K_{T}, ANTI$-K_{\mathrm{T}}$ AND SISCONE JETS AND THE STRONG COUPLING α_S AT HERA

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Recent measurements by the H1 and ZEUS experiments at HERA of inclusive jet and multijet production in deep-inelastic scattering are presented, covering a wide range in the energy scales relevant for the strong interactions. For the first time measurements obtained using the anti$-k_{\mathrm{T}}$ and SISCone jet finders are shown in addition to those using the more traditional k_{T} jet finder. The measurements are compared to NLO QCD calculations, and the extracted values of the strong coupling α_s as a function of the renormalization scale and at the scale M_Z are shown.

1 Introduction

The HERA ep-collider operated with electrons or positrons of 27.6 GeV and protons of 820 or 920 GeV. Each of the two collider experiments H1 and ZEUS collected about 120 pb^{-1} from 1995 to 2000 (HERA-1) and after a luminosity and detector upgrade about 370 pb^{-1} from 2003 to 2007 (HERA-2). Since the results presented here do not depend on whether the incident lepton was an electron or a positron, the term "electron" is used to mean either of them. The kinematic region of deep-inelastic scattering (DIS) is defined by measuring the scattered electron with photon virtualities in the range $5 \leq Q^2 < 20000$ GeV^2. To ensure a well measured hadronic final state, the requirement on the inelasticity $0.2 < y < 0.7$ or on the angle of the scattered quark in the quark-parton model (QPM), $|\cos\gamma_{\mathrm{h}}| < 0.65$, measured via the scattered electron and/or the hadronic final state, completes the definition of the DIS phase space.

The n-jet cross sections in DIS can be schematically written as

$$d\sigma_{\mathrm{n-jet}} = \sum_{i=q,\bar{q},g} \int dx\, f_i(x,\mu_f) d\hat{\sigma}_i(x, \alpha_s^{n-1}(\mu_r), \mu_r, \mu_f) \;\; (1+\delta_{\mathrm{had}})\,, \tag{1}$$

where f_i refers to the parton density function (PDF) of parton i in the proton, $\hat{\sigma}_i$ to the matrix element with parton i, which is calculable in perturbative Quantumchromodynamics (QCD), and μ_{F} and μ_{R} to the factorization and renormalization scale respectively. The hadronization correction $(1+\delta_{\mathrm{had}})$ needs to applied to the QCD calculation when comparing to data. In jet production in DIS there are two relevant hard scales, i.e. Q $(2-140$ GeV) and $P_{\mathrm{T,jet}}$ $(5-80$ GeV), while in photoproduction or hadron-hadron collisions there is only $P_{\mathrm{T,jet}}$. In order to have a smooth transition from DIS to photoproduction the scale $\sqrt{(Q^2+P_{\mathrm{T,jet}}^2)/2}$ is often used. Furthermore in DIS at HERA we have a more complicated interplay of the two scales. Depending on the kinematic regions in Q and $P_{\mathrm{T,jet}}$, either one of them can be larger than the other or they both can have rather similar magnitude.

In the lowest order (QPM) process only one jet is produced, and only the production of two and more jets involves QCD processes. In the Breit [1] frame (or in longitudinally boosted equivalent frames) QCD processes generate jets with transverse momenta in contrast to the QPM process. In order to suppress QPM events this frame or the hadronic center-of-mass frame are used to find jets. Therefore, in this frame jet production depends on α_s already in leading order (LO), in contrast to the totally inclusive measurement, for example F_2, which depends on α_s only at next-to-leading order (NLO). When comparing jet measurements to QCD calculations, a collinear and infrared safe jet algorithm has to be applied in the jet finding. The k_{T}-algorithm [2], which has been used by the HERA experiments for many years already, and the more recent anti$-k_{\mathrm{T}}$ [3] and SISCone [4] algorithms, for which results will be shown for the first time, fulfill this requirement.

The slides of the talk, which include more figures than possible in this written version, can be found in ref. [5].

2 Measurements of k_{T} multijets at low Q^2 by H1

A measurement of multijet cross sections at low Q^2 by H1, corresponding to an integrated luminosity of 44 pb^{-1} of HERA-1 data, has just been published [6]. The DIS phase space of this measurement is defined by $5 < Q^2 < 100$ GeV^2 and $0.2 < y < 0.7$. The jet phase phase space is specified by requiring that inclusive jets, 2-jets and 3-jets have $P_{\mathrm{T,jet}} > 5$ GeV and $-1.0 < \eta_{\mathrm{jet}} < 2.5$ in the Breit and laboratory frame respectively. In addition, for both 2-jet and 3-jet events, the invariant mass of the two leading jets must fulfill $M_{1,2} > 18$ GeV. Single and double differential jet cross sections as well as the 3-jet to 2-jet ratio are measured as a function of Q^2, $P_{\mathrm{T,jet}}$ or $<P_{\mathrm{T,jet}}>$ of the two leading jets and ξ, the fractional momentum at LO of the incident parton in the hard interaction. They are compared to NLO calculations using NLOJET++ [7] for 5 massless quark flavors, using for the proton PDFs the CTEQ6.5M [8] parameterization and $\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = \sqrt{(Q^2 + P_{\mathrm{T,jet}}^2)/2}$. In Fig.1 left, the single differential inclusive jet, 2-jet and 3-jet cross sections as a function of Q^2 and $P_{\mathrm{T,jet}}$ or $<P_{\mathrm{T,jet}}>$ and their description by NLO QCD predictions are shown. The main experimental uncertainties are due to the jet

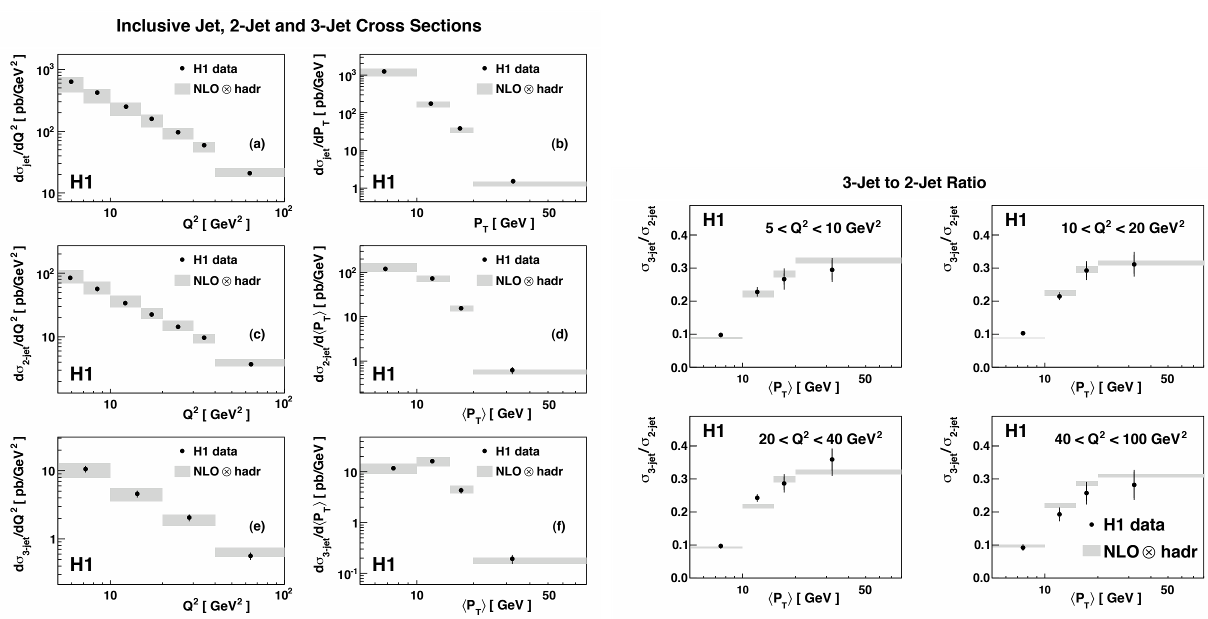

Figure 1: Inclusive jet, 2-jet and 3-jet cross sections (left) and the 3-jet to 2-jet ratio (right) as a function of Q^2 and $P_{\mathrm{T,jet}}$ or $<P_{\mathrm{T,jet}}>$ of the two leading jets compared to NLO calculations corrected for hadronization effects.

energy scale ($\pm 2\%$) and the acceptance, leading to an error on the cross section between $4-10\%$ and $2-15\%$ respectively. In Fig.1 left primarily the theoretical uncertainties are visible. They are dominated by the renormalization scale uncertainty of $\approx 30\%$ ($\approx 10\%$) at lowest Q^2 and $P_{\rm T,jet}$ (highest Q^2 and $P_{\rm T,jet}$). The uncertainty due to the PDFs varies from $2-6\%$. With the scale choice for $\mu_{\rm R}$ the data are well described by NLO, however, calculations beyond NLO are needed to match the precision of the measurements. Choosing $\mu_{\rm R} = P_{\rm T,jet}$ decreases the NLO prediction by $10-20\%$ at lowest Q^2 and $P_{\rm T,jet}$ and is disfavored by the data.

In Fig.1 right, the double differential 3-jet to 2-jet ratio is shown as a function of the average $P_{\rm T,jet}$ of the two leading jets in four bins of Q^2. In the ratio the normalization error cancels and other systematic experimental uncertainties are reduced by $\approx 50\%$. Also the sensitivity to the variation of the renormalization scale in the theory is reduced. The ratio is well described by the NLO calculation. For the ratio we find that the experimental errors (dominated by statistical errors) of this HERA-1 data sample are larger than the theoretical ones. With HERA-2 data the statistics will be improved by about a factor of 9.

The extraction of the strong coupling α_s from these measurements on inclusive jet, 2-jet and 3-jet cross section will be discussed in sect.4.

3 Measurements of inclusive $k_{\rm T}$, anti$-k_{\rm T}$ and SISCone jets at high Q^2 by ZEUS

A first comparison [9] of inclusive jet cross sections measured using the $k_{\rm T}$, see [10], and anti$-k_{\rm T}$ and SISCone jet algorithms, see[9], has been performed by ZEUS. The HERA-1 data analyzed corresponds to an integrated luminosity of 82 pb^{-1}. The DIS phase space is defined by $Q^2 > 125$ GeV^2 and $|\cos\gamma_{\rm h}| < 0.65$. The jets are reconstructed using the $k_{\rm T}$, anti$-k_{\rm T}$ or SISCone jet algorithms, and at least one jet with $E_{\rm T,jet} > 8$ GeV and $-2 < \eta_{\rm jet} < 1.5$ in the Breit frame is required. Single and double differential inclusive jet cross sections are measured as a function of Q^2 and $E_{\rm T,jet}$. The main experimental uncertainties are due to the hadronic jet energy and the acceptance. The former ($\pm 1\%$ for $E^{\rm lab}_{\rm T,jet} > 10$ GeV and increasing up to $\pm 3\%$ for lower $E^{\rm lab}_{\rm T,jet}$) yields an uncertainty on the cross section of $\approx \pm 5\%$, the latter, determined using different models, leads to an uncertainty of $\approx \pm 4\%$. The NLO predictions for 5 massless quark flavors are calculated using the program DISENT [11] with $\mu_{\rm F} = Q$ and $\mu_{\rm R} = E_{\rm T,jet}$ and the ZEUS-S parameterization[12] for the proton PDFs.

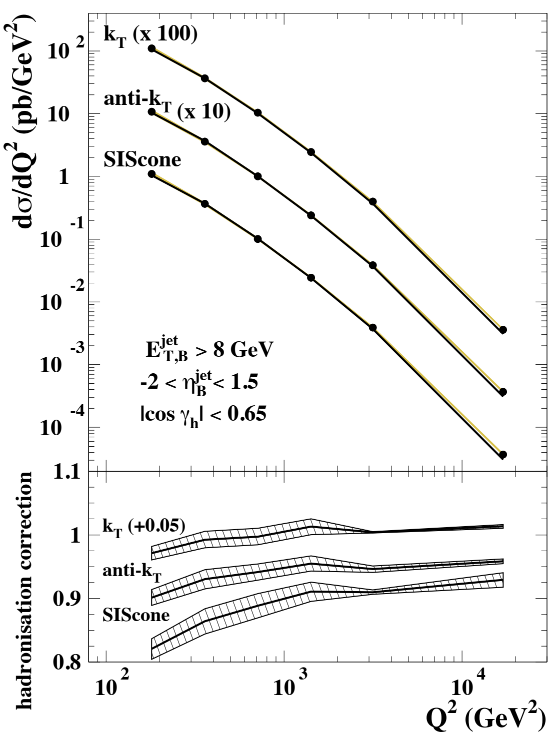

Figure 2: Inclusive jet cross section and NLO prediction (top) and hadronization corrections (bottom) using the $k_{\rm T}$, anti$-k_{\rm T}$ and SISCone jet finding algorithms.

In Fig.2 the inclusive jet cross sections as a function of Q^2 are shown for the three different jet algorithms. The measurements are found to be well described by their respective NLO predictions [a]. This also holds for the distributions as a function of $E_{\rm T,jet}$. As can be also seen in Fig.2 (bottom), the hadronization corrections to

[a] Since the different jet cross sections are very similar, two have been offset by factors of 10 and 100 in Fig.2.

the NLO calculations are smallest for the k_T and anti$-k_T$ and somewhat larger for the SISCone algorithm. For all three jet algorithms the parameter R_0 was set to 1.

In a study[9] of the theoretical uncertainties it is found that all three jet algorithms have similar sensitivity to variations of PDFs, $\alpha_s(M_Z)$ and to different models, while SISCone shows slightly larger sensitivity to terms beyond NLO, i.e. to the conventional variations of renormalization and factorization scales. As a function of Q^2 for example, the theoretical uncertainty varies from about $3-7\%$ ($3-10\%$) for the anti$-k_T$ (SISCone) algorithm.

Calculations of inclusive jet cross sections are currently available up to $\mathcal{O}(\alpha_s^2)$. However, the ratios of inclusive jet cross sections [9] for different jet algorithms, which can be written in terms of differences of jet cross sections, can be calculated up to $\mathcal{O}(\alpha_s^3)$ using NLOJET++. In the ratio the theoretical uncertainty is dominated by the hadronization uncertainty. The data and the QCD predictions are shown in Fig.3 as a function of $E_{\mathrm{T,jet}}$ and Q^2. For the data they differ from unity by less than 3.6%, except at the highest $E_{\mathrm{T,jet}}$ where it is about 10%. The data ratios are well described by calculations including terms up to $\mathcal{O}(\alpha_s^3)$.

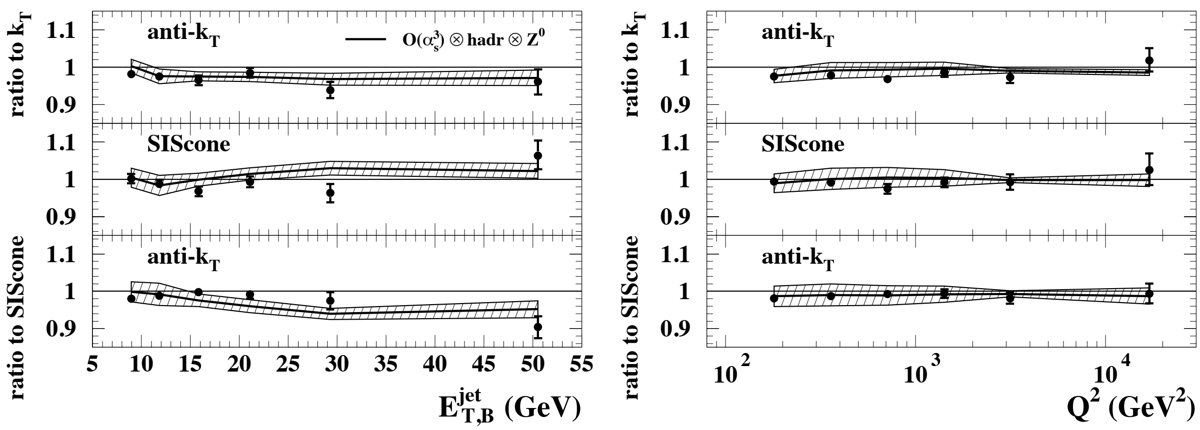

Figure 3: Inclusive jet cross section ratios (anti$-k_T$ to k_T, SISCone to k_T and anti$-k_T$ to SISCone) for data and QCD calculations including terms up to $\mathcal{O}(\alpha_s^3)$. The hatched band displays the theory uncertainty on the ratio.

4 Extraction of running α_s and $\alpha_s(M_Z)$

The jet cross sections discussed in sections 2 and 3 are used to extract α_s at different values of the renormalization scale μ_R and at the Z-boson mass. In the fit procedure the statistical, systematic and correlated uncertainties are taken into account. The dominant theory uncertainty is estimated by a variation of the renormalization and factorization scales by the arbitrary but conventional factor of 1/2 and 2 of the nominal scale. This uncertainty, in the case of H1, is obtained by fitting the changed theory predictions to data. In case of ZEUS it is calculated using a method [13] which does not involve a refit of the data. It leads to smaller theory uncertainties than the H1 method.

The extraction of $\alpha_s(M_Z)$ using the double differential inclusive jet, 2-jet and 3-jet cross sections from H1, using the k_T jet finder as discussed in sect.2, yields:

$$k_T: \ \alpha_s(M_Z) = 0.1160 \pm 0.0014\,(\mathrm{exp.})\,^{+0.0093}_{-0.0077}\,(\mathrm{th.}) \pm 0.0016\,(\mathrm{pdfs}) \qquad 5 < Q^2 < 100 \ \mathrm{GeV}^2\,.$$

This value can be compared with a value from a recent extraction[14] of α_s from H1 using HERA-1 and HERA-2 data on double differential normalized inclusive jet, 2-jet and 3-jet cross sections in the high Q^2 region, corresponding to an integrated luminosity of 395 pb^{-1}:

$$k_T: \ \alpha_s(M_Z) = 0.1168 \pm 0.0007\,(\mathrm{exp.})\,^{+0.0046}_{-0.0030}\,(\mathrm{th.}) \pm 0.0016\,(\mathrm{pdfs}) \quad 150 < Q^2 < 15000 \ \mathrm{GeV}^2\,.$$

The two results are in very good agreement. The higher precision of the latter result is due to full or partial cancelation of a number of systematic uncertainties in normalized jet cross sections (normalized to inclusive events in the Q^2 bins) and reduced theory uncertainty at the higher Q^2. Using the anti$-k_{\rm T}$ jet finder, H1 finds that the central value of $\alpha_s(M_Z)$ remains within 0.6% [14] of the nominal $k_{\rm T}$ value.

The running of α_s as a function of the renormalization scale is shown in Fig.4 as extracted from the low and high Q^2 data. The $\alpha_s(M_Z)$ value and uncertainties from the high Q^2 extraction are used to extrapolate to lower scales using the two-loop renormalization group equation. The values and experimental uncertainties of α_s in the low Q^2 region (square points) are found to be in very good agreement with the QCD expectation.

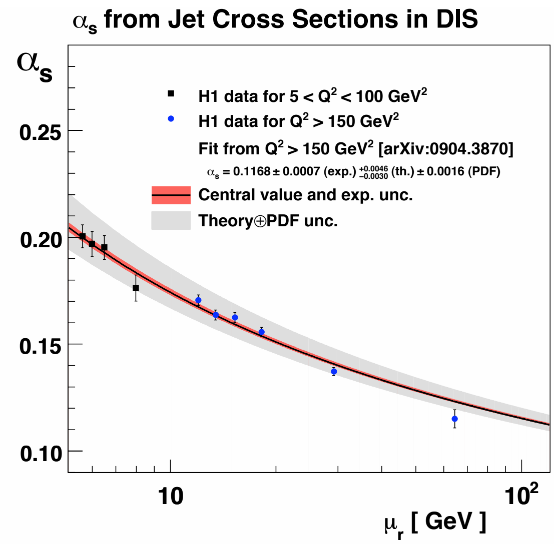

Figure 4: $\alpha_s(\mu_{\rm R} = \sqrt{(Q^2 + P^2_{\rm T,jet})/2})$ obtained from inclusive jet, 2-jet and 3-jet cross sections measured at low and high Q^2, compared to the prediction from the renormalization group equation using $\alpha_s(M_Z)$ from the fit of the high Q^2 jet data.

The inclusive $k_{\rm T}$, anti$-k_{\rm T}$ and SISCone jet cross sections, discussed in sect.3, are used by ZEUS to also extract values for $\alpha_s(M_Z)$. For this purpose the single differential cross sections in Q^2 are used. Only data for $Q^2 > 500$ GeV^2 are taken in order to reduce the theory uncertainty while minimizing the total uncertainty in $\alpha_s(M_Z)$. The following results are obtained:

$$
\begin{aligned}
k_{\rm T}: &\quad \alpha_s(M_Z) = 0.1207 \pm 0.0014\,({\rm stat.})\,^{+0.0035}_{-0.0033}\,({\rm exp.})\,^{+0.0022}_{-0.0023}\,({\rm th.}) \quad Q^2 > 500~{\rm GeV}^2 \\
{\rm anti}-k_{\rm T}: &\quad \alpha_s(M_Z) = 0.1188 \pm 0.0014\,({\rm stat.})\,^{+0.0033}_{-0.0032}\,({\rm exp.})\,^{+0.0022}_{-0.0022}\,({\rm th.}) \quad Q^2 > 500~{\rm GeV}^2 \\
{\rm SISCone}: &\quad \alpha_s(M_Z) = 0.1186 \pm 0.0013\,({\rm stat.})\,^{+0.0034}_{-0.0032}\,({\rm exp.})\,^{+0.0025}_{-0.0025}\,({\rm th.}) \quad Q^2 > 500~{\rm GeV}^2\,.
\end{aligned}
$$

These values for $\alpha_s(M_Z)$ are very similar as they should be; the differences observed are comparable to terms beyond NLO.

5 Summary

Recent measurements on multijet cross sections at low Q^2 are found to be in good agreement with NLO calculations and yield a value for $\alpha_s(M_Z)$ consistent with extractions from similar measurements at high Q^2. These and previous jet measurements at HERA have primarily used the $k_{\rm T}$ jet finder. First measurements of inclusive jet cross sections using the anti$-k_{\rm T}$ and SISCone have been performed. The cross sections have very similar shapes and normalization and are in good agreement with NLO predictions. The theoretical precisions are similar, with the SISCone algorithm leading to slightly less precise results. The $k_{\rm T}$, anti$-k_{\rm T}$ and the SISCone jet finder lead to similar values for $\alpha_s(M_Z)$ with similar precision.

The values for $\alpha_s(M_Z)$ at NLO presented here are summarized in Fig.5. Additional values are shown from preliminary jet analyses using deep-inelastic [15] and photoproduction [16] data from ZEUS. The values shown here have become available after the conference. Also displayed are the currently most precise determinations of $\alpha_s(M_Z)$ from the three-jet rate at NNLO [17] in e^+e^- annihilation at LEP and from inclusive jet cross sections [18], at NLO including higher order threshold corrections, obtained by D0 in $p\bar{p}$ collisions at the TEVATRON.

Finally, the 2009 world average[19] is indicated as band in Fig.5. All values shown are consistent with each other and with the world average. One may notice that at HERA the theoretical uncertainties do not yet match the experimental precision, however, calculations of higher orders are expected to improve this situation.

Further experimental progress at HERA, in terms of precision and statistics, is possible by using the final reconstructed data and by performing combined extractions of α_s using H1 and ZEUS jet cross sections.

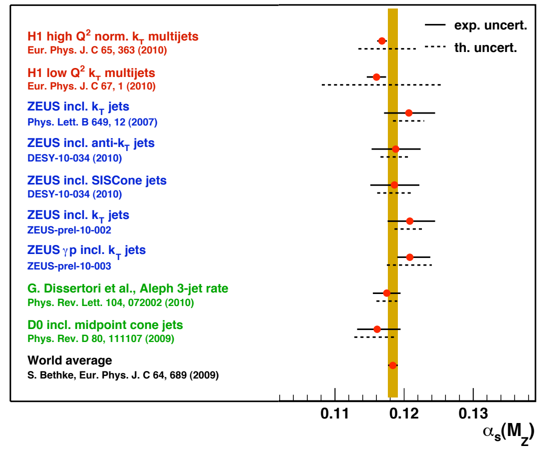

Figure 5: Recent values of $\alpha_s(M_Z)$ from jets and the world average.

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