HIGH-ENERGY SIGNALS FROM HEAVY-FLAVOR PHYSICS*

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Working in the hybrid high-energy/collinear factorization, where the next-to-leading resummation of energy logarithms is combined with collinear parton densities and fragmentation functions, we study observables sensitive to high-energy dynamics in the context of heavy-flavor physics.

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1. Introduction

High-energy emissions of heavy-quark flavored-objects in hadronic reactions are widely considered as gold-plated probes for the dynamics of fundamental interactions. Heavy quarks can couple with beyond-the-Standard-Model (BSM) particles. This supports our search for signals of new physics. Yet, they represent a key ingredient for precision analyses of strong interactions [1–4], the charm and bottom masses being confined in the perturbative Quantum Chromodynamics (QCD) domain. In this work, we consider the production of a semi-hard heavy-flavored jet emitted in association with a light-flavored one at the LHC [5], as a novel channel for the manifestation of high-energy dynamics. Then, we provide predictions for the semi-inclusive detection of an ultraforward $D^{*\pm}$ meson at the planned Forward Physics Facility (FPF) [6, 7] plus a Higgs boson at ATLAS [8]. Our analysis extends the program of high-energy QCD studies (for recent applications, see [8–61]) via the hybrid high-energy/collinear factorization [5, 62–66] (see also [67–72]) built by means of the leading and next-to-leading BFKL resummation [73, 74] of energy logarithms (LLA and NLA) and enhanced by the inclusion of collinear parton distribution functions (PDFs) and fragmentation functions (FFs).

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2. Phenomenology

In the left (right) panels of Fig. 1, we present the NLA rapidity (azimuthal-angle) distributions for the inclusive emission of a heavy–light two-jet system at the LHC (upper panels) and the inclusive $D^{*\pm}$ plus Higgs detection via the FPF + ATLAS narrow-timing coincidence (lower panels). NLO proton PDFs are taken from the NNPDF4.0 set [75], while NLO $D^{*\pm}$ FFs are described by the KKKS08 determination [76]. Rapidity distributions exhibit the typical pattern coming from high-energy dynamics. Here, the increase with the energy of partonic cross sections, predicted by BFKL, combines with the dampening effect originating from their convolution with the collinear PDFs, thus resulting in a downtrend of distributions as the rapidity distance ΔY between the two final-state particles grows. A clear manifestation of a reached stability under NLA corrections is given by the size of uncertainty bands, which is sensibly lower when passing from LLA to NLA. For some sub-ranges of ΔY, NLA bands are nested. Moreover,

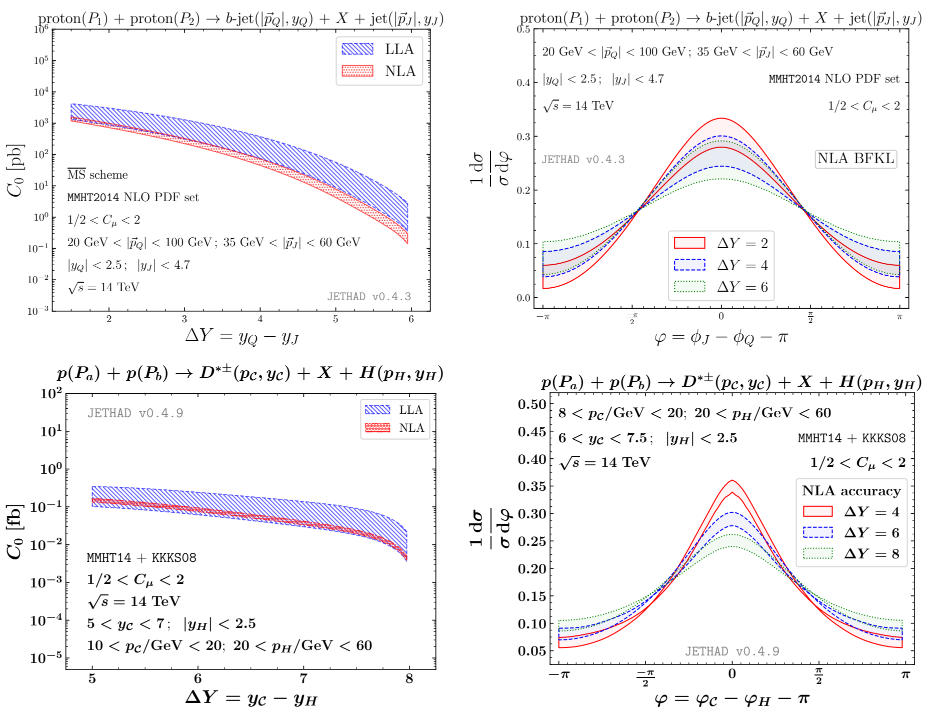

Fig. 1. Rapidity (left) and azimuthal-angle (right) distributions for the inclusive production of a heavy–light two-jet system at 14 TeV LHC (upper) and of a $D^{*\pm}$ meson plus a Higgs boson at 14 TeV FPF + ATLAS (lower). Shaded bands refer to the uncertainty coming from scale variation. Text boxes inside panels display final-state kinematic cuts. Figures from [5, 8].

NLA contributions become more and more negative as ΔY grows. This is why pure LLA results are always larger. Azimuthal distributions are shown as functions of φ, namely the azimuthal-angle distance between the tow emitted objects, minus π. The peculiar behavior of these observables braces the message that we have entered a kinematic domain where the high-energy resummation works well. All the distributions feature a clear peak at $\varphi = 0$, *i.e.* where the two particles are emitted back-to-back. Then, as ΔY grows, the peak height shrinks, whereas the distribution width enlarges. This happens because larger rapidity intervals lead to a stronger decorrelation between the two objects, so that the number of back-to-back events falls off. As a final remark, we note that all the presented observables present solid stability under renormalization- and factorization-scale variations at NLA, by which our uncertainty bands are built. This supports the key message that semi-inclusive emissions of heavy-flavored jets as well as bound states lead to a *natural stabilization* (see also [33, 34, 65, 77]) of the high-energy resummation. This remarkable property represents a core element to lay the groundwork for precision studies of high-energy QCD, and to develop a *multilateral* formalism that combines different resummation mechanisms.

3. Toward new directions

The reactions investigated in this work represent a step forward in our ongoing program on heavy-flavored emissions at high energies, started from the analytic calculation of heavy-quark pair impact factors [29–31] and pointing toward the analysis of heavy quarkonia [36, 37, 65]. In this context, both two-particle and single-particle detection are relevant. In particular, the second ones will allow us to deepen our understanding of the high-energy QCD at new-generation colliders [6, 7, 78–92] via small-x transverse-momentum-dependent gluon densities [93–118].

REFERENCES

[1] S. Catani *et al.*, *J. High Energy Phys.* **2021**, 029 (2021).
[2] NNPDF Collaboration (R.D. Ball *et al.*), *Nature* **608**, 483 (2022).
[3] F. Maltoni *et al.*, *J. High Energy Phys.* **2022**, 027 (2022).
[4] R. Maciuła, A. Szczurek, *Phys. Rev. D* **107**, 034002 (2023), arXiv:2210.08890 [hep-ph].
[5] A.D. Bolognino *et al.*, *Phys. Rev. D* **103**, 094004 (2021).
[6] L.A. Anchordoqui *et al.*, *Phys. Rep.* **968**, 1 (2022).
[7] J.L. Feng *et al.*, *J. Phys. G: Nucl. Part. Phys.* **50**, 030501 (2023), arXiv:2203.05090 [hep-ex].
[8] F.G. Celiberto *et al.*, *Phys. Rev. D* **105**, 114056 (2022).
[9] B. Ducloué *et al.*, *J. High Energy Phys.* **2013**, 096 (2013).

[10] B. Ducloué *et al.*, *Phys. Rev. Lett.* **112**, 082003 (2014).
[11] F. Caporale *et al.*, *Eur. Phys. J. C* **74**, 3084 (2014).
[12] F.G. Celiberto *et al.*, *Eur. Phys. J. C* **75**, 292 (2015).
[13] F.G. Celiberto *et al.*, *Acta Phys. Pol. B Proc. Suppl.* **8**, 935 (2015).
[14] F.G. Celiberto *et al.*, *Eur. Phys. J. C* **76**, 224 (2016).
[15] F.G. Celiberto *et al.*, *PoS* **DIS2016**, 176 (2016).
[16] F. Caporale *et al.*, *Nucl. Phys. B* **935**, 412 (2018).
[17] F.G. Celiberto, A. Papa, *Phys. Rev. D* **106**, 114004 (2022), arXiv:2207.05015 [hep-ph].
[18] F.G. Celiberto *et al.*, *Phys. Rev. D* **94**, 034013 (2016).
[19] F.G. Celiberto *et al.*, *AIP Conf. Proc.* **1819**, 060005 (2017).
[20] F.G. Celiberto *et al.*, *Eur. Phys. J. C* **77**, 382 (2017).
[21] F.G. Celiberto *et al.*, arXiv:1709.01128 [hep-ph].
[22] F.G. Celiberto *et al.*, arXiv:1709.04758 [hep-ph].
[23] F.G. Celiberto, Ph.D. Thesis, 2017, arXiv:1707.04315 [hep-ph],
[24] A.D. Bolognino *et al.*, *Eur. Phys. J. C* **78**, 772 (2018).
[25] A.D. Bolognino *et al.*, *PoS* **DIS2019**, 049 (2019).
[26] A.D. Bolognino *et al.*, *Acta Phys. Pol. B Proc. Suppl.* **12**, 773 (2019).
[27] F.G. Celiberto *et al.*, *Phys. Rev. D* **102**, 094019 (2020).
[28] K. Golec-Biernat *et al.*, *J. High Energy Phys.* **2018**, 091 (2018).
[29] F.G. Celiberto *et al.*, *Phys. Lett. B* **777**, 141 (2018).
[30] A.D. Bolognino *et al.*, *PoS* **DIS2019**, 067 (2019).
[31] A.D. Bolognino *et al.*, *Eur. Phys. J. C* **79**, 939 (2019).
[32] A.D. Bolognino *et al.*, *PoS* **DIS2019**, 067 (2019).
[33] F.G. Celiberto *et al.*, *Eur. Phys. J. C* **81**, 780 (2021).
[34] F.G. Celiberto *et al.*, *Phys. Rev. D* **104**, 114007 (2021).
[35] A.D. Bolognino *et al.*, *PoS* **EPS-HEP2021**, 389 (2022).
[36] R. Boussarie *et al.*, *Phys. Rev. D* **97**, 014008 (2018).
[37] F.G. Celiberto, *Phys. Lett. B* **835**, 137554 (2022).
[38] F.G. Celiberto, M. Fucilla, arXiv:2208.07206 [hep-ph].
[39] A.D. Bolognino *et al.*, *SciPost Phys. Proc.* **8**, 068 (2022).
[40] F. Caporale *et al.*, *Phys. Rev. Lett.* **116**, 012001 (2016).
[41] F. Caporale *et al.*, *Eur. Phys. J. C* **76**, 165 (2016).
[42] F. Caporale *et al.*, *Nucl. Phys. B* **910**, 374 (2016).
[43] F. Caporale *et al.*, *PoS* **DIS2016**, 177 (2016).
[44] F. Caporale *et al.*, *Eur. Phys. J. C* **77**, 5 (2017).
[45] F.G. Celiberto, *Frascati Phys. Ser.* **63**, 43 (2016), arXiv:1606.07327 [hep-ph].
[46] F. Caporale *et al.*, *AIP Conf. Proc.* **1819**, 060009 (2017).
[47] F. Caporale *et al.*, *J. Cent. Eur. Green Innov.* **5**, 47 (2017), arXiv:1610.04765 [hep-ph].

[48] G. Chachamis *et al.*, *PoS* **DIS2016**, 178 (2016).
[49] G. Chachamis *et al.*, arXiv:1610.01342 [hep-ph].
[50] F. Caporale *et al.*, *EPJ Web Conf.* **164**, 07027 (2017).
[51] F. Caporale *et al.*, *Phys. Rev. D* **95**, 074007 (2017).
[52] G. Chachamis *et al.*, *PoS* **DIS2017**, 067 (2018).
[53] F. Caporale *et al.*, arXiv:1801.00014 [hep-ph].
[54] F.G. Celiberto *et al.*, *Eur. Phys. J. C* **81**, 293 (2021).
[55] F.G. Celiberto *et al.*, *SciPost Phys. Proc.* **8**, 039 (2022).
[56] F.G. Celiberto *et al.*, *PoS* **EPS-HEP2021**, 589 (2022).
[57] F.G. Celiberto *et al.*, *PoS* **PANIC2021**, 352 (2022).
[58] F.G. Celiberto *et al.*, *SciPost Phys. Proc.* **10**, 002 (2022).
[59] M. Hentschinski *et al.*, *Eur. Phys. J. C* **81**, 112 (2021).
[60] F.G. Celiberto *et al.*, *J. High Energy Phys.* **2022**, 092 (2022).
[61] F.G. Celiberto, M. Fucilla, A. Papa, *EPJ Web Conf.* **270**, 00001 (2022), arXiv:2209.01372 [hep-ph].
[62] D. Colferai *et al.*, *J. High Energy Phys.* **2010**, 026 (2010).
[63] F.G. Celiberto, *Eur. Phys. J. C* **81**, 691 (2021).
[64] F.G. Celiberto *Phys. Rev. D* **105**, 114008 (2022).
[65] F.G. Celiberto *et al.*, *Eur. Phys. J. C* **82**, 929 (2022).
[66] F.G. Celiberto, *Eur. Phys. J. C* **83**, 332 (2023), arXiv:2208.14577 [hep-ph].
[67] M. Deak *et al.*, *J. High Energy Phys.* **2009**, 121 (2009).
[68] E. Blanco, A. van Hameren, P. Kotko, K. Kutak, *J. High Energy Phys.* **2020**, 158 (2020).
[69] A. van Hameren *et al.*, *J. High Energy Phys.* **2022**, 103 (2022).
[70] L. Motyka *et al.*, *J. High Energy Phys.* **2015**, 087 (2015).
[71] D. Brzeminski *et al.*, *J. High Energy Phys.* **2017**, 005 (2017).
[72] F.G. Celiberto *et al.*, *Phys. Lett.* **B786**, 201 (2018).
[73] V.S. Fadin *et al.*, *Phys. Lett. B* **60**, 50 (1975).
[74] I. Balitsky, L. Lipatov, *Sov. J. Nucl. Phys.* **28**, 822 (1978).
[75] R.D. Ball *et al.*, *Eur. Phys. J. C* **82**, 428 (2022).
[76] T. Kneesch *et al.*, *Nucl. Phys. B* **799**, 34 (2008).
[77] F.G. Celiberto, arXiv:2211.11780 [hep-ph].
[78] R.A. Khalek *et al.*, *Nucl. Phys. A* **1026**, 122447 (2022).
[79] R.A. Khalek *et al.*, arXiv:2203.13199 [hep-ph].
[80] E. Chapon *et al.*, *Prog. Part. Nucl. Phys.* **122**, 103906 (2022).
[81] M. Begel *et al.*, arXiv:2209.14872 [hep-ph].
[82] S. Dawson *et al.*, arXiv:2209.07510 [hep-ph].
[83] T. Bose *et al.*, arXiv:2209.13128 [hep-ph].
[84] M. Hentschinski *et al.*, arXiv:2203.08129 [hep-ph].
[85] D. Acosta *et al.*, arXiv:2203.06258 [hep-ex].

[86] ILC International Community Collaboration (I. Adachi *et al.*), arXiv:2203.07622 [physics.acc-ph].

[87] A. Arbuzov *et al.*, *Prog. Part. Nucl. Phys.* **119**, 103858 (2021).

[88] S. Amoroso *et al.*, *Acta Phys. Pol. B* **53**, 12-A1 (2022), arXiv:2203.13923 [hep-ph].

[89] K.M. Black *et al.*, arXiv:2209.01318 [hep-ex].

[90] Muon Collider Collaboration (J. de Blas *et al.*), arXiv:2203.07261 [hep-ph].

[91] C. Aimè *et al.*, arXiv:2203.07256 [hep-ph].

[92] Muon Collider Collaboration (N. Bartosik *et al.*), arXiv:2203.07964 [hep-ex].

[93] A.D. Bolognino *et al.*, *Eur. Phys. J. C* **78**, 1023 (2018).

[94] A.D. Bolognino *et al.*, *Frascati Phys. Ser.* **67**, 76 (2018), arXiv:1808.02958 [hep-ph].

[95] A.D. Bolognino *et al.*, *Acta Phys. Pol. B Proc. Suppl.* **12**, 891 (2019).

[96] A.D. Bolognino *et al.*, *Phys. Rev. D* **101**, 054041 (2020).

[97] F.G. Celiberto, *Nuovo Cim.* **C42**, 220 (2019).

[98] A.D. Bolognino *et al.*, *Eur. Phys. J. C* **81**, 846 (2021).

[99] A.D. Bolognino *et al.*, *SciPost Phys. Proc.* **8**, 089 (2022).

[100] A.D. Bolognino *et al.*, arXiv:2202.02513 [hep-ph].

[101] F.G. Celiberto, arXiv:2202.04207 [hep-ph].

[102] A.D. Bolognino *et al.*, arXiv:2207.05726 [hep-ph].

[103] A. Cisek, W. Schäfer, A. Szczurek, *Phys. Lett. B* **836**, 137595 (2023), arXiv:2209.06578 [hep-ph].

[104] A. Łuszczak *et al.*, *Phys. Lett. B* **835**, 137582 (2022).

[105] A. Arroyo Garcia *et al.*, *Phys. Lett. B* **795**, 569 (2019).

[106] A. Bacchetta *et al.*, *Eur. Phys. J. C* **80**, 733 (2020).

[107] F.G. Celiberto, *Nuovo Cim.* **C44**, 36 (2021).

[108] A. Bacchetta *et al.*, *SciPost Phys. Proc.* **8**, 040 (2022).

[109] A. Bacchetta *et al.*, *PoS* **EPS-HEP2021**, 376 (2022).

[110] A. Bacchetta *et al.*, *PoS* **PANIC2021**, 378 (2022).

[111] A. Bacchetta, F.G. Celiberto, M. Radici, *JPS Conf. Proc.* **37**, 020124 (2022), arXiv:2201.10508 [hep-ph].

[112] A. Bacchetta *et al.*, *Rev. Mex. Fis. Suppl.* **3**, 0308108 (2022), arXiv:2206.07815 [hep-ph].

[113] A. Bacchetta *et al.*, arXiv:2208.06252 [hep-ph].

[114] F.G. Celiberto, *Universe* **8**, 661 (2022), arXiv:2210.08322 [hep-ph].

[115] S. Forte, C. Muselli, *J. High Energy Phys.* **2016**, 122 (2016).

[116] R.D. Ball *et al.*, *Eur. Phys. J. C* **78**, 321 (2018).

[117] M. Bonvini *et al.*, *Eur. Phys. J. C* **76**, 597 (2016).

[118] F. Silvetti, M. Bonvini, *Eur. Phys. J. C* **83**, 267 (2023), arXiv:2211.10142 [hep-ph].