Forward Jet and Pion Production in Deep-Inelastic Scattering at H1

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Measurements of deep inelastic events containing jets and π^0 mesons produced at small angles with respect to the proton remnant in the laboratory frame are discussed. The data are used to discriminate between different QCD evolution schemes for the parton ladder between proton and photon.

1 Introduction

In deep-inelastic scattering (DIS) at HERA, when the squared $\gamma^* p$ energy W^2 is much larger than Q^2, the momentum fraction of the struck quark, $x \approx Q^2/W^2$, becomes small. The large energies available at small x give rise to a large phase space for gluon cascades exchanged between the parton in the proton and the photon. Several perturbative QCD-based prescriptions are available to describe the dynamics of the partonic evolution process. The DGLAP evolution equations[1] resum leading $\ln(Q^2)$ terms and ignore $\ln(1/x)$ terms. In this approach gluon emissions are strongly ordered in transverse momentum. The BFKL evolution equation[2] resums $\ln(1/x)$ terms, which may become important at low x. Here there is no ordering in transverse momentum of the partons along the ladder. A parton ladder without transverse momentum ordering is also provided by allowing the virtual photon to have a partonic structure. In this approach two DGLAP cascades are initiated one from the proton and one from photon. The CCFM evolution equation[3] is based on angular ordering and colour coherence and behaves like the DGLAP and BFKL schemes in the appropriate limits. Studies of DIS events accompanied by an energetic jet of high transverse momentum close to the proton remnant are considered to be especially sensitive to the QCD dynamics at low x. These measurements, inspired by the proposal of Mueller[4], are restricted to the phase space region:

1. transverse momentum of the jet $k_{T,jet} \approx Q^2$ to suppress DGLAP evolution in Q^2 and sufficiently large to minimize the k_T diffusion into the infrared region[5]
2. $x_{jet} = E_{jet}/E_p$ as large and x as small as kinemtaically possible to select events with large phase space for BFKL effects[1]

In addition, at large $k^2_{T,jet}$ and x_{jet}, the initial parton distributions needed for theoretical calculations are well measured. The selected jets are close to the proton remnant direction in the laborarory frame[2], the so-called forward region.

Studies of single forward particles are complementary to measurements of forward jet production. An advantage of studying single particles as opposed to jets is the easier experimental identification without the dependence on the jet-finding algorithm and the potential to reach angles closer to the proton remnant direction. Especially in the H1 detector, forward π^0-mesons can be identified at very low angles. A disadvantage is that the cross section for the process is supressed in comparison to forward jet production, and that the fragmentation effects are more significant. It should be noted that, at HERA, the range between the hard scattering and the forward jet covers about 4 units of rapidity and slightly more for forward π^0 measurement. Such separation may not be sufficient to discriminate between BFKL and DGLAP parton dynamics.

In this analysis we present recent results of the H1 Collaboration on high transverse momentum forward jet and π^0-mesons produced in DIS at low x. The data are confronted with various QCD-based models.

2 Forward jets

Recently the H1 Collaboration has measured the forward jet production cross section in the region $5 < Q^2 < 75$ GeV^2 and $0.1 < y < 0.7$ based on a data sample corresponding to an integrated luminosity of 13.72 pb^{-1}.

The jets are defined using the inclusive k_t algorithm in the Breit-frame. In the laboratory frame the requirements are made that $p_{T,jet} > 3.5$ GeV and

[1] $E_{jet}(E_P)$ denotes the energy of the forward jet(proton) in the laboratory system.

[2] H1 uses a right-handed coordinate system with the z-axis definded by the incident proton beam.

$7^\circ < \theta_{jet} < 20^\circ$. In addition, the restrictions $x_{jet} = E_{jet}/E_p > 0.035$ and $0.5 < p_{jet}^2/Q^2 < 2$ are applied. In Fig. 1 we show the forward jet cross section as a function of x corrected to the hadron level. The data are compared with hadron level Monte Carlo (MC) calculations which implement various QCD models. RAPGAP[6] matches first-order QCD matrix elements to DGLAP based leading-log parton showers. In addition to the direct photon processes, labelled RG(DIR), RAPGAP simulates resolved photon interactions, in which the virtual photon is assumed to have structure. Here, the sum of the direct and resolved processes is marked RG(DIR+RES). The RAPGAP package allows a choice of renormalization and factorization scales. For the predictions presented in Fig. 1, these are set to $Q^2 + p_T^2$, where p_T is the transverse momentum of the partons taking part in the hard scattering process. The prediction of RAPGAP with a point-like photon is well below the data. The inclusion of an additional photon contribution gives a reasonable description of the forward jet data. The MC predictions using the Color Dipole Model as implemented in ARIADNE[7], marked CDM, also gives a good description of the measurement. In the CDM the parton emissions perform a random walk in transverse momentum, leading to a situation similar to that expected in BFKL. In CASCADE[8] off-shell QCD matrix elements are supplemented with parton emissions based on the CCFM equation using a backward evolution approach. An unintegrated gluon density, which describes the F_2 structure function measurements of H1 and ZEUS, is used as input to this model. The rate of forward jet events predicted by this version of CASCADE is a little too high. A later version with an improved treatment of the soft region and a new parametrization of the unintegrated gluon density, gives a much better description of the data, as shown in Fig. 1.

3 Forward π^0 mesons

The new measurements of forward π^0 meson production in DIS interactions at low x correspond to a total integrated luminosity of 21.21 pb^{-1}. This data sample is more than three times larger than was available in the previous H1 publication on forward pions[9] and makes possible the measurement of more differential distributions and additional final state observables. The analysis is restricted in the kinematic range $2 < Q^2 < 70$ GeV^2, $0.1 < y < 0.6$, $5^\circ < \theta_\pi < 25^\circ$, $x_\pi = E_\pi/E_p > 0.01$ and $p^*_{T,\pi} > 2.5$ GeV, where $p^*_{T,\pi}$ is defined in the

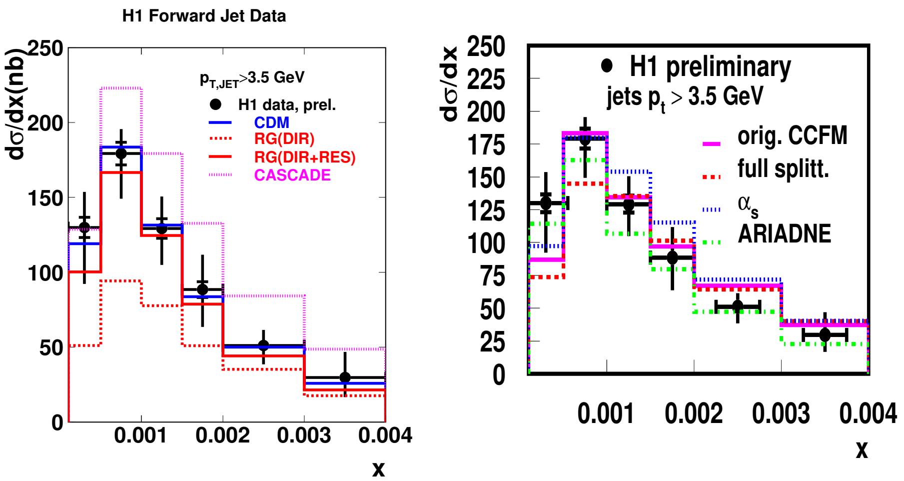

Figure 1: Left: The cross section for forward jet production at the hadron level, as a function of x. Also shown are the predictions of various MC calculations. Right: Predictions of CASCADE with an improved treatment of the soft region and modified parton distributions (see H. Jung, these proceedings).

photon-proton centre-of-mass system. The resulting Bjorken x extends down to $x \approx 4 \cdot 10^{-5}$. Inclusive forward π^0 cross sections are shown as a function of x for different regions of Q^2 in Fig. 2. The prediction of RAPGAP with a point like photon, marked DIR, is well below the data. The addition of a resolved photon contribution (DIR+RES) gives a reasonable description, although it is necessary to provide rather large renormalization and factorization scales, $\mu = Q^2 + 4p_T^2$, in order to get a sufficiently large resolved photon component. Predictions based on CCFM evolution, marked CASCADE, fail to match the measured π^0 cross section at low values of x and Q^2, in the region not covered by the forward jet measurements. A reasonable description of the data is also given by the CDM model. Analytical calculations based on LO BFKL with a consistency constraint which mimics higher order of BFKL effects have been discussed in [10] for DIS events containing forward jet or π^0. Predictions of the π^0 cross section at the parton level convoluted with π^0 fragmentation functions from [11], labelled mod. LO BFKL, are also shown in Fig. 2. The data are well described in the lowest Q^2 region; small deviations are seen for higher Q^2.

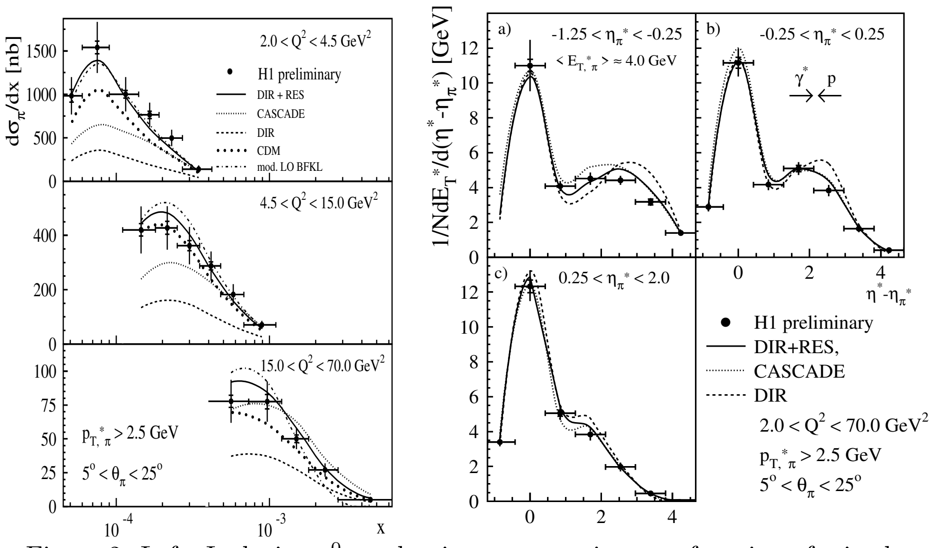

Figure 2: Left: Inclusive π^0 production cross section as a function of x in three regions of Q^2. Right: Transverse energy flow relative to π^0 in various ranges of $\eta^*_{\pi^0}$.

However, these predictions are very sensitive to the choice of scale for α_s and the infra-red cut-off.

Studies of transverse energy flow provide a complementary means of investigating QCD processes. The transverse energy flow in the hadronic centre-of-mass system, $\frac{1}{N}dE^*_T/d(\eta^* - \eta^*_\pi)$, in events containing at least one forward π^0 is shown in Fig. 2. The energy flow, which includes the contribution from the forward π^0, is plotted as a function of the distance in pseudorapidity $\Delta\eta^* = (\eta^* - \eta^*_\pi)$ from the forward π^0. The spectra are presented in three intervals of the π^0 pseudorapidity ranging from close (Fig. 2a) to far (Fig. 2c) from the proton direction. The QCD-based approaches all describe the transverse energy flow around the π^0 but give different predictions in the current region. The differences between the models can be qualitatively understood as a consequence of the ordering or otherwise of the k_T in the parton cascades implemented within MC models. Calculations which include resolved photon processes tend to agree better with the data.

4 Conclusions

Measurements of DIS events at low x containing a forward jet or a forward π^0 are sensitive to the dynamics of parton evolution. Measurements of the cross sections indicate that more hard radiation is observed in the forward region than predicted by standard DGLAP models. Inclusion of resolved photon processes improves the description of the data. However, in the case of the forward π^0 the large factorization and renormalization scales are needed. The BFKL and CCFM calculations are compatible with the data, but the lowest x region, covered only by the forward π^0 data, is not well described by the CCFM approach. Parton radiation in the very forward region is much more complicated than previously believed and is still a challenge for theory and phenomenology.

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