Three- and Four Jet Production in Deep Inelastic Scattering and Low-x Parton Dynamics at HERA

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Parton dynamics characterized by initial state gluon radiation has been studied in deep inelastic e-p processes at low x and Q^2 at HERA using events with three- and four jets in final state both in the full kinematical range and for restrictive topologies with forward (close to the proton direction) jets. The measurement of three jet cross sections are compared to order α_s^2 and α_s^3 of fixed order QCD predictions and to leading order MC programs. Results indicate the presence of large contribution from gluon emission not ordered in transverse momentum at low x and forward rapidities.

1 Introduction

The study of parton dynamics at low x at HERA allows to test the predictions of the DGLAP evolution equations in this kinematic region. In leading order (LO) these approximations neglect terms $\propto \alpha_s \cdot \ln(1/x)$ which become large at small x. Inclusion of these terms may lead to an enhancement of gluon radiation not ordered in transverse momentum $k_\perp$ with respect to the DGLAP expectations. The enhancement should be the largest for high $p_\perp$ forward jets (near to the proton direction). Earlier measurements [2] have shown that the rate of forward jets at low x is much higher compared to QCD predictions with $k_\perp$ -ordered initial state parton showers.

The present analysis [3] includes the measurements of three- and four jet cross sections which require at least one or two gluons, respectively, radiated away from the hard scattering subprocess ($\gamma^\star g \to q\bar{q}$). The data are compared to fixed order QCD predictions at parton level calculated using NLOjet++ program [4] which is able to predict three jet parton cross sections in leading (LO,(α_s^2)) and next to leading (NLO,(α_s^3)) order and four jet cross sections in (LO,(α_s^3)). In addition two LO Monte Carlo (MC) generators which were able to describe forward jet and dijet production at low x are tested: RAPGAP [5] with initial state parton radiation ordered in $k_\perp$ including resolved photon component and DJANGO [6] which uses the color dipole model (CDM) to produce additional gluon radiation.

2 Event and Jet Selection

The data used in this analysis were taken in the 1999 and 2000 running periods, in which HERA collided 920 GeV protons with 27.5 GeV positrons, corresponding to an integrated luminosity of 44.2 pb^{-1}. The kinematic range is defined by: 5 GeV^2 $< Q^2 <$ 80 GeV^2, 0.1 $< y <$ 0.7, $10^{-4} < x < 10^{-2}$.

Jets are found using the inclusive $k_\perp$ cluster algorithm in the $\gamma^\star p$ rest frame. At least 3 jets are required with transverse momenta $p_\perp^\star >$ 4 GeV and within the pseudorapidity range: -1$< \eta_{jet}^{lab} <$2.5, with $p_{\perp 1}^\star + p_{\perp 2}^\star >$ 9 GeV for the the sum of leading and subleading jets and one jet in the central part of the detector in the range -1 $< \eta_{jet}^{lab} <$ 1.3. After all cuts 38400 events are selected with at least 3 jets of which 6000 events have more than 3 jets.

3 Results

The differential cross sections are measured as a function of the number of jets (N_{Jet}), the Bjorken variable x, the pseudorapidities of the jets and transverse momenta of the jets. Figure 1 shows the differential cross sections for the N_{Jet}, x and pesudorapidity η of the leading jet compared to fixed order QCD predictions in LO and NLO. For the jet multiplicity distribution which extends up to $N_{Jet} = 7$ also the prediction of the two LO MC programs are shown. The color dipole model (DJANGO(CDM)) gives a very good description of this distribution while RAPGAP is below data for all N_{Jet}. The NLO prediction agrees for $N_{Jet} = 3$, misses a fraction of four jet events and produces no events with more than 4 jets, resulting in a total deficit of 18% of events with four or more jets.

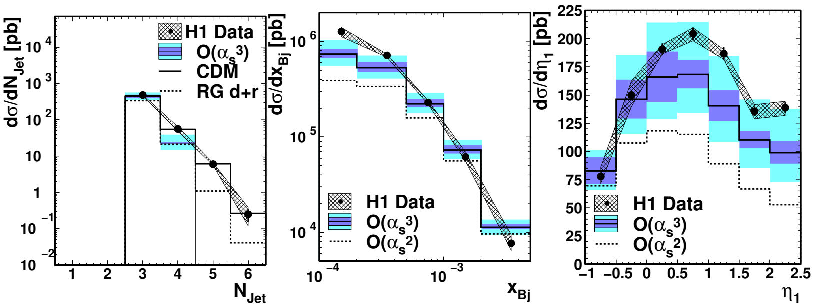

Figure 1: Differential cross sections as a function of jet multiplicity N_{Jet}, the Bjorken variable x_{Bj} and the pseudorapidity of the leading $p_\perp^\star$ jet η_1. The inner error bars represent the statistical error of the data, the total error bars correspond to the statistical and uncorrelated systematic srrors added in quadrature. The hatched error bands show the estimate of the correlated systematic uncertainties. The dark shaded (inner) error band shows the NLO (α_s^3) prediction including the uncertainties of the hadronization corrections, the light shaded (outer) band shows the scale uncertainty of the NLO calculations added in quadrature to the hadronization uncertainty, the dashed line represents the LO (α_s^2) prediction. The latter is not shown in the N_{Jet} distribution which is also compared to the two LO MC programs RAPGAP (dotted line) and DJANGO(CDM) (solid line).

The kinematic distributions are not described by the LO QCD predictions neither in shape nor in magnitude. Main discrepancies are observed at low x and large η (forward region) where predictions are too low. The NLO calculation shows a clear improvement in all regions where the discrepancies are observed leading to the conclusion that events with more than 3 jets are missing mainly at low x and large η. This is exactly the kinematic region where an excess of jets due to unordered gluon emission is expected.

3.1 Forward Jet Selection

The yield of events with three jets is underestimated by the predictions at low x and large η (in the forward direction). This discrepancy is further investigated using a forward jet selection. A forward jet is defined by $\Theta_{jet} < 20°$ and $x_{jet} = E_{jet}/E_{p,beam} > 0.035$. Two subsamples are studied: one sample with two central jets ($-1 < \eta_{jet} < 1$) and one forward jet and the second one with one central jet and two forward jets (one of them with $\eta_{jet} > 1$). Results compared to QCD calculation are shown in Fig. 2 for the variables x and η_1. Going from LO to NLO improves the agreement at low x and large η significantly for both samples but still a large discrepancy remains at low x and large rapidities for the sample with two forward jets.

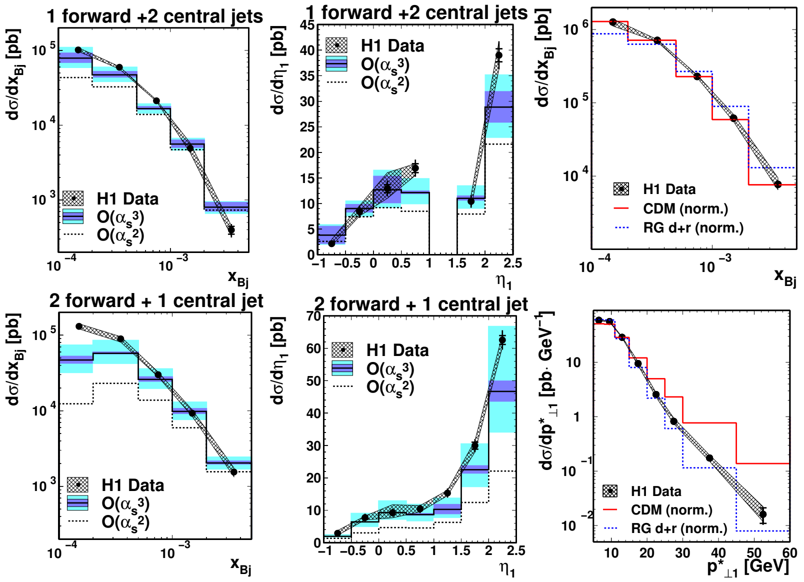

Figure 2: Differential cross sections as a function of the Bjorken variable x_{Bj} (left) and the pseudorapidity of the leading $p_\perp^\star$ jet η_1 (mid) for forward jet selection. Other details are as in the caption to Fig. 1. The two plots (right) are differential three jet cross sections in the Bjorken variable x_{Bj} and the transverse momentum of the leading jet $p_{\perp 1}^\star$. The inner error bars represent the statistical error of the data, the total error bars correspond to the statistical and uncorrelated systematic srrors added in quadrature. The hatched error bands show the estimate of the correlated systematic uncertainties. The data are compared to the two LO MC programs RAPGAP (dashed line) and DJANGO(CDM) (solid line) scaled to the data by factors 1.05 (CDM) resp. 1.51 (RAPGAP).

3.2 Comparison of Three Jet Cross Sections to the LO Monte Carlo Programs

The measured cross sections are compared to the two LO MC programs RAPGAP and DJANGO. The latter describes well the data as shown in Fig. 2 (right) for the Bjorken variable x_{Bj} but does not describe $p_\perp^\star$ distribution. It predicts too many jets with $p_{\perp 1}^\star >15$ GeV. The RAPGAP prediction fails to describe data with the exception of the momentum and energy distributions.

3.3 Four Jet Cross Section

Cross sections for events with at least four jets can be compared to the fixed order QCD predictions in LO (α_s^3). As already shown in Fig. 1 these predictions are below the data by a factor of 1.8. According to a study using the DJANGO (CDM) program in the four jet sample there are too few events with three gluon emissions to give new insight into the QCD dynamics compared to the three jet analysis. The four jet cross sections as a function of $p^\star_{\perp 1}$ and $\eta_1 - \eta_4$ as shown in Fig. 3 are therefore only compared to the LO MC generators RAPGAP and DJANGO (CDM). The CDM figure agrees well with data with again the exception of the jet momentum $p^\star_\perp$ distribution. This distribution is again correctly described by the RAPGAP prediction which fails to describe other distributions.

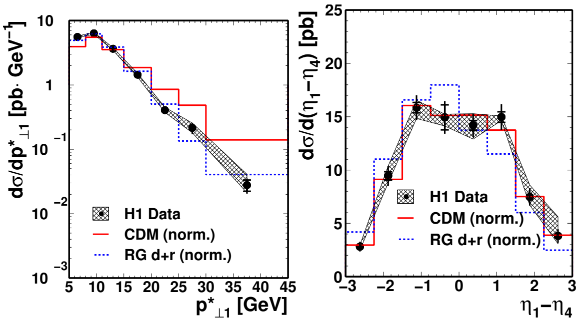

Figure 3: Differential four jet cross sections as a function of the transverse momentum of the leading jet $p^\star_{\perp 1}$ and the pseudorapidity difference of the leading $p^\star_\perp$ jet and the fourth jet $\eta_1 - \eta_4$ (with $p^\star_{\perp 1} > p^\star_{\perp 2} > p^\star_{\perp 3} > p^\star_{\perp 4}$). The inner error bars represent the statistical error of the data, the total error bars correspond to the statistical and uncorrelated systematic errors added in quadrature. The correlated systematic errors are shown by hatched error band. The data are compared to the two LO MC generators RAPGAP (dashed line) and DJANGO (CDM) (solid line). Both MC cross sections are normalized to the data cross sections by factors of 1.01 (CDM) resp. and 2.82 (RAPGAP).

4 Summary

The three- and four jet events at low x are remarkably well described by color dipole model (CDM) with additional gluon radiation not ordered in $k_\perp$ for moderate transverse momenta of the gluons. The remaining discrepancies at higher momenta require further studies. Compared to order α_s^2 predictions, the NLO(α_s^3) QCD calculations show a significant improvement in the data description. Remaining discrepancies are found at low x and large rapidities for the sample with two forward and one central jet. This is the kinematic region where unordered gluon radiation is expected to give a large contribution. We conclude therefore that unordered in $k_\perp$ gluon emission at low x plays an important role.

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