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Measurement of the E(T,Jet)/ ^{2} /Q ^{2} Dependence of Forward-Jet Production at HERA

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ZEUS Collaboration

Abstract

The forward–jet cross section in deep inelastic e^+p scattering has been measured using the ZEUS detector at HERA with an integrated luminosity of 6.36 pb^{-1}. The jet cross section is presented as a function of jet transverse energy squared, $E^2_{T,jet}$, and Q^2 in the kinematic ranges $10^{-2} < E^2_{T,jet}/Q^2 < 10^2$ and $2.5 \cdot 10^{-4} < x < 8.0 \cdot 10^{-2}$. Since the perturbative QCD predictions for this cross section are sensitive to the treatment of the $\log(E^2_{T,jet}/Q^2)$ terms, this measurement provides an important test. The measured cross section is compared to the predictions of a next–to–leading order pQCD calculation as well as to various leading–order Monte Carlo models. Whereas the predictions of all models agree with the measured cross section in the region of small $E^2_{T,Jet}/Q^2$, only one model, which includes a resolved photon component, describes the data over the whole kinematic range.

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1 Introduction

The wide kinematic range available at the HERA ep collider at DESY has allowed QCD to be tested in regions of phase space not available to previous experiments. Both the H1 and ZEUS collaborations have studied the forward–jet cross sections [1, 2] in order to search for BFKL effects [3, 4]. For these analyses, the two hard scales involved in jet production in deep inelastic scattering (DIS), the negative square of the four–momentum transfer at the lepton vertex, Q^2, and the squared transverse jet energy, $E^2_{T,jet}$, were chosen to be of the same order of magnitude. This paper extends our previous study [2] by investigating the forward–jet cross section as a function of the ratio of these two scales, $E^2_{T,jet}/Q^2$, for the entire available range.

Three different kinematic regions can be distinguished, depending on the dominant scale. In the first region, $Q^2 \gg E^2_{T,jet}$, Q^2 is the standard deep inelastic process hard scale. Typically, leading–order (LO) Monte Carlo models approximate pQCD contributions in this regime by parton showers. In the second region, where $E^2_{T,jet} \approx Q^2$, all terms with $\log(Q^2/E^2_{T,jet})$ become small and the effects of DGLAP evolution [5] are suppressed. Therefore BFKL effects are expected to be observable in this region, which was selected for the analysis of forward–jet production [2], where it was discussed in detail. In the third region, where $Q^2 \ll E^2_{T,jet}$, the NLO pQCD prediction is sensitive to the treatment of terms proportional to $\log(E^2_{T,jet}/Q^2)$, which ought to be resummed. Conventional Monte Carlo models do not include these terms.

In this letter, measurements of the forward–jet cross sections covering all three regions are presented and compared to the predictions of various LO Monte Carlo models in which the hard–scattering process is described by direct photon diagrams, namely boson–gluon fusion and QCD Compton diagrams. The models under consideration differ in their way of describing the higher–order contributions to the LO process. LEPTO [6] and HERWIG [7] use parton showers that evolve according to the DGLAP equations. ARIADNE [8] employs the color–dipole model, in which gluons are emitted from the color field between quark–antiquark pairs. Since color dipoles radiate independently, the gluons are not ordered in transverse momentum, k_T. The linked–dipole–chain model, LDC [9], implements the structure of the CCFM equation [10], which is intended to reproduce both DGLAP and BFKL evolution in their respective ranges of validity. In all these models, Q^2 is normally used as the relevant scale. Finally, RAPGAP [11] introduces a resolved photon contribution in addition to the direct photon cross section and uses $Q^2 + E^2_{T,jet}$ as the factorization scale. The inclusion of the resolved photon contribution partially mimics the higher–order contributions to the direct photon component, namely the $\log(E^2_{T,jet}/Q^2)$ terms, which are not included in the conventional DIS LO Monte Carlo models. The scattering of the partons from those contained in the resolved photon can lead to final state partons with a high transverse momentum in the forward direction. Since this process was suggested to provide an explanation for the observed excess in forward–jet production [12], the previously published forward cross section [2] as a function of the Bjorken scaling variable, x, is compared to predictions of the RAPGAP model.

2 Measurement

This study is based on data taken with the ZEUS detector in 1995, corresponding to an integrated luminosity of 6.36 pb^{-1}. As the analysis follows very closely that for the forward–jet cross section [2], details about the experimental setup, event selection, jet finding and systematic error are not repeated here.

The selected DIS events were required to have a scattered electron with a minimum energy of $E_{e'} =$ 10 GeV. The fractional energy transfer by the virtual photon had to be $y > 0.1$. The x range was extended with respect to [2] from $4.5 \cdot 10^{-4} < x < 4.5 \cdot 10^{-2}$ to $2.5 \cdot 10^{-4} < x < 8.0 \cdot 10^{-2}$. An additional cut, $Q^2 > 10$ GeV^2, was applied in order to be well within the DIS regime.

Jets were selected with a cone algorithm in the laboratory frame. The cone radius, R, was chosen to be 1.0. The transverse energy of the jets in the laboratory frame, $E_{T,jet}$, was required to be larger than 5 GeV and the jet pseudorapidity[1] range was restricted to $\eta_{jet} < 2.6$. The scaled longitudinal jet momentum $x_{jet} = p_{Z,jet}/p_{beam}$, where $p_{beam} = 820$ GeV, had to be larger than 0.036 to select forward jets [4]. Furthermore, only jets with a positive Z–momentum in the Breit frame were considered, thus avoiding those jets originating from the scattered quark at large values of x. These cuts are given in Table 1.

$Q^2 > 10$ GeV^2
$2.5 \cdot 10^{-4} < x < 8 \cdot 10^{-2}$
$y > 0.1$
$E_{e'} > 10$ GeV
$\eta_{jet} < 2.6$
$E_{T,jet} > 5$ GeV
$x_{jet} > 0.036$
$p_{Z,jet}(Breit) > 0$

Table 1: Selected kinematic region for the cross section measurement.

The jet cross sections presented here have been corrected to the hadron level for detector acceptance and smearing effects using the ARIADNE model, since it gave the best description of the data [2]. The purity for reconstructing forward jets in the given phase space rises from 40% to 80% with increasing $E^2_{T,jet}/Q^2$, while the efficiency rises from 35% to 55%. For the lowest bin in $E^2_{T,jet}/Q^2$, both purity and efficiency are around 20%, but here the statistical errors are large. The factors required to correct the data for detector effects lie between 0.8 and 1.4 and increase as $E^2_{T,jet}/Q^2$ increases.

3 Results

The forward–jet cross section is presented in Fig. 1 as a function of $E^2_{T,jet}/Q^2$. The numerical values are given in Table 2. The treatment of the systematic errors closely follows the published results [2] and leads to errors of similar size. The shaded band corresponds to the uncertainty coming from the energy scale of the calorimeter.

Predictions from different LO Monte Carlo models are shown in Fig. 1 and Fig. 2. Three regions are distinguished, separated by the dashed vertical lines. In the region where $Q^2 \gg E^2_{T,jet}$, all the models describe the data reasonably well.

In the regime $Q^2 \approx E^2_{T,jet}$, only ARIADNE 4.08 and RAPGAP 2.06 reproduce the measured distributions. In RAPGAP the resolved component of the virtual photon is modeled using the SaS-2D parametrization for the parton distribution function (pdf) of the photon [13], which in this Q^2 range evolves as $\sim \log(E^2_T/Q^2)$. The factorization scale has been set to $\mu^2 = E^2_{T,jet} + Q^2$.

In Fig. 3 the x–dependence in this regime is compared with RAPGAP, using the cuts $0.5 < E^2_{T,jet}/Q^2 < 2.0$ and $4.5 \cdot 10^{-4} < x < 4.5 \cdot 10^{-2}$ [2]. RAPGAP gives a good description of the cross section. The contribution of the direct photon component is indicated separately. As expected, it matches the LEPTO prediction.

For $Q^2 \ll E^2_{T,jet}$, none of these models, except RAPGAP, reproduces the data. In particular ARIADNE overshoots the data by up to an order of magnitude at the upper limit of the displayed range. The other models, LEPTO 6.5, HERWIG 5.9 and LDC 1.0, lie far below the data. These comparisons using corrected cross sections are similar to those made previously [2], using the uncorrected distributions. The

[1]The ZEUS coordinate system is defined as right–handed with the Z–axis pointing in the proton beam direction, referred to as forward direction, and the X–axis horizontal, pointing towards the center of HERA. The pseudorapidity is defined as $\eta = -\ln(\tan\frac{\theta}{2})$, where the polar angle θ is taken with respect to the proton beam direction.

same data are shown in Fig. 2 together with the prediction of the RAPGAP Monte Carlo model, which describes the data well over the full range of $E^2_{T,jet}/Q^2$.

Recently, the parton level NLO calculation JetViP [14] has become available, to which our data can also be compared, with the proviso that the hadronization corrections are model–dependent and are of the order of up to 20%. JetViP sums contributions from the direct and resolved virtual photon and uses the SaS-1D photon pdf [13]. For the first three bins in Fig. 2 only the direct contribution has been taken into account, since Q^2 is large enough ($Q^2 > 83$ GeV^2) that the resolved component can be neglected. The renormalization and factorization scales have been set to $E^2_{T,jet} + Q^2$ [15]. The agreement over the full range of $E^2_{T,jet}/Q^2$ is good. The x dependence of the cross section in the range $0.5 < E^2_{T,jet}/Q^2 < 2.0$ has also been calculated with JetViP [16] and good agreement was found. The fact that only RAPGAP and JetViP describe the data implies that a resolved photon component is necessary for $E^2_{T,jet}/Q^2 > 1$.

The necessity of a resolved photon component in a DIS process has also been discussed by the H1 collaboration in the context of dijet production in a Q^2 range of 5 to 100 GeV^2 [17], where the measured dijet cross section could only be described with the inclusion of the resolved component.

In comparing the performance of RAPGAP and JetViP it should be noted that while they both agree with the data, their predictive power is limited. On the one hand both RAPGAP and JetViP use the SaS photon pdf, which for $Q^2 > 0$ is not very well constrained by experimental data. On the other hand there is a large variation of the results when the factorization scale is varied, as shown by the light shaded band in Fig. 3 for RAPGAP. A similar effect is seen for JetViP [16].

4 Summary

The cross sections for forward–jet production over a wide range of $E^2_{T,jet}/Q^2$ have been compared to different Monte Carlo models. All leading–order Monte Carlo models tested here give a good description of the region in which $E^2_{T,jet} \ll Q^2$. However, only those models which include non–k_T–ordered gluon emissions, or contributions from a resolved photon, reproduce the $E^2_{T,jet} \approx Q^2$ region. The full range of $E^2_{T,jet}/Q^2$ can be described only by the RAPGAP model and the JetViP NLO QCD calculation, both of which include a resolved photon contribution. The forward–jet differential cross section, as a function of x [2], is also well reproduced by RAPGAP and JetViP. However, the large dependence of its predictions on the factorization scale diminishes the significance of this agreement.

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$E^2_{T,jet}/Q^2$	$\frac{d\sigma}{d(E^2_T/Q^2)} \pm$ stat. $\pm$ syst. [pb]	syst. E_{CAL}–scale [pb]
0.01 − 0.03	$59.5 \pm 32.3 \; ^{+26.5}_{-10.7}$	(−0.1, +19.5)
0.03 − 0.1	$164 \pm 33 \; ^{+26}_{-43}$	(−9, +2)
0.1 − 0.3	$255 \pm 22 \; ^{+24}_{-17}$	(−6, +13)
0.3 − 1.0	$288 \pm 12 \; ^{+12}_{-53}$	(−16, +9)
1.0 − 3.0	$190 \pm 6 \; ^{+2}_{-7}$	(−19, +18)
3.0 − 10.	$41.2 \pm 1.4 \; ^{+4.8}_{-0.9}$	(−4.0, +3.5)
10. − 30.	$2.95 \pm 0.19 \; ^{+0.13}_{-0.13}$	(−0.33, +0.27)
30. − 100.	$0.120 \pm 0.020 \; ^{+0.007}_{-0.045}$	(−0.021, +0.014)

Table 2: Cross section values and errors for the corrected data in bins of $E^2_{T,jet}/Q^2$. The last column shows the systematic errors due to the energy scale uncertainty of the calorimeter, which is not included in the central column. The table refers to the points shown in Fig. 1. The phase space under investigation is defined by the cuts: $\eta_{Jet} < 2.6$, $x_{Jet} > 0.036$, $E_{T,jet} > 5$ GeV, $E_{e'} > 10$ GeV, $y > 0.1$, $Q^2 > 10$ GeV^2, $p_{Z,jet}(Breit) > 0$ and $2.5 \cdot 10^{-4} < x < 8.0 \cdot 10^{-2}$.

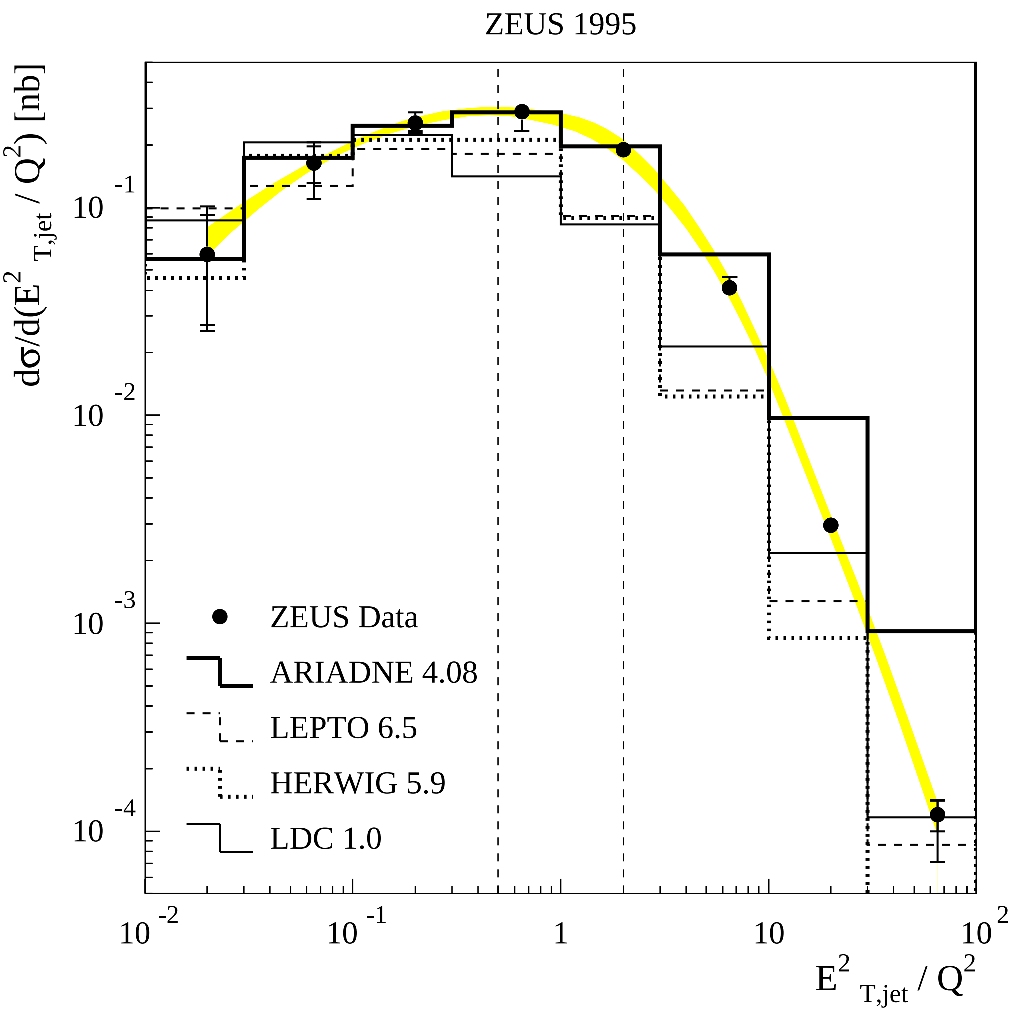

Figure 1: Forward–jet cross sections as a function of $E^2_{T,jet}/Q^2$. ZEUS data are shown as points with the inner error bars indicating the statistical errors. The outer error bars give the statistical and systematic errors added in quadrature. The shaded band corresponds to the uncertainty from the energy scale of the calorimeter. The Monte Carlo predictions from ARIADNE (thick, full line), LEPTO (dashed line), HERWIG (dotted line) and LDC (thin, full line) are shown for comparison. The vertical dashed lines indicate the region used for the previous forward cross section measurement [2].

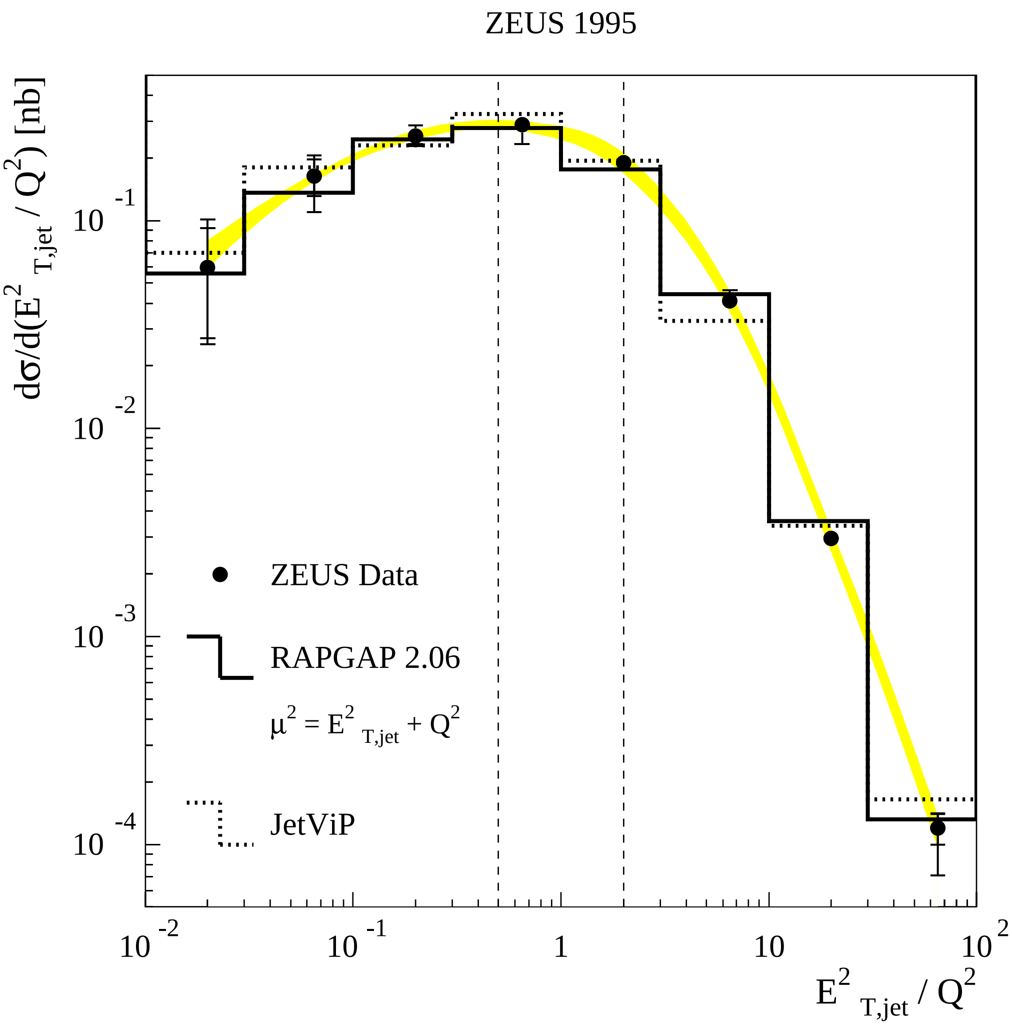

Figure 2: Forward–jet cross section as a function of $E^2_{T,jet}/Q^2$. Data points, error bars and the error band are the same as in Fig. 1. The data are compared to the RAPGAP Monte Carlo model with direct and resolved contributions (full histogram). The results of the NLO calculation JetViP are shown as the dotted histogram [15].

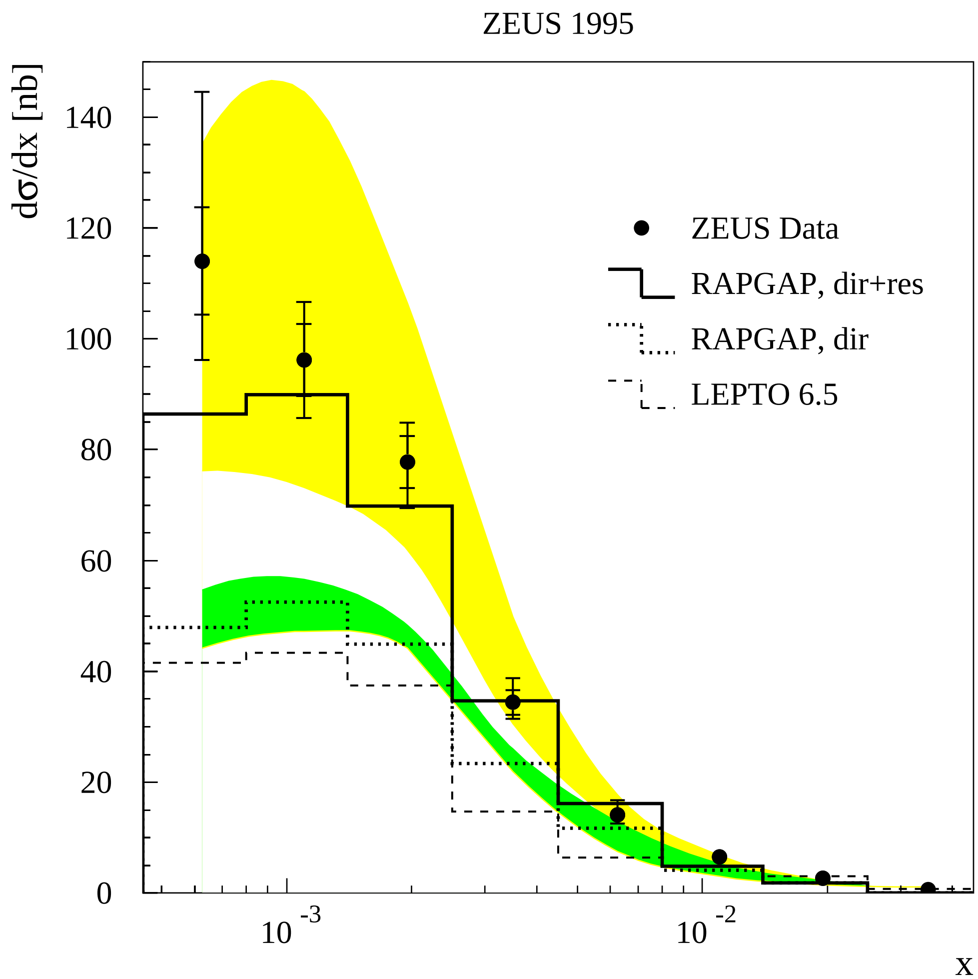

Figure 3: Forward–jet cross section as a function of x, in the region $0.5 < E^2_{T,jet}/Q^2 < 2.0$. The ZEUS data, shown as points, are compared to the RAPGAP Monte Carlo model with direct and resolved photon contributions (full line) and to LEPTO (dashed line). The ARIADNE prediction (not shown) is very similar to RAPGAP. The direct contribution of RAPGAP is indicated by the dotted line. The factorization scale in RAPGAP has been varied from $\mu^2 = E^2_{T,jet}/2 + Q^2$ to $\mu^2 = 4 \cdot E^2_{T,jet} + Q^2$. This corresponds to the light shaded band which refers to the full RAPGAP histogram (sum of the resolved and direct components) and to the dark shaded band which refers to the direct RAPGAP histogram. The histograms correspond to the nominal scale $\mu^2 = E^2_{T,jet} + Q^2$.