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Fixed-Order QCD Backgrounds to BFKL Dynamics in Forward Jet Production

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Abstract: The production of forward jets of transverse momentum $p_T(j) \approx Q$ and large momentum fraction $x_{jet} \gg x$ probes the onset of BFKL dynamics at HERA. A full $\mathcal{O}(\alpha_s^2)$ calculation of the inclusive forward jet cross section is presented and compared to the expected BFKL cross section.

Deep-inelastic scattering (DIS) at HERA provides an ideal place to probe strong interaction dynamics. One focus of interest has been the small Bjorken-x region, where one would like to distinguish BFKL evolution [1], which resums the leading $\alpha_s \ln 1/x$ terms, from the more traditional DGLAP evolution equation [2], which resums leading $\alpha_s \ln Q^2$ terms. Unfortunately, the measurement of $F_2(x, Q^2)$ in the HERA range is probably too inclusive to discriminate between the two [3].

A more sensitive test of BFKL dynamics at small x is expected from deep inelastic scattering with a measured forward jet (in the proton direction) and $p_T^2(j) \approx Q^2$ [4]. The idea is to study DIS events which contain an identified jet of longitudinal momentum fraction $x_{jet} = p_z(jet)/E_{proton}$ which is large compared to Bjorken x. When tagging a forward jet with $p_T(j) \approx Q$ this leaves little room for DGLAP evolution while the condition $x_{jet} \gg x$ leaves BFKL evolution active. This leads to an enhancement of the forward jet production cross section proportional to $(x_{jet}/x)^{\alpha_P - 1}$ over the DGLAP expectation.

A conventional fixed order QCD calculation up to $\mathcal{O}(\alpha_s^2)$ does not yet contain any BFKL resummation and must be considered a background for its detection; one must search for an enhancement in the forward jet production cross section above the expectation for two- and three-parton final states. In this contribution we perform a full next-to-leading order (NLO) analysis of this "fixed order" background. Such an analysis has become possible with the implementation of QCD radiative corrections to dijet production in DIS in a fully flexible Monte Carlo program, MEPJET [5].

Numerical results below will be presented both for leading order (LO) and NLO simulations. The LO 1-jet and 2-jet results employ the LO parton distributions of Glück, Reya and Vogt [6]

	with forward jet $p_T^B, p_T^{lab} > 4$ GeV	$k_T^B > 4$ GeV	without forward jet $p_T^B, p_T^{lab} > 4$ GeV
$\mathcal{O}(\alpha_s^0)$: 1 jet	0 pb	0 pb	8630 pb
$\mathcal{O}(\alpha_s)$: 2 jet	18.9 pb	22.4 pb	2120 pb
$\mathcal{O}(\alpha_s^2)$: 1 jet inclusive	100 pb	100 pb	
2 jet inclusive	83.8 pb	98.3 pb	2400 pb
2 jet exclusive	69.0 pb	66.8 pb	2190 pb
3 jet	14.8 pb	31.5 pb	210 pb

Table 1: Cross sections for n-jet events in DIS at HERA at order α_s^0, α_s, and α_s^2. The jet multiplicity includes the forward jet which, when required, must satisfy $p_T(j) > 5$ GeV and the cuts of Eqs. (1,2). The transverse momenta of additional (non-forward) jets must only exceed cuts of 4 GeV (first and third column). This requirement is replaced by the condition $k_T^B > 4$ GeV in the second column. No p_T^B cut is imposed in the 1-jet case at $\mathcal{O}(\alpha_s^0)$ and the factorization scale is fixed to Q.

together with the one-loop formula for the strong coupling constant. At $\mathcal{O}(\alpha_s^2)$ all cross sections are determined using the NLO GRV parton distribution functions $f(x_i, \mu_F^2)$ and the two loop formula for $\alpha_s(\mu_R^2)$. With this procedure the 2-jet inclusive rate at NLO is simply given as the sum of the NLO 2-jet and the LO 3-jet exclusive cross sections. The value of α_s is matched at the thresholds $\mu_R = m_q$ and the number of flavors is fixed to $n_f = 5$ throughout, *i.e.* gluons are allowed to split into five flavors of massless quarks.

Unless otherwise stated, both the renormalization and the factorization scales are tied to the sum of parton k_T's in the Breit frame, $\mu_R = \mu_F = \frac{1}{2}\sum_i k_T^B(i)$, where $(k_T^B(i))^2 = 2E_i^2(1-\cos\theta_{ip})$. Here θ_{ip} is the angle between the parton and proton directions in the Breit frame. $\sum_i k_T^B(i)$ constitutes a natural scale for jet production in DIS [7] because it interpolates between Q, in the naive parton model limit, and the sum of jet transverse momenta, when Q becomes negligible.

We are interested in events with a forward jet with $p_T(j) \approx Q$ and $x_{jet} \gg x$ and impose kinematical cuts which closely model the H1 selection[8] of such events. Jets are defined in the cone scheme (in the laboratory frame) with $\Delta R = 1$ and $|\eta| < 3.5$. Here $\eta = -\ln\tan(\theta/2)$ denotes the pseudorapidity of a jet. Unless noted otherwise, all jets must have transverse momenta of at least 4 GeV in both the laboratory and the Breit frames. Events are selected which contain a forward jet (denoted "j") in the pseudorapidity range $1.735 < \eta(j) < 2.9$ (corresponding to $6.3^o < \theta(j) < 20^o$) and with transverse momentum $p_T^{lab}(j) > 5$ GeV. This jet must satisfy

$$\begin{aligned} x_{jet} &= p_z(j)/E_p > 0.05\,, && (1)\\ 0.5 &< p_T^2(j)/Q^2 < 4 && (2) \end{aligned}$$

in the laboratory frame. The condition $x_{jet} \gg x$ is satisfied by requiring $x < 0.004$. Additional selection cuts are $Q^2 > 8$ GeV^2, $0.1 < y < 1$, an energy cut of $E(l') > 11$ GeV on the scattered lepton, and a cut on its pseudorapidity of $-2.868 < \eta(l') < -1.735$ (corresponding to $160^o < \theta(l') < 173.5^o$). The energies of the incoming electron and proton are set to 27.5 GeV and 820 GeV, respectively.

Numerical results for the multi-jet cross sections with (or without) a forward jet are shown in Table 1. Without the requirement of a forward jet, the cross sections show the typical decrease with increasing jet multiplicity which is expected in a well-behaved QCD calculation. The 3-jet cross section in the last column constitutes only about 10% of the 2-jet cross section and both rates are sizable. The requirement of a forward jet with large longitudinal momentum fraction ($x_{jet} > 0.05$) and restricted transverse momentum ($0.5 < p_T^2(j)/Q^2 < 4$) severely restricts the available phase space. In particular one finds that the 1-jet cross section vanishes at LO, due to the contradicting $x < 0.004$ and $x_{jet} > 0.05$ requirements: this forward jet kinematics is impossible for one single massless parton in the final state.

Suppose now that we had performed a full $\mathcal{O}(\alpha_s^2)$ calculation of the DIS cross section, which would contain 3-parton final states at tree level, 1-loop corrections to 2-parton final states and 2-loop corrections to 1-parton final states. These 2-loop contributions would vanish identically, once $x \ll x_{jet}$ is imposed. The remaining 2-parton and 3-parton differential cross sections, however, and the cancellation of divergences between them, would be the same as those entering a calculation of 2-jet inclusive rates. These elements are already implemented in the MEPJET program which, therefore, can be used to determine the inclusive forward jet cross section, within the cuts discussed above. At $\mathcal{O}(\alpha_s^2)$ this cross section is obtained from the cross section for 2-jet inclusive events by integrating over the full phase space of the additional jets, without any cuts on their transverse momenta or pseudorapidities. Numerical results are shown in the third row of Table 1.

The table exhibits some other remarkable features of forward jet events: the NLO 2-jet inclusive cross section exceeds the LO 2-jet cross section by more than a factor of four and the 3-jet rate at $\mathcal{O}(\alpha_s^2)$ is about as large as the 2-jet rate at $\mathcal{O}(\alpha_s)$. The smallness of the LO 2-jet compared to the NLO 2-jet inclusive cross section means that at least three final-state partons are required to access the relevant part of the phase space. This three-parton cross section, however, has only been calculated at tree level and is subject to the typical scale uncertainties of a tree level calculation. Thus, even though we have performed a full $\mathcal{O}(\alpha_s^2)$ calculation of the forward jet cross section at HERA, including all virtual effects, our calculation effectively only gives a LO estimate of this cross section and large corrections may be expected from higher order effects.

The characteristics of forward jet events are demonstrated in Fig. 1 where the transverse momentum and the pseudorapidity distributions of the recoil jet with the highest p_T^{lab} are shown, subject only to a nominal requirement of $p_T^{lab}, p_T^B > 1$ GeV. Here the recoil system is defined as the complement of the forward jet, in the final state which arises in the photon-parton collision. Almost all forward jet events contain at least one additional jet in the recoil system, with $p_T^{lab} \gtrsim 4$ GeV and, typically, in the central part of the detector.

In the usual cone scheme final-state collinear singularities are regulated by the ΔR separation cut while infrared singularities and initial state collinear emission are regulated by the p_T cut. In $\gamma^* p$ collisions the photon virtuality, Q^2, eliminates any collinear singularities for initial state emission in the electron direction and therefore a large k_T is as good a criterion to define a cluster of hadrons as a jet as its p_T. The dashed line in Fig. 1(a) shows the k_T distribution in the Breit frame of the recoil jet candidate with the largest k_T^B. Basically all forward jet events in this NLO analysis possess a recoil "jet" with $k_T^B > 4$ GeV and would thus be classified as 2-jet inclusive events in a variant of the cone scheme where the $p_T > 4$ GeV condition is replaced by a $k_T^B > 4$ GeV cut. This observation makes intuitively clear why we are able to calculate the 1-jet inclusive forward jet cross section with a program designed for the 2-jet inclusive cross section at NLO: there exists a jet definition scheme in which all forward jet events contain at least one additional hard jet.

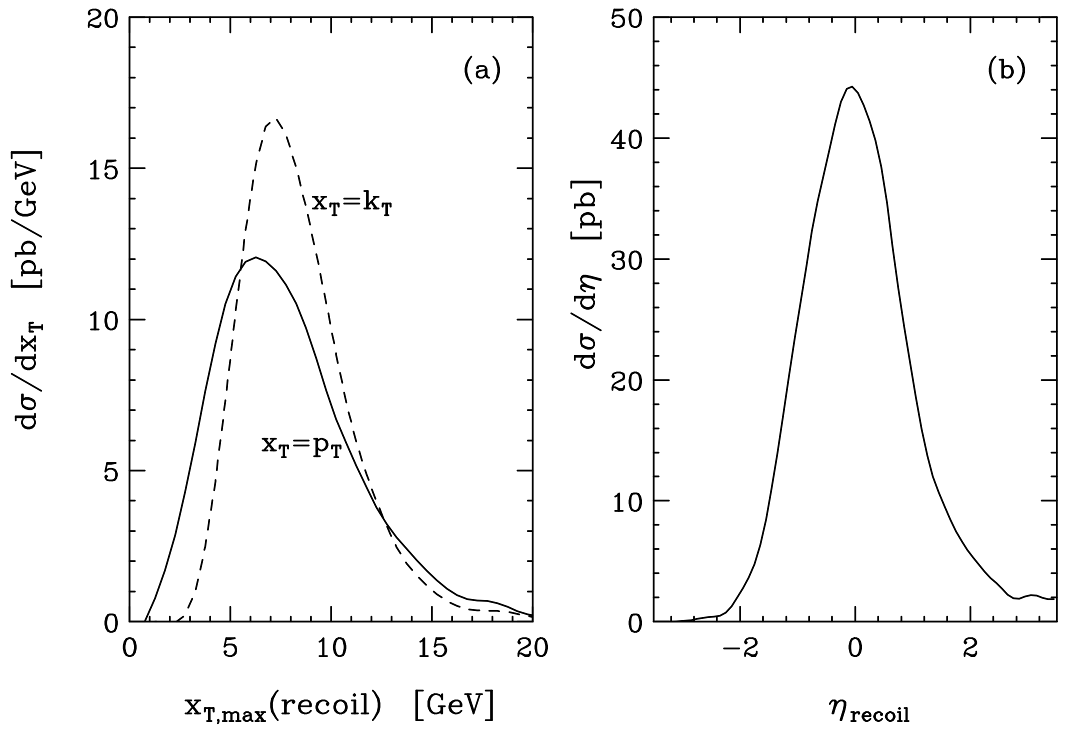

Figure 1: Characteristics of the highest transverse momentum "jet" in the recoil system, i.e. excluding the forward jet. Distributions shown are (a) $d\sigma/dp_T$ in the lab frame (solid line) and $d\sigma/dk_T$ in the Breit frame (dashed line) and (b) the jets pseudorapidity distribution in the laboratory frame. All distributions are calculated at order α_s^2. Jet transverse momentum cuts have been relaxed to $p_T^{lab}, p_T^B > 1$ GeV.

An estimate for higher order corrections may be obtained by comparing to BFKL calculations or to existing experimental results. The H1 Collaboration has published such a measurement which was made during the 1993 HERA run with incident electron and proton energies of $E_e = 26.7$ GeV and $E_p = 820$ GeV [9]. The acceptance cuts used for this measurement differed somewhat from the ones described before. Because of the lower luminosity in this early HERA run the x_{jet} cut on the forward jet was lowered to 0.025 and defined in terms of the jet energy as opposed to the longitudinal momentum of the jet in the proton direction,

$$x_{jet} = E(j)/E_p > 0.025 \, , \tag{3}$$

and the pseudorapidity range of the forward jet was chosen slightly larger, $1.735 < \eta(j) < 2.949$ (corresponding to $6^o < \theta(j) < 20^o$). Scattered electrons were selected with an energy of $E(l') > 12$ GeV and in the pseudorapidity range $-2.794 < \eta(l') < -1.735$ (corresponding to $160^o < \theta(l') < 173^o$). Finally the Bjorken-$x$ and Q^2 ranges were chosen as $0.0002 < x < 0.002$ and $5 \text{ GeV}^2 < Q^2 < 100 \text{ GeV}^2$. Within these cuts H1 has measured cross sections of $709 \pm 42 \pm 166$ pb for $0.0002 < x < 0.001$ and $475 \pm 39 \pm 110$ pb for $0.001 < x < 0.002$. These two data points, normalized to bin sizes of 0.0002, are shown as diamonds with error bars in Fig. 2. Also included (dashed histogram) is a recent calculation of the BFKL cross section [10].

As shown before, the MEPJET program allows to calculate the full 1-jet inclusive forward jet cross section[1] for $x \ll x_{jet}$. The LO result is shown as the dash-dotted histogram in Fig. 2

[1]We have checked that also for the kinematical region considered now almost all forward jet events contain

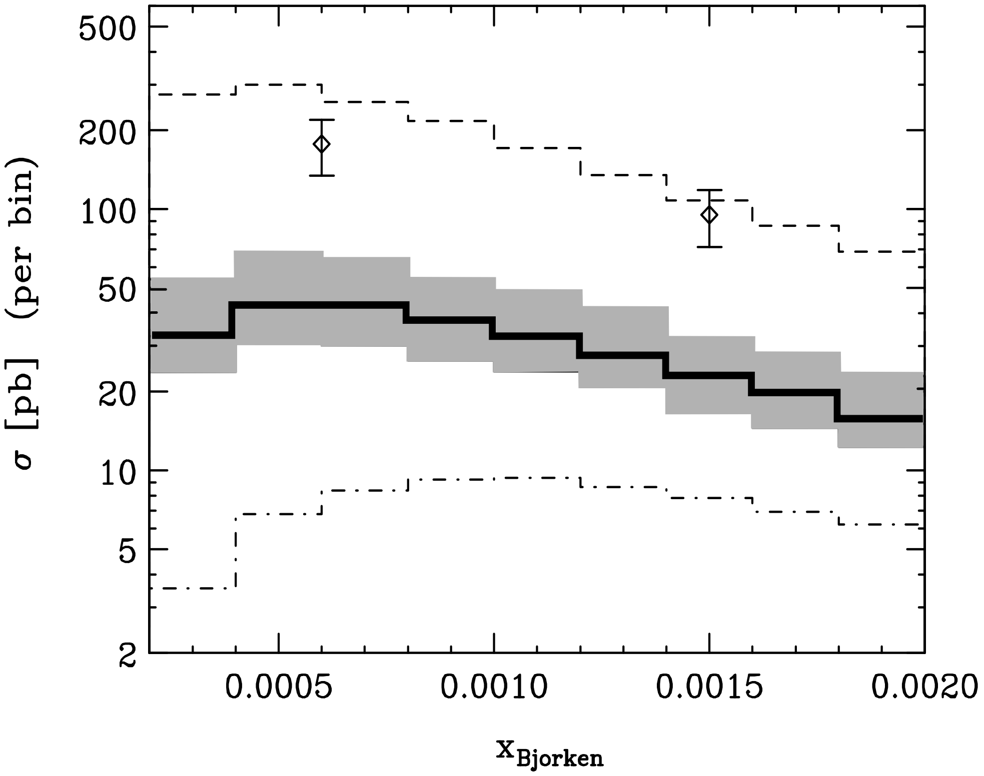

Figure 2: Forward jet cross section at HERA as a function of Bjorken x within the H1 acceptance cuts [9] (see text). The solid (dash-dotted) histogram gives the NLO (LO) MEPJET result for the scale choice $\mu_R^2 = \mu_F^2 = \xi(0.5\sum k_T)^2$ with $\xi = 1$. The shaded area shows the uncertainty of the NLO prediction, corresponding to a variation of ξ between 0.1 and 10. The BFKL result of Bartels et al. [10] is shown as the dashed histogram. The two data points with error bars correspond to the H1 measurement [9].

and the NLO result is shown as the solid histogram. The shaded area corresponds to a scale variation $\mu_R^2 = \mu_F^2 = \xi\ \frac{1}{4}\left(\sum_i k_T^B(i)\right)$, from $\xi = 0.1$ to $\xi = 10$, and indicates a range of "reasonable" expectations for the forward jet cross section at $\mathcal{O}(\alpha_s^2)$.

While the BFKL results [10] agree well with the H1 data, the fixed-order perturbative QCD calculations clearly fall well below the measured cross section, even when accounting for variations of the factorization and renormalization scales. The measured cross section is a factor of 4 above the NLO expectation. The shape of the NLO prediction, on the other hand, is perfectly compatible with the H1 results, and not very different from the BFKL curve in Fig. 2. At LO a marked shape difference is still observed, which can be traced directly to kinematical arguments given in Ref. [11]. Additional details, including a study of the NLO scale dependence of the forward jet cross section, can be found there. First NLO studies for forward jet production have been presented in Ref. [12]. For a study of forward jet cross sections with the ZEUS detector, see Ref. [13].

We conclude that the existing H1 data show evidence for BFKL dynamics in forward jet events via an enhancement in the observed forward jet cross section above NLO expectations.

at least one second jet with $p_T^{lab} > 4$ GeV and $k_T^B > 4$ GeV.

The variation of the cross section with x, on the other hand, is perfectly compatible with either BFKL dynamics or NLO QCD. Since MEPJET provides a full NLO prediction of the 1-jet inclusive forward jet cross section for arbitrary cuts and jet definition schemes, more decisive shape tests may be possible as additional data become available.

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