Jet shapes in \( ep \) collisions at HERA

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Abstract

New measurements of the jet shape in \( ep \) collisions at HERA using the \( k_T \)-cluster jet algorithm are presented.

1 Introduction

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 spray of hadrons. The internal structure of a jet is expected to depend mainly on the type of primary parton, quark or gluon, from which it originated and to a lesser extent on the particular hard scattering process. A useful representation of the jet’s internal structure is given by the jet shape \( [1] \). At sufficiently high jet energy, where fragmentation effects become negligible, the jet shape should be calculable by perturbative QCD. Measurements of the jet shape provide a stringent test of pQCD calculations beyond leading order. Gluon jets are predicted to be broader than quark jets due to the larger colour charge of the gluon. The dependence of the structure of quark and gluon jets on the production process can be investigated by comparing measurements of the jet shape in different reactions in which the final-state jets are predominantly quark or gluon initiated.

Measurements of the jet shape were made in \( \bar{p}p \) collisions at \( \sqrt{s} = 1.8 \text{ TeV} \) \( [2, 3] \) and in \( e^+e^- \) interactions at LEP1 \( [4] \). It was observed \( [4] \) that the jets in \( e^+e^- \) are significantly narrower than those in \( \bar{p}p \) and most of this difference was ascribed to the different mixtures of quark and gluon jets in

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the two production processes. At HERA, measurements have been presented of the jet shape in quasi-real photon proton collisions (photoproduction) \[5\] and in neutral- and charged-current deep inelastic scattering (DIS) \[6\]. In photoproduction, the jets were observed to become broader as the jet pseudorapidity (\(\eta_{\text{jet}}\)) increases in agreement with the predicted increase in the fraction of final-state gluon jets. In DIS, the jet shapes in neutral- and charged-current processes were found to be very similar. The jet shapes in DIS were observed to be similar to those in \(e^+e^-\) interactions and narrower than those in \(\bar{p}p\) collisions. Since the jets in \(e^+e^-\) interactions and \(e^+p\) DIS are predominantly quark initiated in both cases, the similarity in the jet shapes indicates that the pattern of QCD radiation within a quark jet is to a large extent independent of the hard scattering process in these reactions.

New measurements of the jet shape using the \(k_T\)-cluster algorithm \[7, 8\] in photoproduction \[9\] and DIS \[10\] at HERA provide an improved test of pQCD calculations \[11\] and are presented here. During 1994-1997 HERA operated with positrons of energy \(E_e = 27.5\) GeV colliding with protons of energy \(E_p = 820\) GeV.

2 Measurement of the jet shape in photoproduction

At HERA, quasi-real photon proton collisions are studied via ep scattering at low four-momentum transfers (\(Q^2 \approx 0\), where \(Q^2\) is the virtuality of the exchanged photon). Jets are searched for in the pseudorapidity (\(\eta\) - azimuth (\(\varphi\)) plane of the laboratory frame using the inclusive \(k_T\)-cluster algorithm \[8\] (see \[12\] for the experimental implementation). The jet variables are defined according to the Snowmass convention \[13\]. The inclusive sample of jets with transverse energy \(E_T^{\text{jet}} > 17\) GeV and \(-1 < \eta^{\text{jet}} < 2\) has been studied.

The differential jet shape is defined as the average fraction of the jet’s transverse energy that lies inside an annulus in the \(\eta - \varphi\) plane of inner (outer) radius \(r - \Delta r/2\) \((r + \Delta r/2)\) concentric with the jet axis \[8\]:

\[
\rho(r) \equiv \frac{1}{N_{\text{jets}}} \frac{1}{\Delta r} \sum_{\text{jets}} \frac{E_T(r - \Delta r/2, r + \Delta r/2)}{E_T(0, 1)},
\]

where \(E_T(r - \Delta r/2, r + \Delta r/2)\) is the transverse energy within the given annulus and \(N_{\text{jets}}\) is the total number of jets in the sample. The differential
Figure 1: Measured differential jet shapes corrected to the hadron level, $\rho(r)$, using the $k_T$-cluster algorithm for jets with $E_T^{\text{jet}} > 17$ GeV in different $\eta^{\text{jet}}$ regions (black dots). For comparison, the predictions of PYTHIA for photoproduced jets (solid histogram) and separately for quark and gluon jets are shown in the left-hand side of the figure. The measurements using the cone algorithm with $R = 1$ (open circles) are compared to those with the $k_T$-cluster algorithm in the right-hand side of the figure.

The differential jet shape has been measured for $r$ values varying from 0.05 to 0.95 in $\Delta r = 0.1$ increments.

The differential jet shape has been measured using the ZEUS uranium-scintillator calorimeter and corrected to the hadron level. The measurements are given in the kinematic region defined by $Q^2 < 1$ GeV$^2$ (with a median of $Q^2 \approx 10^{-3}$) and photon-proton centre-of-mass energies between 134 and 277 GeV. The measured differential jet shapes for different regions in $\eta^{\text{jet}}$ are shown in Figure 1 (black dots). It is observed that the jet broadens as $\eta^{\text{jet}}$ increases in agreement with our previous observation using an iterative cone algorithm with radius $R = 1$.

The predicted jet shapes at the hadron level from a leading-logarithm parton-shower Monte Carlo calculation using PYTHIA are compared to the measurements in the left-hand side of Figure 1. The calculations include initial- and final-state parton radiation, and the fragmentation into hadrons is
performed using the LUND string model. The measured jet shapes are found to be well described by the predictions (solid histogram). The jet shapes, as predicted by PYTHIA, for quark (dot-dashed histogram) and gluon (dashed histogram) jets are also shown in Figure 1: the broadening of the jets in the data as $\eta^{jet}$ increases is consistent with an increasing fraction of gluon jets.

It has been shown [11] that the inclusive $k_T$-cluster algorithm provides, at present, the best jet algorithm from the theoretical point of view since the problem of overlapping jets, which affects e.g. the iterative cone algorithm [15], is avoided. To quantify the effects of the specific jet algorithm on the jet shape, the measurements have been repeated using the iterative cone algorithm with radius $R = 1$. The results (open circles) are compared to those using the $k_T$-cluster algorithm (black dots) in the right-hand side of Figure 1: the measured jet shapes differ by less than 10% in the region $r < 0.6$. For larger values of $r$ differences are expected since in the case of the iterative cone algorithm only those particles within a cone concentric to the jet axis are assigned to the jet while in the $k_T$ no such a restriction is imposed. Thus, in spite of the differences between the two algorithms the jet shapes are observed to be very similar in the region $r < 0.6$ and demand pQCD calculations which are able to reproduce the features of the specific jet algorithm with an accuracy better than 10%. Next-to-leading order QCD calculations of the jet shape with the $k_T$-cluster algorithm, which are not available at present, are needed to meet such a requirement.

3 Measurement of the jet shape in deep inelastic scattering

Measurements have been made of the internal jet structure in a sample of inclusive dijet neutral-current DIS events [10], $e^+ + p \rightarrow e^+ + \text{jet + jet + X}$, in the kinematic region defined by $10 < Q^2 \lesssim 120 \text{ GeV}^2$ and $2 \cdot 10^{-4} \lesssim x_{Bj} \lesssim 8 \cdot 10^{-3}$. Jets are searched for in the $\eta - \varphi$ plane of the Breit frame using the inclusive $k_T$-cluster algorithm [8]. The jet variables are defined according to the Snowmass convention [13]. The sample of inclusive dijet events with transverse energy (with respect to the direction of the virtual photon in the Breit frame) $E_T^{jet} (\text{Breit}) > 5 \text{ GeV}$ and $-1 < \eta^{jet} (\text{Lab}) < 2$ has been investigated.
In this analysis the internal structure of a jet is studied in terms of the integrated jet shape, $\Psi(r)$, which is defined as the average fraction of the jet’s transverse energy that lies inside a subcone in the $\eta - \phi$ plane of radius $r$ concentric with the jet axis [1]:

$$\Psi(r) \equiv \frac{1}{N_{jets}} \sum_{jets} \frac{E_T(r)}{E_T^{jet}(\text{Breit})},$$

where $E_T(r)$ is the transverse energy within the subcone of radius $r$ and $N_{jets}$ is the total number of jets in the sample.

The measured integrated jet shapes [10] are shown in Figure 2 for two ranges in $E_T^{\text{jet}}(\text{Breit})$ and three regions in $\eta^{\text{jet}}(\text{Breit})$ (negative $\eta^{\text{jet}}(\text{Breit})$ corresponds to the virtual-photon hemisphere). The jets are observed to be more collimated as $E_T^{\text{jet}}(\text{Breit})$ increases. On the other hand, the jets become broader as $\eta^{\text{jet}}(\text{Breit})$ increases and this effect is more pronounced at lower $E_T^{\text{jet}}(\text{Breit})$. The measured dependence of the jet shape on $E_T^{\text{jet}}(\text{Breit})$ and $\eta^{\text{jet}}(\text{Breit})$ is roughly reproduced by the predictions of various QCD-based models (not shown here; see [10]). However, studies based on these models show that in the region of $E_T^{\text{jet}}(\text{Breit})$ considered in this analysis the jet shape is strongly influenced by hadronization. Thus, measurements with higher $E_T^{\text{jet}}$ (see [3, 4]) are needed to test pQCD calculations.

The measurements have been repeated [10] using a version of the iterative cone algorithm [16] which allows improved pQCD calculations of the jet
shape. The measured jet shapes with the $k_T$-cluster and the iterative cone algorithms are observed to be very similar in the region $E_T^{jet}(\text{Breit}) > 8$ GeV and $\eta^{jet}(\text{Breit}) < 2.2$. For lower $E_T^{jet}(\text{Breit})$ or higher $\eta^{jet}(\text{Breit})$ the jets identified with the cone algorithm are broader. From this comparison and that in photoproduction (with $E_T^{jet} > 17$ GeV), it is concluded that the effects of the specific jet algorithm decrease rapidly as $E_T^{jet}$ increases. The measurements of jet shapes with the $k_T$-cluster algorithm at high $E_T^{jet}$ ($E_T^{jet} > 17$ GeV) constitute a challenge to pQCD calculations.

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