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Event shapes and subjet distributions at HERA

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At lowest-order QCD, the diagrams that contribute to neutral current (NC) deep inelastic ep scattering (DIS) at HERA are the boson-gluon fusion (BGF) ($Vg \rightarrow q\bar{q}$, where $V = \gamma^*$ or Z^0) and QCD-Compton (QCDC) ($Vq \rightarrow qg$) processes. Any observable can be expressed as the convolution of the parton densities in the proton, f_a, times the matrix elements. Thus, in the regions of phase space where the parton densities are well constrained, measurements of e.g. jet cross sections can be used to perform tests of perturbative QCD (pQCD) and determinations of α_s. The hadronic final state in NC DIS can also be used to study the pattern of parton radiation by means e.g. of subjets inside jets. Subjets observables are calculable in pQCD and so they provide stringent tests of the theory. On the other hand, the hadronisation process, a non-perturbative effect, can be studied by means of the event shapes. Recent developments on the model of power-law corrections have prompted revived interest in understanding hadronisation within the framework of pQCD.

Recent results on subjet distributions from ZEUS are presented. The measured normalised cross sections were used to study the pattern of parton radiation. The comparison of the measurements with leading-logarithm parton-shower Monte Carlo models and perturbative QCD calculations shows a good agreement between data and predictions. Results on event-shape mean values and distributions are also presented. These measurements were used to test the predictions of the power-correction model for hadronisation. A universal value, within 10%, of the effective parameter $\bar{\alpha}_0$ of the model was obtained.

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1. Subjet distributions

The investigation of the internal structure of jets gives insight into the transition between a parton produced in a hard process and the experimentally observable jet of hadrons. At sufficiently high jet transverse energy, $E_T^{\rm jet}$, where the effects of fragmentation can be neglected, the jet structure can be calculated perturbatively. The lowest non-trivial-order contribution to the jet substructure is given by $\mathcal{O}(\alpha_s)$ calculations for NC DIS in the laboratory (LAB) frame. Next-to-leading-order (NLO) calculations of jet substructure can be obtained in the LAB frame since, in such a case, it is possible to have three partons inside one jet.

The k_T cluster algorithm was used in the longitudinally invariant inclusive mode to define jets in the hadronic final state. The internal structure of the jets can be studied by means of the subjet topology.

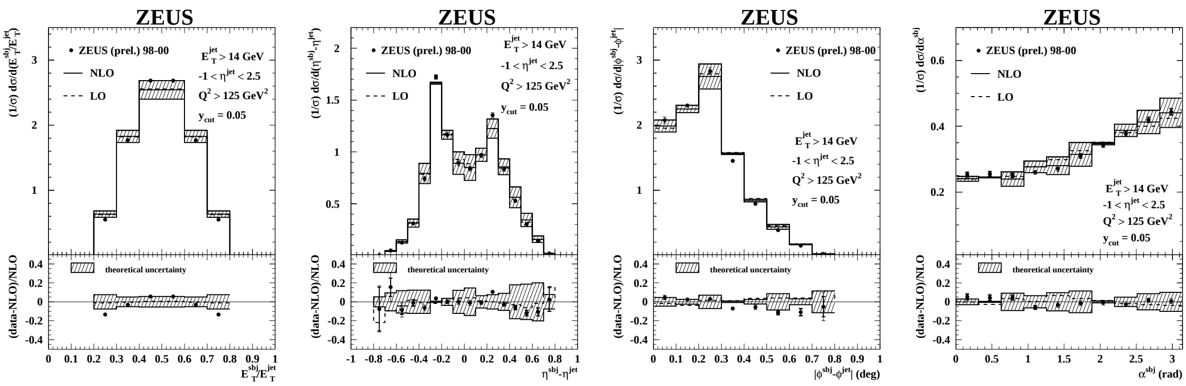
The pattern of QCD radiation from a primary parton has been studied [1] by measuring normalised cross sections as a function of subjet observables: the ratio between the subjet transverse energy and that of the jet, $E_T^{\rm sbj}/E_T^{\rm jet}$, the difference between the subjet pseudorapidity (azimuth) and that of the jet, $\eta^{\rm sbj}-\eta^{\rm jet}$ ($|\phi^{\rm sbj}-\phi^{\rm jet}|$), and $\alpha^{\rm sbj}$, the angle, as viewed from the jet centre, between the highest transverse energy subjet and the beam line in the pseudorapidity-azimuth plane. The measurements were done for $Q^2 > 125$ GeV^2, where Q^2 is the momentum transfer. Jets of $E_T^{\rm jet} > 14$ GeV and $-1 < \eta^{\rm jet} < 2.5$ were selected. The final sample consisted of those jets which had two subjets for $y_{\rm cut} = 0.05$.

The $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$ QCD calculations used to compare with the data are based on the program DISENT. For these calculations, the number of flavours was set to five; the renormalisation and factorisation scales were both set to $\mu_R = \mu_F = Q$; α_s was calculated at two loops using $\Lambda^{(5)}_{\overline{\rm MS}} =$ 220 MeV, which corresponds to $\alpha_s(M_Z) = 0.1175$. The MRST99 parameterisations of the proton parton density functions (PDFs) were used.

The cross-section $(1/\sigma)(d\sigma/d(E_T^{\rm sbj}/E_T^{\rm jet}))$ is presented in Fig. 1a. The distribution of the fraction of transverse energy contains two entries per jet and is symmetric with respect to $E_T^{\rm sbj}/E_T^{\rm jet} =$ 0.5 by construction. The data distribution has a peak at $E_T^{\rm sbj}/E_T^{\rm jet} = 0.5$, which shows that the two subjets tend to have similar transverse energies. The distribution for the difference in pseudorapidity is shown in Fig. 1b and also has two entries per jet. The measured cross section has a two-peak asymmetric structure, with a dip at $\eta^{\rm sbj}-\eta^{\rm jet} \sim 0$, which shows that the subjets cannot be reconstructed too close together. Figure 1c presents the normalised cross section as a function of $|\phi^{\rm sbj}-\phi^{\rm jet}|$. There are two entries per jet in this distribution. The data distribution has a peak at $|\phi^{\rm sbj}-\phi^{\rm jet}| = 0.2-0.3$; the suppression at $|\phi^{\rm sbj}-\phi^{\rm jet}| \sim 0$ comes also from the fact that the subjets cannot be resolved when they are too close together. The distribution as a function of $\alpha^{\rm sbj}$ (one entry per jet) increases as $\alpha^{\rm sbj}$ increases (see Fig. 1d). This shows that the highest transverse energy subjet tends to be in the rear direction. This is consistent with the asymmetric peaks observed in the $\eta^{\rm sbj}-\eta^{\rm jet}$ distribution.

The fixed-order QCD calculations are compared to the data in Fig. 1. The QCD predictions give a good description of the data in shape, within 10%. This shows that the mechanism driving the subjet topology are the $q \to qg$ and $g \to q\bar{q}$ subprocesses as implemented in the pQCD calculations.

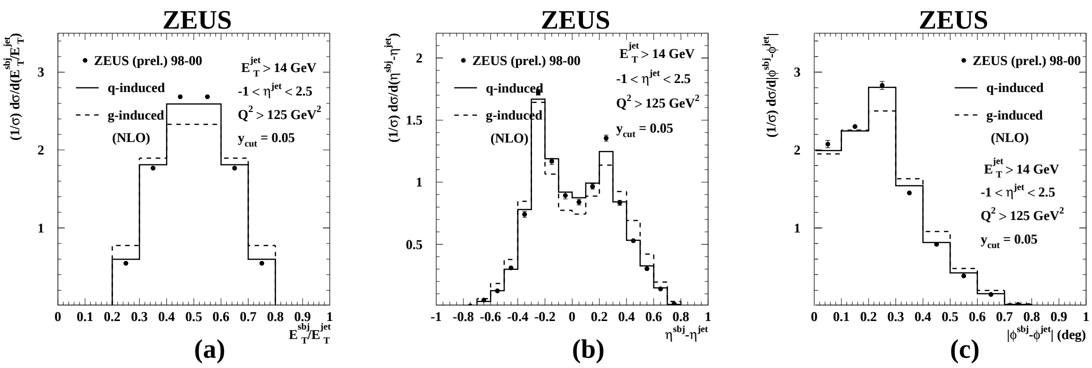
To study in more detail the pattern of parton radiation, the predictions of quark- and gluon-induced processes are compared separately with the data in Fig. 2. The NLO calculations predict



(a) (b) (c) (d)

Figure 1: Normalised differential subjet cross sections as functions of (a) $E_T^{\rm sbj}/E_T^{\rm jet}$ and (b) $\eta^{\rm sbj}-\eta^{\rm jet}$. For comparison, the predictions of DISENT at LO (dashed histograms) and NLO (solid histograms) are included.

that the two-subjet rate is dominated by quark-induced processes: the relative contribution of quark- (gluon-) induced processes is 82% (18%). The predictions for these two types of processes are different: in quark-induced processes, the two subjets have more similar transverse energies (Fig. 2a) and are closer to each other (Figs. 2b and 2c) than in gluon-induced processes. The comparison with the measurements shows that the data are better described by the calculations for jets arising from a *qg* pair than those coming from a $q\bar{q}$ pair.



(a) (b) (c)

Figure 2: Normalised differential subjet cross sections as functions of (a) $E_T^{\rm sbj}/E_T^{\rm jet}$, (b) $\eta^{\rm sbj}-\eta^{\rm jet}$ and (c) $|\phi^{\rm sbj}-\phi^{\rm jet}|$. For comparison, the NLO predictions for quark- (solid histograms) and gluon-splitting (dashed histograms) are included.

2. Event shapes

Event-shape observables are particularly sensitive to the details of the non-perturbative effects of hadronisation and can be used to test the models for these effects. In this type of analysis, the data are compared to model predictions which combine NLO calculations and the theoretical expectations of the power-corrections (PC) model, which is characterised by an effective coupling $\bar{\alpha}_0$. The total prediction for any event-shape observable is then given by the sum of the perturbative and PC predictions. Previous results supported the concept of power corrections in the approach of Dokshitzer et al., but a large spread of the results suggested that higher-order corrections were needed. Now, resummed next-to-leading-logarithm (NLL) calculations matched to NLO are available and so it is possible to study event-shape mean values as well as distributions.

The event-shape observables studied are thrust, T, broadening, B, the C parameter and the jet mass, M. A suitable frame in which to study event shapes at HERA is the Breit frame since in this frame, the separation between the current jet and the proton remnant is maximal. The event-shape variables are reconstructed for all the particles in the current hemisphere of the Breit frame.

Measurements of event-shape means have been made [2] as a function of Q for each observable in the kinematic region given by $80 < Q^2 < 2 \cdot 10^4$ GeV^2 and $0.0024 < x < 0.6$. Predictions consisting of NLO + PC calculations have been fitted to the data, leaving α_s and $\bar{\alpha}_0$ as free parameters. Each observable was fitted separately. The NLO predictions were calculated using the program DISASTER++. The proton PDFs have been parameterised using the CTEQ4M sets. A reasonable fit is obtained for all the event-shape observables within the Q^2 range studied.

Figure 3 shows the event-shape differential distributions [2] for some of the observables in different regions of Q. In this case, the fit was done using NLO + NLL + PC. The NLO predictions have been calculated using the DISASTER++ and DISPATCH programs with the MRST99 proton PDF sets. The PC and matched NLL predictions were calculated using the DISRESUM package. In DISRESUM, the power correction is applied as a shift of the distribution, which has the same functional form as the power correction for the mean. For B_γ, there is in addition a change in shape. The range of the fit for each observable was restricted to the regions where the predictions were valid. A reasonable fit is obtained for all the event-shape observables within the restricted ranges studied.

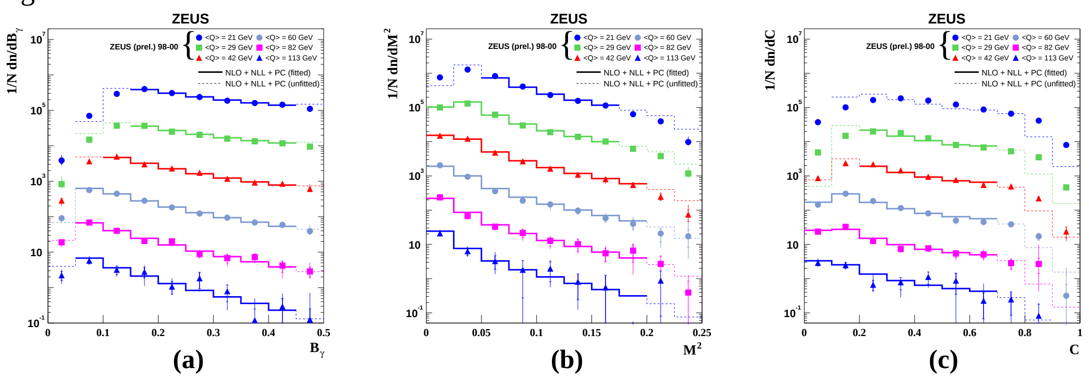


Figure 3: Event-shape distributions as functions of (a) B_γ, (b) M^2 and (c) C, fitted with NLL resummed calculations matched to NLO + PC.

The extracted values of α_s and $\bar{\alpha}_0$ from the means and differential distributions are shown in Figs. 4a and 4b, respectively. It is possible to obtain a universal value for $\bar{\alpha}_0$ of 0.45 at the 10% level, except for T_γ (means) and C parameter (distributions). The extracted values of $\bar{\alpha}_0$ and $\alpha_s(M_Z)$ from the means show a dispersion that could be due to higher-order terms. The extracted values of $\alpha_s(M_Z)$ from the distributions are consistent with the world average.

Measurements of an event-shape observable sensitive to higher-order effects have been made [2]. The out-of-plane momentum, $K_{\mathrm{OUT}} = \sum_i |p_i^{\mathrm{out}}|$, which is defined as the energy flow out of the plane defined by the proton direction and the axis which maximises the thrust, is sensitive both to perturbative and non-perturbative contributions. The lowest non-trivial contribution comes from non-

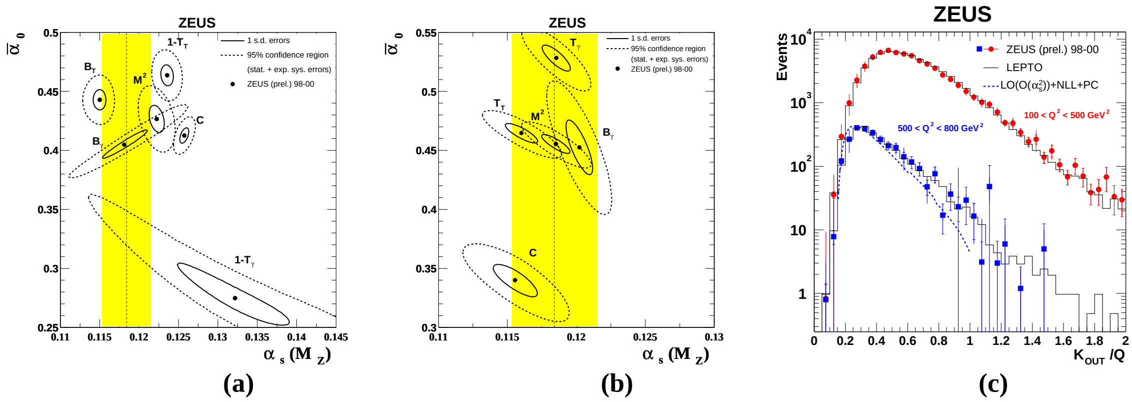


Figure 4: Extracted $\alpha_s(M_Z)$ and $\bar{\alpha}_0$ parameters from (a) mean values and (b) distributions. (c) Distribution of K_{OUT}/Q compared with LEPTO and leading-order + NLL + PC calculation.

perturbative effects or from $\mathscr{O}(\alpha_s^2)$ contributions. Figure 4c shows the measurements of K_{OUT}/Q in two ranges of Q^2. The data are well described by the predictions of the leading-logarithm parton-shower model of LEPTO. This constitutes the first comparison of calculations which include leading-order + NLL + PC with the data, in the high-Q^2 range only. The description of the data by the prediction is reasonable, but a more precise test of the model needs higher-order calculations.

3. Summary

Subjet normalised cross sections have been measured in NC DIS using 81.7 pb^{-1} of data collected with the ZEUS detector at HERA with a centre-of-mass energy of 318 GeV. A reasonable description of the data is obtained by the QCD predictions. This means that the pattern of parton radiation as implemented in a NLO calculation reproduces the behaviour of the data. In addition, the data are well described by the calculations for jets arising from the splitting of a quark into a quark-gluon pair.

Event-shape means and distributions have been measured in NC DIS using 82.2 pb^{-1} of data collected with the ZEUS detector at HERA with a centre-of-mass energy of 318 GeV. Calculations including NLO + PC, and including resummed NLL predictions matched to NLO for the differential distributions, give a reasonable description of the data. The extracted values of the power-correction parameter, $\bar{\alpha}_0$, are consistent within 10%. The extracted values of the strong coupling constant are consistent with the world average. However, more theoretical input is needed to fully exploit the potential of these measurements.

References

[1] ZEUS Coll., Contributed paper N-384 to the HEP2005 International Europhysics Conference on High Energy Physics, July 21st-27th, 2005, Lisbon, Portugal.

[2] ZEUS Coll., Contributed paper N-381 to the HEP2005 International Europhysics Conference on High Energy Physics, July 21st-27th, 2005, Lisbon, Portugal.