TTP96-30
MADPH-96-955

NLO Corrections to Jet Cross Sections in DIS[a]

E. MIRKES
Inst. f. Theor. Teilchenphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany

D. ZEPPENFELD
Department of Physics, University of Wisconsin, Madison, WI 53706, USA

Next-to-leading order corrections to jet cross sections in deep inelastic scattering at HERA are studied. The predicted jet rates allow for a precise determination of $\alpha_s(\mu_R)$ and the gluon density at HERA. We argue, that the "natural" renormalization and factorization scale is in general set by the average k_T^B of the jets in the Breit frame. Some implications for the associated forward jet production in the low x regime at HERA are discussed.

1 Introduction

One of the main topics to be studied at HERA is the deep inelastic production of multi jet events, where good event statistics are expected allowing for precision tests of QCD [1,2,3]. Clearly, next-to-leading order (NLO) QCD corrections are mandatory on the theoretical side for such tests. Full NLO corrections for one and two-jet production cross sections and distributions are now available [4] and implemented in the fully differential $ep \to n$ jets event generator MEPJET, 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 $\alpha_s(\mu_R)$ over a range of scales μ_R from dijet production. b) The measurement of the gluon density in the proton (via $\gamma g \to q\bar{q}$) c) The measurement of the polarized gluon density Δg with polarized beams of electrons and protons at HERA [5]. d) Associated forward jet production in the low x regime as a signal of BFKL dynamics.

The importance of higher order corrections and recombination scheme dependencies of the two jet cross sections for four different jet algorithms (cone, k_T, JADE, W) was already discussed in Refs. [4,6,7]. While the higher order corrections and recombination scheme dependencies in the cone and k_T

[a]Talk presented by E. Mirkes at the 'International Workshop on Deep Inelastic Scattering and Related Phenomena' (DIS96), April 1996, Rome.

schemes are small, very large corrections can appear in the W-scheme. Depending on the definition of the jet resolution mass and on the recombination scheme, the NLO cross sections in the W-scheme can differ by almost a factor of two [4,6]. Trefzger [1] and Rosenbauer [2] find similarly large differences in the experimental jet cross sections (which are in good agreement with the theoretical predictions from MEPJET), if the data are processed with exactly the same jet resolution mass and recombination prescription as used in the theoretical calculation. Note however, that the dependence on the recombination scheme first appears in the NLO calculation, where a jet may be composed of two partons. This internal jet structure is thus only simulated at tree level and thus the dependence of the cross section on the recombination scheme is subject to potentially large higher order corrections. An alternative fully differential NLO MonteCarlo program DISENT is under construction [8].

Previous programs [9,10] were limited to a JADE type algorithm and are not flexible enough to implement the various recombination schemes. In addition, approximations were made to the matrix elements in these programs which are not valid in large regions of phase space [4]. It is therefore not surprising, that one finds inconsistent values for α_s using these programs [2], if data are processed with different recombination schemes.

We conclude from these studies that the cone and k_T schemes appear better suited for precision QCD tests and will concentrate only on those schemes in the following.

In the cone algorithm (which is defined in the laboratory frame) the distance $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ between two partons decides whether they should be recombined to a single jet. Here the variables are the pseudo-rapidity η and the azimuthal angle ϕ. We recombine partons with $\Delta R < 1$. Furthermore, a cut on the jet transverse momenta of $p_T(j) > 5$ GeV in the lab frame is imposed.

For the k_T algorithm (which is implemented in the Breit frame), we follow the description introduced in Ref. [11]. The hard scattering scale E_T^2 is fixed to 40 GeV^2 and $y_{cut} = 1$ is the resolution parameter for resolving the macro-jets.

2 The determination of $\alpha_s(\mu_R)$ from dijet production

The dijet cross section is proportional to $\alpha_s(\mu_R)$ at leading order (LO), thus suggesting a direct measurement of the strong coupling constant. However, the LO calculation leaves the renormalization scale μ_R undetermined. The NLO corrections substantially reduce the renormalization and factorization scale dependencies which are present in the LO calculations (see below) and thus reliable cross section predictions in terms of $\alpha_s(m_Z)$ are made possible.

Clearly, a careful study of the choice of scale in the dijet cross section is needed in order to extract a reliable value for $\alpha_s(M_z)$. Jet production in DIS is a multi-scale problem and it is not a priori clear at which scale α_s is probed. However, it was argued [7], that the "natural" scale for jet production in DIS is set by the average k_T^B of the jets in the Breit frame. 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 (all quantities are defined in the Breit frame). It can be shown [7] that $\sum_j k_T^B(j)$ smoothly interpolates between the correct limiting scale choices, it approaches Q in the parton limit and it corresponds to the jet transverse momentum p_T^B (with respect to the γ^*-proton direction) when the photon virtuality becomes negligible. It therefore appears to be the "natural" scale for multi jet production in DIS.

Fig. 1a shows the scale dependence of the dijet cross section in LO and NLO for the k_T scheme. We have considered scales related to the scalar sum of the partons k_T^B (solid curves), the scalar sum of the partons p_T with respect to the γ^*-boson direction (dashed curves) and the virtuality Q of the incident photon. The LO (NLO) results are based on the LO (NLO) parton distributions from GRV [12] together with the one-loop (two-loop) formula for the strong coupling constant. Kinematical cuts are imposed to closely model the H1 event selection. More specifically, we require an energy cut of $E(e') > 10$ GeV on the scattered electron, and a cut on the pseudo-rapidity $\eta = -\ln\tan(\theta/2)$ of the scattered lepton depending on Q^2, i.e. $-2.794 < \eta(l') < -1.735$ for $Q^2 < 100$ GeV^2 $-1.317 < \eta(l') < 2.436$ for $Q^2 > 100$ GeV^2. In addition, we require $-1.154 < \eta(j) < 2.436$. The scale dependence of the dijet cross section does not markedly improve in NLO for $\mu^2 = \xi Q^2$ (dotted lines in Fig. 1a). The resulting ξ dependence for $\mu_R^2 = \mu_F^2 = \xi\ (\sum_i k_T^B(i))^2$ ($\mu_R^2 = \mu_F^2 = \xi\ (\sum_i p_T^B(i))^2$) is shown as the solid (dashed) lines in Fig. 1a. The uncertainty from the variation of the renormalization and factorization scale scale is markedly reduced compared to the LO predictions. Hence, the theoretical uncertainties due to the scale variation are small suggesting a precise determination of $\alpha_s(< k_T^B >)$ for different $< k_T^B >$ bins, where $< k_T^B >= \frac{1}{2}\ (\sum_{j=1,2} k_T^B(j))$. It has also been shown [7], that the $< k_T >$, $< p_T >$ and Q distributions can differ substancially for different $< k_T^B >$ bins (in particular for low Q^2), which explains the large differences in the scale dependence in Fig. 1. Fig. 1b shows the scale dependence of the dijet cross section in cone scheme for cuts similar to the ZEUS selection: 40 GeV$^2 < Q^2 < 2500$ GeV^2, $0.04 < y < 1$, and a cut on the pseudo-rapidity $\eta = -\ln\tan(\theta/2)$ of the scattered lepton and jets of $|\eta| < 3.5$. The results are very similar to the results for the k_T scheme shown in Fig. 1a.

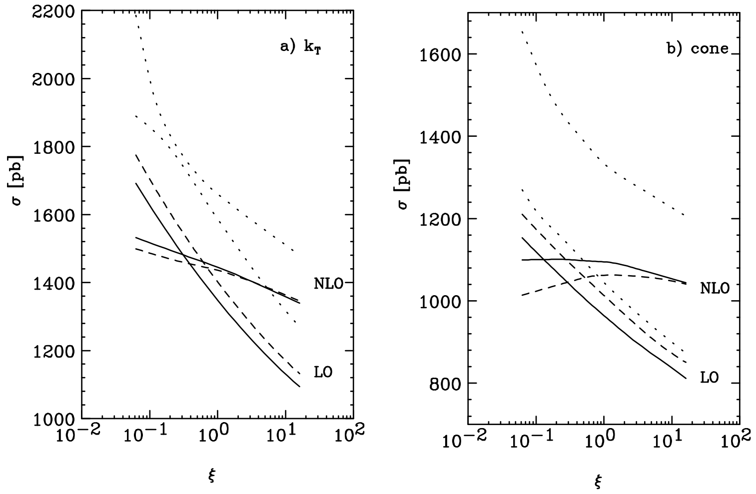

Figure 1: a) Dependence of the two-jet exclusive cross section in the k_T scheme on the scale factor ξ. The dashed curves are for $\mu_R^2 = \mu_F^2 = \xi\ (\sum_i\ p_T^B(i))^2$. Choosing $(\sum_i\ k_T^B(i))^2$ as the basic scale yields the solid curves. Choosing Q^2 as the basic scale yields the dotted curves. Results are shown for the LO (lower curves) and NLO calculations; b) the same as a) for the cone scheme. The kinematical cuts are explained in the text.

3 The measurement of the gluon density

Dijet production in DIS at HERA allows for a direct measurement of the gluon density in the proton (via $\gamma g \to q\bar{q}$). Some investigations of the feasibility of the parton density determination from dijet production have been discussed in Ref. [6] (see also Ref. [5]). Repond showed first results [13] of the gluon distribution determination in NLO in the cone scheme.

4 Forward Jet Production in the Low x Regime

Deep inelastic scattering with a measured forward jet with relatively large momentum fraction x_{jet} (in the proton direction) and $p_T^{2\,lab}(j) \approx Q^2$ is expected to provide sensitive information about the BFKL dynamics at low x [15,16]. In this region there is not much phase space for DGLAP evolution with transverse momentum ordering, whereas large effects are expected for BFKL evolution in x. In particular, BFKL evolution is expected to substantially enhance cross sections in the region $x << x_{jet}$ [15,16]. In order to extract information on the $\ln(1/x)$ BFKL evolution, one needs to show that cross section results based on

Table 1: Cross sections for n-jet exclusive events in DIS at HERA. See text for details.

	with forward jet	without forward jet
1 jet (LO)	0 pb	9026 pb
2 jet (LO)	19.3 pb	2219 pb
2 jet (NLO)	68 pb	2604 pb
3 jet (LO)	30.1 pb	450 pb

fixed order QCD with DGLAP evolution are not sufficient to describe the data. Clearly, next-to-leading order QCD corrections to the DGLAP predictions are needed to make this comparison between experiment and theory.

In Table 1 we show numerical results for the multi jet cross sections with (or without) a forward jet. The LO (NLO) results are based on the LO (NLO) parton distributions from GRV [12] together with the one-loop (two-loop) formula for the strong coupling constant. Kinematical cuts are imposed to closely model the H1 event selection. More specifically, we require $Q^2 > 8$ GeV^2 , $x < 0.004$, $0.1 < y < 1$, an energy cut of $E(e') > 11$ GeV on the scattered electron, and a cut on the pseudo-rapidity $\eta = -\ln\tan(\theta/2)$ of the scattered lepton of $-2.868 < \eta(e') < -1.735$ (corresponding to $160^o < \theta(l') < 173.5^o$). Jets are defined in the cone scheme (in the laboratory frame) with $\Delta R = 1$ and $|\eta(j)| < 3.5$. We require a forward jet with $x_{jet} = p_z(j)/E_P > 0.05$, $E(j) > 25$ GeV, $0.5 < p_T^2(j)/Q^2 < 4$, and a cut on the pseudo-rapidity of $1.735 < \eta(j) < 2.9$ (corresponding to $6.3^o < \theta(j) < 20^o$). In addition all jets must have transverse momenta of at least 4 GeV in the lab frame and 2 GeV in the Breit frame.

The cross sections of Table 1 demonstrate first of all that 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 for low jet multiplicities. The 1-jet exclusive cross section vanishes at LO, due to the contradicting $x < 0.004$ and $x_{jet} > 0.05$ requirements. For $x << x_{jet}$, a high invariant mass hadronic system must be produced by the photon-parton collision and this condition translates into

$$2E(j)m_T\, e^{-y} \quad\approx\quad \hat{s}_{\gamma,parton} \approx Q^2 \left(\frac{x_{jet}}{x} - 1\right) >> Q^2\,, \qquad (1)$$

where m_T and y are the transverse mass and rapidity of the partonic recoil system, respectively. Thus a recoil system with substantial transverse momentum and/or invariant mass must be produced and this condition favors recoil systems composed out of at least two additional energetic partons.

As a result one finds very large fixed order perturbative QCD corrections (compare 2 jet LO and NLO results with a forward jet in Table 1). In addition, the LO ($\mathcal{O}(\alpha_s^2)$) 3-jet cross section is larger than the LO ($\mathcal{O}(\alpha_s)$) 2-jet cross section. Thus, the forward jet cross sections in Table 1 are dominated by the ($\mathcal{O}(\alpha_s^2)$) matrix elements. The effects of BFKL evolution must be seen and isolated on top of these fixed order QCD effects. We will analyze these effects in a subsequent publication.

References

1. T. Trefzger, ZEUS collaboration, these proceedings.
2. K. Rosenbauer, H1 collaboration, these proceedings.
3. K. Flamm, H1 collaboration, these proceedings.
4. E. Mirkes and D. Zeppenfeld, hep-ph/9511448, *Phys. Lett.* B **380**, 205 (1996).
5. J. Feltesse, F. Kunne, and E. Mirkes, these proceedings.
6. E. Mirkes and D. Zeppenfeld, hep-ph/9604281, In the proceedings of the "Cracow Epiphany Conference on Proton Structure", Krakow, January 5-6,1996.
7. E. Mirkes and D. Zeppenfeld, hep-ph/9606332, In the proceedings of "QCD and QED in Higher Orders" 1996 Zeuthen Workshop on Elementary Particle Theory, April 22-26, 1996.
8. S. Catani, these proceedings.
9. D. Graudenz, Comp. Phys. Commun.92:65 (1995) hep-ph/9408383.
10. T. Brodkorb and E. Mirkes, Z. Phys. **C66** (1995) 141; hep-ph/9402362; *idib* hep-ph/9404287.
11. S. Catani, Y.L. Dokshitzer and B.R. Webber, Phys. Lett. **B285** (1992) 291.
12. M. Glück, E. Reya and A. Vogt, Z. Phys. **C67** (1995) 433.
13. J. Repond, ZEUS collaboration, these proceedings.
14. W. T. Giele and E. W. N. Glover, Phys. Rev. D **46** (1992) 1980. W. T. Giele, E. W. N. Glover and D.A. Kosower, Nucl. Phys. **B403** (1993) 633.
15. A.H. Mueller, Nucl. Phys. **B** (Proc. Suppl.) **18C** (1990) 125; J. Phys. **G17** (1991) 1443.
16. J. Kwiecinski, A.D. Martin and P.J. Sutton, Phys. Rev. **D46** (1992) 921;
    J. Bartels, A. De Roeck and M. Loewe, Z. Phys. **C54** (1992) 635;
    W.K. Tang, Phys. Lett. **B278** (1992) 363.