Jet Production in Deep Inelastic e-p Collisions at High Q^2 and Determination of α_S

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The production of jets is studied in deep-inelastic $e^{\pm}p$ scattering at large negative four momentum transfer squared using HERA data taken in 1999-2007, corresponding to an integrated luminosity of $395\,\mathrm{pb}^{-1}$. Inclusive jet, 2-jet and 3-jet cross sections, normalised to the neutral current deep-inelastic scattering cross sections, are measured as functions of Q^2, jet transverse momentum and proton momentum fraction. The measurements are well described by perturbative QCD calculations at next-to-leading order corrected for hadronisation effects.

Jet production in neutral current (NC) deep-inelastic scattering (DIS) at HERA provides an important testing ground for Quantum Chromodynamics (QCD). Analyses of inclusive jet production in DIS at high Q^2 were previously performed by the H1 [1] and ZEUS [2] collaborations at HERA. These analyses are based on HERA-I data and use jet observables to test the running of the strong coupling and extract its value at the Z^0 boson mass.

Here, the ratios of jet cross sections to the corresponding NC DIS cross section are measured. These normalised cross sections benefit from a partial cancellation of experimental and theoretical uncertainties. The measurements are compared with perturbative QCD (pQCD) predictions at next-to-leading order (NLO) corrected for hadronisation, and α_s is extracted from a fit of the predictions to the data.

Event and jet selection, Observables, and Uncertainties

The details of the H1 detector, event selection, jet reconstruction, definition of the observables, and error analysis can be found in [3, 4]. The data sample used in this analysis comprises $153\,\mathrm{pb}^{-1}$ of e^-p and $242\,\mathrm{pb}^{-1}$ of e^+p collisions, both at a centre-of-mass energy $\sqrt{s} = 319\,\mathrm{GeV}$. It corresponds to a total integrated luminosity six times larger than in the previous H1 analysis [1]. The kinematical range of this analysis is defined by $150 < Q^2 < 15000\ \mathrm{GeV}^2$ and $0.2 < y < 0.7$ where $y = Q^2/(s\,x_{\mathrm{Bj}})$, as reconstructed from the four momenta of the scattered electron and the hadronic final state particles respectively. The jet finding is performed in the Breit frame [5] using the inclusive k_T algorithm [6] (massless P_T recombination scheme, $R_0 = 1$). Every jet with the transverse momentum P_T in the Breit frame satisfying $7 < P_T < 50\,\mathrm{GeV}$ contributes to the inclusive jet cross section. Events with at least two (three) jets with transverse momentum $5 < P_T < 50\,\mathrm{GeV}$ are considered as 2-jet (3-jet) events. By addditionally requiring the invariant mass M_{12} of the two leading jets to be greater than 16 GeV regions of phase-space where fixed order perturbation theory is not reliable are avoided [7]. Normalised inclusive jet cross sections (2-jet cross sections) are measured double differentially as functions of Q^2 and the individual (average) transverse momentum P_T in the Breit frame. Normalised 3-jet cross sections are measured functions of Q^2 only. The normalised inclusive jet cross section, in particular, is the average jet multiplicity in a given Q^2 region. The data are corrected bin by bin for detector acceptance

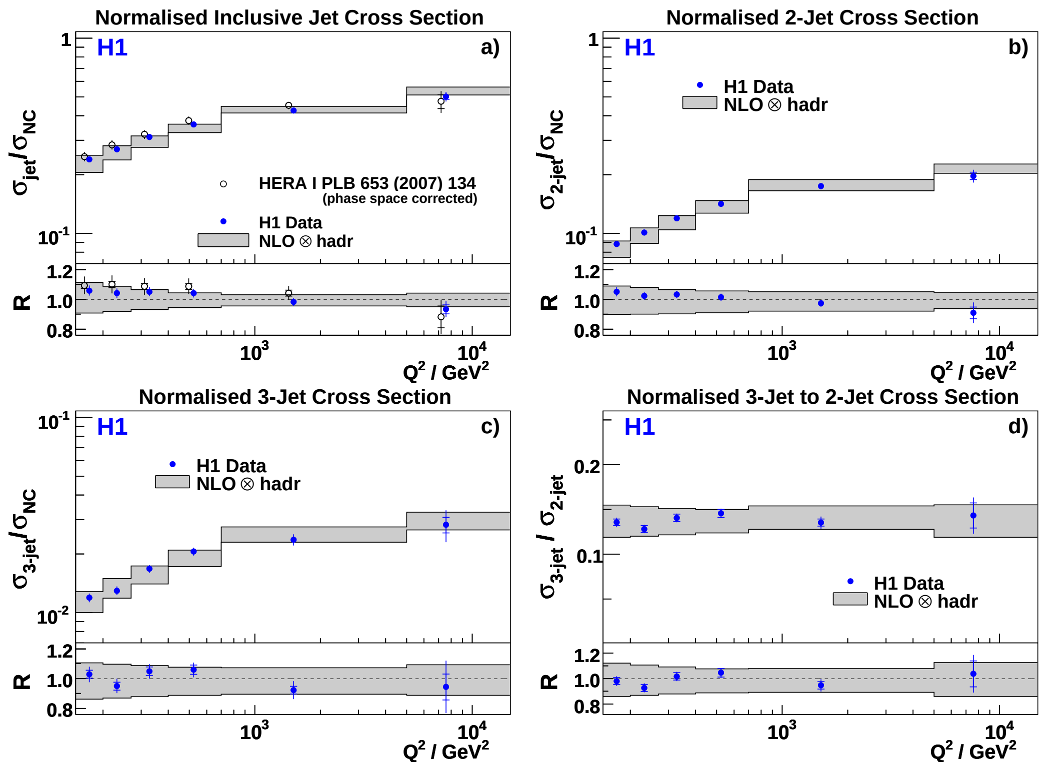

Figure 1: *The normalised inclusive jet (a), 2-jet (b) and 3-jet (c) cross sections and the ratio of 3-jet to 2-jet cross sections (d) in NC DIS measured as a function (of the average value) of* Q^2 *within each bin (points) and the corresponding NLO QCD predictions (band).*

and resolution using the LO MC event generators which alternatively model hadronisation and soft QCD effets by the Color Dipole Model (DJANGOH [8, 9]) or matched leading log parton showers (RAPGAP [10]). QED radiation and electro-weak effects (at high Q^2) are corrected for. The dominant experimental errors on the jet cross sections arise from the uncertainty on the hadronic energy scale followed by the model dependence of the data correction in regions of highest jet P_T. Statistical errors are insignificant except at highest Q^2 and P_T. The overall experimental error ranges typically between 3 and 6%, but increases up to 15% in the regions of highest P_T or Q^2. The experimental errors for normalised cross sections are reduced by 30-50% compared to those for unnormalised cross sections.

NLO QCD prediction of jet cross sections

The QCD predictions for the jet cross sections are calculated using the NLOJET++ program at NLO in the strong coupling [11]. The NC DIS cross section for normalisation is calculated at $\mathcal{O}(\alpha_s)$ with the DISENT package [12]. The PDFs of the proton are taken from the CTEQ6.5M set [13]. The factorisation scale μ_f is taken to be Q and the renormalisation scale μ_r to be $\sqrt{(Q^2 + P_T^2)/2}$. Hadronisation corrections are determined using

Measurement	$\alpha_S(M_Z)$	Uncertainty			χ^2/ndf
		exp.	theory	PDF	
$\frac{\sigma_{\text{jet}}}{\sigma_{\text{NC}}}\,(Q^2, P_T)$	0.1195	0.0010	$^{+0.0049}_{-0.0036}$	0.0018	24.7/23
$\frac{\sigma_{\text{2-jet}}}{\sigma_{\text{NC}}}\,(Q^2, \langle P_T\rangle)$	0.1155	0.0009	$^{+0.0042}_{-0.0031}$	0.0017	30.4/23
$\frac{\sigma_{\text{3-jet}}}{\sigma_{\text{NC}}}\,(Q^2)$	0.1172	0.0013	$^{+0.0052}_{-0.0031}$	0.0009	7.0/5
$\frac{\sigma_{\text{jet}}}{\sigma_{\text{NC}}}, \frac{\sigma_{\text{2-jet}}}{\sigma_{\text{NC}}}, \frac{\sigma_{\text{3-jet}}}{\sigma_{\text{NC}}}$	0.1168	0.0007	$^{+0.0046}_{-0.0030}$	0.0016	65.0/53

Table 1: *Values of $\alpha_s(M_Z)$ obtained from fits to the individual normalised inclusive jet, 2-jet and 3-jet cross sections and from a simultaneous fit to all of them. Fitted values are given with experimental, theoretical and PDF errors as well as with the normalised χ^2.*

the abovementioned LO MC event generators. The dominant theoretical error is due to the uncertainty related to the neglected higher orders in the perturbative calculation, conventionally estimated by separately varying the chosen scales for μ_f and μ_r by factors in the arbitrary range 0.5 to 2. The uncertainties originating from the PDFs are estimated using the CTEQ6.5M set of parton densities.

Cross section measurements compared to NLO predictions

The normalised inclusive, 2-jet and 3-jet cross sections are shown as a function of Q^2 only in figs. 1a–c together with the NLO predictions. The average jet multiplicity produced in NC DIS increases with Q^2 as the available phase space opens as do the 2-jet and 3-jet rates. The 3-jet cross section normalised to the 2-jet cross section (fig. 1d) as function of Q^2 is almost constant. Also shown in fig. 1a is the previous measurement of the inclusive cross section by H1 based on HERA-I data [1], corrected for the slightly different phase space. The new measurement of the normalised inclusive jet cross section is compatible with the previous H1 data. The precision, however, is improved by typically a factor of two. The NLO QCD predictions for all normalised jet cross sections provide a good description of the data over the whole phase space. In almost all bins the theory error, dominated by the μ_r scale uncertainty, is significantly larger than the total experimental uncertainty, which is dominated by the hadronic energy scale uncertainty. The double differential results (not shown) for the inclusive and 2-jet rates as a function of P_T and Q^2 are also in good agreement with the NLO QCD prediction.

Extraction of the strong coupling

The strong coupling α_s is determined by fitting the QCD predictions of the normalised jet cross sections to the measured values in several steps: For each jet observable the running of $\alpha_s(Q)$ is verified first. Next, a common value of $\alpha_s(M_Z)$ is fitted to all data points of each jet observable separately, taking into account the correlations of experimental uncertainties between data points as estimated from Monte Carlo simulations. The results of the individual fits for each jet observable are shown in fig. 2 and compared to the Q dependence of the fitted value of $\alpha_s(M_Z)$. Finally, a common fit to all 54 data points of all jet observables is performed, also taking into account the error correlations between the observables. Table 1

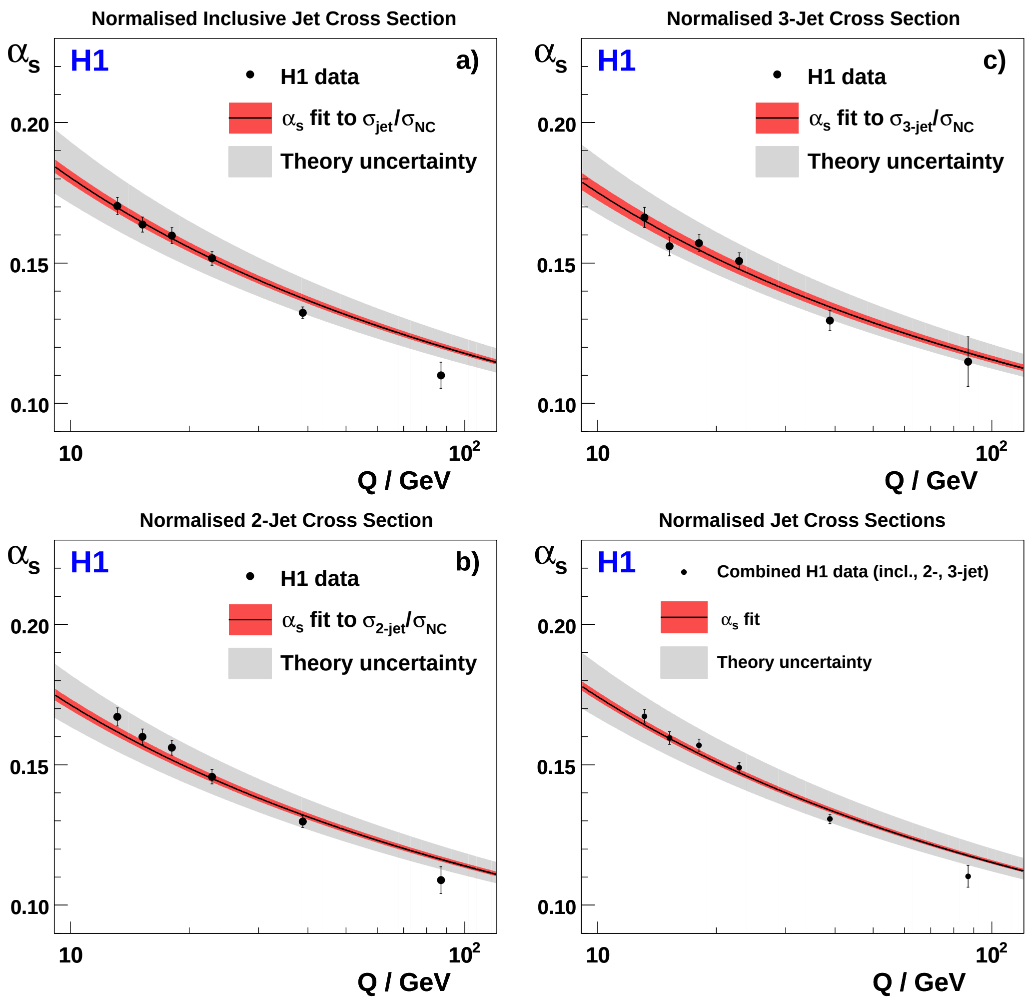

Figure 2: *$\alpha_s(Q)$ values extracted by fitting the P_T dependence in different regions of Q^2 of the normalised inclusive jet cross section (a), of the normalised 2-jet cross section (b) the normalised 3-jet cross section (c), and the ratio of the 3-jet to 2-jet rate (d). In each case, the solid lines shows the two loop solution of the renormalisation group equation obtained by evolving the corresponding central fitted value of $\alpha_s(M_Z)$.*

shows the resulting values together with their experimental and theory errors. The theory errors are estimated by varying the renormalization and factorization scale, the PDFs, and the hadronization corrections within their respective uncertainties. The dependence of the NLO calculation on the renormalisation scale, typically 3 to 4%, is the largest theory uncertainty.

Conclusion

Measurements of the normalised inclusive, 2-jet and 3-jet cross sections in the Breit frame in deep-inelastic electron-proton scattering are presented. Calculations at NLO QCD provide a good description of the single and double differential cross sections as functions of Q^2 and the jet transverse momentum P_T. The normalisation by the inclusive DIS cross section leads to cancellation of systematic effects, which results in improved experimental and PDFs uncertainties. The experimentally most precise determination of $\alpha_s(M_Z)$ is derived from a common fit of the NLO prediction to the set of normalised jet cross sections, yielding:

$$\alpha_s(M_Z) = 0.1168 \ \pm 0.0007\,(\text{exp.})\ ^{+0.0046}_{-0.0030}\,(\text{th.})\ \pm 0.0016\,(\textsc{pdf})\,.$$

The dominating source of the uncertainty is due to the renormalisation scale dependence, which is used to estimate the effect of missing higher orders beyond NLO in the pQCD prediction. This measurement improves the experimental precision on α_s determinations from other recent jet measurements at HERA [1, 2]. The result is competitive with those from fitting NNLO predictions to e^+e^- data [14, 16] and is in good agreement with different world averages [15, 14].

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