HEAVY QUARK PRODUCTION AT HERA IN $K_T$ FACTORIZATION SUPPLEMENTED WITH CCFM EVOLUTION

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The application of $k_t$-factorization, supplemented with the CCFM small-$x$ evolution equation, to heavy quark production is discussed. Differential cross sections of $b\bar{b}$ production and also inelastic $J/\psi$ production as measured at HERA are compared to the hadron level CCFM Monte Carlo generator CASCADE, using the unintegrated gluon density obtained within the CCFM evolution approach from a fit to HERA $F_2$ data.

1 Introduction

The calculation of inclusive quantities, like the structure function $F_2(x,Q^2)$ at HERA, performed in NLO QCD is in perfect agreement with the measurements. But in exclusive quantities like jet or heavy quark production large so-called $K$-factors (normalization factors) are needed to bring the NLO calculations close to the data.

At large energies (small $x$), the evolution of parton densities proceeds over a large region in rapidity $\Delta y \sim \log(1/x)$ and effects of finite transverse momenta of the partons may become increasingly important. Cross sections can then be $k_t$-factorized into an off-shell ($k_t$ dependent) partonic cross section $\hat{\sigma}(\frac{x}{z},k_t)$ and a $k_t$-unintegrated parton density function $F(z,k_t)$:

$$\sigma = \int \frac{dz}{z} q^2 k_t \sigma(\frac{x}{z},k_t) F(z,k_t)$$ (1)

The unintegrated gluon density $F(z,k_t)$ is described by the BFKL evolution equation in the region of asymptotically large energies (small $x$). An appropriate description valid for both small and large $x$ is given by the CCFM evolution equation, resulting in an unintegrated gluon density $A(x,k_t,\bar{q})$, which is a function also of the additional evolution scale $\bar{q}$.

Catani argues that by explicitly carrying out the $k_t$ integration in eq.(1), one can obtain a form fully consistent with collinear factorization: the coefficient functions and also the DGLAP splitting functions are no longer evaluated in fixed order perturbation theory but supplemented with the all-order resum-
mation of the $\alpha_s \log 1/x$ contribution at small $x$. This all-loop resummation shows up in a so-called non-Sudakov form factor $\Delta_{ns}$ for CCFM.

In this paper the $k_t$ factorization approach is discussed with respect to resolved photon structure and next-to-leading corrections in the collinear approach. Then calculations for $b\bar{b}$ and inelastic $J/\psi$ production at HERA are presented, using the unintegrated gluon density obtained previously from a CCFM fit to the HERA structure function $F_2(x, Q^2)$.

2 $k_t$-factorization versus higher order processes in collinear factorization

The diagrams for LO, NLO and resolved photon processes in the collinear approach are shown schematically in Fig. 1. In collinear factorization, the incoming parton is on-mass-shell and has vanishing transverse momentum $k_t$, whereas in $k_t$-factorization the partons entering the hard scattering matrix element are free to be off-mass-shell. The advantage of the $k_t$-factorization approach becomes visible, when additional hard gluon radiation to a $2 \rightarrow 2$ process like $\gamma g \rightarrow Q\bar{Q}$ is considered. If the transverse momentum $p_g$ of the additional gluon is of the order of that of the quarks, then in the collinear approach the full $O(\alpha_s^2)$ matrix element for $2 \rightarrow 3$ has to be calculated. In $k_t$-factorization such processes are naturally included, even if only the LO $\alpha_s$ off-shell matrix element is used, since the $k_t$ of the incoming gluon is not restricted from above, and therefore can acquire a virtuality similar to the ones in a complete fixed order calculation. In Fig. 1 the basic ideas are shown schematically. Not only does $k_t$-factorization include (at least parts of) NLO diagrams, it also includes diagrams of the resolved photon type with the natural transition from real to virtual photons.
The $\mathcal{O}(\alpha_s)$ matrix element in $k_t$-factorization includes the $\mathcal{O}(\alpha_s)$ matrix element of collinear factorization but in addition also higher order contributions because the incoming gluon is off-shell and the unintegrated gluon density resums parts of the virtual corrections (Fig. 2).

The unintegrated gluon density $x_A(x, k_T^2, \bar{q})$ was obtained in the framework of $k_t$-factorization using the CCFM evolution equation to fit the structure function $F_2(x, Q^2)$. This gluon density $x_A(x, k_T^2, \bar{q})$ is used in the hadron level Monte Carlo generator CASCADE for any comparison with measurements.

3 Heavy quark production at HERA

The prediction of CASCADE for the total $b\bar{b}$ cross section was compared to the extrapolated measurements of the H1 and ZEUS experiments at HERA. Since CASCADE generates full hadron-level events, a direct comparison with measurements can be done, before extrapolating the measurement over the full phase space to the total $b\bar{b}$ cross section. It has been shown that the visible $b\bar{b}$ cross section as measured by the ZEUS experiment is in perfect agreement with the predictions from CASCADE. However, large uncertainties come from the extrapolation of the measured cross section to the total $b\bar{b}$ cross section. If the extrapolation is performed with CASCADE (or any other program of the Lund family), approximate agreement with the NLO prediction is also achieved in the case of the ZEUS measurement.

The prediction of CASCADE has also been compared to the measurement of H1, where it was also shown that the experimental results from H1 and ZEUS agree well with each other.
ZEUS are different by a factor $\sim 2$. It has been checked, that the difference between the experiments is not due to different kinematics.

Figure 4. Differential bottom cross section as a function of the muon pseudo-rapidity (transverse momentum) for event with two jets and a muon, compared to Cascade and Pythia (with and w/o heavy quark excitation).

In Fig. 4 the differential cross section of $\mu$'s coming from $b$-quark decays as measured by ZEUS is compared with the prediction of Cascade. Again good agreement is observed, except in the region of large $\eta$. However this region is dominated by large $x_g > 0.03$ (see Fig. 3), where the application of $k_t$-factorization is questionable and also where the unintegrated gluon density is not at all constrained by the fit to $F_2$.

Figure 5. The cross section of $\gamma p \rightarrow J/\psi + X$ as a function of the transverse momentum (a) and of the fractional momentum $z$ (b) of the $J/\psi$ as measured by H1 compared to the predictions of Cascade and EPJpsi.

The cross section for $\gamma p \rightarrow J/\psi + X$ as a function of the transverse momen-
tum of the $J/\psi$ shows a significant deviation from the leading order color singlet model prediction (as implemented in Epjpsi) in collinear factorization. In Fig. 5, the preliminary H1 measurement is compared to the prediction of EPJPSI. In collinear factorization, the harder transverse momentum spectrum is interpreted as a signal for significant next-to-leading order corrections. Also shown in Fig. 5 is the prediction of CASCADE using the same CCFM unintegrated gluon density as before together with the $k_t$-factorized matrix element for $\gamma g^* \rightarrow J/\psi g$. The inelastic $J/\psi$ photoproduction cross section ($z < 0.9$) as a function of $p_T$ is nicely described by CASCADE. Especially the large transverse momentum part is explained as additional hard initial state QCD radiation. The same is also observed in full NLO calculations, and it shows again the advantage of the $k_t$-factorization in simulating a large part of the NLO correction of the collinear approach, due to the non zero virtuality of the incoming gluon. The distribution in the fractional momentum $z$ of the $J/\psi$ is also reasonably well described (Fig. 5b).

4 Conclusion

The application of the $k_t$-factorization approach to heavy quark production at HERA has been discussed. It is shown, that the visible $b\bar{b}$ production cross section at ZEUS is nicely reproduced by CASCADE, using the CCFM evolved unintegrated gluon density obtained from a fit to $F_2(x,Q^2)$. It was pointed out, that the extrapolation from the measured to the total $b\bar{b}$ cross section contains large model dependencies.

The differential cross sections for inelastic $J/\psi$ photoproduction can be reasonably well described with CASCADE, both in terms of shape and normalization. The large transverse momentum tail is a direct signal for additional hard initial state QCD radiation.

It is the advantage of the $k_t$-factorization approach that important parts of NLO and even NNLO contributions are consistently included due to the off-shell gluons, which enter into the hard scattering process.

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References

1. CDF Collaboration; F. Abe et al., Phys. Rev. D 55 (1997) 2546.
2. D0 Collaboration; B. Abbott et al., Phys. Lett. B 487 (2000) 264.
3. S. Catani, M. Ciafaloni, F. Hautmann, Nucl. Phys. B 366 (1991) 135.
4. M. Ciafaloni, Nucl. Phys. B 296 (1988) 49.
5. S. Catani, F. Fiorani, G. Marchesini, Phys. Lett. B 234 (1990) 339.
6. S. Catani, F. Fiorani, G. Marchesini, Nucl. Phys. B 336 (1990) 18.
7. G. Marchesini, Nucl. Phys. B 445 (1995) 49.
8. S. Catani, $k_t$-factorisation and perturbative invariants at small $x$, in Proceedings of the International Workshop on Deep Inelastic Scattering, DIS 96 (Rome, Italy, 15-19 April, 1996), hep-ph/9608310.
9. S. Catani, Aspects of QCD, from the Tevatron to LHC, in Proceedings of the International Workshop Physics at TeV Colliders (Les Houches, France, 8-18 June, 1999), hep-ph/0005233.
10. H. Jung, G. Salam, Eur. Phys. J. C 19 (2001) 351, hep-ph/0012143.
11. S. Baranov, N. Zotov, Phys. Lett. B 491 (2000) 111.
12. ZEUS Collaboration; M. Derrick et al., Beauty photoproduction in the muon semi-leptonic decay mode at HERA, in Contributed paper 496 to IECHEP 2001, Budapest, Hungary (2001).
13. H. Jung, Unintegrated parton densities applied to heavy quark production in the CCFM approach, in Proceedings of the Rinberg workshop on "New trends in HERA physics", Ringberg Castle, Tegernsee, Germany, (2001), hep-ph/0109146.
14. H. Jung, submitted to Phys. Rev. D (2001), DESY-01-136, hep-ph/0110034.
15. H. Jung, The CCFM Monte Carlo generator CASCADE for lepton - proton and proton - proton collisions, Lund University, accepted by Comp. Phys. Comm., 2001, hep-ph/0109102, DESY 01-114, http://www.quark.lu.se/~hannes/cascade/.
16. H1 Collaboration; C. Adloff et al., Phys. Lett. B 467 (1999) 156, and erratum ibid.
17. ZEUS Collaboration; J. Breitweg et al., Eur. Phys. J. C 18 (2001) 625.
18. H1 Collaboration; C. Adloff et al., Inelastic photoproduction of $J/\psi$ and $\psi(2s)$ at H1, in Contributed paper 157aj to IECHEP 1999, Tampere, Finnland (1999).
19. H. Jung, EPJPSI: A Monte Carlo generator for $J/\psi$ mesons in high energy $\gamma - p$, $e - p$ and $p - \bar{p}$ collisions, version 3.3, Lund University, 1995, http://www-h1.desy.de/~jung/epjpsi.html.
20. V. Saleev, N. Zotov, Mod. Phys. Lett. A 9 (1994) 151.