ELECTROPRODUCTION OF DIJETS AT SMALL JET SEPARATION*

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Dijet production in deep-inelastic scattering (DIS) in the range $150 < Q^2 < 35000$ GeV^2 has been measured by the H1 collaboration using the Durham jet algorithm in the laboratory frame. QCD calculations in next-to-leading order (NLO) are found to give a good description of the data when requiring a small minimum jet separation, which selects a dijet sample containing 1/3 of DIS events in contrast to approximately 1/10 with more typical jet analyses.

1. Introduction

One of the remarkable results of the measurements of inclusive cross sections in DIS at HERA is that the data can be sucessfully described by perturbative QCD calculations down to quite small momentum transfers squared Q^2. Investigations of the hadronic final state have shown that QCD is also able to describe events containing two energetic jets. Such investigations tended to require large jet separation, *i.e.* large relative jet transverse momentum or large transverse jet energy in the Breit frame. These requirements typically result in a sample consisting of 1/10 of DIS events. Here I present the results [1] of an investigation on the minimum jet separation needed in order to still successfully describe the data by perturbative QCD.

2. Modified Durham jet algorithm

The definition of minimum jet separation used derives from the criterion used by the Durham $k_\perp$ jet algorithm [2]. This algorithm was invented to improve the JADE jet algorithm, widely and successfully used in the study of e^+e^- annihilation. The JADE algorithm uses the invariant mass between partons or particles as a measure of jet separation. It was noticed that for certain configurations 2 soft gluons are combined into a jet instead of

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associating each of the gluons to the two energetic partons in the event. This was remedied by the Durham $k_\perp$ algorithm. For DIS the algorithm was further modified by adding a proton remnant pseudo particle (missing momentum in the proton direction) in order to better deal with initial state radiation by the colliding proton.

The algorithm runs through the following steps: a) compute all combinations $k^2_{\perp ij} = 2\min[E_i^2, E_j^2](1-\cos\theta_{ij})$, b) combine the pair with the minimum $k^2_{\perp ij}$ by adding the four-momenta, c) iterate this procedure until *e.g.* exactly $(2+1)$ jets, *i.e.* 2 final state jets and the proton remnant jet remain, then d) define *significant* dijets by imposing a lower limit $y_{\rm cut}$ on $y_2 = k^2_{\perp ij}/{\rm scale}^2$ with the total hadronic energy W or Q typically chosen as scale. In the analysis presented here W is chosen for the scale, which has the advantage that the uncertainty of the hadronic energy scale of the calorimetric energy measurement partially cancels in y_2. The algorithm is applied in the laboratory frame with the further advantage of not having an additional boost error.

3. Previous results

Three different previous examples of measurements and applications of jet observables as a function of $y_{\rm cut}$ are briefly discussed.

The jet rates R_{1+1}, R_{2+1}, and R_{3+1} have been presented in ref. [3]. The data are well described by NLO QCD in the measured range $0.01 \leq y_{\rm cut} \leq 0.06$ and allowed a determination of the strong coupling using R_{2+1} for $y_{\rm cut} = 0.02$.

The 2nd example chosen is a measurement of subjet multiplicities in the range $0.001 \leq y_{\rm cut} \leq 0.1$ presented in ref. [4] for jets found in the Breit frame using the inclusive $k_\perp$ jet algorithm and demanding $E_{\rm T,jet} > 8$ GeV. These data are well described by Monte Carlo (MC) models incorporating leading order (LO) matrix elements, parton showers, and hadronization.

Finally, in a paper on event shapes [5] normalized dijet cross sections have been shown as a function of y-values for which the transition from $(2+1)$ to $(1+1)$ jets occurs. These data are of interest in measuring power corrections and the strong coupling. In most of the range $0.05 < y_2 < 1$ and for not too small Q^2, the data are well described by NLO QCD.

These examples show that perturbative QCD is able to describe y_2 distributions down to small values corresponding to $k_\perp$ of a few GeV and that MC models can even describe subjet multiplicities down to $k_\perp \approx 0.3$ GeV. This motivates the investigation presented here: what is the minimum y_2 for which NLO QCD gives a good description of the characteristic observables of dijets? In addition one may ask how well are they described by MC models.

4. Data and dijet selection

About $6\,10^4$ DIS events are selected in the range $150 < Q^2 < 35000$ GeV^2 and $0.1 < y < 0.7$ for an integrated luminosity of 35 pb^{-1}. Dijet events are found in the laboratory frame as a function of $y_2 = \min k_{\perp ij}^2/W^2$ by applying the modified Durham jet algorithm. In addition the jets have to lie within $10° < \theta_{\rm jet} < 140°$ to be well measured.

The dominant systematic errors of $\approx 5\%$, 4%, and $< 1\%$ are due to the model dependence of the corrections and the uncertainty of the hadronic and electromagnetic energy scales of the calorimeters.

5. Results

The normalized dijet cross section as a function of y_2 is compared in Fig. 1 with an NLO QCD prediction [6]. The calculation uses the CTEQ5M

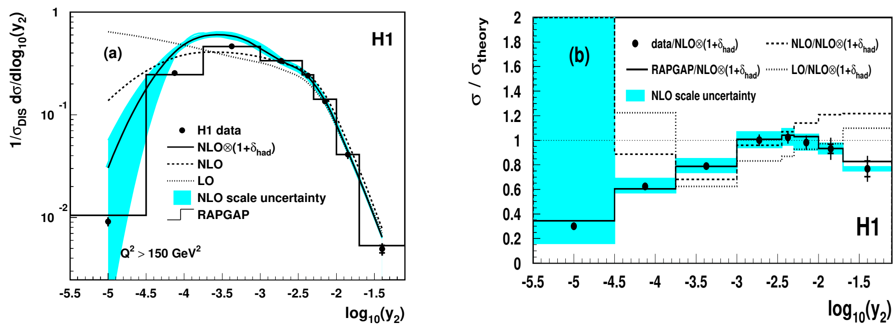

Fig. 1. **a** The normalized dijet cross section. Here and in the following figure the statistical errors are given by the inner error bars and the outer error bars correspond to the quadratic sum of the statistical and systematic errors. Also shown are perturbative QCD predictions in LO, in NLO with and without hadronization corrections, and the predictions of the QCD model RAPGAP. The shaded band shows the renormalization scale uncertainty of the NLO calculation. **b** The ratios of the data and various predictions. The vertical error bars correspond to the errors of the data only.

parton density functions (pdf) and Q as the renormalization and factorization scale. The value of $\alpha_s(M_Z)$ is set to 0.1183. In addition the LO prediction, the NLO prediction corrected for hadronization effects, and the dependence on the renormalization scale ($Q/2 \le \mu_R \le 2Q$) are shown.

We observe that for $y_2 \ge 0.001$ the data are well described by QCD, while for decreasing y_2 QCD increasingly overestimates the data. In the region of very small jet separation the difference between the LO and NLO prediction as well as the renormalization scale dependence and the hadronization correction are all large. This suggests that fixed order perturbative QCD predictions are not reliable in the region $y_2 < 0.001$. The deviation of NLO QCD in the highest y_2 bin is due to large sensitivity to the pdf in this region of dijet phase space and suggests that they need improvement there.

The data are also compared to RAPGAP [7] which models QCD using LO matrix elements matched to parton showers and which uses the Lund string model for hadronization. It provides an excellent description of the data over the full y_2 range, in particular describing well the low y_2 region of multiple parton emissions.

Motivated by the agreement of NLO QCD with data for $y_2 \geq 0.001$, we investigate this sample of dijets, containing about 1/3 of the selected DIS events, in more detail. The following observables have been investigated [1]: the mean transverse energy of the dijets in the Breit frame, the polar angle of the forward and backward jet in the laboratory frame, and x_p and z_p, which are frequently used to express LO matrix elements. They are calculated according to $x_p = \frac{Q^2}{Q^2+m_{1,2}^2}$ and $z_p = \frac{\min_{i=1,2} E_i(1-\cos\theta_i)}{\sum_{i=1,2} E_i(1-\cos\theta_i)}$. In Fig. 2 the distributions in $\overline{E}_{T,\mathrm{Breit}}$, x_p, and z_p are shown. The NLO QCD calculations describe these distributions well. For $\overline{E}_{T,\mathrm{Breit}}$it is shown that the differences between the two choices of renormalization scale, Q and $\overline{E}_{T,\mathrm{Breit}}$ are small. There is a sizable fraction of events with $\overline{E}_{T,\mathrm{Breit}} < 5$ GeV, which is however well descibed by the predictions. Also RAPGAP agrees well with the data. The quark-induced contribution of the NLO calculation is shown in Fig. 2 as a function of x_p. It varies from 30% at the lowest Q^2 to almost 100% in the highest Q^2 bins. This illustrates that these measurements are sensitive to both the quark and the gluon-initiated contributions to the cross section.

6. Summary

The minimum jet separation has been investigated for which NLO QCD can give a good description of dijet production in DIS in the range $150 < Q^2 < 35000$ GeV^2 and $0.1 < y < 0.7$. The required jet separation is found to be small, *i.e.* $y_2 = 0.001$, selecting a dijet sample containing 1/3 of the DIS events, significantly larger than the approximately 1/10 obtained with more typical selection criteria. The good description obtained holds for either choice of renormalization scale Q or $\overline{E}_{T,\mathrm{Breit}}$ and covers regions in which both gluon and quark induced processes dominate.

These measurements are also a significant challenge to QCD Monte Carlo models, which besides LO martix elements and parton showers also include hadronization and particle decays. RAPGAP is found to give a good description of all data.

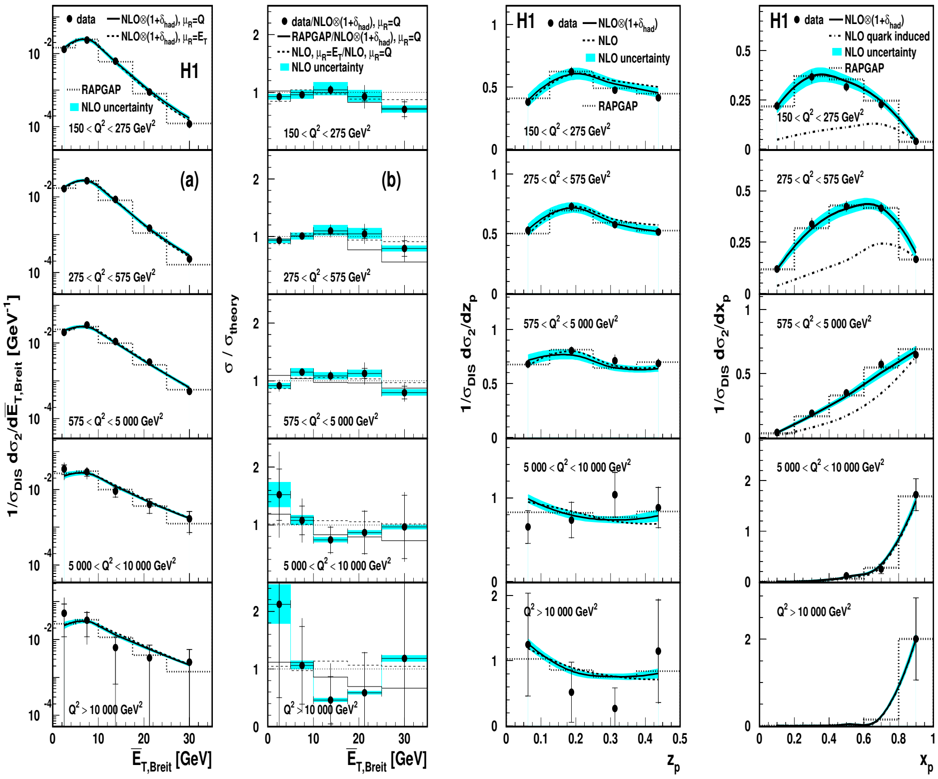

Fig. 2. The normalized dijet cross sections. The predictions of NLO QCD and RAPGAP are shown. The shaded band corresponds to the quadratic sum of the hadronization and renormalization scale uncertainties. **a** Besides the NLO QCD predictions with the scale $\mu_R = Q$, calculations with $\mu_R = \overline{E}_{T,\mathrm{Breit}}$ are also shown. **b** The ratios of the data and various predictions.

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