



Heavy flavor puzzle from data measured at the BNL Relativistic Heavy Ion Collider: Analysis of the underlying effects

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Suppressions of light- and heavy-flavor observables are considered to be excellent probes of QCD matter created in ultrarelativistic heavy ion collisions. Suppression predictions of quark and gluon jets appear to suggest a clear hierarchy according to which neutral pions should be more suppressed than D mesons, which in turn should be more suppressed than single electrons. However, joint comparison of neutral pion (light probe) and nonphotonic single-electron (heavy probe) suppression data at the BNL Relativistic Heavy Ion Collider (RHIC) unexpectedly showed similar jet suppression for these two probes, which presents the well-known heavy-flavor puzzle at RHIC. We here analyze which effects are responsible for this unexpected result by using the dynamical energy-loss formalism. We find that the main effect is a surprising reversal in the suppression hierarchy between neutral pions and D mesons, which is due to the deformation of the suppression patterns of light partons by fragmentation functions. Furthermore, we find that, due to the decay functions, the single-electron suppression approaches the D -meson suppression. Consequently, we propose that these two effects, taken together, provide a clear intuitive explanation of this longstanding puzzle.

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I. INTRODUCTION

Studying properties of QCD matter created in ultrarelativistic heavy ion collisions is a major goal of experiments at the BNL Relativistic Heavy Ion Collider (RHIC). A powerful tool [1–3] to study these properties is suppression [4] of light- and heavy-flavor observables. It is intuitively expected that these observables should exhibit a clear hierarchy in the suppression patterns, which is based on the clear differences in the suppression of the underlying partons. The differences in the parton suppression can be clearly observed in the left panel of Fig. 1, which shows the suppression patterns for all types of quarks and gluons. From this figure, we see that charm- and light-quark suppression are expected to be similar, but we also note that, due to steeper initial distributions of charm quarks, charm-quark suppression is somewhat larger than light-quark suppression, despite smaller charm-quark energy loss. Furthermore, we see that, due to a larger color factor in the energy loss, perturbative QCD (pQCD) predicts that gluon suppression should be significantly larger than for any other type of quark, while due to a large mass (and consequently significant dead-cone effect [5]), bottom-quark suppression is significantly smaller than suppression for other partons. Furthermore, the central and right panels in Fig. 1 show that both light quarks and gluons contribute significantly to the neutral-pion production, while both charm and bottom quarks significantly contribute to single-electron production; also note that D mesons are composed exclusively of charm quarks. The parton suppression in the left panel of Fig. 1 then leads to the clear expectation for the probe-suppression hierarchy: it is expected that pions should have a notably larger suppression than D mesons, which are, in turn, expected to have a significantly higher suppression than single electrons.

However, these intuitive expectations are clearly not supported by the measured data, which are shown in Fig. 2. This figure shows similar suppression for neutral pions and single

electrons, and this surprising result is called the heavy-flavor puzzle at RHIC [11]. The puzzle has, up to now, inspired a significant amount of theoretical work [12] and has even led to proposals that explaining the puzzle requires explanations outside of conventional pQCD [13–16]. The main goal of this paper is analyzing effects that are responsible for the heavy-flavor puzzle at RHIC and consequently providing a clear intuitive explanation behind the puzzle.

The analysis in this paper is based on our dynamical energy-loss formalism [17–19], which was recently extended to finite magnetic mass [20] and running coupling [6] and was integrated in a numerical procedure for suppression predictions [6]. Our approach in this analysis is based on the expectation that D -meson suppression should be in between pion and single-electron suppressions. Consequently, to compare the pion suppression with single-electron suppression—as relevant for the heavy-flavor puzzle—we first compare suppressions of neutral pions and D mesons, and then suppressions of D mesons and single electrons. We show that the obtained (surprising) relative hierarchy can qualitatively explain the puzzle and consequently provide the desired intuitive explanation. Finally, we also show that our most up-to-date numerical procedure can also provide an excellent quantitative explanation of the puzzling data.

II. NUMERICAL FRAMEWORK

In our analysis, we use our recently developed theoretical formalism for high-momentum-hadron suppression, outlined in detail in Ref. [6]. The procedure is based on *(i)* radiative and collisional jet energy losses, computed in a finite-size dynamical QCD medium [17–19], extended to the case of finite magnetic mass [20], and running coupling [6], *(ii)* multigluon [21], and path-length fluctuations [22,23], and *(iii)* most up

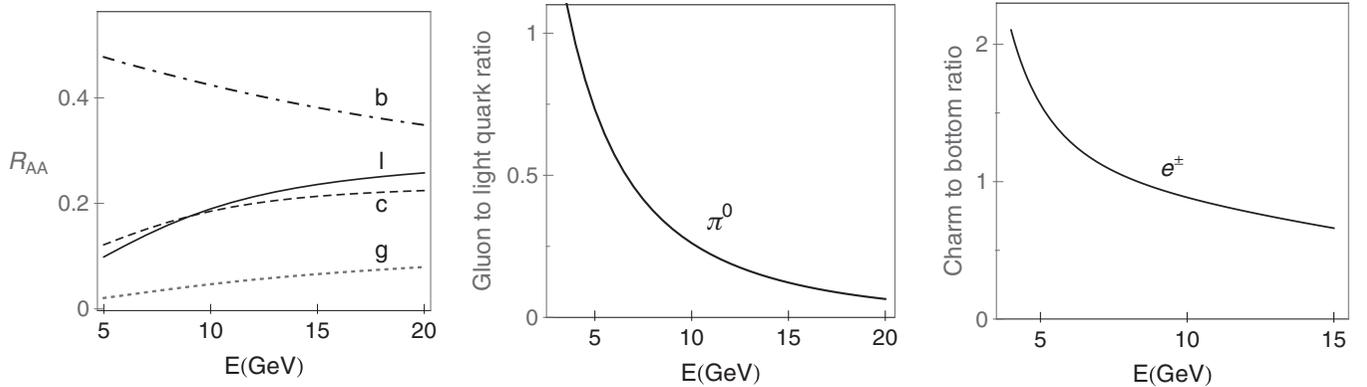


FIG. 1. Parton suppression and contribution to pions and single electrons. Momentum dependence of the jet suppression is shown in the left panel, for charm quarks (dashed curve), bottom quarks (dot-dashed curve), light quarks (full curve), and gluons (dotted curve). Electric to magnetic mass ratio is fixed to $\mu_M/\mu_E = 0.4$. The central panel of the figure shows the gluon to light quark contribution ratio in the initial distributions of charged hadrons. The right panel of the figure shows the charm to bottom quark ratio in the initial distributions of nonphotonic single electrons. The suppression predictions and the parton contributions are computed according to the numerical procedure described in Ref. [6] and outlined in the numerical framework section.

to date functions for production [24], fragmentation [25], and decay [26].

For RHIC conditions, we consider a QGP with $n_f = 2.5$ effective light-quark flavors and a perturbative QCD scale of $\Lambda_{\text{QCD}} = 0.2$ GeV. For the average temperature in our calculations, we use effective $T = 221$ MeV (as extracted by PHENIX [27]). For charm and bottom masses we use, respectively, $M = 1.2$ GeV and $M = 4.75$ GeV. For the light quarks, we assume that their mass is dominated by the thermal mass $M = \mu_E/\sqrt{6}$, and the gluon mass is $m_g = \mu_E/\sqrt{2}$ [28], where the Debye mass $\mu_E \approx 0.7$ GeV is obtained by self-consistently by solving Eq. (3) from Ref. [6] (see also Ref. [29]). The magnetic mass μ_M is taken as $0.4\mu_E < \mu_M < 0.6\mu_E$ [30,31]. For all partons, the initial distributions are obtained from Ref. [24]. For light

hadrons, we use DSS fragmentation functions [25]. For D mesons we use BCFY fragmentation functions [32], while for B mesons we use KLP parametrization [33]. The decays of D and B mesons to nonphotonic single electrons are obtained according to Ref. [26]. Path length distributions are extracted from Ref. [23]. Note that our computational procedure uses no free parameters, i.e., the parameters above correspond to the standard literature values, and we do not explicitly include the medium evolution (i.e., we take average medium parameters).

III. NEUTRAL-PION VS D -MESON SUPPRESSION

To understand the heavy-flavor puzzle at RHIC, we first compare neutral-pion with D -meson suppression, as outlined in the introduction. To this end, we use the dynamical energy-loss formalism (see the previous section) to generate suppression predictions for neutral pions and D mesons. The predictions are shown in Fig. 3, where we directly compare the two suppressions. We see that, surprisingly, we obtain that D mesons should have a larger suppression compared to neutral pions. Note that this result is despite the fact that both light quarks and gluons significantly contribute to neutral pions (see the central panel of Fig. 1) and that gluons have significantly higher suppression compared to both light-quark and charm suppressions (see the left panel of Fig. 1), while suppressions of light and charm quarks are similar. We analyze below the effects behind this unexpected result.

To this end, we next concentrate on how the fragmentation functions modify the parton suppressions, since these functions modify transfer from parton to hadron level. To study this, we first note that D -meson fragmentation functions do not modify charm suppression, i.e., D -meson suppression is indeed a genuine probe of charm-quark suppression [34]. On the other hand, the situation with neutral pions at RHIC is significantly more complicated: from the left panel of Fig. 4, we see that pion fragmentation functions modify light-quark and gluon suppressions in such a way that their resultant

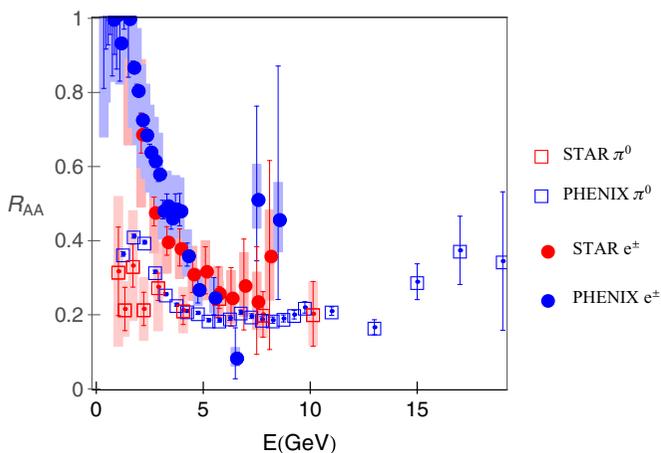


FIG. 2. (Color online) The heavy-flavor puzzle at RHIC. The figure shows together the experimentally measured 0%–10% central 200 GeV RHIC R_{AA} data for neutral pions (open red squares from STAR [7] and open blue squares from PHENIX [8]) and nonphotonic single electrons (full red circles from STAR [9] and full blue circles from PHENIX [10]). Shaded areas represent systematic error bars, while lines represent statistical error bars.

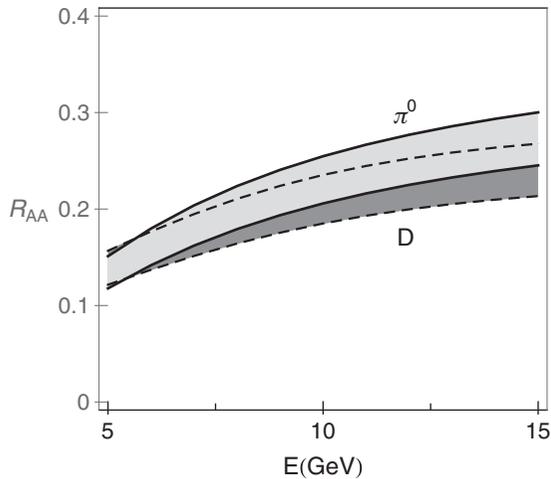


FIG. 3. Comparison of pion and D -meson suppression predictions. The figure shows the comparison of neutral-pion suppression predictions (light-gray band) with D -meson (dark-gray band) suppression predictions, as a function of momentum. Gray regions correspond to $0.4 < \mu_M/\mu_E < 0.6$, where the upper (lower) boundary on each band corresponds to $\mu_M/\mu_E = 0.6$ ($\mu_M/\mu_E = 0.4$).

neutral-pion suppression is even smaller than bare light-quark suppression. This counterintuitive result can be understood from the right panel in Fig. 4 and the central panel in Fig. 1. In the right panel of Fig. 4, we plot what would be the suppression if pions were composed only of light quarks (dashed curve) and, alternatively, what would be the suppression, if pions were composed only of gluons (dot-dashed curve). By comparing the left and the right panel in Fig. 4, we see that fragmentation functions significantly lower the suppression of its bare parton constituents (e.g., compare the dashed curves in these two figures). Furthermore, from the right panel of Fig. 4, we see that pion suppression is much closer to the dashed curve (suppression if pions consist only of light quarks), then to the

dot-dashed curve (suppression if pions consist only of gluons), which is due to the fact that the light-quark contribution to pions dominates the gluon contribution. Consequently, lowering of the bare parton suppressions and dominance of the light-quark contribution to pions lead to the (naively unexpected) smaller suppression of pions compared to light quarks, which is observed in the left panel of Fig. 4. From this result and the suppression hierarchy shown in the left panel of Fig. 1, it follows that, at RHIC, high-momentum D -meson suppression should be larger than neutral-pion suppression, as shown in Fig. 3; this result in itself presents an unintuitive reversal of the expected hierarchy prediction to be tested against the upcoming high-precision D -meson R_{AA} data from STAR.

IV. SINGLE-ELECTRON VS D -MESON SUPPRESSION

According to the outline in the introduction, we next compare the single-electron suppression with D -meson suppression. While for single electrons (similarly as for D mesons) the fragmentation functions do not modify transfer from parton to hadron level [34], this transfer may be influenced by decay functions. To analyze this, we start by comparing our theoretical predictions for single-electron R_{AA} with R_{AA} s for D and B mesons, which is shown in the left panel of Fig. 5. Due to the fact that both D and B mesons significantly contribute to single electrons (see right panel in Fig. 1), we see that the resultant single-electron suppression (coming from the decay of these two mesons) is clearly in between these two suppression observables. However, we also note that single-electron suppression is closer to D - than to B -meson suppression, despite the fact that, for higher momenta, B mesons dominate the single-electron production (see right panel of Fig. 1). To understand this, we plot in the right panel what would be the single-electron suppression if single electrons were composed only of D mesons (dashed band) and, alternatively, what would be the single electron suppression if single electrons were composed only of B

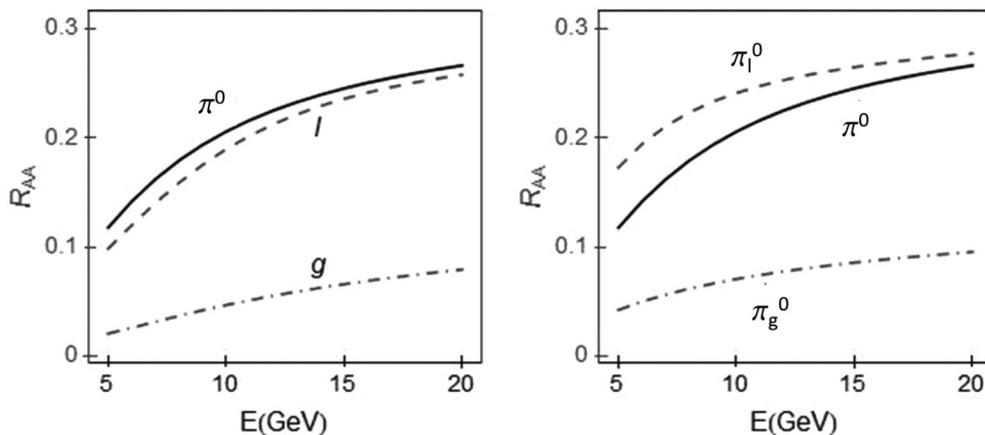


FIG. 4. Comparison of the light-flavor suppression predictions. The left panel shows the comparison of neutral-pion suppression predictions (full curve) with light-quark (the dashed curve) and gluon (the dot-dashed curve) suppression predictions, as a function of momentum. On the right panel, the dashed curve shows what would be the neutral-pion suppression if only light quarks contributed to pions. The dot-dashed curve shows what would be the neutral-pion suppression if only gluons contributed to pions, while the full curve shows the actual neutral-pion suppression predictions. In each panel, the electric to magnetic mass ratio is fixed at $\mu_M/\mu_E = 0.4$.

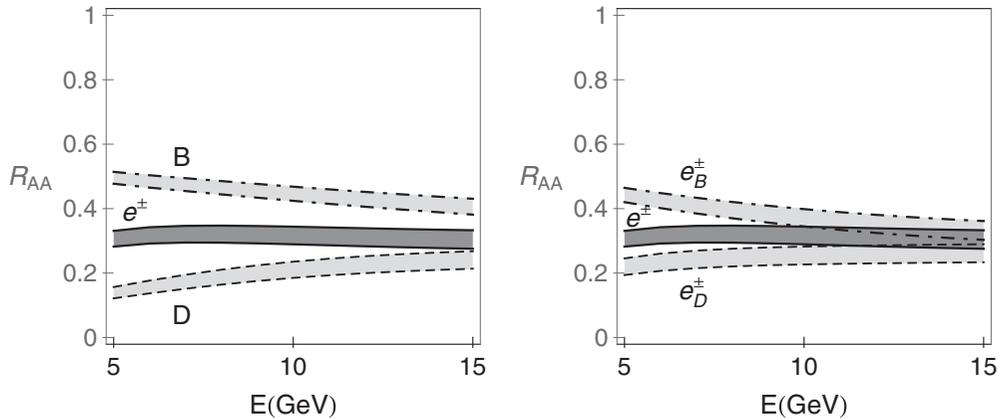


FIG. 5. Comparison of single-electron with D - and B -meson suppression predictions. The left panel shows the comparison of nonphotonic single-electron suppression predictions (dark-gray band with full curve boundaries) with D -meson (light-gray band with dashed curve boundaries) and B -meson (light-gray band with dot-dashed curve boundaries) suppression predictions, as a function of momentum. The right panel shows the comparison of nonphotonic single-electron suppression predictions (dark-gray band with full curve boundaries) with single-electron suppression from D mesons (light-gray band with dashed curve boundaries) and single-electron suppression from B mesons (light-gray band with dot-dashed curve boundaries), as a function of momentum. Gray regions correspond to $0.4 < \mu_M/\mu_E < 0.6$, where the upper (lower) boundary on each band corresponds to $\mu_M/\mu_E = 0.6$ ($\mu_M/\mu_E = 0.4$).

mesons (dot-dashed band). We see that actual single-electron suppression is closer to the single electrons from B mesons, in agreement with the production ratio shown in the right panel of Fig. 1. However, by comparing these two panels, we also see that the decay functions modify D - and B -meson suppressions in such a way that their resultant single-electron suppression is closer to D -meson suppression.

V. HEAVY-FLAVOR PUZZLE AT RHIC

In the analysis above, we obtained two important results, which directly lead to an intuitive explanation of the heavy-flavor puzzle at RHIC: We unexpectedly predicted that neutral-pion suppression should be smaller than D -meson suppression (Fig. 3) and that single-electron suppression approaches D -meson suppression (Fig. 5). Taken together, these two results clearly lead to an expectation that single-electron and neutral-

pion suppression patterns should approach each other. This expectation is confirmed in the left panel of Fig. 6, where we show together the calculated single-electron and neutral-pion suppressions. While the left panel in Fig. 6 shows that our predictions qualitatively agree with the experimental data that form the heavy-flavor puzzle at RHIC (see Fig. 2), in the central and right panels of Fig. 6 we show a direct comparison of our theoretical predictions with, respectively, pion and single-electron suppressions. Therefore, from Fig. 6, we observe that we achieved both qualitative and quantitative agreement with RHIC pion and single-electron suppression data, where we note that we use no free parameters in the model testing.

VI. CONCLUSIONS

This paper addresses the heavy-flavor puzzle at RHIC, i.e., the surprising experimental observation that the single-

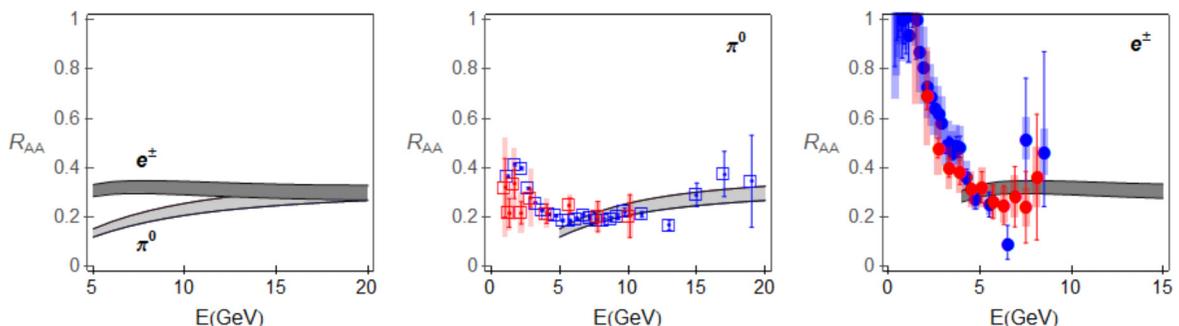


FIG. 6. (Color online) Comparison of neutral-pion and single-electron suppression predictions with experimental data. The left panel shows the comparison of neutral-pion suppression predictions (light-gray band) with nonphotonic single-electron suppression predictions (dark-gray band). The central panel compares theoretical predictions for neutral pions (light-gray band) with available pion R_{AA} data at 0%–10% central 200 GeV RHIC (open red squares from STAR [7] and open blue squares from PHENIX [8]). The right panel compares theoretical predictions for single electrons (dark-gray band) with the available RHIC single electron R_{AA} data (full red circles from STAR [9] and full blue circles from PHENIX [10]). Gray regions correspond to $0.4 < \mu_M/\mu_E < 0.6$, where the upper (lower) boundary on each band corresponds to $\mu_M/\mu_E = 0.6$ ($\mu_M/\mu_E = 0.4$).

electron suppression approaches the neutral-pion suppression. There has been a significant amount of work on this topic (see, e.g., recent work [22,35–37]) that address quantitative improvements in explaining the data. In distinction, this study concentrates on providing the qualitative understanding behind the effect responsible for the puzzling observation.

We found that qualitatively explaining the puzzle involves an interplay of energy loss, fragmentation, and decay patterns. That is, by comparing the suppression of pions and single electrons with that of D mesons, we found that the puzzle can be intuitively explained in terms of the following: (i) We surprisingly predict that pion suppression should be smaller than D -meson suppression, which is due to deformation of bare light-quark and gluon suppressions by fragmentation functions. (ii) We also found that, due to the deformation of D - and B -meson suppression patterns by the decay functions, single-electron suppression approaches D -meson suppression; this then inevitably leads to single-electron suppression approaching the pion suppression, given the previous result

that D -meson suppression exceeds the pion suppression. This qualitative explanation is further complemented by a very good quantitative agreement of our model with measured data of neutral-pion and single-electron suppression. Consequently, we argue that we provide both qualitative and quantitative understanding of the relevant data. We therefore conclude that the pQCD description of the medium, and the corresponding calculations, can fully account for the heavy-flavor puzzle at RHIC.

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