DEUTSCHES ELEKTRONEN-SYNCHROTRON

DESY 94-015
February 1994

Hard Processes at HERA: Theoretical Status

D. Bödeker

II. Institut für Theoretische Physik, Universität Hamburg

ISSN 0418-9833

NOTKESTRASSE 85 - 22603 HAMBURG

DESY 94-015 ISSN 0418-9833
February 1994

HARD PROCESSES AT HERA: THEORETICAL STATUS†

DIETRICH BÖDEKER‡

II. Institut für Theoretische Physik, Universität Hamburg,
Luruper Chaussee 149, 22761 Hamburg, Germany

ABSTRACT

Hard scattering processes in electron-proton collisions which can be treated within a fixed order of perturbative QCD are discussed. Recent next-to-leading order results for HERA are reviewed, in particular on the photoproduction and electroproduction of jets, heavy quarks and single hadrons.

† To appear in the *Proceedings of the International Europhysics Conference on High Energy Physics*, Marseille, France, July 22–28, 1993, edited by J. Carr and M. Perrottet.

‡ Present address: University of Minnesota, Theoretical Physics Institute, 116 Church Street SE, Minneapolis, MN 55455, USA.

HARD PROCESSES AT HERA: THEORETICAL STATUS

D. BÖDEKER
II. Inst. f. Theor. Physik, Universität Hamburg, Germany

ABSTRACT

Hard scattering processes in electron-proton collisions which can be treated within a fixed order of perturbative QCD are discussed. Recent next-to-leading order results for HERA are reviewed, in particular on the photoproduction and electroproduction of jets, heavy quarks and single hadrons.

Introduction

The electron-proton (ep) collider HERA provides a unique opportunity to study a variety of hard scattering processes. This will allow for tests of QCD and will yield information about the structure of the proton and the photon. If the involved momentum transfer is large compared to the QCD scale parameter $\Lambda_{\rm QCD}$, the corresponding cross sections can be expanded in powers of the strong coupling constant α_s. Since the contributions due to W and Z boson exchange are small at HERA energies only the pure photon exchange will be considered. The leptonic variables will be denoted by

$$x = \frac{Q^2}{2p \cdot q}, \quad z = \frac{p \cdot q}{p \cdot l} \tag{1}$$

with $Q^2 = -q^2$, $q = l - l'$. Here p, l and l' are the momenta of the proton, the incoming electron and the scattered electron, respectively.

For small Q^2 the exchanged photon may be treated as real (photoproduction) and the ep cross section can be expressed by the photon-proton cross section using the Weizsäcker-Williams approximation. Then there are two distinct production mechanisms. Firstly, the photon may couple directly to the partons involved in the hard scattering process (direct photon contribution). In the second case it gets resolved into its hadronic constituents, one of which scatters off a parton from the proton (resolved photon contribution). The distribution function of parton type a carrying a fraction ξ_a of the photon momentum $f_a^\gamma(\xi_a, M_\gamma)$ is of the order $\alpha_{\rm em}/\alpha_s$. Therefore the direct and resolved contributions are of the same order in α_s. Here M_γ denotes the factorization scale associated with the photon. The distinction of direct and resolved part is unambiguosly defined only for the leading order (LO) cross sections. In the real corrections to the direct contribution a quark or antiquark may be emitted in the direction of the incoming photon. This causes a collinear singularity, which has to be absorbed into the (anti-) quark distribution of the photon. In this way one obtains an explicit M_γ dependence of the direct contribution and only the sum of direct part and resolved part is independent of M_γ up to higher order terms.

At large Q^2 (electroproduction) there are contributions from both transversely (T) and longitudinally (L) polarized photons:

$$\frac{d\sigma}{dxdz} = \frac{\alpha_{\rm em}}{2\pi}\frac{1}{xz}\left[\left(1+(1-z)^2\right)\sigma_{\rm T} + 2\,(1-z)\,\sigma_{\rm L}\right] \tag{2}$$

Additional terms are obtained if one considers correlations between the scattered electron and the hadrons in the final state.

In this article we concentrate on processes for which the LO cross sections are $\mathcal{O}(\alpha_{\rm em}\alpha_s)$, in particular the production of hadronic jets and single hadrons with large transverse energy and the production of heavy quarks.

Jets

Photoproduction

In the small E_t region the one-jet-inclusive cross section $d\sigma/dE_t dy$, where E_t and y denote the transverse energy and the rapidity of the jet, at HERA is dominated by the resolved photon contribution. There a sizable fraction of the cross section is due to the gluon component of the photon. At higher E_t ($\sim$ 25 GeV) the size of the direct part becomes comparable to that of the resolved one. The one-jet-inclusive cross section has been computed at next-to-leading order (NLO) for the resolved [1, 2, 3] and the direct photon contribution [2, 4]. In all these calculations jets have been defined in terms of the cone algorithm od refs. [5, 6]. The results for the resolved part have been obtained by using the calculation of ref. [7]. There the real corrections to the one-jet-inclusive cross section for parton-parton scattering have been calculated analytically in the limit of vanishing jet cone size. The finite cone corrections are nonsingular and have been computed numerically. In ref. [4] the phase space integral of the real corrections has been made finite by subtracting the singular contributions under the integral sign. Then the integration has been performed numerically. On the other hand the subtracted terms have been added to the virtual corrections. After the factorization of the initial state collinear singularities this yields a finite sum for any infrared safe jet cross section (for details see ref. [8]). In ref. [2] the calculation of ref. [9] has been employed, where the integrals over the soft and collinear regions of the phase space have been performed analytically in the limit of small cut parameters. The remaining finite part of the real corrections has been evaluated numerically.

The $\mathcal{O}(\alpha_{\rm em}\alpha_s^2)$ corrections turned out to be moderate and all the mentioned groups find the full NLO results to be more stable with respect to variation of the renormalization scale and factorization scales than the LO ones. Thus this allows for quantitative predictions of the cross sections at HERA. In ref. [4] this has been found to be valid only if M_γ is fixed in the direct contribution. A strong M_γ dependence also of the NLO resolved contribution has been observed in ref. [3]. This suggests that only the sum of direct and resolved part is a meaningful quantity in the kinematic range relevant for HERA. The dependence of the jet cone size for the direct and resolved part turned out to be significant and should be observable.

More detailed information about the parton dynamics and the parton distributions can be obtained considering the two-jet-inclusive cross section $d\sigma/dM_{\rm jj}dy_{\rm jj}dy^*$. Here $M_{\rm jj}$ and $y_{\rm jj}$ are the invariant mass and the rapidity of the two jets and y^* is the rapidity of one jet with respect to the other. The corresponding $\mathcal{O}(\alpha_{\rm em}\alpha_s^2)$ corrections for the direct contribution have been computed in ref. [8]. They turned out to be $\sim 10\%$ over a wide range of $M_{\rm jj}$, when the jet radius is chosen as $R = 0.7$. The shape of the y^* distributions, which should allow for a clear distinction of direct photon contribution and the resolved one is flattened when the $\mathcal{O}(\alpha_{\rm em}\alpha_s^2)$ corrections are included.

Electroproduction

QCD corrections to jet electroproduction have been calculated in refs. [10, 11, 12]. In these calculations jets have been defined by a modified JADE cluster algorithm where the remnant jet of the proton is included in the clustering procedure. In refs. [10, 11] the (1+1) jet and (2+1) jet cross sections, where '+1' denotes the proton remnant, for transversely polarized photons have been calculated at NLO. It turned out that the scale dependence of the LO results is reduced significantly when the $\mathcal{O}(\alpha_{\rm em}\alpha_s^2)$ corrections are included. Choosing the jet recombination cut M^2 as $M^2 = cW^2$, where W is the photon-proton c.m. energy, the corrections turned out to be small for $c > 0.01$. The large corrections for smaller values of c indicate a breakdown of the fixed order perturbative expansion. In ref. [11] it has also been discussed how to investigate the small ξ_a behavior of the parton distributions of the proton $f_a^p(\xi_a)$. With $M^2 = cW^2$ the probed ξ_a-range is limited to $\xi_a > c$. Therefore alternative choices for M^2 have been investigated, which allow for probing smaller values of ξ_a. In ref. [12] analytic results for the $\mathcal{O}(\alpha_{\rm em}\alpha_s^2)$ corrections to the longitudinal photon contribution and to some lepton-hadron correlations have been obtained.

Heavy Quarks

Photoproduction

Photon-gluon fusion is expected to be the dominant mechanism for heavy quark photoproduction. Therefore this process should allow for a measurement of the gluon distribution of the proton $f_g^p(\xi_g)$. The total and single inclusive NLO cross sections for the direct and the resolved contribution have been calculated in refs. [13, 14]. This calculation has been confirmed by refs. [15, 16].

In refs. [17, 18] an $\mathcal{O}(\alpha_{\rm em}\alpha_s^2)$ calculation of the exclusive heavy quark production in parton-parton and photon-parton scattering has been performed. It can be used to compute any infrared safe quantity like heavy quark correlations or heavy quark jet cross sections with cuts on any final state parton momentum. In ref. [19] this calculation has been applied to the double inclusive $c\bar{c}$ cross section at HERA. In particular, these authors investigated the determination of $f_g^p(\xi_g)$ from the direct photon contribution to $d\sigma/d\xi_g$, when ξ_g is reconstructed from the heavy quark momenta. Only very little is known about the gluon density in the photon and so the resolved contribution might dominate the cross section completely (see ref. [20]). It has been shown in ref. [19] that the resolved contribution can be strongly suppressed by applying a cut on the invariant mass of the heavy quark pair. With these cuts a determination of $f_g^p(\xi_g)$ should be possible in the range $10^{-3} < \xi_g < 10^{-1}$. Furthermore, these authors found the $\mathcal{O}(\alpha_{\rm em}\alpha_s^2)$ corrections to be moderate. They can, however, not simply be accounted for by a K-factor, since they slightly change the shape of the ξ_g-distributions.

Electroproduction

The difficulties in the determination of $f_g^p(\xi_g)$ can also be circumvented by considering heavy quark production via off shell photons. The corresponding NLO cross sections have been calculated in refs. [21, 22] for both transversely polarized photons, which yield the dominant contribution, and longitudinally polarized ones. There numerical results for charm and bottom production at HERA have been presented. The cross sections, which are totally inclusive with respect to the final state partons, contribute to the proton structure functions F_2 and F_L and have been discussed in ref. [21]. The single inclusive transverse momentum and rapidity distributions of charm quarks, $dF_{2,L}/dp_t$ and $dF_{2,L}/dy$ have been investigated in ref. [22]. The $\mathcal{O}(\alpha_{em}\alpha_s^2)$ corrections turned out to be large at HERA energies and they significantly modify the shapes of the distributions. The corrections to the p_t distributions are in general positive except at very small p_t. For dF_2/dp_t they have been found to be $\sim 50\%$ in the range $10^{-4} < x < 10^{-3}$. The relative size of the corrections to dF_L/dp_t in general turned out to be larger and strongly p_t dependent. However they are still moderate in the small p_t region, which yields the dominant contribution to the p_t integrated cross section F_L.

Photoproduction of Single Hadrons

The cross sections for single hadron production can be obtained from the partonic ones by convolution with fragmentation functions. These have to be extracted from data. Their variation with the factorization scale is predicted by QCD. NLO cross sections for the resolved photoproduction at HERA have been computed in ref. [23]. These authors have used the results of ref. [7] for the NLO partonic cross sections together with LO fragmentation functions for charged hadrons and a NLO parameterization for π^0. They have found that the $\mathcal{O}(\alpha_{em}\alpha_s^2)$ corrections increase the cross sections relative to the LO results by a factor between 2.5 and 1.6 when p_t varies between 1 GeV and 10 GeV. Furthermore, they have investigated the contribution due to the gluon content of the photon, which yields 60% and 30% of the cross section at $p_t = 2$ GeV and $p_t = 10$ GeV, respectively. It turned out that these values are hardly affected by the $\mathcal{O}(\alpha_{em}\alpha_s^2)$ corrections. The shape of the p_t distribution of charged hadrons has been found to be consistent with the H1 data.

Acknowledgement

This work has been supported by the 'Graduiertenkolleg für theoretische Elementarteilchenphysik', Universität Hamburg.

References

[1] G. Kramer, S. G. Salesch, in Proceedings of the Workshop *Physics at HERA* (1992), Vol. 1, eds. W. Buchmüller and G. Ingelman; DESY-93-01.

[2] L. E. Gordon, J. K. Storrow, *Phys. Lett.* **B291** (1992) 320.

[3] M. Greco, A. Vicini, LNF-93/017.

[4] D. Bödeker, in Proceedings of the Workshop *Physics at HERA* (1992), Vol. 1, eds. W. Buchmüller and G. Ingelman; *Phys. Lett.* **B292** (1992) 164.

[5] S. D. Ellis, Z. Kunszt, D. E. Soper, *Phys. Rev.* **D40** (1989) 2188.

[6] J. E. Huth et al. , FERMILAB-Conf-90/249-E.

[7] F. Aversa, P. Chiappetta, M. Greco, J. Ph. Guillet, *Nucl. Phys.* **B327** (1989) 105; *Z. Phys.* **C46** (1990) 253.

[8] D. Bödeker, *Z. Phys.* **C59** (1993) 501.

[9] H. Baer, J. Ohnemus, J. F. Owens, *Phys. Rev.* **D40** (1989) 2844.

[10] D. Graudenz, DESY-T-90-01; *Phys. Lett.* **B256** (1991) 518.

[11] D. Graudenz, LBL-34147 (1993).

[12] T. Brodkorb, J. Körner, *Z. Phys.* **C54** (1992) 519.

[13] P. Nason, S. Dawson, R. K. Ellis, *Nucl. Phys.* **B303** (1988) 607.

[14] R. K. Ellis, P. Nason, *Nucl. Phys.* **B312** (1989) 551.

[15] W. Beenakker, H. Kuijf, W. L. van Neerven, J. Smith, *Phys. Rev.* **D40** (1989) 54.

[16] J. Smith, W. L. van Neerven, *Nucl. Phys.* **B374** (1992) 36.

[17] M. L. Mangano, P. Nason, G. Ridolfi, *Nucl. Phys.* **B373** (1992) 295.

[18] S. Frixione, M. L. Mangano, P. Nason, G. Ridolfi, CERN-TH-6921/93.

[19] S. Frixione, M. L. Mangano, P. Nason, G. Ridolfi, *Phys. Lett.* **B308** (1993) 137.

[20] S.Riemersma, J. Smith, W. L. van Neerven, *Phys. Lett.* **B282** (1992) 171.

[21] E. Laenen, S.Riemersma, J. Smith, W. L. van Neerven, *Nucl. Phys.* **B392** (1993) 162.

[22] E. Laenen, S.Riemersma, J. Smith, W. L. van Neerven, *Nucl. Phys.* **B392** (1993) 229.

[23] F. M. Borzumati, B. A. Kniehl, G. Kramer, *Z. Phys.* **C59** (1993) 341