Inclusive production of heavy-flavored hadrons at NLO in the GM-VFNS

Bernd A. Kniehl

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

We summarize recent progress in the theoretical description of heavy-flavored-hadron inclusive production at next-to-leading order in the general-mass variable-flavor-number scheme. Specifically, we discuss the influence of finite-mass effects on the determination $D$-meson fragmentation functions from a global fit to $e^+e^-$ annihilation data and on the transverse-momentum distribution of $B$-meson hadroproduction. We also demonstrate that the fixed-flavor-number scheme, implemented with up-to-date parton density functions and strong-coupling constant, provides a surprisingly good description of $B$-meson data from run II at the Fermilab Tevatron.

1 Introduction

The general-mass variable-flavor-number scheme (GM-VFNS) provides a rigorous theoretical framework for the theoretical description of the inclusive production of single heavy-flavored hadrons, combining the fixed-flavor-number scheme (FFNS) and zero-mass variable-flavor-number scheme (ZM-FVNS), which are valid in complementary kinematic regions, in a unified approach that enjoys the virtues of both schemes and, at the same time, is bare of their flaws. Specifically, it resums large logarithms by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution of non-perturbative fragmentation functions (FFs), guarantees the universality of the latter as in the ZM-VFNS, and simultaneously retains the mass-dependent terms of the FFNS without additional theoretical assumptions. It was elaborated at next-to-leading order (NLO) for photo- [2] and hadroproduction [3,4]. In this presentation, we report recent progress in the implementation of the GM-VFNS at NLO. In Sec. 2, we present mass-dependent FFs for $D$-mesons extracted from global fits to $e^+e^-$ annihilation data [5]. In Sec. 3, we compare with transverse-momentum ($p_T$) distributions of $B$ mesons produced in run II at the Tevatron [6]. Our conclusions are summarized in Sec. 4.

2 $D$-meson fragmentation functions

In Ref. [5], we determined non-perturbative FFs for $D^0$, $D^+$, and $D^{*+}$ mesons by fitting experimental data from the Belle, CLEO, ALEPH, and OPAL Collaborations [7], taking dominant electroweak corrections due to photonic initial-state radiation into account. The fits for $D^0$, $D^+$, and $D^{*+}$ mesons using the Bowler ansatz [9] yielded $\chi^2$/d.o.f. = 4.03, 1.99, and 6.90, respectively. We assessed the significance of finite-mass effects through comparisons with a similar analysis in the ZM-VFNS. Under Belle and CLEO experimental conditions, charmed-hadron mass effects on the phase space turned out to be appreciable, while charm-quark mass effects on the partonic matrix elements are less important. In Figs. (a) and (b), the scaled-momentum distributions from Belle and CLEO and the normalized scaled-energy distributions from ALEPH and OPAL, respectively, for $D^+$ mesons are compared to the global fits. We found that the Belle and CLEO data tend to drive the
average $x$ value of the $c \to D$ FFs to larger values, which leads to a worse description of the ALEPH and OPAL data. Since the $b \to D$ FFs are only indirectly constrained by the Belle and CLEO data, their form is only feebly affected by the inclusion of these data in the fits. Usage of these new FFs leads to an improved description of the CDF data \cite{8} from run II at the Tevatron, as may be seen by comparing Fig. 1(c) with Fig. 2(b) of Ref. \cite{4}.

3 $B$-meson hadroproduction

In Ref. \cite{6}, we performed a comparative analysis of $B$-meson hadroproduction in the ZM-VFNS and GM-VFNS. For this, we also updated the determination of $B$-meson FFs in the ZM-VFNS \cite{10} by fitting to recent $e^+e^-$ data from ALEPH, OPAL, and SLD \cite{13} and also adjusting the values of $m_b$ and the energy scale $\mu_0$ where the DGLAP evolution starts to conform with modern PDF sets. The fit using the Kartvelishvili-Likhoded ansatz \cite{14} yielded $\chi^2/d.o.f. = 1.495$ (see Fig. 2). We found that finite-$m_b$ effects moderately enhance the $p_T$ distribution; the enhancement amounts to about 20% at $p_T = 2m_b$ and rapidly decreases with increasing value of $p_T$, falling below 10% at $p_T = 4m_b$ (see Fig. 3a). Such effects are thus comparable in size to the theoretical uncertainty due to the freedom of choice in the setting of the renormalization and factorization scales. This finding contradicts earlier assertions \cite{12} that mass corrections have a large size up to $p_T \approx 20$ GeV and that lack of mass effects \cite{11} will therefore erroneously overestimate the production rate at small $p_T$ in all respects.

In this connection, we also wish to point out that the statement made in Ref. \cite{15} that large logarithmic corrections in the function $D(x, m^2)$ are simply discarded in the approach of Ref. \cite{10} is misleading. In fact, in the ZM-VFNS with non-perturbative FFs adopted in Ref. \cite{10}, the Sudakov logarithms are fully included at NLO, namely both in the coefficient functions and evolution kernels, and there is no room for large logarithmic corrections in the ansatz for the heavy-quark FF at the initial scale $\mu_0$, which represents non-perturbative input to be fitted to experimental data. Looking at Fig. 1 in Ref. \cite{10}, we observe that
the theoretical results for \((1/\sigma_{\text{had}})(d\sigma/dx)(e^+e^- \to B + X)\) exhibit excellent perturbative stability and nicely agree with the OPAL data \([16]\) in the large-\(x\) regime, indicating that Sudakov resummation is dispensable in this scheme, in contrast to the fixed-order-next-to-leading-logarithm (FONLL) scheme \([12,17]\), where the FFs are arranged to have perturbative components.

We must also caution the reader of the potential of comparisons of experimental data with theoretical predictions in recent CDF II publications \([18,19]\) to be misinterpreted. In Fig. 11 of Ref. \([18]\) (see Fig. 3b), the variation of the ad-hoc weight function, \(G(m, p_T) = p_T^2/(p_T^2 + c^2m^2)\) with \(c = 5\) \([12,17]\), which has a crucial impact on the prediction in the small-\(p_T\) range by substantially suppressing its ZM-VFNS component, is not included in the theoretical error. In Fig. 11 of Ref. \([19]\) (see Fig. 3c), the FFNS result, labeled NLO, is evaluated with the obsolete MRSD0 proton PDFs \([20]\), revoked by their authors long ago, and a value of \(\alpha_s(5)/(m_z)\) falling short of the present world average \([21]\) by 3.3 standard deviations. Unfortunately, this historical result is still serving as a benchmark \([22]\). Despite unresummed large logarithms and poorly implemented fragmentation, the FFNS prediction, evaluated with up-to-date input, happens to almost coincide with the GM-VFNS one in the range 15 GeV < \(p_T\) < 25 GeV. It also nicely reproduces the peak exhibited about \(p_T \approx 2.5\) GeV by the CDF II data of Ref. \([18]\).

In Fig. 11 preliminary CDF II data \([23]\), which explore the range 25 GeV < \(p_T\) < 40 GeV for the first time, are compared with NLO predictions in the GM-VFNS, ZM-VFNS, and FFNS \([6]\). In the large-\(p_T\) limit, the GM-VFNS result steadily merges with the ZM-VFNS one as per construction, while the FFNS breaks down due to unresummed large logarithms. The CDF II data point in the bin 29 GeV < \(p_T\) < 40 GeV favors the GM-VFNS and ZM-VFNS results, while it undershoots the FFNS result.

\(\text{DIS 2008}\)
4 Conclusions

The GM-VFNS provides a rigorous theoretical framework for global analyses of heavy-flavored-hadron inclusive production, retaining the full mass dependence of the FFNS, preserving the scaling violations and universality of the FFs in the ZM-VFNS, avoiding spurious $x \to 1$ problems, and doing without ad-hoc weight functions. It has been elaborated at NLO for single production in $\gamma\gamma$, $\gamma p$ [2], $p\bar{p}$ [3][4][6], and $e^+e^-$ collisions [5]. More work is in progress.

Acknowledgments

The author thanks T. Kneesch, G. Kramer, I. Schienbein, and H. Spiesberger for the collaboration on the work presented here. This work was supported in part by DFG Grant No. KN 365/7–1 and by BMBF Grant No. 05 HT6GU.

References

[1] Slides: http://indico.cern.ch/contributionDisplay.py?contribId=237&sessionId=14&confId=24657
[2] G. Kramer and H. Spiesberger, Eur. Phys. J. C22 289 (2001); C28 405 (2003); C38 309 (2004).
[3] B.A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger, Phys. Rev. D71 014018 (2005); Eur. Phys. J. C41 199 (2005).
[4] B.A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger, Phys. Rev. Lett. 96 012001 (2006).
[5] T. Kneesch, B.A. Kniehl, G. Kramer and I. Schienbein, Nucl. Phys. B799 34 (2008).
[6] B.A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger, Phys. Rev. D77 014011 (2008).
[7] G. Alexander et al. (OPAL Collaboration), Z. Phys. C72 1 (1996); K. Ackerstaff et al. (OPAL Collaboration), Eur. Phys. J. C1 439 (1998); R. Barate et al. (ALEPH Collaboration), Eur. Phys. J. C16 597 (2000); M. Artuso et al. (CLEO Collaboration), Phys. Rev. D70 112001 (2004); R. Seuster et al. (Belle Collaboration), Phys. Rev. D73 032002 (2006).
[8] D. Acosta et al. (CDF Collaboration), Phys. Rev. Lett. 91 241804 (2003).
[9] M.G. Bowler, Z. Phys. C11 (1981) 169.
[10] J. Binnewies, B.A. Kniehl and G. Kramer, Phys. Rev. D58 034016 (1998).
[11] F. Abe et al. (CDF Collaboration), Phys. Rev. Lett. 75 1451 (1995); D. Acosta et al. (CDF Collaboration), Phys. Rev. D65 052005 (2002).
[12] M. Cacciari, S. Friixione, M.L. Mangano, P. Nason and G. Ridolfi, JHEP 0407 033 (2004).
[13] K. Abe et al. (SLD Collaboration), Phys. Rev. Lett. 84 4300 (2000); Phys. Rev. D65 092006 (2002); D66 079905(E) (2002); A. Heister et al. (ALEPH Collaboration), Phys. Lett. B512 30 (2001); G. Abbiendi et al. (OPAL Collaboration), Eur. Phys. J. C29 463 (2003).
[14] V.G. Kartvelishvili and A.K. Likhoded, Yad. Fiz. 42 1306 (1985) [Sov. J. Nucl. Phys. 42 823 (1985)].
[15] M. Cacciari and E. Gardi, Nucl. Phys. B664 299 (2003).
[16] G. Alexander et al. (OPAL Collaboration), Phys. Lett. B364 93 (1995).
[17] M. Cacciari, M. Greco and P. Nason, JHEP 9805 007 (1998); M. Cacciari and P. Nason, Phys. Rev. Lett. 89 122003 (2002).
[18] D. Acosta et al. (CDF Collaboration), Phys. Rev. D71 032001 (2005).
[19] A. Abulencia et al. (CDF Collaboration), Phys. Rev. D75 012010 (2007).
[20] A.D. Martin, W.J. Stirling and R.G. Roberts, Phys. Rev. D47 867 (1993).
[21] W.M. Yao et al. (Particle Data Group), J. Phys. G33 1 (2006).
[22] F. Happacher, P. Giromini and F. Ptohos, Phys. Rev. D73 014026 (2006).
[23] J.A. Kraus, Ph.D. thesis, University of Illinois, Urbana-Champaign, 2006, Report No. FERMILAB-THESIS-2006-47; A. Annovi (CDF Collaboration), J. Phys.: Conf. Ser. 110 022003 (2008).

DIS 2008