Heavy Flavor Puzzle at LHC: A Serendipitous Interplay of Jet Suppression and Fragmentation

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Both charged hadrons and D mesons are considered to be excellent probes of QCD matter created in ultrarelativistic heavy ion collisions. Surprisingly, recent experimental observations at LHC show the same jet suppression for these two probes, which—contrary to pQCD expectations—may suggest similar energy losses for light quarks and gluons in the QCD medium. We here use our recently developed energy loss formalism in a finite-size dynamical QCD medium to analyze this phenomenon that we denote as the "heavy flavor puzzle at LHC." We show that this puzzle is a consequence of an unusual combination of the suppression and fragmentation patterns and, in fact, does not require invoking the same energy loss for light partons. Furthermore, we show that this combination leads to a simple relationship between the suppressions of charged hadrons and D mesons and the corresponding bare quark suppressions. Consequently, a coincidental matching of jet suppression and fragmentation allows considerably simplifying the interpretation of the corresponding experimental data.

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Introduction.—Jet suppression [1] is considered an excellent probe of the QCD matter created in ultrarelativistic heavy ion collisions [2–5]. Specifically, charged hadrons and D mesons are a focus of theoretical and experimental research, since they represent the most direct probes of light and heavy flavor in QCD matter. However, while D meson suppression is indeed a clear charm quark probe, this is not the case for charged hadrons. That is, while experimentally measured prompt D mesons are exclusively composed of charm quarks [6], charged hadrons are composed of both light quarks and gluons [7]. Furthermore, gluons are known to have larger jet energy loss compared to that of light and heavy quarks, while light and charm quarks are expected to have similar suppressions [8]. Consequently, charged hadron suppression should be significantly greater compared to D meson suppression, but preliminary ALICE measurements [6,9] surprisingly show that charged hadrons and D mesons have the same R_{AA}. This observation is here denoted the "heavy flavor puzzle at LHC," and explaining this puzzle is the main goal of this Letter.

We note that perhaps the most straightforward explanation of the puzzle would be that, contrary to pQCD expectations, gluons and light quarks in fact lose the same amount of energy in the medium created at ultrarelativistic heavy ion collisions. In fact, the same possibility was also suspected in the context of RHIC experiments [10,11], where similar suppressions were observed for pions and single electrons; this has led some theorists to seek explanations outside conventional QCD [12–15]. For the LHC case, current predictions cannot jointly explain charged hadron and D meson experimental data [16]. Accordingly, the main goal of this Letter is to analyze phenomena behind the "heavy flavor puzzle at LHC" and investigate if pQCD is able to explain such unexpected experimental data.

Results and discussion.—To analyze the puzzle described in the previous section, we will here use our recently developed theoretical formalism, which is outlined in detail in Ref. [17]. The procedure is based on (i) jet energy loss (both collisional [18] and radiative [8,19]) in a finite-size dynamical QCD medium, (ii) finite magnetic mass effects [20], (iii) running coupling [17], (iv) multigluon fluctuations [21], (v) path-length fluctuations [22,23], and (vi) most up to date production [7,24] and fragmentation functions [25]. Note that the dynamical energy loss model used in this Letter presents an extension of the well-known Djordjevic-Gyulassy-Levai-Vitev model, from which three main deficiencies are removed—the absence of collisional energy loss and assumptions of static scattering centers and zero magnetic mass. This model is complementary to another well-known model (Arnold- Moore-Yaffe [26]); though both models consider dynamical scattering centers, Arnold- Moore-Yaffe applies to an infinite size, optically thick QCD medium, while our model applies to a finite size, optically thin QCD medium.

Furthermore, note that the computational procedure uses no free parameters; i.e., the parameters stated below correspond to the following literature values: We consider a QGP with $n_f = 3$ effective light quark flavors and perturbative QCD scale of $\Lambda_{\rm QCD} = 0.2$ GeV. For the temperature, we use effective $T = 304$ MeV extracted by ALICE [27]. For the light quarks, we assume that their mass is dominated by the thermal mass $M = \mu_E/\sqrt{6}$, and

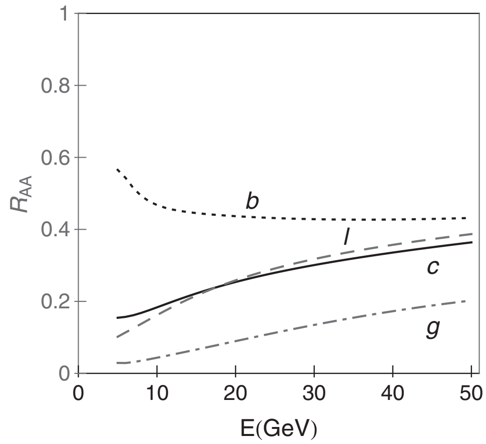

FIG. 1. Suppression of parton jets. Momentum dependence of the jet suppression is shown for gluons (dot-dashed curve), light quarks (dashed curve), charm (full curve), and bottom quarks (dotted curve). Electric to magnetic mass ratio is fixed to $\mu_M/\mu_E = 0.5$.

the gluon mass is $m_g = \mu_E/\sqrt{2}$ [28]. Here, Debye mass $\mu_E \approx 0.9$ GeV is obtained by self-consistently solving Eq. (3) from Ref. [17] (see also Ref. [29]), and magnetic mass μ_M is taken to be $0.4\mu_E < \mu_M < 0.6\mu_E$, as in Refs. [30,31]. Charm and bottom mass are, respectively, $M = 1.2$ and 4.75 GeV. For charm and bottom, the initial quark spectrum $E_i d^3\sigma(Q)/dp_i^3$ is computed at next-to-leading order using the code from Refs. [24,32]; for gluons and light quarks, the initial distributions are computed at next-to-leading order as in Ref. [7]. For charged hadrons, we use fragmentation functions from [25]. For D mesons we use fragmentation functions from [33]. Path length distributions are extracted from Ref. [23], while fragmentation functions are implemented according to Ref. [34].

We start by quantitatively reproducing the expectations summarized in the Introduction, in order to obtain a clear view of the relevant hierarchies for the suppression and the initial distributions. Figure 1 shows the comparison of the suppressions for quark and gluon jets. We see that the suppression of gluon jets is significantly greater compared to the corresponding suppression of quark jets, whereas the suppression predictions for light and charm quarks are similar [35]. We also see that, due to the "dead cone effect" [36], bottom quark suppression is notably smaller than suppression for charm, light quarks or gluons. Furthermore, in Fig. 2 we show that both light quarks and gluons significantly contribute to the charged hadron production—in fact, in the lower momentum range, gluons dominate over light quarks; therefore, both contributions from gluons and light quarks have to be taken into account when analyzing charged hadron suppression. On the other hand, D mesons present a clear charm quark probe, since the feed-down from B mesons is subtracted from the experimental data [6]; therefore, bottom quarks will not be further considered, since they do not contribute to D meson suppression.

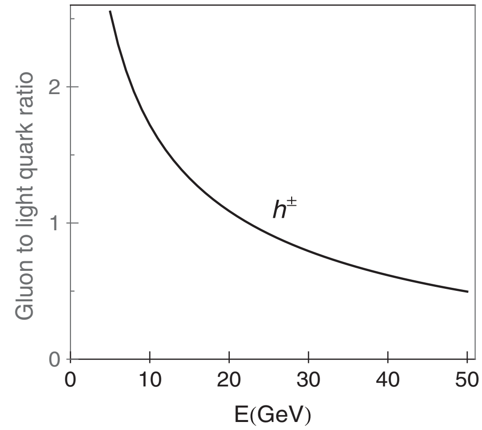

FIG. 2. Ratio of gluon to light quark contribution in the initial distributions of charged hadrons, as a function of momentum.

As discussed above, Figs. 1 and 2 lead to the expectation that the charged hadron suppression should be significantly greater than the D meson suppression. Surprisingly, this expectation is not confirmed by the experimental data, which are shown in the left panel of Fig. 3; these data clearly suggest the same suppression for both pions and D mesons. We can also calculate these $R_{AA}s$ through the computational procedure discussed above, which is shown in the right panel of Fig. 3. Even more surprisingly, these calculations are in accordance with the experimental data; i.e., they show the same suppression patterns for charged hadrons and D mesons. Moreover, we see that the theoretical predictions even reproduce the experimentally observed smaller suppression of D mesons compared to that of charged hadrons in the lower momentum range. This difference is the consequence of the dead cone effect [36], as can be seen in Fig. 1. Consequently, we see that our theoretical predictions show a very good agreement with the experimental data, which is in an apparent contradiction with the qualitative expectations discussed above; we will concentrate below on finding the explanation for these unexpected results.

We start by asking how fragmentation functions modify charged hadron and D meson suppressions, since these functions define the transfer from the parton to the hadron level. We first analyze how fragmentation functions modify the D mason suppression, compared to the bare charm quark suppression. In the left panel of Fig. 4, we see that there is a negligible difference between these two suppression patterns so that D meson fragmentation does not modify bare charm quark suppression ($\langle z \rangle$ for D mesons is 0.89) [37]. Consequently, the D meson suppression is indeed a genuine probe of the charm quark suppression in the QCD medium.

However, there is a significantly more complex interplay between suppression and fragmentation in charged

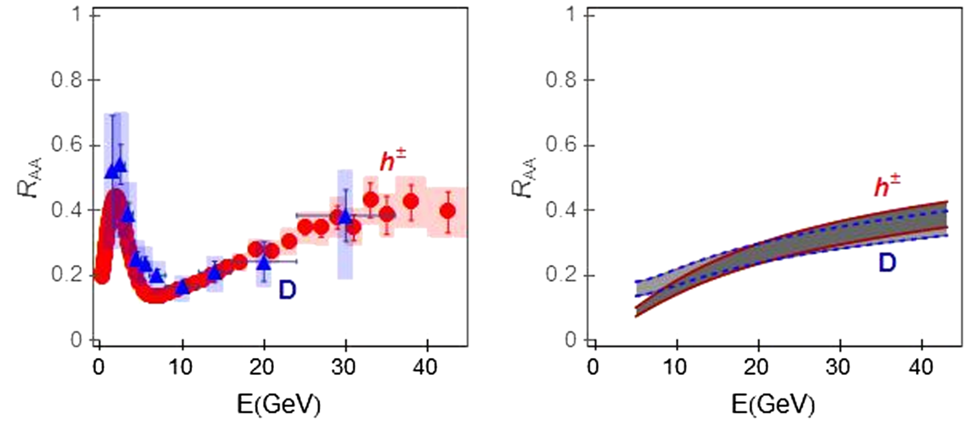

FIG. 3 (color online). Momentum dependence of charged hadron and D meson R_{AA}. The left panel shows together the experimentally measured 0%–5% central 2.76 Pb + Pb ALICE preliminary R_{AA} data for charged hadrons [9] (red circles) and D mesons [6] (blue triangles). The right panel shows the comparison of the charged hadron suppression predictions (gray band with full-curve boundaries) with the D meson suppression predictions (gray band with dashed-curve boundaries). Both gray regions correspond to $0.4 < \mu_M/\mu_E < 0.6$, where the upper (lower) boundary on each band corresponds to $\mu_M/\mu_E = 0.6$ ($\mu_M/\mu_E = 0.4$).

hadrons. In the central panel of Fig. 4, we compare the charged hadron suppression with the bare light quark and gluon suppressions. Surprisingly, we see that the charged hadron suppression almost exactly coincides with the bare light quark suppression. This may suggest that gluon jets do not contribute to the charged hadron suppression, which is, however, clearly inconsistent with the significant (even dominant) gluon contribution in charged hadrons (see Fig. 2). To further investigate this, in the right panel of Fig. 4, we show what would be the charged hadron suppression if hadrons were composed of only light quark jets (the dashed curve) or only gluon jets (the dot-dashed curve). We see that, as expected from Fig. 2, the actual charged hadron suppression is clearly in between the two suppression alternatives so that both light quarks and gluons indeed significantly contribute to the charged hadron suppression. However, by comparing the central and the right panels in Fig. 4, we see that charged hadron fragmentation functions modify the bare light quark and gluon suppressions so that the corresponding charged hadron suppression becomes significantly milder than the suppression of its parton constituent (note that $\langle z \rangle$ for charged hadrons coming from light quarks and gluons is 0.48 and 0.39, respectively). These milder suppression patterns then combine so that, coincidentally, their "resultant" charged hadron suppression almost identically reproduces the bare light quark suppression. Consequently, the heavy flavor puzzle at LHC is a consequence of a specific combination of the suppression and fragmentation patterns for light partons, and it does not require invoking an assumption of the same energy loss for light partons.

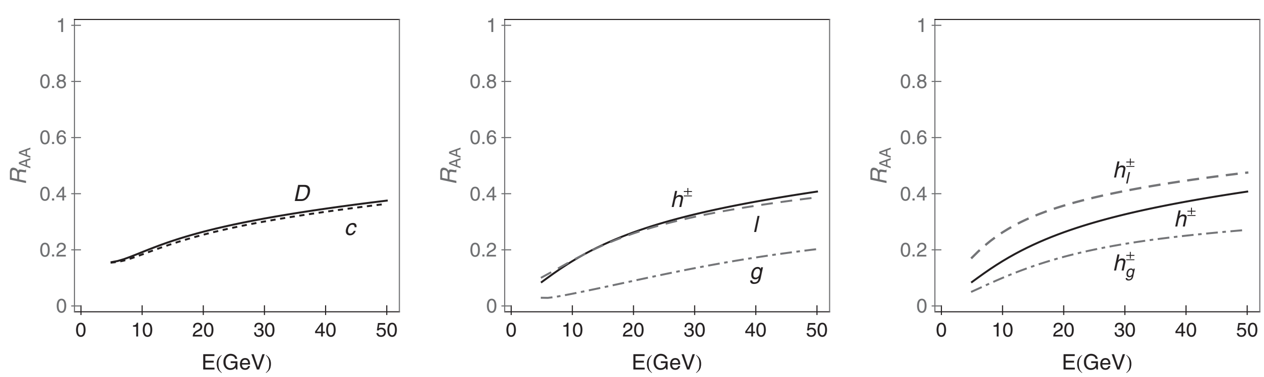

FIG. 4. Comparison of suppression predictions. The left panel shows a comparison of the charm quark suppression predictions (dotted curve) with the D meson suppression predictions (full curve), as a function of momentum. The central panel shows the comparison of charged hadron suppression predictions (full curve) with light quark (dashed curve) and gluon (dot-dashed curve) suppression predictions. In the right panel, the dashed curve shows what would be the charged hadron suppression if only light quarks contributed to charged hadrons. The dot-dashed curve shows what would be the charged hadron suppression if only gluons contributed to charged hadrons, whereas the full curve shows the actual hadron suppression predictions. On each panel, the electric to magnetic mass ratio is fixed to $\mu_M/\mu_E = 0.5$.

*Conclusions.—*We here analyzed a suppression puzzle at the LHC, which follows from the comparison of charged hadron and D meson R_{AA} data in central 2.76 TeV Pb + Pb collisions. While the solution of this puzzle is inherently quantitative, it can be qualitatively summarized in the following way: Despite the dominant gluon contribution in the charged hadron production, LHC charged hadron suppression turns out to be a genuine probe of bare light quark suppression. A major effect responsible for this key result is the distortion of the bare suppression patterns by jet fragmentation. Furthermore, D meson suppression correctly represents charm quark suppression, and bare charm and light quark suppressions are very similar. Taken together, these results in fact explain the observed puzzle, i.e., similar suppressions for charged hadrons and D mesons at LHC.

Therefore, the explanation of the puzzle follows directly from pQCD calculations of the energy loss and fragmentation, where no model parameter is adjusted to get a good agreement with the data. A major ingredient in explaining the puzzle is the significant—but often neglected—role of fragmentation in modifying the suppression patterns. Importantly, these calculations also directly relate the bare quark suppressions to the experimentally observed charged hadron suppressions. Consequently, the heavy flavor puzzle at LHC is not only a coincidental combination of energy loss and fragmentation patterns but also their serendipitous interplay, which can substantially simplify the interpretation of the relevant experimental data.

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[1] J. D. Bjorken, FERMILAB-PUB-82V059-THY **287**, 292 (1982).
[2] M. Gyulassy, Lect. Notes Phys. **583**, 37 (2002).
[3] D. d'Enterria and B. Betz, Lect. Notes Phys. **785**, 285 (2010).
[4] U. A. Wiedemann, Nucl. Phys. **A904–905**, 3c (2013).
[5] I. Vitev and B. W. Zhang, Phys. Rev. Lett. **104**, 132001 (2010).
[6] A. Grelli (for the ALICE collaboration), Nucl. Phys. **A904–905**, 635c (2013).
[7] Z. B. Kang, I. Vitev, and H. Xing, Phys. Lett. B **718**, 482 (2012); R. Sharma, I. Vitev, and B. W. Zhang, Phys. Rev. C **80**, 054902 (2009).
[8] M. Djordjevic, Phys. Rev. C **80**, 064909 (2009).
[9] K. Aamodt *et al.* (ALICE Collaboration), Phys. Lett. B **720**, 52 (2013).
[10] M. Gyulassy, Physics **2**, 107 (2009).
[11] M. Djordjevic, J. Phys. G **32**, S333 (2006).
[12] A. Ficnar, J. Noronha, and M. Gyulassy, J. Phys. G **38**, 124176 (2011).
[13] J. Noronha, M. Gyulassy, and G. Torrieri, Phys. Rev. C **82**, 054903 (2010).
[14] S. S. Gubser, D. R. Gulotta, S. S. Pufu, and F. D. Rocha, J. High Energy Phys. 10 (**2008**) 052; P. M. Chesler, K. Jensen, A. Karch, and L. G. Yaffe, Phys. Rev. D **79**, 125015 (2009).
[15] W. A. Horowitz and M. Gyulassy, Phys. Lett. B **666**, 320 (2008); B. Betz, M. Gyulassy, J. Noronha, and G. Torrieri, Phys. Lett. B **675**, 340 (2009).
[16] B. Abelev *et al.* (ALICE Collaboration), J. High Energy Phys. 09 (**2012**) 112.
[17] M. Djordjevic and M. Djordjevic, arXiv:1307.4098.
[18] M. Djordjevic, Phys. Rev. C **74**, 064907 (2006).
[19] M. Djordjevic and U. Heinz, Phys. Rev. Lett. **101**, 022302 (2008).
[20] M. Djordjevic and M. Djordjevic, Phys. Lett. B **709**, 229 (2012).
[21] M. Gyulassy, P. Levai, and I. Vitev, Phys. Lett. B **538**, 282 (2002).
[22] S. Wicks, W. Horowitz, M. Djordjevic, and M. Gyulassy, Nucl. Phys. **A784**, 426 (2007).
[23] A. Dainese, Eur. Phys. J. C **33**, 495 (2004).
[24] M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, and G. Ridolfi, J. High Energy Phys. 10 (**2012**) 137.
[25] D. de Florian, R. Sassot, and M. Stratmann, Phys. Rev. D **75**, 114010 (2007).
[26] P. Arnold, G. D. Moore, and L. G. Yaffe, J. High Energy Phys. 11 (**2001**) 057; 06 (**2002**) 030; P. Arnold, G. D. Moore, and L. G. Yaffe, J. High Energy Phys. 01 (**2003**) 030.
[27] M. Wilde (ALICE collaboration), Nucl. Phys. **A904–905**, 573c (2013).
[28] M. Djordjevic and M. Gyulassy, Phys. Rev. C **68**, 034914 (2003).
[29] A. Peshier, arXiv:hep-ph/0601119.
[30] Y. Maezawa, S. Aoki, S. Ejiri, T. Hatsuda, N. Ishii, K. Kanaya, N. Ukita, and T. Umeda (WHOT-QCD Collaboration), Phys. Rev. D **81**, 091501 (2010); (WHOT-QCD Collaboration), LATTICE2008 (**2008**) 194.
[31] D. Bak, A. Karch, and L. G. Yaffe, J. High Energy Phys. 08 (**2007**) 049.
[32] M. Cacciari, M. Greco, and P. Nason, J. High Energy Phys. 05 (**1998**) 007; M. Cacciari, S. Frixione, and P. Nason, J. High Energy Phys. 03 (**2001**) 006.
[33] M. Cacciari and P. Nason, J. High Energy Phys. 09 (**2003**) 006; E. Braaten, K.-M. Cheung, S. Fleming, and T. C. Yuan, Phys. Rev. D **51** 4819 (1995).
[34] I. Vitev, Phys. Lett. B **639** 38 (2006).
[35] Note that the obtained crossover between charm and light quark suppressions in Fig. 1 happens because the initial distribution of charm quarks is steeper than the distribution of light quarks.
[36] Y. L. Dokshitzer and D. Kharzeev, Phys. Lett. B **519**, 199 (2001).
[37] A similar conclusion holds for B mesons ($\langle z \rangle \approx 0.93$).