Nuclear modification factor for heavy flavors: An energy loss effect or more baryons than mesons?

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Abstract. The properties of the nuclear modification factor for heavy flavors are usually attributed to the energy loss suffered by the heavy quark propagating in a QCD plasma. Nevertheless it is a bit surprising that the suppression of this factor is as strong as the one suffered by light flavors. In this work we show that when accounting for the momentum shift associated to the opening of the recombination channel to produce hadrons in the QCD plasma, it is not necessary to invoke such a strong energy loss. We show that when the heavy baryon to meson ratio is larger in nuclear than in proton collisions, data from RHIC and LHC for the nuclear modification factor of electrons coming from heavy flavor decays as well as for charmed mesons can be accounted for.

1. Introduction
The medium created during relativistic heavy-ion collisions has been a subject of intense studies since the early experiments at the GSI-SIS and the CERN-SPS. The heavy-ion program has been successfully pursued reaching the so called ultrarelativistic domain at RHIC and LHC. The results indicate that a new state of the matter has been created, where the fundamental QCD degrees of freedom are at play, the so called quark-gluon plasma. A paradigm for the interpretation of these results is the energy loss suffered by fast moving partons. This energy loss is often times associated to the nuclear modification factor ($R_{AA}$), defined as the ratio of single hadron transverse momentum spectra in heavy-ion collisions to the same quantity obtained in proton proton collisions, normalized to the number of binary collisions. First results on $R_{AA}$ indicated a suppression for increasing transverse momentum ($p_t$). An intriguing result is that heavy flavor hadrons are equally as suppressed as light hadrons [1, 2]. 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 [3, 4]. The last results are preliminary and, with more statistics, they could be modified, although the overall behavior is not expected to change significantly.
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 [5] should prevent heavy quarks from losing as much energy as light ones. This motivated the reviewing of energy loss scenarios to incorporate contributions from collisional processes, diffusion, geometry, as well as dynamical properties of the medium [6]. However, even these refined scenarios do not yet provide a fully convincing explanation for the properties of the heavy flavor $R_{AA}$.

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 [7].

The recombination model [8] was put forward to explain the production of mesons at intermediate $p_t$. Recombination becomes less important at large $p_t$ due to the opening of the fragmentation channel with increasing $p_t$. Recently, the model has been modified accordingly to incorporate the description of hadron production in heavy-ion collisions. Among the results of this model are the description of spectra of identified hadrons [9] at LHC energies, as well as the baryon to meson ratio. Although the model works well, it depends on unknown experimental parameters like two or three-quark distribution functions, to make mesons or baryons respectively, in addition to other not well controlled approximations.

In order to overcome some of these limitations, in Refs. [10] we used Monte Carlo techniques to estimate the probability to form clusters of two and three quarks. The physical picture is that, in average, the three quarks forming a 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. A direct consequence of this momentum redistribution is an increase of the baryon to meson ratio in ion-ion ($ AA $) with respect to proton-proton ($ pp $) collisions. This ratio has been measured for a large variety of light and strange hadrons in high-energy nuclear collisions [11]. The upshot is that for intermediate transverse momenta, the ratio is enhanced in nuclear 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 under different approaches this enhancement [12, 13, 14].

In the present work we use the Dynamical Quark Recombination Model (DQRM) [10] to compute the heavy baryon to meson ratio which in turn is used to compute $R_{AA}^{c}$ and $R_{AA}^{D}$. We show that when this increase is accounted for, only a moderate energy loss is needed to reproduce the data.

2. Model for nuclear modification factor
Measurements of the nuclear modification factor have been made for charged light hadrons and more recently for heavy flavor hadrons. The present work develops a model to quantify this nuclear modification factor. It relies on counting the hadron species containing a heavy flavor, when these hadrons are produced in $ AA $ and comparing this number when produced in $ pp $. For definitiveness, let us concentrate on describing the nuclear modification factor for a single heavy flavor, say charm ($ c $) quarks. Considering that the number of hadrons containing $ c $-quarks produced in $ AA $ or $ pp $ collisions in a given momentum bin can be obtained from counting the number of open charm mesons ($ N_{AA}^{D} / pp $), charm baryons ($ N_{AA}^{A} / pp $) and hidden charm mesons ($ N_{AA}^{c\bar{c}} / pp $), the follow relation is valid,

$$ N_{AA}^{Hc} / pp = (N_{AA}^{D} / pp + N_{AA}^{A} / pp + N_{AA}^{c\bar{c}} / pp). \quad (1) $$

In the case of $ pp $, we normalize these numbers to the average number of binary collisions, $ \langle n_b \rangle $. A simple possibility to account for the shift in energy is considered by means of introducing
the energy loss parameter $\varepsilon$. Then the number of produced hadrons containing charm in both environments will be related by

$$ (N_{AA}^D + N_{AA}^{\Lambda} + N_{AA}^{c\bar{c}}) = \varepsilon \langle n_b \rangle (N_{pp}^D + N_{pp}^{\Lambda} + N_{pp}^{c\bar{c}}). \quad (2) $$

From Eq. (2), we can build the nuclear modification factor for $D$-mesons in terms of the number of charm mesons, obtaining (see Ref [15] for details),

$$ R_{AA}^D \approx \varepsilon \left( 1 + \frac{N_{pp}^\Lambda}{N_{pp}^D} \right) / \left( 1 + \frac{N_{AA}^\Lambda}{N_{AA}^D} \right), \quad (3) $$

where we have neglected the term describing the ratio of hidden charm to $D$ mesons in $pp$ collisions, $N_{pp}^{c\bar{c}}/N_{pp}^D$, since this ratio is very small. From this equation, we can see that 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.

In the case of non-photonic single electrons, the nuclear modification factor $R_{AA}^e$ can be expressed as [13, 16],

$$ R_{AA}^e \equiv \frac{1}{\langle n_b \rangle} \frac{N_{AA}^\Lambda B_{AA}^{\Lambda \rightarrow e} + N_{AA}^D B_{AA}^{D \rightarrow e}}{N_{pp}^\Lambda B_{pp}^{\Lambda \rightarrow e} + N_{pp}^D B_{pp}^{D \rightarrow e}}, \quad (4) $$

where $B_{D,\Lambda \rightarrow e}$ is the branching ratio for the decay of $D$ mesons and charm baryons into electrons, respectively. Using Eq. (3), we can write Eq. (4) as

$$ R_{AA}^e \equiv \varepsilon T_{AA}^e, \quad (5) $$

where again the energy loss factor $\varepsilon$ has been introduced and the contribution from hidden charm mesons was ignored (see Ref [15] for details). The function $T_{AA}^e$ is given by

$$ T_{AA}^e \equiv \left[ \left( 1 + \frac{N_{pp}^\Lambda}{N_{pp}^D} \right) / \left( 1 + \frac{N_{AA}^\Lambda}{N_{AA}^D} \right) \right] \times \left( 1 + x \frac{N_{AA}^\Lambda / N_{AA}^D}{1 + x N_{pp}^\Lambda / N_{pp}^D} \right) \quad (6) $$

where $x = B_{\Lambda \rightarrow e}/B_{D \rightarrow e}$.

The result in Eq. 6 indicates that when $x < 1$, $T_{AA}^e$ is also smaller than one when the ratio of charm hadrons to mesons is enhanced in $AA$ with respect to $pp$ collisions [13]. Therefore Eq. (5) states that $R_{AA}^e$ is less than one, even in the absence of energy loss, since the electrons are more copiously produced from open charm mesons that baryons ($x < 1$).

### 3. Dynamical quark recombination model and nuclear modification factor

In general terms, recombination can be understood as a means to explain hadron production whereby after a heavy-ion reaction, several liberated partons, sharing a phase space cell transform into hadrons. However, this scenario has no quantitative significance without some meaningful input on the parton distributions at earlier times. On this bases, the recombination model, can be given quantitative meaning in terms of different hadronization scenarios. One of such is the dynamical quark recombination model (DQRM). This is thermal model that is
Figure 1. (Color on line) DQRM charm baryon to meson ratio in AA compared to the same ratio in pp collisions. The DQRM curves are computed for two transverse expansion velocities $v_t = 0$ and 0.65. For the ratio in pp we use PYTHIA simulations at $\sqrt{s_{NN}} = 200$ GeV and 2.7 TeV with $35 \times 10^6$ and $15 \times 10^6$ events, respectively. Shown are also fits to the simulations.

The model uses a Monte Carlo simulation to compute the probability $P$ for quarks to coalesce and form cluster of two quarks (mesons) and of three quarks (baryons). This probability in turn depends on density and temperature and thus on the proper time hadronization. Once these probabilities are computed, they are shown to be larger for baryons than for mesons at low energy densities [13]. The relative population of one or the other kind of cluster at low densities can be fixed by combinatorial arguments, describing the baryon and meson production and its ratio at low and intermediate $p_t$ (see [13, 10] for details).

In order to estimate the hadron transverse momentum distribution in central AA, we take into account the space time evolution of the collision. Assuming Bjorken scenario which incorporates the fact that initially the expansion is along the beam direction, and considering the situation of central collisions, and assuming that there is not dependence of the particle yield on the transverse polar coordinates, the transverse momentum distribution can be written as: (see details in Ref [13])

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

where $v_t$ is the transverse velocity expansion, $m_t$ is the transverse mass, $\Delta y$ the rapidity interval, $\rho_{nuct}$ the nuclear radius, $\Delta \tau = \tau_f - \tau_0$ the proper time interval and $T$ the proper time dependent
Figure 2. (Color on line) Nuclear modification factor for $D$ mesons compared to ALICE data. The curves are computed using the DQRM with $v_t = 0.65$ as appropriate for LHC energies. The charm baryon to meson ratio in $pp$ is taken from the PYTHIA simulation described in Fig. 1. For simplicity, the energy loss parameter is taken as two constant values, $\varepsilon = 0.55$ (upper curve) and $\varepsilon = 0.4$ (lower curve).

\[
T = T_0 \left( \frac{\tau_0}{\tau} \right)^{\frac{v_t^2}{3}} ,
\]

with $v_t^2 = 1/3$. $I_0$ is a Bessel function $I$ 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.

This method to compute the transverse momentum distribution in $AA$ collision is used to get the results of the next section.

4. Results
Figure 1 shows the DQRM charm baryon to meson 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. (8), corresponds to $\tau_f = 8$ fm. Shown are the cases between $v_t = 0$ and $v_t = 0.65$. The values are in agreement with LHC results.

The baryon to meson ratio in $pp$ at $\sqrt{s_{NN}} = 200$ GeV and 2.7 TeV, obtained from PYTHIA simulations with $35 \times 10^6$ and $15 \times 10^6$ events, respectively, is also shown. The fit of the simulation present not dependence on the energy, at RHIC and LHC seems to be almost the same, contrary
to different theoretical models which suggest that the maximum of the ratio is shifted to higher transverse momentum as the energy increase. The behaviors of the ratio simulated is that we expect, it present an enhancement in AA with respect to pp collisions.

Figure 2 shows $R_\AA^D$ compared to ALICE data [4]. The theoretical curves are computed using Eq. (3) 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 effects 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 $\varepsilon \simeq 0.22$, to account for the suppression in $R_\AA^D$.

In fact, the experimental results show that the nuclear modification factor at low $p_t$ is not suppressed. It may seem that our calculation does not properly describe this behavior. However, notice that the $R_\AA^D$ rise with decreasing $p_t$, is not an energy loss effect. This rise is known to be due to the Cronin effect, that is to soft multiple interactions in a nuclear environment with respect to pp collisions. There is also evidence that in this region, gluon shadowing also contributes to the rise of the yield.

Since our goal was to concentrate on effects at intermediate $p_t$, and not on a detailed model for $R_\AA$, we did not attempt to address the low $p_t$ region, given that there different effects from the one studied, are at work.

Figure 3 shows $R_\AA^c$ compared to data from STAR [2] and ALICE [4]. The theoretical curves are computed using Eq. (5) 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 $p_t \geq 5$ GeV [17], here we consider a single species of heavy baryons and mesons with effective masses. We take $m_c^{D} = 3.57$ GeV, the average between the masses of the $D^0$ and the $B^0$ mesons and $m_c^{A} = 3.95$ GeV, the average between the masses of the $\Lambda_c$ and the $\Lambda_c$. Also, we consider that the possible charm and beauty mesons decaying into electrons or positrons are $D^\pm$ ($B^{D\pm\rightarrow e\pm} = 16\%$), $\bar{D}^0$, $\bar{D}^0$ ($B^{D^0\rightarrow D^{0\pm}\rightarrow e\pm} = 6.53\%$), $D^\pm_s$ ($B^{D^\pm_s\rightarrow e\pm} = 8\%$) and $B^{\pm}$ ($B^{B^{\pm}\rightarrow e\pm} = 10.8\%$), $B^0$, $\bar{B}^0$ ($B^{B^0\rightarrow e\pm} = 10.1\%$). The possible charm and beauty baryons decaying into electrons or positrons are $\Lambda_c$, $\bar{\Lambda}_c$ ($B^{\Lambda_c\rightarrow \bar{\Lambda}_c\rightarrow e\pm} = 4.5\%$), $\Lambda_b$ and $\bar{\Lambda}_b$ ($B^{\Lambda_b\rightarrow \bar{\Lambda}_b\rightarrow e\pm} = 5.35\%$) (the experimentally reported branching ratio corresponds to the semileptonic decay $\Lambda_b \rightarrow \Lambda_c \ell \bar{v}_\ell$. 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 $v_t = 0.55$ for the RHIC case and $v_t = 0.65$ for the LHC case. For simplicity, the energy loss parameter is taken also as two constant values $\varepsilon = 0.55$ (upper curves) and $\varepsilon = 0.4$ (lower curves). Once again, even in this simple scenario, data are well described for $p_t \geq 2$ 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 $R_\AA^c$.

For $p_t \leq 2$ GeV, the rise in the data is usually attributed to other effects like shadowing, which is not considered in our approach. We have checked that the model results are not affected if the effective masses used are slightly varied.

5. Conclusions

In summary, we have shown that considering a momentum redistribution of quarks in a medium, caused by their recombination to form mesons and baryons, the nuclear modification factor for heavy flavors can be described without the need of a large energy loss. This momentum redistribution is manifested through the heavy baryon to meson ratio. We have shown that an increase of this ratio in nuclear, with respect to proton collisions is directly related to the suppression of the nuclear modification factor. This result is not model dependent, since the effect...
Figure 3. (Color on line) Nuclear modification factor for non-photonic single electrons compared to STAR and ALICE data. The curves are computed using the DQRM with $t = 0.65$ for the LHC case and $t = 0.55$ for the RHIC case. The charm baryon to meson ratio in pp is taken from PYTHIA simulations for $\sqrt{s_{NN}} = 200$ GeV and $\sqrt{s_{NN}} = 2.7$ TeV for the sum of charm and beauty hadrons. For simplicity the energy loss parameter is taken as two constant values, $\varepsilon = 0.55$ (upper curves) and $\varepsilon = 0.4$ (lower curves).

will be present whenever the baryon to meson ratio increases in nuclear with respect to proton collisions. Details on this increase are of course model dependent. Given that we are dealing with a hadronization process, which belongs to the realm of non-perturbative effects, we have resorted to using the dynamical quark recombination model to make explicit calculations. We expect that this model works at intermediate $p_t$. At low $p_t$ the problem should take into account Cronin and shadowing effects, while at high momentum, fragmentation should be the dominant effect. The energy loss considered in the present work was introduced as a constant parameter, with the purpose to better illustrate the effect of a baryon to meson ratio enhancement. The baryon to meson ratio has a dependence on collective phenomena such as transverse flow, which is known to make the momentum distribution for heavier hadrons to fall less steeply than for lighter ones. Since we want to keep matters as simple as possible, we did not address all the above mentioned issues, concentrating only on the increase of the baryon to meson ratio and the probability to form clusters of two and three quarks within a thermal environment. Whether the observed trend of baryon to meson ratio increase is also present in data for heavy flavors will ultimately be determined by the upcoming data from the LHC.

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References

[1] S.S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 96, 032301 (2006); A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. 98, 172301 (2007); Y. Pachmayer (for the ALICE Collaboration) J. Phys. G 38, 124186 (2011).

[2] B.I. Abelev et al. (STAR Collaboration), Phys. Rev. Lett. 98, 192301 (2007).

[3] A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. 98, 162301 (2007).

[4] A. Dainese (for the ALICE Collaboration), J. Phys. G 38, 124032 (2011).

[5] Y. L. Dokshitzer and D. E. Kharzeev, Phys. Lett. B 519, 199 (2001); B.-W. Zhang, E. Wang, and X.-N. Wang, Phys. Rev. Lett. 93, 072301 (2004).

[6] H. van Hees and R. Rapp, Phys. Rev. C 71, 034907 (2005); H. van Hees, M. Mannarelli, V. Greco and R. Rapp, Phys. Rev. Lett. 100, 192301 (2008); M. Djordjevic, M. Gyulassy, S. Wicks, Eur. Phys. J. C 43, 135 (2006); G. D. Moore and D. Teaney, Phys. Rev. C 71, 064904 (2005); N. Armesto, M. Cacciari, A. Dainese, C. Salgado and U. Wiedemann, Phys. Lett. B 637, 362 (2006); M. Djordjevic, Phys. Rev. C 74, 064907 (2006); Nucl. Phys. A 783, 197c (2007); Nucl. Phys. A 830, 163c (2009); S. Wicks, W. Horowitz, M. Djordjevic and M. Gyulassy, Nucl. Phys. A 784, 426 (2007); S. Wicks and M. Gyulassy, J. Phys. G 34, (2007) S989; M. Djordjevic, and U. Heinz, Phys. Rev. Lett. 101, 022302 (2008); A. Ayala, M. Montaño, and E. Rojas, Phys. Rev. C 77, 044904 (2008); B. Z. Kopeliovich, I. K. Potashnikova, and I. Schmidt, Phys. Rev. C 82, 037901 (2010); J. Uphoff, O. Fochler, Z. Xu and C. Greiner, Phys. Rev. C 84, 024908 (2011); W. M. Alberico, A. Beraudo, A. De Pace, A. Molinari, M. Montero, M. Nardi and F. Prino, Eur. Phys. J. C 71, 1666 (2011).

[7] R. C. Hwa and C. B. Yang, Phys. Rev. C 67, 034902 (2003); R. J. Fries, B. Muller, C. Nonaka, and S. A. Bass, Phys. Rev. Lett. 90, 202303 (2003); V. Greco, C. M. Ko, and P. Levai, ibid. 90, 202302 (2003); R.C. Hwa and C.B. Yang, Phys. Rev. C 70, 024904 (2004).

[8] K.P. Das and Rudolph Hwa, Phys. Lett. B 68B, 459 (1977).

[9] Rudolph C. Hwa and Lilin Zhu, Phys. Rev.C 84, 064914 (2011).

[10] A. Ayala, M. Martinez, G. Paic, and G. T. Sánchez, Phys. Rev. C 77, 044901 (2008).

[11] S.S. Adler et al. (PHENIX Collaboration), Phys. Rev. C 69, 034909 (2004); J. Adams et al. (STAR Collaboration) Measurements of identified particles at intermediate transverse momentum in the STAR experiment from Au+Au collisions at √sNN = 200 GeV, nucl-ex/0601042; A. Ayala, J. Magnin, L. M. Montaño, and E. Rojas, Phys. Rev. C 77, 044904 (2008); B. Z. Kopeliovich, I. K. Potashnikova, and I. Schmidt, Phys. Rev. C 82, 037901 (2010); J. Uphoff, O. Fochler, Z. Xu and C. Greiner, Phys. Rev. C 84, 024908 (2011); W. M. Alberico, A. Beraudo, A. De Pace, A. Molinari, M. Montero, M. Nardi and F. Prino, Eur. Phys. J. C 71, 1666 (2011).

[12] Y. Oh, C. M. Ko, S. H. Lee, and S. Yasui, Phys. Rev. C 79, 044905 (2009). However see also Y. Oh, C. M. Ko, Phys. Rev. C 79, 067902 (2009).

[13] A. Ayala, J. Magnin, L. M. Montaño, and G. Toledo Sánchez, Phys. Rev. C 80, 064905 (2009).

[14] I. Bautista and C. Pajares, Phys. Rev. C 82, 034912 (2010).

[15] Alejandro Ayala, Eleazar Cuautle, J. Magnin, Luis Manuel Montano, G.Toledo Sanchez, Heavy flavor nuclear modification factor: more baryons than mesons less energy loss (arXiv:1110.4587 [nucl-th]).

[16] P. R. Sorensen and X. Dong, Phys. Rev. C 74, 024902 (2006); G. Martinez-Garcia, S. Gadrat, and P. Crochet, arXiv:hep-ph/07072035; G. Martinez-Garcia, S. Gadrat, and P. Crochet, Phys. Lett. B 663, 55 (2008); [Erratum-ibid. B 666, 533 (2008)].

[17] M. M. Aggarwal et al. (STAR Collaboration), Phys. Rev. Lett. 105, 202301 (2010).