

Measurement of the longitudinal structure function of the proton, F_L

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Abstract. The ZEUS and H1 collaborations have made the first direct measurements of the longitudinal proton structure function, F_L , which is strongly correlated to the gluon density in the proton. The ZEUS collaboration have also extracted the structure function, F_2 , which, for the first time, has been done so at high y without any assumptions about F_L .

1. Introduction

The inclusive $e^\pm p$ deep inelastic scattering (DIS) cross section, $\sigma^{e^\pm p}$, can be expressed in terms of the two structure functions, F_2 and F_L , so long as the virtuality of the exchanged boson, Q^2 , is small enough such that weak interactions can be ignored. Symbolically,

$$\frac{d^2\sigma^{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4} \left[F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \right] = \frac{2\pi\alpha^2 Y_+}{xQ^4} \tilde{\sigma}(x, Q^2, y), \quad (1)$$

where α is the fine structure constant, x is the Bjorken scaling variable, y is the inelasticity and $Y_+ = 1 + (1 - y)^2$. The quantity $\tilde{\sigma}$ is known as the reduced cross section.

The structure function F_2 is proportional to the total virtual-photon/proton scattering cross section, whereas F_L is only sensitive to its longitudinally polarised virtual-photon component. This is only non-zero due to gluon exchange within the proton, hence F_L is strongly correlated to the gluon density in the proton. The ratio $R = F_L/(F_2 - F_L)$, is the ratio of the longitudinally- to transversely-polarised virtual-photon/proton scattering cross sections.

The reduced ep DIS cross section and related F_2 [1, 2] measurements at HERA provide the strongest constraints on the proton parton distribution functions (PDFs) at low x . Within the DGLAP QCD formalism, F_2 directly relates to the valence quark and $q\bar{q}$ sea distributions, while sensitivity to the gluon distribution, $g(x, Q^2)$, is achieved through the scaling violations in F_2 at low x . However, fits of $g(x, Q^2)$ (or equivalently indirect extractions of F_L [3, 4]) derived from the scaling violations depend on the precise formalism adopted. In the same vein, all previously published values of F_2 have required assumptions to be made about F_L at low x .

The ZEUS and H1 collaborations have, for the first time, directly measured F_L , thus providing an important check of the QCD formalisms. Moreover, by extracting F_2 and F_L simultaneously, ZEUS have made the first measurement of F_2 that did not require any QCD assumptions at low x /high y .

2. The experimental method

The direct F_L extractions required both collaborations to measure the reduced cross sections at fixed (x, Q^2) spanning a range of y . In ep scattering, the centre-of-mass energy is given

by $\sqrt{s} = \sqrt{Q^2/xy}$, therefore these measurements required data with multiple \sqrt{s} values. The structure functions F_2 and F_L were then evaluated in each bin of x and Q^2 using a Rosenbluth plot [5], in which a straight line is fit to $\tilde{\sigma}(y^2/Y_+)$. This is motivated by Eq. 1, which implies that $F_2(x, Q^2) = \tilde{\sigma}(x, Q^2, y = 0)$, the intercept, and $F_L(x, Q^2) = -\partial\tilde{\sigma}(x, Q^2, y)/\partial(y^2/Y_+)$, the slope.

The precision of this procedure depends on the range of y^2/Y_+ spanned by the data. This was maximised by collecting data at the nominal HERA energy, $\sqrt{s} = 318$ GeV, and at $\sqrt{s} = 225$ GeV, which was the lowest possible energy at which adequate instantaneous luminosity could be delivered. Data were also collected at $\sqrt{s} = 251$ GeV. The change in the \sqrt{s} was achieved by varying the proton beam energy, $E_{p\text{-beam}}$, keeping the electron beam energy constant, $E_{e\text{-beam}} = 27.5$ GeV. Data were collected in 2006-07 with $E_{p\text{-beam}} = 920, 575$ and 460 GeV, referred to respectively as the HER, MER and LER samples, standing for high-, medium- and low-energy-running.

Both experiments reconstructed the event kinematics based purely on the measured scattered electron. At high y , the scattered electron tends to be low in energy and poorly separated from the hadronic final state. In this case, photoproduction is a significant background due to the misidentification of hadrons as electrons. Both collaborations remove this on a statistical basis, however, H1 derived the background spectrum using wrongly charged electron candidates, while ZEUS used a Monte Carlo simulation.

3. The results

The H1 measurement was conducted in two parts, referred to as the mid- and high- Q^2 analyses¹. The distinction is driven by the specific sub-components of the H1 calorimeter used in each analysis. The published mid- Q^2 analysis [6] spans the kinematic region, $12 < Q^2 < 90 \text{ GeV}^2/c^4$ and $2.4 \times 10^{-4} < x < 3.6 \times 10^{-3}$. The preliminary high- Q^2 analysis spans the kinematic region, $35 < Q^2 < 800 \text{ GeV}^2/c^4$ and $2.8 \times 10^{-4} < x < 3.53 \times 10^{-2}$.

The ZEUS F_L measurement [7] spans the kinematic region, $24 < Q^2 < 110 \text{ GeV}^2/c^4$ and $5 \times 10^{-4} < x < 7 \times 10^{-3}$. In addition to F_L , ZEUS also published the HER, MER and LER reduced cross sections, shown in Fig. 1 at six Q^2 values as a function of x , and the first F_2 values extracted at low x /high y without implicit F_L assumptions. Also shown in Fig. 1 are predictions based on the NLO ZEUS-JETS proton PDF set [8], with both the expected F_L contribution and with it set

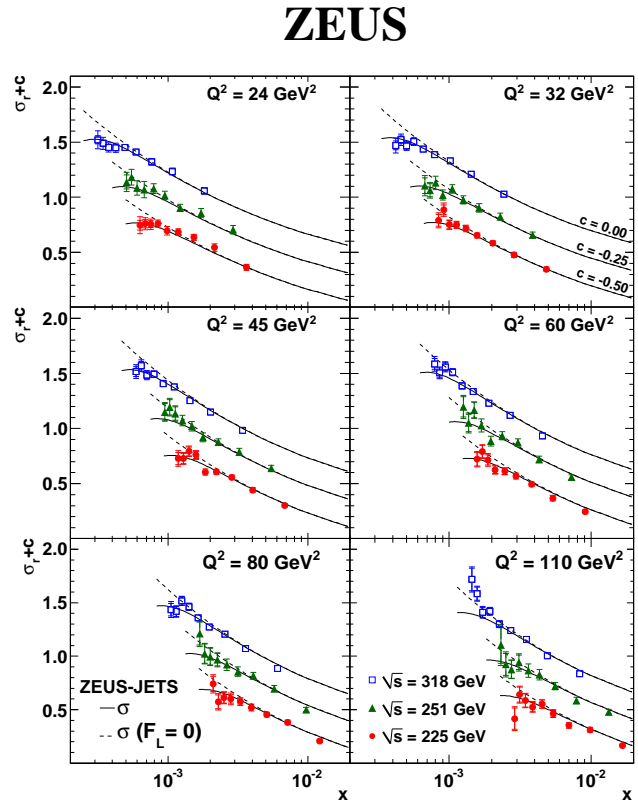


Figure 1. The HER, MER and LER reduced cross sections, shifted by c_i (see top right) for clarity. The inner (outer) error bars on the data represent the statistical uncertainties (statistical and systematic uncertainties added in quadrature).

¹ Additional H1 analyses have been made preliminary since LLWI09: a low- x analysis, extending the kinematic reach down to $x = 5.9 \times 10^{-5}$ and a diffractive F_L analysis. These analyses won't be discussed here.

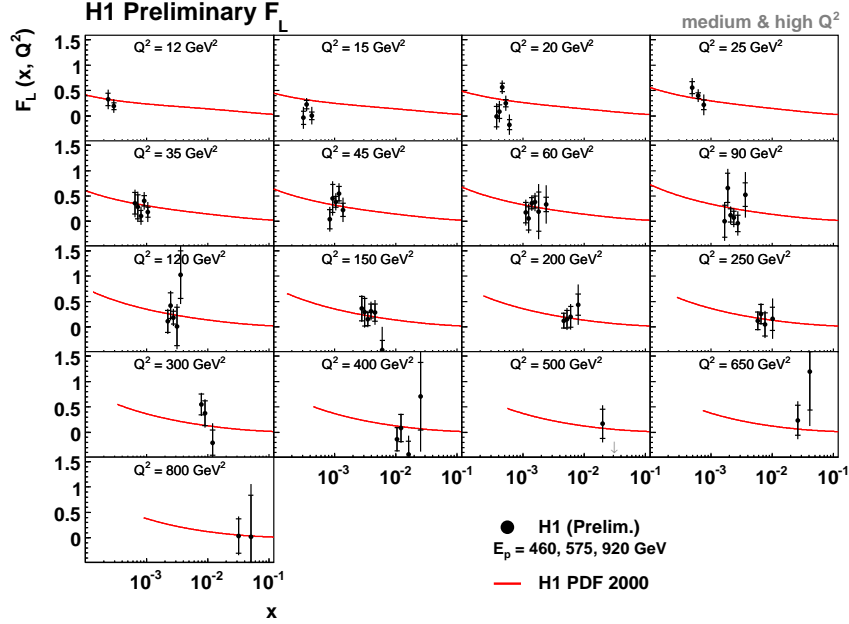


Figure 2. F_L as a function of x and Q^2 . The F_L prediction based on the NLO H1 PDF 2000 set is also shown. Other details as in the caption to Fig. 1.

to zero. This indicates how F_L is expected to suppress the cross sections at low x , the mechanism by which the experiments gain sensitivity to F_L . The data turn over at low x as expected.

Once the reduced cross sections are measured, F_L can be extracted. Shown in Fig. 2 are results from the combined mid- and high- Q^2 H1 analyses, given as a function of x at fixed Q^2 points. Also shown is the F_L prediction based on the NLO H1 PDF 2000 set [4]. Generally, the agreement between theory and data is good. In most cases the F_L points are positive.

More precise F_L values can be obtained by averaging these data. The results are shown in Fig. 3 as a function of x and Q^2 . Clearly, F_L is observed to be non-zero over much of the (x, Q^2) range probed. Also included in the plot are F_L predictions based on an NLO and NNLO PDF set, and an NLO F_2 prediction, scaled by 0.27. Each of the curves are consistent with the data.

The equivalent data from ZEUS are shown in Fig. 4a, albeit in a restricted kinematic region. Again, F_L is observed to be positive. The extraction method used by ZEUS, while fully accounting for the correlations in the uncertainties, blurs the distinction between the statistical and systematic components. The ZEUS results are consistent with those of H1. The data have been compared to theoretical predictions (see figure caption), the majority of which follow the

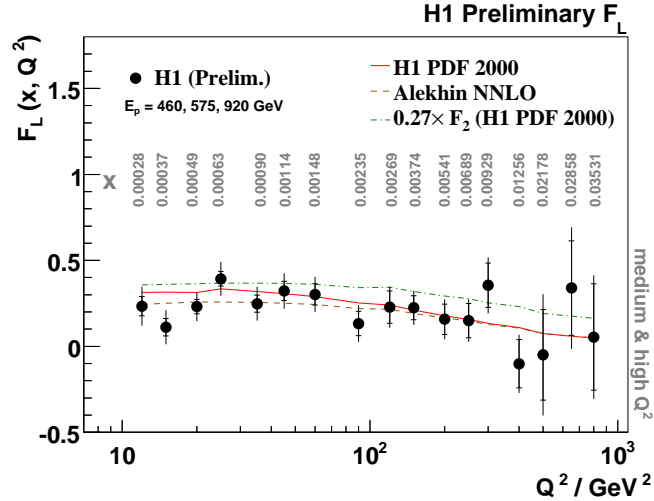


Figure 3. F_L as a function of Q_2 at the given values of x . Shown too are F_L predictions based on the NLO H1 PDF 2000 and NNLO Alekhin [9] PDF sets and the H1 PDF 2000 F_2 prediction scaled by 0.27. Other details as in the caption to Fig. 1.

DGLAP formalism at either NLO, NNLO or using an impact dependent dipole saturation model approach. The resummed prediction is based on the BFKL formalism. The predictions are all consistent with the data.

Shown in Fig. 4b is the ZEUS measurement of the ratio $R = F_L/(F_2 - F_L)$ as a function of x and Q^2 , as well as a band indicating the 68% probability interval for the overall value of R in the kinematic region studied, $R = 0.18^{+0.07}_{-0.05}$. The data are compared to predictions based on the same set of PDFs used in Fig. 4a. Again, all of the predictions are consistent with the data.

4. Summary

The ZEUS and H1 collaborations have published measurements of the structure function F_L . The combined H1 analyses span a wide kinematic space. The results from both collaborations are consistent in the region where they overlap. The ZEUS collaboration have also published the reduced cross sections at $\sqrt{s} = \{318, 251, 225\}$ GeV and the the first F_2 values extracted without implicit F_L assumptions. The measurements are consistent with predictions based on different QCD formalisms.

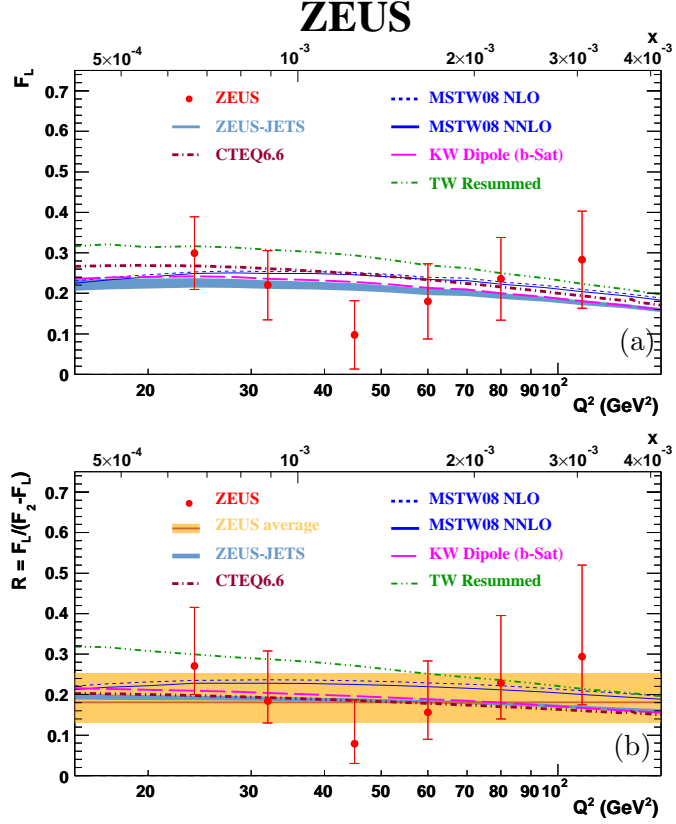


Figure 4. F_L (a) and R (b) as functions of Q_2 at the given values of x . The error bars represent the combined statistical and systematic uncertainties. Shown too are predictions based on the ZEUS-JETS and CTEQ6.6 [10] NLO and MSTW08 [11] NLO and NNLO PDF fits as well as a resummed fit from Thorne and White [12] and a fit based on a colour glass condensate dipole model from Kowalski and Watt [13].

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