Jet Production in DIS at NLO [1]

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Abstract. Dijet production in DIS is an important laboratory for testing our understanding of perturbative QCD. Flexible NLO Monte Carlo programs allow to investigate general jet definition schemes. For forward jet production at $p_{Tj} \approx Q$ and $x_{jet} \gg x$ the NLO predictions fall well below HERA data, thus providing evidence for BFKL dynamics.

Multi-jet production in DIS is an important topic of study at HERA. Good event statistics allow for precise measurements and thus for a variety of tests of our understanding of QCD dynamics. Such tests include a) the determination of $\alpha_s(\mu_R)$ from dijet production over a range of renormalization scales [1], b) the measurement of the gluon density in the proton (via $\gamma g \to q\bar{q}$) [2], c) forward jet production in the low-x regime as a signal of BFKL dynamics [3,4], d) the determination of $\alpha_s(\mu_R)$ and power corrections in DIS event shapes [5]. For quantitative studies one clearly needs to compare data with calculations which include next-to-leading order (NLO) QCD corrections.

Here we concentrate on issues related to dijet production at HERA. The present status of NLO Monte Carlo programs is reviewed. Second, we compare predictions in different jet definition and parton recombination schemes. Finally, the $\mathcal{O}(\alpha_s^2)$ predictions for forward jet production are discussed.

NLO MONTE CARLO PROGRAMS

NLO QCD corrections to one and two-jet production cross sections and distributions, for γ^* exchange, are implemented in the fully differential $ep \to n$ jets event generators MEPJET [6] and DISENT [7]. Full neutral current exchange (γ^* and/or Z) is now available in MEPJET 2.0 for tree level cross sections up to $\mathcal{O}(\alpha_s^3)$, *i.e.* up to 4-jet final states. NLO corrections to two-jet production including Z and W exchange will be available soon. Both programs

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	DISENT	MEPJET	$p_{Tj} > 5$ GeV DISENT	$\lvert\eta_j\rvert < 3.5$ MEPJET
LO 2 jet	395.6 ± 1.5 pb	392.6 ± 0.5 pb	339.0 ± 0.4 pb	337.5 ± 0.4 pb
LO 3 jet	33.0 ± 0.5 pb	32.5 ± 0.2 pb	27.7 ± 0.2 pb	27.2 ± 0.2 pb
NLO 2 jet incl.	561 ± 7 pb	559 ± 6 pb	463 ± 8 pb	480 ± 5 pb

TABLE 1. Comparison of DISENT [7] and MEPJET [6] predictions for n-jet cross sections in DIS at HERA. See text for details.

allow to study arbitrary experimental cuts and jet definition schemes. Previous calculations [8] were limited to a JADE type algorithm and important single jet-mass effects were neglected. Because of the disagreement with these earlier calculations a comparison of the two new calculations is particularly important.

In Table 1 we compare results from MEPJET and DISENT for 2- and 3-jet rates at HERA ($E_e = 26.7$ GeV, $E_p = 820$ GeV) in the k_T-scheme with $y_{cut} = 1$ and a hard scattering scale $E_T^2 = Q^2$. MRS D'_- parton distributions are used [9], we fix $\alpha_{QED} = 1/137$, and require $Q^2 > 40$ GeV^2. Factorization and renormalization scales are set to $\mu_F^2 = \mu_R^2 = Q^2$. No further cuts are imposed in the first column while in the second column reconstructed jets must have transverse momenta $p_{Tj} > 5$ GeV and pseudo-rapidities $|\eta_j| < 3.5$. We find agreement at the 2–3% level, which is slightly larger than, but still compatible with the statistical errors determined by the Monte Carlo integration routines. For all practical applications this agreement is satisfactory.

JET DEFINITION SCHEMES

The internal structure of jets is first modeled at NLO where two massless partons may be recombined to form a jet. The dependence of jet cross sections on the details of the internal jet structure can be investigated by studying different recombination schemes: the E-scheme where parton 4-momenta are added to form massive jet 4-momenta, and the $E0$ and P-schemes in which the jets are made massless by rescaling either the 3-momentum or the energy of the resulting cluster.

We use MEPJET for numerical studies with MRS D-' parton distribution functions [9]. The renormalization and factorization scales are set to one half the sum of parton transverse momenta in the Breit frame. A minimal set of kinematical cuts is imposed. We require 40 GeV$^2 < Q^2 < 2500$ GeV^2, $0.04 < y < 1$, an energy cut of $E(l') > 10$ GeV on the scattered lepton, and pseudo-rapidities $|\eta| < 3.5$ for the scattered lepton and jets. Also, jets must have transverse momenta of at least 2 GeV in the lab and the Breit frame.

Within these general cuts four different jet definition schemes are considered. i) A cone algorithm with a jet separation cut of $\Delta R < 1$ and a minimum jet transverse momentum of $p_{Tj} > 5$ GeV in the lab frame. ii) The k_T algorithm

	2-jet LO	2-jet excl. NLO (E)	2-jet incl. NLO (E)	2-jet incl. NLO ($E0$)	2-jet incl. NLO (P)
cone	1107 pb	1047 pb	1203 pb	1232 pb	1208 pb
k_T	1067 pb	946 pb	1038 pb	1014 pb	944 pb
W	1020 pb	2061 pb	2082 pb	1438 pb	1315 pb
JADE	1020 pb	1473 pb	1507 pb	1387 pb	1265 pb

TABLE 2. Two-jet cross sections in DIS at HERA. Results are given at LO and NLO for the four jet definition schemes and acceptance cuts described in the text. The 2-jet inclusive cross section at NLO is given for three different recombination schemes.

(in the Breit frame) as defined in Ref. [10] with a hard scattering scale $E_T^2 = 40\ \mathrm{GeV}^2$ and a resolution parameter $y_{cut} = 1$ for resolving the macro-jets. In addition, jets are required to have a minimal transverse momentum of 5 GeV in the Breit frame. iii) The W-scheme where parton/cluster pairs (including the proton remnant) with invariant mass squared, $M_{ij}^2 = (p_i + p_j)^2 < y_{cut} W^2$ are recombined [8]. iv) The "JADE" algorithm [11] which is obtained from the W-scheme by replacing the invariant definition M_{ij}^2 by $2E_iE_j(1-\cos\theta_{ij})$. In the W and JADE schemes we set $y_{cut} = 0.02$.

The resulting cross sections (see Table 2) show large NLO corrections for the JADE and W-schemes while K-factors close to unity are found for the k_T and cone algorithms. Another disadvantage of the W and JADE schemes is their strong recombination scheme dependence. Since even in a NLO calculation the internal structure of a jet is only calculated at tree level, these strong variations point to large uncertainties from two-loop effects in the W and JADE schemes. In both schemes widely separated but relatively soft partons tend to be clustered to what is then defined as a jet, even though these clusters can be very massive and quite distinct from the pencil-like and low-mass objects which one starts out with in the parton model or at LO [6]. These differences then result in the large higher order corrections to jet cross sections shown in Table 2. These effects are much smaller in the cone and the k_T schemes which are hence favored for precision QCD studies in DIS.

PROBING BFKL IN FORWARD JET PRODUCTION

Recently much interest has been focused on the small Bjorken-x region, where one would like to distinguish BFKL evolution [12], which resums the leading $\alpha_s \ln 1/x$ terms, from the more traditional DGLAP evolution equation [13], which resums leading $\alpha_s \ln Q^2$ terms. BFKL evolution can be enhanced and DGLAP evolution suppressed by studying DIS events which contain an identified jet of longitudinal momentum fraction $x_{jet} = p_z(jet)/E_{proton}$ (in the proton direction) which is large compared to Bjorken x [14]. When

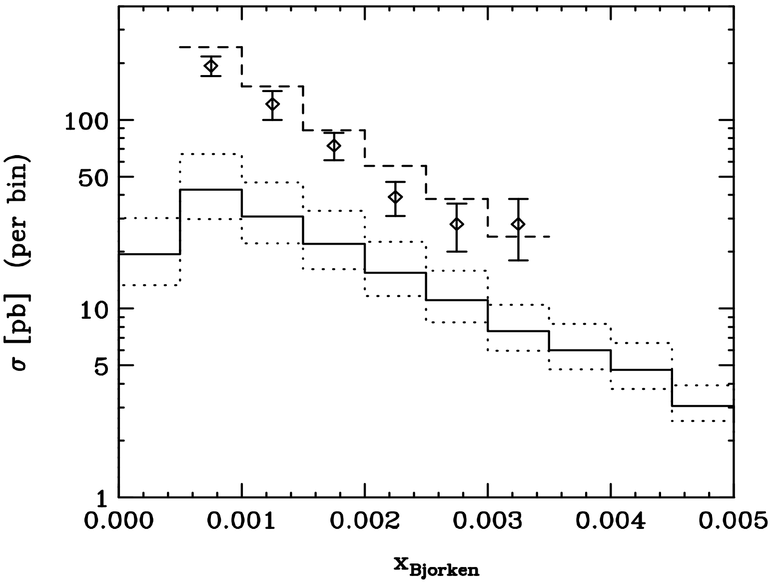

FIGURE 1. Forward jet cross section at HERA as a function of Bjorken x within the H1 acceptance cuts [3]. The solid histogram gives the NLO MEPJET result for the scale choice $\mu_R^2 = \mu_F^2 = \xi(0.5\sum k_T)^2$ with $\xi = 1$. The two dotted histograms show the uncertainty of the NLO prediction, corresponding to a variation of ξ between 0.1 and 10. The BFKL result of Bartels et al. [15] is shown as the dashed histogram. The data points are the new, preliminary H1 measurements [3].

tagging a forward jet with $p_{Tj} \approx Q$ 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.

The full calculation of the forward jet inclusive cross section in DIS, at $\mathcal{O}(\alpha_s^2)$, has been performed in Ref. [16]. Ordinarily, such a calculation 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. However, these 2-loop contributions vanish identically, once the condition $x \ll x_{jet}$ is imposed. The remaining 2-parton and 3-parton differential cross sections, and the cancellation of divergences between them, are 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 at $\mathcal{O}(\alpha_s^2)$.

In Fig. 1 numerical results are compared with recent data from H1 [3]. Here the conditions $p_{Tj} \approx Q$ and $x_{jet} \gg x$ are satisfied by selecting events with forward jets (in the angular region $7^o < \theta_j < 20^o$) with

$$0.5 < p_{Tj}^2/Q^2 \ < \ 2 \ , \tag{1}$$
$$x_{jet} \approx E_j/E_{proton} > 0.035 \ . \tag{2}$$

Clearly H1 observes substantially more forward jet events than expected from NLO QCD. However, since H1 accepted jets of rather low transverse momentum, $p_{Tj} > 3.5$ GeV, the comparison of our parton level calculation to the data may be subject to sizable hadronization corrections. A recent BFKL calculation [15] (dashed histogram) agrees better with the data, but here the overall normalization is uncertain and the agreement may be fortuitous. A very rough estimate of the uncertainty of the NLO calculation is provided by the two dotted lines which correspond to variations by a factor 10 of the renormalization and factorization scales μ_R^2 and μ_F^2.

Very similar results are found by ZEUS [4]. We conclude that the HERA data show evidence for BFKL dynamics in forward jet events via an enhancement in the observed forward jet cross section above NLO expectations. However, additional data, with harder forward jets, are needed to make the comparison of QCD calculations with data more reliable.

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