MEASUREMENT OF THE LONGITUDINAL PROTON STRUCTURE FUNCTION AT LOW X AT HERA

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The theoretical interest in the longitudinal inclusive $F_L(x, Q^2)$ and diffractive $F_L^D(x_{I\!P}, x, Q^2)$ Structure Functions are briefly mentionned. A simulation based on running HERA for three months with a reduced proton beam energy shows that measurements are possible with five and three sigma significance for F_L and F_L^D respectively.

1. Motivations

Since 1992 the H1 and ZEUS experiments have been central in testing the properties of QCD and discovered surprising behaviours in unexplored regions. Principle among these is the rise of the Structure Function and the strong gluon density at very low x. The HERA facility is scheduled to end operation by mid-2007 and an important piece of the program is still missing: the measurement of the longitudinal Structure Function $F_L(x, Q^2)$. It is simply related to the double inclusive differential cross section

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

with $y = Q^2/sx$, $Y_+ = 1 + (1-y)^2$, $f(y) = y^2/Y_+$ and s the centre of mass system energy squared. The Functions $F_2(x, Q^2)$ and $F_L(x, Q^2)$ are basic Structure Functions to study the proton's interior structure down to the smallest reachable dimensions. The extraction of $F_2(x, Q^2)$ from the measured differential cross section has only been possible at low y where the contribution of $F_L(x, Q^2)$ can be neglected or in making assumptions on $F_L(x, Q^2)$ at large y. The measurement of $F_L(x, Q^2)$ is difficult and has never been performed at very low x, the domain of excellence of HERA. After more than ten years of in depth study of systematic effects in the measurement of the inclusive cross-sections, the HERA experiments are probably the best experiments that ever were to perform an accurate measurement of the longitudinal Structure Function of the proton. In the Quark Parton Model, due to helicity conservation [1], F_L =0. In QCD, the presence of gluons interacting with quarks leads to a sizeable longitudinal Structure Function $F_L(x,Q^2)$ at low x, which is directly related to the gluon distribution $xg(x,Q^2)$ at Leading Order [2]

$$F_L = \frac{\alpha_s(Q^2)}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} F_2(z,Q^2) + 8(\Sigma e_q^2) \left(1 - \frac{x}{z}\right) zg(z,Q^2) \right] \qquad (2)$$

At small x, the right-hand side is dominated by the gluon distribution $g(x,Q^2)$. There is a very direct relation between the gluon distribution and F_L which persists when b-quark threshold effects or terms at order α_s^2 (see reference [3]) and even α_s^3 (see reference [4]) are included, at least above $Q^2 \approx 10\ GeV^2$. The longitudinal Structure Function would be a clean probe of the gluon distribution in the x domain $(10^{-4}, 10^{-3})$.

At present the gluon density at low x is poorly constrained by the data . It has only been indirectly determined from a fit of the scaling violations of the $F_2(x,Q^2)$ Structure Function. Good fits of the inclusive cross sections from MRST [5] and CTEQ [6] deviate in the relative contributions of sea quarks and gluons at low x to F_L by almost a factor two (see Figure 1). Moreover, the fit rely on the NLO DGLAP evolution equations without

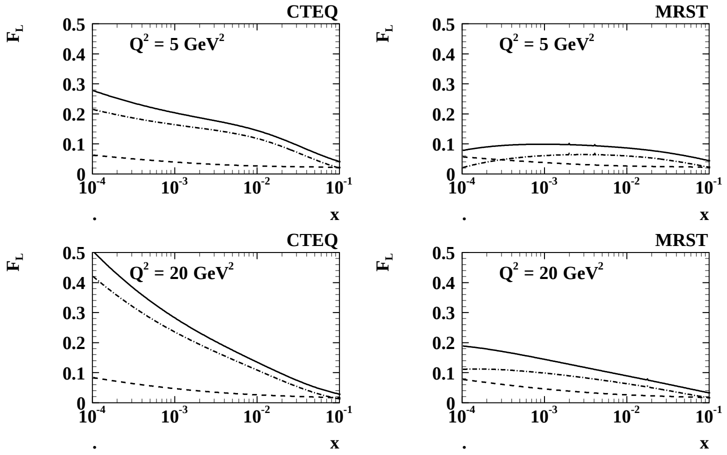

Figure 1. F_L prediction (solid line) from parametrisations of MRST and CTEQ. The dashed-dotted lines and the dashed lines represent the gluon and the F_2 components of F_L respectively.

resummation which become questionable at the lowest x values [7]. There are suspicions that higher twist effects would cancel in the Structure Function F_2 but would generate large difference on F_L at low x [8].

The dynamics of large density of partons at low x is still not well understood. A direct measurement of F_L at HERA would be a powerful consistency check of the theory at small x [4,9]. In addition, it would provide a constraint on the determination of the gluon density in the x range of the W and Higgs production at LHC [10].

2. Direct measurement of F_L

2.1. *Method*

The method to measure $F_L(x, Q^2)$ is simply to measure the differential cross section at fixed Q^2 and x at different y, by varying the beam energies (see Eq. (1)) and to perform a straight line fit of the reduced cross section

$$\sigma_r = [F_2(x, Q^2) - f(y) \cdot F_L(x, Q^2)] \tag{3}$$

as a function of $f(y)$ to extract F_2 and F_L.

To illustrate the method, the reduced cross section, at $x = 2\ 10^{-4}$ and $Q^2 = 10\ GeV^2$, is plotted onto Figure 2 for three proton beam energies. One can notice that:

- F_L is very sensitive to small relative shifts of the cross sections and not to absolute errors.
- The precision on F_L requires the difference between the $f(y)$ values at low and high beam energies, $f(y_{low}) - f(y_{high})$, to be large. So the difference between the two centre of mass energies should be large.
- The precision varies as $1/f(y_{low}) \approx 1/y_{low}^2$. So y_{low} should be as high as possible.
- For a relative systematic shift of 3.5 % between the cross sections at $E_p = 920\ GeV$ and $E_p = 460\ GeV$, the systematic error on F_L would be $\approx 0.035/0.18 = 20\%$.
- A measurement at intermediate beam energy of 575 GeV would not improve significantly the error on F_L but would be an excellent cross check of the systematics.

2.2. *Reducing proton or electron beam energy ?*

To reduce energy in the centre of mass, the proton beam energy E_p or the electron beam energy E_e or both can be reduced. However, in HERA

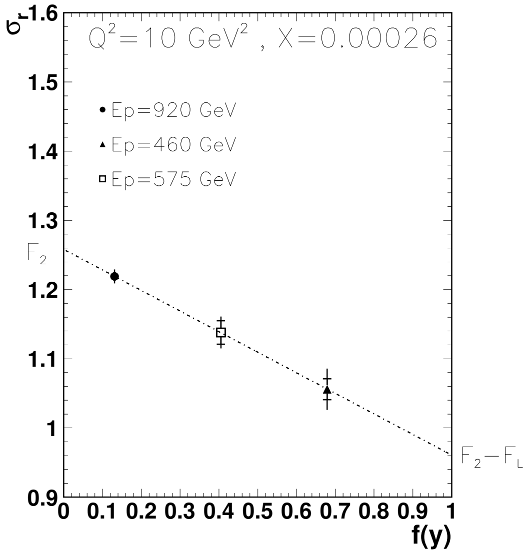

Figure 2. Simulated measurement of the reduced cross section for data at 920 GeV (30 pb^{-1}), 575 GeV (3.5 pb^{-1}) and 460 GeV (5 pb^{-1}). The inner error bar is the statistical error. The full error bar denotes the statistical and systematic uncertainty added in quadrature.

electron-proton kinematics it is preferable to only reduce the proton energy to optimise the experimental systematics by comparing cross sections mainly in the same part of the apparatus [11].

The choice of the reduced proton beam energy is a compromise between the requirement to have the lowest proton beam energy and the luminosity which varies as the square of the beam energy. A reasonable guess for the lowest beam energy is 460 GeV, a value which could be tuned when the luminosity would be better known.

2.3. *Using Initial State Radiation events ?*

To access differenty y values at fixed Q^2 and x a clever method based on using initial state radiation events in DIS events has been tried. The emission of hard photons in a direction close to the incoming electron

$$e + p \longrightarrow e + \gamma + X \tag{4}$$

can be interpreted as a reduced effective beam energy. The hard photon can be measured in the photon detectors which are part of the luminosity systems of H1 or ZEUS [12]. Unfortunately an irreducible pile up of Bethe-Heitler quasi-elastic electron proton scattering events

$$e + p \longrightarrow e + \gamma + p \tag{5}$$

has prevented a clean reconstruction of the photon energy in the photon detector. The Q^2, x and y variables of the radiative DIS events have been reconstructed using the electron energy and angle combined to the total momentum of the hadronic final state in the main detector, yielding to disappointing results on F_L [13,14].

2.4. *Indirect determination*

The H1 Collaboration has invented methods to determine F_L from the measurement of the differential cross section at standard beam energies [15]. These methods rely on extrapolating fits of data obtained at relatively low y into the region of high y where the longitudinal Structure Function starts to contribute significantly to the cross section. The extrapolation is not model independent, different theoretical models will lead to different extrapolations [16]. These methods are not fully satisfying and cannot replace a true deconvolution of the two Structure Functions F_2 and F_L by varying the beam energies.

3. Simulation of a direct measurement

3.1. *Parameters*

In the simulation we have considered two beam energy settings : i) the standard beam energies of $E_e = 27.6\ GeV$ and $E_p = 920$, ii) a reduced proton beam energy $E_p =$ and $460\ GeV$ combined to the standard electron beam energy, with luminosities of 30 and 10 pb^{-1} respectively. We have have used H1 parameterisation of F_2 and F_L [17], which provide F_L values around 0.3. In a case study for the workshop we have assumed systematic errors based on the state of analysis reached so far in inclusive low Q^2 cross section of H1. With the H1 detector, at large y and low Q^2, the kinematics of the scattered electron can be best reconstructed using the backward high resolution Spacal calorimeter for a scattered electron energy E'_e as low as 3 GeV and a precise angle measurement in the Backward Silicon tracker BST or the Central Jet Chamber. A cut on the sum $\sum E - p_z$ of the hadronic final state reduces the size of the radiative corrections and the residual photoproduction background. The following sources of systematic error have been considered:

- Relative shift on the energy of the scattered electron rising from 0.2% at 30 GeV to 2% at 3 GeV.
- Relative shift on the electron angle of 0.2 mrad for $175^0 > \theta_e > 165^0$ in the Backward Silicon Tracker and of 1 mrad for $\theta_e < 165^0$
- Uncertainty on the photo-production background subtraction varying from 0 % at $y = 0.65$ to 4 % at $y = 0.9$.
- 0.5 % uncertainty on the residual radiative corrections.
- An overall uncertainty of 1 % on the measurement of the cross section at low beam energy settings covers relative uncertainties on electron identification, trigger efficiency, vertex efficiency, and relative luminosity.

3.2. *Results*

To evaluate the errors two independent methods have been considered: analytic calculation [18] and a fast Monte-Carlo. The two methods provide statistical and systematic errors which are in excellent agreement. In the following we refer to detailed numbers obtained by the fast simulation. As

Table 1. Statistical and systematic errors in percent in the range $7 < Q^2 < 13\ GeV^2$ based on data at 920 GeV (30 pb^{-1}) and 460 GeV (10 pb^{-1}). The first three lines contain the y range, the average x value and F_L values for each bin. These are followed by the statistical uncertainty (δ_{stat}), the uncorrelated (δ_{unc}) and the radiative corrections (δ_{rad}) uncertainties and the correlated systematics due to the photoproduction background ($\delta_{\gamma p}$) the electron energy ($\delta_{E'_e}$) and the angle ($\delta_{\theta'_e}$). The last two lines summarise the systematic (δ_{syst}) and total (δ_{tot}) uncertainties.

y at 460 GeV	0.90-0.78	0.78-0.68	0.68-0.58	0.58-0.40
$< x >$	0.00023	0.00026	0.00030	0.00040
$< F_L >$	0.303	0.293	0.283	0.266
δ_{stat}	7.2	10.0	13.3	16.3
δ_{unc}	6.4	9.3	13.8	28.0
δ_{rad}	3.2	4.7	7.0	13.9
$\delta_{\gamma p}$	13.0	4.6	1.0	0.0
$\delta_{E'_e}$	5.7	2.5	0.2	5.5
$\delta_{\theta'_e}$	0.7	1.9	6.2	13.5
δ_{syst}	17.2	11.8	16.7	34.5
δ_{tot}	18.6	15.5	21.3	38.2

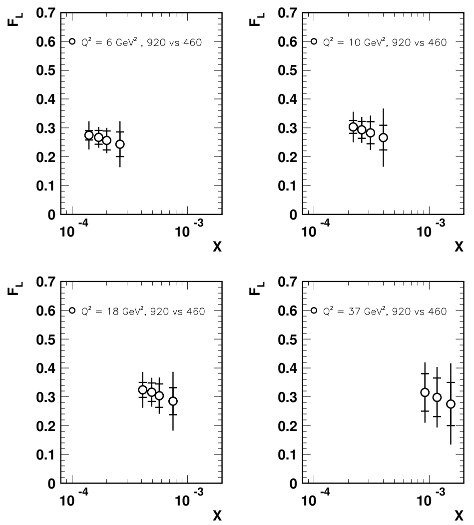

Figure 3. Simulated measurement of the longitudinal Structure Function $F_L(x, Q^2)$ for data at 920 GeV (30 pb^{-1}) and 460 GeV (10 pb^{-1}). The inner error bar is the statistical error. The full error bar denotes the statistical and systematic uncertainty added in quadrature.

an example, the statistical error and the errors on F_L due to each source of systematic are given on Table 1 in the range $7 < Q^2 < 13\ GeV^2$ and in four intervals in y. In the first 3 bins the overall precision on F_L is around 20 %. It is remarkable that, had the statistical error or the larger source of systematic turned out to be twice larger, would the overall precision stay below 25 %. The result of simulated F_L is displayed onto Figure 3 showing that with the above assumptions F_L can be measured at the three to five sigma accuracy level, in four bins of Q^2 at very low x values.

4. Direct measurement of the longitudinal diffractive Structure Function F_L^D

In diffractive processes $ep \to eXp$, a reduced cross section can be defined by analogy with inclusive scattering [19]. It is related to the triple diffrential cross section by

$$\frac{d^3\sigma}{dx_{I\!P}\,dx\,dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x} \cdot \sigma_r^D(x_{I\!P}, x, Q^2) \tag{6}$$

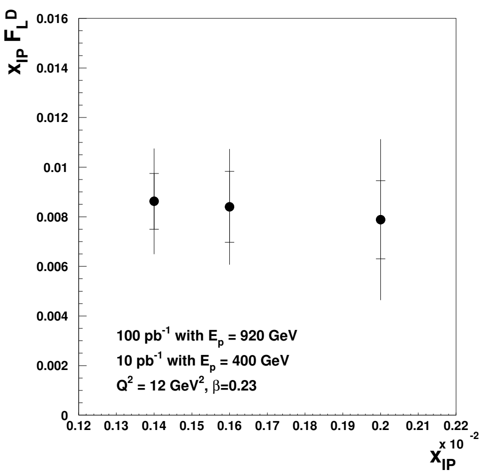

Figure 4. Illustration of the simulated result for F_L^D with statistical (inner bars) and total (outer bars) errors.

where

$$\sigma_r^D(x_{\mathbb{P}}, x, Q^2) = [F_2^D(x_{\mathbb{P}}, x, Q^2) - f(y) \cdot F_L^D(x_{\mathbb{P}}, x, Q^2)] \tag{7}$$

and $x_{\mathbb{P}}$ is the fraction of the proton longitudinal momentum lost by the momentum. Nothing is experimentally known about $F_L^D(x_{\mathbb{P}}, x, Q^2)$. The dominant role played by gluons in the diffractive parton densities [19] implies that F_L^D must be relatively large. A measurement of F_L^D to even modest precision would provide a very powerful independent tool to verify our understanding of the underlying dynamics of deep inelastic diffractive scattering. As in the inclusive measurements the most promising possibility to extract F_L^D is to compare data at fixed Q^2, $x_{\mathbb{P}}$ and x, but from different centre of mass energies s and hence from different y values. The expected uncertainties on the measurement are estimated using the RAPGAP generator [20] and values of F_2^D and F_L^D from the H1 NLO QCD fit [19]. The expected sources of uncertainties are the same as in the inclusive measurement, combined with an overall uncorrelated error of 2.4 % for luminosities, efficiencies and acceptance corrections and with a 4 % uncertainty on the energy scale of the hadronic final state (to reconstruct $x_{\mathbb{P}}$). An illustration of the expected measurement, in the range $7 < Q^2 < 30$ GeV^2 at the average $\beta = 0.23$ (where $\beta = x/x_{\mathbb{P}}$), is shown in Figure 4. In this first simulation [21] the assumed luminosity is 10 pb^{-1} , as for the inclusive measurement, but at a proton beam energy of 400 GeV, which is of no significant influence for the estimation. The results are encouraging. The diffractive longitudinal Structure Function , based on the H1 2002 fit, would be measured to a three sigma accuracy. The dominant errors come from uncertainties which are uncorrelated between the two beam energies and which can still be improved.

5. Possible Scenarios

Based on a recent estimate of the luminosity at reduced proton energy [22] it is possible two consider two possible scenarios:

(i) *One reduced proton energy at*$E_p = 460\ GeV$. It would need 3 weeks to change the configuration of the machine and to tune the luminosity plus 10 weeks to record 10 pb^{-1} of good data with High Voltage of trackers on.

(ii) *Two reduced proton energies at* $E_p = 460\ GeV$ *and* $E_p = 575\ GeV$: 3 weeks to prepare the machine at $E_p = 460\ GeV$ plus 5 weeks of data taking to get 5 pb^{-1} of good data, plus 3 weeks to prepare the machine at $E_p = 575\ GeV$ followed by 2 weeks to record 3.5 pb^{-1} of good data.

The first scenario would have the advantage to provide more statistics to reduce the error on F_L at x around 10^{-3} and to provide enough luminosity to perform a 3 sigma measurement of F_L^D . The second scenario would provide an excellent check of the systematic errors. The two scenarios require the same total amount of time. At the present level of uncertainty on the luminosity at reduced proton energy the scenario (i) looks rather safer and preferable.

6. Conclusion

A direct measurement of the longitudinal Structure Function $F_L(x, Q^2)$with five sigma significance, in the x range from 10^{-4} to 10^{-3} in four bins of Q^2 , can be performed at HERA. It requires about three months at reduced proton beam energy. In addition it would provide the first measurement of the diffractive Structure Function $F_L^D(x_{I\!P}, x, Q^2)$ at the three sigma level. Due to possible conflict with alternative scenarios where the increase of recorded luminosity at normal beam settings would be privileged, it would be wise to do the measurement in the last three months of HERA running in spring 2007 and to wait on the last development on searches for physics beyond the standard model [23] to take a decision by the end of 2006.

Acknowledgments

I would like to thank Laurent Schoeffel for useful discussions and help in preparing the manuscript.

References

1. C. Callan and D. Gross, *Phys. Rev. Lett.*. **22** (1969) 145.
2. G. Altarelli and G. Martinelli, *Phys. Lett.* **B 76** (1978) 89.
3. L.H. Orr and W J. Stirling Phys. Rev. Lett. bf 66 (1991) 1673.
4. S. Moch, J.A.M. Vermaseren and A. Vogt *Phys. Lett.* **B 606** (2005) 123.
5. A. D. Martin et al., *Eur. Phys. J* **C 23** (2002) 73.
6. J. Pumplin et al., *JHEP* 207 (2002) 12.
7. R. Ball, these proceedings.
8. J. Bartels, K. Golec-Biernat and K. Peters, *Eur. Phys. J.*
9. R.S. Thorne, these proceedings.
10. V. Lendermann, these proceedings.
11. M. Klein, "On the future measurement of the longitudinal Structure Function", Proc. Workshop DIS 2004, Strbske Pleso, Slovakia, Eds D. Bruncko, J. Ferencei and P. Strizenec, Vol 1 p. 309. [http://www.saske.sk/UEF/OSF/DIS].
12. M. W. Krasny, W. Placzek and H. Spiesberger, *Z. Phys.* **C 53** (1992) 687.
13. C. Issever, Ph.D. thesis, Dortmund University, Germany, 2000 [http://www.h1-desy.de].
14. J. Cole," Structure Function Measurements using Radiative Events", Proc. Workshop DIS 2003, St Petersburg, Russia , Eds V. Kim and L. Lipatov and A. Bornheim, Ph. D. thesis, Bonn University, Germany, 1999 [http://www.zeus-desy.de].
15. H1 Coll., C. Adloff et al., *Eur. Phys. J* **C 21** (2001) 33 [hep-ex/0012053]; H1 Coll.," Determination of the longitudinal proton Structure Function $F_L(x, Q^2)$ at low Q^2 at HERA", Proc. ICHEP04, Beijing, China,[http://www.h1-desy.de].
16. R.S. Thorne, *Phys. Lett.* **B 418** (1998) 371.
17. H1 Coll., C. Adloff et al., *Eur. Phys. J* **C 30** (2003) 1.
18. M. Klein, private communication.
19. H1 Coll., Paper 980 contributed to ICHEP 2002, Amsterdam, H1 prelim-02-012) [http://www.h1-desy.de].
20. H. Jung, *Comp. Phys. Commun.* **86**, 147 (1995).
21. P. Newman, private communication.
22. F. Willeke, "Prospects for operating HERA with lower proton energy", informal memo, 15 Sept. 2005, unpublished.
23. E. Perez, these proceedings.