Investigation of High Energy Behaviour of HERA Data

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Introduction

- We analyse the high precision HERA F_2 data in the low-x, $x < 0,01$, and very-low-x, $x < 0.001$, regions using λ-fits.
- λ is a measure of the rate of rise of F_2 defined by $F_2 \propto (1/x)^{\lambda}$.
- We show that λ determined in these two regions, at various Q^2 values, is systematically smaller in the very-low-x region as compared to the low-x region.
- We discuss some possible physical interpretations of this effect.
- The analysis is based on publication: "*Investigation of High Energy Behaviour of HERA Data*", A.Luszczak, H.Kowalski, Phys.Lett.B802 (2020), 135199.

Description of fits

- We determine the λ parameter from a fit of the function $F_2 = A\,(1/x)^{\lambda}$ to the final, high precision H1 and ZEUS data, measured at HERA. Here, A is a normalisation constant dependent on Q^2.
- The fits are made in the range $x < 0.01$ and $x < 0.001$, for each Q^2 value separately, with $0.3 < Q^2 < 250$ GeV^2.
- The final data are given as reduced cross sections, which are connected to F_2 and F_L by:

$$\sigma_{red} \approx F_2 - \frac{y^2}{Y_+} F_L,$$

  with $Y_+ = 1 + (1-y)^2$, where y denotes the inelasticity parameter. In the selected kinematic region, the contribution of the structure function F_3 can be neglected.
- Following the discussion of the properties of F_L in the H1 papers we assume that F_L is proportional to F_2. This is also in agreement with the ZEUS results.

Description of fits

- We have then

$$F_2 = \frac{\sigma_{red}}{1 - \frac{y^2 R}{Y_+(1+R)}},$$

where $R = F_L/(F_2 - F_L)$. The evaluation of F_L shows that the ratio R is only weakly dependent on x and Q^2, especially in the kinematic region of the present investigation, $0.01 < y < 0.8$. Thus we assumed $R = 0.25$, in agreement with data, the QCD DGLAP predictions and the dipole models.

Results of fits

	$x < 0.01$				$x < 0.001$			
Q^2	λ	$\delta\lambda$	N_{df}	χ^2/N_{df}	λ	$\delta\lambda$	N_{df}	χ^2/N_{df}
0.35	0.110	0.008	10	0.850	0.110	0.0081	10	0.850
0.4	0.082	0.009	7	0.915	0.082	0.009	7	0.915
0.5	0.100	0.009	7	0.768	0.100	0.009	7	0.768
0.65	0.121	0.011	7	0.813	0.121	0.011	7	0.813
0.85	0.150	0.014	7	0.759	0.150	0.014	7	0.759
1.2	0.133	0.013	8	2.074	0.133	0.013	8	2.074
1.5	0.142	0.009	10	1.741	0.142	0.009	10	1.741
2	0.159	0.007	10	1.246	0.159	0.007	10	1.246
2.7	0.169	0.005	12	1.745	0.168	0.007	10	1.462
3.5	0.173	0.004	18	1.391	0.168	0.007	16	1.485
4.5	0.189	0.004	13	1.908	0.192	0.008	10	2.347
6.5	0.200	0.003	29	0.990	0.189	0.008	25	1.002
8.5	0.208	0.004	34	1.252	0.192	0.009	27	1.047
10	0.226	0.007	5	1.005	0.205	0.024	2	0.518
12	0.215	0.005	33	1.016	0.202	0.009	24	0.715
15	0.237	0.003	32	1.217	0.219	0.010	21	1.303
18	0.242	0.003	11	0.401	0.234	0.012	6	0.358
22	0.258	0.007	11	0.961	0.241	0.018	6	0.601
27	0.267	0.004	10	0.632	0.267	0.020	5	0.136
35	0.280	0.003	35	1.144	0.251	0.021	13	1.759
45	0.292	0.004	33	0.877	0.263	0.057	5	1.085
60	0.313	0.005	32	1.274				
70	0.332	0.009	10	0.812				
90	0.321	0.007	27	0.925				
120	0.352	0.008	31	0.506				
150	0.339	0.011	17	1.101				
200	0.373	0.010	16	0.545				
250	0.417	0.014	13	0.727				

- Table 1 shows the values of λ constant with its error $\delta\lambda$ for two low-x regions, $x < 0.01$ and $x < 0.001$. The fits are of good quality, as the average value of χ^2/N_{df} is 1.05, at $x < 0.01$.

Results of fits

	$x < 0.01$				$x < 0.001$			
Q^2	A	δA	N_{df}	χ^2/N_{df}	A	δA	N_{df}	χ^2/N_{df}
0.35	0.0957	0.008	10	0.850	0.0957	0.008	10	0.850
0.4	0.143	0.013	7	0.915	0.143	0.014	7	0.915
0.5	0.136	0.013	7	0.768	0.136	0.013	7	0.768
0.65	0.133	0.015	7	0.813	0.133	0.015	7	0.813
0.85	0.120	0.018	7	0.759	0.120	0.018	7	0.759
1.2	0.170	0.022	8	2.074	0.170	0.022	8	2.074
1.5	0.180	0.016	10	1.741	0.184	0.016	10	1.741
2	0.172	0.012	10	1.246	0.172	0.012	10	1.246
2.7	0.179	0.008	12	1.745	0.181	0.012	10	1.462
3.5	0.195	0.007	18	1.391	0.203	0.012	16	1.485
4.5	0.191	0.007	13	1.908	0.186	0.0013	10	2.347
6.5	0.201	0.006	29	0.990	0.221	0.015	25	1.002
8.5	0.211	0.007	34	1.252	0.234	0.016	27	1.047
10	0.192	0.010	5	1.005	0.226	0.044	2	0.518
12	0.225	0.008	33	1.016	0.247	0.018	24	0.715
15	0.202	0.005	32	1.217	0.232	0.019	21	1.303
18	0.208	0.005	11	0.401	0.218	0.021	6	0.358
22	0.197	0.010	11	0.961	0.223	0.030	6	0.601
27	0.196	0.005	10	0.632	0.195	0.029	5	0.136
35	0.193	0.005	35	1.144	0.239	0.037	13	1.759
45	0.190	0.005	33	0.877	0.234	0.096	5	1.085
60	0.179	0.005	32	1.274				
70	0.164	0.009	10	0.812				
90	0.188	0.008	27	0.925				
120	0.163	0.008	31	0.506				
150	0.183	0.011	17	1.101				
200	0.158	0.008	16	0.545				
250	0.129	0.010	13	0.727				

- Table 2 shows the values of A constant and its errors in the same x regions.

Results of fits

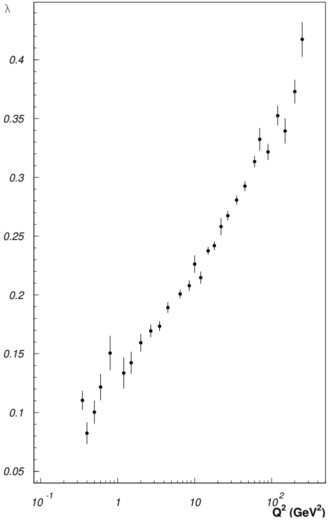


Figure: The power λ as determined from the fits in the $x < 0.01$ region, at all accessible Q^2 values, Table 1.

Results of fits

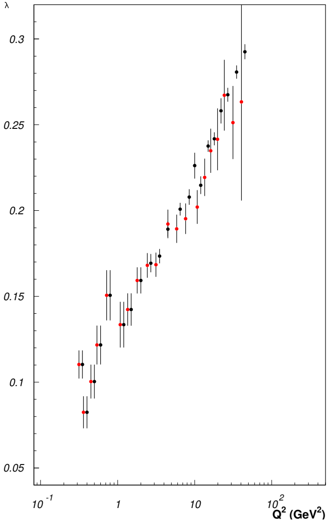


Figure: Comparison of the results of the λ-fit in the low-x, $x < 0.01$, and very-low-x, $x < 0.001$, regions. Only points determined with differing data are shown, see Table 1.

Results of fits

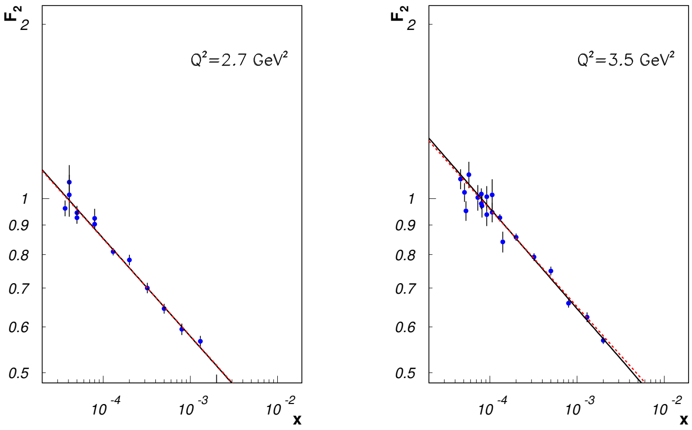
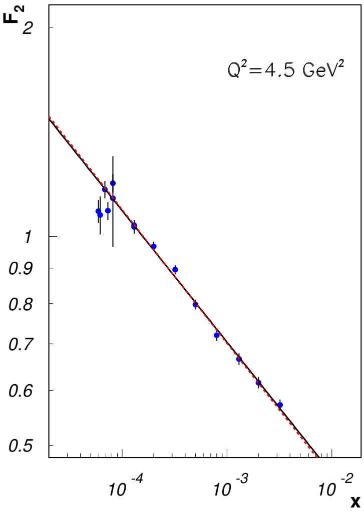
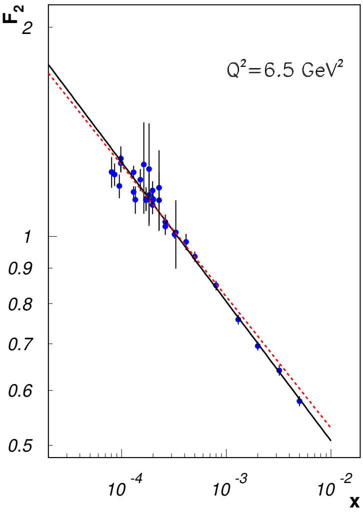


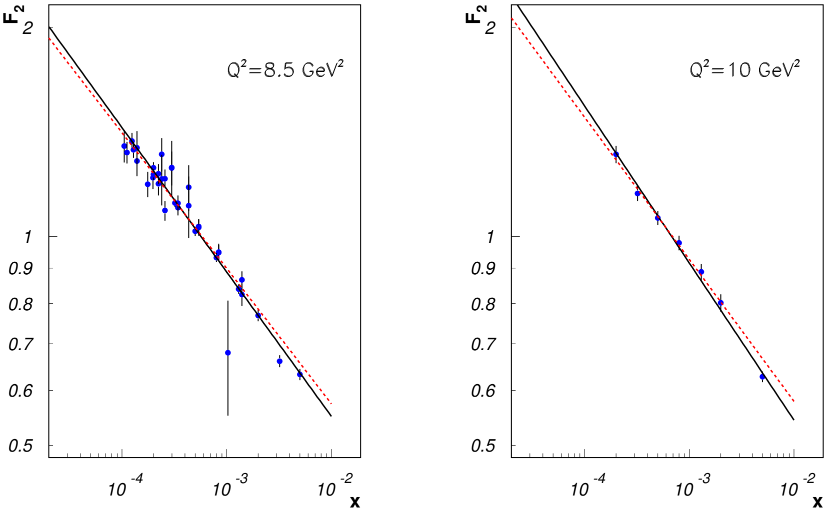
Figure: The fitted curves, $F_2 \propto (1/x)^\lambda$, are shown together with the data at indicated Q^2 values. The full line shows the fit in the range $x < 0.01$, the dotted line in the range $x < 0.001$. The dots show the data with errors bars given by the statistical and systematical errors added in quadrature. In the fit, all correlations of errors were taken into account.

Results of fits

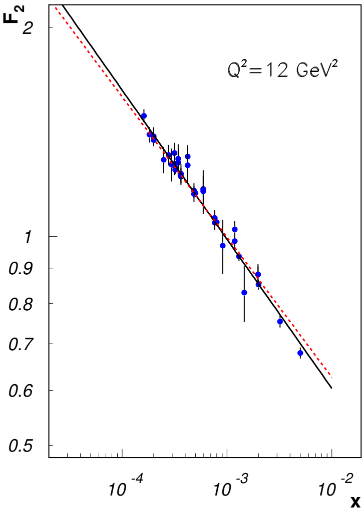


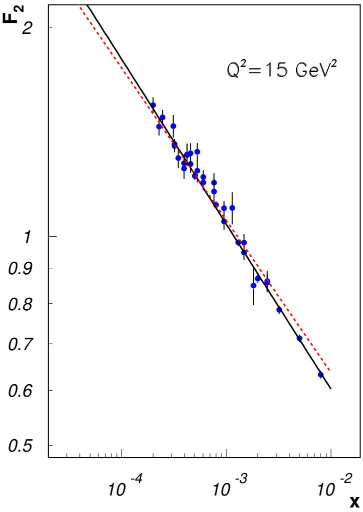


Results of fits

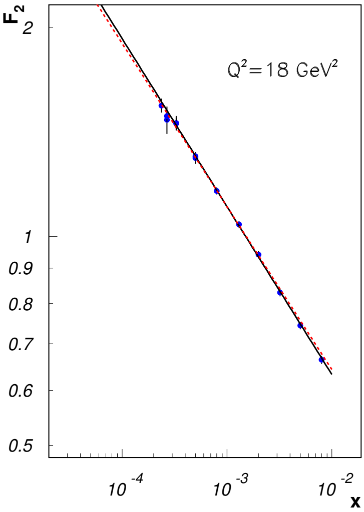


Results of fits

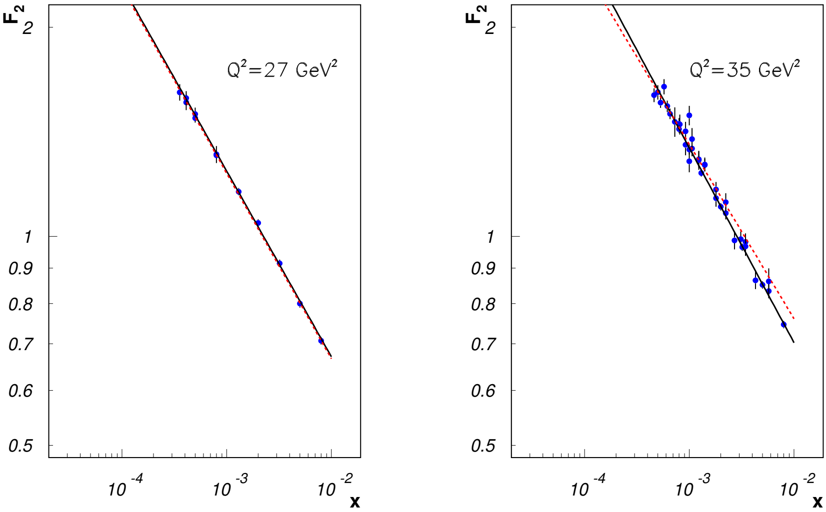




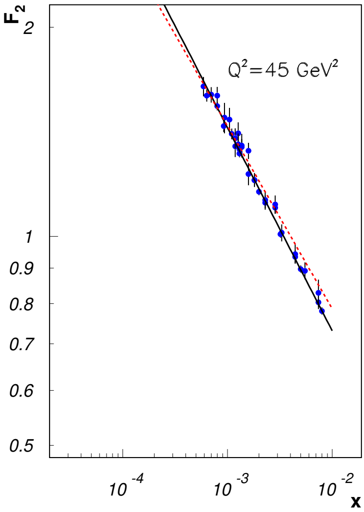
Results of fits



Results of fits



Results of fits



Results of fits

- In these plots we compare the fitted curves to the corresponding data in all Q^2 regions, between 2.7 and 45 GeV^2. The curves are drawn with the values of the constants λ and A given in Tables 1 and 2.
- The full line shows the fit in the region $x < 0.01$ and the dashed one the fit to the region $x < 0.001$. The curves are drawn in a larger region than the fit are performed, to emphasise the systematic differences between them.
- The figures show quite clearly that the dashed lines are almost always below the full lines in the region of very small $x < 0.001$.
- On the opposite end, around $x \approx 0.01$, the full line is almost always above the dashed one. Since the figures are drawn on a double logarithmic scale (and are relatively large) it is possible to see, even clearly in some cases, a slight "bowing" of data due to a systematic decrease of λ at smaller x values, seen in Fig.from page.7 and Table 1.

Results of fits

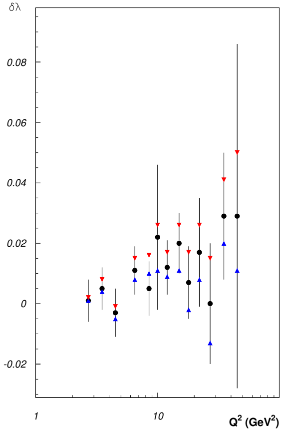


Figure: *Plot of differences between the values of λ determined in the low-x and very-low-x region, $\Delta_\lambda = \lambda_{x<0.01} - \lambda_{x<0.001}$. The black dots show the results for $R = 0.25$, the triangles pointing down show the results for $R = 0.2$ and the triangles pointing up show the results for $R = 0.3$. The errors of black dots were obtained from the quadratic addition of errors, $\delta_{\Delta_\lambda} = \sqrt{\delta^2_{\lambda_{x<0.01}} + \delta^2_{\lambda_{x<0.001}}}$. The errors of the triangles are of about the same magnitude and were not displayed, for clarity.*

Summary

- We have confirmed that the simple phenomenological function, $F_2 \propto (1/x)^\lambda$, fits very well the high precision HERA data in the low x region, $x < 0.01$, at all Q^2 values between $0.3 < Q^2 < 250$ GeV^2.
- Moreover, we have shown that this is also true for the very low x region, $x < 0.001$.
- The new result of this investigation is that the rate of rise, λ, determined in the two regions, indicate that λ is systematically smaller in the very low x region as compared to the low x region, for $Q^2 > 6$ GeV^2. This result is obtained due to the high precision of the latest HERA data (the earlier investigations concluded that the power λ is not dependent on x, within the experimental errors.)
- This observation may indicate the onset of BFKL behaviour in the very low x region, $x < 0.001$, $Q^2 > 6$ GeV^2, in agreement with the analysis of H. Kowalski, L.N. Lipatov, D. A. Ross, O. Schulz, Eur. Phys. J **C77** (2017).
- Our observation that the value of the exponent λ decreases at small values of x, indicates that measurements at the future ep colliders, like VHEeP or LHeC will become exciting, as they will approach the high energy limit of the virtual photon-hadron cross sections, where DGLAP and BFKL meets and the confinement effects should become simple.

Backup slide

- This observation may indicate the onset of BFKL behaviour in the very low x region, $x < 0.001$, $Q^2 > 6$ GeV^2, in agreement with the analysis of ref. H. Kowalski, L.N. Lipatov, D. A. Ross, O. Schulz, Eur. Phys. J **C77** (2017).
- The analysis has shown that the BFKL gluon density describe data very well in this region and that the dominant contribution is provided by the second pole, which has $\omega \approx 0.14$, a value which is substantially smaller than the λ value observed in this region, see Table 1.
- Note that the evaluation of the ref. does not allow a quantitive estimate of the expected change of the power λ between the low x and very low x regions, as the high quality of BFKL description was obtained only in the second region.
- The observation of a systematic decrease of λ with diminishing x could also indicate that the double asymptotic region, in which $F_2 \approx \exp c\sqrt{\ln(1/x)}$, may be only few decades away from the $x < 0.001$ region observed at HERA.
- In a more recent investigation: [H1 Collaboration], Eur.Phys.J. **C71** (2011), it was noticed, although indirectly, that λ values may diminish with decreasing x, in agreement with the present investigation.