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QCD STUDIES AT HERA

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Abstract

I present a small selection of the many QCD studies that have been performed at HERA. I concentrate on results that have been made available in the past year. Results are presented on the QCD description of the parton density functions, determinations of α_S, jets and heavy flavour production. Where possible comparisons are made with next to leading order (NLO) QCD predictions. The neutral and charged current cross sections at very high Q^2 are also discussed.

1 Introduction

It is fair to say that most of the HERA I programme has had something to do with QCD. Such a talk could, and maybe should, cover about 50% of HERA physics. As this is impossible in the time available I will concentrate on a few selected topics. With the data taken up to the end of 2000, each of the collider experiments H1 and ZEUS have over 120 pb^{-1} of data available for analysis. Considerable progress on reducing systematic uncertainties has also been made, leading to a number of results that have accuracies at the few percent level. At the same time next to leading order (NLO) QCD calculations are available for many of the processes considered. In some cases these predictions also have the same level of accuracy as the data. Given the large corrections between leading order (LO) and NLO calculations it is also clear that NNLO is needed in many places. Some first calculations have recently been released and the experimental groups are eagerly waiting for more. For a number of the measurements, particularly of α_S, the dominant systematic uncertainty is due to the (somewhat) arbitrary definition of the uncertainty on the factorisation and renormalisation scales. More theoretical input on reasonable values to take for these uncertainties would be welcome.

In this talk I will discuss: Parton Density Functions (PDFs); the determination of α_S; three jet production; dijets in photoproduction; measurements at the highest values of Q^2 and heavy flavour production.

Interactions at HERA are characterised by a number of interdependent kinematic variables:

- s, the centre-of-mass energy squared,
- $Q^2 = -q^2$, the negative four-momentum transfer squared,
- x, the Bjorken-x variable,
- y the inelasticity, and
- W the photon-proton centre-of-mass energy.

The first 4 variables are related by the equation:

$$Q^2 = sxy \tag{1}$$

The centre-of-mass energy was 300 GeV until 1997. In 1998 the proton beam energy was increased from 820 GeV to 920 GeV, resulting in a centre-of-mass energy of 318 GeV.

2 Parton Density Functions

The determination of the parton density functions (PDFs) was, and still is, one of the main goals of the HERA physics programme. The QCD factorisation theorem allows one to separate the cross-section into a short-range part that is described by QCD and a long-range part. One can use the so-called DGLAP$^{1)}$ equations to evolve the long-range part from a given value to Q^2 to higher values. The experimental data have to constrain the PDFs at a starting value Q_0^2.

The neutral current cross section for $e^{\pm}p$ scattering can be written in the form:

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left(Y_+F_2 - y^2F_L \mp Y_-xF_3\right) \tag{2}$$

where $Y_{\pm} = (1 \pm (1-y)^2)$. At small y and for $Q^2 \ll m_Z^2$ the cross section is dominated by F_2. An example of the determination of the structure function F_2 by ZEUS$^{2)}$ is shown in fig. 1. Many systematic effects have to be studied in such measurements; therefore the data shown here are only those taken in 1996 and 1997. In the kinematic range shown the errors are dominated by systematics. These are now at the level of about 2% over much of the kinematic range. The figure also includes some fixed target measurements. In the regions where the kinematic range overlaps, good agreement with previous measurements is seen. The HERA data extends the measurements to much lower values of x and the rapid rise of the structure function there is clearly visible and well measured.

The complete set of ZEUS and H1 deep inelastic scattering (DIS) data cover a very wide range in x and Q^2. This is illustrated in fig. 2. At present it is still necessary to also include some fixed target data in order to fix the PDFs at large x. With the full HERA I dataset this may no longer be necessary. Both ZEUS and H1 fit their data in a similar way. However, some of the details are different, which can affect the extracted parton densities. As a first step the PDFs have to be parametrised. The form used is:

$$f = p_1 x^{p_2}(1-x)^{p_3}\left(1 + p_4\sqrt{x} + p_5 x\right) \tag{3}$$

where p_1, p_2, p_3, p_4 and p_5 are free parameters. Both collaborations use the NLO DGLAP equations. The differences between the inputs are summarised in Table 1.

Examples of the fit results are shown in fig. 3. As can be seen the ZEUS and H1 data and their fits agree over a very wide range in the kinematic plane. There are some small differences at small x, which I will briefly discuss below. At high Q^2 the differences are due to the limited statistics. In a new development, the fits

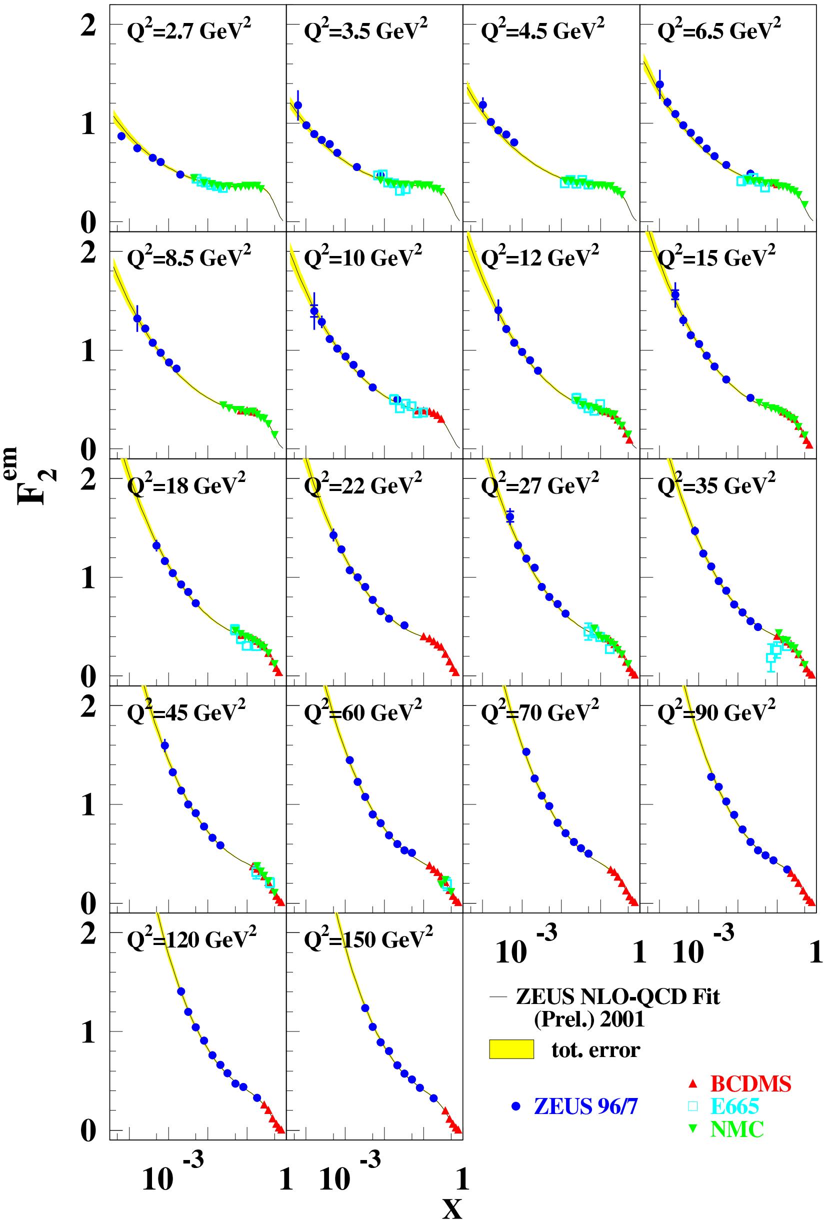

Figure 1: *ZEUS Measurements of the structure function* F_2

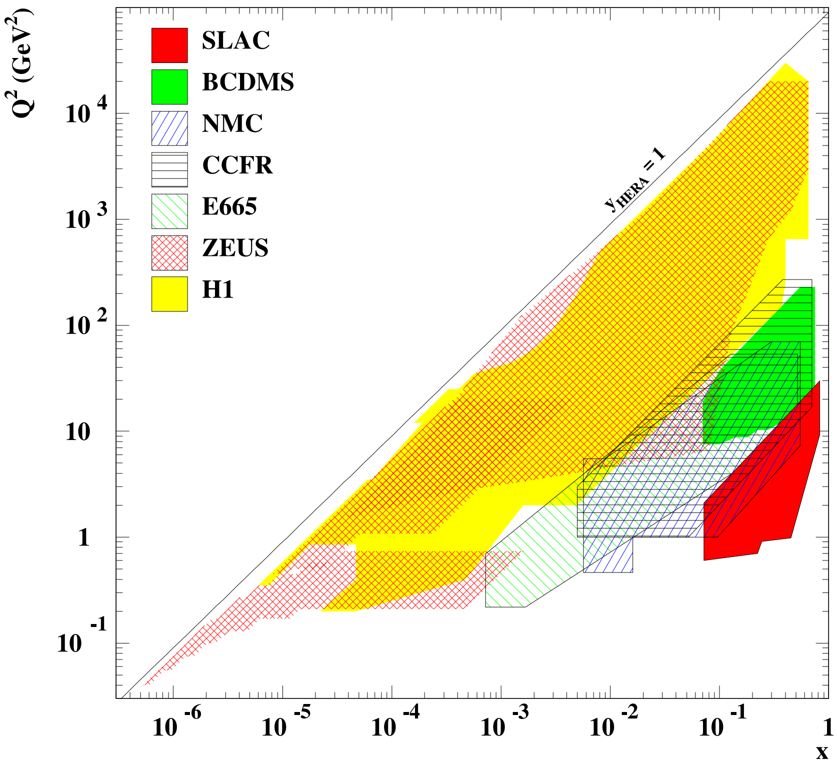

Figure 2: *The kinematic range covered by fixed target and the HERA experiments.*

Table 1: *Differences between H1 and ZEUS fits of PDFs.*

	ZEUS[2)]	H1[3)]
Fixed target data	BCDMS, E665, NMC	BCDMS
Q_0^2	7 GeV^2	4 GeV^2
p_4	Set to zero plus other constraints	Zero for gluon
Heavy quarks	RT variable flavour number scheme	Fixed flavour number scheme

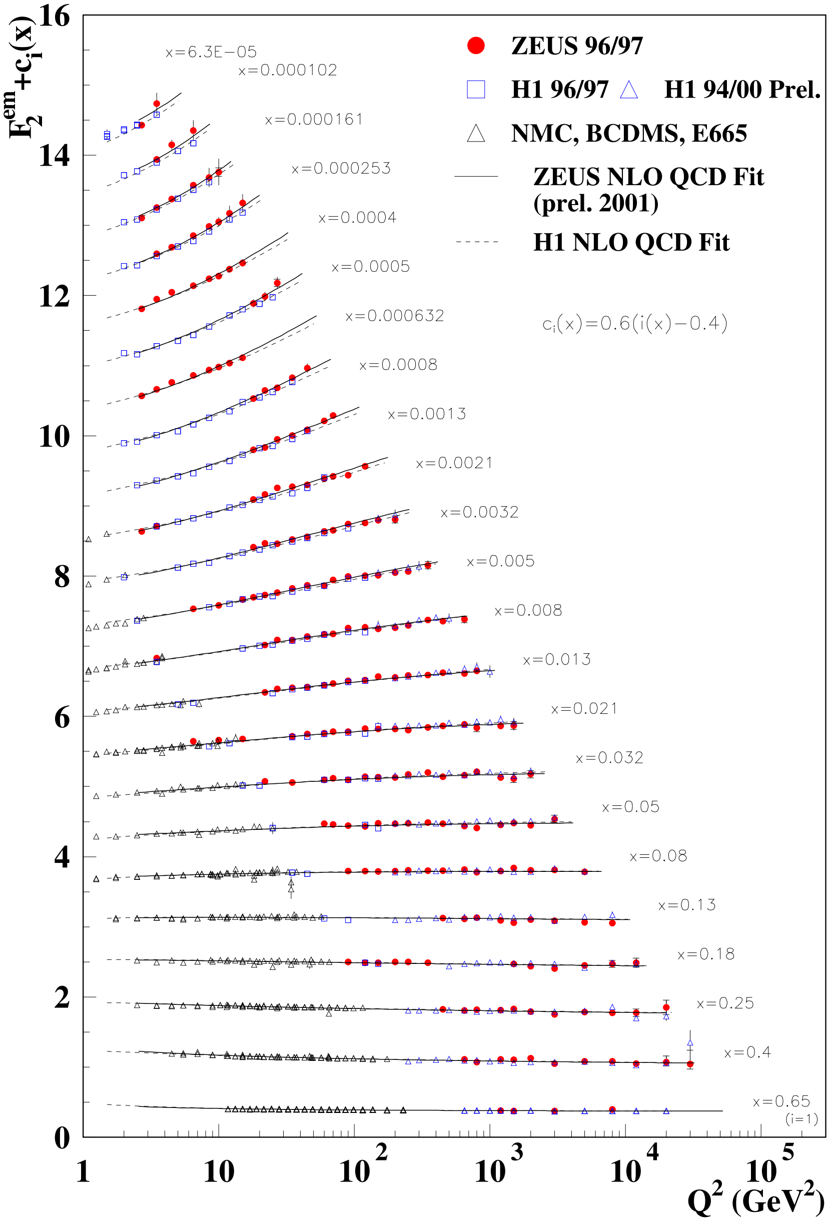

Figure 3: *Results of NLO QCD fits to HERA data.*

now also calculate errors on the PDFs. The correlations between the experimental errors are taken into account. The gluon distribution that is extracted by the two collaborations agrees in general well, but there are again some differences. This can be seen in fig. 4. The evolution of the gluon density as a function of Q^2 is clearly visible. The differences between the fits at low x and around $x \approx 0.05$ are being discussed by the collaborations and are probably due to a combination of the heavy flavour scheme and the parameterisation used. If one looks at the right-hand figure, the strong correlation of the error on $xg(x)$ with α_S is seen. One also sees though that for high Q^2 and certain ranges of x the effect is smaller.

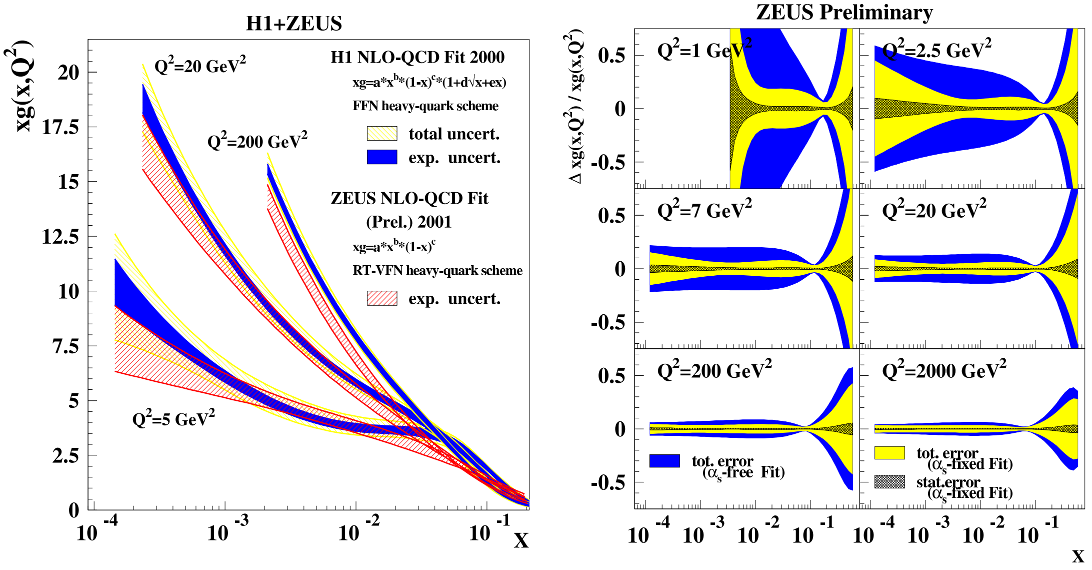

Figure 4: *The left-hand plot show the gluon densities from ZEUS and H1 at* $Q^2 = 20\,\mathrm{GeV}^2$*. The right-hand plot shows the ZEUS error on* $xg(x)$ *for different* Q^2 *values as a function of* x*.*

The reduced cross section is defined as:

$$\tilde{\sigma} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \frac{d^2\sigma}{dx\, dQ^2} \tag{4}$$

and can be written as:

$$\tilde{\sigma} = F_2 - \frac{y^2}{Y_+} F_L \tag{5}$$

where F_L is the longitudinal structure function and xF_3 has been neglected. The best way to measure F_L is to take data at significantly different centre-of-mass energies. As the centre-of-mass energy of HERA has not changed substantially the collaborations have tried other methods. ZEUS used events with significant initial state radiation.[4] H1 has developed a new method.[5] They measure F_2 in a region where the F_L contribution is small and use the DGLAP equations to extrapolate this measurement to regions where the contribution of F_L to the reduced cross section is expected to be significant (high y). By comparing the reduced cross section to the extrapolation they can extract F_L (see fig. 5). This method works best at high Q^2. At lower Q^2 they look at $\partial\sigma/\partial \ln y$. As F_L depends directly on the gluon density, the agreement between F_L and the QCD fit for both methods confirms the validity of the fit. The results are shown in fig. 6.

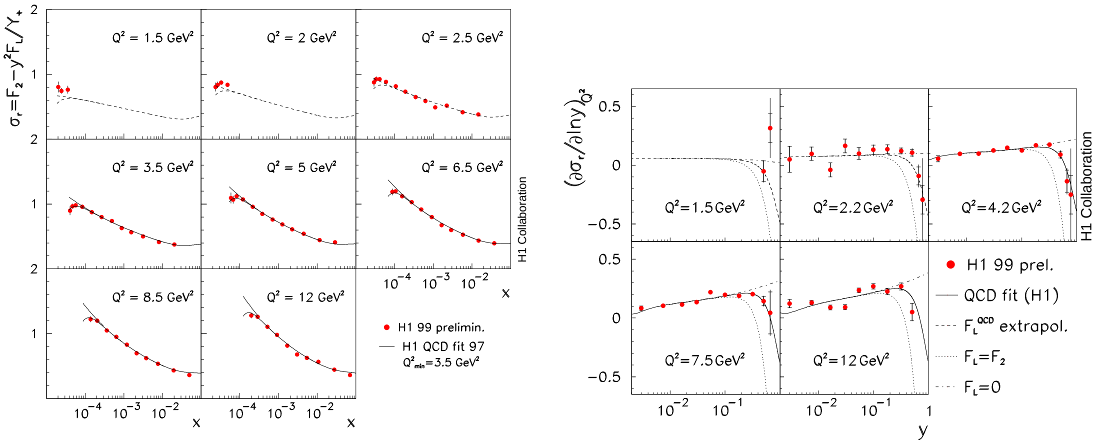

Figure 5: *Two methods used by H1 to extract* F_L.

3 Determinations of α_S

A number of new methods have been developed that allow a precise determination of α_S. Most of them use jets reconstructed in either the laboratory or the Breit frame.

Jet are usually found using clustering algorithms. H1 recently investigated how low they could set the cut that defines a jet and still find agreement with perturbative QCD.[6] They found that even with a cut at $y_{\text{cut}} \approx 0.001$, where about 30% of events in DIS could be classified as having two or more jets, good agreement is still seen.

Many of the jet studies are made in the Breit frame. In this frame jets with a significant transverse energy are produced via the QCD-Compton or the boson-gluon-fusion process in LO. Their production rate depends on α_S, but the data is in general more sensitive to $\alpha_S \cdot xg(x)$.

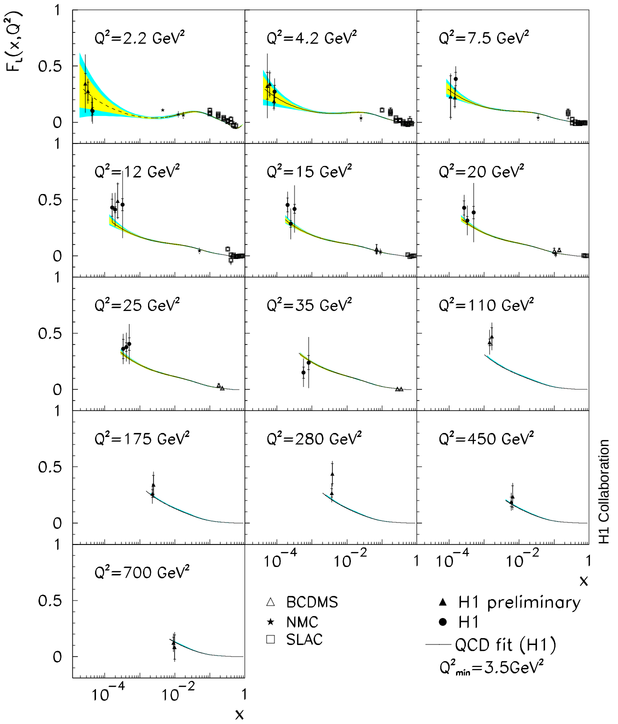

Figure 6: *F_L as measured by H1 (low x) and lepton-nucleon fixed-target experiments (high x).*

The single jet cross sections measured by ZEUS[7)] as a function of Q^2 and E_T are shown in fig. 7. Good agreement is seen as a function of both variables over a very wide range. The main theoretical error comes from the uncertainty on the renormalisation and factorisation scales. As indicated in the introduction, this is a common problem for many such jet analyses. α_S has been extracted from these measurements. H1 has also extracted α_S from the inclusive jet cross section.[8)] By studying the size of the correction factors from the observed jets to the parton level it appears that such methods are reliable for $Q^2 > 150\,\mathrm{GeV}^2$ or $E_T > 15$ GeV. The value of α_S as a function of E_T is shown in fig. 8. The running of α_S is clearly seen. Correcting each value to m_Z the measurements are all consistent. The theory error is at the level of about 5%.

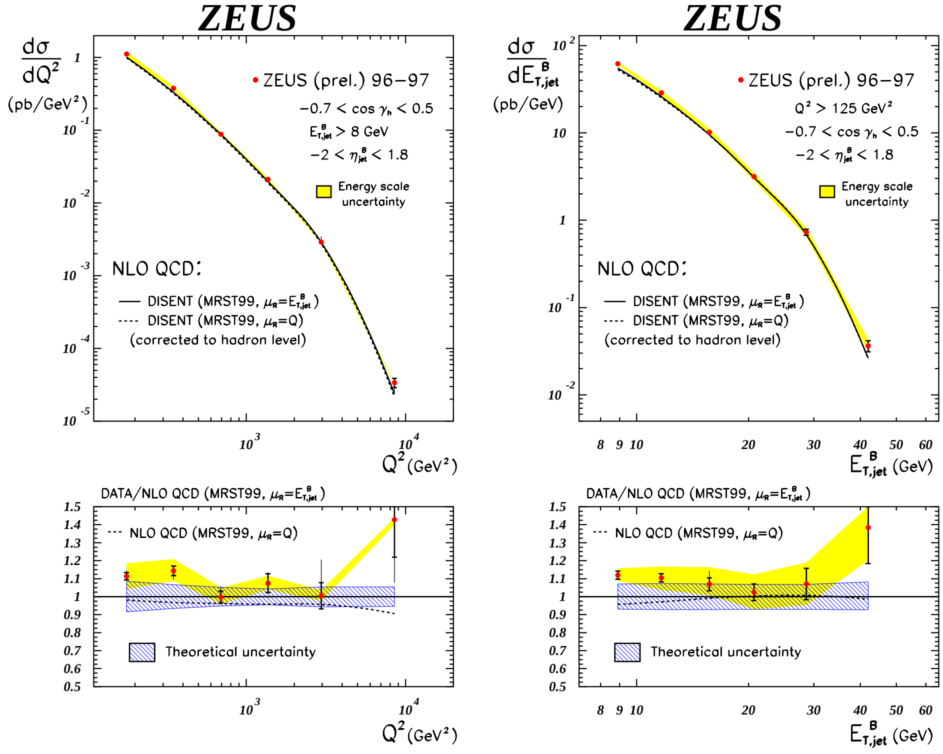

Figure 7: *Jet cross sections as a function of* Q^2 *and* E_T.

The dijet cross sections can also be used to determine α_S. H1 studied the cross section as a function of many kinematic variables and for different jet algorithms.[8)] They find very good agreement between the different methods as can be seen in fig. 9.

ZEUS has compared the cross sections for single and dijet production.[9)]

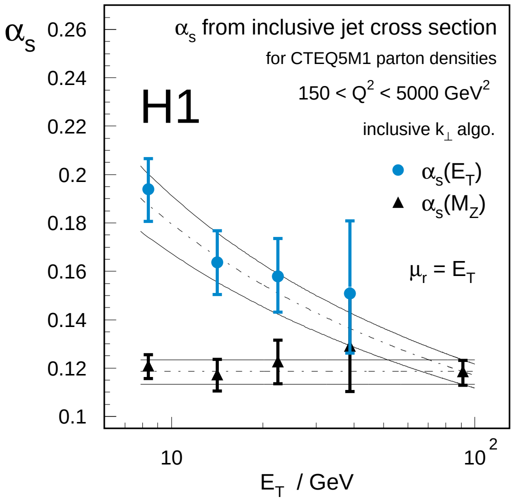

Figure 8: *α_S measured by H1 using the inclusive jet cross section as a function of E_T.*

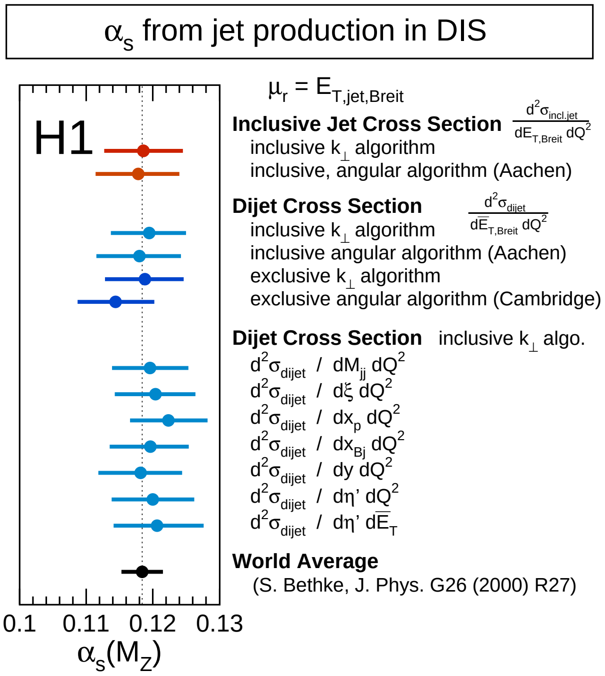

Figure 9: *Comparison of α_S results from fits to different double-differential jet distributions.*

The cross sections and their ratio are shown in fig. 10. The ratio of the cross sections

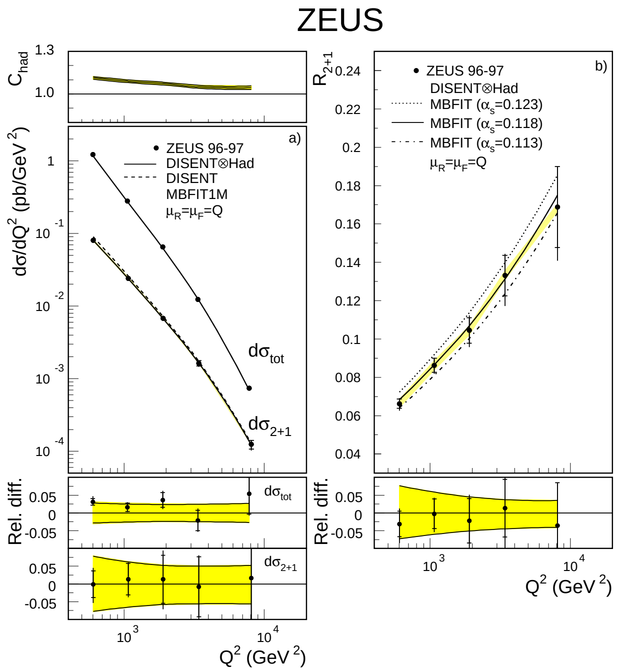

Figure 10: *The single and dijet cross sections as a function of Q^2. The size of the hadron to parton correction in the case of dijets is indicated at the top of the left-hand figure. The right-hand figure shows the ratio of the dijet to the single jet cross section and compares it with the predictions for different values of α_S.*

is proportional to α_S. This can be seen in the right-hand figure, where the ratio is compared to curves for different values of α_S. H1 has studied the dependence of the dijet cross section on the jet algorithm at high Q^2. By comparing the LO and NLO predictions, it is clear that NLO is needed. They extract α_S in the range $150 \leq Q^2 \leq 5000\,\mathrm{GeV}^2$ so that the correction factors from LO to NLO are not too large.

Jet substructure can even be used to extract α_S. ZEUS look for jet-like components inside a jet.[10)] The jets are reconstructed in the lab system, in order to keep the large single-jet sample. Once again a region has to be found where the parton to hadron corrections are relatively small, defined in this analysis to be $< 15\%$. The number of subjets is then measured in the data and compared to NLO predictions. The measurements are sensitive to α_S, as can be seen in fig. 11.

The various HERA α_S measurements are summarised in fig. 12. A number of the measurements are at the same level of statistical accuracy as the world

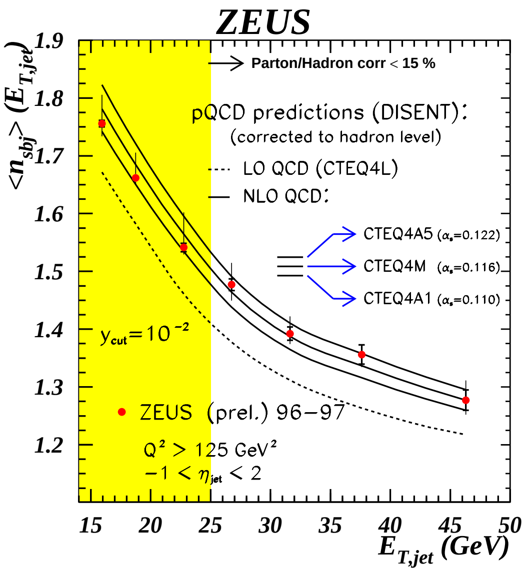

Figure 11: *Number of subjets as a function of* $E_{T,\mathrm{jet}}$.

average. However, their influence on the average depends on being able to reduce the theoretical uncertainties, particularly those associated with the renormalisation and factorisation scales.

4 Three Jet Production

Moving up a further power of α_S, to α_S^3, H1 has looked at three jet production.$^{11)}$ The cross section is proportional to α_S^2 at lowest order and has been compared with NLO calculations (order α_S^3) as a function of Q^2. The results are shown in fig. 13. The NLO contributions are clearly necessary, particularly at low Q^2. With the contributions included, good agreement between data and theory is seen over the whole range.

5 Dijets in Photoproduction

Studies have been made by both H1$^{12)}$ and ZEUS$^{13)}$ of dijets in photoproduction events. Leading order calculations did not describe the rates particularly well. The cross section has been measured as a function of E_T, x_γ and x_p, where x_γ (x_p) is the fraction of the photon (proton) momentum that participates in the hard scattering. The H1 results are shown in fig. 14. The need for the NLO calculations is clear, particularly at high x_γ.

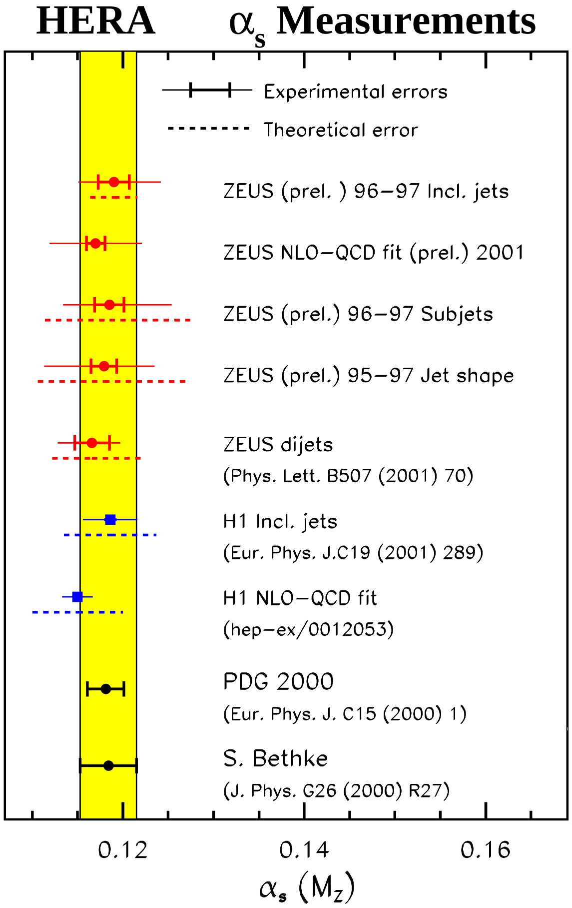

Figure 12: *Different determinations of α_S at HERA.*

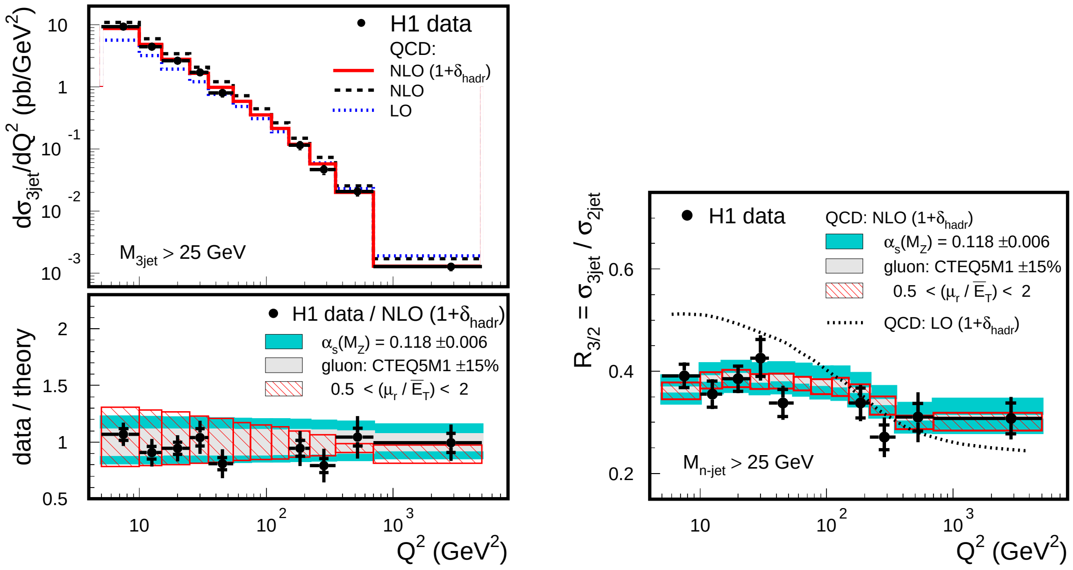

Figure 13: *The three jet cross section as a function of Q^2. The right-hand plot shows the ratio of three-jet to two-jet production.*

6 The Highest Q^2 Range

At the highest values of Q^2, both H1 and ZEUS saw an excess in the cross section with the data collected up to 1995. Newer data did not support this excess. The cross sections for both neutral and charged current scattering now include the data taken up to the end of 2000.14) In both neutral and charged current scattering very good agreement with the standard model predictions using the CTEQ5 description of the PDFs is seen (fig. 15).

7 Heavy Quark Production

Charm production at HERA has been studied for quite a while and there are already a large number of publications. Data on bottom production has only become available more recently with the steady increase in HERA luminosity.

As the dominant heavy flavour production mechanism is boson-gluon fusion, measurements of charm production give a direct handle on the gluon content of the proton. The results are consistent with those obtained from the fits described in Section 2, but are not yet at the same level of statistical precision.

For both charm and bottom quark production, the mass of the quark provides the hard scale necessary for perturbative QCD calculations. One would

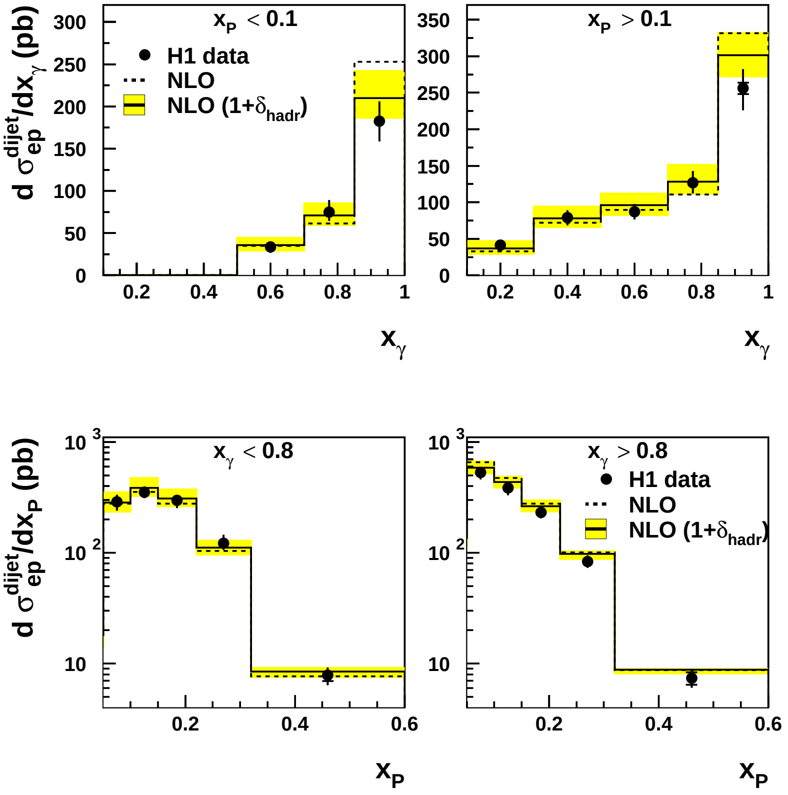

Figure 14: *Dijet cross sections in photoproduction.*

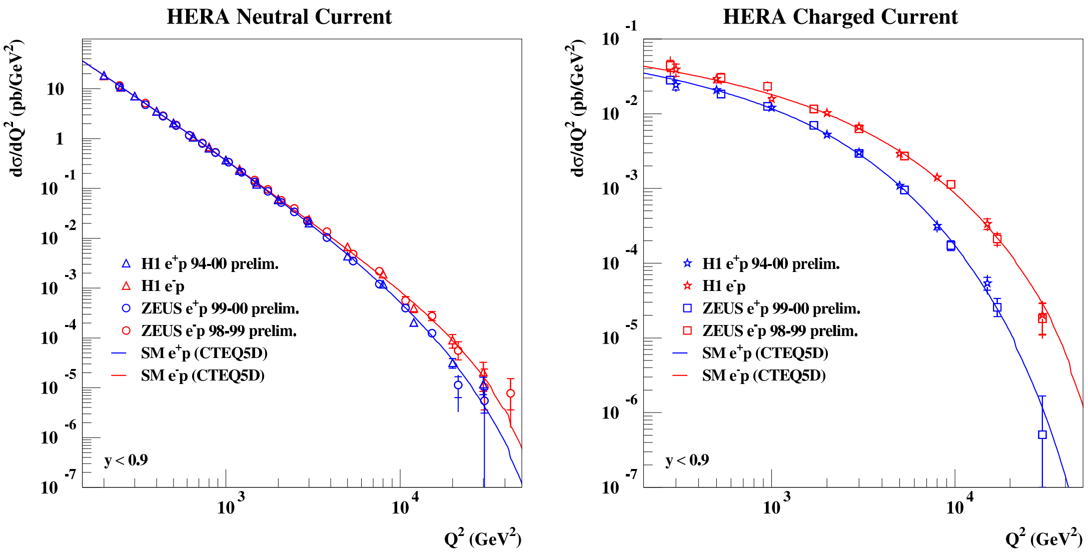

Figure 15: *Neutral and charged current cross sections as measured by H1 and ZEUS.*

also expect that the calculations for b quark production should be more reliable than those for c quarks. H1 measured the b quark production cross section for the first time a couple of years ago and found it to be significantly higher than the expectation.$^{15)}$ They have now extended their analysis to DIS.$^{16)}$ An excess at about the same level is seen. They use a combination of a muon tag and impact parameter measurements and achieve a signal to background ratio of about 1:1. In fig. 16 one can see a clear b signal at high values of impact parameter and transverse momentum. The measured cross sections are shown in fig. 17. The recent ZEUS measurements$^{17)}$ are consistent with those from H1. ZEUS has also looked at Monte Carlos that include b excitation. While the predicted cross-sections are higher, they still lie below the data.

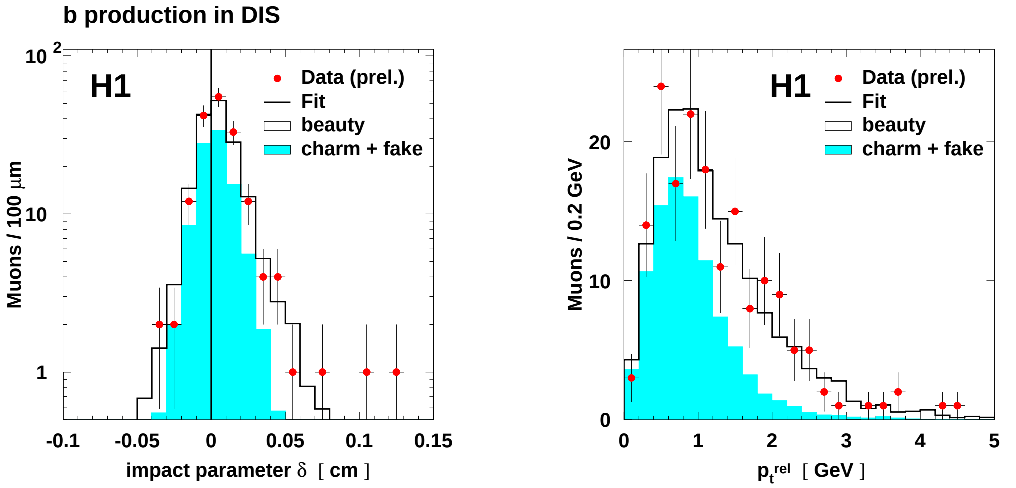

Figure 16: *b quark signals as seen by H1 in DIS.*

8 Conclusions

The HERA data provide many precise tests of perturbative QCD. NLO predictions are necessary for many processes and more and more such predictions are now available. In general they show an impressive level of agreement over a huge kinematic range. However, in order to make further progress more input is needed on what are appropriate uncertainties to use for the renormalisation and factorisation scales. Some NNLO calculations have recently been completed and more would be very welcome.

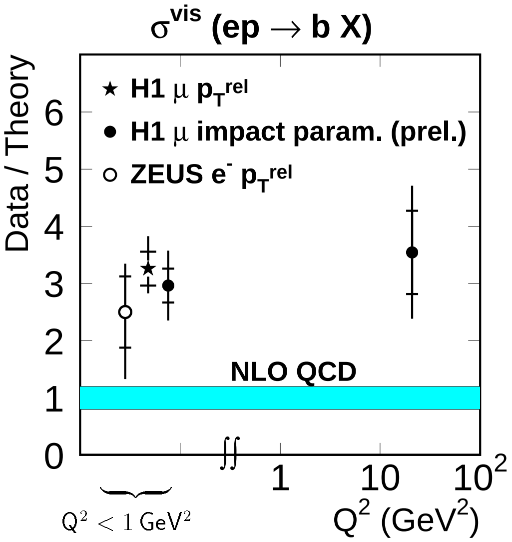

Figure 17: *H1 and ZEUS b quark production cross sections as a function of* Q^2.

A number of accurate measurements of α_S have been made by both experiments that agree well with each other and with the world average. Many different aspects of jet production have been measured. If one restricts the kinematic range to regions where the NLO to LO corrections factors are not too large, or to regions where the hadron to parton corrections are small, very good agreement with the NLO predictions are seen.

While one would naively expect heavy flavour production to agree well with perturbative QCD calculations, this is not the case. Charm cross sections are in poor agreement with expectations, particularly in the forward direction; bottom production is about a factor of two to three higher than the predictions, both in photoproduction and DIS. Statistics are still very limited here and the results will benefit from the HERA II luminosity upgrade and the use of microvertex detectors, which have now been installed in both experiments. We are looking forward to the 1 fb^{-1} that should be provided for each experiment by 2006, and to the new possibilities offered by the longitudinal beam polarisation.

9 Acknowledgements

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