

# Jet cross sections and $\alpha_s$ in deep inelastic scattering and photoproduction at HERA

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Recent ZEUS measurements of inclusive-jet and dijet cross sections in neutral current deep inelastic  $ep$  scattering at HERA are presented. The data correspond to more than a two-fold increase in statistics compared to previous studies. The cross sections are measured in the Breit frame, for boson virtualities of  $Q^2 > 125 \text{ GeV}^2$ , as functions of various kinematic and jet observables. The data are found to be well described by NLO QCD and have the potential to constrain the gluon density in the proton. Two new extractions of the strong coupling,  $\alpha_s$ , are also presented: the first is determined from the inclusive-jet neutral current DIS measurement presented here, while the second is from a re-analysis of previously published data on inclusive jet photoproduction. Both measurements are of competitive precision and in agreement with the world average.

## 1 Introduction

Jet production in  $ep$  collisions at HERA provides an important testing ground for perturbative Quantum Chromodynamics (QCD), as well as giving direct access to the strong coupling constant,  $\alpha_s$ . Furthermore, HERA jet measurements are sensitive to the parton distribution functions (PDFs) of the proton.

At HERA, there are broadly two kinematic regimes: Deep Inelastic Scattering (DIS), where the virtuality of the exchanged boson is large ( $Q^2 \gg 1 \text{ GeV}^2$ ), and photoproduction ( $\gamma p$ ), which proceeds via the exchange of a quasi-real photon ( $Q^2 \approx 0$ ). In this contribution, recent measurements of inclusive-jet [2] and dijet [3] production in neutral current (NC) DIS are presented. The data used in these measurements correspond to more than a two-fold increase in statistics compared to previous studies. The measurements are sensitive to the parton content of the proton, especially the gluon density at high momentum fractions, and may serve as valuable inputs to future QCD fits for the PDFs. In addition to the jet cross section measurements, two new determinations of  $\alpha_s$  are presented: the first is extracted from the NC DIS inclusive-jet measurement [2] presented here, and the second is derived from a re-analysis [4] of previously published data [5] on inclusive jets in  $\gamma p$ .

## 2 Data selection and correction

The data used for the jet cross section measurements were collected with the ZEUS detector at HERA. For the inclusive-jet analysis, the data are from the 05 – 06 running period and correspond to  $188 \text{ pb}^{-1}$ . For the dijet case, the data are from 98 – 00 and 04 – 05 running, combined, corresponding to a total of  $209 \text{ pb}^{-1}$ . During these times, HERA operated with protons of energy  $E_p = 320 \text{ GeV}$  and electrons of energy  $E_e = 27.5 \text{ GeV}$ .

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\*On behalf of the ZEUS Collaboration [1].

The phase space of the measurements is restricted to the region  $Q^2 > 125 \text{ GeV}^2$  and  $-0.65 < \cos(\gamma_{had}) < 0.65$ , where  $\gamma_{had}$  is the polar angle of the hadronic system<sup>a</sup>. For the dijet case, a further requirement of  $Q^2 < 5000 \text{ GeV}^2$  was imposed: this restricts the data to a region where the contribution from  $Z^0$  exchange is negligible.

Jets were reconstructed in the Breit<sup>b</sup> frame [6], using the longitudinally invariant  $k_T$ -clustering algorithm [7] in the inclusive mode [8], and were required to lie in the pseudo-rapidity range  $-2 < \eta_{Breit} < 1.5$ . For the inclusive-jet analysis, events were selected if they contained at least one jet with  $E_{T,Breit} > 8 \text{ GeV}$ . For the dijet case, at least two jets were required with  $E_{T,Breit}^{1,2} > 12, 8 \text{ GeV}$ : the asymmetric cut is made in order to avoid infra-red sensitive regions where the next-to-leading order (NLO) QCD programs are not reliable.

The data were corrected for detector efficiency and acceptance effects using the ARIADNE [9] and LEPTO [10] Monte Carlo (MC) models. The MC programs were also used to correct the measured cross sections for QED radiative effects and the running of  $\alpha_{em}$ .

The typical statistical precision on the final cross section measurements is  $\sim 1 - 5\%$ . The dominant experimental systematic comes from the uncertainty on the jet energy scale (known to  $\pm 3\%$  for  $E_{T,Lab} < 10 \text{ GeV}$  and  $\pm 1\%$  for higher jet-transverse-energies), leading to effects on the cross sections of typically  $5 - 10\%$ . The second-most-important is the model uncertainty arising from using ARIADNE versus LEPTO to correct for detector effects (this leads to uncertainties of typically  $\lesssim 3\%$  on the cross sections).

### 3 NLO QCD calculations

The NLO QCD ( $\mathcal{O}(\alpha_s^2)$ ) calculations used to compare with the data were obtained using the program DISENT [11]. The factorisation scale was taken to be  $\mu_F = Q$  and the renormalisation scale<sup>c</sup> was taken to be  $\mu_R = E_{T,Breit}$  (of each jet) for the inclusive-jet measurement and  $\mu_R = (Q^2 + \overline{E}_{T,Breit}^2)^{1/2}$  for the dijet case, where  $\overline{E}_{T,Breit}$  is the average transverse energy of the two jets. The strong coupling was calculated at two loops using  $\Lambda_{\overline{MS}}^{(5)} = 226 \text{ MeV}$ , corresponding to  $\alpha_s(M_Z) = 0.118$ . The calculations were performed using the ZEUS-S [12] proton PDF for the inclusive-jet and CTEQ6 [13] for the dijet measurement. In order to compare directly with the data, the NLO QCD predictions were corrected for hadronisation using the average of the corrections obtained from ARIADNE and LEPTO. The inclusive-jet predictions were also corrected for  $Z^0$  exchange.

Several sources of theoretical uncertainty were considered: uncertainties due to neglected terms beyond NLO in the perturbative expansion; uncertainties from the input proton PDFs; uncertainties from  $\alpha_s$ ; hadronisation correction uncertainties; and those due to the choice of factorisation scale. The dominant theoretical uncertainty is due to the contribution from terms beyond NLO, which was estimated by varying the renormalisation scale by the (conventional) factors of  $\frac{1}{2}$  and 2. This resulted in variations in the predicted cross section of  $\sim 5 - 20\%$ . All other sources typically resulted in only small changes to the predicted cross sections.

<sup>a</sup>In Quark Parton Model type events,  $\gamma_{had}$  is the angle of the scattered quark.

<sup>b</sup>In NC DIS, the Breit frame is preferred to conduct the jet search since jet production is directly sensitive to hard QCD sub-processes at  $\mathcal{O}(\alpha_s)$  (and higher); in the Born level process ( $eq \rightarrow eq$ ), the virtual boson  $V^*$  (where  $V^* = \gamma, Z^0$ ) is absorbed by the struck quark, which is back-scattered with zero transverse momentum with respect to the  $V^*$  direction. At leading order in  $\alpha_s$ , the Boson-Gluon-Fusion ( $V^*g \rightarrow q\bar{q}$ ) and QCD Compton ( $V^*q \rightarrow qg$ ) processes give rise to two hard jets with opposite transverse momenta.

<sup>c</sup>Other choices of scale were also checked.

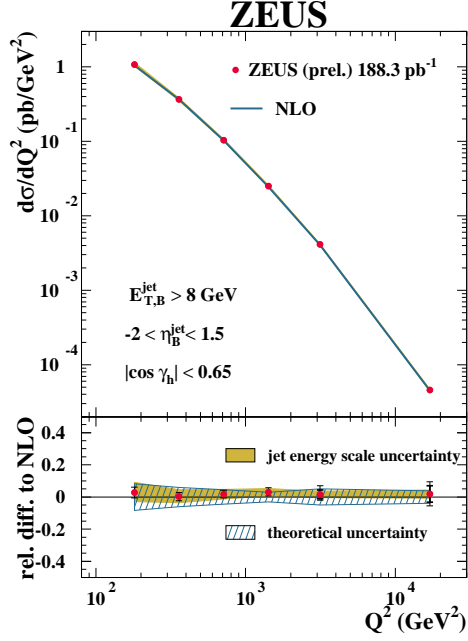


Figure 1: Single differential cross section  $d\sigma/dQ^2$  for inclusive-jet production with  $E_{T,Breit} > 8$  GeV and  $-2 < \eta_{Breit} < 1.5$  from ZEUS [2].

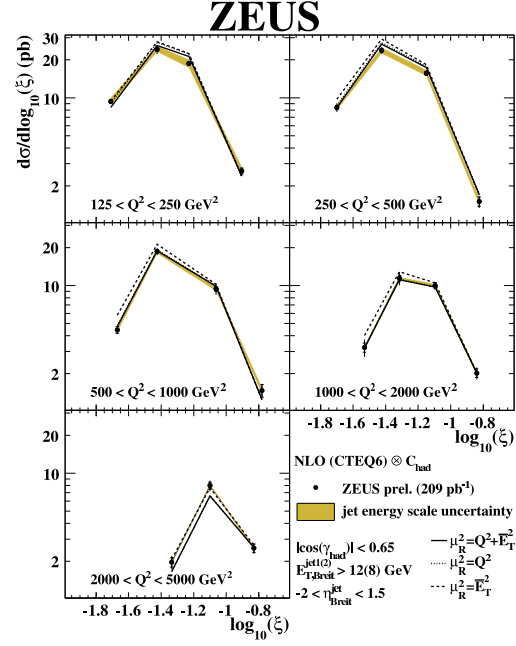


Figure 2: Double differential dijet cross sections as a function of  $\log_{10}(\xi)$  in regions of  $Q^2$  from ZEUS [3].

## 4 Results

### 4.1 Jet cross sections

The inclusive-jet cross sections were measured differentially as functions of  $Q^2$ ,  $E_{T,Breit}$  and  $\eta_{Breit}$ . Figure 1 shows the single differential cross section as a function of  $Q^2$ : the inner and outer error bars show the statistical and uncorrelated systematic uncertainties respectively; the shaded band indicates the bin-by-bin correlated systematic uncertainty due to the jet energy scale; and the hashed area gives the theoretical uncertainty. The results show that the data are well described by NLO QCD over the measured range. Except at the very highest  $Q^2$  values, the theoretical uncertainties dominate over the experimental. Double differential cross sections as a function of  $E_{T,Breit}$ , in 6 bins of  $Q^2$ , were also measured. Previously, a similar measurement of inclusive jets in NC DIS [14] was included<sup>d</sup> in a NLO QCD fit [16] performed by the ZEUS collaboration. The results showed that the HERA jet data were able to significantly constrain the gluon PDF at mid-to-high values of the proton momentum fraction. The new measurement presented here is in the same region of phase space but corresponds to  $\sim 4.5$  times the statistics. The very high experimental precision makes it a promising candidate for inclusion in future QCD analyses, potentially providing substantial further constraints on the gluon density in the proton.

<sup>d</sup>Along with a measurement of dijets in photoproduction [15].

The dijet cross sections were measured differentially as functions of a number of kinematic and jet observables, including  $Q^2$ ,  $M_{jj}$  (the dijet invariant mass),  $\overline{E}_{T,Breit}$  and  $\log_{10}(\xi)^e$ . The data are generally well described by the predictions of NLO QCD. Double differential cross sections as a function of  $\log_{10}(\xi)$ , in 5 regions of  $Q^2$ , were also measured (Fig. 2). The data are reasonably well described by NLO QCD, although there is some sensitivity to the choice of renormalisation scale. At large  $Q^2$ , the statistical uncertainties dominate. The contribution of gluon-induced events to the total cross section was also estimated as a function of  $Q^2$  and  $\xi$ . It is observed that the contribution from gluon-induced processes is at least 30%, even for high values of  $Q^2$  ( $\approx 3000 \text{ GeV}^2$ ) and  $\xi$ . The uncertainties on the predicted cross sections, arising from the gluon PDF, are found to be substantial. Therefore, these data are also expected to provide potentially strong constraints on the gluon content of the proton.

## 4.2 Strong coupling, $\alpha_s$

An NLO QCD analysis was performed on the single-differential NC DIS inclusive-jet cross section as a function of  $Q^2$  in order to determine a value of  $\alpha_s(M_Z)$  (see Fig. 1). Only the region  $Q^2 > 500 \text{ GeV}^2$  was used, giving the best overall uncertainty on the extracted value. The QCD calculations were performed using the program DISENT (as described in Sec. 3), using 5 different sets of PDFs from the ZEUS-S fit, each with different values of  $\alpha_s(M_Z)$ . The value of  $\alpha_s(M_Z)$  used in each cross section calculation was that associated with the PDF used. The  $\alpha_s$  dependence of the predicted cross sections, in each  $Q^2$  bin, was parameterised using a function quadratic in  $\alpha_s(M_Z)$ . The value obtained is:  $\alpha_s(M_Z) = 0.1192 \pm 0.0009(\text{stat.})^{+0.0035}_{-0.0032}(\text{exp.})^{+0.0020}_{-0.0021}(\text{th.})$ , corresponding to a total uncertainty of 3.7%. The experimental uncertainties are dominated by the contribution from the jet energy scale ( $\pm 1.9\%$ ) while the theoretical uncertainties are dominated by terms beyond NLO ( $\pm 1.8\%$ ), as evaluated using the method of Jones et al. [17]. The uncertainties from other sources (proton PDFs, hadronisation corrections and  $\mu_F$ ) are generally small.

A similar method was employed to extract a new value of  $\alpha_s(M_Z)$  from a previously published measurement of inclusive-jets in  $\gamma p$  [5]. The single differential inclusive-jet cross section as a function of  $E_T^{jet}$  was used for the determination. The NLO QCD calculations were performed using the program of Klasen, Kleinwort and Kramer [18]. The factorisation and renormalisation scales were taken to be  $\mu_R = \mu_F = E_T^{jet}$  and the photon PDF was GRV-HO [20]. With respect to the original publication, the input proton PDF was updated to MRST01 [19] (c.f. MRST99) and the method of Jones et al. [17] was used to evaluate the uncertainties from terms beyond NLO. The value of  $\alpha_s(M_Z)$  extracted is:  $\alpha_s(M_Z) = 0.1223 \pm 0.0001(\text{stat.})^{+0.0023}_{-0.0021}(\text{exp.})^{+0.0029}_{-0.0030}(\text{th.})$ , corresponding to a 3.1% total uncertainty. The central value is almost identical to that obtained in the original publication using the same data. The dominant experimental uncertainty arises from the jet energy scale ( $\pm 1.5\%$ ) and the theoretical uncertainty is again dominated by terms beyond NLO ( $\pm 2.4\%$ )<sup>f</sup>.

Both measurements are in agreement with other determinations from HERA, and with the world average, and are of competitive precision. NNLO calculations will be needed to further improve the theoretical uncertainties in the future.

<sup>e</sup> $\xi = x_{Bj} \left(1 + M_{jj}^2/Q^2\right)$  is the parton momentum fraction, where  $x_{Bj}$  is the Bjorken- $x$  variable.

<sup>f</sup>The method of Jones et al. results in a smaller theoretical uncertainty than in previously.

## 5 Summary

Inclusive-jet and dijet cross sections have been measured in NC DIS at HERA, for  $Q^2 > 125 \text{ GeV}^2$ , using more than a two-fold increase in statistics compared to previous studies. The measurements are well described by the predictions of NLO QCD and are sensitive to the proton PDFs, especially the gluon density at high momentum fractions. The measurements are therefore natural candidates for inclusion in future QCD fits for the proton PDFs.

In addition, a value of  $\alpha_s(M_Z)$  has been extracted from the NC DIS inclusive-jet single-differential cross section as a function of  $Q^2$  (for  $Q^2 > 500 \text{ GeV}^2$ ). A further determination has been obtained from a re-analysis of previously published data on inclusive-jet  $\gamma p$ . Both extractions are of competitive precision and in agreement with the world average.

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