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Forward jet production at HERA

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Forward jet and particle cross sections have been measured in lepton-proton collisions by the H1 and ZEUS collaborations at HERA. Parton evolution schemes are tested by requiring a forward jet or particle with $E_T \sim Q^2$ or a forward jet plus a central dijet system. The measurements are compared to next-to-leading order QCD predictions and various QCD-based Monte Carlo models.

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1. Introduction

Deep inelastic scattering (DIS) of a lepton off a parton in the proton at HERA enables precision measurements of Quantum Chromodynamics (QCD). In DIS the parton induces a QCD cascade consisting of several parton emissions before it interacts with the virtual photon. The general form of the parton evolution equations require a summation over all leading double logarithms in $\ln(Q^2)\cdot\ln(1/x)$. The most commonly used DGLAP evolution equation [1] resums only over the single logarithms in $\alpha_s\ln(Q^2)$, neglecting the $1/x$ terms, and is expected to be valid in regions where x is not too small. The partons in the cascade are strongly ordered in k_T and ordered in x, where the parton interacting with the photon has the highest k_T and lowest x. The BFKL equation [2] resums over single logarithms in $\alpha_s\ln(1/x)$ and is therefore valid in regions of low x and Q^2 not too large. The partons in the cascade are ordered in x in the same way as those in DGLAP, but are not ordered in k_T. The CCFM equation [3] resums over both $\alpha_s\ln(Q^2)$ and $\alpha_s\ln(1/x)$ and should therefore be valid in large regions of x and Q^2.

The DGLAP model is valid over most of the HERA kinematic range. In order to test the validity of other models it is necessary to select a region where DGLAP may not be valid and the other models may be needed. Because of the k_T ordering of partons in DGLAP, which does not occur in BFKL or CCFM, such a kinematic region can be found by requiring a forward jet with $E_T^{Jet}\sim Q^2$ as suggested by Mueller [5] , a forward particle with $E_T^{Particle}\sim Q^2$, or a forward jet plus a central dijet system.

2. Forward Jet Production in the low-x, low-Q^2 Region

The H1 forward jet results for 1997 data [4] are shown in Fig. 1. The region of phase space was defined by $5<Q^2<85\,\mathrm{GeV}^2$ and $0.0001<x_{Bj}<0.004$. Jets were defined using the k_T-jet algorithm [6] in its inclusive mode [7] applied in the Breit frame, and by requiring in the laboratory frame that $p_T^{Jet}>3.5\,\mathrm{GeV}$ and $7.0^\circ<\theta^{Jet}<20.0^\circ$. The DGLAP evolution was suppressed by requiring $0.5<\left(p_T^{Jet}\right)^2/Q^2<5$ and $E^{Jet}/E^{Proton}>0.035$. The plot on the left side of Fig. 1 shows that the prediction based on the DISENT NLO QCD calculation is below the data at low x_{Bj}. The plot on the right side of Fig. 1 shows that the RAPGAP Monte Carlo (MC) with only direct photon contribution lies below the data at low x_{Bj} and that RAPGAP with both direct and resolved photon contributions and ARIADNE give better agreement. The CASCADE MC prediction fails to describe the shape of the data.

The results of the ZEUS forward jet measurements for 1996-97 data [8] can be found in reference [9]. The phase space selected was $Q^2>25\,\mathrm{GeV}^2$. Jets were reconstructed using the k_T cluster algorithm in the laboratory frame and were required to have $E_T^{Jet}>6\,\mathrm{GeV}$. The BFKL region was selected by requiring that $0.5<\left(E_T^{Jet}\right)^2/Q^2<2$, at least one jet with $0<\eta_{lab}^{Jet}<3$, and $\cos\gamma_h<0$. The ARIADNE MC describes the forward jet data reasonably well and the LEPTO and the DISENT NLO calculations are slightly lower than the data. The biggest differences between the data and NLO predictions are observed in the low x region and for very forward jets ($2<\eta^{Jet}<3$).

3. Very Forward Jets at ZEUS

The forward jets in the H1 measurement had a maximum η of 2.7 and those in the ZEUS mea-

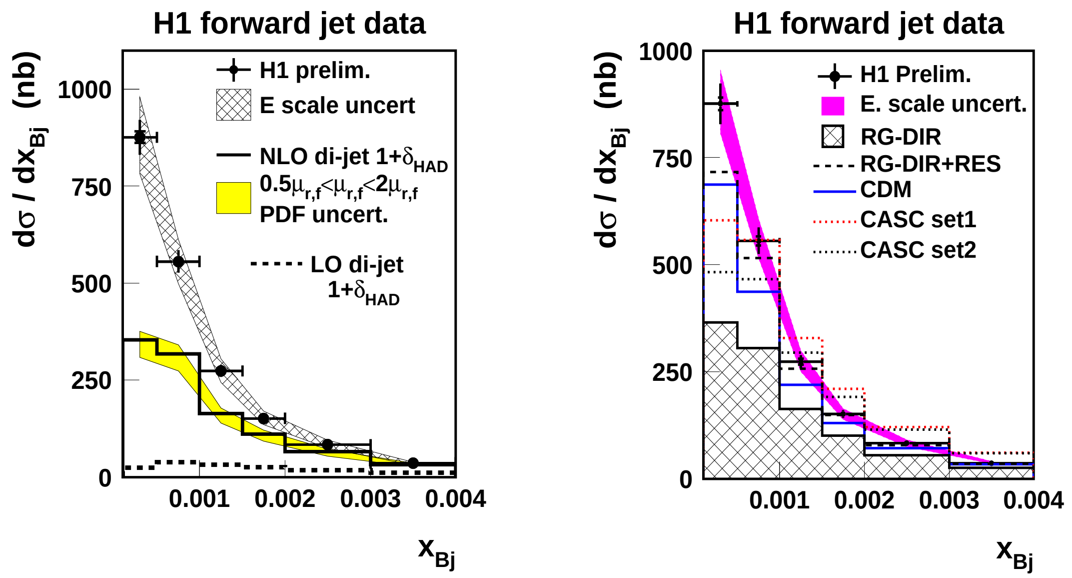

Figure 1: The hadron level cross section for inclusive forward jet production as a function of x_{Bj} compared to predictions from NLO QCD calculations (left) and MC models (right).

surement had a maximum η of 3. ZEUS has extended the measurements to $\eta^{Jet} = 3.5$ [10] by using the Forward Plug Calorimeter, which was newly installed for the 1998-2000 data taking. The phase space was $20 < Q^2 < 100\,\text{GeV}^2$ and $0.0004 < x_{Bj} < 0.005$. Jets were reconstructed using the k_T cluster algorithm and were required to have $E_T^{Jet} > 5\,\text{GeV}$. Forward jets with high energy were selected by requiring $p_z^{Jet}/p > 0.036$ and $0.5 < \left(E_T^{Jet}\right)^2/Q^2 < 2$. The plot on the left in Fig. 2 shows that ARIADNE describes the data but LEPTO does not, with large disagreements at low Q^2 and low x. CASCADE with J2003 Set 1 of the unintegrated PDFs does not describe the data but CASCADE with J2003 Set 2 gives a good description of Q^2 and E_T^{Jet} and a reasonable description of x and η. The plot on the right in Fig. 2 shows that the DISENT NLO describes the forward jets data within the theoretical uncertainties, but there is a large variation with renormalization scale, which suggests that higher order calculations may be necessary.

4. Forward Jets with Central Dijets at H1

H1 has tested for a possible signature of BFKL dynamics by requiring a central dijet system in addition to a forward jet [4]. The jets are ordered in η in the Breit frame as follows: $\eta_{Fwd-Jet} > \eta_{Dijet2} > \eta_{Dijet1} > \eta_{Electron}$. Two variables are defined: $\Delta\eta_1 \equiv \eta_{Dijet2} - \eta_{Dijet1}$ and $\Delta\eta_2 \equiv \eta_{Fwd-Jet} - \eta_{Dijet2}$. The BFKL region is suppressed by applying the same p_T cut to all three jets and by selecting events with $\Delta\eta_1 < 1$. The other event selection criteria are the same as those described for the H1 analysis in Section 2. RAPGAP with direct and resolved contributions falls below the data for the region of *ALL* $\Delta\eta_1$ (Fig. 3 left) and for the region of $\Delta\eta_1 < 1$ (Fig. 3 right). LEPTO gives a reasonable description for the data for $\Delta\eta_1 < 1$. CASCADE Set 1 does not describe the data in either region and Set 2 describes the data for $\Delta\eta_1 < 1$, except for the lowest bin of $\Delta\eta_2$.

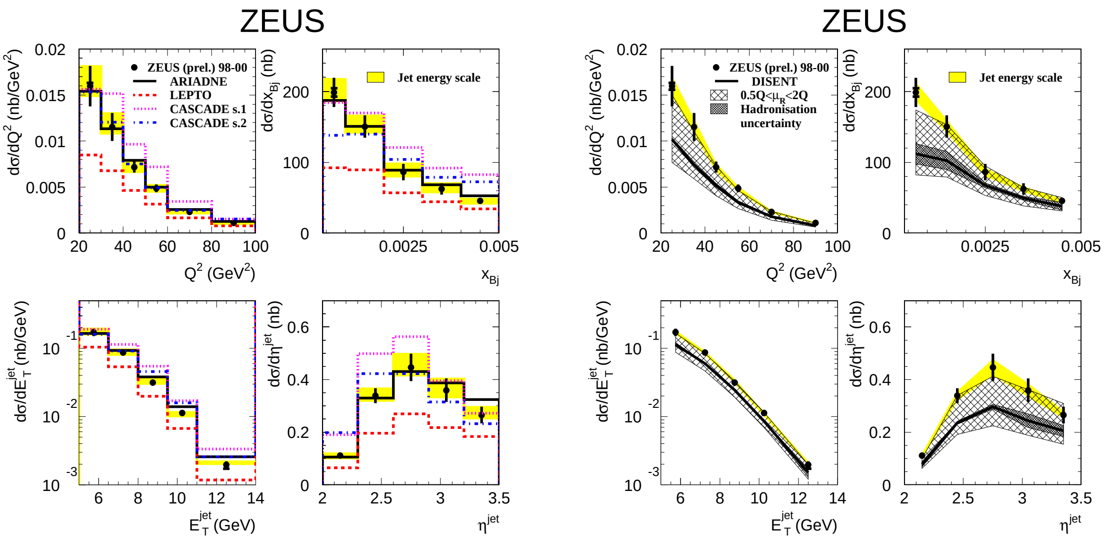

Figure 2: Differential cross sections for inclusive jet production measured by ZEUS. The shaded area is the calorimeter energy scale uncertainty, the inner error bars are the statistical uncertainties, and the outer error bars are the statistical and systematic uncertainties added in quadrature. The data are compared to MC (left) and QCD NLO (right) predictions.

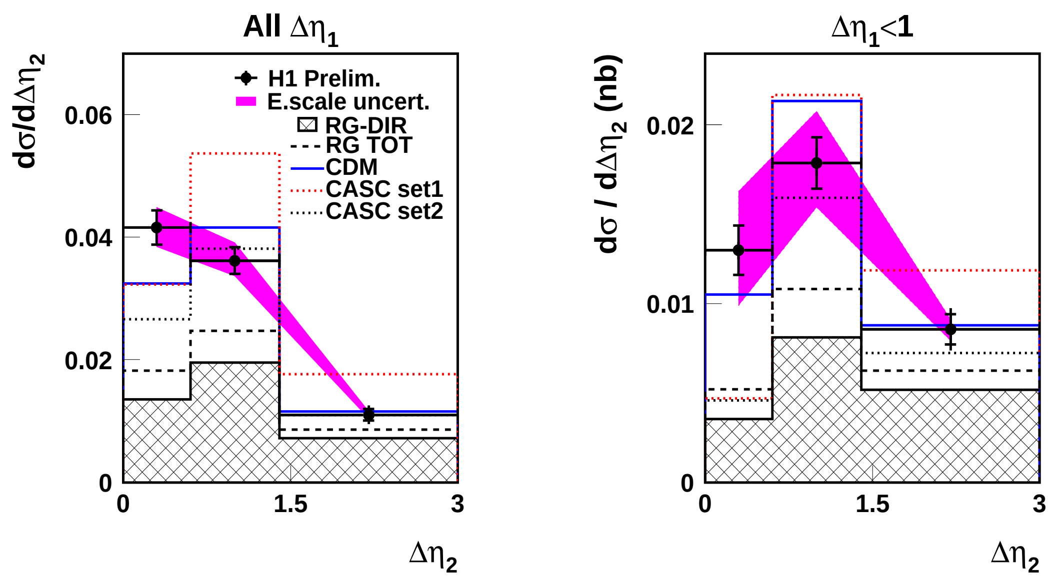

Figure 3: The cross section for events with a reconstructed high p_T central dijet system and a forward jet as a function of pseudorapidity difference between the forward jet and the most forward-going central jet, $\Delta\eta_2$. The figure on the left is for *ALL* $\Delta\eta_1$ and the figure on the right is for $\Delta\eta_1 < 1$, the BFKL region. The data are compared to QCD MC models.

5. Forward π° Production at H1

H1 measured forward particle production [11] as a complementary method for testing the BFKL phase space using 1996-97 data in the kinematic region $2 < Q^2 < 70\,\mathrm{GeV}^2$ and $0.00004 < x < 0.006$. Forward π° candidates were required to lie in the polar region $5^\circ < \theta^\pi < 25^\circ$ and have a transverse momentum in the photon-proton center of mass system $p_T^\pi > 2.5\,\mathrm{GeV}$ or $p_T^\pi > 3.5\,\mathrm{GeV}$. The BFKL region was selected by requiring $E^\pi/E^{Proton} > 0.01$. Cross sections as a function of p_T^π and x can be found in reference [12]. The cross section as a function of x_{Bj}, with $p_T^\pi > 2.5\,\mathrm{GeV}$, is described by RAPGAP with direct and resolved contributions, is above the prediction of RAPGAP with only a direct contribution, and is described by CASCADE only at high x and Q^2. The cross sections as a function of x with $p_T^\pi > 3.5\,\mathrm{GeV}$ are 2 to 4 times lower than those with $p_T^\pi > 3.5\,\mathrm{GeV}$, but the MC describes them similarly. The DISENT NLO also describes these measurements.

6. Conclusions

BFKL phase space was selected by requiring $E_T^2 \sim Q^2$ for forward particles or forward jets, or requiring a forward jet plus a central dijet system. ARIADNE and RAPGAP with direct and resolved contributions describe the data much better than LEPTO or RAPGAP with only direct contributions. CASCADE does not describe all the data. The DGLAP-based NLO calculations describe the data at low Q^2 and low x only within large theoretical uncertainties. Comparisons of the data to the predictions of the different MC models and the QCD calculations demonstrate a need for resolved photon contributions, higher order DGLAP based QCD calculations, or a new type of BFKL-based QCD prediction.

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