Jet Physics and Event Shape Studies at HERA

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A review is given of the latest results on jet production and studies of event shape variables in deep inelastic scattering at HERA. Jet cross sections studies for inclusive jet and dijet events are presented and compared to next-to-leading order QCD calculations. Extraction of the strong coupling constant $\alpha_s$ is discussed.

1 Introduction

At HERA, studies of the hadronic final state of electron-proton deep inelastic scattering (DIS) $ep \rightarrow eX$ allow to test QCD over a large range of $Q^2$, $Q$ being the virtuality of the probing boson. We will here focus on the latest measurements of jet production cross sections and event shape variables. The sensitivity of the measured observables to the value of $\alpha_s$ will be exploited to determine its value.

In the Breit frame, the production of high transverse energy events can be related to the gluons emitted in the hard QCD process. Most of the analyses were carried out in this frame.

![Figure 1: Inclusive cross section measurements in the Breit frame as a function of (a) $Q^2$ and (b) $\phi_{jet}^B$, where $\phi_{jet}^B$ is the jet’s azimuthal angle as measured with respect to the lepton scattering plane.](image)

2 Jet production in DIS

Studies of inclusive jet production provide a powerful means of investigating QCD: the DIS inclusive jet cross section definition does not present the infrared-sensitivity problems related to the jet selection, as in the case of dijet production. And furthermore, the inclusive jet
cross section is very sensitive to the value of the strong coupling constant $\alpha_s$, hence providing a powerful method of extraction of its value.

ZEUS performed an analysis of inclusive jet production in DIS in the Breit frame. Jets were found in the Breit frame with the inclusive $k_T$-clustering algorithm, and only jet cuts in the Breit frame were applied. Figure 1(a) shows the inclusive jet cross section as a function of $Q^2$. The set of selection cuts is displayed in figure 1.

Next-to-leading order (NLO) QCD calculations are able to describe the data over the 5 orders of magnitude within 10 – 15%. The value of $\alpha_s$ as determined from a comparison of the data to the NLO QCD calculations in the high $Q^2$ region ($Q^2 > 500 \text{ GeV}^2$) is

$$\alpha_s(M_Z) = 0.1190 \pm 0.0017(\text{stat})^{+0.0049}_{-0.0023}(\text{syst})^{+0.0026}_{-0.0026}(\text{th}).$$

For comparison, H1 has found a value of

$$\alpha_s(M_Z) = 0.1186 \pm 0.0030(\text{exp})^{+0.0039}_{-0.0045}(\text{th})^{+0.0033}_{-0.0023}(\text{pdf}).$$

in similar studies of inclusive jet production. Both results are in excellent agreement with the world average $\alpha_s(M_Z) = 0.1184 \pm 0.0031$.

The same ZEUS analysis was also used to measure for the first time the azimuthal angle distribution of jets in the Breit frame, with respect to the lepton scattering plane (figure 1(b)). The shape of the distribution, of the form

$$\frac{d\sigma}{d\phi_{jet}^B} = A + C \cos 2\phi_{jet}^B,$$

is in very good agreement with NLO QCD, and provides a detailed test of the QCD matrix elements of the hard process.

Two possible hard energy scales are natural for the renormalisation scale $\mu_R$ in NLO QCD calculations: $Q$ and the transverse energy, $E_T$, of the event. H1 investigated the effect of this choice in dijet production at medium $Q^2$. The study was done in the photon-proton centre-of-mass frame in the kinematic region defined by $10^{-4} < x < 10^{-2}$ and $5 < Q^2 < 100 \text{ GeV}^2$. In this region of relatively low $x$ and $Q^2$, where higher order corrections are expected to be larger, the choice of $\mu_R$ is still a matter of discussion; and $Q$ is of the same order as the jets transverse energies.

The jets obtained with the $k_T$-cluster algorithm were selected with $E_{T,1}^{jet} > 7 \text{ GeV}$ and $E_{T,2}^{jet} > 5 \text{ GeV}$ in the pseudorapidity range $-1 < \eta_{jet} < 2$. Figure 2 shows the dijet rate as a function of Bjorken $x$ in different regions of $Q^2$. The NLO calculations with $\mu_R^2 = Q^2$ are able to describe the data but present large scale uncertainties, whereas the choice $\mu_R^2 = Q^2 + \overline{E}_T^{jet}$ results in smaller scale uncertainties but fails to describe the distributions.

![Figure 2: Dijet rate as a function of Bjorken $x$ in different regions of $Q^2$. Data is compared with NLO QCD calculations with 2 different choices of the renormalisation scale $\mu_R$.](image-url)
At higher $Q^2$ the particular choice of $\mu_R$ has a smaller impact on the perturbative QCD (pQCD) predictions, which describe reasonably well the dijet data. Also the theoretical uncertainties become smaller. But these jet analyses usually require a large inter-jet separation: either the jets have a large relative transverse energy or they are selected with a large transverse momentum, to avoid the effects of multi-parton emissions becoming significant. About 10% of the DIS sample is then classified as dijet events in these “standard” jet analyses performed at HERA.

H1 has investigated the minimum jet separation necessary for the NLO calculation to give an accurate description of dijet production. The study was undertaken in a region of relatively high $Q^2$: $150 < Q^2 < 35000$ GeV$^2$ and $0.1 < y < 0.7$. The jets were reconstructed in the laboratory frame with the modified Durham algorithm. Dijet events were analysed by means of the variable $y_2 = \frac{\min k_T^{2,i,j}}{W}$ ($W$ is the invariant mass of the particles clustered), where $k_T^{2,i,j} = 2 \min[E_T^2, E_T^2](1 – \cos \theta_{ij})$ is the relative measure of the separation between jets $i$ and $j$, and $\theta_{ij}$ the angle between them.

Figure 3 shows the measured $y_2$ distribution normalised to the inclusive DIS cross section $\sigma_{DIS}$. NLO QCD predictions are in good agreement with the data for values of $y_2 > 0.001$, with about $1/3$ of the events being classified as dijet events. But it overestimates the data dramatically in the region where the inter-jet separations are small. Such behaviour was expected since in the small $y_2$ region the difference between LO and NLO is the largest, and also the renormalisation scale uncertainty and the hadronisation corrections are large, making the NLO calculations (fixed order) unreliable. The RAPGAP LO Monte Carlo program is seen to be in good agreement with the data over all the $y_2$ range.

The dijet sample defined by $y_2 > 0.001$ was then further analysed. NLO QCD calculations were found to describe well the distributions of several relevant jet variables.

## Event shape variables

Event shape variables are interesting observables that are sensitive to the overall topology of the event and therefore to higher order QCD radiation. Within the QCD framework the mean of an event shape $F$ is given by

$$< F > (Q) = \frac{< F >^{pQCD}}{\mathcal{O}(\alpha_s^2)} + \frac{< F >^{Pow.Corr.}}{f(\alpha_s, \alpha_0)},$$

the pQCD part being calculated at present to next-to-leading order. The second term in the above equation, the “power correction”, refers to the non-perturbative part, necessary for the theory to describe the data. This non-perturbative contribution which accounts for hadronisation corrections is expressed as a power law correction, which depends on the value of the strong coupling constant $\alpha_s$ and on an empirical non-perturbative parameter $\alpha_0$.

The mean values as a function of $Q$ of the thrust, broadening, jet mass and C-parameter were studied in the Breit frame by both the ZEUS and H1 collaborations. A general good
agreement was found between the ZEUS and H1 results. The simultaneous 2-dimensional fit to all mean event shapes yielded $\alpha_0 \approx 0.5 \pm 20\%$ and a relatively spread range of values for $\alpha_s(M_Z)$, suggesting the need for inclusion of higher order terms in the theoretical calculations.

H1 has also performed fits to the differential distributions of the event shapes (see [13]). The values obtained for $\alpha_s$ and $\alpha_0$ were found to be inconsistent with those obtained from the fits to the means of the event shapes. Fits using QCD resummed calculations improve significantly the description of the differential distributions of the event shapes (cf. figure 4[14]). Latest theoretical work [15] suggests that a consistent picture can be obtained when applying the concept of resummed QCD calculations in a simultaneous fit to all the event shape distributions.

Figure 4: Differential distributions for the (a) jet mass $\rho$ and (b) the thrust $T_{1E} = 1 - T$: fits to the H1 data including QCD resummed calculations with power corrections.

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