Forward Jet and Particle Production at HERA

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Production of high transverse momentum charged particles, π^0s and jets is studied in deep-inelastic scattering data taken with the H1 and ZEUS detectors at the ep collider HERA. The rate of the particles and jets observed at small angles with respect to the proton axis is strongly correlated to the underlying parton dynamics. Results are presented as a function of Bjorken-x and x_i, the fraction of the incident proton's energy carried by the particle or jet, at low Bjorken-x and large x_i. The interplay between the two hard scales, Q^2 and $E_{T\mathrm{jet}}$ is also investigated. Comparisons are made with a BFKL inspired calculation and with Monte-Carlo predictions based on DGLAP evolution, on the CCFM equation and on the Colour Dipole Model.

1 Introduction

The positron-proton collider HERA has significantly increased the available kinematic region for the study of deep inelastic scattering (DIS) towards large four-momentum transfer Q^2 (up to $Q^2 \approx 5 \cdot 10^4$ GeV^2) and small Bjorken-x ($x \approx 10^{-5}$). The hadronic final state in such events is a very sensitive environment in which to disentangle different QCD processes. In particular the region near the proton remnant (forward region) will allow new insights to be gained into dynamical features of QCD at low Bjorken-x [1] since it provides a large phase space for parton emissions. Several prescriptions for the QCD evolution of the dynamics of such emissions have been proposed.

DGLAP [2] evolution in which the relevant evolution parameter is $\log(\frac{Q^2}{Q_0^2})$ and in which emitted partons are strongly ordered in transverse momentum, k_T, has been successfully tested over wide ranges in Q^2 and provides, for instance, a good description of the structure function scaling violations. The BFKL[3] evolution equation, where the relevant evolution parameter is $\log(\frac{1}{x})$ and for which there is no ordering in partonic k_T, is expected to become applicable at small enough x when the $\log(\frac{1}{x})$ terms dominate the evolution. CCFM [4] evolution, in which the parton emissions obey angular ordering, is expected to be valid for both low and high Bjorken-x thereby forming a bridge between the BFKL and DGLAP approaches. Hadronic final state calculations for all three prescriptions are, for the first time, becoming available [5].

It has been noted that another approach based on a resolved photon component in deep inelastic scattering can emulate the random walk behaviour in k_T observed in the BFKL approach[6]. The resolved photon picture can be considered to be applicable when the squared transverse momentum of the parton of the hard scattering process is larger than Q^2 of the photon. In that case the photon can be considered to interact via its hadronic structure.

A complication in using the hadronic final state to investigate QCD evolution is the effect of soft hadronisation processes and it has been suggested that these can be reduced by studying forward jet production [7,8,9]. Single high-p_T particle production has also been proposed as a probe of QCD dynamics [10,11], the advantage of which, compared to jets, is the lack of dependence on the choice of jet finding algorithm and also the potential to reach smaller angles than is possible with jets with broad spatial extent. Previous measurements [12,13] on charged particle production which exploit this feature have been limited by experimental acceptance mostly to the central region of the detector.

In this report, results from the H1 and ZEUS experiments are presented on single jets, di-jets and high transverse momentum single particles in the forward region at small Bjorken-x.

2 Results

2.1 Single Particles

Results are presented as spectra in Bjorken-x of single charged particles and π^0-mesons with $5^\circ < \theta < 25^\circ$ and $p_T > 1$ GeV, where θ and p_T refer to the polar angle and transverse momentum of the single particle respectively (both measured w.r.t. incoming proton direction). All distributions are normalised to the number of DIS events, N, that fall into the kinematic range: $E_{e'} > 12$ GeV, $156^\circ < \Theta_e < 173^\circ$, $y > 0.1$ and $0.0002 < x < 0.00236$. Here $E_{e'}$ and θ_e refer to the energy and polar angle of the scattered lepton and y and x are the familiar Bjorken variables.

Charged particle results are shown in Fig. 1 (top left) for the lower threshold of $x_{cp} = \dfrac{E_{cp}}{E_{proton}}$ greater than 0.0098, where E_{cp} and E_{proton} are the charged particle and incoming proton energies respectively. Here, as in all the following distributions presented in this report, where two error bars are shown, the full errors are the quadratic sum of the statistical (inner error bars) and systematic uncertainties.

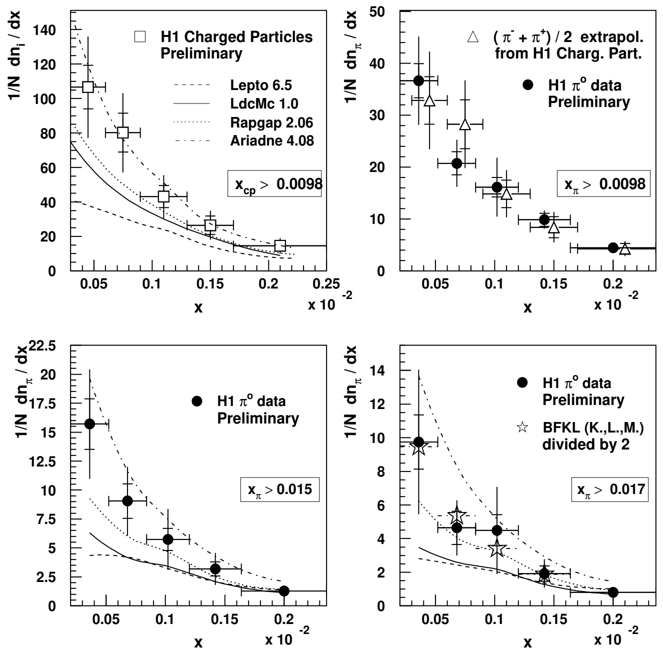

Figure 1: The forward charged particle and π^0 spectra in Bjorken-x for $p_T > 1$ GeV and $5° < \theta < 25°$ are shown for different values of the lower energy threshold $x_{cp} = \frac{E_{cp}}{E_{proton}}$ (charged particles) $x_\pi = \frac{E_\pi}{E_{proton}}$ (π^0-mesons). Here n_{cp} (n_π) is the number of charged particles (π^0-mesons) and N is the number of events that enter the distribution. For comparison, predictions of four different QCD models are overlayed. For the highest x_π bin a BFKL calculation is available. Its predictions have been divided by two for presentation purposes.

The charged particle rate clearly rises with decreasing Bjorken-x providing evidence of much more hard partonic radiation than predicted by DGLAP type QCD models as represented by LEPTO [14]. A reasonable description of the data can be obtained by adding contributions from processes in which the photon is not point-like but acts as a resolved object as is implemented in RAPGAP [15]. The renormalisation and factorisation scales were both set to $p_T^2 + Q^2$ in these calculations where p_T^2 is the transverse momentum squared of the outgoing partons from the hard sub-process. Measurements are also presented in Fig. 1 for π^0-mesons for the three lower thresholds of $x_\pi >$ [0.0098, 0.015, 0.017]. To further check the consistency of both measurements ARIADNE [16] with JETSET [17] was used to estimate the contribution of charged pions to the charged particle data. The results divided by two are compared to the π^0 measurement in Fig. 1 (top right) and are in good agreement. For the first time the data can also be compared to a MC model based on the CCFM approach (LDCMC [5]). Although it is close to the data for the single particle spectra with the lower energy cutoffs it becomes increasingly similar to the DGLAP based model in the higher energy π^0 spectra.

The Colour Dipole Model as implemented in ARIADNE tends to overshoot the data in most of the measured distributions. BFKL calculations, folded with fragmentation functions, are available for the highest momentum π^0 points [18]. These predictions were found to over-estimate the observed π^0 yield and the calculated points are shown in Fig. 1 divided by two. Despite this large normalisation discrepancy the calculations are seen to describe well the x dependence of the π^0 measurements. More details appertaining to this analysis can be found in [19] and [20].

2.2 Forward Jet and Di-jet Production

The ZEUS forward single jet cross-section is shown in Fig. 2 as a function of x. Jets are selected in the phase space region $\eta_{jet} < 2.6$, $x_{\rm jet} = \frac{E_{\rm jet}}{E_p} > 0.036$, $0.5 < \frac{E_{T\rm jet}{}^2}{Q^2} < 2$, $\mathrm{E}_{e'} > 10$ GeV, $y > 0.1$. Here η_{jet}, $E_{\rm jet}$ and $E_{T\rm jet}$ refer to the pseudorapidity, energy and transverse energy of the jet respectively.

These cuts are similar to the H1 single particle analysis although the further cut, $0.5 < \frac{E_{T\rm jet}^2}{Q^2} < 2$, is designed to suppress DGLAP radiation by exploiting the k_T ordering feature of this scheme [7].

Several QCD-based models are compared to the data. LEPTO, HERWIG [21] and the LDC underestimate the cross-section while predictions from RAPGAP with a resolved photon contribution and ARIADNE are closer to the data.

The single jet cross-sections also show a strong rise as x is lowered. DGLAP calculations from LEPTO and HERWIG and CCFM predictions from LDC fail to match the data although predictions from ARIADNE come close. The ZEUS forward jet data are shown again in Fig. 3 and compared to RAPGAP and LEPTO. RAPGAP is used here again with the renormalisation and factorisation scales were set equal to $p_T^2 + Q^2$. The RAPGAP predictions are shown for "direct" only and "direct+resolved" interactions of the photon. The dependence of RAPGAP predictions on choice of scale has been investigated. The effects of varying the renormalisation and factorisation scales between $\frac{p_T^2}{2} + Q^2$ and $4.p_T^2 + Q^2$ are shown as bands around the respective "RAPGAP resolved and direct" and "RAPGAP direct" predictions. Clearly, a significant scale dependence exists for both calculations although the effect is larger for the resolved

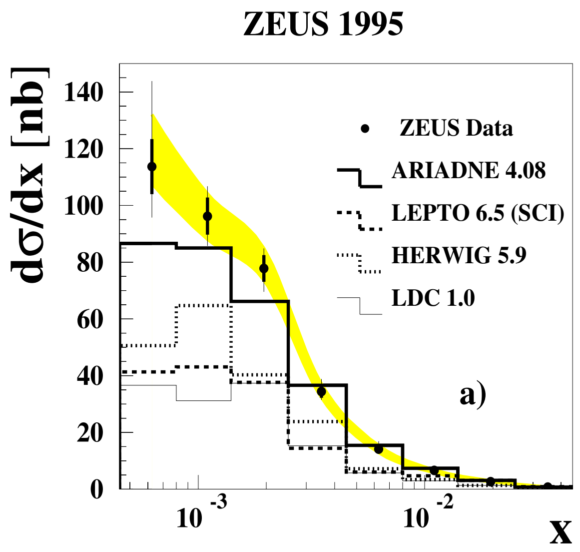

Figure 2: Forward jet cross section at hadron level as a function of x in the kinematic region $\eta_{jet} < 2.6$, $x_{jet} > 0.036$, $0.5 < \frac{E^2_{T\,\mathrm{jet}}}{Q^2} < 2$, $E_{e'} > 10$ GeV, $y > 0.1$. Statistical errors are shown as thick error bars and statistical and systematic errors added in quadrature as thin error bars. The errors due to the uncertainty of the jet energy scale are shown as the shaded band

photon prediction. However, even with a change in scale, the direct calculations from RAPGAP still lie far below the data and are, as expected, close to those from LEPTO.

It is of interest to expand the kinematic range studied and investigate the interplay between scales p_T^2 and Q^2. In Fig. 4, the forward jet cross-section as a function of $\frac{P_T^2}{Q^2}$ is shown, as measured by ZEUS. For this spectra, the cut $0.5 < \frac{E^2_{T\,\mathrm{jet}}}{Q^2} < 2$ has been removed allowing the study of the jet production in a range of environments. For $p_T^2 << Q^2$, interactions are conventionally treated as DIS scattering of a point-like photon off a constituent in the proton whereas a photoproduction-like regime is achieved for $p_T^2 >> Q^2$ for which a partonic photon is probed by a parton from the proton. From Fig. 4 it can be seen that LEPTO fails for $\frac{E_T^2}{Q^2}$ greater than about 0.1. ARIADNE describes well the data at low $\frac{E_T^2}{Q^2}$ and $p_T^2 \approx Q^2$. However, this model fails for $p_T^2 >> Q^2$ and the only model to describe well the forward jet cross-section over the full $\frac{E_T^2}{Q^2}$ considered here is RAPGAP. In this plot, the shaded band represents the error due to the uncertainty on the jet energy scale. Further details of the ZEUS analyses can be found in [22].

H1 measurements of the forward jet cross-section in bins of x are displayed in Fig. 5 for jets defined by $x_{\mathrm{jet}} = \frac{E_{\mathrm{jet}}}{E_p} > 0.035$, $0.5 < \frac{p^2_{T\,\mathrm{jet}}}{Q^2} < 2$, $7^\circ < \Theta_{\mathrm{jet}} < 20^\circ$, $p_{T\,\mathrm{jet}} > 3.5$

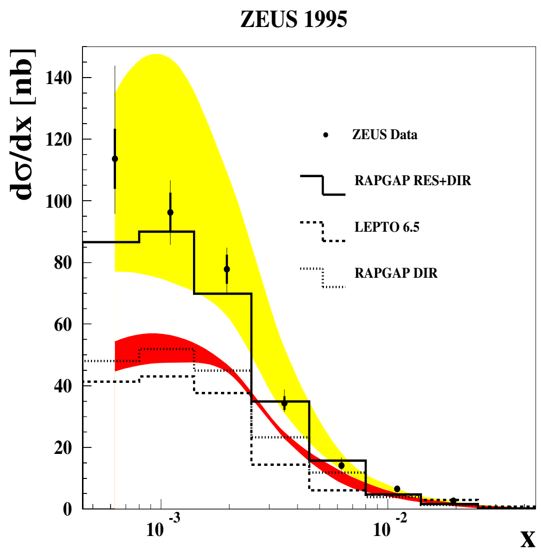

Figure 3: Forward jet cross section at hadron level as a function of x in the kinematic region $\eta_{jet} < 2.6$, $x_{jet} > 0.036$, $0.5 < \frac{E^2_{T\,\mathrm{jet}}}{Q^2} < 2$, $E_{e'} > 10$ GeV, $y > 0.1$. Statistical errors are shown as thick error bars and statistical and systematic errors added in quadrature as thin error bars. The two bands show the result of varying the factorisation and renormalisation scales in the RAPGAP calculations.

GeV falling into the kinematic region $E_{e'} > 12$ GeV, $156^\circ < \Theta_e < 173^\circ$, $y > 0.1$. The same QCD-based models are compared to the data. LEPTO again underestimates the cross-section while predictions from RAPGAP with a resolved photon contribution and ARIADNE are closer to the data. Numerical BFKL calculations at the parton level [23] lie above the data although they describe well the shape of the distribution. Exact NLO parton calculations from DISENT [24] using DGLAP parton densities are far from the data in both shape and normalisation. Further details of this analysis can be found in [25].

H1 has also measured the forward di-jet cross-section [20] for the same kinematic range as the single jet analysis. This has been measured as $6.0 \pm 0.8(stat.) \pm 3.2(syst.)$ pb or roughly 1% of the forward jet cross section.

Recent numerical BFKL calculations at the parton level [26] predict that a fraction of 3 to 6% of the forward jet data should contain 2 or more forward jets. Table 1 compares the forward 2-jet cross-section in data with a number of QCD models with only ARIADNE and RAPGAP giving reasonable descriptions and LEPTO and the LDC failing to match the data.

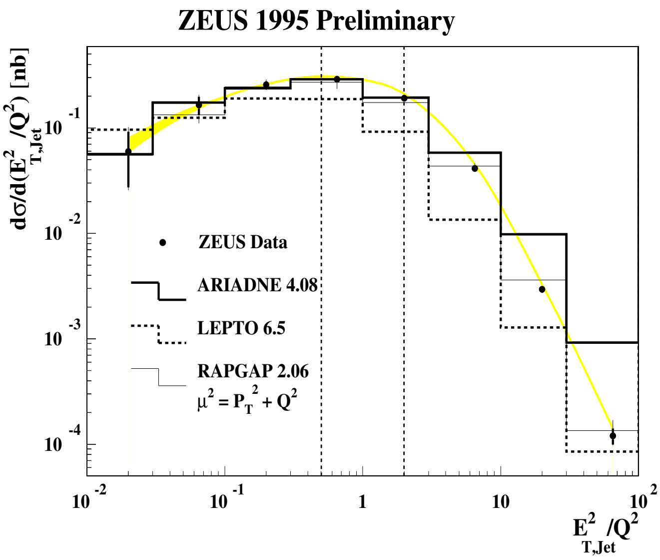

Figure 4: Forward jet cross section at hadron level as a function of x in the kinematic region $\eta_{jet} < 2.6$, $x_{jet} > 0.036$, $0.5 < \frac{E^2_{T\mathrm{jet}}}{Q^2} < 2$, $E_{e'} > 10$ GeV, $y > 0.1$. Statistical errors are shown as thick error bars and statistical and systematic errors added in quadrature as thin error bars. The errors due to the uncertainty of the jet energy scale are shown as the shaded band

Event Sample	Forward 2-jet cross-section / pb
H1 Prel. 1994 Data	$6.0 \pm 0.8 \pm 3.2$
ARIADNE	5.9
RAPGAP	6.0
LEPTO	2.8
LDC	1.6

Table 1: H1 Preliminary data and QCD calculations for forward di-jet events, with each jet satisfying $x_{\mathrm{jet}} = \frac{E_{\mathrm{jet}}}{E_p} > 0.035$, $0.5 < \frac{p^2_{T\mathrm{jet}}}{Q^2} < 2$, $7° < \Theta_{\mathrm{jet}} < 20°$ and $p_{T\mathrm{jet}} > 3.5$ GeV in the kinematic range $E_{e'} > 11$ GeV , $156° < \Theta_e < 173°$ and $y > 0.1$.

3 Summary

Measurements of high transverse momentum single particle rates and single and di-jet cross-sections in low x DIS in the forward region have been presented. Models based on DGLAP and CCFM evolution provide insufficient hard QCD radiation to match the data. Predictions from ARIADNE give a good description of the data as do those from RAPGAP which includes a resolved photon component. Analytical BFKL calculations over-estimate the yield of forward jets and single particles but provide a good description of the shape of their x dependence.

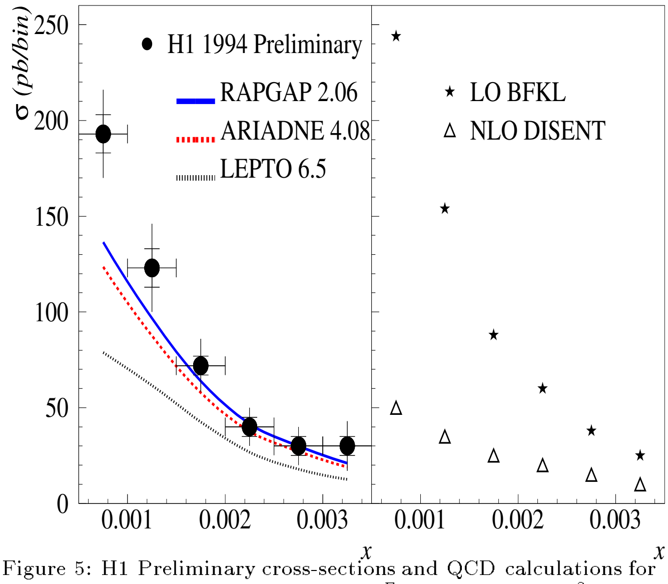

Figure 5: H1 Preliminary cross-sections and QCD calculations for inclusive forward jets satisfying $x_{\mathrm{jet}} = \frac{E_{\mathrm{jet}}}{E_p} > 0.035$, $0.5 < \frac{p^2_{T\mathrm{jet}}}{Q^2} < 2$, $7° < \Theta_{\mathrm{jet}} < 20°$ and $p_{T\mathrm{jet}} > 3.5$ GeV.

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