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Substructure of jets in neutral-current deep inelastic scattering at HERA

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Abstract. Measurements are presented of jet shapes and subjet distributions in neutralcurrent deep inelastic ep scattering at HERA using the ZEUS detector.

1. Introduction

Jet production in neutral current (NC) deep inelastic ep scattering (DIS) represents a fruitful arena for precise tests of perturbative quantum chromodynamics (QCD) in a hadron-induced reaction. For a given ep centre-of-mass energy $(\sqrt{s_{ep}})$ the kinematics of the reaction e(k) + $p(P) \rightarrow e(k') + X$ can be described by two independent variables such as the negative of the squared momentum transfer between the electron and the proton $(Q^2 = -q^2 = -(k - k')^2)$ and the Bjorken-*x* variable defined by $x_{Bj} = Q^2/(2P \cdot q)$. At HERA, electrons (or positrons) of energy $E_e = 27.5$ GeV collided head-on with protons of energy $E_p = 920$ GeV yielding $\sqrt{s_{ep}} = 318$ GeV. Measurements of jet cross sections in NC DIS at high Q^2 at HERA have allowed stringent tests of the predictions of perturbative QCD (pQCD), precise measurements of the strong coupling constant (α_s) and an improved determination of the parton distribution functions (PDFs) of the proton. The development of flexible programs to compute the predictions of pQCD for final states with up to four partons provides a powerful tool to extend the studies of jets beyond production rates. The internal structure of jets is a promising avenue in which to study the validity of a perturbative description and the extent to which the pattern of parton radiation results in the observed substructure of jets. With this goal in mind, measurements of jet substructure in NC DIS at HERA have been performed using the ZEUS detector [1] and compared to next-to-leading-order (NLO) QCD calculations.

2. Measurements of jet shapes

Jets have been identified using the k_T -cluster algorithm [2] in the longitudinally invariant inclusive mode [3]. The jet search was performed in the pseudorapisity (η)-azimuth (ϕ) plane of the laboratory frame. The mean integrated jet shape [4] is defined as the average fraction of the jet transverse energy that lies inside a circle of radius r in the η - ϕ plane concentric with the jet axis: $\langle \Psi(r) \rangle = 1/N_{jets} \sum E_T(r)/E_T^{jet}$, where $E_T(r)$ is the transverse energy within the given circle of radius r, E_T^{jet} is the jet transverse energy and N_{jets} is the total number of jets in the sample.

Measurements of $\langle \Psi(r) \rangle$ have been made in NC DIS [5] in the kinematic region defined by $Q^2 > 125 \text{ GeV}^2$ using an integrated luminosity of 368 pb⁻¹. The mean integrated

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jet shape has been measured for two samples of events: 1) events with only one jet with $E_T^{jet} > 14$ GeV and jet pseudorapidity in the range $-1 < \eta^{jet} < 2.5$ (sample A); 2) events with only two jets with $E_T^{jet} > 14$ GeV, $-1 < \eta^{jet} < 2.5$ and the interjet distance $d_{jj} \equiv \sqrt{(\eta^{jet,1} - \eta^{jet,2})^2 + (\phi^{jet,1} - \phi^{jet,2})^2} \leq 2$; in this case, only the jet with next-to-highest E_T^{jet} is considered in the measurement of $\langle \Psi(r) \rangle$ (sample B). The measurements refer to jets at the hadron level and have been corrected for detector and QED effects; the detector effects amount to < 10% for $r \geq 0.4$.



Figure 1. Measurements and NLO pQCD calculations of $\langle \Psi(r) \rangle$ as functions of r in NC DIS

The measurements of $\langle \Psi(r) \rangle$ are presented for the sample of one-jet events (dots) and for the jet with next-to-highest E_T^{jet} in two-jet events (squares) in figure 1(a). It is observed that the jets in sample B are significantly broader than those in sample A. These differences can be understood in terms of the subprocesses contributing to each sample: in sample A, the Born subprocess $eq \rightarrow eq$ is dominant and gives rise only to quark-initiated jets; in sample B, the subprocesses $eq \rightarrow eqg$ (QCD Compton) and $eg \rightarrow q\bar{q}$ (photon-gluon fusion) are dominant and give rise both to quark- and gluon-initiated jets. Since gluon jets are predicted to be broader than quark jets due to the larger colour charge of the gluon, sample B is expected to have a larger fraction of gluon jets and, as a result, broader jets than in sample A. Since jets become narrower as E_T^{jet} for the two samples. To disentangle this effect, measurements of $\langle \Psi(r) \rangle$ have been made restricted to jets with E_T^{jet} in the range $14 < E_T^{jet} < 17$ GeV. The results are shown in figure 1(b) and still significant differences are observed between the two samples.

For the sample of one-jet events, the mean integrated jet shape has been calculated at NLO pQCD from the fraction of the jet transverse energy, due to parton emission, that lies outside the circle of radius $r: \langle 1 - \Psi(r) \rangle = (1/\sigma(jet))(\int dE_T (E_T/E_T^{jet}) (d\sigma(ep \to 2, 3 \text{ partons})/dE_T))$, where $\sigma(jet)$ is the cross section for the production of one-jet events. In the above ratio of cross sections, the numerator is calculated up to $\mathcal{O}(\alpha \alpha_s^2)$ whereas the denominator is calculated up to $\mathcal{O}(\alpha \alpha_s)$. For the sample of two-jet events, the integrand in the numerator involves the differential cross sections for $ep \to 3, 4$ partons and is computed up to $\mathcal{O}(\alpha \alpha_s^3)$, whereas the denominator refers to the cross section for the production of two-jet events and is computed up to $\mathcal{O}(\alpha \alpha_s^2)$.

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The NLO QCD calculations of the mean integrated jet shape for the sample of one-jet (twojet) events are based on the program DISENT [6] (NLOJET++ [7]). The number of flavours was set to five; the renormalisation (μ_R) and factorisation (μ_F) scales were both set to $\mu_R = \mu_F = Q$; α_s was calculated at two loops using $\Lambda_{\overline{MS}}^{(5)} = 226$ MeV, which corresponds to $\alpha_s(M_Z) = 0.118$. The CTEQ6 [8] parametrisations of the proton PDFs were used. Since the measurements refer to jets of hadrons, whereas the QCD calculations refer to partons, the predictions were corrected to the hadron level using samples of Monte Carlo generated events. The multiplicative correction factor was calculated as $C_{had} = \langle \Psi(r) \rangle_{had} / \langle \Psi(r) \rangle_{par}$, where $\langle \Psi(r) \rangle_{par}$ ($\langle \Psi(r) \rangle_{had}$) is the mean integrated jet shape before (after) the hadronisation process in the Monte Carlo generator. The hadronisation corrections thus obtained amount to < 10% for $r \geq 0.4$.

The NLO QCD calculations of $\langle \Psi(r) \rangle$ for the two samples, corrected for hadronisation effects, are compared to the data in figures 1(a) and (b). The NLO QCD calculations reproduce the data reasonably well. In particular, the observed differences in the mean integrated jet shape between the samples of one-jet and two-jet events are accounted for by the calculations.

3. Measurements of subjet distributions

The use of the k_T -cluster algorithm to define jets provides another observable to investigate the internal structure of jets, namely subjets [9]. Subjets are resolved within a jet by considering all particles associated with the jet and repeating the application of the k_T -cluster algorithm until, for every pair of particles *i* and *j* the quantity $d_{ij} = \min(E_{T,i}, E_{T,j})^2 \cdot ((\eta^i - \eta^j) + (\phi^i - \phi^j)^2)$ is greater than $d_{\text{cut}} = y_{\text{cut}} \cdot (E_T^{jet})^2$. All remaining clusters are called subjets. The subjet multiplicity depends upon the value chosen for the resolution parameter y_{cut} . The pattern of QCD radiation from a primary parton has been studied by measuring normalised cross sections as functions of the subjet variables: E_T^{sbj}/E_T^{jet} , $\eta^{sbj} - \eta^{jet}$, $\phi^{sbj} - \phi^{jet}$ and α^{sbj} , where E_T^{sbj} is the subjet transverse energy, η^{jet} is the subjet pseudorapidity, ϕ^{sbj} is the subjet azimuthal angle and α^{sbj} is the angle, as viewed from the jet centre, between the highest transverse energy subjet and the beam line in the η - ϕ plane of the laboratory frame.

Measurements of subjet distributions have been made in NC DIS [10] for those jets with $E_T^{jet} > 14$ GeV and $-1 < \eta^{jet} < 2.5$ which have exactly two subjets for $y_{\text{cut}} = 0.05$ in the kinematic region defined by $Q^2 > 125$ GeV² using an integrated luminosity of 81.7 pb⁻¹. The measurements refer to jets and subjets at the hadron level and have been corrected for detector effects. The results are shown in figure 2.



Figure 2. Measurements and pQCD calculations of subjet distributions in NC DIS

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The normalised differential cross-section $(1/\sigma)(d\sigma/d(E_T^{sbj}/E_T^{jet}))$, displayed in figure 2(a), has a peak at $E_T^{sbj}/E_T^{jet} = 0.5$, which shows that the two subjets tend to have similar transverse energies. The normalised cross section as a function of $\eta^{sbj} - \eta^{jet}$ has a two-peak structure (see figure 2(b)); the dip at $\eta^{sbj} - \eta^{jet} \sim 0$ comes from the fact that the subjets cannot be reconstructed too close to each other. The normalised cross section as a function of α^{sbj} , which is displayed in figure 2(c), increases as α^{sbj} increases and shows that the highest transverse energy tends to be in the rear direction.

Leading-order (LO) and NLO QCD calculations are compared to the data in figure 2. The pQCD calculations have been obtained using the program DISENT with the same settings as mentioned in the previous section, except that the MRST99 [11] parametrisations of the proton PDFs and $\Lambda_{\overline{MS}}^{(5)} = 220$ MeV, which corresponds to $\alpha_s(M_Z) = 0.1175$, were used. The hadronisation correction C_{had} was typically in the range 0.8 - 1.2. The pQCD calculations give a good description of the data and, in particular, reproduce the peak at $E_T^{sbj}/E_T^{jet} = 0.5$, the two-peak structure observed in the distribution of $\eta^{sbj} - \eta^{jet}$ and the increase with α^{sbj} . This comparison shows that the mechanisms driving the subjet topology are the $q \to qg$ and $g \to q\bar{q}$ subprocesses as implemented in the pQCD calculations. In addition, the predictions for quark- and gluon-induced subprocesses are compared to the data in figure 3. The NLO calculations predict that the two-subjet rate is dominated by quark-induced subprocesses (82%). Furthermore, the predictions for these two types of subprocesses are different: in quark-induced subprocesses, the two subjets have more similar transverse energies (see figure 3(a)) and are closer to each other (see figures 3(b) and (c)) than in gluon-induced subprocesses. It is concluded that the data are well described by the calculations for jets arising from the splitting of a quark into a quark-gluon pair.



Figure 3. Measurements and pQCD calculations of subjet distributions in NC DIS

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