ASSOCIATED D^* AND DIJET PRODUCTION AT HERA AS A TEST OF THE k_T-FACTORIZATION APPROACH*

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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 a short version of our paper [1] where we have attempted a systematic comparison of the theoretical predictions of the k_T-factorization approach [2–4] 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

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generalization of the usual parton model to the $k_{\rm T}$-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 matrix-element squared for open heavy quark production has already been calculated in [3,4], which we label CE-CCH in the following. In [5] (labelled as SZ) the calculation of the matrix elements for open heavy quark production has been repeated. In [6,7] (labelled as BZ) the method of orthogonal amplitudes [8] was applied. In the calculation of CE-CCH and SZ the photon is treated in a similar way as was the gluon in [3]:

$$G^{\mu\nu} = \overline{\varepsilon_g^{\mu}\varepsilon_g^{*\nu}} = \frac{k_{{\rm T}\,g}^{\mu} k_{{\rm T}\,g}^{\nu}}{|k_{{\rm T}\,g}|^2} \,. \tag{1}$$

This formula converges to the usual $\sum \varepsilon^{\mu}\varepsilon^{*\nu} = -g^{\mu\nu}$ when $k_{\rm T} \to 0$.

In SZ and BZ the complete set of matrix elements have been tested for gauge invariance by substituting the gluon momenta with their polarization vectors showing explicitly the gauge invariance of the matrix element in order $\mathcal{O}(\alpha_{\rm s})$.

The hard scattering cross section for a boson gluon fusion process is written as a convolution of the partonic cross section $\hat{\sigma}(x_g, k_{\rm T};\ \gamma^* g^* \to q\bar{q})$ with the $k_{\rm T}$ dependent (unintegrated) gluon density $\mathcal{A}(x, k_{\rm T}^2, \mu^2)$ (here and in the following $k_{\rm T}$ is a shorthand notation for $|\vec{k}_{\rm T}|$ with $\vec{k}_{\rm T}$ being the two-dimensional vector of the transverse momentum of the gluon):

$$\sigma = \int dk_{\rm T}^2 dx_g \mathcal{A}(x_g, k_{\rm T}^2, \mu^2) \hat{\sigma}(x_g, k_{\rm T};\ \gamma^* g^* \to q\bar{q}) \,, \tag{2}$$

with the off-shell matrix elements either given by CE-CCH, SZ or by BZ. The multidimensional integrations can be performed by means of Monte-Carlo technique either by using VEGAS [9] for the pure parton level calculations, or by using the full Monte Carlo event generator Cascade [10–12].

Since it is difficult to compare the different matrix elements with each other analytically, we have performed several numerical checks. Whereas the calculations of CE-CCH and SZ agree perfectly in all cases, a systematic difference of the order of $\sim 10\%$ to the calculation of BZ is observed. Since we obtained agreement in the high energy limit, this can be attributed to the effect of the small x approximation.

It is also interesting to consider the limit $k_{\rm T} \to 0$ of the matrix elements. A smooth behavior for $k_{\rm T} \to 0$ is observed. It is also interesting to note that the parton subprocess cross section starts to decrease at $k_{\rm T}^2 \gtrsim 4m^2$. The region $k_{\rm T}^2 > 4m^2$ is still contributing to the total cross section significantly, showing one of the main differences to the usual collinear approximation, where this region is completely ignored.

2. The unintegrated gluon distributions

Cross section calculations require an explicit representation of the $k_{\rm T}$ dependent (unintegrated) gluon density $\mathcal{A}(x, k_{\rm T}^2, \mu^2)$. We have used three different representations, one (*JB*) coming from a leading-order perturbative solution of the BFKL equations [13], the second set (*JS*) derived from a numerical solution of the CCFM equation [10, 11] and the third (*KMR*) from solution of a combination of the BFKL and DGLAP equations [14].

We show a comparison of the gluon density distributions at $\mu^2 = 100$ GeV^2 obtained from *JB*, *JS* and *KMR* as a function of x for different values of $k_{\rm T}^2$ and as a function of $k_{\rm T}^2$ for different values of x. All three unintegrated gluon distributions show a significantly different behavior as a function of x but even more as a function of $k_{\rm T}$. It will be interesting to see, how this different behavior is reflected in the prediction of cross sections for experimentally observable quantities like charm production at HERA.

3. 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 $k_{\rm T}$-factorization and using explicitly off-shell matrix elements for the hard scattering process convoluted with $k_{\rm T}$-unintegrated gluon densities is presently only offered by the CASCADE [10–12] program which uses the CCFM unintegrated gluon distribution.

In the Ref. [1] we systematically compared the predictions from the $k_{\rm T}$-factorization approach to published data on charm production at HERA. For this we use D^* photo-production data from ZEUS [16] and D^* production in deep inelastic scattering from both ZEUS [17] and H1 [18]. First we calculate observables using a pure parton level calculation based on the matrix element calculation of BZ including the Peterson fragmentation function [19] 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 CE-CCH. Also here the Peterson fragmentation function is used but now with z being defined as the light-cone momentum fraction in the center-of-mass system of the string connecting the charm quark with its light quark partner, as implemented in JETSET/PYTHIA [20]. We choose the *JS* unintegrated gluon for this comparison.

Next we investigate on parton level different unintegrated gluon densities. After the optimal choice of model parameters has been found for the *JB* gluon density, giving the best possible agreement with data, we show a comparison to the *JS* and *KMR* unintegrated gluon density. We then study the sensitivity of the model predictions to the details of the unintegrated gluon density, the charm mass and the scale.

We observed [1] that the p_T distribution of D^* mesons both in photoproduction 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 little sensitive to the details of the charm fragmentation.

We also consider the rapidity distribution of the produced D^*. In photoproduction and in DIS the differential cross section $d\sigma/d\eta$, where η is the pseudo-rapidity of the D^* meson, is sensitive to the choice of the unintegrated gluon distribution, but one has to keep in mind that especially the η distribution is also sensitive to the details of the $c \to D^*$ fragmentation, and therefore a clear distinction of the unintegrated gluon distributions based on this quantity alone might be questionable.

We observed, that the parton level prediction including the Peterson fragmentation function is not able to describe the measurement over the full range of η. The effect of a full hadron level simulation is clearly visible as CASCADE provides a much better description of the experimental data.

Then we investigate the x_γ 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.

At the end we showed, motivated by preliminary studies of ZEUS [21], predictions which are sensitive to the details of the heavy quark production mechanism.

The ZEUS collaboration has measured charm and associated jet production [16]. The experimentally observed $x_\gamma^{\rm OBS}$ spectrum shows a tail to small values of $x_\gamma^{\rm OBS}$, indicating that the hardest emission is indeed not always coming from the charm quarks. A significant part of the cross section comes from events, where the gluon is the jet with the largest transverse momentum [7]. A comparison of the measurement from the ZEUS collaboration [16] with the prediction from the full event simulation of CASCADE using the *JS* unintegrated gluon distribution and applying jet reconstruction and jet selection at the hadron level shows a reasonably good agreement. 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 gluon cascade.

Other interesting quantities are the angular distributions of resolved photon like events ($x_\gamma^{\rm OBS} < 0.75$) compared to the direct-photon like events ($x_\gamma^{\rm OBS} > 0.75$) [21] and also the ones of dijet events when the D^* proceeds along the photon direction, (*i.e.* $\eta_{D^*} < 0$) and one where it travels along the proton direction (*i.e.* $\eta_{D^*} > 0$). In the $k_{\rm T}$-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 Padhi at this Workshop [22].

4. Conclusion

We have shown, that the $k_{\rm T}$-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 $k_{\rm T}$-factorization, resolved photon like processes are effectively simulated including the proper angular distributions. The $k_{\rm T}$-factorization approach has become now a challenging tool to understand the underlying dynamical processes in high energy collisions.

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REFERENCES

[1] S.P. Baranov, H. Jung, L. Jönsson, S. Padhi, N.P. Zotov, *Eur. Phys. J.* **C24**, 425 (2002).

[2] L. Gribov, E. Levin, M. Ryskin, *Phys. Rep.* **100**, 1 (1983).

[3] J. Collins, R. Ellis, *Nucl. Phys.* **B360**, 3 (1991).

[4] S. Catani, M. Ciafaloni, F. Hautmann, *Nucl. Phys.* **B366**, 135 (1991).

[5] V. Saleev, N. Zotov, *Mod. Phys. Lett.* **A11**, 25 (1996).

[6] S. Baranov, N. Zotov, *Phys. Lett.* **B458**, 389 (1999).

[7] S. Baranov, N. Zotov, *Phys. Lett.* **B491**, 111 (2000).

[8] R. Prange, *Phys. Rev.* **110**, 240 (1958).

[9] G.P. Lepage, *J. Comp. Phys.* **27**,192 (1978).

[10] H. Jung, `hep-ph/9908497`.

[11] H. Jung, G. Salam, *Eur. Phys. J.* **C19**, 351 (2001).

[12] H. Jung, *Comput. Phys. Commun.* **143**, 100 (2002), `http://www.quark.lu.se/ hannes/cascade/`.

[13] J. Blümlein, On the k_t dependent gluon density of the proton, in Proc. of the Workshop on Deep Inelastic Scattering and QCD, eds. J. Laporte, Y. Sirois (1995), DESY 95-121.

[14] M.A. Kimber, A.D. Martin, M.G. Ryskin, *Phys. Rev.* **D63**, 114027 (2001).

[15] M. Kimber, Extrapolation of unintegrated gluon density, private communication.

[16] ZEUS Collaboration, J. Breitweg *et al.*, *Eur. Phys. J.* **C6**,67 (1999).

[17] ZEUS Collaboration, J. Breitweg *et al.*, *Eur. Phys. J.* **C12**, 35 (1999), DESY 99-101.

[18] H1 Collaboration, C. Adloff *et al.*, *Phys. Lett.* **B528**, 199 (2002).

[19] C. Peterson, D. Schlatter, I. Schmitt, P.M. Zerwas, *Phys. Rev.* **D27**, 105 (1983).

[20] T. Sjostrand *et al.*, *Comput. Phys. Commun.* **135**, 238 (2001).

[21] ZEUS Collaboration, Dijet angular distributions in D^* photoproduction at HERA, contributed paper 499 to HEP, Budapest, Hungary, July 12–18, 2001.

[22] S. Padhi, *Acta Phys. Pol.* **B33**, 3189 (2002).