Event shapes and forward Jet production at HERA

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1. EVENT SHAPES

A recent revival of interest in the study of event shape measurements has been prompted by theoretical developments in the understanding of hadronisation or power corrections. Here, perturbative QCD calculations are extended into the region of low momentum transfers using approximations to higher-order graphs. At HERA, the Q^2 scale can be varied over four orders of magnitude enabling power corrections (proportional to $1/Q^p$, where p is the power) to be studied in detail. The data are compared to theoretical expectations for the power corrections, characterised by an effective coupling $\overline{\alpha}_0(\mu_I)$ specified at the infra-red matching scale $\mu_I \simeq 2$ GeV, and NLO pQCD calculations, determined by $\alpha_s(M_Z)$.

The Breit frame is where the exchanged gauge boson in DIS is purely space-like. Viewed in this frame, the incoming QPM quark is back-scattered with equal and opposite momentum ($Q/2$). Event shapes have been measured in the direction of the struck quark, corresponding to the current region, which is directly analogous to one hemisphere of a purely time-like e^+e^- interaction. A series of event shape variables have been studied which have varying sensitivity to hadronisation/power corrections and are noted below. Thrust ($\tau = 1 - T_z$) and jet broadening (B) sum the longitudinal and transverse momenta, respectively, of individual particles along the photon axis. τ_c is also defined with respect to the reconstructed thrust axis, in order to compare directly with e^+e^-. Jet mass (ρ) and the C parameter sum the product of two particle momenta weighted by $1 - \cos\theta_{ij}$ and $\sin^2\theta_{ij}$, respectively. These variables are each measured in the current region of the Breit frame and are scaled by the total visible energy (E_{vis}).

Mean values of these event shapes haves been measured by H1 [1] and ZEUS [2] which can be interpreted theoretically via

$$\langle F \rangle = \langle F \rangle^{\text{pert}} + \langle F \rangle^{\text{pow}}$$

where

$$\langle F \rangle^{\text{pert}} = c_{1,F}(x,Q) \cdot \alpha_s(Q) + c_{2,F}(x,Q) \cdot \alpha_s^2(Q)$$

with $c_{1,F}(x,Q)$ and $c_{2,F}(x,Q)$ being calculable coefficients of pQCD determined by the DISENT NLO program [3] with renormalisation/factorisation scales set at $\mu_R = \mu_F = Q$.

The power corrections are proportional to $1/Q$ with

$$\langle F\rangle^{\rm pow} = \mathcal{M}'\frac{a_F}{Q}\frac{16\mu_I}{3\pi}\Big[\overline{\alpha}_0(\mu_I) - \alpha_s(Q) - \frac{23}{6\pi}\left(\ln\frac{Q}{\mu_I} + 1.45\right)\alpha_s^2(Q)\Big].$$

Here a_F is a calculable F-dependent coefficient and $\mathcal{M}' = 2\mathcal{M}/\pi \simeq 1.14$ [4] [1] is a two-loop level refinement to the calculations called the Milan factor.

The results of two-parameter fits to the H1 data are given in Table 1 and Figure 1(left). The χ^2 per degree of freedom are consistent with unity. The correlation of $\overline{\alpha}_0(\mu_I)$ and $\alpha_s(M_Z)$ is high and negative for $\langle\tau\rangle$ but is less for other variables. Results from similar fits (excluding the Milan factor) to ZEUS charged-hadron data and the earlier H1 published data are shown in Figure 1(right). In each case, the data for the means of τ, B, τ_C, C and ρ, [2] are described reasonably well by the theory, with a value of the universal non-perturbative parameter $\overline{\alpha}_0(\mu_I)$ of $\simeq 0.5 \pm 20\%$ and a value of $\alpha_s(M_Z)$ close to the world average. In conclusion, the theoretical approach works remarkably well and ongoing refinements will generate further insight into non-perturbative QCD mechanisms in the generation of hadronic final states at high energies. *

Table 1
H1 preliminary results of two-parameter fits of $\overline{\alpha}_0(\mu_I)$ and $\alpha_s(M_Z)$ to mean event shape variables using the NLO power correction approach described in the text. The χ^2 per degree of freedom, χ^2/n, and the correlation coefficient, κ, are also given.

$\langle F\rangle$	a_F	$\overline{\alpha}_0(\mu_I)$	$\alpha_s(M_Z)$	χ^2/n	$\kappa/\%$
$\langle\tau\rangle$	1	$0.480 \pm 0.028\ ^{+0.048}_{-0.062}$	$0.1174 \pm 0.0030\ ^{+0.0097}_{-0.0081}$	0.5	-97
$\langle B\rangle$	1/2	$0.491 \pm 0.005\ ^{+0.032}_{-0.036}$	$0.1106 \pm 0.0012\ ^{+0.0060}_{-0.0057}$	0.7	-58
$\langle\tau_C\rangle$	1	$0.475 \pm 0.003\ ^{+0.044}_{-0.048}$	$0.1284 \pm 0.0014\ ^{+0.0100}_{-0.0092}$	1.3	$+19$
$\langle\rho\rangle$	1/2	$0.561 \pm 0.004\ ^{+0.051}_{-0.058}$	$0.1347 \pm 0.0015\ ^{+0.0111}_{-0.0100}$	1.2	$+7$
$\langle C\rangle$	$3\pi/2$	$0.425 \pm 0.002\ ^{+0.033}_{-0.039}$	$0.1273 \pm 0.0009\ ^{+0.0104}_{-0.0093}$	0.9	$+63$

2. FORWARD JET PRODUCTION

The first phase of running established HERA as the place to study QCD in the hitherto unexplored region of low-x. The rise of the structure function F_2 stimulated significant theoretical developments in the understanding of QCD at high energies. However, two approaches to perturbative QCD calculations can be made, corresponding to whether $\alpha_s(Q^2)\ln(Q^2)$ (DGLAP) terms or $\alpha_s(Q^2)\ln(1/x)$ (BFKL) terms are considered to be largest in the perturbative splitting functions. Both approaches describe the F_2 data at low-x: the measurement of forward jet production cross-sections is motivated as a test to distinguish between the DGLAP and BFKL approximations in low-x events.

Jets with $E_T^2 \sim Q^2$ and $x_{jet} \gtrsim x$, where x_{jet} is the momentum fraction of the jet relative to the incoming proton, are selected in order to enhance BFKL-like contributions where forward gluons may be emitted at relatively large E_T. H1 [6] and ZEUS [7] have made

[1] The latest theoretical evaluation determines $\mathcal{M}' \simeq 0.95$ [5].

[2] Note that the H1 published result for jet mass is normalised to Q^2 rather than E_{vis}^2.

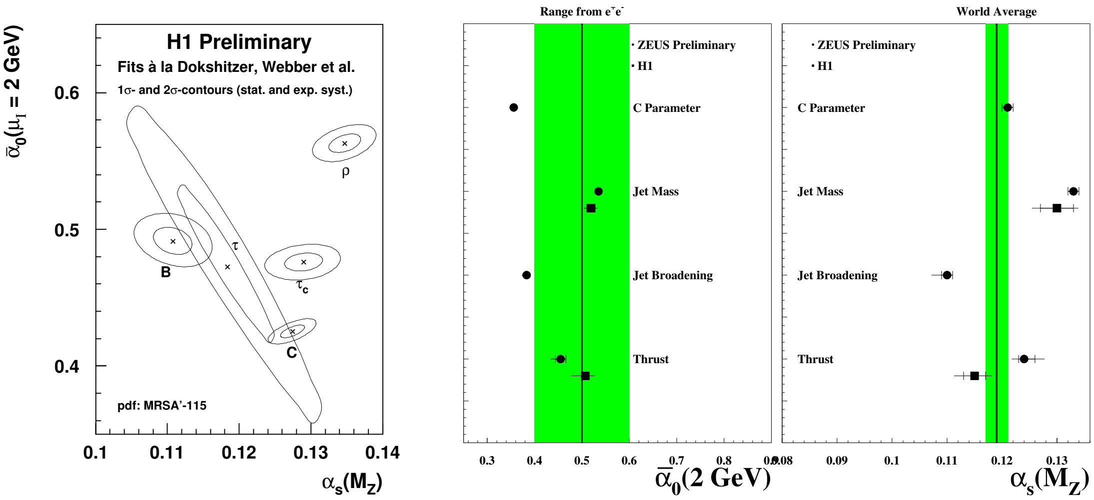


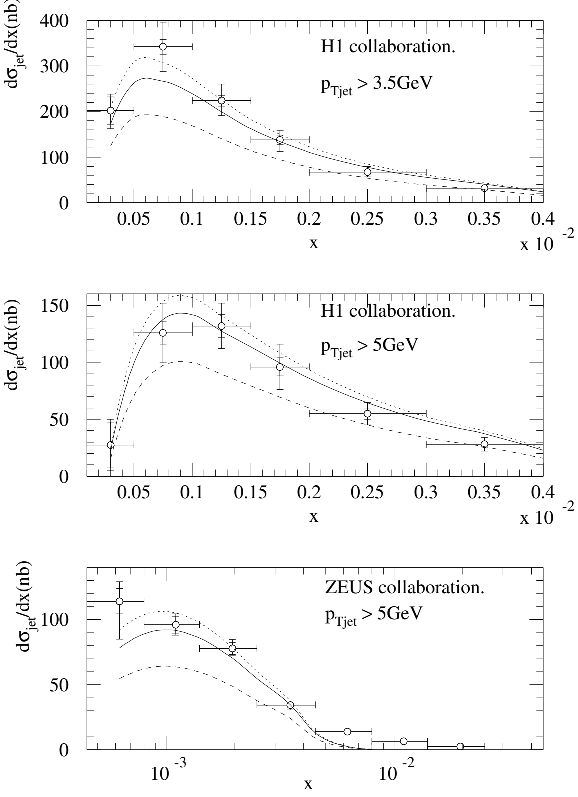
Figure 1. Summary of two-parameter fits of $\overline{\alpha}_0(\mu_I)$ and $\alpha_s(M_Z)$ to mean event shape variables. Left, H1 preliminary 1σ and 2σ stat$\oplus$sys contours for τ, B, τ_C, ρ and C parameter, incorporating the Milan factor. Right, ZEUS preliminary fits compared to published H1 results using leading-order power correction calculations.

measurements of forward jet cross-sections evaluated for $Q^2/2 < E_T^2 < 2Q^2$ as a function of x for $x_{jet} > 0.035$ and $E_T > 3.5$ or 5 GeV, with additional experimental cuts which differ in the two analyses and account for the differences in the experimentally defined cross-sections. There are residual ($\sim 20\%$) uncertainties in determining the hadron-to-parton level corrections and therefore the measurements are presented at hadron level. The data are shown in Figure 2 where the rise of F_2 at low-x is mirrored by the rise of the forward jet cross-sections with decreasing x.

In Figure 2(a) the data are compared to HO (Higher Order) BFKL calculations [8]. Sub-leading corrections to the LO (Leading Order) cross-section are significant in the measured region reducing the original predictions by a factor of two. The renormalisation scale dependence produces the largest uncertainty in the calculations and is indicated by the dotted/dashed lines where the scale $\mu^2 \simeq E_T^2$ is varied by a factor of four, corresponding to a variation of the cross-section of 50%. The calculations describe the low-x H1 and ZEUS data although there are hints that the low-x approximations are not valid for the higher-$x \sim 10^{-2}$ ZEUS data.

In Figure 2(b) the ZEUS data are compared to NLO DGLAP calculations [9]. In the upper plot, only direct contributions of the virtual photon are included: the calculations underestimate the cross-section by a factor of four. In the lower plot, resolved photon contributions, where partons from the virtual photon interact with partons from the proton, are added: these enhance the cross-section such that data and theory agree. The renormalisation/factorisation scale dependence again produces the largest uncertainty and is indicated by the dashed/dotted lines where the scale $\mu^2 \simeq 2E_T^2$ is varied by a factor of three.

In conclusion, the low-x forward jet data can be described either by the BFKL approach *provided* that sub-leading terms are included or by the NLO DGLAP approach *provided* that resolved photon contributions are added. In both cases, the scale uncertainties are up to 50% in the currently measured ranges of E_T and x_{jet}.



(a) HO BFKL

(b) NLO DGLAP

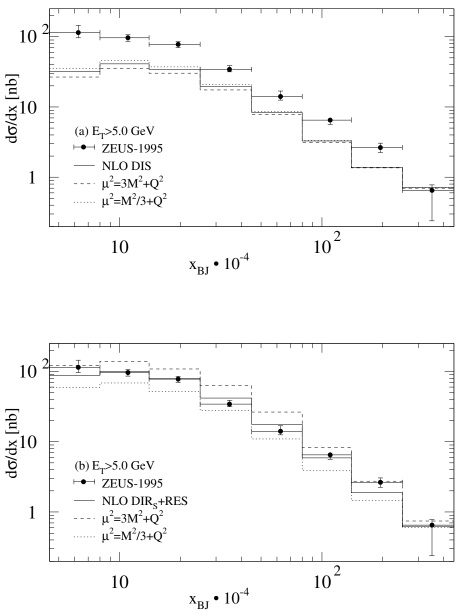


Figure 2. (a) H1 ($E_T > 3.5$ GeV and $E_T > 5$ GeV) and ZEUS ($E_T > 5$ GeV) forward jet cross-sections compared to HO BFKL calculations including sub-leading contributions [8] shown on a linear scale. (b) ZEUS ($E_T > 5$ GeV) forward jet cross-section compared to NLO DGLAP calculations [9] for direct (above) and direct plus resolved (below) processes shown on a logarithmic scale. The scale dependences, discussed in the text, are indicated by the dotted/dashed lines.

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