LOW X PHYSICS AT HERA

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Recent HERA data on structure functions and reduced cross-sections are presented and their significance for our understanding of the low-x region is dicussed

In the course of the last year both ZEUS and H1 have presented data (see refs. [1], [2]) on structure functions and reduced cross-sections from the 1996/7 runs of e^+p interactions. The kinematics of lepton hadron scattering is described in terms of the variables Q^2, the invariant mass of the exchanged vector boson, Bjorken x, the fraction of the momentum of the incoming nucleon taken by the struck quark (in the quark-parton model), and y which measures the energy transfer between the lepton and hadron systems. The cross-section for the process is given in terms of three structure functions by

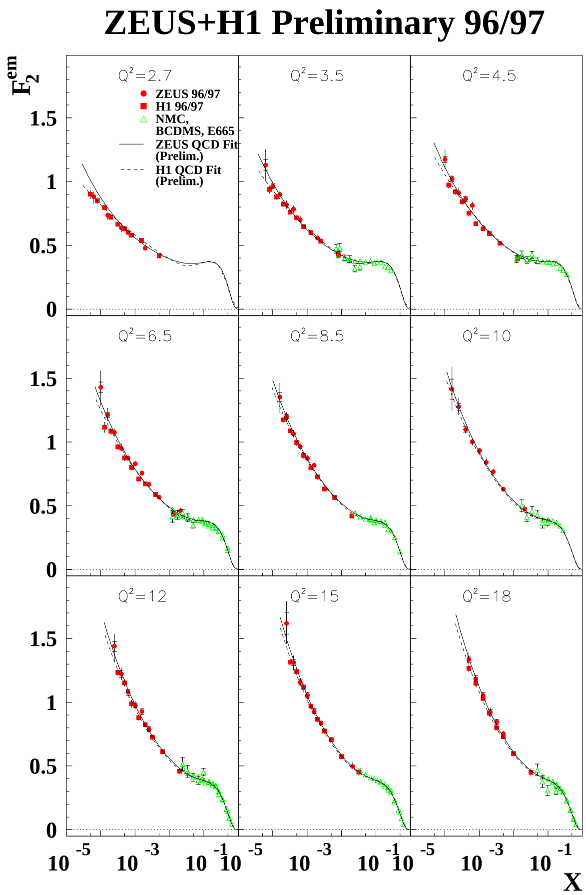
$$\frac{d^2\sigma(e^+p)}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4x}\left[Y_+\, F_2(x,Q^2) - y^2\, F_L(x,Q^2) - Y_-\, xF_3(x,Q^2)\right], \tag{1}$$

where $Y_\pm = 1 \pm (1-y)^2$, and we have ignored mass terms. The new data have extended the measured region in the x, Q^2 plane to cover $10^{-6} < x < 0.65$ and $0.045 < Q^2 < 30000 GeV^2$. The precision of measurement is such that systematic errors as small as $\sim 3\%$ have been achieved for $2 < Q^2 < 800 GeV^2$, with much smaller statistical errors. Thus the HERA data rival the precision of fixed target data, and there is now complete coverage of the kinematic plane over a very broad range. In Fig.1 we show a subsample of the HERA F_2 data in comparison to fixed target data, for low Q^2 values which cover the interesting low x region. This plot show the characteristic rise of F_2 at small x which becomes more dramatic as Q^2 increases. In this kinematic region, the parity violating structure function xF_3 is negligible and the structure functions F_2, F_L are given purely by γ^* exchange. At leading order (LO) in perturbative QCD, F_2 is given by

$$F_2^{ep}(x,Q^2) = \Sigma_i e_i^2 * (xq_i(x,Q^2) + x\bar{q}_i(x,Q^2)), \tag{2}$$

a sum over the (anti)-quark momentum distributions of the proton multiplied by the corresponding quark charge squared e_i^2. At the same order, the spin-1/2 nature of the quarks implies that $F_L = 0$, thus cross-section data measure F_2 and tell us about the behaviour of the quark distributions, and futhermore, their Q^2 dependence, or scaling violation, is predicted by pQCD. Preliminary

Fig.1: HERA F_2 data compared to fixed target data at low Q^2

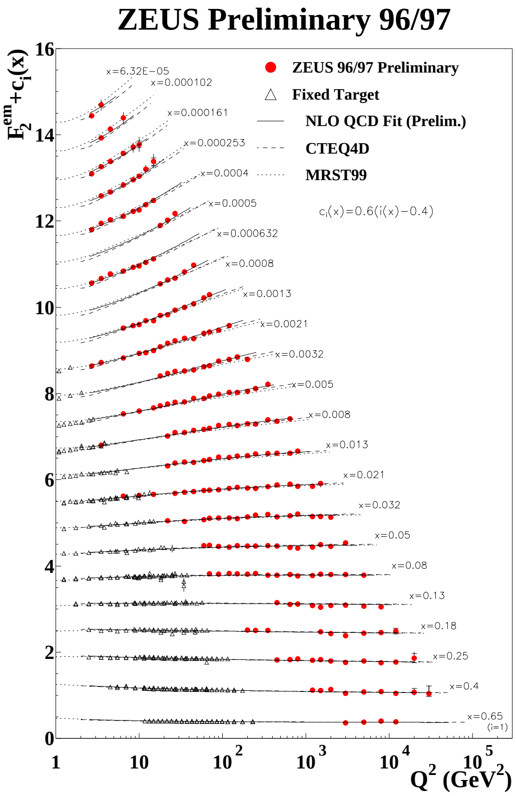


NLO pQCD fits to the F_2 data from each of the collaborations are shown on Fig.1.

To appreciate the significance of the QCD scaling violations we also show the HERA96/7 data as a function of Q^2 in fixed x bins in Fig.2. Such data has been used to extract parton distributions using an NLOQCD fit to the DGLAP equations. For example,

$$\frac{dq_i(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j q_j(y,Q^2)P_{q_iq_j}(\frac{x}{y}) + g(y,Q^2)P_{q_ig}(\frac{x}{y})\right] \qquad (3)$$

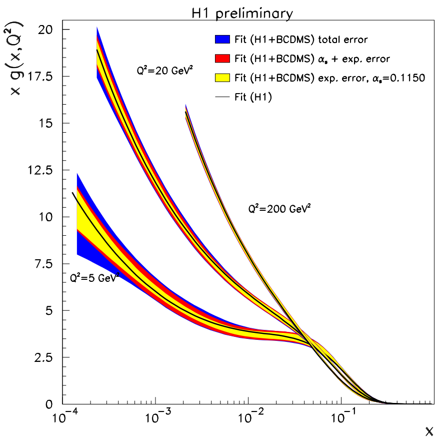
Fig.2: ZEUS and fixed target F_2 data as a function of Q^2 in fixed x bins



describes the Q^2 evolution of a quark distribution in terms of parent parton (either quark or gluon) distributions, where the 'splitting function' $P_{ij}(z)$ (predicted by QCD) represents the probability of the parent parton j emitting a parton i, with momentum fraction z of that of the parent, when the scale changes from Q^2 to $Q^2 + d\ln Q^2$. The QCD running coupling, $\alpha_s(Q^2)$, determines the rate of such processes. Thus although the structure function F_2 is directly related to quark distributions, we may also gain information on the gluon distribution from its scaling violations. In fact at low x the gluon contribution dominates the evolution of F_2.

In recent years more emphasis has been placed on estimating errors on extracted parton distributions. Fig.3 shows the gluon distribution extracted from a fit to H196/7 data, where the errors include not only experimental

Fig.3: H196/7 gluon illustrating experimental and model dependent errors



correlated systematic errors but also model errors, such as the uncertainty of α_s, scale uncertainties etc. (see ref [1]). Precision meausrements of α_s are also possible using this scaling violation data and H1 have combined their data with that of BCDMS to obtain, $\alpha_s = 0.115 \pm 0.0017(exp) \pm 0.0007(model) \pm 0.005(scale)$. It is clear that the largest uncertainties are now theoretical and that pQCD calculations to NNLO should help to reduce this uncertainty.

However, when doing such fits the question arises how low in x should one go using conventional theory? The DGLAP formalism makes the approximation that only dominant terms in leading (and next to leading) $ln(Q^2)$ are resummed. However at low x terms in leading (and next to leading) $ln(1/x)$ may well be just as important. This requires an extension of conventional theory such as that of the BFKL resummation. One may also question how low in Q^2 one should go. The DGLAP formalism only sums diagrams of leading twist, and it is also clear that α_s becomes large at low Q^2 such that perturbative calculations cannot be used, see ref. [6] and references therein for a full discussion of these matters. When DGLAP fits to F_2 data are used to extract gluon distributions at $Q^2 \leq 2GeV^2$ one finds the surprising result that the gluon becomes valence-like in shape, falling rather than rising at $x \leq 10^{-3}$ (see ref [3]). This effect is accentuated when account is taken of NNLO terms [4],

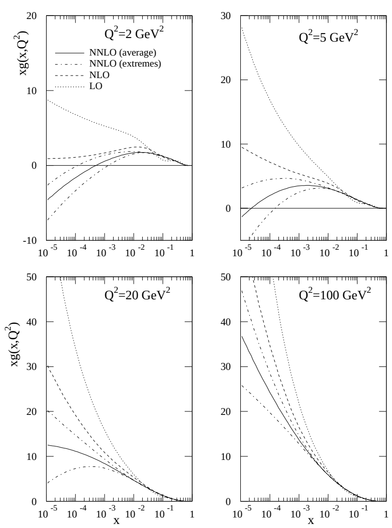
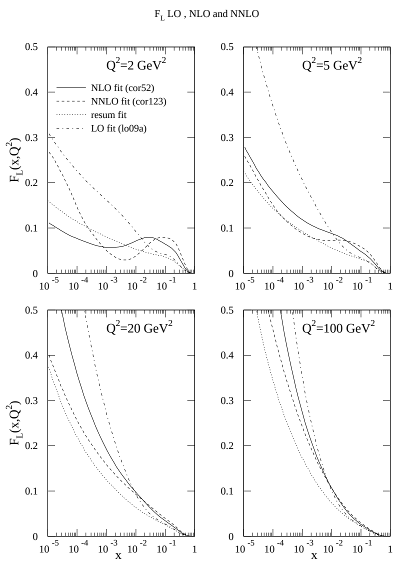


Figure 4: The evolution of the gluon obtained in the LO, NLO and NNLO global analyses. The gluons obtained using the extreme forms, A and B, of the NNLO splitting functions are shown (dot-dashed curves), together with that from the average (continuous curves).

19

when the gluon distribution may even become negative, see Fig.4. Such a prediction is not in itself a problem, since the gluon is not a physical observable, but there would be a problem if the corresponding longitudinal structure function F_L were to be negative. At NLO (and higher orders) QCD predicts that the longitudinal structure function F_L is no longer zero. It is a convolution of QCD coefficient functions with F_2 and the gluon distribution such that at small x ($x \leq 10^{-3}$) the dominant contribution comes from the glue. The NNLO prediction for F_L is not negative but it is still a rather peculiar shape, see Fig.5, where the DGLAP predictions for LO, NLO, NNLO are shown and compared to a fit involving resummation of $ln(1/x)$ terms [5]. One can see

Fig.5: Predictions for F_L from conventional DGLAP and from low x resummation

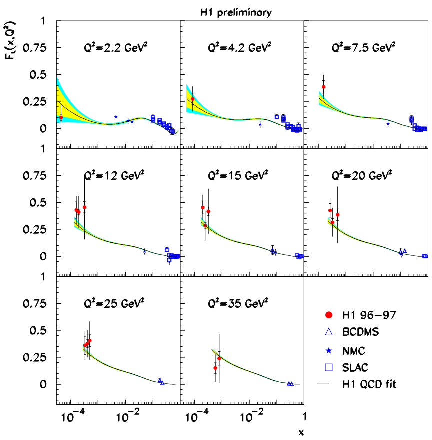


that inclusion of such terms results in a more reasonable shape for F_L.

Such predictions indicate that measurements of F_L are very important. A model independent measurement at the interesting low values of x cannot be done without varying the HERA beam energy [7], but H1 have made a measurement which depends only on the validity of extrapolation of data on the reduced cross-section, $\sigma_r = F_2 - y^2/Y^+ F_L$, from low y, where F_L is not important, to high y (see ref [1] for details of the method). The measurements, shown in Fig.6, are consistent with conventional NLO DGLAP calculations, but presently there is insufficient precision to discriminate against alternative calculations.

ZEUS has also presented data from their Beam Pipe Tracker (BPT) which enables measurements in the very low Q^2 region [9]. There has been a lot of work on trying to understand the transition from non-perturbative physics at $Q^2 \to 0$ to larger Q^2 where pQCD predictions are valid. Since very low Q^2 also means very low x, there are further possible modifications to conventional theory, when the high parton densities generated at low x result in the need for non-linear terms in the evolution equations. Such effects have been termed shadowing and may lead to saturation of the proton's parton densities [6]. As we have seen, the strong rise of the gluon density at small x is tamed when

Fig.6: H1 and fixed target F_L measurements and the H1 QCD fit



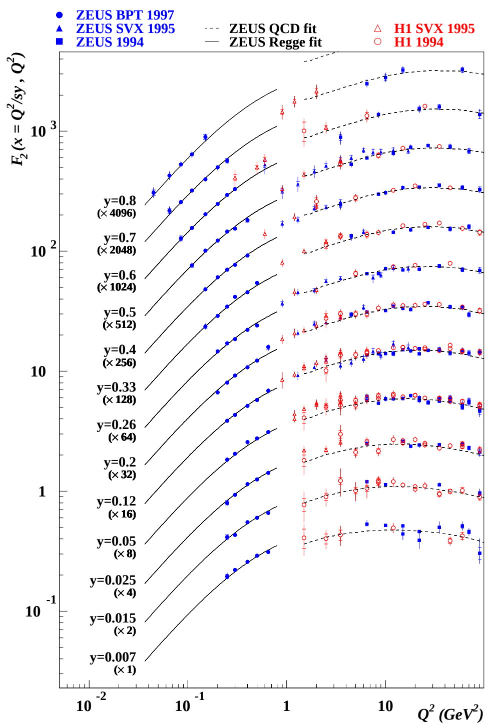
we go to lower Q^2, but the change to a valence-like shape may be a feature of our using incorrect evolution equations in the shadowing regime. Clearly precision data in this regime are very important.

In Fig.7 we present the low Q^2 data as F_2 data as a function of Q^2 in fixed y bins. The higher Q^2 data are also shown, so that one can see the shape of the transition. At low x, the centre of mass energy of the $\gamma^* p$ system is large ($W^2 = Q^2/x$) so that we are in the Regge region for this interaction. For $Q^2 < 1GeV^2$, pQCD calculations become inadequate to describe the shape of the data, so that Regge inspired models have been used. These in turn cannot describe data at larger Q^2, but there have been many attempts to extend such models to incorporate QCD effects at higher Q^2, see [6]. At low x,

$$\sigma^{\gamma^* p}(W^2, Q^2) \approx \frac{4\pi^2\alpha}{Q^2} F_2(x, Q^2) \tag{4}$$

relates F_2 to the $\gamma^* p$ cross-section. Since we know that the real photon cross-section at $Q^2 = 0$ is finite, this implies that $F_2 \rightarrow 0$ as $Q^2 \rightarrow 0$. Whereas at larger Q^2, we know that F_2 becomes flattish (baring the QCD logarithmic scaling violations). All successful models must predict such a transition, but it is now more of a challenge to fit the exact shape of the new precision data.

Fig.7: HERA F_2 versus Q^2 for fixed y bins, with QCD and Regge fits



The low Q^2 measurements have also been combined with the main data sample to produce updated plots of $dF_2/dln_{10}Q^2$ versus x and Q^2 at fixed W, see Fig.8. These plots show a turn over, which moves to lower Q^2 and higher x as W falls, and this has been interpreted as evidence for dipole models of the transition region which involve parton saturation [8]. However, at low x values, this derivative is related to the shape of the gluon distribution, and the turnover can be fitted by pQCD DGLAP fits, if we believe that the low Q^2 gluon is really valence-like. It is also true that if $dF_2/dln_{10}Q^2$ is plotted against x at fixed Q^2 there is no sign of a turnover down to the lowest Q^2 values. The signal of saturation in such a plot would be a change in the slope. Looking at Fig.9 it is clear that data of even higher precision would be necessary to establish this.

Fig.8: ZEUS $dF_2/dln_{10}Q^2$ data versus x and Q^2 at fixed W values

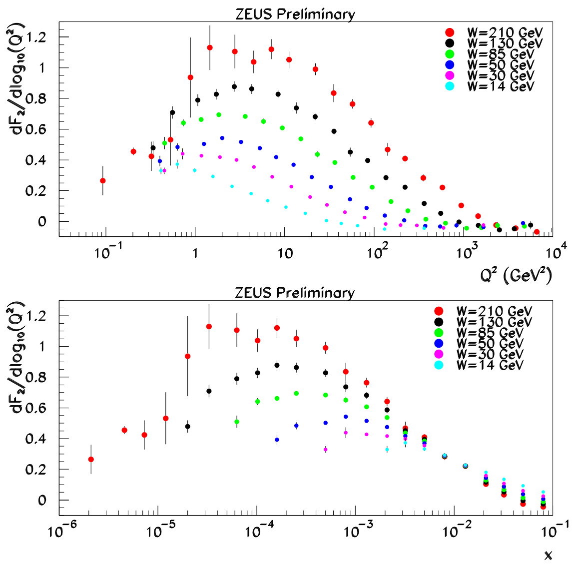


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Fig.9: ZEUS $dF_2/dln_{10}Q^2$ data versus x at fixed Q^2 values