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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.

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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 $E_p = 460\,\text{GeV}$ and $575\,\text{GeV}$ and compared with existing high energy data at $920\,\text{GeV}$ while the positron beam energy was kept constant, $E_e = 27.5\,\text{GeV}$. 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 $460\,\text{GeV}$ 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 $575\,\text{GeV}$ 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 $R \simeq F_L/(F_2 - F_L)$ 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,

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

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 α is the fine structure constant. Apparently, σ_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 σ_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 $13\,\mathrm{pb}^{-1}$ of data at 460 GeV and $7\,\mathrm{pb}^{-1}$ 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 $y \simeq 1 - E_e'/E_e$. If therefore one intends to measure the cross section at high $y \simeq 0.9$ 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 $Q^2 \simeq 0$, 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 (γp) background: part of the γp 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 γp 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 $E_e' > 6\,\mathrm{GeV}$, in which subprocesses simulated in PYTHIA are weighted using ZEUS γp cross section data. H1 has primarily used the charge measurement and included data for $E_e' > 3\,\mathrm{GeV}$. 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 γp 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 σ_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 $24 \le Q^2 \le 110\,\mathrm{GeV}^2$, 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.

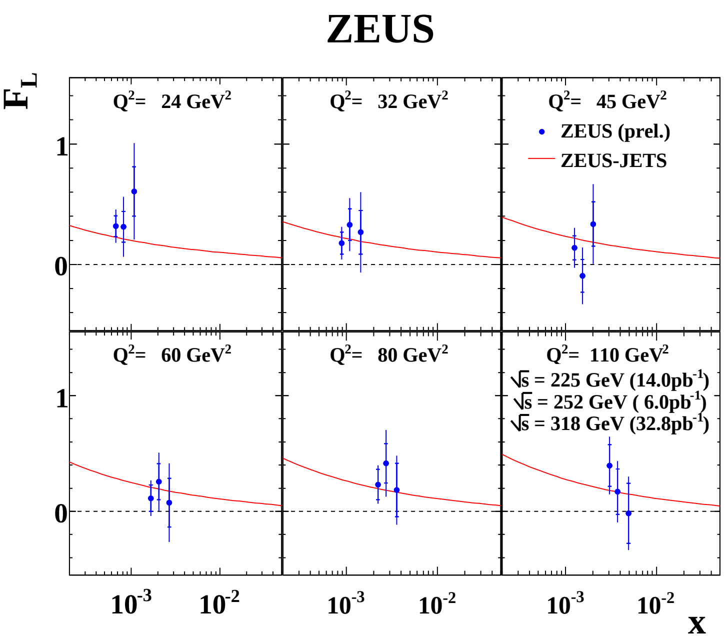

Figure 1: Measurement of $F_L(x, Q^2)$ by ZEUS compared with an NLO QCD prediction based on other ZEUS data.

For H1, a combination of the published, medium Q^2, result based on SpaCal data [7], for $12 \leq Q^2 \leq 90\,\mathrm{GeV}^2$, with a preliminary result based on LAr data at higher Q^2, $35 \leq Q^2 \leq 800\,\mathrm{GeV}^2$, 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,

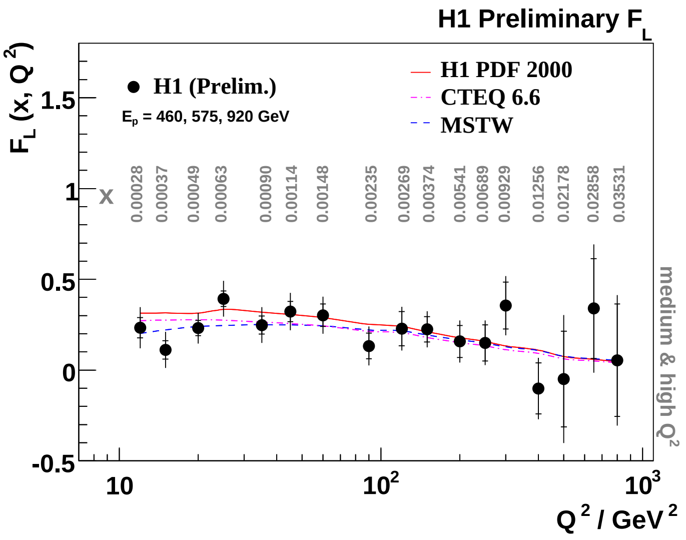

Figure 2: Measurement of $F_L(x, Q^2)$ by H1 compared with different predictions in higher order QCD.

this ratio is determined to be $\partial F_2/\partial \ln Q^2 \;\; /2 \; F_L = 1.09 \pm 0.13(stat) \pm 0.20(syst)$ 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 $F_L \leq 0.27F_2$ 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 γp 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.

Acknowledgments

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