Propagation of heavy baryons in heavy-ion collisions

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(Received 4 May 2016; published 30 December 2016)

The drag and diffusion coefficients of heavy baryons (Λ_c and Λ_b) in the hadronic phase created in the latter stage of the heavy-ion collisions at RHIC and LHC energies have been evaluated recently. In this work we compute some experimental observables, such as the nuclear suppression factor R_{AA} and the elliptic flow v_2 of heavy baryons at RHIC and LHC energies, highlighting the role of the hadronic phase contribution to these observables, which are going to be measured at Run 3 of LHC. For the time evolution of the heavy quarks in the quark and gluon plasma (QGP) and heavy baryons in the hadronic phase, we use the Langevin dynamics. For the hadronization of the heavy quarks to heavy baryons we employ Peterson fragmentation functions. We observe a strong suppression of both the Λ_c and Λ_b. We find that the hadronic medium has a sizable impact on the heavy-baryon elliptic flow whereas the impact of hadronic medium rescattering is almost unnoticeable on the nuclear suppression factor. We evaluate the Λ_c/D ratio at RHIC and LHC. We find that the Λ_c/D ratio remains unaffected due to the hadronic phase rescattering which enables it as a nobel probe of QGP phase dynamics along with its hadronization.

I. INTRODUCTION

Ongoing experiments on relativistic heavy-ion collisions at high energies, like the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), have been designed to reach a new state of matter known as quark and gluon plasma (QGP). It is a deconfined strongly interacting plasma behaving like an almost perfect fluid. The bulk properties of this high-temperature phase are governed by the light quarks and gluons. However, charm and bottom quarks (collectively denoted as heavy quarks) are responsible for several observables which are essential to probe the QGP properties. The reason is that these heavy quarks are witnesses of the entire plasma evolution as they are produced in the initial hard scatterings and remain abiding until hadronization. In their final state they appear as constituents of heavy hadrons, mainly D and B mesons. Indeed, these states have generated significant interest in the recent past because they serve as indicators of QGP dynamics [1] due to the suppression of their momentum distribution at large p_T in the thermal medium, reflected in a low nuclear suppression factor R_{AA}, and a sizable value of the elliptic flow v_2, a measure of the azimuthal anisotropy in the plasma. Noticeably R_{AA} and v_2 have similar values like the light hadrons.

Thanks to the last upgrades in the experimental detectors, RHIC and LHC can reconstruct D mesons from their hadronic decay products (like $D^0 \to K^- \pi^+$), instead of collecting nonphotonic electrons coming from semileptonic decays. With recent experimental results from STAR (RHIC) [2] as well as ALICE (LHC) [3–6], one can now contrast the predictions of the theory groups, which have computed the R_{AA} and v_2 of heavy mesons, using numerical simulations for the heavy-ion evolution under different models [7–24].

In addition to heavy mesons, future upgrades in the ALICE detector will allow one to study Λ_c and Λ_b baryons within the so-called Run 3 of LHC [25–27] (see [28] for a recent study on the Λ_c baryon reconstruction in $p + p$ collisions by the LHCb Collaboration). As presented in Ref. [25], the ALICE collaboration plans to study several observables related to Λ_c baryons, namely the R_{AA}, v_2 and Λ_c/D ratio. Given some key upgrades in the ALICE detector capabilities, the Λ_b physics in heavy-ion collisions has also been considered for the Run 3 [25,26].

These experimental advances on heavy baryons (Λ_c and Λ_b) are of general interest because they will allow us to have novel information on the hadronization mechanism and, more specifically, on the evaluation of the heavy baryon-to-meson ratio [29,30]. In the light and strange sectors, this ratio has shown an anomalous enhancement with respect to $p + p$ collisions. Also an enhancement would affect the R_{AA} of nonphotonic electrons [31,32]. This

is because the branching ratio of heavy-baryon decay [33] to electrons is larger than the branching ratio of heavy mesons to electrons. Furthermore the heavy baryon to meson ratio, (Λ_c/D and Λ_b/B), is very fundamental for the understanding of the in-medium hadronization [34,35].

In a recent work [36] some of us have extensively studied the microscopical details of the Λ_c and Λ_b interactions with light mesons, such as π, K, $\bar{K}$, η (see also Ref. [37] for a first study in this direction). In Ref. [36] the authors used an effective field theory at low energies to describe the hadronic interactions, which are, in addition, unitarized to account for the required unitarity property of the scattering amplitudes. They presented the typical cross sections for both Λ_c and Λ_b baryons, containing many resonant states. Then, the authors computed the relevant transport coefficients, drag force and diffusion coefficients, as a function of the temperature and heavy baryon momentum for the conditions expected after the hadronization in high-energy heavy ion collisions. Either the individual cross sections, or the transport coefficients themselves, can be readily used in transport simulations to account for the R_{AA} or v_2 of heavy baryons at heavy-ion collisions at RHIC and LHC.

As an application of the findings in [36], we now present predictions for R_{AA} as well as v_2 of Λ_c and Λ_b baryons for RHIC and LHC energies for an eventual comparison with experimental results and to understand if we can describe both the heavy meson and heavy baryon observables simultaneously. We also present prediction for the Λ_c/D ratio for RHIC and LHC energies. We will accommodate a Langevin equation for the momentum evolution of the heavy particles (equivalent to a Fokker-Planck realization) whose parameters are related to the drag and diffusion coefficients. These are taken from a quasiparticle model [38] for the heavy quark propagation, and from Ref. [36] for the hadronic phase.

This manuscript is organized as follows. In Sec. II we describe the Langevin equations to be solved for the dynamics of the heavy particle. In particular, we explain how the coefficients of the equations of motion are related to the transport coefficients computed in our previous work [36]. In Sec. III we provide some details about the practical implementation of our model: we describe our prescription for the initial state, the quasiparticle model used for the propagation of heavy quarks in the hot plasma, the hadronization mechanism for the confined phase transition, and the freeze-out condition. Our results are presented in Sec. IV, where we give our predictions for R_{AA} (IV A) and v_2 (IV B). Section V is devoted for the heavy baryon to meson ratio. Finally, we draft our conclusions in Sec. VI.

II. LANGEVIN EQUATION FOR HEAVY PARTICLES

The standard approach to heavy-quark dynamics in the QGP and the propagation of open-heavy hadrons in the hadronic medium is to follow their evolution by means of a Fokker-Planck equation solved stochastically by the Langevin equations [1]. The relativistic Langevin equations of motion for the time evolution of the position and momentum of the heavy quarks/heavy hadrons can be written in the form

$$\begin{cases} dx_i = \frac{p_i}{E}\,dt, \\ dp_i = -F(p)p_i dt + C_{ij}(p)\rho_j\sqrt{dt}, \end{cases} \quad (1)$$

where dx_i and dp_i are the shift of the coordinate and momentum in each discrete time step dt. $F(p)$ and $C_{ij}(p)$ are the drag force and the covariance matrix respectively. ρ is the noise which obeys the probability distribution of independent Gaussian-normal distributed random variables, $P(\rho) = (2\pi)^{-3/2}e^{-\rho^2/2}$, along with the relations $\langle\rho_i\rho_j\rangle = \delta_{ij}$ and $\langle\rho_i\rangle = 0$. The covariance matrix is related to the transverse and longitudinal diffusion coefficients,

$$C_{ij} = \sqrt{2\Gamma_0(p)}\Delta_{ij} + \sqrt{2\Gamma_1(p)}\frac{p_i p_j}{p^2}, \quad (2)$$

where $\Delta_{ij} = \delta_{ij} - p_i p_j/p^2$ is the transverse projector operator. Under the assumption, $\Gamma_0(p) = \Gamma_1(p) = \Gamma(p)$, Eq. (2) reduces to $C_{ij} = \sqrt{2\Gamma(p)}\delta_{ij}$. Such an assumption, strictly valid for $p \to 0$, is usually employed at finite p for heavy quark dynamics in the QGP [8–11,39–41]. With the knowledge of $F(p)$ and $\Gamma(p)$ as functions of T and p, the Langevin equation is ready to be solved. We use the pre-Ito discretization scheme for the numerical implementation of the Langevin dynamics.

III. DYNAMICAL MODEL

To solve the Langevin equation in the QGP/hadronic phase one needs the drag and diffusion coefficients of heavy quarks/heavy baryons as a function of temperature and momentum in the QGP/hadronic medium. The drag and diffusion coefficients of the heavy quarks in the QGP are calculated inspired by the quasiparticle model (QPM) [42–44]. The quasiparticle approach accounts for the nonperturbative dynamics by means of temperature-dependent quasiparticle masses for light quarks and gluons, respectively,

$$m_q^2 = \frac{2N_c + N_f}{12}g^2(T)T^2, \quad (3)$$

$$m_g^2 = \frac{N_c^2 - 1}{8N_c}g^2(T)T^2, \quad (4)$$

as well as a T-dependent background field known as bag constant. The strong coupling constant is obtained by a fit of the lattice energy density and is parametrized as follows:

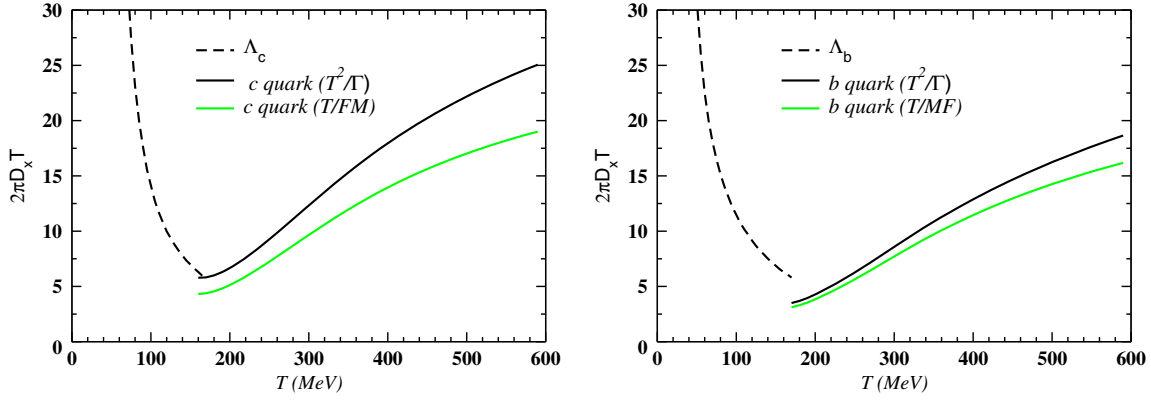$$g^2(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left[\lambda(T/T_c - T_s/T_c)\right]^2}, \quad (5)$$

FIG. 1. D_x as a function of T for c quark and Λ_c (left) and for b quark and Λ_b (right).

with $N_c = N_f = 3$, $\lambda = 2.6$ and $T_s/T_c = 0.57$ [45]. The quasiparticle scheme is able to successfully reproduce the thermodynamics of lattice QCD [45] by fitting the strong coupling $g(T)$. For the evaluation of the drag and diffusion coefficients in the QGP medium, we use the QPM approach recently addressed in Ref. [38] to describe heavy quark R_{AA} and v_2 at RHIC and LHC energies. A self-consistent dynamical treatment should include the finite width of the quasiparticle; however the drag and diffusion are not significantly affected; see Refs. [43,44]. The drag has been calculated in Ref. [38] and shows a very mild T dependence in comparison with perturbative QCD (pQCD) or AdS/CFT. We notice that a similar dependence is found in the T-matrix approach [46,47].

Within the Fokker-Planck approach, the spatial diffusion coefficient [39,48], D_x, can be calculated in the static limit ($p \rightarrow 0$) in two different ways. It can be obtained from the diffusion coefficient in momentum space,

$$D_x = \frac{T^2}{\Gamma},\tag{6}$$

or from the drag coefficient using the Einstein relation ($\Gamma = MFT$),

$$D_x = \frac{T}{MF}.\tag{7}$$

However, the Einstein relation may not be strictly valid at high temperatures in the QGP phase. Hence, we are using both approaches (6) and (7) to evaluate the spatial diffusion coefficient in the QGP phase.

In Fig. 1 the spatial diffusion coefficient in the QGP phase [38] is compared with the one for heavy baryons in hadronic matter [36]. In the left panel of this figure, we show $2\pi D_x T$ as a function of the temperature for c quarks (high temperature) and Λ_c baryons (low temperature). We find that the Λ_c diffusion coefficient also supports a continuous evolution with a minimum around T_c like the heavy-meson case (D meson) [11,22,49]. The differences of the D_x in the QGP phase by the two different approaches are due to the violation of the Einstein relation. In the

hadronic sector we have observed that the Einstein relation is satisfied for all temperatures [36].

In the right panel of Fig. 1 we show $2\pi D_x T$ as a function of temperature for b quarks (high temperature) and for Λ_b baryons (low temperature). In this case we also find an almost continuous evolution with a minimum around T_c. For the bottom case, the calculations of the spatial diffusion coefficient using Eq. (6) and Eq. (7) are in better agreement than for the charm case. The reason is that due to the heavier mass of the b quark, the Einstein relation is better satisfied than the charm case (violations are more severe at high temperature), and the two ways of computing D_x are practically equivalent.

Once the temperature of the QGP phase goes below T_c, the QGP phase gives way to the hadronic phase. In this phase heavy hadrons, produced after hadronization, suffer from collisions with light mesons. To fully characterize the QGP phase, the impact of the hadronic phase should be then taken into account. Several attempts have been made in this direction to study the hadronic medium interaction and their impact on heavy mesons (D and B) observables at RHIC and LHC energies. However, little effort has been given to the study of heavy baryon interaction in the hadronic phase.

Here, we use the recent results in Ref. [36], where some of us analyzed the heavy baryon interaction with the hadronic medium consisting of light mesons (π, K, $\bar{K}$ and η) within unitarized interactions from effective field theories that respect chiral and heavy-quark symmetries. With these interactions, we have obtained the heavy-baryon transport coefficients (drag and diffusion) as a function of temperature and momentum. In the present work we aim at studying the heavy baryon evolution in the hadronic phase within the Langevin dynamics using the drag and diffusion coefficients calculated in the previous paper and highlight its impact on several observables potentially measurable at RHIC and LHC energies, in particular on R_{AA} and v_2.

A. Initialization and heavy quark dynamics

The solution of the Langevin equation needs a background medium describing the space-time evolution of the

bulk matter. To describe the expansion and cooling of the bulk matter and its elliptic flow $v_2(p_T)$ at both RHIC and LHC colliding energies, we have employed a $3D + 1$ relativistic transport code with an initial condition given by a standard Glauber model. Such a model allows us to describe the evolution of a fluid with a fixed η/s in the same way as is done by viscous hydrodynamical simulation. For more details we refer the reader to Refs. [50–53].

In this work we have performed simulations of Au + Au collisions at $\sqrt{s} = 200$ AGeV for the minimum bias. The initial conditions for the bulk evolution in the coordinate space are given by the Glauber model. In momentum space we use a Boltzmann-Jüttner distribution function up to a transverse momentum $p_T = 2$ GeV, while at larger momenta mini-jet distributions as calculated within pQCD at next-to-leading order (NLO) order [54,55].

At RHIC energies for Au + Au at $\sqrt{s} = 200$ AGeV, the maximum initial temperature of the fireball at the center is $T_0 = 340$ MeV and the initial time for the fireball simulations is chosen as $\tau_0 = 0.6$ fm/c (according to the criterion $\tau_0 \cdot T_0 \sim 1$ and to standard setting in hydrodynamics). We have also extended our calculation to study the heavy baryons R_{AA} and v_2 at LHC energies performing simulations of Pb + Pb collisions at $\sqrt{s} = 5.5$ ATeV energy. In this case the maximum initial temperature at the center of the fireball is $T_0 = 610$ MeV and the initial time for the simulations is chosen as $\tau_0 \sim 1/T_0 = 0.25$ fm/c. We have performed simulations for 0%–20% centrality class.

The heavy-quark distribution in momentum space, both for RHIC and LHC, is taken in accordance with the charm distribution in $p + p$ collisions, calculated within fixed order + next-to-leading log (FONLL), taken from Refs. [56,57], where in the coordinate space they are distributed according to number of binary nucleon-nucleon collisions (N_{coll}) from the Glauber model for both RHIC and LHC energies. We solve the Langevin dynamics to study the time evolution of heavy quark momentum in QGP created in Au + Au collision as discussed in Sec. II. The interaction between the heavy quarks and the bulk has been embedded through the drag and diffusion coefficients calculation within the QPM approach discussed at the beginning of this section.

B. Hadronization and hadronic evolution

Another important aspect of a heavy-ion collision is the hadronization mechanism, when heavy quarks combine into color-neutral objects. Hadrons are formed when the temperature reaches $T = T_c = 160$ MeV [58]. One of the basic mechanisms of hadronization, widely considered in this context, is the fragmentation of an individual quark where the hadron momentum is a fraction z of the quark momentum. For gluons and light quarks the fragmentation functions are rather broad distributions around $z = 0.5$, but for heavy quarks the fragmentation functions become rather

sharply peaked towards $z = 1$. The charm quark fragmentation for D meson and Λ_c can be described using the Peterson fragmentation function [59],

$$f(z) \propto \frac{1}{z[1 - \frac{1}{z} - \frac{\epsilon_c}{1-z}]^2}, \qquad (8)$$

where ϵ_c is a free parameter to fix the shape of the fragmentation function in comparison with the experimental data in $p + p$ collision. Unlike D meson, the heavy baryon fragmentation function is not precisely known as it is yet to be measured in $p + p$ collisions. The D meson spectra in $p + p$ collision at RHIC energy using FONLL calculation for the initial charm production can be reproduced using $\epsilon_c = 0.01$. The D meson spectra at LHC energy can be also reproduced using $\epsilon_c = 0.01$. In the absence of the $p + p$ data for the Λ_c production at RHIC and LHC energies, we are using the electron-positron annihilation data to fix the shape of the Λ_c fragmentation. In electron-positron annihilation, the ϵ_c for the Λ_c is about a factor two larger than the D meson one [60]. This means that the Λ_c fragmentation function is softer than the D meson fragmentation. This is because Λ_c contains one heavy quark and two light quarks, whereas the D meson has one heavy quark and one light antiquark. So in accordance with the electron-positron annihilation data, we are using $\epsilon_c = 0.02$ for the Λ_c, a factor two larger than the D meson.

In Fig. 2 we show the variation of Λ_c fragmentation function with the fraction of momentum together with the D meson fragmentation function. As expected, the Λ_c fragmentation function is softer than the D meson as it takes more energy to pop up two quarks from the vacuum in the fragmentation picture. For Λ_b we use $\epsilon_c = 0.006$, a factor two larger than the B-meson fragmentation function.

After the hadronization from the charm and bottom quarks to Λ_c and Λ_b, respectively, we solve the Langevin dynamics for the propagation of Λ_c and Λ_b in an hadronic bath that consists of π, K, $\bar{K}$ and η. The interaction between
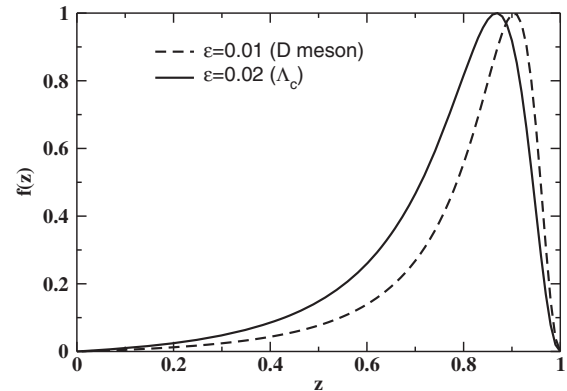

FIG. 2. Variation of the fragmentation function with the fraction of momentum.
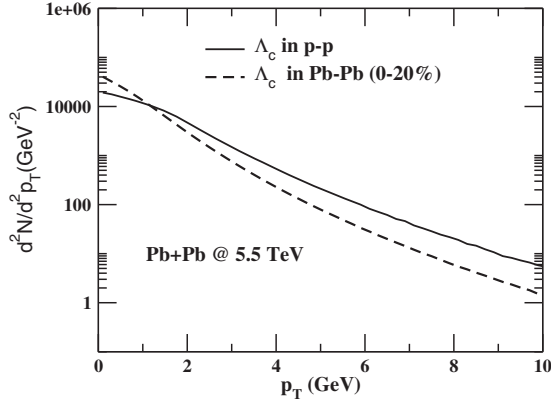
FIG. 3.   Variation of Λ_c spectra in $p + p$ and Pb + Pb collision at LHC colliding energy in arbitrary normalization.

the heavy baryons with the bath has been treated within unitarized interactions based on effective field theories that respect chiral and heavy-quark symmetries. Specifically, the interaction of Λ_c and Λ_b scattering off π, K, $\bar{K}$ and η mesons is obtained within a unitarized meson-baryon coupled-channel model that incorporates heavy-quark spin symmetry [61–66]. This is a predictive model for four flavors including all basic hadrons (pseudoscalar and vector mesons, and $1/2^+$ and $3/2^+$ baryons) which reduces to the Weinberg-Tomozawa interaction in the sector where Goldstone bosons are involved. This scheme has SU(6) × HQSS symmetry, i.e., spin-flavor symmetry in the light sector and HQSS in the heavy (charm/bottom) sector, and it is consistent with chiral symmetry in the light sector. For more details of the hadronic interaction we refer the reader to the earlier work [36]. The time evolution of heavy baryons within the hadronic phase is continued until the temperature reaches $T_{\mathrm{kin}} = 120$ MeV [67], at the kinetic freeze out.

In Figs. 3 and 4 we show the variation of Λ_c and Λ_b spectra in $p + p$ and Pb + Pb at LHC colliding energies in arbitrary normalization. In the Pb + Pb collision, due to
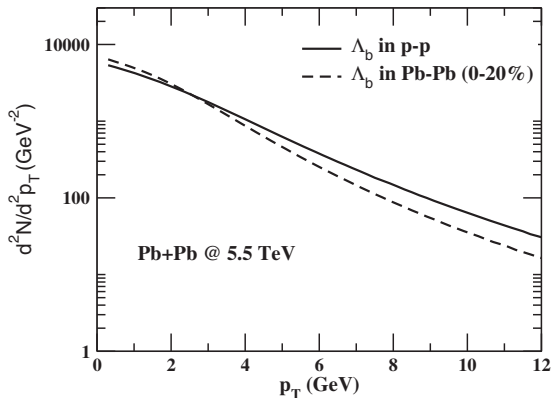

FIG. 4.   Variation of Λ_b spectra in $p + p$ and Pb + Pb collision at LHC colliding energy in arbitrary normalization.

interaction between heavy quarks and the bulk in the QGP phase as well as heavy baryons and the bulk in the hadronic phase, the heavy baryons rearrange their spectra with larger population at low momentum.

IV. RESULTS: EXPERIMENTAL OBSERVABLES

The heavy-baryon observables which are going to be measured at LHC Runs 2 and 3 [25,68] are the nuclear suppression factor (R_{AA}) and the elliptic flow (v_2). We evaluate these observables at both RHIC and LHC energies using Peterson fragmentation function as described above. One of our main motivations is to highlight the impact of the hadronic medium rescattering on heavy baryon observables.

A. Nuclear modification factor, R_{AA}

One of the key observables related to heavy quark propagation, which is measured at RHIC and LHC energies, is the nuclear suppression factor R_{AA}. It measures the depletion of high transverse momentum (p_T) hadrons (D and B mesons) produced in nucleus + nucleus collisions with respect to those produced in proton + proton collisions scaled with the number of binary collision.

The ALICE physics program for Runs 3 and 4 [25,68] is going to measure the nuclear suppression factor R_{AA} for heavy baryons. Keeping this in mind, we are keen to study the R_{AA} of heavy baryons highlighting the possible impact of the hadronic medium. To access the effects of the QGP phase without hadronic interaction, we take the initial distribution of heavy quarks f_i at $t = \tau_i$, and compare it with the distribution of heavy baryons right after the heavy quark fragmentation takes place ($f_{\mathrm{QGP} \rightarrow \mathrm{HP}}$ at T_c), that is

$$R_{AA}^{\mathrm{QGP} \rightarrow \mathrm{HP}}(p) = \frac{f_{\mathrm{QGP} \rightarrow \mathrm{HP}}(p)}{f_i(p)}. \qquad (9)$$

Similarly, the suppression factor in the hadronic phase alone can be written as

$$R_{AA}^{\mathrm{HP}}(p) = \frac{f_{\mathrm{HP}}(p)}{f_{\mathrm{QGP} \rightarrow \mathrm{HP}}(p)}, \qquad (10)$$

where f_{HP} is the solution of the Langevin equation describing the evolution in the hadronic phase at the freeze out $T_{\mathrm{kin}} = 120$ MeV. Notice that in the absence of any hadronic rescattering effect $R_{AA}^{\mathrm{HP}} = 1$.

The net suppression of the heavy mesons during the entire evolution process, from the beginning of the QGP phase to the end of the hadronic phase, is given by

$$R_{AA}(p) = R_{AA}^{\mathrm{QGP} \rightarrow \mathrm{HP}}(p) \times R_{AA}^{\mathrm{HP}}(p) = \frac{f_{\mathrm{HP}}(p)}{f_i(p)}, \qquad (11)$$

which in the absence of genuine hadronic effects $R_{AA}(p) \simeq R_{AA}^{\mathrm{QGP} \rightarrow \mathrm{HP}}(p)$.
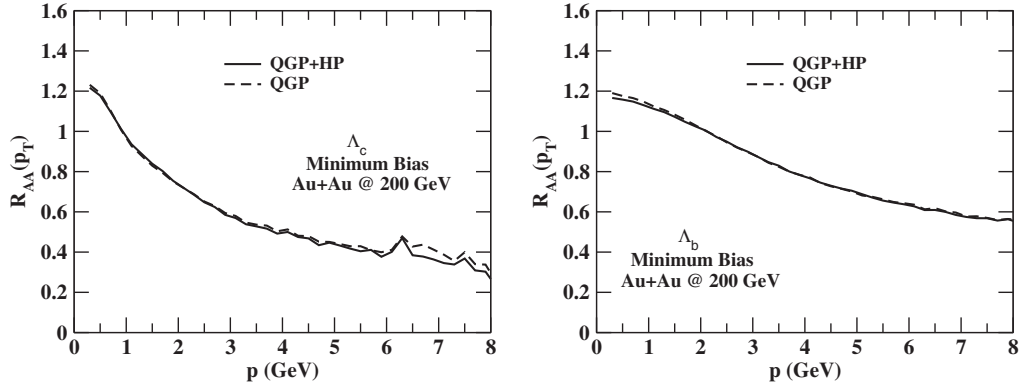
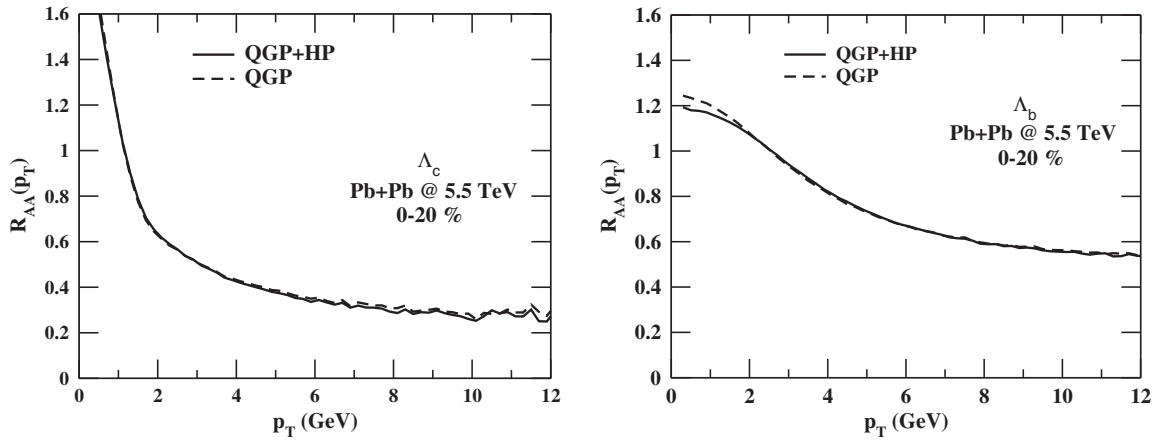FIG. 5. R_{AA} as a function of p_T for Λ_c (left) and Λ_b (right) at RHIC energy.

In Fig. 5 we show the variation of R_{AA} as a function p_T for the Λ_c (left panel) and Λ_b (right panel) in the QGP as well as in the QGP + HP at RHIC energy. For the Λ_c the suppression is stronger as we increase p_T than the Λ_b, mainly due to the different interaction of c and b quarks in the QGP phase. We find that the role of the hadronic phase on both the Λ_c and the Λ_b R_{AA} is almost unnoticeable. This can be explained because R_{AA} is very sensitive to the early stages of the expansion (at high temperatures) where the energy density is the highest [69]. Therefore, collisions take place at a high rate in the early stages, before hadronization. This translates into a strong initial suppression (R_{AA}) which then gets saturated within 3–4 fm due to the radial flow that is able to compensate the baryon energy loss. Hence, further rescattering in the hadronic medium is unable to alter this spectrum.

Note that the spectra of Λ_c and Λ_b baryons is obtained here from the fragmentation of high-energy charm and bottom quarks using the Peterson fragmentation function. Such mechanism of hadronization may not be valid for low-momentum hadrons which are expected to be produced from the coalescence of a heavy quark with thermal light partons [34].

We have also extended our calculation to study R_{AA} of Λ_c and Λ_b at LHC colliding energy by performing simulations of Pb + Pb at $\sqrt{s} = 5.5$ ATeV. These are our predictions for the upcoming heavy-baryon data at ALICE energy. In Fig. 6 we present the variation of R_{AA} as a function of p_T for the Λ_c (left panel) and Λ_b (right panel) in the QGP as well as in the QGP + HP at LHC energy. As seen before for RHIC energies, the suppression is stronger for Λ_c than Λ_b. This is mainly due to the larger drag coefficient of charm quark than bottom quark, which shifts the high-p_T particles to lower p_T resulting in a higher population at low p_T. In addition, the bottom quark initial distribution is harder than the initial charm quark distribution. We have not considered the effect of shadowing [70] in the initial charm distribution which could be significant at low momentum. In the case of LHC energy we find that the role of the hadronic phase on R_{AA} is almost unnoticeable for both Λ_c and Λ_b.

B. Elliptic flow, v_2

Another key observable related to heavy quarks measured at the RHIC and LHC energies is the elliptic flow induced by the spatial anisotropy of the bulk medium. It can be calculated as

FIG. 6. R_{AA} as a function of p_T for Λ_c (left) and Λ_b (right) at LHC energy.
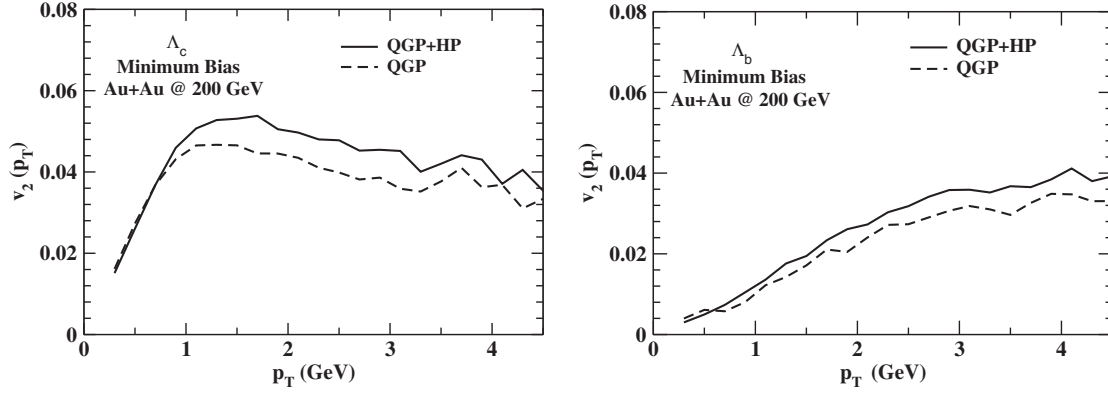
FIG. 7. v_2 as a function of p_T for Λ_c (left) and Λ_b (right) at RHIC energy.

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle. \qquad (12)$$

We define the v_2 generated in QGP phase taking p_x, p_y and p_T as the momenta of the heavy baryons at T_c. The v_2 for the heavy baryons during the entire evolution process, from the beginning of the QGP phase to the end of the hadronic phase, is computed by taking p_x, p_y and p_T the momenta at the freeze-out T_f.

In Fig. 7 we see the variation of v_2 as a function of p_T for the Λ_c (left panel) and Λ_b (right panel) in the QGP as well as in the QGP + HP at RHIC energy. We find that the v_2 is enhanced due to the presence of the hadronic phase. As mentioned earlier, the R_{AA} is quite sensitive to the early stages of the expansion (at high T) where the energy density is the highest, and therefore collisions take place at a higher rate. However such a strong interaction will not be accompanied by a build-up of v_2 because the bulk medium has not yet developed a sizable part of its elliptic flow. First, the bulk will generate its own v_2 and then the bulk will transfer it to the heavy quarks. This usually happens at the later stage of the evolution. Hence, the v_2 is sensitive to the heavy particle-bulk interaction.

It should be mentioned that the heavy baryons develop a substantial part of their v_2 mainly from the interaction they

suffer at the quark level (as c or b quarks) in the QGP phase as well as due to their interaction in the hadronic phase. But they also can get some part of their v_2 (mainly at low momentum) from the thermal light quarks during hadronization by coalescence, which cannot be captured using only fragmentation.

We have also extended the calculation for LHC energies at Run 2. In Fig. 8 we have shown the variation of v_2 as a function of p_T for the Λ_c (left panel) and Λ_b (right panel) in the QGP as well as in the QGP + HP phase at $\sqrt{s} = 5.5$ ATeV. We find the v_2 further enhanced up to 15% due to the presence of the hadronic phase.

We find the enhancement of the v_2 due to the presence of hadronic phase is larger for RHIC colliding energy than the LHC energy, which is clearly shown on the v_2 plots. The difference in the magnitude of v_2 due to the hadronic phase contribution at the RHIC and LHC energies can be understood from the magnitude of the drag and diffusion coefficients in the hadronic medium as well as from the initial distribution. The coefficients and the initial distribution are inputs in Langevin dynamics at the beginning of the hadronic phase. The temperature of the hadronic medium for both the RHIC and LHC colliding energies varies from T_c to T_f (from 160 to 120 MeV), and therefore the values of the drag and diffusion coefficients will not
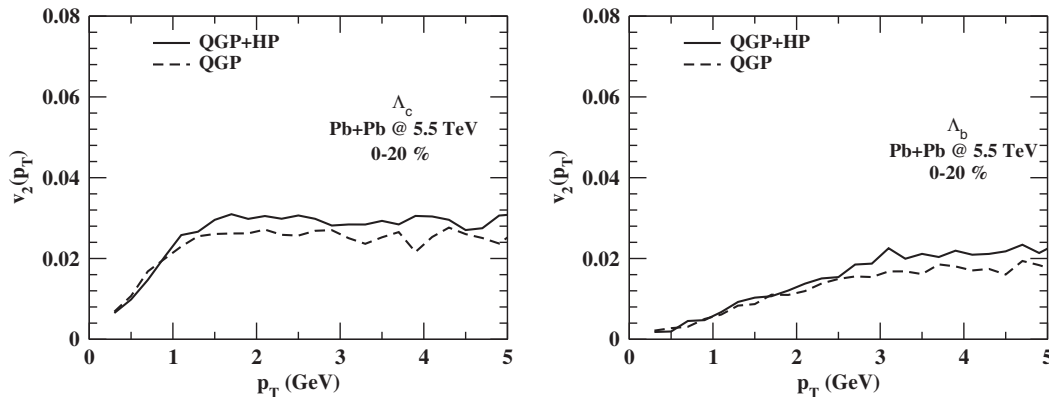
FIG. 8. v_2 as a function of p_T for Λ_c (left) and Λ_b (right) at LHC energy.

change much. However, the input initial distribution to the hadronic matter is harder at the LHC energy than at the RHIC energy, resulting in less v_2 at the LHC energy. Also the lifetime of the hadronic phase remains the same for both RHIC and LHC energies, whereas the lifetime of the QGP phase is longer at LHC energy than RHIC, hence, having the hadronic phase less impact at LHC energy. Indeed, the effect of the hadronic phase on the v_2 will be more significant for low-energy nuclear collision due to the diminishing lifetime of the QGP phase.

Note that, as compared to v_2, the impact of the hadronic phase in R_{AA} is much smaller both at RHIC and LHC energy. Hence, the R_{AA} may play a unique role in characterizing the QGP phase. It is also important to mention that the impact of the hadronic medium is almost mass independent, i.e. the impact of the hadronic medium in the v_2 of Λ_b and Λ_c is similar.

V. HEAVY BARYON TO MESON RATIO

The heavy baryon to heavy meson ratios (Λ_c/D and Λ_b/B) are fundamental for the understanding of in the medium hadronization [34] with respect to the light flavored baryon to meson ratio [54,55]. Enhancement of Λ_c/D and Λ_b/B in Au + Au collisions compared to p + p collisions affects the nonphotonic single-electron spectra resulting from semileptonic decays of hadrons containing heavy flavors; hence, their nuclear suppression factor (R_{AA}) [31–33,35]. This is because the branching ratio for the decay process $\Lambda_c \rightarrow e + X(4.5\% \pm 1.7\%)$ is smaller than $D \rightarrow e + X(17.2\% \pm 1.9\%)$, resulting in less electrons from decays of Λ_c than D. Therefore, enhancement of the Λ_c/D ratio in Au + Au/Pb + Pb collisions will affect the observed nonphotonic single electrons. hence, the R_{AA}. In this manuscript we investigate the Λ_c/D ratio for both RHIC and LHC energies. We study the possible impact of a hadronic medium, if any, on a heavy baryon to heavy meson ratio. This investigation is very timely, because LHC is preparing for Runs 2 and 3 having major interest on a heavy baryon to meson ratio. It becomes particularly appealing to study if heavy baryon observables are carrying signature of the QGP phase or QGP + hadronic phase.

To evaluate the heavy baryon to meson ratio we use the fragmentation as well as fragmentation plus coalescence model for heavy qurak hadronization. The coalescence mechanism we employ for D meson and Λ_c is similar to the one used for the hadronization of light quarks in [54,55,71]. Given the momentum distribution of the heavy quarks obtained solving the Langevin dynamics, the contribution due to coalescence can be evaluated as follows:

$$\frac{d^2N_H}{dP_T^2} = g_H \int \prod_{i=1}^{n} \frac{d^3p_i}{(2\pi)^3E_i} p_i \cdot d\sigma_i f_{q_i}(x_i, p_i)$$

$$\times f_H(x_1 \ldots x_n, p_1 \ldots p_n)\delta^{(2)}\left(P_T - \sum_{i=1}^{n} p_{T,i}\right) \quad (13)$$

where $d\sigma_i$ denotes an element of a spacelike hypersurface, n is the number of quarks, g_H is the statistical factor to form a colorless hadron from quark and antiquark with spin 1/2. f_{q_i} are the quark (antiquark) distributions in phase space. f_H is the Wigner function and describes the spatial and momentum distribution of quarks in a hadron. It depends in principle on the overlap of the quark and antiquark distribution functions with the wave function of the meson as well as the interactions of emitted virtual partons, which are needed for balancing the energy and momentum, with the partonic matter. Neglecting the off-shell effects the coalescence probability function is then simply the covariant hadron Wigner distribution function. The longitudinal momentum distributions of the quarks and antiquarks are assumed to be boost invariant. For details, we refer to Ref. [55].

In the Greco-Ko-Levai (GKL) approach [55] for a heavy meson the Wigner function is taken as a Gaussian of radius Δ_x in coordinate space and Δ_p in momentum space, these two parameters being by the uncertainty principle $\Delta_x\Delta_p = 1$,

$$f_M(x_1, x_2; p_1, p_2) = 8\exp(x_r^2/(2\Delta_x^2))$$
$$\times \exp((p_r^2 - \Delta m_{12}^2)/(2\Delta_p^2)) \quad (14)$$

where we have defined the quadri-vectors for the relative coordinates $x_r = x_1 - x_2$, $p_r = p_1 - p_2$ and the scalar $\Delta m_{12} = m_1 - m_2$. We use $\Delta_x = 1.06$ fm for D meson.

To extend the calculations for mesons to the formation of baryons from the parton distribution functions, we take the baryon coalescence probability function as

$$F_B(x_1, x_2, x_3; p_1, p_2, p_3)$$
$$= 8^2\exp(x_r^2/(2\Delta_x^2))\exp((p_r^2 - \Delta m_{12}^2)/(2\Delta_p^2))$$
$$\times \exp\left(\frac{1}{6}(x_1 + x_2 - 2x_3)^2/(2\Delta_x^2)\right)$$
$$\times \exp\left(\frac{1}{6}((p_1 + p_2 - 2p_3)^2 - (m_1 + m_2 - 2m_3)^2)/(2\Delta_p^2)\right).$$
$$(15)$$

We use $\Delta_x = 0.98$ fm for Λ_c. Starting from the charm quark distributions, the coalescence probability of D and Λ_c has been calculated using Eq. (13) at T_c with the appropriate choice of Wigner function. The charm quarks that do not coalescence, are eventually fragmented in accordance with the fragmentation functions of D and Λ_c discussed in Sec. III B. In the present calculations, we have included the contributions from resonances decay coming from Σ_c, $\Lambda(2526)$, $\bar{\Sigma}_c$ and $\bar{\Lambda}_c$. It can be mentioned that the contribution from resonance decays affect the ratio (heavy baryon to meson) [29] as it involves the ratio of two different hadron species having different contribution from the resonance decays. But the impact of resonances decays
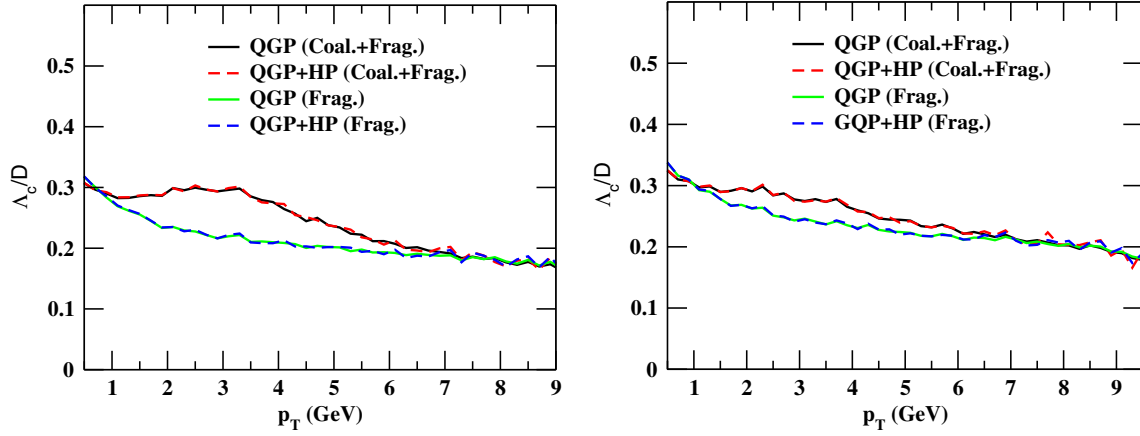
FIG. 9. Λ_c/D as a function of p_T at RHIC (left) and at LHC energy (right).

on R_{AA} is negligible, even if not vanishing, as it affects similarly the numerator and denominator of the ratio because its impact is similar in $p + p$ and $Au + Au/Pb + Pb$. After the hadronization, we perform the time evolution of heavy hadrons (D and Λ_c) within the hadronic phase until the temperature reaches $T_{\rm kin} = 120$ MeV.

In Fig. 9 we see the variation of Λ_c/D as a function of p_T at RHIC (left panel) and at LHC energy (right panel) for QGP and QGP + hadronic phase within coalescence plus fragmentation and fragmentation. The impact of coalescence is mainly restricted to the low p_T region (within p_T 1–5 GeV) above which the hadronization mechanism is dominated by fragmentation. The coalescence probability involves the product of two distribution functions which fall very fast at high momentum making way for the fragmentation as the dominant mechanism of hadronization. As shown, the impact of coalescence is less significant at LHC energy than RHIC energy. This is because impact of coalescence depends on the slope of the charm quark p_T distribution. For a harder distribution the gain in momentum reflects in a smaller increase of the slope of the charm quark distribution, instead if the distribution decreases fast in momentum then the same momentum gain due to coalescence will result in a stronger increase of the spectrum. For a hard distribution, which is the case at LHC energy (in contrast to RHIC), the impact of coalescence will be less pronounced. The present study gives the possibility to disentangle/understand different hadronization mechanisms of heavy quarks once the data will be available. More significantly, the Λ_c/D is independent of the hadronic phase both at RHIC and LHC energies. As discussed earlier, the impact of hadronic phase is almost unnoticeable on R_{AA} of Λ_c, hence, on the spectra. Thus, the impact of the hadronic medium on another ratio, such as Λ_c/D, is negligible, which enables Λ_c/D as a noble probe of QGP phase dynamics including its hadronization. We prefer to ignore the bottom case to avoid uncertainty in the final ratios due to lack of knowledge of the resonance feed-down from higher states.

VI. CONCLUSIONS

We have studied the R_{AA} and v_2 of heavy baryons highlighting the impact of the hadronic medium on these observables within a Langevin dynamics. The QGP medium interaction of the c and b quarks with the light quarks and gluons have been treated within a quasiparticle model [38]. To fix the shape of heavy baryon fragmentation function, we have used the information available from electron-positron annihilation data on heavy baryon fragmentation function. Heavy baryon fragmentation function is softer than the heavy meson fragmentation function as the baryon involves three-body fragmentation whereas the meson a two-body fragmentation. We find that the impact of hadronic medium on the R_{AA} for heavy baryons (Λ_c and Λ_b) is almost unnoticeable while the hadronic medium contribution is sizable on v_2, which is about 20%. We have also calculated the Λ_c/D ratio at RHIC and LHC energies. The heavy hadron suppression does not change in the hadronic phase, hence the spectra. Thus, the impact of the hadronic medium on another ratio, such as Λ_c/D, is negligible, which enables Λ_c/D as a noble probe of QGP phase. So the enhancement of heavy baryon to meson ratio, if any, in $Au + Au/Pb + Pb$ collisions with respect to $p + p$ collisions would be an indication of QGP phase dynamics including its hadronization. Furthermore, the Λ_c/D can serve as a tool to disentangle different hadronization mechanisms once the data will be available.

ACKNOWLEDGMENTS

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