Forward Jets at HERA and at the Tevatron

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Abstract

In this talk I consider forward-jet production at HERA and at the Tevatron as a probe of the multiple gluon radiation induced by the BFKL evolution.

To appear in the Proceedings of
the International Workshop on
Deep Inelastic Scattering and Related Phenomena
Roma, Italy, April 1996
1 Introduction

In DIS at HERA semi-hard processes, for which the squared center-of-mass energy $s$ is much larger than the momentum transfer $Q^2$, are investigated and values of $x_{bj} = Q^2/s$ of the order of $10^{-5}$ have been attained [1]. The evolution of the $F_2(x_{bj}, Q^2)$ structure function in $\ln(Q^2)$ is usually described by the DGLAP equation. However, at very small values of $x_{bj}$ we may consider to resum the leading logarithmic (LL) contributions in $1/x_{bj}$ to $F_2$, by using the BFKL evolution equation [2, 3].

A caveat is in order: the BFKL equation computes the radiative corrections to parton-parton scattering in the high-energy limit, assuming that the outgoing partons are balanced in transverse momentum. Therefore there is no transverse-momentum evolution in the process. It is not possible to assess whether this constraint is fulfilled in the configurations that drive the rise of $F_2$ at small $x_{bj}$, but it may be forced upon the DIS process by tagging a jet in the proton direction [4] and by requiring that the squared jet transverse momentum is of the order of $Q^2$. An analogous process for which the multiple gluon radiation induced by the BFKL evolution may be relevant is dijet production at large rapidity intervals $\eta$ in $p\bar{p}$ collisions [5].
2 Forward jets

In the high-energy limit parton-parton scattering is dominated by gluon exchange in the cross channel, which is typically an $O(\alpha_s^2)$ process. This occurs at leading order (LO) in dijet production in $p\bar{p}$ collisions [3], and at next-to-leading order (NLO) in dijet production with a forward jet in DIS [4] (or at LO in three-jet production [5, 7, 8]). Indeed, in DIS the NLO dijet production and the LO three-jet production turn out to be bigger [7] than the LO dijet production, which is $O(\alpha_s)$, when a forward jet is required. On top of the cross-channel-gluon dominated processes, the BFKL equation resums the LL contributions, in $\ln(s/Q^2)$, to all orders in $\alpha_s$ in the multi-Regge kinematics, which assumes that the outgoing partons are strongly ordered in rapidity $\eta$ and have comparable transverse momentum. The higher-order corrections to gluon exchange yield a gluon ladder in the cross channel [2]. The leading logarithms are resummed by the function,

$$f(k_{a\perp}, k_{b\perp}, \tilde{\phi}, \eta) = \frac{1}{(2\pi)^2 k_{a\perp} k_{b\perp}} \sum_{n=-\infty}^{\infty} e^{in\tilde{\phi}} \int_{-\infty}^{\infty} d\nu e^{\omega(\nu, n)\eta} \left( \frac{k_{a\perp}^2}{k_{b\perp}^2} \right)^{i\nu},$$

(1)

with $k_{a\perp}$ and $k_{b\perp}$ the transverse momenta of the gluons at the ends of the ladder, $\tilde{\phi}$ the azimuthal angle between them, $\eta \simeq \ln(s/k^2)$ an evolution parameter of the ladder required to be large, and $\omega(\nu, n)$ the eigenvalue of the BFKL equation whose maximum $\omega(0, 0) = 4\ln 2N_c\alpha_s/\pi$ yields the known power-like growth of $f$ in energy [2].

In inclusive dijet production in $p\bar{p}$ collisions the resummed parton cross section is [3].
\[ \frac{d\hat{\sigma}}{dk_{a\perp}^2 dk_{b\perp}^2 d\phi} = \frac{\pi N_c^2 \alpha_s^2}{2k_{a\perp}^2 k_{b\perp}^2} f(k_{a\perp}, k_{b\perp}, \tilde{\phi}, \eta), \quad (2) \]

with \( \phi \) the azimuthal angle between the tagging jets, \( \phi = \tilde{\phi} + \pi \). At the hadron level, \( \eta \) is the rapidity difference between the tagging jets, \( \eta = \eta_{j_1} - \eta_{j_2} \), and accordingly evidence of the BFKL dynamics is searched in dijet events at large rapidity intervals \([10]\).

In forward-jet production in DIS in the lab frame the lepton-parton cross section is \([4, 8, 11]\)

\[ \frac{d\hat{\sigma}}{dydQ^2 dk_{\perp}^2 d\phi} = \sum_q e_q^2 N_c \alpha_s^2 \alpha_s^2 \frac{1}{\pi^2 (Q^2)^2 k_{\perp}^2 y} \int \frac{dv_{\perp}^2}{v_{\perp}^2} f(v_{\perp}^2, k_{\perp}^2, \tilde{\phi}, \eta) \mathcal{F}(v_{\perp}^2, Q^2, \hat{\phi}, y), \quad (3) \]

with \( y \) the electron energy loss; \( Q^2 \) the photon vituality; the function \( \mathcal{F} \) accounting for the \( q \bar{q} \) pair that in the high-energy limit mediates the scattering between the photon and the cross-channel gluon; \( k_{\perp} \) and \( v_{\perp} \) respectively the transverse momenta of the forward jet and of the gluon attaching to the \( q \bar{q} \) pair; \( \hat{\phi} \) the azimuthal angle between the photon and the gluon; \( \phi \) the azimuthal angle between the outgoing electron and the jet, with \( \phi = \hat{\phi} + \tilde{\phi} + \pi \); and with the sum over the quark flavors in the \( q \bar{q} \) pair. \( \eta \) is then related to \( x_{bj} \) and to the momentum fraction \( x \) of the parton initiating the hard scattering within the proton through \( \eta = \ln(x/x_{bj}) \). Producing the jet forward ensures that \( x \) is not small; \( \eta \) is then made large by selecting events at small \( x_{bj} \).

The BFKL ladder \( f \) \([11]\) induces a strong enhancement in the parton cross sections \((2)\) and \((3)\) when \( \eta \) grows \([4]\). In a hadron collider \( \eta = \eta_{j_1} - \eta_{j_2} \simeq \ln(x_1 x_2 s/k_{\perp}^2) \). At fixed \( s \), like at the Tevatron, \( \eta \) grows by increasing \( x_1 \) and \( x_2 \). This introduces a damping in
the production rate, due to the falling parton luminosity \([9]\), and conceals the growth due to \(\mathcal{f}(1)\). The advantage of HERA is that a fixed-energy \(ep\) collider is nonetheless a variable-energy collider in the photon-proton frame \([4]\), thus it is possible to increase 
\[ \eta = \ln(x/x_{bj}) \]
by decreasing \(x_{bj}\) while keeping fixed \(x\).

The truncation to \(\mathcal{O}(\alpha_s^2)\) of the forward-jet rate derived from eq. (3), which has three final-state partons, corresponds to the lowest-order approximation to the BFKL ladder and is in good agreement with the exact LO three-jet rate with a forward jet \([8]\). However, the BFKL calculation with the full ladder \((1)\) yields a curve whose normalization is bigger by an order of magnitude, and which grows faster than the \(\mathcal{O}(\alpha_s^2)\) evaluations as \(x_{bj}\) decreases. The H1-Collaboration data \([12]\) seem to favor the BFKL calculation \([8]\). This looks encouraging, however as a caveat we recall that in dijet production at the Tevatron a comparison of the \(\mathcal{O}(\alpha_s^3)\) matrix elements, exact and in the BFKL approximation, shows that the latter overestimates the available phase space \([8]\).

3 The azimuthal-angle decorrelation

In two-jet production at large rapidity intervals in \(p\bar{p}\) collisions the BFKL evolution predicts that the \(\phi\) correlation between the tagging jets decreases as the rapidity difference between the tagging jets increases \([9]\). This phenomenon has been observed by the D0 Collaboration at the Tevatron \([10]\), however, the BFKL ladder yields too much decorrelation while the Monte Carlo JETRAD \([14]\), based on the exact NLO dijet production,
yields too little decorrelation. The data is in good agreement with a simulation from the Monte Carlo HERWIG [15]. This seems to suggest that corrections higher than $O(\alpha_s^3)$ are needed to describe the data, but not so much of it as contained in the BFKL ladder.

In jet production in DIS we know that at the parton-model level, i.e. at $x = x_{bj}$, the jet and the electron are produced back-to-back, and we expect that when $x > x_{bj}$, but with $\eta = \ln(x/x_{bj})$ still small, the jet production is dominated at the parton level by the photon-gluon fusion diagram, which has two final-state partons and is expected to yield the usual correlation at $\phi = \pi$ between the electron and the parton tagged as the jet. However as $\eta$ grows the jet production is increasingly dominated by diagrams with three-final state partons and with gluon exchange in the cross channel, and eventually by the higher-order corrections to them induced by the BFKL ladder.

The lowest-order approximation to the BFKL ladder yields a $\phi$ distribution peaked at $\phi = \pi/2$. Implementing then the full BFKL ladder (1), the $\phi$ correlation is completely washed out [8]. However, the high-energy limit can not appreciate the transition from a distribution peaked at $\phi = \pi$ at large $x_{bj}$ to one peaked at $\phi = \pi/2$ at small $x_{bj}$. It was suggested that an exact $O(\alpha_s^2)$ calculation should see it [11], and indeed it does [8]. It is to be seen if it will also be observed in the data.
Acknowledgments

I thank PPARC and the Travel and Research Committee of the University of Edinburgh for the support, and the organizers of DIS96 for the hospitality.

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