First Measurements of $F_L$ at Low Bjorken $x$

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The first measurements of the longitudinal proton structure function $F_L$ in deep inelastic positron-proton scattering at low Bjorken $x$ are described. Theoretical predictions in higher order QCD and using dipol model calculations are consistent with the measurements. The data were taken by the HERA experiments H1 and ZEUS in a series of runs with different proton beam energies in 2007.

1. $F_L$ at HERA

The measurement of the longitudinal proton structure function had long been recognised as an important part of the HERA programme. The first estimates on the measurement accuracy of $F_L$ were presented more than 20 years ago within the 1987 workshop on HERA physics [1]. In 1996 both experiments had pursued quite some preparations for the measurement of $F_L$ with lowered proton beam energies [2]. The measurement was yet postponed by 10 years, basically for clarification of anomalies in the data at large scales, which were possibly related to leptoquarks and to peculiar events with isolated leptons accompanied by large missing transverse momentum [3]. In 2004, at the annual DIS workshop the interest in a measurement of $F_L$ was renewed [4]. Meanwhile the HERA collider had successfully completed a luminosity upgrade program which for the $F_L$ measurement was particularly important as the luminosity decreases $\propto E_p^2$ with the proton beam energy. In 2005 (2006) the H1 (ZEUS) experiments did request to lower the proton beam energy in order to measure $F_L$ prior to the termination of HERA which had been announced for June 2007. Both experiments had performed essential upgrades on their detector, H1 with the SpaCal calorimeter, a Backward Silicon Tracker and improved trigger and backward chambers, ZEUS with a Micro Vertex Silicon Detector and a renewed electron tagging device. Both experiments therefore were well prepared for a measurement of $F_L$.

The understanding of the machine had reached a most impressive level [5], as became clear during the low energy run when the optics, the polarisation (for HERMES), the luminosity and the overall operation efficiency were all up to or even beyond expectation. The data have promptly been analysed by both collaborations.

Data were taken with proton beam energies of $E_p = 460$ GeV and 575 GeV and compared with existing high energy data at 920 GeV while the positron beam energy was kept constant, $E_e = 27.5$ GeV. At the DIS08 workshop first observations were reported by both Collaborations [6]: the H1 Collaboration had released its first data for both lower proton energies, using the backward calorimeter SpaCal and the central Liquid Argon Calorimeter (LAr). The ZEUS Collaboration did present a first analysis on their 460 GeV data set. The present report is based on updates by H1 and ZEUS prepared for the ICHEP conference: the SpaCal data of H1 were published [7] while ZEUS did present a combined $F_L$ analysis based on also the 575 GeV data.

The measurements presented to ICHEP08 were the first ever direct determinations of $F_L$ in the region of low Bjorken $x$. Data at large $x$ had been obtained by a number of fixed target lepton-proton scattering experiments [8], beginning with the discovery at SLAC that the ratio $R \approx F_L/(F_2 - F_L)$ was close to zero which was a most convincing evidence for quarks to be spin $1/2$ fermions. While subsequent measurements with muon and neutrino beams mostly observed small values of $R$, indirect measurements of $F_L$ by H1 [9] did hint to larger values of the longitudinal proton structure function at low $x$. This had been expected, in the region of deep inelastic scattering, from the large size of the gluon distribution in this range. While $R$ at large $x$ is a measure of the quark’s spin, at low $x$ it rather quantifies the dynamics of gluon interactions and as such is of particular theoretical interest [10].
2. Measurement of $F_L$

The inclusive, deep inelastic electron-proton scattering cross section at low $Q^2$, written in its reduced form,

$$\sigma_r = \frac{d^2\sigma}{dx dQ^2} \cdot \frac{Q^2 x}{2\pi\alpha^2 Y_+} = F_2(x, Q^2) - \frac{y^2}{Y_+} \cdot F_L(x, Q^2)$$

(1)

is defined by two proton structure functions, $F_2$ and $F_L$, where $Q^2$ is the negative four-momentum transfer squared, $y$ the inelasticity $y = Q^2/sx$ with $Y_+ = 1 + (1 - y)^2$, $s = 4E_eE_p$ the centre of mass energy squared given by the positron and the proton beam energies and $\alpha$ is the fine structure constant. Apparently, $\sigma_r$ is a direct measure of $F_2$ apart from a limited region of high $y$, corresponding to small $x$, where the contribution of $F_L$ may be sizeable. Disentangling the two cross section terms requires to measure $\sigma_r$ at fixed $x$ and $Q^2$ at various beam energies. The analysis of the reduced cross section determines $F_2$ as the intercept, at $y = 0$, and $F_L$ as the negative slope of its linear dependence on $y^2/Y_+$. The variation in $y$ was achieved at HERA by comparing high statistics data at highest energy with about 13 pb$^{-1}$ of data at 460 GeV and 7 pb$^{-1}$ at 575 GeV. The values of $E_p$ had been chosen for about equidistant separation of the measurements in $y^2/Y_+$. The low energy runs took place from March to June 2007, with only a few days of setup time for the machine.

The inelasticity is determined by the energy and polar angle of the scattered positron, $y = 1 - (E'_e/E_e)\sin^2(\theta_e/2)$, which at large scattering angles, corresponding to small $Q^2 = 4E_eE'_e\cos^2(\theta_e/2)$, reduces to $y \approx 1 - E'_e/E_e$. If therefore one intends to measure the cross section at high $y \approx 0.9$ one needs to master the trigger rate and the electron identification at small energies of a few GeV. Such energies are deposited much more frequently by hadrons from photoproduction processes, for which $Q^2$ is large, than by the genuine scattered DIS positron. Removal of the photoproduction background constitutes the major challenge of the measurement of $F_L$ at HERA.

There are two ways to control the photoproduction ($\gamma p$) background: part of the $\gamma p$ events is uniquely identified by tagging the scattered positron near to the beam axis in tagging calorimeters downstream the $e^+$ beam. That measurement can be used to tune the Monte Carlo simulation of the background, subject to uncertainties of the tagger acceptance and its extrapolation. In a further method one can employ the charge symmetry of the background. While a DIS positron carries the lepton beam charge, energy depositions due to hadrons from $\gamma p$ processes are charge symmetric, apart from a small proton-antiproton cross section difference one can correct for. With a tracking detector in front of the calorimeter one may determine the charge of the DIS lepton candidate and subtract the wrong charge signal statistically. ZEUS has subtracted the background with a tagger based simulation, for $E'_e > 6$ GeV, in which subprocesses simulated in PYTHIA are weighted using ZEUS $\gamma p$ cross section data. H1 has primarily used the charge measurement and included data for $E'_e > 3$ GeV. Both analyses require a track detector signal associated to the calorimeter energy deposition which reduces the contribution from neutral particles, in particular of the electromagnetic energy deposition from $\pi_0 \rightarrow \gamma\gamma$. Energy momentum conservation is imposed requiring $E - p_z > 35 (42)$ GeV, for H1 (ZEUS), which further reduces the $\gamma p$ background and higher order QED effects.

Extraction of $F_L(x, Q^2)$ for each $x, Q^2$ is achieved by fitting the cross section measurements as a function of $y^2/Y_+$. Utilising the large range in inelasticity $y$, both the ZEUS and the H1 analyses at this stage have renormalised the measured cross sections at low $y$ where at each energy, for fixed $x$ and $Q^2$, the same $F_2(x, Q^2)$ measurement is provided by the measurements of $\sigma_r$ from the up to three data sets. The systematic errors are taken into account source by source in an offset method which leads to a reduction of their effect on the final measurement.

3. Results

The resulting measurement of ZEUS, for $24 \leq Q^2 \leq 110$ GeV$^2$, is illustrated in Figure 1. The preliminary result is compared with a ZEUS QCD fit to NLO to previous ZEUS DIS and jet data. At low $x$ and not too small $Q^2$ the prediction on $F_L$ relies nearly completely on the behaviour of the gluon distribution. That is determined at low $x$ by the scaling violations of $F_2(x, Q^2)$. The consistency of the theoretical calculation on $F_L$ [11] with the data is therefore a non-trivial test of QCD to high orders.
Figure 1: Measurement of $F_L(x, Q^2)$ by ZEUS compared with an NLO QCD prediction based on other ZEUS data.

For H1, a combination of the published, medium $Q^2$, result based on SpaCal data [7], for $12 \leq Q^2 \leq 90$ GeV$^2$, with a preliminary result based on LAr data at higher $Q^2$, $35 \leq Q^2 \leq 800$ GeV$^2$, is shown in Figure 2. The overlap of the cross section measurements with the two calorimeters at different $E_p$ reduces the uncertainty on the $F_L$ measurement, compared to [7]. At each value of $Q^2$ one value on $F_L$ is derived which results from an average of typically three data points adjacent in $x$. The data are compared with three QCD predictions at higher orders, from the H1PDF2000 fit and recent CTEQ and MSTW fits on the parton distributions. The QCD predictions describe the measurements well. There are two additional observations worth mentioning here: i) at low $x$ one expects that $\partial F_2/\partial \ln Q^2 / 2 F_L$ is approximately one, because both the derivative [12] and $F_L$ [1] to LO are proportional to the dominating gluon density. From the published H1 data on the derivative and on $F_L$, for $Q^2$ between 10 and 30 GeV$^2$,
this ratio is determined to be $\frac{\partial F_2}{\partial \ln Q^2} / 2 F_L = 1.09 \pm 0.13({\text{stat}}) \pm 0.20({\text{syst}})$ and indeed consistent with one; ii) the measurement of $F_L$ is also consistent with predictions within the dipole model, e.g. [13]. In particular, no violation is observed of the constraint $F_L \leq 0.27 F_2$ which reflects the wave function relations in the dipole model [14]. The results presented here are the first, not the final measurements of $F_L$ at low $x$ at HERA. There are a number of improvements being investigated regarding the extension of the kinematic range to lower $Q^2$, to lower and possibly higher $y$, the understanding of the systematic errors, of the $\gamma p$ background in particular, or the unfolding of $F_2$ and $F_L$ from the measured cross sections. One can thus expect the accuracy of $F_L$ to be enhanced in the future.

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