Structure Functions: low x, high y, low Q^2

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Recent experimental results contributing to the understanding of the structure of the proton from H1 and ZEUS at HERA are presented. They include results on the proton structure function $F_2(x, Q^2)$ and QCD analysis of these data which allow the extraction the gluon density of the proton at low x. A quantity directly related to the gluon density is the charm contribution $F_2^{c\bar{c}}$ to the structure function of the proton at low x. It was measured by both collaborations and compared to the expectations of NLO QCD. With the cross section data extended to large values of the inelasticity parameter y the information on the longitudinal structure function F_L at very low x is provided.

1 Introduction

The investigation of the proton structure is mainly based on measurements of proton structure functions in Deep Inelastic Scattering (DIS). The aims of the proton structure studies are a test of the theory of strong interactions and the determination of the momentum distributions of the partons within the proton.

The ep collider at HERA has been designed to study the structure of the proton in DIS and is an important source of experimental information at low and very high four-momentum transfer squared Q^2. The increased center-of-mass energy $\sqrt{s} \approx 300 GeV$ extends the accessible kinematic region in Bjorken variable x and Q^2 by two orders of magnitude over previous fixed target experiments.

In this report the recent experimental results on proton structure of H1 and ZEUS collaborations are discussed. They include results on proton structure function F_2 at medium and low Q^2, on the gluon density, on the determination of F_L and on the charm contribution $F_2^{c\bar{c}}$ to the F_2 of the proton.

2 Proton Structure Function F_2

For Q^2 much below the Z^0 mass squared the differential cross section for neutral current deep inelastic scattering of a charged lepton on a nucleon is related to the structure functions F_2 and F_L according to

$$\frac{d^2\sigma^{l^\pm N}}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4 x} \cdot \left[(1 + (1-y)^2) F_2(x, Q^2) - y^2 F_L(x, Q^2)\right], \qquad (1)$$

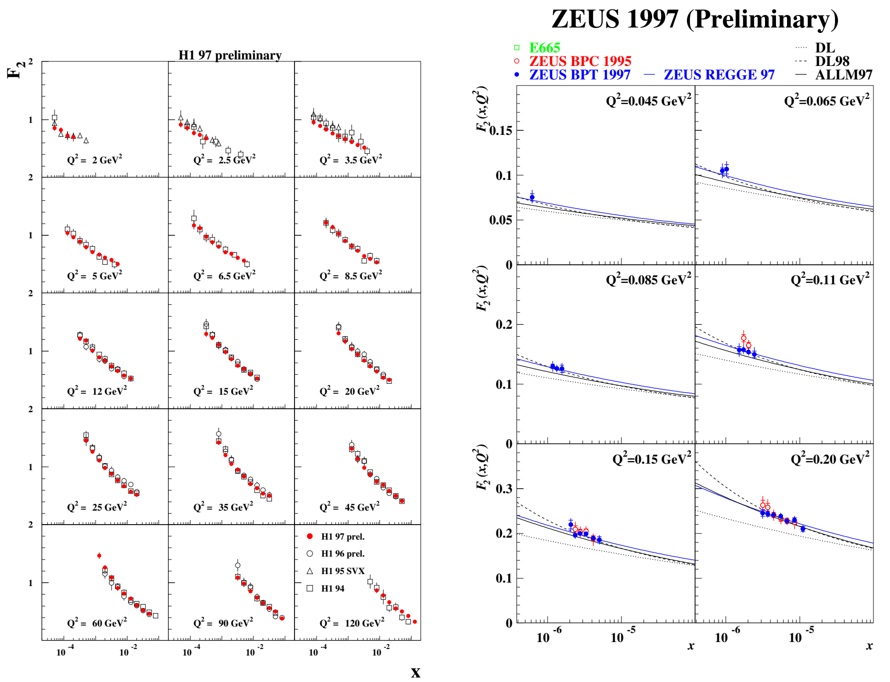

Figure 1: F_2 data from HERA at medium(left) and low(right) Q^2 as a function of x.

where $y = Q^2/xs$ denotes the inelasticity, and α is the fine structure constant. In this case the contribution of parity violating structure function xF_3 is negligible and the structure function F_2 is given purely by photon exchange.

The contribution of the longitudinal structure function F_L to the cross section is important only at large y, typically $y \geq 0.4$.

The F_2 measurements reported at HERA [1,2], covered a range in Q^2 and x corresponding to $1.5 < Q^2 < 5000$ GeV^2 and $3 \cdot 10^{-5} < x < 0.5$. Figure 1(left) shows new, preliminary H1 results [3] on F_2 from the data taken in 1997 in comparison with previous structure function results of H1. The accuracy of this new measurements surpasses all previous F_2 results obtained by H1. Higher statistics and new instrumentation allowed the systematic uncertainties to be reduced to the level of 3-4% for the largest part of the kinematic region covered.

The pronounced rise of F_2 with decreasing x can be understood as an increase of the quark-antiquark sea driven by a rapid increase of the gluon density. This rise diminishes at low Q^2 as was shown with HERA data from the shifted interaction vertex run [4,5] where F_2 measurements were extended to $Q^2 = 0.35$ GeV^2.

With a small tungsten-scintillator calorimeter (BPC) and silicon tracking detector (BPT) installed by ZEUS collaboration behind the rear Calorimeter close to the beam pipe the kinematical range was extended to extremely low $Q^2 = 0.045$ GeV^2.

The F_2 results [6], [7] measured with these detectors at fixed very low Q^2 values are shown in Figure 1(right) as function of x . In the region of overlap the results are in good agreement. The data are displayed together with parametrizations inspired by Regge theory. The best description of the F_2 data is given by the ZEUS REGGE 97 fit based on Generalized Vector Meson Dominance (GVMD). At low x and low Q^2, DL98 [8] gives good description of the data but disagrees at higher x and Q^2. DL [9] gives a good description of the shape, but the normalization is too low. The ALLM97 [10] prediction is about 10-15 % too low at lowest Q^2.

The scaling violation of Q^2 dependence of structure function F_2 is well described [11] by the NLO QCD fit over five orders of magnitude in x. The scaling violation is directly related to the gluon density and caused by gluon bremsstrahlung from quarks and quark pair production from gluons.

3 Gluon density

The essence of a QCD analysis of structure functions is the comparison of their Q^2 dependence with the prediction of pQCD [12].

Both the H1 and the ZEUS collaborations performed NLO QCD fits to their F_2 data with the goal to determine the gluon distribution at low x.

The resulting gluon distributions at medium Q^2 as determined by the HERA experiments [13,14] are rising steeply towards low x.

The qualitative features of a QCD analysis at low values of Q^2 have been investigated [5] by studying the low x behaviour of the gluon and sea quark distributions(see Fig. 2). In standard fit procedure the Q^2_{min} parameter was equal to 1 GeV^2 (left-hand plots). The error bands shown correspond to the quadratic sum of all error sources. It can be seen that even at the smallest Q^2 the quark singlet distribution is rising at small x whereas the gluon distribution has become almost flat and compatible with zero. To investigate the stability of results at low Q^2 the full QCD fit was repeated with Q^2_{min} raised to 4 GeV^2 (right-hand plots). Qualitatively the features shown by the standard fit are unchanged. Gluon evolves much faster than the sea and adopts a non-singular behaviour at low Q^2. Sea remains singular down to lowest Q^2 and drives F_2 at low x and low Q^2.

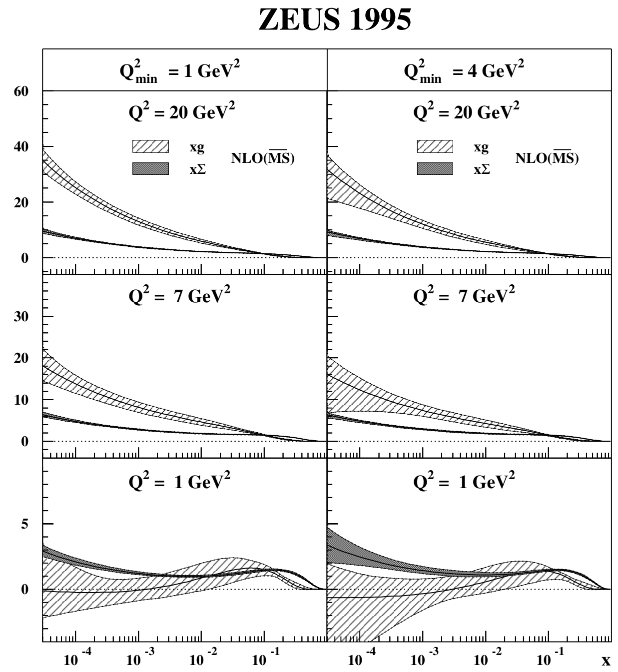

Figure 2: The momentum distributions of quark singlet and gluon as function of x at different values of Q^2 from ZEUS QCD fit.

4 The Longitudinal Proton Structure Function $F_L(x, Q^2)$

In the region of lowest x at fixed Q^2 the weights of F_2 and F_L in eq. 1 become of comparable size: F_L acts in reducing the cross-section. One can define the so called reduced cross-section:

$$\sigma_r = \frac{1}{\kappa} \cdot \frac{d^2\sigma}{dx dQ^2} = F_2 - \frac{Y_+}{y^2} \cdot F_L \tag{2}$$

with $\kappa = (2\pi\alpha^2 \cdot Y_+)/(Q^4 x)$ and $Y_+ = 1 + (1-y)^2$

The H1 collaboration has attempted [3,15] to measure the cross-section at the maximum possible y and to derive F_L exploiting eq. 2. Two methods were used to extract F_L in the y region of high sensitivity of cross section to F_L contribution. In the first method F_L was extracted by assuming that the contribution of F_2 is given by the NLO DGLAP evolution equations. A NLO QCD fit was performed on these data as was done for the gluon extraction described

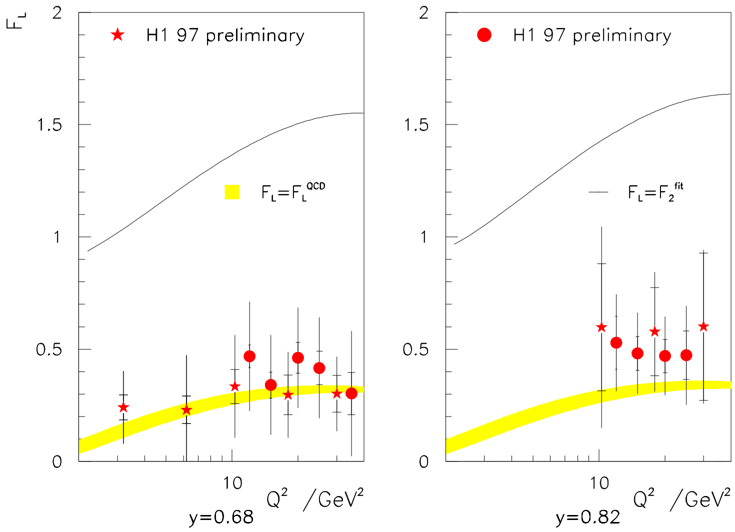

Figure 3: Determination of F_L using *subtractive* (closed points) and *derivative* (stars) methods. The quoted y values apply to the closed points. The narrow band represents the uncertainty range of F_L calculated from NLO QCD fit to H1, NMC and BCDMS data.

above. However, in this case only data for $y < 0.35$ were included where F_L contribution is negligible. F_L determination in this case comes directly from eq. 2 as subtraction of the measured cross-section at high y from the QCD extrapolation of F_2 into high y region.

In the second method the measurement of derivative $\partial\sigma_r/\partial log\ y$ is used to determine the longitudinal structure function. This derivative is defined as:

$$\frac{\partial\sigma_r}{\partial logy} = -\frac{\partial F_2}{\partial logx} - F_L \cdot 2y^2 \cdot \frac{2-y}{Y_+^2} + \frac{\partial F_L}{\partial logx} \cdot \frac{y^2}{Y_+} \tag{3}$$

For $y \to 1$ the cross section derivative tends to the limit $\partial F_2/\partial logx - 2 \cdot F_L$ with a negligible contribution from the derivative of F_L. In the analysis the assumption has been made that the derivative $\partial F_2/\partial log\ y$ is a linear function of $log\ y$ up to large y. For all Q^2 straight line fits were made to the derivative data for $y < 0.2$ which describe the data very well. The extrapolation of a straight line was taken to represent the contribution of F_2 at high y.

The extracted values of F_L are shown in Fig. 3 for two y bins at $y = 0.68$ and $y = 0.82$. Good agreement is seen with the F_L values obtained in two methods. Second method allows to extend F_L measurements down to $Q^2 = 3$ GeV^2.

The calculation of F_L in NLO QCD is given in Fig. 3 by a shaded band. The data points are in agreement with QCD expectation, however, they are slightly higher than expected at $y = 0.82$. The experimental uncertainty of this calculation is about 6%.

A direct measurement of F_L at HERA which is free of any input assumptions is foreseen by measuring the ep inclusive cross section at different proton beam energies.

5 Charm Contribution $F_2^{c\bar{c}}(x, Q^2)$ to the Proton Structure Function

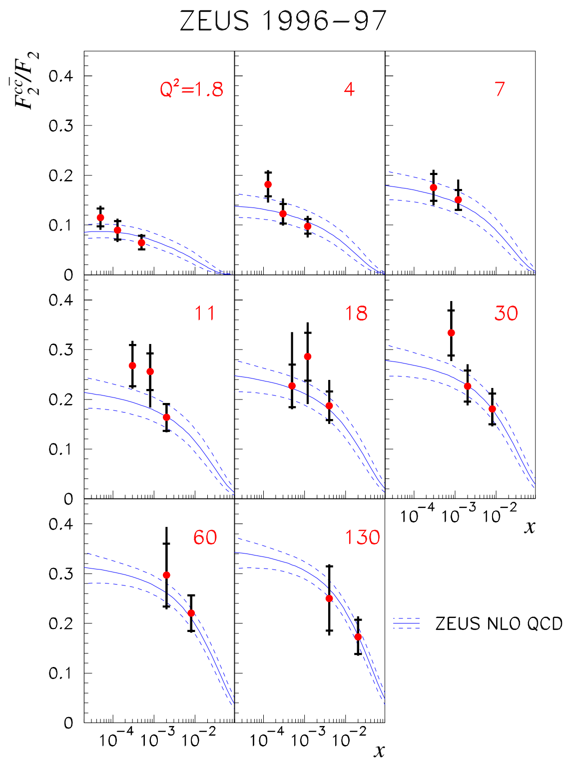

Figure 4: The ratio of $F_2^{c\bar{c}}$ over the proton structure function F_2 as a function of x. The band represents the NLO calculations with different charm masses from 1.3 to 1.5 GeV.

The H1 and ZEUS experiments have published results on open charm production in deep inelastic scattering [16,17] based on the 1994 data. Recently the ZEUS collaboration presented an update [18] of their results using the 1996-97 data.

The tagging of charm events is performed by reconstructing D^{*+} [a] mesons via their decays into $D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+)\pi_s^+$ and $D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+\pi^+\pi^-)\pi_s^+$. For the D^{*+} analysis the mass difference $\Delta m = m(D^{*+}) - m(D^0)$, being very close to the π mass, leads to a good resolution and signal to background ratio. Cuts on the transverse momenta and polar angle of the particles in the final state guarantee a reliable measurement and suppress combinatorial background.

The structure function $F_2^{c\bar{c}}(x,Q^2)$ shows a strong rise with decreasing x at constant values of Q^2. To quantify this rise the ratio of $F_2^{c\bar{c}}$ over the proton structure function F_2 as a function of x is shown in figure 4. To determine the ratio for the data points the value of F_2 was taken from NLO QCD fit at the same Q^2, x for which $F_2^{c\bar{c}}$ is quoted. The error on F_2 was neglected. The charm contribution to F_2 is rising steeply with decreasing x. In the measured x region, $F_2^{c\bar{c}}$ accounts for about 10 % of F_2 at low Q^2 and about 30% of F_2 for $Q^2 > 11\ GeV^2$ at the lowest x measured.

In Figure 4 the data are also compared with NLO QCD calculations [19] shown as a band, where the upper and lower limit corresponds to a charm quark mass of 1.3 and 1.5 GeV, respectively. The measured rise of $F_2^{c\bar{c}}(x,Q^2)$ from the high to the low x region is reasonably described in the three flavour number scheme with charm production via boson gluon fusion.

6 Conclusions

The analysis of the HERA data on structure functions F_2 in the framework of pQCD using NLO DGLAP evolution led to a determination of the gluon distribution at low x. The gluon density is rising steeply towards low x, as one could expect from the strong rise of F_2 with decreasing x. Around the lower Q^2 limit of the QCD fit it was found that the quark-antiquark sea distribution is still rising at small x, whereas the gluon distribution is strongly suppressed.

H1 made an attempt to derive F_L from the measured cross section at high y. The obtained F_L values are in agreement with QCD expectation.

H1 and ZEUS measured the charm contribution $F_2^{c\bar{c}}$ to the F_2 of the proton. This contribution is found to be $\approx 25\%$ and the results are reasonably described in the three flavour number scheme with charm production via boson gluon fusion.

[a] Charge conjugates are always implied.

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