# Forward jets in DIS at ZEUS

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**Abstract.** Jet cross sections in neutral current deep inelastic scattering at low $x_{\mathrm{Bj}}$ have been measured with the ZEUS detector in the forward region towards the proton direction. Hadronic final-state measurements in this region are expected to be particularly sensitive to QCD evolution effects. The measurements have been compared with leading-logarithm parton-shower Monte Carlo models and perturbative QCD calculations.

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## INTRODUCTION

In deep inelastic scattering (DIS) a parton in the proton can induce a QCD cascade consisting of several subsequent parton emissions before a quark absorbs the virtual photon. The scattered quark then radiates partons until hadronization sets in. Several different models of parton evolution dynamics have been proposed.

One set of parton evolution equations, derived on the basis of the collinear factorization theorem is that of the DGLAP evolution equations. They are characterized by resummation of the terms of $\alpha_s \ln(Q^2)$, where $Q^2$ is the virtuality of exchanged boson. This approach assumes that the dominant contribution to the evolution comes from subsequent gluon emissions which are strongly ordered in transverse momenta $k_T$. DGLAP is applicable for the region $\ln(Q^2) \gg \ln(1/x)$, where $x$ is the fraction of the proton's momentum carried by the struck parton.

The BFKL evolution equations allow resummation of terms independently of $\ln(Q^2)$. Therefore, the gluon ladder need not be ordered in $k_T$. The BFKL equations can be applied in the region $\ln(1/x) \gg \ln(Q^2)$ in the leading-logarithmic approximation, so that they are expected to primarily contribute to the evolution at low $x$.

The CCFM evolution equations are based on the idea of coherent gluon radiation, which leads to angular ordering of gluon emissions in the gluon ladder such that $\theta_i > \theta_{i-1}$, where $\theta_i$ is the $i$-th gluon with respect to the incoming parton. The CCFM approach incorporates both types of evolution, DGLAP and BFKL, so that it should be applicable across the whole kinematic plane.

Differences between these different approaches are expected to be most prominent in the phase-space region towards the proton-remnant (forward) direction. The results of two ZEUS analyses [1] which study forward jet production in DIS, are presented here.

# FORWARD JET PRODUCTION

Jets with transverse energy $E_T^{\rm jet} > 6$ GeV and pseudorapidity $0 < \eta^{\rm jet} < 3$ were selected in the laboratory frame with the longitudinally-invariant $k_T$ cluster algorithm in the inclusive mode. A phase-space region, called "BFKL", was defined by the additional condition $0.5 < \frac{(E_T^{\rm jet})^2}{Q^2} < 2$. The requirement on $(E_T^{\rm jet})^2/Q^2$ restricts the jet kinematics to the region where BFKL effects are expected to be large. The jet cross sections were measured as functions of $E_T^{\rm jet}$, $\eta^{\rm jet}$, $Q^2$ and $x$.

Only events with $Q^2 > 25$ GeV$^2$ and $y > 0.04$ were considered in the measurement. The analysis was performed with $\cos\gamma_h < 0$, where $\gamma_h$ is hadronic angle which corresponds to the direction of the outgoing quark. The restriction was made to reject quark-parton model events.

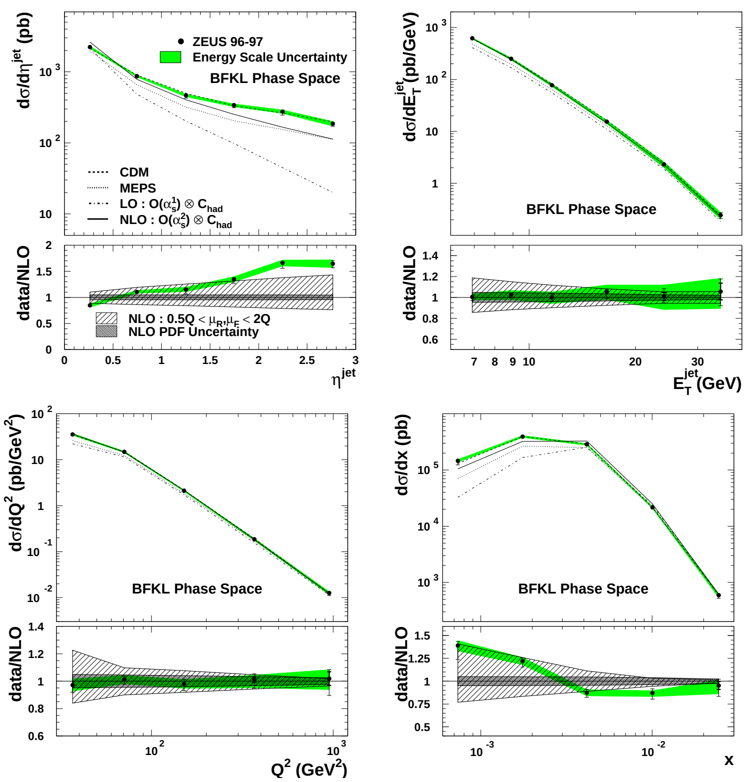


**FIGURE 1.** Differential cross sections (dots) in the BFKL phase space for inclusive jet production in DIS as functions of $\eta^{\rm jet}$, $E_T^{\rm jet}$, $Q^2$ and $x$. The calculations of CDM (dashed lines), MEPS (dotted lines), $\mathcal{O}(\alpha_s^1)$ (dot-dashed lines) and $\mathcal{O}(\alpha_s^2)$ (solid lines) QCD calculations are shown.

The data are compared to predictions from the Monte Carlo (MC) programs ARIADNE and LEPTO, and to perturbative QCD calculations using the program DISENT. The ARIADNE MC is based on the BFKL-like Color Dipole Model (CDM) which produces a cascade of gluons not strongly ordered in transverse momentum. LEPTO MC is a pure DGLAP type MC based on the first-order QCD matrix elements plus parton showers (MEPS).

The program DISENT, using DGLAP-evolved proton PDFs, allows calculations that sum up to two orders of the perturbation series (LO = $\mathcal{O}(\alpha_s^1)$ and NLO = $\mathcal{O}(\alpha_s^2)$). The uncertainty on the calculations due to higher-order terms was estimated by changing the renormalisation scale.

The measurements are presented in Fig. 1. The predictions of ARIADNE describe well all data distributions. The predictions of LEPTO fail to describe the data, especially in the $\eta^{\rm jet}$ distribution and low-$x$ region. Fixed-order QCD calculations describe the data well for $Q^2$, $E_T^{\rm jet}$ and $x$, but underestimate the data at high values of $\eta^{\rm jet}$.

## FORWARD JET PRODUCTION IN EXTENDED $\eta^{\rm JET}$ REGION

During the 1998-2000 running period, the forward plug calorimeter (FPC) [2] was installed with a small hole of radius 3.15 cm in the center to accommodate the beam pipe. The FPC increased the forward calorimetric coverage by about 1 unit of pseudorapidity to $\eta \leq 5$. This new component allowed to extend the reconstruction of jets by 0.5 unit of pseudorapidity.

In the following, cross sections are presented as functions of the variables $Q^2$, $x$, $E_T^{\rm jet}$ and $\eta^{\rm jet}$. The differential jet cross sections were determined in the kinematic region $20 < Q^2 < 100$ GeV$^2$, $0.04 < y < 0.7$ and $0.0004 < x < 0.005$. The jet search was performed using the $k_T$ cluster algorithm in the longitudinally invariant inclusive mode in the Breit frame. The reconstructed jets were then boosted to the laboratory frame. The following jet selection cuts were applied in the laboratory frame: $E_T^{\rm jet} > 5$ GeV, $2 < \eta^{\rm jet} < 3.5$, $0.5 < (E_T^{\rm jet})^2/Q^2 < 2$; the scaled longitudinal momentum was required to satisfy $x_{\rm jet} = p_z^{\rm jet}/p > 0.036$, where $p$ is the proton momentum and $p_z^{\rm jet}$ is the longitudinal jet momentum, which selected forward jets with a large energy.

The left side of Figure 2 compares the measured cross sections as function of $Q^2$, $x$, $E_T^{\rm jet}$ and $\eta^{\rm jet}$ with the predictions of different MC models. The predictions of ARIADNE reproduce the shapes and the normalizations of the differential cross sections. LEPTO describes well the shapes of the data but is lower than the data by a factor of two.

The CASCADE MC based on CCFM parton evolution uses $k_T$-factorization of the cross section into an off-shell matrix element and an unintegrated gluon density function. The following sets of CCFM unintegrated gluon density function have been tried for comparison with the data: J2003 set 1 and J2003 set 2. The latter version includes non-singular terms in the splitting function and lowers the cross sections at low $x$. CASCADE with J2003 set 2 describes the absolute values of the cross sections better than J2003 set 1. However it does not reproduce the shapes of the distributions in $x$ and $\eta^{\rm jet}$.

The right side of the Figure 2 compares the measurements with the predictions of $\mathcal{O}(\alpha_s^2)$ QCD calculations as it is implemented in DISENT. The calculations describe the measurement within the theoretical uncertainties. The variation of the calculations with the renormalization scale is large, emphasizing the need for higher-order calculations.

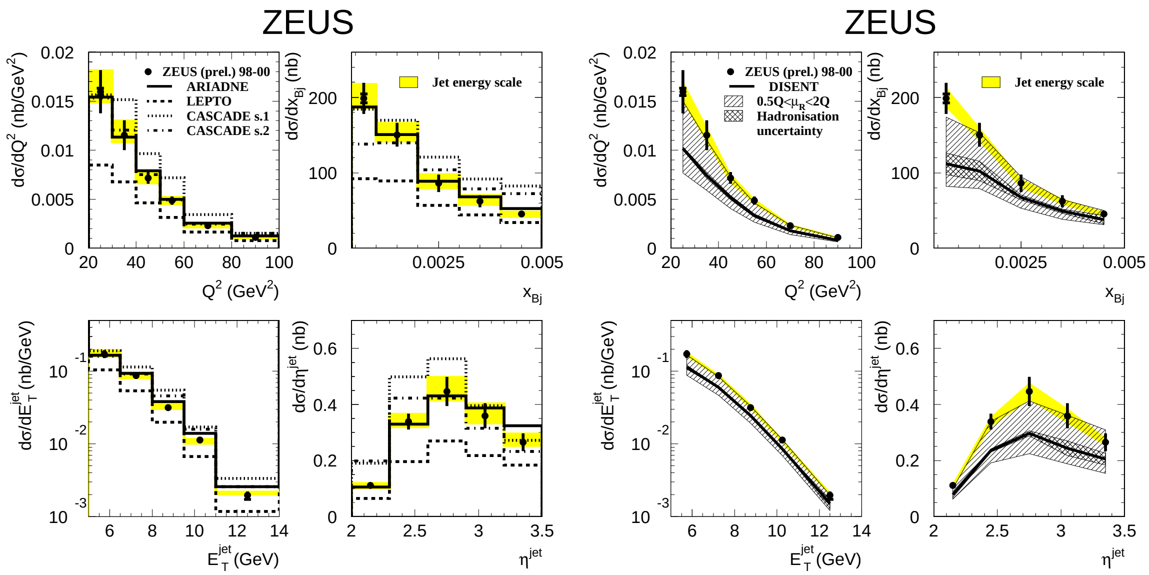


**FIGURE 2.** Differential cross sections for inclusive jet production for the data (dots) compared with ARIADNE (solid histogram), LEPTO (dashed histogram) and CASCADE (dotted and point-dashed histograms) predictions (left side), and compared with the NLO QCD calculations (solid line, right side). The cross sections are shown as a function of $Q^2$, $x$, $E_{T,jet}$, and $\eta^{jet}$.

## CONCLUSIONS

Two ZEUS measurements of differential inclusive jet cross sections were performed in the forward region, in $Q^2$, $x$, $E_T^{\rm jet}$ and $\eta^{\rm jet}$. The ARIADNE MC model gives the best overall description of the cross sections. CASCADE with J2003 set 2 reproduces the normalisation of the measured cross sections, but fails to describe the shapes of the differential cross sections in $x$ and $\eta^{\rm jet}$. These experimental results may be used to adjust the parameters of the intrinsic $k_T$ distribution. The perturbative QCD calculations are consistent with the data within the large theoretical uncertainties, which prevent us to draw any strong conclusion.

## REFERENCES


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2. A. Bamberger et al., Nucl. Inst. Meth. **A 450**, 235 (2000).