Measurement of the Proton Structure Function
$F_L(x, Q^2)$ at Low $x$ and Medium $Q^2$ in the H1 Experiment at HERA

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A measurement of the longitudinal proton structure function $F_L(x, Q^2)$ derived from inclusive deep inelastic $e^+p$ scattering cross section measurements with the H1 detector at HERA is presented. The data were taken in the year 2007 at a positron beam energy of $E_e = 27.5$ GeV and proton beam energies of $E_p = 920$ GeV, 575 GeV and 460 GeV. The measurement of $F_L$ is performed in a range of medium four-momentum transfer squared $12 \leq Q^2 \leq 90$ GeV$^2$ and low Bjorken-$x$ $0.00024 \leq x \leq 0.0036$. The measured longitudinal structure function is found to be consistent with the NLO QCD calculations based on the H1PDF2000 fit and the MSTW fit.

1 Introduction

The first direct measurement of the longitudinal proton structure function $F_L(x, Q^2)$ performed by the H1 collaboration at HERA is presented. It is based on the extraction from the inclusive neutral current (NC) deep inelastic scattering (DIS) cross section at low $Q^2$

$$\sigma_r(x, Q^2, y) = \frac{d^2\sigma}{dx dQ^2} \frac{Q^4 x}{2\pi \alpha_s Y_\gamma} = F_2(x, Q^2) - \frac{y^2}{Y_\gamma} F_2(x, Q^2), \quad Y_\gamma = 1 + (1-y)^2. \quad (1)$$

Here $x$ is the Bjorken variable which in the Quark Parton Model (QPM) corresponds to the fraction of the proton momentum carried by the struck quark, $Q^2$ is the negative four-momentum transfer squared from the positron to the proton and $y = Q^2/sx$ is the inelasticity depending on $s$, the center of mass energy squared. In QPM $F_L$ is predicted to be zero since longitudinally polarised photons do not couple to the spin 1/2 quarks [3]. However, in QCD $F_L$ acquires a non-zero value due to gluon radiation receiving contributions from quarks and gluons [4] and at low $x$ the gluon contribution becomes dominant. Therefore, the $F_L$ measurement gives a direct constraint on the gluon density at low $x$.

The direct measurement of the proton structure function $F_L$ at HERA is based on the reduced cross section measurement (see Eq. 1) at the same values of $x$ and $Q^2$ by varying the inelasticity $y$. This is achieved by changing the proton beam energy $E_p = 920, 575, 460$ GeV while keeping the same electron beam energy $E_e = 27.5$ GeV which leads to variation of the center of mass energy since $s = 4E_pE_e$. The three proton beam energies are chosen to achieve approximately equal span in $y^2/Y_\gamma$. The corresponding luminosities of 21.9 pb$^{-1}$, 6.2 pb$^{-1}$ and 12.4 pb$^{-1}$, respectively.

2 Data Analysis

Since the $F_L$ contribution to $\sigma_r$ is proportional to $y^2$, the measurement must be extended to highest possible $y$ which at low $Q^2$ corresponds to a low energy of the scattered positron.
$E'_e$ following the relation $y \approx 1 - E'_e/E_e$. The scattered positron is identified as a compact energy deposition in the backward lead-scintillator calorimeter (SpaCal) with an energy of a few GeV. At high $y$ there is a large contribution of the photo-production ($\gamma p$) background in which the scattered electron escapes down the beam pipe and the hadronic final state leaves an energy deposition in the electromagnetic part of the calorimeter which can be misidentified as the scattered electron. This background is suppressed by requirements on the small transverse extension of the shower profile and the small fraction of the energy deposition in the hadronic calorimeter behind the electromagnetic cluster. The background events which do not originate from $ep$ interactions are suppressed by the requirement of a well reconstructed vertex in the central jet chamber (CJC). Furthermore, the condition $E - p_z = \sum_i (E_i - p_{z,i}) + E'_e (1 - \cos \Theta_e) \approx 2E_e$ efficiently rejects $\gamma p$ events and events suffering from large initial state QED radiation. In addition, the low energy cluster in the SpaCal must be matched to a track in the CJC within 6 cm.

The $\gamma p$ background is determined directly from the data. It is identified using the electric charge of the electron candidate measured from the curvature of the associated track. The contributions of the positively and negatively charged track samples are approximately the same. Nevertheless, a small charge asymmetry remains [5], mainly caused by the enhanced energy deposition by anti-protons compared to protons at low energies. The background charge asymmetry is defined as the ratio of events with negatively charged tracks to events with positively charged tracks associated to the scattered positron. It is best determined from the high statistics H1 data collected in period 2003-2006 by comparing negative tracks from the $e^+ p$ sample to positive tracks from $e^- p$ sample resulting in the asymmetry of $k = 1.057 \pm 0.006\%$. The final state electron and photon of a fraction of the $\gamma p$ events scattered at very low $Q^2$ can be detected in the electron and photon “tagger calorimeters” located down the beam pipe in the electron beam direction in a limited region of acceptance. The background charge asymmetry measured for these tagged events is $k = 1.06 \pm 0.01\%$. The final sample of $e^+ p$ DIS NC events is obtained after subtracting events with negative tracks from events with positive tracks accounting for the background charge asymmetry factor.

The distributions of kinematic variables of the selected events for all three proton beam energies are compared with the Monte Carlo (MC) simulations of DIS events, which includes higher order QED corrections and are in good agreement (see an example for $E_p = 460$ GeV in Fig. 1). The current $F_L$ measurement covers the range $12 \leq Q^2 \leq 90$ GeV$^2$ corresponding to the combined geometrical acceptance of the SpaCal and the CJC subdetectors.

**Figure 1:** The comparison of the positive charge data (points) with the sum of background determined from the negative charge data (shaded histogram) and the DIS MC (open histogram). The distributions are the scattered electron energy $E'_e$, the scattered electron polar angle $\Theta_e$, the $z$-position of the event vertex $Z_{vtx}$ and the sum $E - p_z$ of all final state particles.

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3 Cross Section Measurement

The reduced deep inelastic scattering cross section $\sigma_r(x, Q^2, y)$ is measured in the range of $12 \leq Q^2 \leq 90$ GeV$^2$ and Bjorken $x$ of $0.00024 \leq x \leq 0.0015$ for $E_p = 460, 575, 920$ GeV. The results are shown in Fig. 2. At large values of $x$ the $F_2$ contribution dominates and the cross sections for different proton beam energies are in good agreement with the prediction from H1PDF2000 fit. The cross sections rise towards low $x$ and at lowest $x$ corresponding to high $y$ turn over due to $F_L$ contribution.

The total uncertainties are obtained by adding in quadrature the statistical and systematic uncertainties. Excluding the overall luminosity uncertainty, which is currently 5% for this measurement, the precision of the data is about 3 – 5%. In order to reduce relative normalisation uncertainty of the data sets at different $E_p$, they are re-normalized to each other at low $y$ where the influence of $F_L$ is negligible. The residual relative normalisation uncertainty is 1.6% which for extracting $F_L$ is attributed to the $E_p = 920$ GeV data set.

Figure 2: The reduced cross section $\sigma_r(x, Q^2, y)$ measured at medium $Q^2$ as a function of $x$ using data taken at proton beam energies of 920 GeV (boxes), 575 GeV (stars) and 460 GeV (points). The error bars represent the statistical and systematic errors added in quadrature. Theoretical predictions of $\sigma_r$ are shown as the solid lines. The dashed line represents the QCD expectation of $F_2$ derived from the H1PDF (2000) fit.

4 Measurement of $F_L$

The longitudinal structure function $F_L$ is determined from linear fits to the $\sigma_r(x, Q^2, y)$ as a function of $y^2/Y_t$ using the statistical and systematic uncertainties (see Fig. 3). The $F_L$ measurement is given by the slope of the fit. The best precision is achieved when two measured cross sections are well separated in $y$ as in the case of $E_p = 920$ GeV and $E_p = 460$ GeV data sets, while $E_p = 575$ GeV data allows an important cross check and an extension to lowest $x$.

The $F_L$ measurements are shown in Fig. 4 together with the prediction obtained using the H1PDF2000 fit [1] and the expectation from the global parton distributions MSTW fit [2] at higher order perturbation theory. The current measurement agrees with the theoretical predictions and it is also consistent with the previous indirect determinations of $F_L$ obtained by H1 [5]. For better illustration of the current $F_L$ measurement and its comparison to the theoretical expectations the $F_L$ values are averaged over $x$ at fixed values of $Q^2$. The averaged $F_L$ is in good agreement with the expectations from the H1PDF2000 fit and the MSTW fit as shown in Fig. 5. This measurement of the longitudinal structure function $F_L$ confirms the validity of DGLAP evolution at low $x$ and medium $Q^2$ at HERA$^a$.

$^a$The final analysis was accepted for publication after the conference[6].
5 Summary

The first measurement of the longitudinal proton structure function $F_L(x, Q^2)$ at low $x$ and medium $Q^2$ by the H1 Collaboration at HERA has been performed. $F_L$ is extracted from cross sections measured at different proton beam energies at fixed values of $x$ and $Q^2$, but at different inelasticity $y$. The result confirms prediction of perturbative QCD which leads to a dominant gluon contribution at low $x$.

![Figure 4: The longitudinal structure function $F_L$ measured as a function of $x$ at fixed values of $Q^2$ obtained by H1 Collaboration. The line represents a QCD prediction of $F_L$ (solid) and $F_L = (1/3)F_2$ (dashed) from the H1PDF2000 fit and the QCD prediction of $F_L$ from the MSTW fit (dashed dotted line).](image)

![Figure 5: The longitudinal structure function $F_L(x, Q^2)$ averaged for a given $Q^2$ as measured by the H1 Collaboration. The $x$ values of the measurements contributing to the $Q^2$-value are indicated in grey. The inner error bars are the statistical errors and the full error bars represent the statistical and the systematic errors added in quadrature. The lines represent QCD predictions based on H1PDF2000 fit (solid) and the QCD prediction of MSTW fit (dashed line).](image)

References


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