour is changing to a weaker dependence compatible with reaching, as $Q^2 \rightarrow 0$, a constant consistent with the soft pomeron intercept $\alpha_{\mathbb{P}} - 1 = 0.08$ which is expected from the energy dependence of soft hadronic interactions [25]. The change takes place at distance scales of $\sim 0.3\,\mathrm{fm}$ and can be interpreted as being related to a transition from partonic to hadronic degrees of freedom. This change is the major challenge for the theory which must interpolate between the two $x$ dependences.

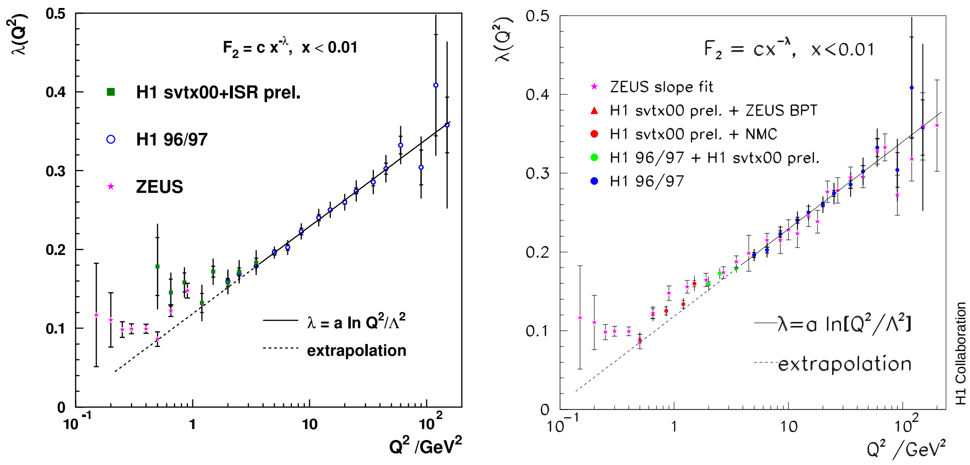


**FIGURE 2.** Selected HERA results of the $\lambda$ extraction from low $x$ data.

## DETERMINATION OF $F_L$

The proton structure function $F_L$ describes the exchange of longitudinally polarised photons. It imposes a constraint on the otherwise highly uncertain behaviour of the gluon distribution function in the proton at low $Q^2$. Though the gluon density is obtained in pQCD analyses of DIS data via the derivative $\partial F_2/\partial Q^2$, its determination at low $Q^2$ and low $x$ suffers from non-perturbative effects becoming significant.

As follows from eq. (1), a direct determination of $F_L$ requires cross section values measured at different $y$ values for the same $x$ and $Q^2$. This can be achieved by varying the $ep$ centre-of-mass energy, *e.g.* by perfoming dedicated runs at lower proton beam energies. Such runs are planned for the end of the HERAII running period.

Using the present data, $F_L$ is extracted indirectly by analysing the reduced cross section behaviour at high $y$ values. The data of the minimum bias 1999 [15] and shifted vertex 2000 [9] runs are used by H1 [24] to extract $F_L$ by various methods.

The highest precision is reached employing the "shape" method which exploits the shape of $\sigma_r$ in a given $Q^2$ bin. The shape is driven at high $y$ by the kinematic factor $y^2/Y_+$ (eq. 1), and to a lesser extent by $F_L(x,Q^2)$ which is considered to be constant: $F_L = F_L(Q^2)$. Based on the analysis of the rise of $F_2$ towards low $x$, the reduced cross section is fitted by

$$\sigma_{r,\mathrm{fit}} = cx^{-\lambda} - \frac{y^2}{Y_+} F_L \ , \tag{2}$$

and $F_L$ is determined from the fit for different $Q^2$ bins. The $x$-dependence cannot be extracted using this method.

The results for a fixed $y = 0.75$ ($W = 276\,\mathrm{GeV}$), are presented in Fig. 3, in which an overview of all current H1 data in the $Q^2$ range $0.75 \leq Q^2 \leq 700\,\mathrm{GeV}^2$ is given. The measurements are compared with pQCD fits and phenomenological models. The significant spread of the $F_L$ predictions in the NLO QCD fits reflects the uncertainty in the initial gluon distribution. The data favour a positive, not small $F_L$ at low $Q^2$.

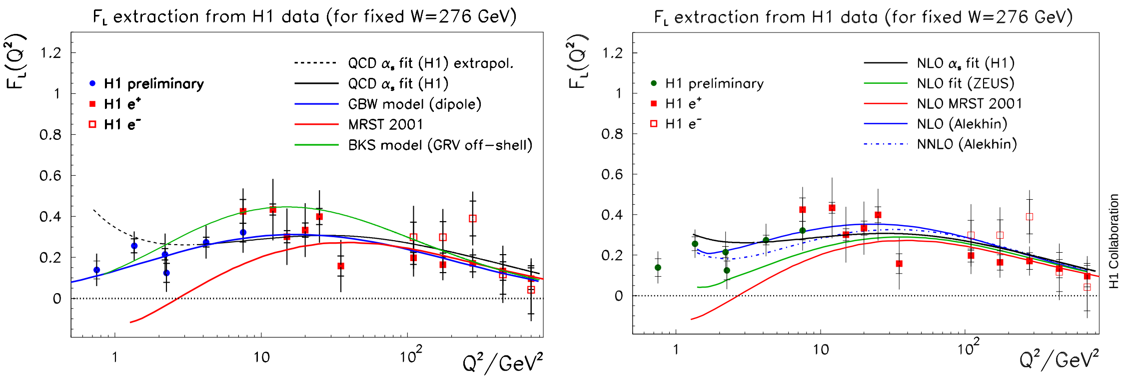


**FIGURE 3.** $Q^2$ dependence of $F_L(x,Q^2)$ at fixed $y = 0.75$, extracted from the H1 data. The lines represent various phenomenological models, as well as pQCD fits.

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