The suppression of the nuclear modification factor for heavy flavor hadrons is usually attributed to the energy loss of heavy quarks propagating in a QCD plasma. Nevertheless it is puzzling that the suppression is as strong as for light flavors. We show that when accounting for the quark momentum shift associated to the opening of the recombination/coalescence channel for hadron production in the plasma, it is not necessary to invoke such strong energy loss. This shift is expressed in terms of an increase of the heavy baryon to meson ratio in nuclear with respect to proton collisions. When this mechanism is included along with a moderate energy loss, data from RHIC and LHC for the nuclear modification factor of electrons coming from heavy flavor decays as well as of charm mesons, can be reasonably described.

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The suppression of single hadron transverse spectra in nuclear collisions, with respect to a superposition of independent proton collisions, is one of the main results from the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC). This suppression is quantified in terms of the nuclear modification factor \( R_{\text{AA}} \) and one of its main features is that heavy flavor hadrons are equally suppressed as light hadrons \( \bar{R}_{\text{AA}} \). Such behavior was first obtained from the analysis of electrons from the decay of heavy flavors and later confirmed from the analysis of charm mesons \( \bar{R}_{\text{AA}} \).

When the suppression of heavy flavors is only attributed to energy loss in the QCD medium, the above result is surprising for if the main contribution comes from radiative processes, the dead cone effect \( \bar{R}_{\text{AA}} \) should prevent heavy quarks from losing as much energy as light ones. This motivated the review of energy loss scenarios to incorporate contributions from collisional processes, diffusion, geometry, as well as dynamical properties of the medium \( \bar{R}_{\text{AA}} \). However even these refined scenarios do not yet provide a fully convincing explanation for the properties of the heavy flavor \( R_{\text{AA}} \).

Much less attention has been paid to the fact that a shift of the hadron momentum in the nuclear medium can come not only from a loss of energy but also from a momentum redistribution when the quarks from the medium form either baryons or mesons. This is the central idea behind the recombination/coalescence scenario as a new channel for hadron production in a heavy-ion environment \( \bar{R}_{\text{AA}} \). In average, the three quarks forming the baryon come from lower momentum bins than the two quarks making up a meson. Since there are more quarks with lower momenta there is a larger chance to form baryons than mesons. Transverse flow increases the effect since this makes the momentum distribution for heavier particles (hadrons) to fall less steeply than for lighter ones (mesons). A direct consequence of this momentum redistribution is an increase of the baryon to meson ratio in nuclear with respect to proton collisions. This ratio has been measured for a large variety of light and strange hadrons in high-energy nuclear collisions \( \bar{R}_{\text{AA}} \). The upshot is that for intermediate transverse momenta, the ratio is enhanced with respect to the corresponding one in proton collisions. Although no measurements exist for the case of heavy flavors, there are model calculations that describe this enhancement \( \bar{R}_{\text{AA}} \). To test this scenario in quantitative terms, we use one of these models, the Dynamical Quark Recombination Model (DQRM) \( \bar{R}_{\text{AA}} \), to compute the heavy baryon to meson ratio which in turn is used to compute \( R_{\text{AA}} \) and \( R_{\text{AA}}^{c} \). We show that when this increase is accounted for, only a moderate energy loss is needed to reproduce the data.

For definitiveness, let us concentrate on describing the nuclear modification factor for a single heavy flavor, say charm (c) quarks. The number of c-quarks produced in nuclear \( (\text{AA}) \) or proton \( (\text{pp}) \) collisions in a given momentum bin can be obtained from counting the corresponding number of hadrons with c-quarks, namely, the number of open charm mesons \( N_{\text{AA}}^{c} / \text{pp} \), charm baryons \( N_{\text{AA}}^{c} / \text{pp} \) and hidden charm mesons \( N_{\text{AA}}^{c} / \text{pp} \)

\[
N_{\text{AA}}^{c} / \text{pp} = (N_{\text{AA}}^{D} / \text{pp} + N_{\text{AA}}^{\Lambda} / \text{pp} + N_{\text{AA}}^{c} / \text{pp}) \tag{1}
\]

Normalizing the proton case to the average number of binary collisions \( \langle n_{b} \rangle \) we have that, accounting also for a possible shift in energy \( \varepsilon \), the number of produced c-quarks in one and the other environments, must satisfy

\[
N_{\text{AA}}^{c} = \varepsilon \langle n_{b} \rangle N_{\text{pp}}^{c} \tag{2}
\]

that is

\[
(N_{\text{AA}}^{D} + N_{\text{AA}}^{\Lambda} + N_{\text{AA}}^{c}) = \varepsilon \langle n_{b} \rangle (N_{\text{pp}}^{D} + N_{\text{pp}}^{\Lambda} + N_{\text{pp}}^{c}) \tag{3}
\]
From Eq. (6), we can build the nuclear modification factor for $D$-mesons in terms of the number of charm mesons and baryons in $pp$ and $AA$ collisions and get

$$R_{AA}^D = \frac{N_{AA}^D}{\langle n_b \rangle N_{pp}^{D}}$$

$$\equiv \varepsilon \left( 1 + \frac{N_{pp}^\Lambda + N_{pp}^{\bar{e}}}{N_{pp}^D} \right) - N_{AA}^\Lambda + N_{AA}^{e \bar{e}}. \quad (4)$$

The last term in Eq. (4) can be written as

$$\frac{N_{AA}^\Lambda + N_{AA}^{e \bar{e}}}{\langle n_b \rangle N_{pp}^{D}} = \left( \frac{N_{AA}^D}{\langle n_b \rangle N_{pp}^{D}} \right) + \left( \frac{N_{AA}^{e \bar{e}}}{\langle n_b \rangle N_{pp}^{D}} \right)$$

$$= R_{AA}^\Lambda + \left( \frac{N_{AA}^{e \bar{e}}}{\langle n_b \rangle N_{pp}^{D}} \right). \quad (5)$$

Using Eq. (5) into Eq. (4), we can write

$$R_{AA}^D \left( 1 + \frac{N_{AA}^\Lambda}{N_{pp}^{D}} \right) = \varepsilon \left( 1 + \frac{N_{pp}^\Lambda + N_{pp}^{e \bar{e}}}{N_{pp}^D} (\varepsilon - \eta) \right), \quad (6)$$

where we have defined $\eta \equiv N_{AA}^{e \bar{e}}/\langle n_b \rangle N_{AA}^\Lambda$. Since the ratio of hidden charm to $D$ mesons in $pp$ collisions, $N_{pp}^{e \bar{e}}/N_{pp}^D$, is very small, to an excellent approximation we can rewrite Eq. (6) as

$$R_{AA}^e \simeq \varepsilon \left( 1 + \frac{N_{pp}^\Lambda}{N_{pp}^D} \right) \left( 1 + \frac{N_{pp}^\Lambda + N_{pp}^{e \bar{e}}}{N_{pp}^D} (\varepsilon - \eta) \right). \quad (7)$$

Therefore, even in the absence of energy loss ($\varepsilon = 1$) the nuclear modification factor for $D$ mesons is smaller than one, provided the ratio of charm baryons to open charm mesons is enhanced in $AA$ with respect to $pp$ collisions.

The same enhancement is responsible for the suppression of the nuclear modification factor for heavy-flavor electrons. For definitiveness, let us again focus on electrons originating from the decay of charm quarks. In a given momentum bin $R_{AA}^e$ can be expressed as

$$R_{AA}^e = \frac{1}{\langle n_b \rangle} \frac{N_{AA}^\Lambda B^{\Lambda \rightarrow e} + N_{AA}^D B^{D \rightarrow e}}{N_{pp}^\Lambda B^{\Lambda \rightarrow e} + N_{pp}^D B^{D \rightarrow e}}$$

$$= \frac{1}{\langle n_b \rangle} \left( \frac{N_{AA}^D}{N_{pp}^D} \right) \frac{B^{D \rightarrow e} + \frac{N_{AA}^\Lambda}{N_{pp}^D} B^{\Lambda \rightarrow e}}{B^{\Lambda \rightarrow e} + \frac{N_{AA}^\Lambda}{N_{pp}^D} B^{\Lambda \rightarrow e}}, \quad (8)$$

where $B^{D,\Lambda \rightarrow e}$ is the branching ratio for the decay of $D$ mesons and charm baryons into electrons, respectively. Using Eq. (4), we can write Eq. (8) as

$$R_{AA}^e = \frac{1}{\langle n_b \rangle} \left( \frac{N_{AA}^D}{N_{pp}^D} + \frac{N_{AA}^\Lambda}{N_{pp}^\Lambda} \right) \frac{N_{AA}^\Lambda (N_{AA}^D + N_{pp}^\Lambda)}{N_{pp}^D (N_{AA}^D + N_{pp}^\Lambda)}$$

$$\times \left[ 1 + \frac{x N_{AA}^\Lambda / N_{pp}^D}{1 + x N_{pp}^\Lambda / N_{pp}^D} \right]$$

$$= R_{AA}^D \left( 1 + \frac{x N_{AA}^\Lambda / N_{pp}^D}{1 + x N_{pp}^\Lambda / N_{pp}^D} \right)$$

$$\equiv \varepsilon T_{AA}^e, \quad (9)$$

where, in order to introduce the energy loss factor $\varepsilon$, we have used Eq. (6) ignoring the contribution from hidden charm mesons. Also $x = B^{\Lambda \rightarrow e} / B^{D \rightarrow e}$ and the function $T_{AA}^e$ is given by

$$T_{AA}^e = \left[ 1 + \frac{N_{pp}^\Lambda}{N_{pp}^D} \right] \left[ 1 + \frac{N_{AA}^\Lambda}{N_{pp}^D} \right]$$

$$\times \left[ 1 + \frac{x N_{AA}^\Lambda / N_{pp}^D}{1 + x N_{pp}^\Lambda / N_{pp}^D} \right]. \quad (10)$$

It has been shown that when $x < 1$, $T_{AA}^e$ is also smaller than one when the ratio of charm hadrons to open charm mesons is enhanced in $AA$ with respect to $pp$ collisions. Therefore Eq. (9) states that even in the absence of energy loss, the nuclear modification factor for single electrons is smaller than one, provided the ratio of charm hadrons to open charm mesons is enhanced in $AA$ with respect to $pp$ collisions and that electrons are more copiously produced from open charm mesons than baryons ($x < 1$), which is indeed the case.

In the DQRM the probability $P$ to recombine quarks into mesons and baryons depends on density and temperature and thus on the proper time $T$ describing the evolution of the heavy-ion reaction up to hadronization. The evolving probability differs for hadrons made up by two and three constituent quarks and is computed by a variational Monte Carlo simulation. The relative population of one or the other kind of cluster at low densities can be fixed by combinatorial arguments (see Refs. [10, 12] for details). This model is well suited to describe baryon and meson production and its ratio at low and intermediate $p_T$. The hadron transverse momentum distribution in central $AA$, assuming Bjorken dynamics and transverse
The velocity expansion $v_t$, is given by

$$\frac{dN}{pdp_tdy} = g \frac{m_t \Delta y}{4\pi} \rho_{\text{nucleus}} \int_{\tau_0}^{\tau_f} \tau d\tau \mathcal{P}(\tau) \times I_0(p_t \sinh \eta_t/T) e^{-m_t \cosh \eta_t/T},$$

where $m_t$ is the transverse mass, $\Delta y$ the rapidity interval, $\rho_{\text{nucleus}}$ the nuclear radius, $\Delta \tau = \tau_f - \tau_0$ the proper time interval and $T$ the proper time dependent temperature

$$T = T_0 \left( \frac{\tau_0}{\tau} \right)^{\frac{1}{2}},$$

with $v_t^2 = 1/3$. $I_0$ is a Bessel function of order zero. $v_t$ and $\eta_t$ are related through $v_t = \tanh \eta_t$. $g$ is the degeneracy factor that takes care of the spin degree of freedom.

Fig. 1 shows the DQRM charm baryon to mesons ratio. We set the masses of the charm baryon and mesons to $m^\Lambda = 2.29$ GeV and $m^D = 1.87$ GeV. We take the initial hadronization proper time $\tau_0 = 1$ fm, at an initial temperature $T_0 = 175$ MeV and the final hadronization temperature $T_f = 100$ MeV that, according to Eq. (12), corresponds to $\tau_f = 8$ fm. Shown are the cases between $v_1 = 0$ and $v_1 = 0.65$. The figure shows also the baryon to meson ratio in $pp$ at $\sqrt{s_{NN}} = 200$ GeV and 2.7 TeV, obtained from PYTHIA simulations with $35 \times 10^3$ and $15 \times 10^6$ events, respectively. Shown are also fits to the simulations. Notice that, as expected, the charm baryon to meson ratio is enhanced in $AA$ with respect to $pp$ collisions.

Fig. 2 shows $R_{AA}^D$ compared to ALICE data [4]. The theoretical curves are computed using Eq. (14) with the heavy baryon to meson ratio obtained in $AA$ from the DQRM with the same parameters as before and the particular value $v_t = 0.65$, which is a standard choice for the transverse expansion velocity at LHC energies. The heavy baryon to meson ratio in $pp$ is obtained from the PYTHIA simulation shown in Fig. 1 for LHC energies. To see the effect of the energy loss parameter, for simplicity, we take two constant values, $\varepsilon = 0.55$ (upper curve) and $\varepsilon = 0.4$ (lower curve). We notice that even in this simple scenario, data are well described and the energy loss parameter does not need to be as small as in the case of light flavors, which in this language means $\varepsilon \approx 2$, to account for the suppression in $R_{AA}^D$.

Fig. 3 shows $R_{AA}^e$ compared to data from STAR [2] and ALICE [4]. The theoretical curves are computed using Eq. (15) with the heavy baryon to meson ratio obtained in $AA$ from the DQRM and in $pp$ from the PYTHIA simulations of Fig. 1. To account for the finding that electrons from heavy flavor decays come almost in equal proportions from the decays of charm and beauty hadrons for $p_t \gtrsim 5$ GeV [14], here we consider a single species of heavy baryons and mesons with effective masses. We take $m^D = 3.57$ GeV, the average between the masses of the $D^0$ and the $B^0$ mesons and $m^\Lambda = 3.95$ GeV, the average between the masses of the $\Lambda_c$ and the $\Lambda_b$. Also, we consider that the possible charm and beauty mesons decaying into electrons or positrons are $D^\pm$ ($B^{D^\pm \rightarrow e^\pm} = 16\%$), $D^0$, $\bar{D}^0$ ($B^{D^0, \bar{D}^0 \rightarrow e^\pm} = 6.53\%$), $D^+ (B^{D^+ \rightarrow e^\pm} = 8\%)$ and $B^\pm$ ($B^{B^\pm \rightarrow e^\pm} = 10.8\%$), $B^0$, $\bar{B}^0$ ($B^{B^0, \bar{B}^0 \rightarrow e^\pm} = 10.1\%$). The possible charm and beauty baryons decaying into electrons or positrons are $\Lambda_c$, $\bar{\Lambda}_c$, ($(B^{\Lambda_c, \bar{\Lambda}_c \rightarrow e^\pm} = 4.5\%)$, $\Lambda_b$ and $\bar{\Lambda}_b$ ($B^{\Lambda_b, \bar{\Lambda}_b \rightarrow e^\pm} = 5.35\%)$ the experimentaly reported branching ratio corresponds to the semileptonic decay $\Lambda_b \rightarrow \Lambda_c \ell \bar{\nu}_\ell$. Here we consider that half of this...
comes from the decay into electrons). The other parameters used for the \( AA \) case are as before, with \( \epsilon_t = 0.55 \) for the RHIC case and \( \epsilon_t = 0.65 \) for the LHC case. For simplicity, the energy loss parameter is taken also as two constant values \( \epsilon = 0.55 \) (upper curves) and \( \epsilon = 0.4 \) (lower curves). Once again, even in this simple scenario, data are well described for \( p_t \gtrsim 2 \) GeV and the energy loss parameter does not need to be as small as in the case of light flavors to account for the suppression in \( R_{AA}^{\pi} \). For \( p_t \lesssim 2 \) GeV, the rise in the data is usually attributed to other effects like shadowing, which is not considered in our approach. The model curves are not significantly affected if the effective masses are slightly varied.

In conclusion, we have shown that when accounting for the medium’s quark momentum redistribution when these recombine/coalesce to form mesons and baryons, the heavy flavor nuclear modification factors can be described without the need of a large energy loss. This momentum redistribution is encoded in the increase of the heavy baryon to meson ratio. We emphasize that the results are valid, independent of the model as long as the baryon to meson ratio increases in \( AA \) with respect to \( pp \) collisions. This increase is expected based on general grounds, since it represents a feature of the opening of the recombination/coalescence hadron formation channel in \( AA \) collisions. Upcoming upgrades to RHIC detectors and to ALICE are expected to increase the capability to directly look at this quantity and thus experimental tests of the mechanism advocated in this work will be available in the near future.

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