

Small- x effects in forward-jet production at HERA

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Abstract. We investigate small- x effects in forward-jet production at HERA in the two-hard-scale region $k_T \sim Q \gg \Lambda_{QCD}$. We show that, despite describing different energy regimes, both a BFKL parametrization and saturation parametrizations describe well the H1 and ZEUS data for $d\sigma/dx$ published a few years ago. This is confirmed when comparing the predictions to the latest data.

INTRODUCTION

Forward-jet production is a process in which a virtual photon strongly interacts with a proton and a jet is detected in the forward direction of the proton. The virtuality of the photon Q^2 and the squared transverse momentum of the jet k_T^2 are hard scales of about the same magnitude. In the Regge limit of perturbative QCD, *i.e.* when the centre-of-mass energy in a collision is much bigger than the fixed hard scales of the problem, the scattering amplitudes grow with increasing energy as described by the BFKL equation [1]. The forward-jet measurement was originally proposed [2] to test the BFKL equation because, if the energy in the photon-proton collision W is large enough, it lies in the kinematic regime corresponding to the Regge limit ($W^2 \gg Q^2$).

The question is whether the BFKL equation is relevant at the present energies, or if usual perturbative QCD in the Bjorken limit is still sufficient to describe the data. We address that problem by computing the forward-jet cross-section in the high-energy regime and by comparing the BFKL predictions with the available data. We also address the problem of saturation [3]: it is well-known that the BFKL growth is damped by saturation effects when energies become too high and the scattering amplitudes approach the unitarity limit. We implement saturation effects in a very simple way, inspired by the Golec-Biernat and Wüsthoff approach [4] and check the consistency with the data.

FORMULATION

The QCD cross-section for forward-jet production in a lepton-proton collision reads

$$\frac{d^{(4)}\sigma}{dx dQ^2 dx_J dk_T^2} = \frac{\alpha_{em}}{\pi x Q^2} \left\{ \left(\frac{d\sigma_T^{\gamma^* p \rightarrow JX}}{dx_J dk_T^2} + \frac{d\sigma_L^{\gamma^* p \rightarrow JX}}{dx_J dk_T^2} \right) (1-y) + \frac{d\sigma_T^{\gamma^* p \rightarrow JX}}{dx_J dk_T^2} \frac{y^2}{2} \right\}, \quad (1)$$

where x and y are the usual kinematic variables of deep inelastic scattering and Q^2 is the virtuality of the intermediate photon that undergoes the hadronic interaction.

$d\sigma_{T,L}^{\gamma^*p \rightarrow JX} / dx_J dk_T^2$ is the cross-section for forward-jet production in the collision of this transversally (T) or longitudinally (L) polarized virtual photon with the target proton. k_T is the jet transverse momentum and x_J its longitudinal momentum fraction with respect to the proton.

Let us now consider the high-energy regime: $x = \log(Q^2/(Q^2 + W^2)) \ll 1$. In an appropriate frame called the dipole frame, the virtual photon undergoes the hadronic interaction via a fluctuation into a colorless $q\bar{q}$ pair, a dipole. The squared wavefunctions ϕ_T^γ and ϕ_L^γ describing the splitting of the virtual photon onto a dipole are well-known. The dipole then interacts with the target proton and one has the following factorization

$$\frac{d\sigma_{T,L}^{\gamma^*p \rightarrow JX}}{dx_J dk_T^2} = \int_0^\infty 2\pi r dr \phi_{T,L}^\gamma(r, Q) \frac{d\sigma_{q\bar{q}}}{dx_J dk_T^2}(r). \quad (2)$$

$d\sigma_{q\bar{q}}(r)/dx_J dk_T^2$ is the cross-section for forward-jet production in the dipole-proton collision. The integration variable r represents the size of the intermediate dipole.

It was shown in [5] that the emission of the forward jet can be described through the interaction of an effective gluonic (gg) dipole:

$$\frac{d\sigma_{q\bar{q}}}{dx_J dk_T^2}(r) = \frac{\pi N_c}{16k_T^2} f_{eff}(x_J, k_T^2) \int_0^\infty d\bar{r} J_0(k_T \bar{r}) \frac{\partial}{\partial \bar{r}} \left(\bar{r} \frac{\partial}{\partial \bar{r}} \sigma_{(q\bar{q})(gg)}(r, \bar{r}, Y) \right) \quad (3)$$

with $Y = \log(x_J/x)$ the rapidity assumed very large. $\sigma_{(q\bar{q})(gg)}(r, \bar{r}, Y)$ is the $q\bar{q}$ dipole (size r)- gg dipole (size \bar{r}) total cross-section with rapidity Y . As usual, the dipoles emerge as the effective degrees of freedom at high energies: $\sigma_{(q\bar{q})(gg)}$ contains any number of gluon exchanges and therefore this formulation goes beyond k_T -factorization which assumes only a two-gluon exchange. The effective parton distribution function f_{eff} is given by: $f_{eff}(x_J, k_T^2) = g(x_J, k_T^2) + C_F (q(x_J, k_T^2) + \bar{q}(x_J, k_T^2)) / N_c$ where g (resp. q, \bar{q}) is the gluon (resp. quark, antiquark) distribution function in the incident proton.

BFKL parametrization

The BFKL $q\bar{q}$ -dipole gg -dipole cross-section reads

$$\sigma_{(q\bar{q})(gg)}^{BFKL}(r, \bar{r}, Y) = 2\pi \alpha_s^2 r^2 \int \frac{d\gamma}{2i\pi} \left(\frac{\bar{r}}{r} \right)^{2\gamma} \frac{\exp\left(\frac{\alpha_s N_c}{\pi} \chi(\gamma) Y\right)}{\gamma^2 (1-\gamma)^2} \quad (4)$$

with the complex integral running along the imaginary axis from $1/2 - i\infty$ to $1/2 + i\infty$ and with the BFKL kernel given by $\chi(\gamma) = 2\psi(1) - \psi(1-\gamma) - \psi(\gamma)$ where $\psi(\gamma)$ is the logarithmic derivative of the Gamma function. It comes about when the interaction between the $q\bar{q}$ -dipole and the gg -dipole is restricted to a two-gluon exchange. One can easily show, putting (4) in (2) and (3), that this formulation is equivalent to using k_T -factorization. We are going to perform a fit of the parametrization (4) to the data. The parameters are $\lambda = 4\alpha_s N_c \log(2)/\pi$ and a normalization.

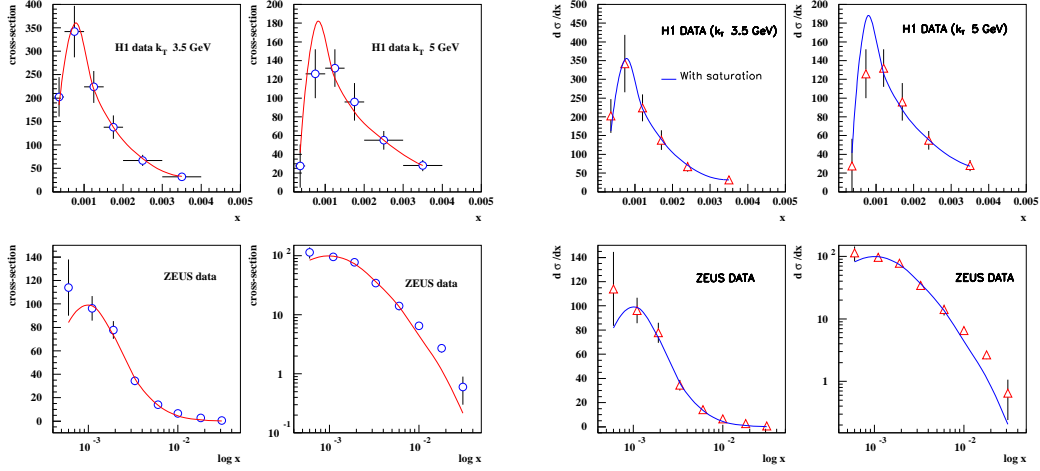


FIGURE 1. Fits to the H1 and ZEUS forward-jet old data for $d\sigma/dx$. The left plot shows the BFKL fit and the right plot shows one of the saturation fits (called sat. in the text).

Saturation parametrization

To take into account saturation effects, let us consider the following parametrization:

$$\sigma_{(q\bar{q})(gg)}^{sat}(r, \bar{r}, Y) = 4\pi\alpha_s^2\sigma_0 \left(1 - \exp\left(-\frac{r_{\text{eff}}^2(r, \bar{r})}{4R_0^2(Y)}\right) \right). \quad (5)$$

The dipole-dipole *effective* radius $r_{\text{eff}}^2(r, \bar{r})$ is defined through the two-gluon exchange:

$$4\pi\alpha_s^2 r_{\text{eff}}^2(r, \bar{r}) \equiv \sigma_{(q\bar{q})(gg)}^{BFKL}(r, \bar{r}, 0) = 4\pi\alpha_s^2 \min(r^2, \bar{r}^2) \left\{ 1 + \log \frac{\max(r, \bar{r})}{\min(r, \bar{r})} \right\} \quad (6)$$

while the saturation radius is parametrized by $R_0(Y) = e^{-\frac{\lambda}{2}(Y-Y_0)}/Q_0$ with $Q_0 \equiv 1 \text{ GeV}$. The parameters for the fit are λ , Y_0 and the normalization σ_0 .

PHENOMENOLOGY

To compare the cross-section (1) with the data for $d\sigma/dx$, the three remaining integration are carried out taking into account the different sets of cuts provided by the different experiments. Fits have been performed to the old sets of data [6, 7] for the BFKL parametrization [8] and the saturation parametrization [9]. With all χ^2 values of about 1, the BFKL fit gives $\lambda = 0.430$ and the saturation fit shows two χ^2 minima for $(\lambda = 0.402, Y_0 = -0.82)$ (sat.) and $(\lambda = 0.370, Y_0 = 8.23)$ (weak sat.). The plots are shown on Fig1. Despite describing different energy regimes, both a BFKL parametrization and saturation parametrizations describe well the data. The first saturation minima corresponds to a strong saturation effect as, for typical values of Y , the saturation scale $1/R_0$ is 5 Gev which is the value of a typical k_T . The second saturation minima corresponds to small saturation effects and rather describes BFKL physics.

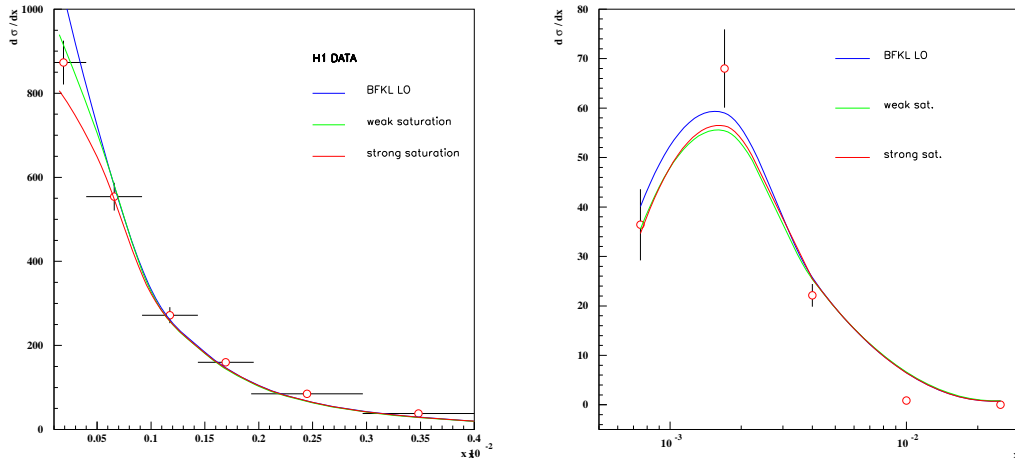


FIGURE 2. Comparisons between the H1 (left plot) and ZEUS (right plot) forward-jet new data for $d\sigma/dx$ and the BFKL and saturation parametrizations.

Let us now look at the new data [10, 11] for $d\sigma/dx$ which go to lower x . Without performing any new fit of the parameters, but rather by taking the values already obtained, the three parametrizations describe very well the new data, as shown on Fig2. One cannot really distinguish between the three curves even if at small values of x , one starts to see the difference between them. At the lowest values of x , NLOQCD predictions are about a factor 1.5 to 2.5 below the data depending on the experiment and the error bars. However, it could be that adding a resolved-photon component to the NLO predictions will pull them within the uncertainties which moderates the conclusion that the BFKL resummation is needed to describe those data. The fact that two saturation parametrizations are consistent with the data also asks for further study.

We intend to complete our analysis [12] by considering the other measurements $d\sigma/dQ^2$ and $d\sigma/dk_T$ by ZEUS and $d\sigma/dxdQ^2dk_T^2$, by H1 and Mueller-Navelet jets [13] at Tevatron or LHC. These could help clarifying the situation [14].

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