HEAVY QUARK PRODUCTION AT HERA
WITH BFKL AND CCFM DYNAMICS∗

S. P. BARANOV
Lebedev Institute of Physics
Leninsky prosp. 53, Moscow 117924, Russia
E-mail: baranov@sci.lebedev.ru

H. JUNG, L. JÖNSSON
Department of Elementary Particle Physics,
Lund University, Box 118 SE 22100 Lund, Sweden
E-mail: jung@mail.desy.de
E-mail: leif.jonsson@quark.lu.se

S. PADHI †
Department Physics, McGill University,
Montreal, Quebec, Canada, H3A 2T8
E-mail: Sanjay.Padhi@desy.de

N. P. ZOTOV ‡
SINP, Moscow State University,
Moscow 119992, Russia
E-mail: zotov@theory.sinp.msu.ru

In the framework of the semi-hard (k_t−factorization) approach, we analyze the various charm production processes in the kinematic region covered by the HERA experiments.

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1. Introduction

The present note is short version of our paper \(^1\) where we have attempted a systematic comparison of the theoretical predictions of the \(k_t\)-factorization approach \(^2\), \(^3\), \(^4\) with experimental data regarding the charm production processes at HERA.

The production of open-flavored \(c\bar{c}\) pairs in \(ep\)-collisions is described in terms of the photon-gluon fusion mechanism. A generalization of the usual parton model to the \(k_t\)-factorization approach implies two essential steps. These are the introduction of unintegrated gluon distributions and the modification of the gluon spin density matrix in the parton-level matrix elements. The hard scattering cross section for a boson gluon fusion process is written as a convolution of the partonic cross section \(\hat{\sigma}(x_g, k_t; \gamma^* g^* \rightarrow q\bar{q})\) with the \(k_t\) dependent (unintegrated) gluon density \(A(x, k_t^2, \mu^2)\).

The multidimensional integrations can be performed by means of Monte-Carlo technique either by using VEGAS \(^5\) for the pure parton level calculations, or by using the full Monte Carlo event generator CASCADE \(^6\), \(^7\), \(^8\).

Cross section calculations require an explicit representation of the \(k_t\) dependent (unintegrated) gluon density \(A(x, k_t^2, \mu^2)\). We have used three different representations, one \((JB)\) coming from a leading-order perturbative solution of the BFKL equations \(^9\), the second set \((JS)\) derived from a numerical solution of the CCFM equation \(^6\), \(^7\) and the third \((KMR)\) from solution of a combination of the BFKL and DGLAP equations \(^10\).

2. Numerical results and discussion

A comparison between model predictions and data in principle has to be made on hadron level and only if it turns out that hadronization effects are small will a comparison to parton level predictions make sense. However, a full simulation even of the partonic final state, including the initial and final state QCD cascade needs a full Monte Carlo event generator. Such a Monte Carlo generator based on \(k_t\)-factorization and using explicitly off-shell matrix elements for the hard scattering process convoluted with \(k_t\)-unintegrated gluon densities is presently only offered by the CASCADE \(^6\), \(^7\), \(^8\) program which uses the CCFM unintegrated gluon distribution.

In the ref. \(^1\) we systematically compared the predictions from the \(k_t\)-factorization approach to published data on charm production at HERA. For this we use \(D^*\) photo-production data from ZEUS \(^11\) and \(D^*\) production in deep inelastic scattering from both ZEUS \(^12\) and H1 \(^13\). First we
calculate observables using a pure parton level calculation based on the matrix element calculation of BZ \cite{14} including the Peterson fragmentation function \cite{15} for the transition from the charm quark to the observed $D^*$ meson. Then we compare the result with a full hadron level simulation using the Monte Carlo generator CASCADE with the matrix element of CCH \cite{4}.

Next we investigate on parton level different unintegrated gluon densities. We study the sensitivity of the model predictions to the details of the unintegrated gluon density, the charm mass and the scale. We observed \cite{1} that the $p_t$ distribution of $D^*$ mesons both in photo-production and deep inelastic scattering is in general well described, both with the full hadron level simulation as implemented in CASCADE and also with the parton level calculation supplemented with the Peterson fragmentation function. We can thus conclude, that the $p_t$ distribution is only slightly dependent on the details of the charm fragmentation.

We also consider the rapidity distribution of the produced $D^*$. In photo-production and in DIS the differential cross section $d\sigma/d\eta$, where $\eta$ is the pseudo-rapidity of the $D^*$ meson, is sensitive to the choice of the unintegrated gluon distribution. We observed, that the parton level prediction including the Peterson fragmentation function is not able to describe the measurement over the full range of $\eta$. The effect of a full hadron level simulation is clearly visible as CASCADE provides a much better description.

Figure 1. Relative differential cross sections $1/\sigma d\sigma/dx\ g_{obs}$ (a) and $1/\sigma d\sigma/d|\cos\theta^*|$ (b) with $Q^2 < 1$ GeV$^2$, $p_T^{D^*} > 3$ GeV, $|\eta^{D^*}| < 1.5$, $130 < W < 280$ GeV, $|\eta^{jet1,2}| < 2.4$, $E_{T}^{jet1,2} > 5$, $M_{jj} > 18$ GeV and $|\eta| < 0.7$. The histograms are results with various MC simulations.
Then we investigate the $x_\gamma$ distribution, which is sensitive to the details of the initial state cascade. We compare the predictions from a pure parton level calculation and a full event simulation of CASCADE with the measurements (Fig. 1(a)). We can conclude that the $k_t$-factorization approach effectively simulates heavy quark excitation and indeed the hardest $p_t$ emission comes frequently from a gluon in the initial state cascade $^{16}$.

Other interesting quantities are the dijet angular distributions of resolved photon like events ($x_{\text{OBS}}^\gamma < 0.75$) compared to the direct-photon like events ($x_{\text{OBS}}^\gamma > 0.75$). In the $k_t$-factorization approach the angular distribution will be determined from the off-shell matrix element, which covers both scattering processes. Comparisons of the CASCADE results with the ZEUS experimental data for these angular distributions were done by S. Padhi $^{17}$ (Fig. 1(b)).

In summary we have shown, that the $k_t$-factorization approach can be consistently used to describe measurements of charm production at HERA, which are known to be not well reproduced in the collinear approach. We have also shown, that in $k_t$-factorization, resolved photon like processes are effectively simulated including the proper angular distributions.

References
1. S.P. Baranov, H. Jung, L. Jönsson et al., Eur. Phys. J. C 24 (2002) 425.
2. L. Gribov, E. Levin, M. Ryskin, Phys. Rep. 100 (1983) 1.
3. J. Collins, R. Ellis, Nucl. Phys. B 360 (1991) 3.
4. S. Catani, M. Ciafaloni, F. Hautmann, Nucl. Phys. B 366 (1991) 135.
5. G. P. Lepage, J. Comp. Phys. 27 (1978) 192, CLNS-80/447.
6. H. Jung, in Proceedings of the Workshop on Monte Carlo generators for HERA physics (DESY, Hamburg, 1999), p. 75, hep-ph/9908497.
7. H. Jung, G. Salam, Eur. Phys. J. C 19 (2001) 351, hep-ph/0012143.
8. H. Jung, Comp. Phys. Comm. 143 (2002) 100, hep-ph/0109102.
9. J. Blümlein, in Proc. of the Workshop on Deep Inelastic Scattering and QCD, edited by J. Laporte, Y. Sirois (1995), DESY 95-121.
10. M. A. Kimber, A. D. Martin, M. G. Ryskin, Phys. Rev. D 63 (2001) 114027.
11. ZEUS Collaboration, J. Breitweg et al., Eur. Phys. J. C 6 (1999) 67.
12. ZEUS Collaboration; J. Breitweg et al., Eur. Phys. J. C 12 (1999) 35.
13. H1 Collaboration; C. Adloff et al., Phys. Lett. B 528 (2002) 199.
14. S. Baranov, N. Zotov, Phys. Lett. B 458 (1999) 389.
15. C. Peterson, D. Schlatter, I. Schmitt, P. M. Zerwas, Phys. Rev. D 27 (1983) 105.
16. S. Baranov, N. Zotov, Phys. Lett. B 491 (2000) 111.
17. S. Padhi, Acta Phys. Pol. B 33 (2002) 3189.