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Jet Production in Deep Inelastic Scattering at Next-to-Leading Order

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Abstract: NLO corrections to jet cross sections in DIS at HERA are studied, with particular emphasis on the two jet final state. High jet transverse momenta are a good criterion for the applicability of fixed order perturbation theory. A "natural" scale choice is the average k_T^B of the jets in the Breit frame, which suggest analyzing the data in different $< k_T^B >$ intervalls.

An important topic to be studied at HERA is the production of multi-jet events in DIS, where the expected good event statistics [1] allows for precision tests of QCD [2]. Such tests require next-to-leading order (NLO) QCD corrections. Full NLO corrections for one and two-jet production cross sections and distributions are now available and implemented in the fully differential $ep \to n$ jets event generator MEPJET [3], which allows to analyze arbitrary jet definition schemes and general cuts in terms of parton 4-momenta. A variety of topics can be studied with these tools. They include: a) The determination of $\alpha_s(\mu_R)$ from dijet production over a range of scales, μ_R, b) The measurement of the gluon density in the proton (via $\gamma g \to q\bar{q}$), c) Associated forward jet production in the low x regime as a signal of BFKL dynamics [4].

The effects of NLO corrections and recombination scheme dependences on the 2-jet cross section were discussed in Refs. [3, 5, 6] already for four different jet algorithms (cone, k_T, JADE, W) . While these effects are small in the cone and k_T schemes, very large corrections can appear in the W-scheme or the modified JADE scheme, which was introduced for DIS in Ref. [7].

At leading order (LO) the W and the JADE scheme are equivalent. The NLO cross sections in the two schemes, however, can differ by almost a factor of two [3, 5], depending on the recombination scheme and on the definition of the jet resolution mass (($M_{ij}^2 = (p_i + p_j)^2$ in the W scheme versus $M_{ij}^2 = 2E_iE_j(1 - \cos\theta_{ij})$ defined in the lab frame in the JADE scheme). Trefzger and Rosenbauer [2] find similarly large differences in the experimental jet cross sections (which are in good agreement with MEPJET predictions[1]), when the data are processed with exactly the same jet resolution mass and recombination prescription as used in the theoretical calculation. The large differences between and within the JADE and W schemes are caused by sizable single jet masses (compared to their energy), predominantly for jets in the central part

[1]The two jet rate in the W scheme (with E recombination) and in the JADE scheme for corrected ZEUS data are $18.6 \pm 0.7\%$ and $8.6 \pm 0.5\%$, respectively. The corresponding NLO predictions from MEPJET for the same kinematics and the same jet definitions are 17.9% and 8.6 % (see T. Trefzger [2]).

of the detector. Such single jet mass effects first appear in a NLO calculation where a jet may be composed of two partons. *Clearly, theoretical calculations must be matched to experimental definitions and such potentially large single jet mass effects must be taken into account.*

Previous programs [8, 9] were limited to a W type algorithm[2] and are not flexible enough to take into account the effects of single jet masses or differences between recombination schemes. In addition, approximations were made to the matrix elements in these programs which are not valid in large regions of phase space [3]. These problems are reflected in inconsistent values for $\alpha_s(M_Z^2)$ [ranging, for example, from 0.114 to 0.127 in the H1 analysis [1], (see K. Rosenbauer [2])], when these programs are used to analyze the data with different recombination schemes. Because of these problems, the older programs cannot be used for precision studies at NLO in their present form [10]. In order to reduce theoretical errors, previous analyses [1] should be repeated with MEPJET or a similar flexible Monte Carlo program [11]. A first reanalysis, with MEPJET, of H1 data by K. Rosenbauer yields a markedly lower central value, $\alpha_s(M_Z^2) = 0.112$, which is *independent* of the recombination scheme (used in both data and theory), and the $\alpha_s(\mu_R^2)$ extracted from different kinematical bins follows nicely the expectation from the renormalization group equation. A similar reanalysis of the ZEUS data has already been performed by T. Trefzger, also with MEPJET.

Single jet mass effects and recombination scheme dependences are fairly small in the cone and k_T schemes [3] which, therefore, appear better suited for precision QCD tests. In the following, we concentrate on these two and the E recombination scheme. A first issue which must be addressed is the dependence of the NLO 2-jet cross section on the renormalization scale, μ_R, and the factorization scale, μ_F. The chosen scale should be characteristic for the QCD portion of the process at hand. For dijet invariant masses, m_{jj}, below Q we are in the DIS limit and Q is expected to be the relevant scale. For large dijet invariant masses, however, $m_{jj} \gg Q$, the situation is more like in dijet production at hadron colliders and the jet transverse momenta set the physical scale of the process. A variable which interpolates between these two limits is the sum of jet k_Ts in the Breit frame [6], $\sum_j k_T^B(j)$. Here, $(k_T^B(j))^2$ is defined by $2\,E_j^2(1-\cos\theta_{jP})$, where the subscripts j and P denote the jet and proton, respectively. $\sum_j k_T^B(j)$ approaches Q in the parton limit and it corresponds to the sum of jet transverse momenta, p_T^B, (with respect to the γ^*-proton direction) when the photon virtuality becomes negligible. We use this "natural" scale for multi-jet production in DIS in the following.

A good measure of the improvement of a NLO over a LO prediction is provided by the residual scale dependence of the cross section. As an example we use the k_T algorithm (implemented in the Breit frame) as described in Ref. [12]. One finds very similar results for the cone scheme. Kinematical cuts are imposed on the final state lepton and jets to closely model the H1 event selection [13]. More specifically, we require 10 GeV$^2 < Q^2 <$ 10000 GeV^2, $0.01 < y < 1$, $0.0001 < x < 1$, and an energy cut of $E(l') > 10$ GeV and a cut on the pseudo-rapidity $\eta = -\ln\tan(\theta/2)$ of the scattered lepton. This η cut is Q^2 dependent: $-2.794 < \eta(l') < -1.735$ for $Q^2 < 100$ GeV^2 and $-1.317 < \eta(l') < 2.436$ for $Q^2 > 100$ GeV^2. In addition, we require $-1.154 < \eta(j) < 2.436$. The hard scattering scale, E_T^2, in the k_T algorithm is fixed to 40 GeV^2 and $y_{cut} = 1$ is the resolution parameter for resolving the macro-jets.

Fig. 1a shows the scale dependence of the dijet cross section in LO and NLO for the k_T scheme. The LO (NLO) results are based on the LO (NLO) parton distributions of GRV [14]

[2]DISJET [9] and PROJET [8] are largely based on the fact that the calculation of the jet resolution mass squared, M_{ij}^2, can be done in a lorentz invariant way, *i.e.* as in the W scheme. Only in LO does this agree with the JADE definition, defined in the lab frame.

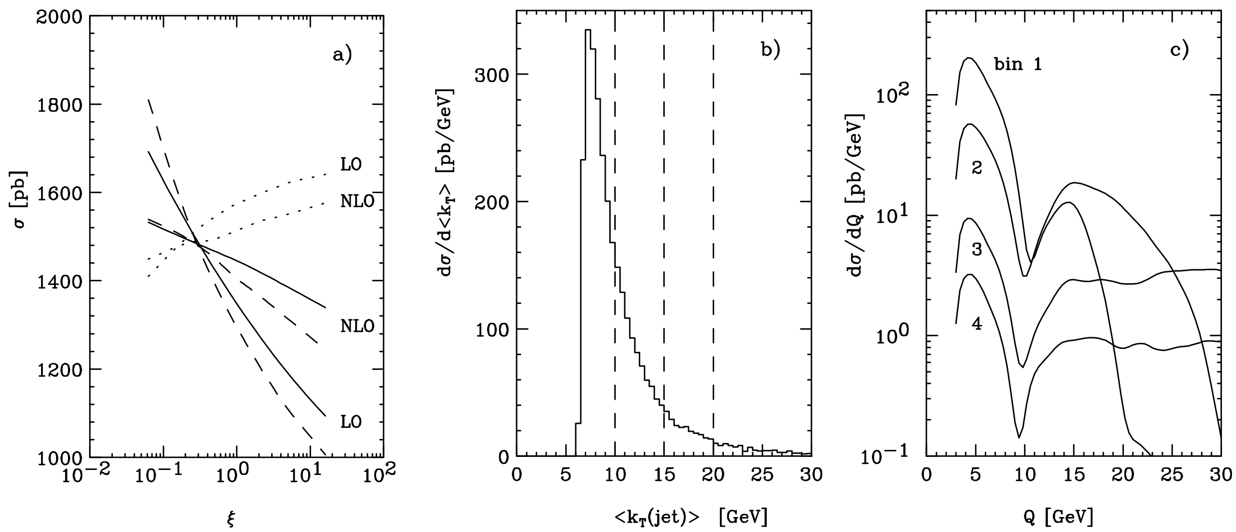

Figure 1: a) Dependence of the two-jet exclusive cross section in the k_T scheme on the scale factor ξ. The solid curves are for $\mu_R^2 = \mu_F^2 = \xi\ (\sum_i\ k_T^B(i))^2$, while for the dashed (dotted) curves only $\xi_R = \xi$ ($\xi_F = \xi$) is varied but $\xi_F = 1/4$ ($\xi_R = 1/4$) is fixed. Results are shown for the LO and NLO calculations. b) NLO $< k_T^B >$ distribution for the two-jet exclusive cross section. c) NLO Q distribution for the four bins in b).

together with the one-loop (two-loop) formula with five flavors for the strong coupling constant. The scale factors ξ are defined via

$$\mu_R^2 = \xi_R\,(\sum_i\ k_T^B(i))^2\,, \qquad \mu_F^2 = \xi_F\,(\sum_i\ k_T^B(i))^2\,. \tag{1}$$

The LO variation by a factor 1.55 is reduced to a 11% variation at NLO when both scales are varied simultaneously over the plotted range (solid curves). Also shown is the $\xi = \xi_R$ dependence of LO and NLO cross sections at fixed $\xi_F = 1/4$ (dashed curves) and the $\xi = \xi_F$ dependence of LO and NLO cross sections at fixed $\xi_R = 1/4$ (dotted curves). The NLO corrections substantially reduce the renormalization and factorization scale dependence. If not stated otherwise, we fix the scale factors to $\xi = \xi_R = \xi_F = 1/4$ in the following discussion.

Let us denote the average k_T^B of the (two) jets in the Breit frame by

$$< k_T^B >= \frac{1}{2}\,(\sum_{j=1,2}\ k_T^B(j)). \tag{2}$$

Fig. 1b shows the $< k_T^B >$ distribution for the NLO 2-jet exclusive cross section in the k_T scheme. We divide the distribution into four $< k_T^B >$ bins (suggesting a separate determination of $\alpha_s(< k_T^B >^2)$ for each). The dependence of the NLO cross section on the scale factor, ξ, is shown in Table 1 for individual bins, and is typically below $\pm 5\%$. These fairly small theoretical uncertainties in the k_T algorithm are due to the relatively high value of the hard scattering scale, $E_T^2 > 40$ GeV^2 (or roughly equivalent cuts of $p_T^{lab}, p_T^B \gtrsim 5$ GeV on the jets in the cone scheme). Thus a precise measurement of $\alpha_s(< k_T^B >^2)$ should be possible.

The Q distributions for the NLO exclusive dijet cross section for these four bins in Fig. 1c show that even events with very large $< k_T^B >$ are dominated by the small Q^2 region. (The dips in the Q distribution around $Q = 10$ GeV are a consequence of the rapidity cuts on the

Table 1: NLO (LO) 2-jet exlusive cross sections in pb for the four $< k_T^B >$ bins and their sum. Results are shown for three different choices of the scale factor $\xi = \xi_R = \xi_F$.

	$\xi = 1$	$\xi = 1/4$	$\xi = 1/16$
bin 1: 5 GeV $<\ < k_T^B >\ <$ 10 GeV	881 (821)	900 (907)	934 (999)
bin 2: 10 GeV $<\ < k_T^B >\ <$ 15 GeV	396 (357)	415 (403)	433 (461)
bin 3: 15 GeV $<\ < k_T^B >\ <$ 20 GeV	105 (102)	107 (118)	106 (137)
bin 4: 20 GeV $<\ < k_T^B >$	63 (68)	64 (80)	57 (95)
sum of bins	1445 (1348)	1486 (1508)	1530 (1692)

scattered lepton, see above). Thus there is a qualitative difference betwen scale choices tied to $< k_T^B >$ versus scales related to Q. One finds that μ_R^2, $\mu_F^2 = \xi Q^2$ gives a much larger ξ dependence for dijet events at NLO than the ones exhibited in Fig. 1a [3]. This is the reason why scales tied to k_T^B are better suited for QCD analyses of multijet events in DIS.

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