Measurements with the ZEUS Leading Proton Spectrometer

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Abstract: The measurements that can be achieved with the use of the ZEUS Leading Proton Spectrometer are reviewed, focussing on the diffractive physics. Estimates of the systematic errors on some of the measurements are given, together with an estimate of the integrated luminosity needed.

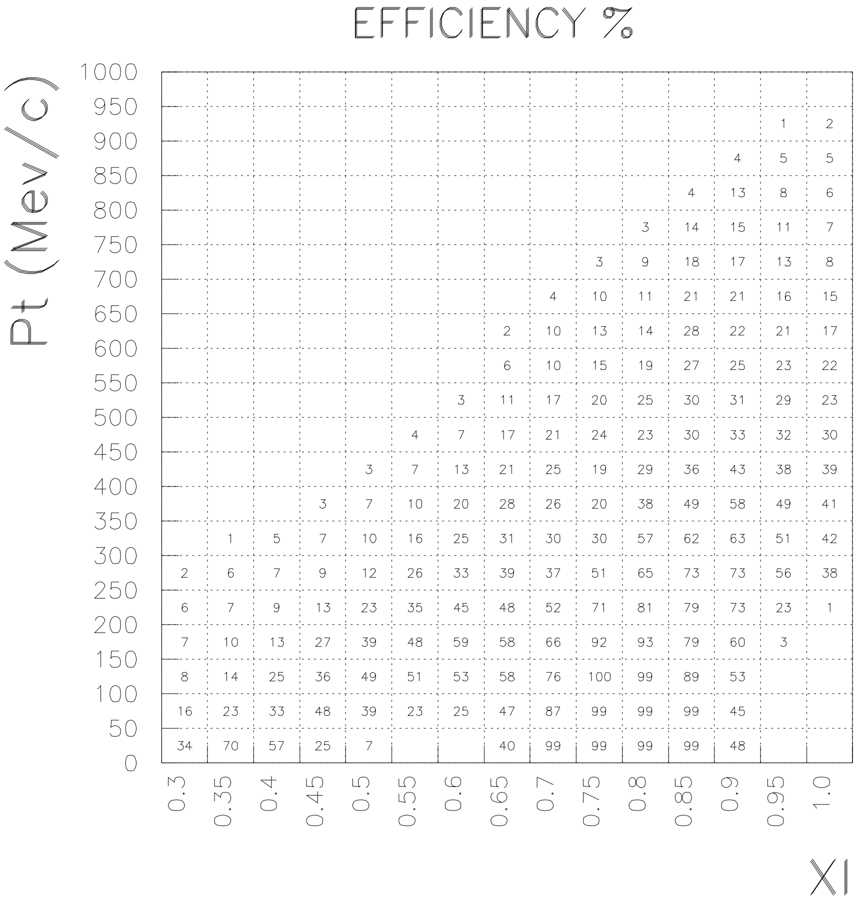
1 Introduction

The two experiments H1 and ZEUS at HERA are equipped with forward spectrometers to detect the scattered proton in ep interaction. This study concentrates on the physics program in diffractive physics achievable with the ZEUS Leading Proton Spectrometer (LPS).

The LPS consists of six stations of silicon microstrip detectors placed along the proton beam line at distances of 23 to 90 m from the interaction point. The LPS detects protons scattered at small angles with respect to the beam, corresponding to proton transverse momenta $p_T \lesssim 1$ GeV. The HERA beam magnets are used to determine the proton momentum. The resolution on the fractional longitudinal proton momentum, $x_L = p'/p$, where p is the incoming proton beam momentum and p' is the momentum of the scattered proton measured in the spectrometer, is 0.4% at high x_L. The p_T resolution of 5 MeV is less than the beam transverse spread at the interaction point of $\lesssim 100$ MeV. The LPS selects a clean sample of single diffractive dissociation events $ep \rightarrow epX$ and measures the square of the four-momentum transfer t at the proton vertex directly.

The first physics results achieved are based on the 1994 data [1], [2], when the three stations S4, S5 and S6, extending from 63 to 90 m, were operational. In this configuration the LPS geometrical acceptance extends approximately from $x_L \simeq 0.5$ to $x_L = 1$ and from $p_T \simeq 0$ to $p_T = 0.8$ GeV, and it varies as a function of x_L and p_T. For $x_L > 0.97$, that is for single photon diffractive dissociation events, the t range covered is between 0.05 and 0.4 GeV^2, with $t \simeq -p_T^2/x_L$. In this range the geometrical acceptance is approximately 6%.

With the complete installation of all six stations, the LPS can measure in an extended region and the acceptance in the region at high x_L is approximately a factor two larger. The resulting acceptance is shown in figure 1, and it will be used in the estimation of the integrated luminosity needed for the LPS measurement.



Pt (Mev/c) \ XI	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95	1.0
950–1000															
900–950														1	2
850–900													4	5	5
800–850												4	13	8	6
750–800											3	14	15	11	7
700–750										3	9	18	17	13	8
650–700									4	10	11	21	21	16	15
600–650								2	10	13	14	28	22	21	17
550–600								6	10	15	19	27	25	23	22
500–550							3	11	17	20	25	30	31	29	23
450–500						4	7	17	21	24	23	30	33	32	30
400–450					3	7	13	21	25	19	29	36	43	38	39
350–400				3	7	10	20	28	26	20	38	49	58	49	41
300–350		1	5	7	10	16	25	31	30	30	57	62	63	51	42
250–300	2	6	7	9	12	26	33	39	37	51	65	73	73	56	38
200–250	6	7	9	13	23	35	45	48	52	71	81	79	73	23	1
150–200	7	10	13	27	39	48	59	58	66	92	93	79	60	3	
100–150	8	14	25	36	49	51	53	58	76	100	99	89	53		
50–100	16	23	33	48	39	23	25	47	87	99	99	99	45		
0–50	34	70	57	25	7			40	99	99	99	99	48		

Figure 1: *Acceptance table in the x_L, p_T plane for coincidences between any two stations of the LPS out of six.*

2 Measurements with the LPS

The list of topics of interest in hard diffractive scattering is long and is discussed in detail in the summary [3]. Among all the processes of interest there are some which cannot be explored fully without the use of the LPS.

The t distribution is claimed to be the testing ground for the hardness of diffractive processes. The LPS is the unique tool for measuring the t distribution for all inclusive processes in which the p_T resolution achieved with the main calorimeter is larger than the typical width of the t distribution itself.

Another area which cannot be explored without heavy use of Monte Carlo simulation is the large mass diffraction, where the existing detectors, except for the LPS, loose their sensitivity to the presence of large rapidity gaps.

Thus this report concentrates on the measurement of the diffractive structure function $F_2^{D(4)}$

and of the t dependence in DIS. The numbers presented here for these specific cases can then be easily rescaled to estimate the luminosity requirements for any diffractive processes.

3 Diffractive Cross Section in DIS

The differential cross section for diffractive DIS events can be written in terms of the diffractive structure function $F_2^{D(4)}$ as:

$$\frac{d^4\sigma_{diff}}{d\beta dQ^2 dx_{I\!P} dt} = \frac{2\pi\alpha^2}{\beta Q^4}\left(1+(1-y)^2\right) F_2^{D(4)}(\beta, Q^2, x_{I\!P}, t), \tag{1}$$

where α is the electromagnetic coupling constant, y is the fractional energy transferred to the proton in its rest frame; in the expression above the contributions of the longitudinal structure function and of Z^0 exchange have been neglected. Assuming that diffractive interactions are due to pomeron exchange, $x_{I\!P}$ is the momentum fraction of the proton carried by the pomeron and β is the momentum fraction of the struck quark with respect to $x_{I\!P}$.

Diffractive DIS events are selected in the LPS requiring a well reconstructed proton track with $x_L > 0.97$. The uniqueness of the LPS for the determination of the diffractive cross section is due to four reasons:

- the ability to select a clean sample of single diffractive dissociation events through the proton tagging (estimates are that the background due to other physics processes is below 5%);
- the ability to measure t directly;
- good resolution in β and $x_{I\!P}$, in the region $0.001 < \beta < 0.1$;
- the ability to determine the background to diffraction by extending the measurement of the proton at low x_L ($x_L < 0.97$).

As shown in the formula above, the differential cross section is a function of four variables, $Q^2, t, x_{I\!P}$ and β. The quantities Q^2 and y are reconstructed from the electron variables (electron angle and energy) or from the double angle variables, as for the inclusive F_2 measurement. The quantities $x_{I\!P}$ and β are reconstructed from the variables at the electron vertex and from the mass M_X of the final hadronic system into which the virtual photon diffractively dissociates:

$$\beta = \frac{Q^2}{Q^2 + M_X^2}; \qquad x_{I\!P} = \frac{x}{\beta} \simeq 1 - x_L \tag{2}$$

where W is the $\gamma^* p$ centre-of-mass energy and x the Bjorken scaling variable. With the LPS, the measurement can extend to higher masses (therefore to lower values of β and higher values of $x_{I\!P}$) compared to measurements based on rapidity gap selection. In the high mass region, M_X can be reconstructed from the momenta of the electron and the proton, $M_X = sy(1-x-x_L)$, achieving a very good resolution (for $M_X \gtrsim 25$ GeV the resolution is 15%, for $M_X \simeq 80$ GeV it is 6%).

3.1 Measurement of $d\sigma/dt$

One of the first measurements performed with the LPS has been the determination of the t dependence in diffractive DIS events. The measurement was performed integrating over the kinematical region $4 < Q^2 < 30$ GeV^2, $70 < W < 210$ GeV, $0.02 < \beta < 0.4$ and $x_L > 0.97$, and for $0.07 < |t| < 0.35$ GeV^2. The resulting distribution is exponential and expressed as $d\sigma/d|t| \sim \exp(-b|t|)$ leads to a value of b which is within errors in agreement with what is expected for the soft pomeron, although on the low side.

One of the prediction of models based on the soft pomeron is the shrinkage of the diffractive peak with increasing c.m. energy. Measuring in two W bins around 50 GeV and 200 GeV, at an average Q^2 of 10 GeV^2 and an average mass of 10 GeV, one expects:

$$b\,(W) \simeq b_0 + 2\alpha' \ln(W^2/(M_X^2 + Q^2))\ \mathrm{GeV}^{-2} \simeq 6\ \mathrm{GeV}^{-2}, \tag{3}$$

$$b\,(W \simeq 200) - b\,(W \simeq 50) \simeq 2\alpha' \ln(200^2/50^2) \simeq 1.4\ \mathrm{GeV}^{-2}, \tag{4}$$

where $b_0 \simeq 4.5$ GeV^{-2} and $\alpha' \simeq 0.25$ GeV^{-2} is the slope of the soft pomeron trajectory. For the hard pomeron the expectations are that $\alpha' \simeq 0$ (no shrinkage), which means that $b\,(W \simeq 200) = b\,(W \simeq 50)$.

In order to measure a difference between the two values at the 3σ level in these two W bins, the error on b should be of the order of 0.3 GeV^{-2}, i.e. of the order of 5% for $b \simeq 6$ GeV^{-2}. With 20 pb^{-1}, about 4000 tagged LPS events can be collected for each W point, obtaining a statistical error on $b\,(W)$ of $3 \div 4\%$. The dominant systematic errors are due to the alignment of the LPS with respect to the beam and to the unfolding of the proton beam transverse momentum spread. The estimate is that, with the present configuration, a systematic error of 3% on b could be achieved, giving the possibility to measure the shrinkage with the required precision. The HERA luminosity upgrade by means of low-β quadrupoles would restrict the range in t where there is acceptance for the LPS, moving the lower $|t|$ limit from 0.07 GeV^2 to 0.27 GeV^2 [4], reducing the statistics. In addition the low β quadrupoles increase the beam dispersion in transverse momentum at the interaction point, thus increasing the systematic error on b. The effect is shown in fig. 2. The observed t distribution is a convolution of the p_T^2 exponential folded with the p_T dispersion caused by the beam emittance represented by a 2-dimensional gaussian in transverse momentum space, whose width increases slowly during the lifetime of the beam. Therefore, the observed p_T^2 distribution is also a 2-dimensional gaussian and can be approximated by an exponential whose slope changes with time. The size of this effect is shown in fig. 2 for the 1994 HERA optics ($\beta_x = 7; \beta_y = 0.7$) and for the proposed low β quadrupoles configuration ($\beta_x = 3; \beta_y = 0.2$); for a slope of 6 GeV^{-2} in the proposed configuration, the beam emittance would change the slope by as much as 20%, with a strong dependence on the size of the emittance of the beam. The systematic error on b induced by this correction is estimated to increase to $7 - 12\%$.

3.2 Measurement of $F_2^{D(4)}$

The systematic errors on $F_2^{D(4)}$ are limited by the kinematic reconstruction of x, Q^2, the M_X reconstruction, the background subtraction and the LPS acceptance. The systematic errors due to the acceptance of DIS events and x, Q^2 reconstruction are the same as for the inclusive F_2 measurement. In the intermediate y region a systematic error below 5% has been achieved [5]

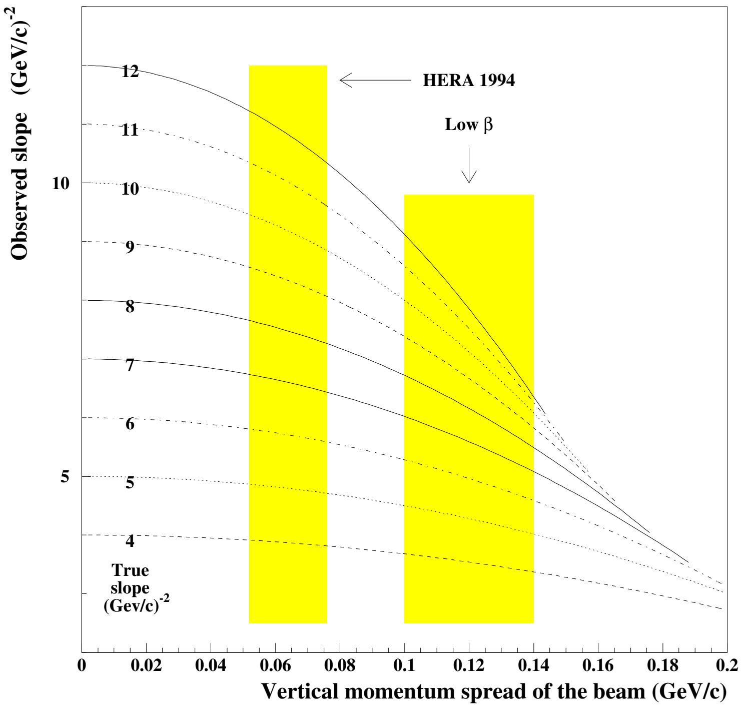


Figure 2: *Effect of the low β optics on the measurement of the diffractive slope b with the LPS. The bands are the range of variation induced by the growth of the emittance during the lifetime of the proton beam.*

and could be reduced to 3% with a better measurement of the electron and hadronic variables in the next years. The M_X reconstruction, as already mentioned, is well under control at high masses, $M_X \gtrsim 10$ GeV, where the LPS information is used, and should provide a precise measurement for $\beta \lesssim 0.1$. A systematic error of 3% could be achieved. The background is due mainly to two processes. The beam halo background comes from interactions of beam protons with the residual gas in the beam pipe or with the beam collimators, accidentally overlapping with genuine DIS events. This type of background can be easily subtracted and estimated requiring energy and longitudinal momentum conservation and can be controlled at the level of 1%. The second type of background is due to processes where the proton does not remain intact, like proton dissociation, Reggeon exchange other than the pomeron and non-diffractive interactions. In this case the x_L spectrum peaks at low values, and study of the low x_L data can shed light on the nature of the remaining background under the diffractive peak. An error due to this background of 2% could be achieved. Finally the error due to the LPS acceptance (LPS alignment and calibration and run-to-run dependence of the acceptance) can reach an ultimate precision of 5%. Summing in quadrature all the above contributions, a systematic uncertainty of 7% could be achieved in each bin. The HERA upgrade would severely affect the LPS acceptance increasing the systematic error due to this contribution.

The LPS allows measurement of the structure function $F_2^{D(4)}$ in the four variables t,$x_{I\!P}$,β,Q^2. If a measurement were made in two t bins ($0.07 < |t| < 0.12$ GeV^2, $0.12 < |t| < 0.35$ GeV^2), in three Q^2 bins in the range $4 < Q^2 < 30$ GeV^2, in seven β bins in the range $0.001 < \beta < 0.5$

and in three to six $x_{I\!P}$ bins in the range $4 \times 10^{-4} < x_{I\!P} < 3 \times 10^{-2}$, 70 events on average per bin are expected with 20 pb^{-1} (in those bins within kinematic range at HERA). This results in an average statistical error of the order of 12% for each bin, to be compared with the systematic error of 7%. Fitting the $x_{I\!P}$ dependence with $(1/x_{I\!P})^a$ for every Q^2, t and β interval, the statistical error on the slope a could be measured with a statistical precision of 5 to 15% and a systematic precision of less than 3%, testing if factorization holds in the mentioned β range. Table 3.2 shows the error on a in individual β bins. The error at low β is larger because the HERA kinematics limit the accessible range in $x_{I\!P}$.

β	Number of $x_{I\!P}$ bins	Number of events per bin	Statistical error (in%) on a
$\simeq 0.01$	$3\ (10^{-2} < x_{I\!P} < 3 \times 10^{-2})$	50	$\pm 15\%$
$\simeq 0.03$	$3\ (2 \times 10^{-3} < x_{I\!P} < 3 \times 10^{-2})$	70	$\pm 10\%$
$\simeq 0.1$	$5\ (4 \times 10^{-4} < x_{I\!P} < 3 \times 10^{-2})$	70	$\pm 6\%$
$\simeq 0.3$	$5\ (4 \times 10^{-4} < x_{I\!P} < 3 \times 10^{-2})$	70	$\pm 5\%$

Table 1: *Estimated number of events in β intervals for 20 pb^{-1} of collected LPS data, for 3 Q^2 bins, 2 t bins and 3-5 $x_{I\!P}$ bins, and relative statistical error on the power a of the $x_{I\!P}$ dependence.*

4 Summary

The LPS provides a very powerful tool to study diffraction at HERA. In particular it provides the direct measurement of t, it allows the selection of a clean sample of single diffractive dissociation events and it extends the measurement to low β and high $x_{I\!P}$. The proposed HERA upgrades would severely limit the LPS acceptance, especially at low t as shown in [4]. An estimated integrated luminosity of 20 pb^{-1} collected with the LPS would allow a measurement of the differential diffractive structure function $F_2^{D(4)}$ in a reasonable binning in $x_{I\!P}, \beta, Q^2, t$ for $Q^2 < 30$ GeV^2, with a statistical error of 12% and a systematic error of the order of 7%. Note that the LPS efficiency compared to the luminosity delivered by HERA is of the order of 50%: 20 pb^{-1} collected by the LPS correspond to 40 pb^{-1} delivered by HERA. The factorization breaking could be tested with a precision of $5 - 15\%$. The shrinkage of the diffractive peak could be tested unambigously in two W bins, integrating over Q^2, with 4000 events per bin, obtaining a precision of 0.3 GeV^{-2} on the slope b and of 0.1 GeV^{-2} on α'.

References

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