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THE INTERNAL STRUCTURE OF JETS AT HERA*

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Measurements of the internal structure of jets in deep-inelastic scattering in terms of the jet shape and the mean subjet multiplicity are used to determine α_s. The data were taken with the ZEUS detector at the HERA collider. From photoproduction dijet events and a sample of charm–quark jets the jet shapes of quark and gluon jets have been statistically extracted to study differences between these types of jets.

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1. Introduction

Jet production in e^+p Deep Inelastic Scattering (DIS) and in photoproduction provides a rich testing ground for perturbative QCD. The internal structure of jets gives insight into the transition from partons to hadrons. Being largely independent of the hard scattering process, it is essentially determined by the type of the primary parton. Gluon-jets are expected to be broader than quark-jets due to the larger colour charge of the gluon.

Measurements of the jet substructure in Neutral Current (NC) DIS allow a determination of α_s. For such measurements the perturbative QCD calculations depend less strongly on the Parton Distribution Functions (PDFs) of the proton. While jets in DIS are predominantly quark-initiated, the photoproduction dijet sample contains both q- and g-jets. Tagging a D^* meson in the event enables one to identify charm–quark jets and to statistically extract the substructure of g-jets.

In the following, results from measurements of the jet substructure in terms of the integrated and the differential jet shape [1] and of the mean subjet multiplicity [2], performed by the ZEUS experiment, are summarised in [3].

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2. Definition of the observables

In the measurements presented, jets have been identified in the laboratory frame applying the longitudinally invariant $k_{\rm T}$ cluster algorithm [4]. The integrated jet shape $\langle\psi(r)\rangle$ is defined as the average fraction of the transverse energy $E_{\rm T}(r)/E_{\rm T}^{\rm Jet}$ associated with the jet, that lies inside a cone of radius $r=\sqrt{(\Delta\eta)^2+(\Delta\phi)^2}$ in the $\eta-\phi$ plane, concentric with the jet axis, where ϕ is the azimuthal angle and $\eta=-\ln\tan\theta/2$ is the pseudo-rapidity. The derivative of $\langle\psi(r)\rangle$ with respect to the radius is the differential jet shape $\rho(r)$, representing the average fraction of transverse jet energy between two cones of radius r and $r+\Delta r$, respectively

$$\langle\psi(r)\rangle=\frac{1}{N_{\rm Jets}}\sum_{\rm Jets}\frac{E_{\rm T}(r)}{E_{\rm T}^{\rm Jet}}\,,\qquad\qquad \rho(r)=\frac{d\psi}{dr}\,.$$

A variable related to the cluster definition of jets is the mean subjet multiplicity, $\langle n_{\rm sbj}\rangle$. The $k_{\rm T}$ cluster algorithm is reapplied to all particles associated with the jet, until for every pair of particles i, j the distance $d_{i,j}$ exceeds a given cut-off value $d_{\rm cut}$:

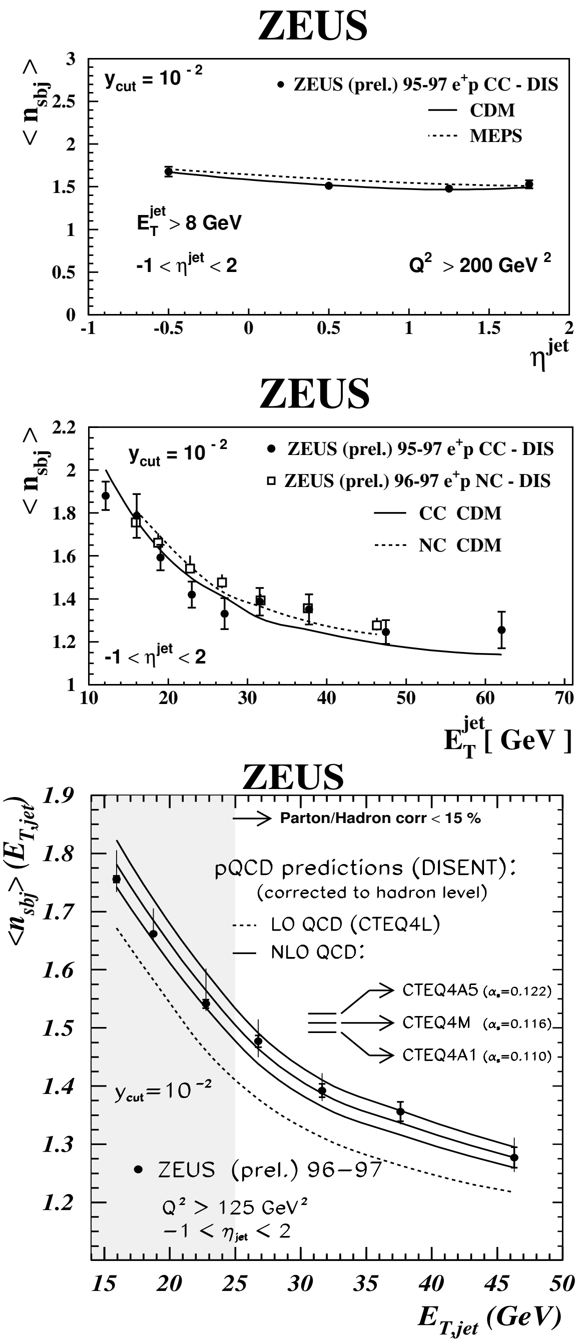
$$d_{i,j}\equiv\min\left\{E_{{\rm T},i}^2,E_{{\rm T},j}^2\right\}\left(\Delta\eta^2+\Delta\phi^2\right)>d_{\rm cut}=y_{\rm cut}\left(E_{\rm T}^{\rm Jet}\right)^2\,.$$

The value of $d_{\rm cut}$ is determined by the resolution parameter $y_{\rm cut}$ and the jet tranverse energy $E_{\rm T}^{\rm Jet}$. All clusters remaining after this procedure are subjets. The mean subjet multiplicity, $\langle n_{\rm sbj}\rangle$, averaged over all jets in the sample, decreases as $y_{\rm cut}$ increases, indicating that less substructure can be resolved, until for a very large value only one subjet is found.

3. Determination of $\alpha_{\rm s}$ from the jet substructure in NC DIS

In DIS at $Q^2>200\,{\rm GeV}^2$, the mean subjet multiplicity $\langle n_{\rm sbj}\rangle$ at a fixed value of $y_{\rm cut}=10^{-2}$ has been measured as a function of the jet's pseudo-rapidity $\eta_{\rm Jet}$ and of its transverse energy $E_{\rm T}^{\rm Jet}$ as shown in Fig. 1. The data are well described by Monte Carlo (MC) simulations. The mean subjet multiplicity exhibits no significant dependence on $\eta_{\rm Jet}$ and decreases as $E_{\rm T}^{\rm Jet}$ increases. Results from NC and charged current (CC) DIS are very similar. As both samples are dominated by quark induced jets, this suggests that the internal jet structure is largely independent of the hard scattering process.

In Fig. 1(c) NC measurements of $\langle n_{\rm sbj}\rangle$ at $y_{\rm cut}=10^{-2}$ as a function of $E_{\rm T}^{\rm Jet}$ are compared to next-to-leading order QCD calculations obtained from the program DISENT [5] with hadronisation effects estimated using the Ariadne MC. The NLO predictions are plotted for three different values of $\alpha_{\rm s}$, illustrating the sensitivity of the measurement.



(a)

(b)

(c)

Fig. 1. (a) $\langle n_{\mathrm{sbj}} \rangle$ in CC as function of η_{Jet}, (b) in NC and CC as function of $E_{\mathrm{T}}^{\mathrm{Jet}}$, (c) $\langle n_{\mathrm{sbj}} \rangle$ *versus* $E_{\mathrm{T}}^{\mathrm{Jet}}$ measured in NC compared to NLO calculations.

To determine $\alpha_{\rm s}$, $\langle n_{\rm sbj}\rangle$ at $y_{\rm cut} = 10^{-2}$ has been used in the region $E_{\rm T}^{\rm Jet} > 25\,{\rm GeV}$, where parton-to-hadron corrections are below 15%. NLO calculations have been performed for the "A" series of CTEQ4 [6], comprising five sets of PDFs. The same value of $\alpha_{\rm s}$ has been used in both the partonic cross section calculation and in the PDFs. Each $E_{\rm T}^{\rm Jet}$ bin yields a separate $\alpha_{\rm s}$ value. The combined value from $\langle n_{\rm sbj}\rangle$ at $Q^2 > 125\,{\rm GeV}^2$, which was determined from a χ^2 fit to all $E_{\rm T}^{\rm Jet}$ bins, is

$$\alpha_{\rm s}(M_Z) = 0.1185 \pm 0.0016 \;({\rm stat.})\; {}^{+0.0067}_{-0.0048} \;({\rm exp.})\; {}^{+0.0089}_{-0.0071} \;({\rm th.})\;,$$

consistent with other recent determinations of the strong coupling by ZEUS [7] and with the current world average $\alpha_{\rm s}(M_Z) = 0.1181 \pm 0.0020$.

4. Jet substructure in photoproduction

For a sample of photoproduction dijet events, jet shapes have been measured as a function of the radius, r, Fig. 2(a), 2(b). They are well described by the PYTHIA MC. The predictions for pure samples of quark- and gluon-jets show that gluon jets are expected to be broader than quark jets. The data lie between the predictions for pure g- and q-jet samples, since the photoproduction sample contains a mixture of these two types of jets.

By using a subset of the dijet photoproduction sample with a reconstructed D^*, it is possible to study quark-jets. The D^* mesons were reconstructed from their decay products:

$$D^{*+} \longrightarrow D^0 + \pi_S^+ \longrightarrow \left(K^- + \pi^+\right) + \pi_S^+$$

and corresponding charge-conjugated decays. The jet closest to the D^* in azimuth has been associated with the charm meson. However, the properties of that jet are strongly determined by the D^* tagging, whereas the other jet, the "untagged-charm jet", represents a largely unbiased quark-jet candidate.

The integrated jet shape of the untagged-charm jet, shown in Fig. 2(c), is well described by the PYTHIA prediction. The prediction for a pure sample of charm jets is consistent with the measurement. By additionally requiring $x_\gamma^{\rm OBS} \equiv \sum_{\rm jets}(E_{\rm T}e^{-\eta})/(2yE_e) > 0.75$, $E_{\rm T}^{\rm Jet} > 15\,{\rm GeV}$ (direct enhanced photoproduction), it is possible to obtain a cleaner sample of charm–quark jets, *cf.* Fig. 2(d).

To statistically extract the substructure of g-jets, the full dijet photoproduction sample has again been used. Observables $\mathcal{O}_d$ for this sample can be written as a linear combination of variables $\mathcal{O}_q$ and $\mathcal{O}_g$ for pure samples of q- and g-jets, respectively, with coefficients f_q, f_g giving the fractions of q- and g-jets in the full dijet sample

$$\mathcal{O}_d = f_q\,\mathcal{O}_q + f_g\,\mathcal{O}_g\,. \tag{1}$$

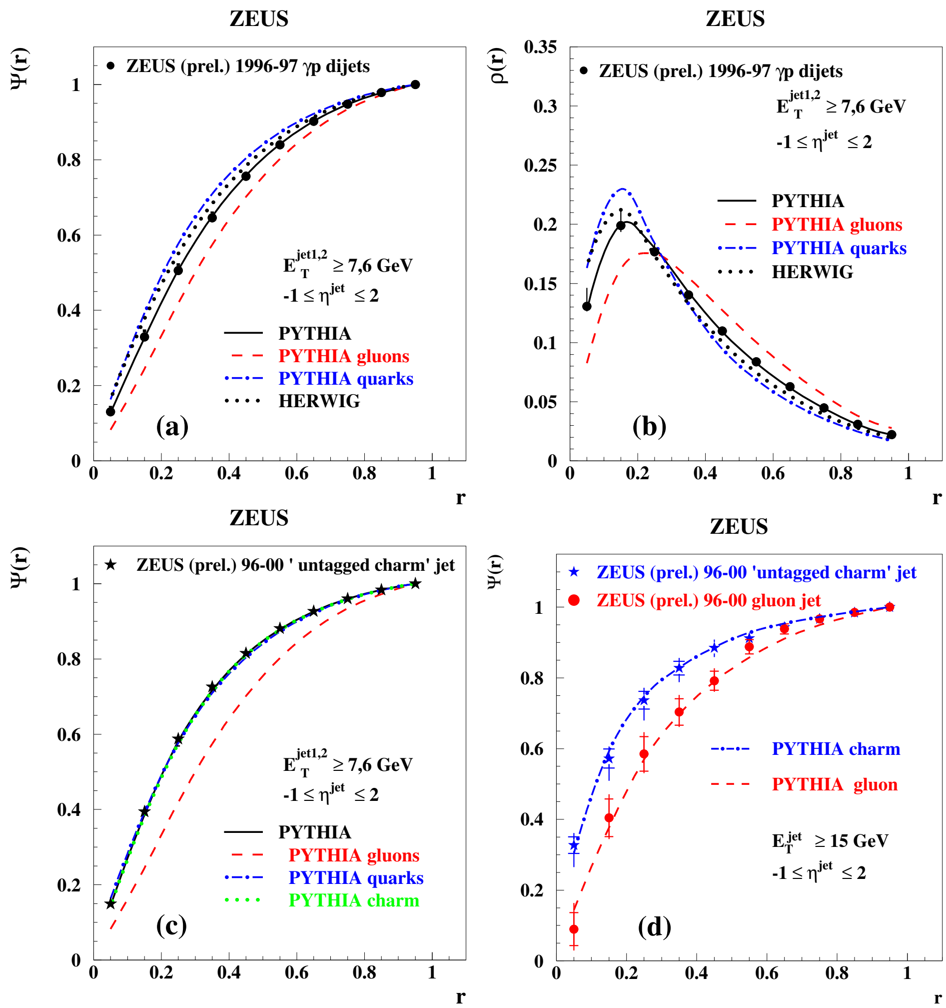


Fig. 2. (a) integrated ($\langle\psi(r)\rangle$) and (b) differential ($\rho(r)$) jet shapes in photoproduction dijet events. (c) $\langle\psi(r)\rangle$ for untagged charm jets compared to PYTHIA. (d) $\langle\psi(r)\rangle$ for untagged charm jets in direct-enriched D^*-tagged sample and for statistically extracted gluon-jets in photoproduction (see text).

$\mathcal{O}_q$ is constrained by the direct-enriched D^* tagged sample, f_q and f_g have been estimated from MC models.

The resulting integrated jet shape, obtained from solving Eq. (1) for $\mathcal{O}_g$, is shown in Fig. 2(d), as well as the untagged-charm jet measurement. The PYTHIA predictions for pure samples of gluon and charm jets provide a good description of the data.

5. Conclusions

The internal structure of jets in DIS has been measured in terms of the subjet multiplicity. Its dependence on transverse energy and pseudo-rapidity is well reproduced by MC models and NLO QCD calculations. A value of α_s has been extracted.

Jet shapes of dijets from photoproduction are described by the MC, lying between pure q- and pure g-jet predictions. Using charm–quark initiated jets, distributions of jet shapes for pure q- and g-jets have been statistically extracted. The results are consistent with PYTHIA predictions.

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