Forward Jet Production at small $x$

in Next-to-Leading Order QCD

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Abstract

The production of forward jets of transverse energy $E_T \simeq Q$ and large momentum fraction $x_{jet} \gg x$ is calculated in next-to-leading order including consistently direct and resolved virtual photon contributions. The predictions are compared to recent ZEUS and H1 data. Good agreement with the data is found.

1 Introduction

The cross section for forward jet production in deep inelastic scattering (DIS) has been proposed as a particularly sensitive means to investigate the parton dynamics at small $x$\(^1\). Analytic calculations based on the BFKL equation\(^2\) in the leading-logarithmic approximation show a strong rise of this cross section with decreasing $x$\(^3\) and were found in reasonable agreement\(^4\) with the first data from the H1 collaboration at HERA\(^5\). More recent measurements of the forward cross section, based on an order of magnitude increased statistics compared to\(^6\), have been presented recently by the ZEUS\(^7\) and the

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We refer to the H1 [7] collaborations confirming the earlier findings [3]. Monte Carlo generators based on direct photon interactions (DIR) calculated from leading order (LO) $O(\alpha_s)$ matrix elements together with leading-logarithm parton showers disagree with the measured jet cross section [6, 7] by an appreciable factor. Also next-to-leading order (NLO), i.e. $O(\alpha_s^2)$, calculations predict too small forward cross sections at small $x$ as already shown by Mirkes and Zeppenfeld [5] using their MEPJET program [9] when comparing to the data in [5]. This has been confirmed also with the new data in [6, 7].

A similar deficiency between NLO calculations and measured data occurs for the dijet rate in the region $E_T^2 > Q^2$ [10], where $E_T$ is the transverse energy of the produced jets and $Q^2$ is the usual squared lepton momentum transfer. This kinematic range is also relevant for the forward jet production, as will be seen later. The region of small enough $Q^2$ is the photoproduction regime where the virtual photon resolves into partons. Indeed, introducing a resolved photon contribution, the measured dijet rate and the forward jet cross section can be described satisfactorily [11, 10, 7] concerning the shape of the cross section as a function of $x$ as well as the absolute normalization. This description is based on the Monte Carlo program RAPGAP [12] which includes a resolved photon contribution in addition to the direct process, which both are evaluated with LO matrix elements with additional emissions in the initial and final state generated by parton showers together with subsequent hadronization.

The dijet rate has been calculated also in NLO including direct and resolved photon contributions [13]. In order to avoid double counting in the full NLO calculation, the contribution from the virtual photon splitting into $q\bar{q}$ pairs, where either the quark or the antiquark subsequently interacts with a parton originating from the proton, had to be subtracted [14], similar as is done in the NLO theory for the photoproduction of jets [15]. The subtracted terms in the NLO direct contribution are part of the parton distribution functions (PDF’s) of the virtual photon and appear in the resolved contribution in an evolved form. With this procedure the whole cross section for two-jet production, which is a superposition of the direct and resolved contributions minus the photon splitting piece, becomes to a large extent independent of the factorization scale at the photon vertex. This full NLO calculation of the dijet rate agreed well with the H1 data over the full $Q^2$ domain, $5 \leq Q^2 \leq 100 \text{ GeV}^2$, and the $x$ domain, $10^{-4} \leq x \leq 10^{-2}$, and for jet transverse momenta $E_T^2 \geq Q^2$ [7, 13].

In this work we want to present the results of a calculation of the forward jet cross section on the basis of the NLO theory used for the dijet rate. Although the kinematic constraints, very low $x$ and $E_T^2/Q^2$ of order one, are rather similar, it is not obvious that the calculated cross sections will agree with the recent ZEUS [3] and H1 [4] experimental results.

After some comparisons with the MEPJET results [3] to make sure that our DIS jet program, called JetViP [13], gives the same results under identical kinematical conditions we shall give our results with the experimental cuts of the ZEUS [3] and H1 [4] analysis. We close with a short summary and an outlook to future studies.
Comparisons and Results

2.1 Comparison with MEPJET

Before we present our results with the ZEUS and H1 kinematical constraints for selecting the forward jets we performed a check of our program JetViP with the forward jet kinematics by comparing with the NLO results of Mirkes and Zeppenfeld [8], who have produced their results with the fixed order program MEPJET [9], which only includes direct photon contributions. We have chosen the same kinematical cuts, which differ somewhat from the cuts used in the ZEUS [6] and H1 [7] analyses.

The $O(\alpha_s)$ results are obtained taking the Glück, Reya and Vogt (GRV) LO proton PDF’s [16] together with the one-loop formula for $\alpha_s$. For the $O(\alpha_s^2)$ results we employ the GRV higher order PDF’s together with the two-loop running $\alpha_s$ formula. We take $N_f = 5$ and match the strong coupling at the charm and bottom thresholds $\mu_R = m_c, m_b$, respectively.

Jets are defined in the laboratory frame using the cone algorithm with the opening angle $\sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = \Delta R \leq 1$ in the so-called E-scheme. In this scheme the four-vector of the combined jet is given as the sum of the four-vectors of the two partons. The differences of pseudorapidities and azimuthal angles with respect to the jet direction are $\Delta \eta$ and $\Delta \phi$. All jets have to fulfill $|\eta| < 3.5$ and $E_T > 4 \text{ GeV}$, where the index B refers to quantities in the Breit frame. $\eta$ and $E_T$ are measured in the HERA laboratory frame. Additional cuts are made for events which contain a forward jet. These requirements are $1.735 < \eta < 2.90$ and $E_T > 5 \text{ GeV}$ with

$$p_z/E_P > 0.05, \quad 0.5 < E_T^2/Q^2 < 4.$$ \hspace{1cm} (1)

The $x$ variable is restricted to the small-$x$ region of $x < 0.004$. The cuts on the electron variables are $Q^2 > 8 \text{ GeV}^2$, $y > 0.1$, $E' > 11 \text{ GeV}$ and $\theta'_e \in [160^0, 173.5^0]$. The electron and proton energies are $E_e = 27.5 \text{ GeV}$ and $E_P = 820 \text{ GeV}$, respectively. The positive $z$-direction is the direction of the incoming proton momentum.

The renormalization ($\mu_R$) and factorization scales ($\mu_F$) are taken equal and are identified with the sum $\mu_R = \mu_F = \frac{1}{2} \sum_i k^B_T(i)$ where $k^B_T(i)$ and $p^B_T$, the parton’s transverse momentum, are related in the Breit frame by

$$[k^B_T(i)]^2 = 2E^2_i(1 - \cos \theta_{ip}) = \frac{2}{1 + \cos \theta_{ip}}[p^B_T(i)]^2,$$ \hspace{1cm} (2)

where $\theta_{ip}$ is the angle between the parton and the proton direction in the Breit system. In LO one-jet production, i.e., in the naive parton model limit, $k^B_T(i) = Q$. With these constraints we obtain the cross sections in Tab. 1, where our JetViP results are compared to results from [8], referenced as MEPJET in the table. In addition to the forward jet cross sections we also list the full 2-jet, inclusive 2-jet and exclusive 3-jet cross sections. Compared to these cross sections, the kinematic constraints defining the forward cross section lead to considerable reductions. Furthermore we notice that the NLO corrections
Table 1: Jet cross sections in the forward region compared to MEPJET results.

| Contribution          | MEPJET  | JetViP  | relat. difference |
|-----------------------|---------|---------|------------------|
| $O(\alpha_s)\ 2\ jet$ | 2120 pb | 2203 pb | +4%              |
| same + forward jet    | 18.9 pb | 20.0 pb | +6%              |
| $O(\alpha_s^2)\ 2\ jet\ inclusive$ | 2400 pb | 2371 pb | −1%              |
| same + forward jet    | 83.8 pb | 89.0 pb | +6%              |
| $O(\alpha_s^2)\ 3\ jet\ exclusive$ | 210 pb | 207 pb | −1%              |
| same + forward jet    | 14.8 pb | 14.5 pb | −2%              |

to the forward jet cross sections are large in agreement with [8]. The $O(\alpha_s^0)$ single-jet cross section is not considered since it vanishes if a forward jet is required, due to the kinematical restrictions of the phase space.

The numbers for MEPJET are taken from ref. [8]. They differ by a few percent from our JetViP results. This is due to a different implementation. In JetViP the azimuthal ($\phi$) dependence of the jet with respect to the electron plane is integrated out in the hadronic center-of-mass system, whereas in MEPJET this $\phi$ dependence is included in this frame and then integrated in the HERA laboratory system. These terms which originate from the interference of the longitudinal and transverse virtual photon polarization ($\sim \cos \phi$) and from the transverse linear photon polarization ($\sim \cos 2\phi$) vanish for $Q^2 \to 0$ [17]. Since in our case the virtuality $Q^2$ is not very large, the contribution of the azimuthal dependent terms is small, which leads to small deviations between MEPJET and JetViP results. In addition, when integrating over the full phase space, it does not matter in which system the $\phi$ integration is performed, so that the observed difference is essentially due to the phase space restrictions in the forward jet selection.

Next we have evaluated the forward jet cross section including a resolved virtual photon contribution. Since the $Q^2$ is fairly large one might think that introducing a resolved virtual photon component is not necessary, because it is equivalent to a contribution generated in the NLO correction to the direct cross section. However, the NLO resolved cross section introduces additional higher order terms that are not contained in the NLO direct cross section, as we will see below. The kinematical cuts for selecting the forward jet are the same as for the comparison with MEPJET. The resolved cross section in LO and up to NLO is calculated as described in our earlier work [13] and which is incorporated in the JetViP program [13]. The PDF’s of the virtual photon are taken from [18], specifically we took the version SaS1D, which was transformed to the $\overline{\text{MS}}$ scheme (see [13]). For the LO resolved cross section it would be more appropriate to choose SaS1D without the transformation to the $\overline{\text{MS}}$ scheme. This would increase the total LO cross section in Tab. 2 by 10%. As in [13] we subtracted a term originating from the $\gamma^* \to q\bar{q}$ splitting in
Table 2: Resolved component in the forward region.

| Contribution                      | $\mathcal{O}(\alpha_s)$ 2 jet | $\mathcal{O}(\alpha_s^2)$ 2 jet incl. |
|-----------------------------------|----------------------------------|----------------------------------------|
| Resolved                          | $61.3 \pm 0.5$ pb               | $109.6 \pm 0.7$ pb                     |
| $\gamma^* \to q\bar{q}$ splitting| $-52.9 \pm 0.3$ pb              |                                        |
| DIS Direct                        | $18.7 \pm 0.2$ pb               | $89.6 \pm 0.3$ pb                      |
| Sum                               | $80.0 \pm 0.5$ pb               | $146.3 \pm 0.8$ pb                     |

the NLO direct photon matrix elements in order to avoid double counting at the NLO level. The SaS parametrizations of the virtual photon PDF vanish if the virtuality $Q^2$ is larger than the factorization scale $\mu_F^2$. Therefore we have chosen $\mu_R^2 = \mu_F^2 = Q^2 + (E_B^2)^2$. This enforces the virtual photon to be present since now always $Q^2 < \mu_F^2$. The results for the various components of the forward cross section are summarized in Tab. 2. From these results we observe the following. First, the sum of the LO direct and resolved contributions coincide within 10% with the NLO direct cross section. Second, adding the subtracted NLO direct contribution, which is the NLO direct minus the contribution from the photon splitting term (given with the minus sign in Tab. 2) to the NLO resolved cross section, leads to a large correction of about 60% if compared to the full NLO direct cross section. This increase has two sources. First, the LO resolved cross section is 15% larger than the subtracted photon splitting term. Part of this increase is due to the evolution of the PDF’s of the photon. The other part comes from the gluon component of the photon PDF, which amounts to 7.3 pb. Second, the NLO corrections to the resolved cross section give a further increase as compared to the LO result of approximately 80%, which originates from the NLO corrections to the resolved matrix elements.

We conclude, that the NLO resolved contribution supplies higher order terms in two ways, first through the NLO corrections in the hard scattering cross section and second in the leading logarithmic approximation by evolving the PDF’s of the virtual photon to the chosen factorization scale. This way we sum the logarithms in $E_T^2/Q^2$, which, however, in the considered kinematical region is not an important effect numerically, as we have seen in Tab. 2. Therefore, the enhancement of the NLO direct cross section through inclusion of resolved processes in NLO is mainly due to the convolution of the pointlike term in the photon PDF with the NLO resolved matrix elements, which gives an approximation to the NNLO direct cross section without resolved contributions. One of the dominant contributions to the forward cross section is shown in Fig. 1 (left part), where the photon splitting term is convoluted with a matrix element that provides two gluons in the final state. This way one gluon rung is added to the gluon ladder as compared to the corresponding NLO direct cross section, shown on the right of Fig. 1. The additional gluon in the NLO resolved term is in our approach calculated from perturbative QCD, producing an additional term which makes a contribution to the forward jet. In the
Figure 1: Diagrams contributing to resolved (left) and direct (right) processes in the forward region.

BFKL approach for the forward jet cross section [3, 4] this extra gluon is part of the BFKL evolution. In contrast, the NLO direct term in Fig. 1 (right part) contains also additional gluons in the DGLAP evolution of the proton PDF, which, however, are not resolved, i.e., go to the proton remnant. Another way to generate a larger forward jet cross section would be to go to the NNLO corrections of the direct cross section, which has not been done yet. We think that including the NLO resolved component produces a reasonable approximation to this NNLO cross section. Such a correspondence is present at one order lower. As already remarked above, the superposition of the LO direct and resolved cross section is almost equal to the NLO direct cross section.

2.2 Comparison with ZEUS and H1 Data

For the comparison with the 1995 ZEUS [6] and the 1994 H1 [7] forward jet cross section data we calculated the NLO cross section with slightly different input and in particular with the exact kinematical constraints for the forward jet selection as used in the two experiments.

As proton PDF’s we apply now the CTEQ4M parametrization [19] with the two-loop $\alpha_s$. We take $N_f = 5$ as before and match the value of $\alpha_s$ at the thresholds $\mu_R = m_c, m_b$ with a $\Lambda_{\overline{MS}}$ as used in CTEQ4M. Jets are defined with the cone algorithm in the HERA frame as described above, except that the axis of the jet is calculated now as the transverse energy weighted mean of $\eta$ and $\phi$ of the two partons or jets belonging to the combined jet. This kind of jet definition was also applied in the experimental jet analysis. As scales we choose $\mu^2 = \mu_R^2 = \mu_F^2 = M^2 + Q^2$ with a fixed $M^2 = 50$ GeV$^2$ related to the mean $E_T^2$ of the forward jet. We take this fixed value of $M$ instead of $E_T$ for technical reasons, since the calculations in JetViP start from the hadronic c.m.s.. The choice $\mu_F^2 > Q^2$ is mandatory if we want to include a resolved contribution. Another choice of scale would be $\mu_F = E_T$ or $\mu_F = M$. In the case $\mu_F^2/Q^2 > 1$ only for $E_T^2/Q^2 > 1$, which covers only part of the ZEUS kinematical range. To have a resolved cross section in all $E_T^2/Q^2$ bins we consider the choice $\mu_F^2 = M^2 + Q^2$ more appropriate.

In the two experiments the forward jet selection criteria are different. In the ZEUS
Figure 2: Dijet cross section in the forward region compared to ZEUS data. (a) NLO DIS, $E_T > 5$ GeV (b) NLO DIR$_S$+RES, $E_T > 5$ GeV.

In the ZEUS experiment the kinematical constraints are: $E'_e > 10$ GeV, $y > 0.1$, $\eta > 2.6$ and $E_T > 5$ GeV with the forward jet constraints $x_{jet} = E_{jet}/E_P > 0.036$, $0.5 < E_T^2/Q^2 < 2$, $p_{z,jet} > 0$ and $4.5 \times 10^{-4} < x < 4.5 \times 10^{-2}$. Our results for the forward jet cross section under these ZEUS kinematical conditions are shown in Fig. 2 a,b. In Fig. 2 a we plotted the full $O(\alpha_s^2)$ inclusive two-jet cross section (DIR) as a function of $x$ for three different scales $\mu^2 = 3M^2 + Q^2$, $M^2 + Q^2$ and $M^2/3 + Q^2$ and compared them with the measured points from ZEUS [6]. As to be expected the calculated NLO direct cross section is by a factor 2 to 4 too small compared to the data. The variation inside the assumed range of scales is small, so that also with a reasonable change of scales we can not get agreement with the data. In Fig. 2 b we show the corresponding forward jet cross sections with the NLO resolved contribution included, as described in the previous subsection, again for the three different scales $\mu$ as in Fig. 2 a. Now we find good agreement with the ZEUS data. The scale variation of the calculated cross section is larger than in Fig. 2 a. In particular, the largest scale gives now the largest cross section opposite to what is observed in Fig. 2 a. This different scale variation comes primarily from the scale dependence of the virtual photon PDF. This factorization scale variation is supposed to be compensated between the LO resolved and the NLO direct contribution but not for the NLO resolved contribution. This could only occur if we could include the NNLO direct contribution which, however, is not available. Since the NLO resolved contribution for the forward jet is rather large, as discussed above, this scale dependence can not be avoided. On the other hand, the scale dependence is not so large that we must fear our results not to be trustworthy. In Fig. 2 b the cross section is labeled DIR$_S$+RES, where DIR$_S$ stands for NLO direct minus the photon-quark-antiquark splitting term. We have calculated the forward jet cross section also with the scale $\mu_F^2 = M^2$. For this choice we obtain a somewhat smaller cross section which is approximately equal to the cross section with the scale $\mu_F^2 = M^2/3 + Q^2$.

In the H1 experiment [7] the forward jets are selected with the kinematical cuts $E'_e >$
Figure 3: Dijet cross section in the forward region compared to H1 data. (a) NLO DIS, $E_T > 3.5$ GeV; (b) NLO DIR$_S$+RES, $E_T > 3.5$ GeV; (c) NLO DIS, $E_T > 5.0$ GeV; (d) NLO DIR$_S$+RES, $E_T > 5.0$ GeV.

$11 \text{ GeV}, y > 0.1, 160^0 < \theta_e^\prime < 173^0, 1.735 < \eta < 2.794$ (this corresponds to $7^0 < \theta_{jet} < 20^0, E_T > 3.5 (5.0) \text{ GeV, } x_{jet} > 0.035$ and $0.5 < E_T^2/Q^2 < 2$. This corresponds approximately to the $Q^2$ range $5 < Q^2 < 100 \text{ GeV}^2$. The forward jet cross section is measured for various $x$ bins ranging from $1.0 \times 10^{-4}$ to $4.0 \times 10^{-5}$. Otherwise the calculated forward cross section is obtained under the same assumptions as for the ZEUS selection cuts. In Fig. 3 a,b,c,d we show the results compared to the H1 data obtained with two $E_T$ cuts in the HERA system, $E_T > 3.5$ GeV (Fig. 3 a,b) and $E_T > 5.0$ GeV (Fig. 3 c,d). In the plots on the left (Fig. 3 a,c) the data are compared with the pure NLO direct prediction, which turns out to be too small by a similar factor as observed in the comparison with the ZEUS data. In Fig. 3 b,c the forward jet cross section is plotted with the NLO resolved contribution included in the way described above. For both $E_T$ cuts, $E_T > 3.5$ GeV (in Fig. 3b) and $E_T > 5.0$ GeV (Fig. 3d), we find good agreement with the 1994 H1 data inside the scale variation window $M^2/3 + Q^2 < \mu^2 < 3M^2 + Q^2$. Compared to the ZEUS data the H1 measurements extend down to smaller $x$. In the lowest $x$ bin,
$1.0 \times 10^{-4} < x < 5.0 \times 10^{-4}$ the forward jet cross section has a dip, which is also reproduced in the theoretical calculation and which is due to the kinematical constraints for selecting forward jets.

We conclude that the NLO theory with a resolved virtual photon contribution gives a good description of both, the ZEUS and the H1 forward jet data. It is important, that both components, the direct and the resolved one, are calculated up to NLO. A LO calculation of both components would fall short of the experimental data, as it is clear from the results presented in Tab. 2, where we compared LO and NLO results.

We remark that the forward jet cross sections as measured by ZEUS and H1 are obtained at the hadron level, i.e., the jets are constructed from measured hadron momenta using the same cone algorithm. In our NLO calculation the jets are combined from partons with the same jet algorithm. The size of the corrections from hadron to parton level has been studied by the ZEUS collaboration [6] using several Monte Carlo simulation programs with the result that for the models which account very well for the ZEUS forward jet cross sections the correction factors are close to unity for all $x$ values considered in the analysis. In the H1 work similar results are reported [7].

In [7] the H1 forward jet data are also successfully described with the RAPGAP model [12] which includes a direct and a resolved component, both in LO, and with a similar scale $\mu$ as we have used. In addition this model has leading logarithm parton showers in the initial and final state built in. We think that these parton shower contributions produce the higher order effects which we found necessary to account for the correct normalization and the $x$ dependence of the forward jet cross section data.

### 3 Concluding Remarks

We conclude that the measurements of the forward jet cross section presented recently by the ZEUS and H1 collaborations can be described very well by the NLO theory with direct and resolved virtual photon contributions added in a consistent way. The theory shows good agreement with the data with respect to the normalization and also the functional dependence with decreasing $x$. Whereas this variation of the cross section with $x$ is also compatible with the NLO predictions based on direct photons, for the correct normalization the resolved component up to NLO is needed. To avoid double counting the $\gamma^* \rightarrow q\bar{q}$ splitting term is removed from the NLO direct contribution.

In contrast, LO BFKL predictions [4] yield much larger forward cross sections than the data [6, 7]. These calculations suffer, however, from several deficiencies. They are asymptotic and do not contain the correct kinematic constraints of the produced jets [21]. Furthermore they do not allow the implementation of a jet algorithm as used in the experimental analysis. Also NLO $\ln(1/x)$ terms in the BFKL kernel [21] predict large negative corrections which are expected to reduce the forward cross section as well. When all these points are taken into account the BFKL approach may give an equally well description
of the forward jet data. Even if this is the case, it is clear from this work that the BFKL theory is not the only theoretical approach that describes the forward jet cross sections.

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