Measurements of multijet production at low-x

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Recent measurements of multijet production in neutral current deep inelastic ep scattering at HERA are presented. Emphasis is put on parton dynamics at low x.

1. INTRODUCTION

Deep inelastic scattering (DIS) off protons has provided decisive information on the parton distribution functions (PDFs) of the proton. Inclusive measurements of the cross section for the reaction $ep \rightarrow e\mathrm{X}$ as a function of the virtuality of the exchanged boson (Q^2) and of the Bjorken scaling variable (x) have been used to determine the proton structure function $F_2^p(x, Q^2)$. Perturbative QCD (pQCD) in the next-to-leading-order (NLO) approximation has been widely used to extract the proton PDFs from such measurements and to test the validity of pQCD. In the standard approach (DGLAP [1]), the evolution equations sum up all leading double logarithms in $\ln Q^2 \cdot \ln 1/x$ along with single logarithms in $\ln Q^2$ and are expected to be valid for x not too small. At low x, a better approximation is expected to be provided by the BFKL formalism [2] in which the evolution equations sum up all leading double logarithms along with single logarithms in $\ln 1/x$.

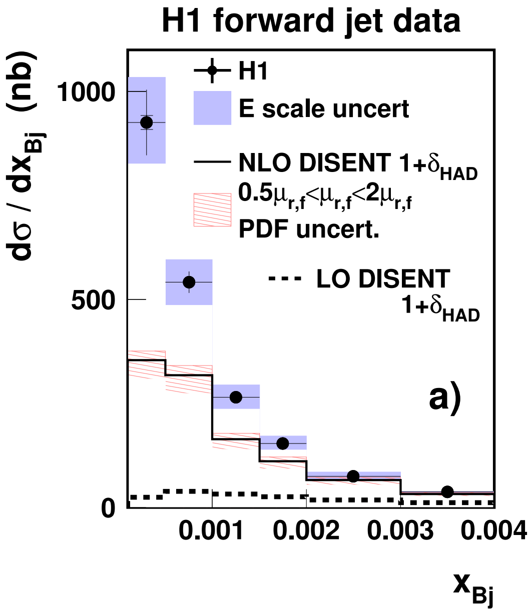
The DGLAP evolution equations have been tested extensively at HERA and were found to describe, in general, the data. In particular, the striking rise of the measured $F_2^p(x, Q^2)$ at HERA with decreasing x can be accomodated in the DGLAP approach. Nevertheless, the inclusive character of $F_2^p(x, Q^2)$ may obscure the underlying dynamics at low x, and more exclusive final states like forward [1] jets [3] need to be studied. BFKL evolution predicts a larger fraction of small-x events containing high-E_T forward jets than predicted by DGLAP [3, 4]. Parton dynamics at low x is particularly relevant for the LHC given that most of the interesting hard processes involve partons with low fractional momenta.

2. FORWARD JET PRODUCTION

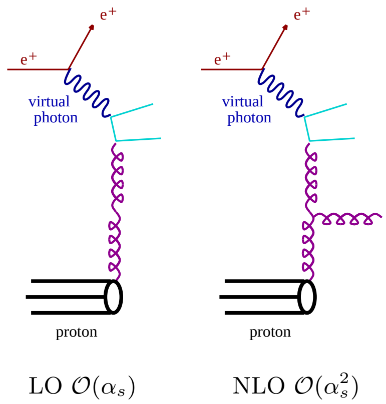
Forward jet production in neutral current (NC) DIS has been studied extensively at HERA. As an example, measurements of forward jet production with $p_{t,\mathrm{jet}} > 3.5$ GeV, polar angle θ_{jet} between 7° and 20°, $0.5 < p_{t,\mathrm{jet}}^2/Q^2 < 5$ and $x_{\mathrm{jet}} \equiv E_{\mathrm{jet}}/E_p > 0.035$, where E_p is the proton-beam energy, in the kinematic region defined by $10^{-4} < x < 4 \cdot 10^{-3}$ and $5 < Q^2 < 85$ GeV^2 are shown in Figure 1a and exhibit a strong rise towards low x [5]. Perturbative QCD apparently does not account for such a rise: the leading-order (LO) QCD calculation does not predict any rise while the one predicted by NLO [6] is still much too low (see Figure 1a). Some of the Feynman diagrams that are accounted for in the LO ($\mathcal{O}(\alpha_s)$) and NLO ($\mathcal{O}(\alpha_s^2)$) calculations are shown in Figure 1b. The former has no additional gluon radiation and helps to understand why in the LO calculation there is hardly any phase space left for forward jet production. In contrast, the NLO calculation accounts for the radiation of one additional gluon. This explains why there is such a huge increase from LO to NLO: due to the opening of a new channel, namely gluon-exchange in the t channel. However, that means that the NLO calculation is effectively a "LO" calculation, since no corrections are included. The NLO calculation should thus have large theoretical uncertainties from higher

[1] The coordinate system used is a right-handed Cartesian system with the Z axis pointing in the proton beam direction, referred to as the "forward direction".

orders. A variation of the renormalisation scale around $\mu_R^2 = \langle p_{t,\mathrm{dijets}}^2 \rangle$ do not give rise to such large theoretical uncertainties (see Figure 1a). However, if Q^2 is instead chosen as the renormalisation scale, the resulting theoretical uncertainties are large, as pointed out in [5] and shown in Figure 1c: measurements of forward jet production [7] with $E_T^{\mathrm{jet}} > 5$ GeV, pseudorapidity in the range $2 < \eta^{\mathrm{jet}} < 4.3$, $0.5 < (E_T^{\mathrm{jet}})^2/Q^2 < 2$ and $x_{\mathrm{jet}} > 0.036$ in the kinematic region given by $4 \cdot 10^{-4} < x < 5 \cdot 10^{-3}$ and $20 < Q^2 < 100$ GeV^2 are compared to NLO QCD calculations [6] with $\mu_R^2 = Q^2$. Large theoretical uncertainties which arise from higher orders in the pQCD calculations prevent a firm conclusion. Further progress can be made by making measurements for which genuine NLO calculations are available, i.e. one gluon radiation at LO and two additional radiated gluons at NLO. That is the case for three-jet production, which was already studied in [5] and has been investigated more thoroughly in [8]. The latter is discussed next.



(a)



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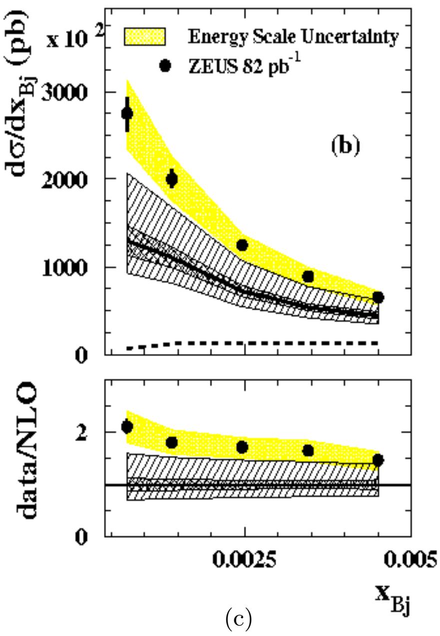


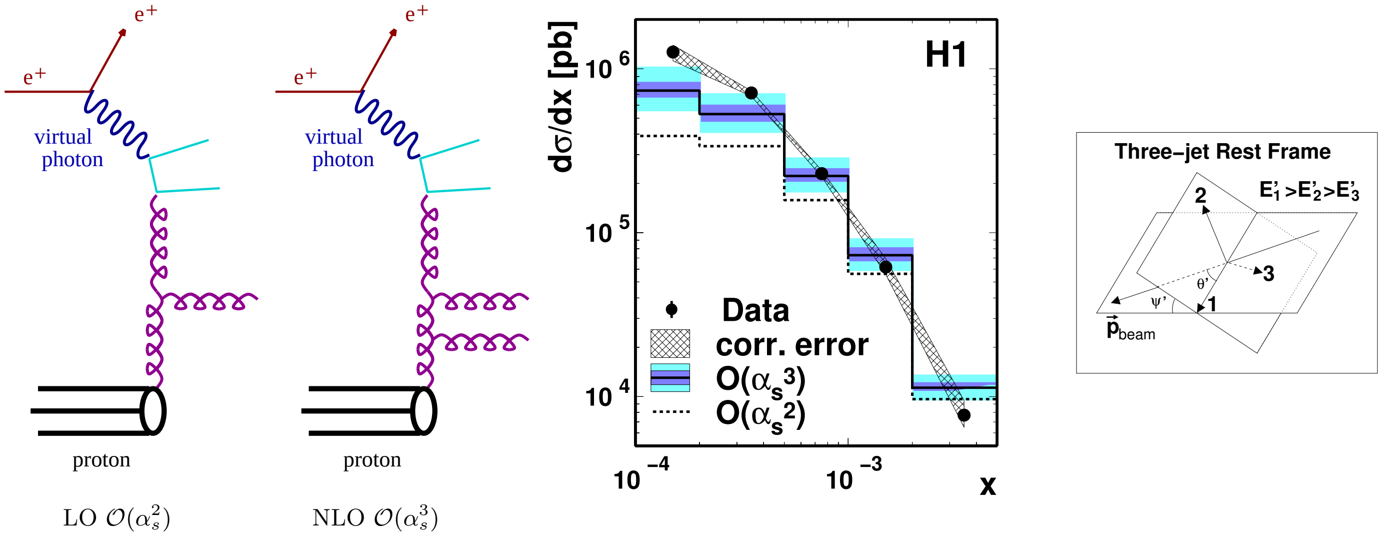
(c)

Figure 1: Measurements of forward jet production in NC DIS as functions of x (a,c). Examples of Feynman diagrams (b).

3. MULTIJET PRODUCTION AT LOW x

Some of the Feynman diagrams accounted for in the pQCD calculations for three-jet production in NC DIS are shown in Figure 2a. A measurement of the differential cross section $d\sigma/dx$ as a function of x for three-jet production [8] is presented in Figure 2b. The jets are reconstructed in the $\gamma^* p$ frame and are required to fulfill the following conditions: the transverse momentum of each jet $p_{t,i} > 4$ GeV, the sum of the highest and next-to-highest p_t jets above 9 GeV, the jet pseudorapidity in the laboratory frame to lie between -1 and 2.5 and at least one of the jets in the central region ($-1 < \eta_{\mathrm{jet}}^{\mathrm{lab}} < 1.3$). The kinematic region is defined by $10^{-4} < x < 10^{-2}$, $5 < Q^2 < 80$ GeV^2 and $0.1 < y < 0.7$, where y is the inelasticity variable. Perturbative QCD calculations are compared to the data in Figure 2b: the LO ($\mathcal{O}(\alpha_s^2)$) calculation still falls short of the data, but the NLO ($\mathcal{O}(\alpha_s^3)$) calculation [9] improves dramatically the description of the data at low x.

The inclusion of the $\mathcal{O}(\alpha_s^3)$ QCD corrections does not only improve the description of the measured rate but also that of the topology of the events. Measurements have been made of the distributions in the variables used to describe the topology of three-jet events in the three-jet centre-of-mass frame: the scaled energy of the jets $X_i' \equiv 2E_i'/(E_1' + E_2' + E_3')$ ($i = 1, 2$; $E_1' > E_2' > E_3'$) and the two angles θ' and ψ' (see Figure 2c). The measurements are shown in Figure 3 and compared to NLO calculations [9]. The inclusion of additional gluon radiation provides an improved description of the data, for example, in the $\cos\theta'$ distribution: the NLO follows the data and exhibits peaks at $\cos\theta' = -1$ and 1, whereas the LO calculation flattens out at $\cos\theta' = -1$.



(a) (b) (c)

Figure 2: Examples of Feynman diagrams (a). Measurement of $d\sigma/dx$ for three-jet production in NC DIS as a function of x (b). Definition of θ' and ψ' in the three-jet centre-of-mass frame (c).

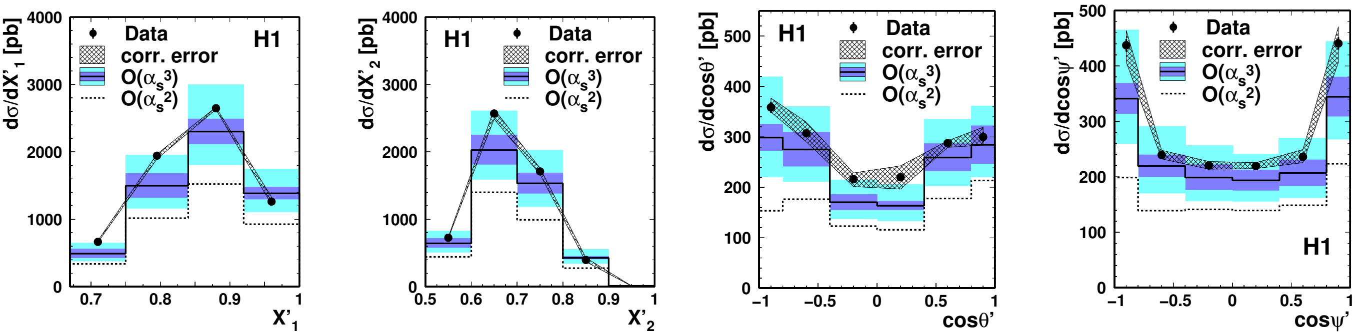


Figure 3: Measurements of the differential cross sections as functions of the variables used to describe the topology of three-jet events in the three-jet centre-of-mass frame.

Further investigations of low-x parton dynamics have been made by studying transverse-energy and angular correlations in dijet and trijet production in NC DIS [10]. Jets are reconstructed in the hadronic centre-of-mass (HCM) frame and required to fulfill the following conditions: $E_{T,\mathrm{HCM}}^{\mathrm{jet1}} > 7$ GeV, $E_{T,\mathrm{HCM}}^{\mathrm{jet2,3}} > 5$ GeV and $-1 < \eta_{\mathrm{lab}}^{jet1,2,3} < 2.5$. The kinematic region is given by $10^{-4} < x < 10^{-2}$, $10 < Q^2 < 100$ GeV^2 and $0.1 < y < 0.6$. One of the most interesting angular correlations is provided by the variable $|\Delta\phi_{\mathrm{HCM}}^{jet1,2}|$, which is defined as the azimuthal separation of the two jets with largest $E_{T,\mathrm{HCM}}^{\mathrm{jet}}$. For dijet events, $\mathcal{O}(\alpha_s)$ kinematics constrain $|\Delta\phi_{\mathrm{HCM}}^{jet1,2}|$ to π and $\mathcal{O}(\alpha_s^2)$ calculations provide the LO contribution; $\mathcal{O}(\alpha_s^3)$ calculations give the NLO correction. Measurements of the doubly differential cross section $d^2d\sigma/d|\Delta\phi_{\mathrm{HCM}}^{jet1,2}|dx$ for dijet production in different regions of x are presented in Figure 4. The $\mathcal{O}(\alpha_s^2)$ predictions increasingly deviate from the data as x decreases, whereas $\mathcal{O}(\alpha_s^3)$ calculations [9] provide a good description of the data even at low x.

In summary, parton dynamics at low x is vigorously pursued at HERA. Precise measurements of multijet production in NC DIS have been made down to $x \sim 10^{-4}$ in terms of jet rates, topologies and correlations. Comparison of perturbative QCD calculations with these measurements demonstrate the big impact of initial-state gluon radiation. Perturbative QCD at $\mathcal{O}(\alpha_s^3)$ reproduces succesfully the measurements. However, the theoretical uncertainties are still significant and the precision of the data demands next-to-next-to-leading-order corrections to be included.

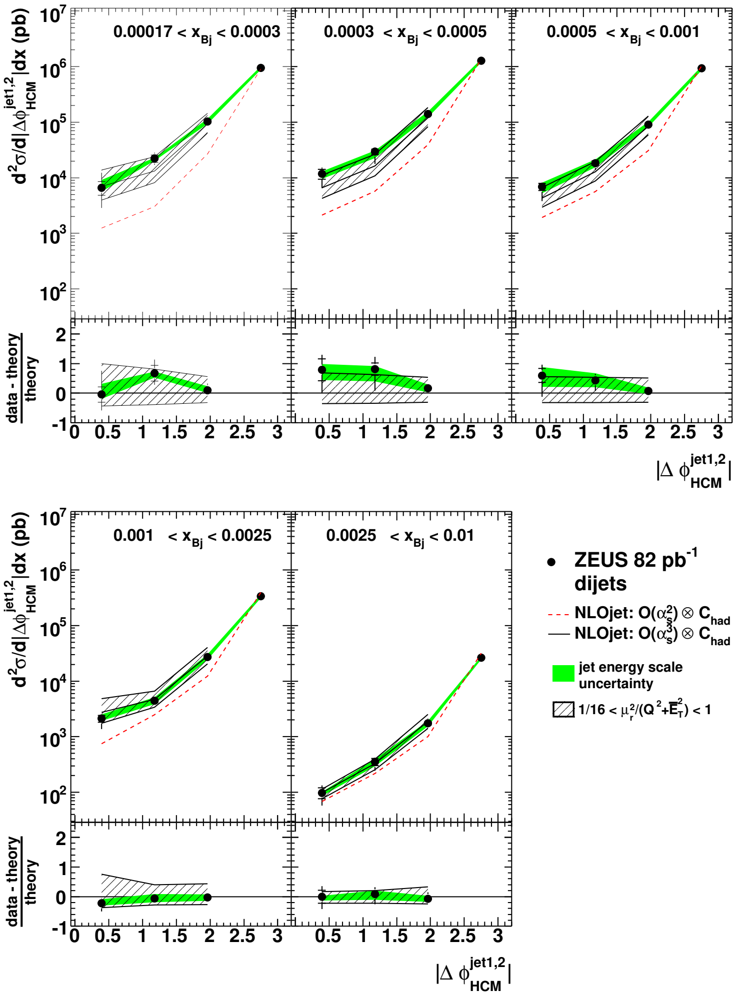


Figure 4: Measurements of the doubly differential cross section $d^2d\sigma/d|\Delta\phi^{jet1,2}_{\mathrm{HCM}}|dx$ for dijet production in different regions of x.

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