Elliptic flow and nuclear modification factors of D-mesons at FAIR in a Hybrid-Langevin approach

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Abstract

The Compressed Baryonic Matter (CBM) experiment at the Facility for Anti-proton and Ion Research (FAIR) will provide new possibilities for charm-quark (D-meson) observables in heavy-ion collisions at low collision energies and high baryon densities. To predict the collective flow and nuclear modification factors of charm quarks in this environment, we apply a Langevin approach for the transport of charm quarks in the UrQMD (hydrodynamics + Boltzmann) hybrid model. Due to the inclusion of event-by-event fluctuations and a full (3+1) dimensional hydrodynamical evolution, the UrQMD hybrid approach provides a realistic evolution of the matter produced in heavy-ion collisions.

As drag and diffusion coefficients we use a resonance approach for elastic heavy-quark scattering and assume a decoupling temperature of the charm quarks from the hot medium of 130 MeV. Hadronization of the charm quarks to D-mesons by coalescence is included. Since the initial charm-quark distribution at FAIR is unknown, we utilize two different initial charm-quark distributions in our approach to estimate the uncertainty of these predictions. We present calculations of the nuclear modification factor, R_{AA}, as well as for the elliptic flow, v_2, in Pb+Pb collisions at $E_{lab} = 25$ AGeV. The different medium modifications of D-mesons and $\bar{D}$-mesons at high baryon-chemical potential are explored by modified drag- and diffusion-coefficients using the corresponding fugacity factor. Here we find a considerably larger medium modification for $\overline{\mathrm{D}}$- than for D-mesons.

I. INTRODUCTION

The new Facility for Anti-proton and Ion Research (FAIR) at GSI in Darmstadt, Germany, will provide novel possibilities of probing strongly interacting matter at high net-baryon densities [1]. This extreme matter is reached by colliding heavy ions (i.e., gold or lead) at high collision energies. So far the most well-known experiments have been focused on increasing the collision energy (i.e., $\sqrt{s_{NN}} = 200$ GeV at RHIC and $\sqrt{s_{NN}} = 2.76$ TeV at LHC). While these experiments already gave and still give great insights to the phase of deconfined matter, where quarks and gluons are quasi free (the Quark Gluon Plasma, QGP), the region of high net-baryon density in the QCD phase diagram has not been explored in detail so far. Nevertheless, the high-density region is extraordinarily interesting for strong-interaction physics, because the region around the critical point of the QCD phase transition to the QGP is expected to be covered with experiments at high baryon chemical potential.

On the theory side a multitude of (potential) signatures and properties of the QCD (phase) transition and the QGP have been predicted [2–4]. Some of these signatures are related to heavy quarks [5]. Since heavy quarks (i.e., c and b quarks) are produced in the primordial hard collisions of the nuclear reaction, they probe the created medium during its entire evolution process. When the system cools down they hadronize and the resulting heavy-flavour mesons can be detected. Therefore, heavy-quark observables provide new insights into the interaction processes within the hot and dense medium. Two of the most interesting observables are the elliptic flow, v_2, and the nuclear modification factor, R_{AA}, of (open) heavy-flavour mesons. Experimentally, the nuclear modification factor shows a large suppression of the open heavy-flavour particles' spectra at high transverse momenta (p_T) compared to the findings in pp collisions at RHIC and LHC. This indicates a high degree of thermalization of the heavy quarks with the bulk medium consisting of light quarks and gluons and, at the later stages of the fireball evolution, the hot and dense hadron gas. The measured large elliptic flow, v_2, of open-heavy-flavour mesons at the various heavy-ion facilities underlines that heavy quarks take part in the collective motion of the bulk medium. A quantitative analysis of the degree of thermalization of heavy quarks in terms of the underlying microscopic scattering processes thus leads to an understanding of the mechanisms underlying the large coupling strength of the QGP and the corresponding transport properties.

In this paper we explore the medium modification of heavy-flavour p_T spectra at FAIR, using a hybrid model, consisting of the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model [6, 7] and a full (3+1)-dimensional ideal hydrodynamical model [8, 9] to simulate the bulk medium (for details of the hybrid approach see [10–16]). The heavy-quark propagation in the medium is described by a relativistic Langevin approach. Similar studies at higher energies have recently been performed in a thermal fireball model with a combined coalescence-fragmentation approach [17–23], in an ideal hydrodynamics model with a lattice-QCD EoS [24, 25], in a model from Kolb and Heinz [26], in the BAMPS model [27, 28], the MARTINI model [29] as well as in further studies and model comparisons [30–34].

Especially at moderate beam energies pQCD based models like BAMPS or MARTINI can not be applied. Also 2+1 dimensional hydrodynamics, e.g. Heinz-Kolb-Hydrodynamics, is not justified due to the strong three-dimensional expansion. Therefore the UrQMD hybrid model provides a major step forward as compared to simplified expanding fireball models employed so far. It provides a realistic and well established background, including event-by-event fluctuations and has been shown to very well describe many collective properties of relativistic heavy-ion collisions.

This study is the first Langevin simulation for heavy quarks to be processed at FAIR energies. Here, a special difficulty is due to the high baryon densities as already mentioned above. To account for these high baryon densities we implement an optional fugacity factor for our drag and diffusion coefficients. Within the here employed resonance-scattering model [35–37] this fugacity factor leads to a stronger medium modification of $\overline{D}$- compared to D-mesons.

II. DESCRIPTION OF THE MODEL

The UrQMD hybrid model combines the advantages of transport theory and (ideal) fluid dynamics [13]. It uses fluctuating initial conditions [13], generated by the UrQMD model [38, 39], for a full (3+1) dimensional ideal fluid dynamical evolution, including the explicit propagation of the baryon current. After a Cooper-Frye transition back to the transport description, the freeze-out of the system is treated gradually within the UrQMD approach. The hybrid model has been successfully applied to describe particle yields and transverse dynamics from AGS to LHC energies [11, 13, 15, 16, 40] and provides therefore a reliable basis for the flowing bulk medium.

The equation of state employed for the present calculations includes quark and gluonic degrees of freedom coupled to a hadronic parity-doublet model [41]. It has a smooth crossover at low baryon densities between an interacting hadronic system and a quark gluon plasma and a (second) first order transition towards higher baryon densities. The thermal properties of the EoS are in agreement with lattice QCD results at vanishing baryon density. For the present study at FAIR energy we rely on the extrapolation to high baryon densities as described in [41].

The diffusion of a heavy quark in a medium consisting of light quarks and gluons can be described with help of a Fokker-Planck equation [17, 30, 35, 37, 42–48] as an approximation of the collision term of the corresponding Boltzmann equation. It can be mapped into an equivalent stochastic Langevin equation, suitable for numerical simulations. In the relativistic realm such a Langevin process reads

$$\begin{aligned} \mathrm{d}x_j &= \frac{p_j}{E}\mathrm{d}t, \\ \mathrm{d}p_j &= -\Gamma p_j \mathrm{d}t + \sqrt{\mathrm{d}t} C_{jk}\rho_k. \end{aligned} \tag{1}$$

Here $\mathrm{d}t$ is the time step in the Langevin calculation, $\mathrm{d}x_j$ and $\mathrm{d}p_j$ are the coordinate and momentum changes in each time-step, m is the heavy-quark mass, $E = \sqrt{m^2 + \boldsymbol{p}^2}$, and Γ is the drag or friction coefficient. The covariance matrix, C_{jk}, of the fluctuating force is related with the diffusion coefficients. Both coefficients depend on $(t, \boldsymbol{x}, \boldsymbol{p})$ and are defined in the (local) rest frame of the fluid. The ρ_k are Gaussian-normal distributed random variables, i.e., its distribution function reads

$$P(\boldsymbol{\rho}) = \left(\frac{1}{2\pi}\right)^{3/2} \exp\left(-\frac{\boldsymbol{\rho}^2}{2}\right). \tag{2}$$

The fluctuating force obeys

$$\left\langle F_j^{(\mathrm{fl})}(t)\right\rangle = 0, \quad \left\langle F_j^{(\mathrm{fl})}(t) F_k^{(\mathrm{fl})}(t')\right\rangle = C_{jl}C_{kl}\delta(t-t'). \tag{3}$$

We use [49]

$$C_{jk} = C_{jk}(t, \boldsymbol{x}, \boldsymbol{p} + \mathrm{d}\boldsymbol{p}). \tag{4}$$

The drag and diffusion coefficients for the heavy quark propagation within this framework are taken from a resonance approach [35, 36]. It is a non-perturbative model, where the existence of D-meson like resonances in the QGP phase is assumed.

The initial production of charm quarks in our approach is based on a space-time resolved Glauber approach. For the realization of the initial collisions for the charm quark production points we use the UrQMD model. First, an UrQMD run with straight trajectories is performed. Here, only elastic 0° scatterings between the colliding nuclei are carried out and the nucleon-nucleon collision space-time coordinates are stored (see [50]). These coordinates are used in a second, full UrQMD run as probability distribution for the production space-time coordinates for the charm quarks.

The initial momentum distribution of the produced charm quarks at FAIR energy is not well known, due to the lack of experimental measurements of D-meson production at these low energies. To account for this uncertainty, we utilize two different momentum distributions for the initial state of D and $\bar{D}$, a parametrization used in HSD calculations and the distribution generated by the PYTHIA model.

The HSD parametrization (derived from higher energies) is taken from a fit to the D-meson distribution in pp collisions at 25 AGeV [51]. As fitting function we use

$$\frac{\mathrm{d}N}{\mathrm{d}p_T} = \frac{C_1}{\left(1 + A_1 \cdot p_T^2\right)^{A_2}}, \tag{5}$$

with the coefficients $A_1 = 0.870/\mathrm{GeV}^2$ and $A_2 = 3.062$. C_1 is an arbitrary normalization constant with the unit 1/GeV.

The PYTHIA parametrization is extracted from a fit to pp collisions generated by PYTHIA [52] at $E_{lab} = 25$ AGeV. Here we use as fitting function

$$\frac{\mathrm{d}N}{\mathrm{d}p_T} = C_2\, p_T^{B_1} \exp\left(-\frac{(p_T - B_2)^2}{2B_3^2}\right), \tag{6}$$

with the coefficients $B_1 = 1.144$, $B_2 = -0.586\,\mathrm{GeV}$ and $B_3 = 0.646\,\mathrm{GeV}$. C_2 is an arbitrary normalization constant with the unit GeV^{-B_1-1}. In the following we normalize the distributions to $\int \mathrm{d}p_T \frac{\mathrm{d}N}{\mathrm{d}p_T} = 1$. These two parametrizations are utilized as our initial charm-quark distributions. Due to the low collision energy, charm quark production in pp collisions is kinematically only allowed up to a transverse momentum of $p_T \approx 2\,\mathrm{GeV}$. Although the production cut-off for charm quarks in Pb+Pb collisions might be somewhat higher due to nuclear effects, our calculations above $p_T \approx 1.5\,\mathrm{GeV}$ should be interpreted with caution only. This is especially true for our R_{AA} calculations.

Starting with these charm-quark distributions as initial condition we propagate the charm quarks on straight lines until the hydro start condition is fulfilled. For the start condition we use $t_{\mathrm{start}} = 2R/\sqrt{\gamma_{\mathrm{CM}}^2 - 1}$, i.e., after the two Lorentz-contracted nuclei have passed through each other (γ_{CM} is the centre-of-mass-frame Lorentz factor, and R is the radius of the nucleus). For the Langevin calculation we use the UrQMD/hydro's cell velocities, cell temperature and the size of the time-step for the calculation of the momentum transfer, propagating all quarks independently. The charm-quark propagation is terminated by hadronization into D-mesons, via quark-coalescence [37, 47, 48].

III. RESULTS

Let us start with the initial and final D-meson p_T-spectra at five different centrality bins for Pb+Pb collisions at $E_{\mathrm{lab}} = 25$ AGeV, as shown in Fig. 1.

The initial D-meson distributions are for both initial state assumptions much softer as compared to D-meson p_T-spectra observed in pp collisions at RHIC or LHC energies. In the HSD parametrization most charm quarks are at very low transverse momenta, and the initial distribution falls down according to a power law. The PYTHIA parametrization has a maximum at

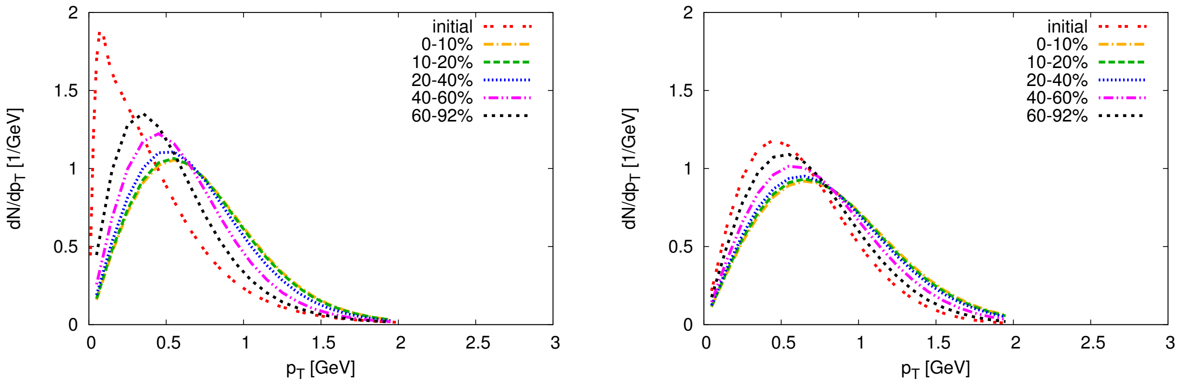

FIG. 1. (Color online) The initial and final normalized p_T spectra of D-mesons in Pb+Pb collisions at 25 AGeV for different centrality bins. The left plot shows our calculation for the HSD initial-state parametrization, the right plot shows it for the PYTHIA initial-state parametrization. We use a rapidity cut of $|y| < 0.35$.

$p_T \approx 0.5$ GeV. At high p_T however, it decreases faster than the HSD parametrization due to the exponential in the distribution function (equation 6).

The final distributions show a thermalization of the charm quarks. The propagation of the charm quarks in the hot medium and the coalescence mechanism drag low-p_T particles to higher p_T bins. This drag is more pronounced at high collision centralities.

In the following we show the elliptic flow, v_2, and the nuclear modification factor, R_{AA}, of D-mesons (for a comparison with the light quark hadron v_2, the reader is referred to [10]). Our results are depicted in Fig. 2, for the elliptic flow, and in Fig. 3, for the nuclear modification factor.

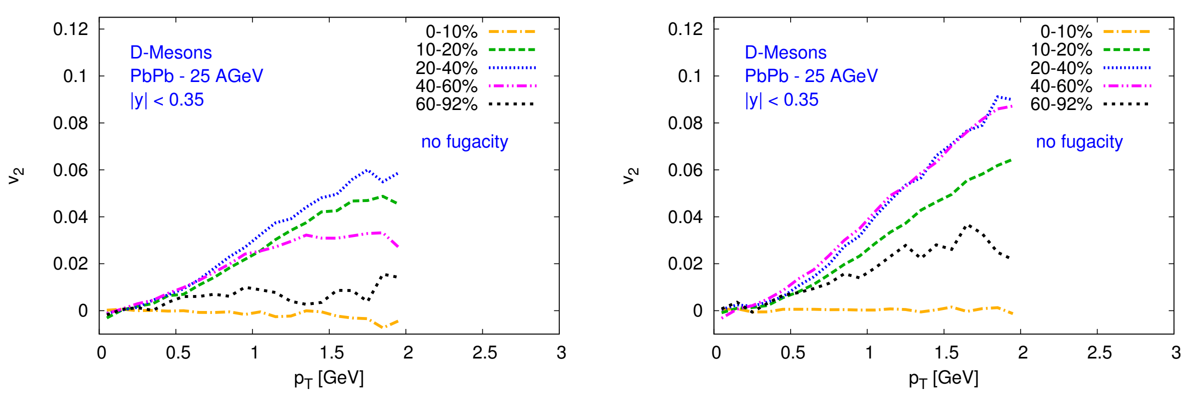

FIG. 2. (Color online) Elliptic flow, v_2, of D-mesons in Pb+Pb collisions at 25 AGeV for different centrality bins. The left plot shows our calculation for the HSD initial-state parametrization, the right plot shows it for the PYTHIA initial-state parametrization. We use a rapidity cut of $|y| < 0.35$.

The strongest elliptic flow in our calculation can be observed for a medium centrality range of $\sigma/\sigma_{\text{tot}} = 20\%$-$40\%$. It reaches up to around 6% in case of the HSD initial-state parametrization, which is approximately half of the elliptic flow which develops at RHIC energies. In case of the PYTHIA parametrization the flow is considerably larger and reaches up to 10%. In both cases the flow for very central and peripheral collisions is, as expected, small. The higher maximal v_2 values with PYTHIA initial conditions are due to the fact that high-p_T charm quarks need more interactions with the medium to reach a high p_T due to the softer p_T spectrum as compared to the HSD intial state.

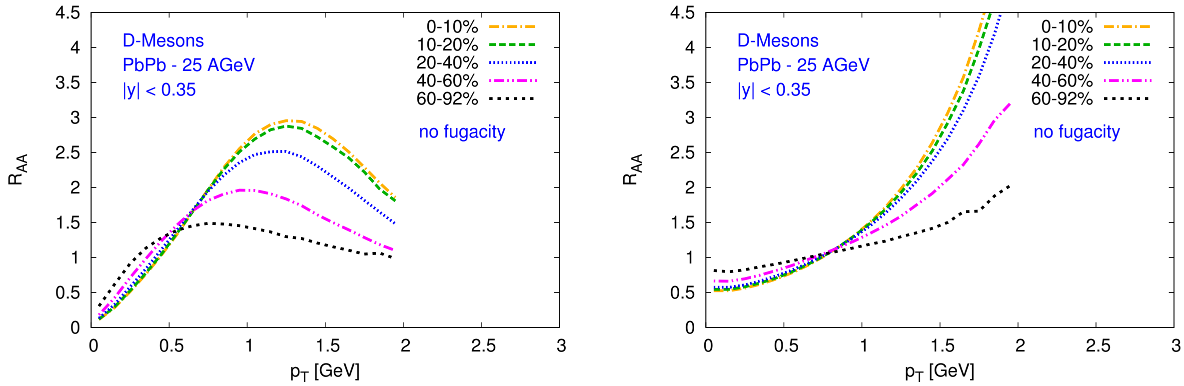

FIG. 3. (Color online) Nuclear modification factor, R_{AA}, of D-mesons in Pb+Pb collisions at 25 AGeV for different centrality bins. The left plot shows our calculation for the HSD initial-state parametrization, the right plot shows it for the PYTHIA initial-state parametrization. We use a rapidity cut of $|y| < 0.35$.

Let us now turn to the nuclear modification factor, R_{AA}, for the case of the HSD parametrization (Fig. 3, left). The strongest modification is reached for central collisions and the lowest for peripheral collisions. We also observe that the highest R_{AA} values move to higher p_T for more central collisions.

Compared to the nuclear modification factor at RHIC and LHC energies [37, 47, 48] the medium modification is extremely large and qualitatively different. On the one hand this effect is due to the initial charm-quark distribution (HSD initial-state parametrization) that we used as one assumption. It is much softer than at RHIC or LHC energies. Therefore it drops off very fast towards higher p_T. Thus the drag of low p_T particles to higher p_T has a large relative influence on the R_{AA} at higher p_T ranges. On the other hand the medium modification of low-p_T heavy quarks seems to be stronger at FAIR energies. As one can see in Fig. 1 (left) a big fraction of the D-mesons at low p_T is shifted to higher p_T. This effect can be explained by the low momenta, also in longitudinal direction, of the heavy quarks and the slow medium evolution at FAIR energies. Therefore the charm quarks stay a long time in the medium and can "heat up" due to the diffusion in our Langevin calculation.

The nuclear modification factor using the PYTHIA initial-state parametrization (Fig. 3, right) looks completely different. At low p_T the PYTHIA parametrization has a similar shape as the medium modified $\mathrm{d}N/\mathrm{d}p_T$ distribution for the HSD calculation (Fig. 1). Therefore the medium modification at low p_T is not as strong as for the former case. For higher p_T the R_{AA} rises drastically, especially for central collisions. The reason is the initial parametrization in equation 6. At high p_T-values it drops faster than a thermal distribution. Therefore, the thermalization of charm quarks drags some of the charm quarks to high-p_T bins that are strongly suppressed (or even forbidden) by energy conservation in the initial state.

In the next step we include fugacity factors in our calculation to account for the high baryon chemical potential at FAIR-energies. Therefore we multiply the anti-charm drag- and diffusion-coefficients by $e^{\mu_B/T}$ and the charm coefficients by $e^{-\mu_B/T}$. Here μ_B is the baryon chemical potential of the surrounding quarks and T is the local temperature of the medium. As initial charm-quark distribution we used the HSD parametrization of equation (5). Fig. 4 shows our results for the elliptic flow and Fig. 5 for the nuclear modification factor.

As one can see the inclusion of fugacity factors changes the results substantially. The elliptic flow for $\overline{\mathrm{D}}$-mesons reaches up to 15% and also the nuclear modification factor changes strongly. The difference between D-mesons and $\bar{D}$-mesons is clearly visible. If we have a look at the difference

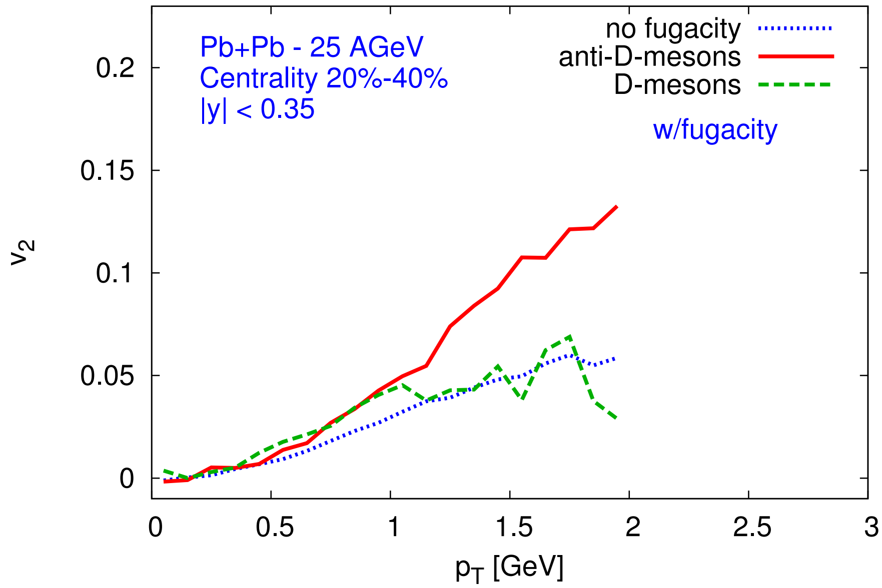

FIG. 4. (Color online) Elliptic flow, v_2, of D-mesons and $\bar{D}$-mesons in Pb+Pb collisions at 25 AGeV using the HSD initial-state parametrization and applying fugacity factors. We use a rapidity cut of $|y| < 0.35$. The results above $p_T \approx 2\,\mathrm{GeV}$ should be interpreted with caution only.

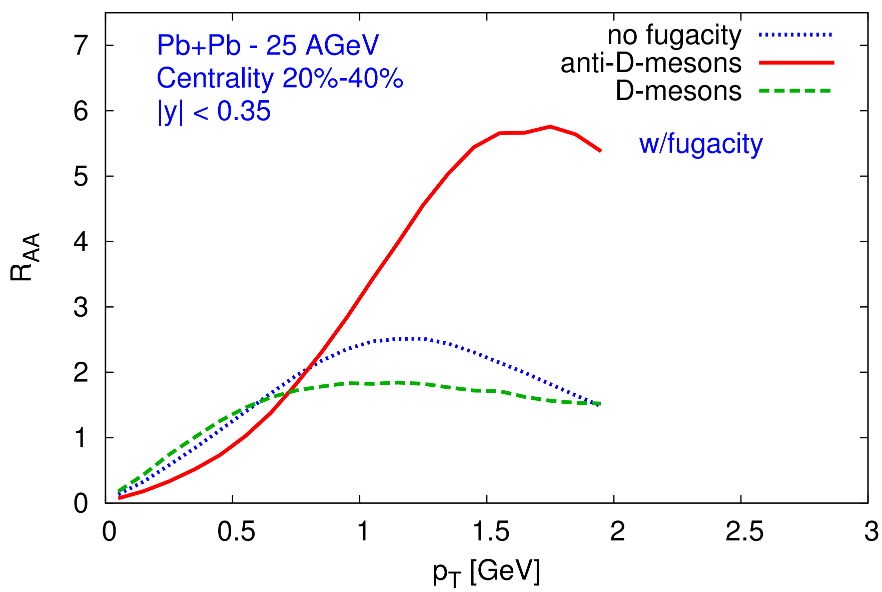

FIG. 5. (Color online) Nuclear modification factor, R_{AA}, of D-mesons and $\bar{D}$-mesons in Pb+Pb collisions at 25 AGeV using the HSD initial-state parametrization and applying fugacity factors. We use a rapidity cut of $|y| < 0.35$. The results above $p_T \approx 2\,\mathrm{GeV}$ should be interpreted with caution only.

between the D-mesons and the calculation neglecting fugacity-factors we realize that the difference is much smaller than for $\overline{\mathrm{D}}$-mesons. This small difference is not due to a small difference of the coefficients used, but to the role of the coalescence mechanism that accounts for the overwhelming fraction of the elliptic flow of D-mesons if the coefficients are small.

Also in case of the nuclear modification factor, R_{AA}, one observes a strong difference between D-mesons and $\overline{\mathrm{D}}$-mesons. Overall the medium modification is considerably stronger than at RHIC and LHC energies. We relate this to two different effects. The first is due to the very soft initial momentum distribution of the charm quarks. Therefore a small change of the R_{AA} at low p_T can result in a substantial R_{AA} change at higher p_T. The second effect comes from the slower bulk-medium evolution at FAIR energies compared to RHIC and LHC energies. This slower evolution results in a longer time that the charm quarks stay in the medium and thus in a stronger drag/diffusion towards thermalization. In the R_{AA} this results in a strong suppression at low p_T due to the resulting "heat-up" of the charm quarks.

We should mention that the difference seen between D-mesons and $\overline{\mathrm{D}}$-mesons is sensitive to the model used to calculate the drag- and diffusion-coefficients. In case of the T-Matrix approach [17] this difference should not arise. Therefore D-meson measurements at FAIR can provide an excellent test for a confirmation or rejection of different heavy-quark-coupling mechanisms to the QGP.

IV. SUMMARY

In this letter we have explored the medium modification of D-meson spectra at FAIR energies. While the elliptic flow is on the same order as compared to higher energies, the R_{AA} shows a strong modification. This modification depends strongly on the initial-state parametrization of the charm-quark momentum distribution. For R_{AA} we observe for the HSD initial-state parametrization (neglecting the energy cut-off for $D\bar{D}$ production) a similar shape as for higher energies, while for the PYTHIA initial-state parametrization R_{AA} rises monotonously with p_T due to the sharp drop-off of the transverse momentum spectra in pp.

We also included fugacity factors in the calculation and found a substantial difference in the medium modification of D-mesons and $\bar{D}$-mesons. However, this difference only appears in case of utilizing the resonance model coefficients and therefore provides an excellent possibility to disentangle models for the calculation of drag and diffusion coefficients.

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