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# Collective flow of open and hidden charm in Au+Au collisions at $\sqrt{s} = 200$ GeV

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We study the collective flow of open charm mesons and charmonia in Au+Au collisions at  $\sqrt{s} = 200$  GeV within the hadron-string-dynamics (HSD) transport approach. The detailed studies show that the coupling of  $D, \bar{D}$  mesons to the light hadrons leads to comparable directed and elliptic flow as for the light mesons. This also holds approximately for  $J/\Psi$  mesons since more than 50% of the final charmonia for central and mid-central collisions stem from  $D + \bar{D}$  induced reactions in the transport calculations. The transverse momentum spectra of  $D, \bar{D}$  mesons and  $J/\Psi$ 's are only very moderately changed by the (pre-)hadronic interactions in HSD which can be traced back to the collective flow generated by elastic interactions with the light hadrons.

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## I. INTRODUCTION

The dynamics of nucleus-nucleus collisions at Relativistic-Heavy-Ion-Collider (RHIC) energies are of fundamental interest with respect to the properties of hadronic/partonic systems at high energy densities. Especially the formation of a quark-gluon plasma (QGP) and its transition to interacting hadronic matter has motivated a large community for more than two decades [1, 2, 3, 4]. However, the complexity of the dynamics has not been unraveled and the evidence for the formation of a QGP and/or the properties of the phase transition is much debated [5]. Apart from the light and strange flavor ( $u, \bar{u}, d, \bar{d}, s, \bar{s}$ ) quark physics and their hadronic bound states in the vacuum ( $p, n, \pi, K, \phi, \Lambda$  etc.), the interest in hadrons with charm ( $c, \bar{c}$ ) has been rising continuously since the heavy charm quark provides an additional energy scale, which is large compared to  $\Lambda_{QCD}$ . Accordingly, the hadronic bound states (with a  $c$  or  $\bar{c}$  quark) have a much larger mass than the ordinary hadrons and one has speculated that especially charmonia ( $c\bar{c}$  bound states) might only be formed in the very early phase of the heavy-ion collision.

In the past the charmonia  $J/\Psi, \chi_c, \Psi'$  have been discussed in context with the phase transition to the QGP since  $c\bar{c}$  states might no longer be formed due to color screening [6, 7]. However, more recent calculations within lattice QCD (LQCD) have shown that at least the  $J/\Psi$  survives up to  $\sim 1.5 T_c$  ( $T_c \approx 0.17$  GeV) such that the lowest  $c\bar{c}$  states remain bound up to energy densities of about  $5 \text{ GeV}/\text{fm}^3$  [8, 9, 10]. It is presently not clear if also the  $D$  or  $D^*$  mesons will survive at temperatures above  $T_c$  but strong correlations between a light quark (antiquark) and a charm antiquark (quark) are likely to persist also above  $T_c$ .

Moreover, it has been pointed out (within statistical models) that at top RHIC energies the charmonium formation from open charm and anticharm mesons might become essential [11, 12, 13, 14] and even exceed the yield from primary nucleon-nucleon ( $NN$ ) collisions

[15]. Such concepts should work out if the early hot and dense medium created in nucleus-nucleus collisions is very strongly interacting and an approximate chemical equilibrium is achieved rapidly. As argued in Refs. [16, 17, 18] an early equilibration might be due to multi-particle interactions either on the partonic [18] or the hadronic side [16, 17].

A previous analysis within the HSD transport model [19] has demonstrated that the charmonium production from open charm and anticharm mesons becomes essential in central Au+Au collisions at RHIC. This is in accordance with independent studies in Refs. [20, 21]. On the other hand, these backward channels – relative to charmonium dissociation with comoving mesons – have been found to be practically negligible at SPS energies. Furthermore, the transport studies in Ref. [22] have shown that chemical equilibrium between the different charmonia  $J/\Psi, \chi_c, \Psi'$  is not obtained in full phase space on the basis of (pre-)hadronic interactions. As pointed out in the latter study this opens up a possibility to distinguish experimentally a statistical freeze-out concept from a hadron/string dynamical picture.

Apart from the total and relative abundancies of charmonia and open charm mesons also their collective properties are of interest. Here especially the transverse momentum (or mass) spectra are expected to provide valuable insight to the dynamics in either the very early or late phase [23, 24, 25, 26, 27]. We recall that the transverse mass spectra at midrapidity show experimentally a 'slope' parameter that increases ( $\sim$  linearly) with the hadron mass [28] if the latter involve only light quarks or only a single strange quark. Multi-strange baryons indeed show a 'slope' parameter below the linear scaling with mass known from the lighter hadrons [29]. The question thus arises if the open charm mesons will follow the trend of the light hadrons similar to kaons (involving only a single  $s$  or  $\bar{s}$  quark)? Also: will the charmonia with their substantially higher mass also show the linear trend as expected from hydrodynamics [23] or do they decouple early as expected in hadron/string dynamical approaches

due to the rather low cross sections with light hadrons [27] (cf. also Ref. [25])?

In this work we extend our previous studies in Refs. [19, 22, 27] with respect to the collective dynamics of  $D, \bar{D}$  mesons and charmonia and concentrate in particular on the transverse mass spectra, the in-plane flow  $v_1$  and the elliptic flow  $v_2$  of these particles. The question we aim at solving is: what is the amount of collectivity generated by (pre-)hadronic interactions in the course of the expansion of the system? Any sincere deviation to future measurements thus will indicate additional sources for pressure and/or strong interactions beyond the standard hadron/string picture.

Our study is organized as follows: After a very brief reminder of the conceptional organization of the HSD transport approach in Section II we will present the input for the transport calculations with respect to the open charm and charmonium dynamics (or provide the relevant references for details). In Section III we present our results for the transverse momentum spectra of  $D$ -mesons and  $J/\Psi$ 's for different centralities in Au+Au collisions at  $\sqrt{s} = 200$  GeV. In order to see the effect of final state interactions more clearly we will, furthermore, present ratios of momentum spectra from Au+Au reactions relative to scaled  $pp$  collisions. Section IV is devoted to the in-plane flow  $v_1$  and elliptic flow  $v_2$  of open charm mesons and charmonia as well as to the freeze-out properties of these particles. Section V concludes this study with a summary.

## II. BASIC CONCEPTS OF THE HSD TRANSPORT APPROACH

We employ the HSD transport model [3, 30] for our study of Au+Au collisions. This approach takes into account the formation and multiple rescattering of formed hadrons as well as unformed 'leading' pre-hadrons and thus incorporates the dominant final state interactions. In the transport approach nucleons,  $\Delta$ 's,  $N^*(1440)$ ,  $N^*(1535)$ ,  $\Lambda$ ,  $\Sigma$  and  $\Sigma^*$  hyperons,  $\Xi$ 's,  $\Xi^*$ 's and  $\Omega$ 's as well as their antiparticles are included on the baryonic side whereas the  $0^-$  and  $1^-$  octet states are included in the mesonic sector. Inelastic hadron-hadron collisions with energies above  $\sqrt{s} \simeq 2.6$  GeV are described by the FRITIOF model [31] (employing PYTHIA v5.5 with JETSET v7.3 for the production and fragmentation of jets [32]), whereas low energy hadron-hadron collisions are modeled in line with experimental cross sections. We stress that no explicit parton cascading or gluon-gluon dynamics is involved in our transport calculations contrary to e.g. the AMPT model [33] or explicit parton cascades [34].

A systematic analysis of HSD results and experimental data for central nucleus-nucleus collisions from 2 A·GeV to 21.3 A·TeV has shown that the spectra for the 'longitudinal' rapidity distribution of protons, pions, kaons, antikaons and hyperons are in reasonable agree-

ment with available data [19, 35, 36]. However, there are problems with the dynamics in the direction transverse to the beam. Whereas the pion transverse momentum spectra are rather well described from lower AGS to top RHIC energies the transverse momentum slopes of kaons/antikaons are clearly underestimated above  $\sim 5$  A·GeV in central Au+Au collisions. In Ref. [36] this failure has been attributed to a lack of pressure generation in the very early phase of the heavy-ion collisions which also shows up in the underestimation of the elliptic flow of charged hadrons at RHIC energies [19].

In spite of the deficiencies pointed out above the overall reproduction of the experimental hadron spectra is sufficiently realistic such that we can proceed with open and hidden charm dynamics.

### A. Perturbative treatment of $D, \bar{D}$ mesons and charmonia

The initial conditions for the production and also subsequent propagation of  $D, \bar{D}$  mesons and charmonia are incorporated in the HSD approach by a superposition of  $pp$  collisions described via scaled PYTHIA [32] simulations [27]. For the production and propagation of open and hidden charm hadrons we employ a perturbative scheme as also used in Refs. [19, 22, 27]. Each 'perturbative' particle ( $h_i$ ) is produced in the transport calculation with a weight  $W_i$  given by the ratio of the actual production cross section divided by the inelastic nucleon-nucleon cross section, e.g.

$$W_i = \frac{\sigma_{NN \rightarrow h_i + X}(s)}{\sigma_{NN}^{\text{inelas.}}(s)}. \quad (1)$$

We then follow the motion of the 'perturbative' particles within the full background of strings/hadrons by propagating them as free hadrons, i.e. neglecting in-medium potentials, but compute their collisional history with baryons and mesons or quarks and diquarks. The actual parametrizations of the total cross sections for  $D, D^*, D_s, D_s^*$  mesons as well as their antiparticles are given in Refs. [19, 27] and [22] together with the cross sections for charmonium production in nucleon-nucleon and pion-nucleon collisions. The only modification introduced here – relative to Refs. [19, 22] – is a change of the parametrisation for the differential production cross section in transverse momentum. Our novel parametrisation follows the first results from STAR [37] and is given by a power law in transverse momentum  $p_T$

$$W(p_T) \sim \left(1 + \frac{p_T}{3.5}\right)^{-8.3}. \quad (2)$$

For simplicity – and lack of further information – we assume that this parametrization holds for all  $D, \bar{D}$  mesons as well as charmonia.

## B. Cross sections involving charm hadrons

In order to study the effect of rescattering we tentatively adopt the following dissociation cross sections of charmonia with baryons independent on the energy (in line with Refs. [19, 22, 27]):

$$\sigma_{c\bar{c}B} = 6 \text{ mb}; \quad \sigma_{J/\Psi B} = 4 \text{ mb}; \quad (3)$$

$$\sigma_{\chi_{cB}} = 5 \text{ mb}; \quad \sigma_{\Psi'B} = 5 \text{ mb}.$$

In (3) the cross section  $\sigma_{c\bar{c}B}$  stands for a (color dipole) pre-resonance ( $c\bar{c}$ ) - baryon cross section, since the  $c\bar{c}$  pair produced initially cannot be identified with a particular hadron due to the uncertainty relation in energy and time. For the lifetime of the pre-resonance  $c\bar{c}$  pair (in it's rest frame) a value of  $\tau_{c\bar{c}} = 0.3 \text{ fm}/c$  is assumed following Ref. [38]. This value corresponds to the mass difference of the  $\Psi'$  and  $J/\Psi$ .

For  $D, D^*, \bar{D}, \bar{D}^*$  - meson ( $\pi, \eta, \rho, \omega$ ) scattering we address to the calculations from Ref. [21, 39] which predict elastic cross sections in the range of 10–20 mb depending on the size of the formfactor employed. As a guideline we use a constant cross section of 10 mb for elastic scattering with mesons and also baryons, although the latter might be even higher for very low relative momenta.

The cross sections for charmonium production by open charm mesons or the inverse comover dissociation cross sections are not well known and the significance of these channels is discussed controversially in the present literature (cf. Ref. [19] and Refs. therein). We here follow the simple 2-body transition model introduced in Refs. [19, 22] with a single free parameter, i.e. a matrix element squared  $M_0^2$ , that allows to implement the backward reactions uniquely by employing detailed balance for each individual channel. The free matrix element has been fixed in Ref. [22] in comparison to  $J/\Psi$  and  $\Psi'$  suppression data at SPS energies. For further details we have to refer the reader to Refs. [19, 22] in order to avoid unnecessary repetitions.

## III. TRANSVERSE MOMENTUM SPECTRA

Since the results for charmonium suppression at SPS and RHIC energies – within the present approach – have been presented in Refs. [19, 22] we directly continue with the transverse dynamics of open charm mesons and charmonia. In Fig. 1 we present the transverse  $p_T$  spectra of the final  $D + \bar{D}$ -mesons (solid lines with full dots, color: blue) and  $J/\Psi$  (solid lines with open squares, color: red) from Au + Au collisions at  $\sqrt{s} = 200 \text{ GeV}$  calculated for impact parameter  $b = 1, 5, 7$  and 12 fm at midrapidity. The dashed lines correspond to the  $p_T$  spectra of  $D$ -mesons at the production point for reference, i.e. without any final state interactions. For very peripheral Au+Au collisions we find no effects from final state interactions whereas with increasing centrality there is an

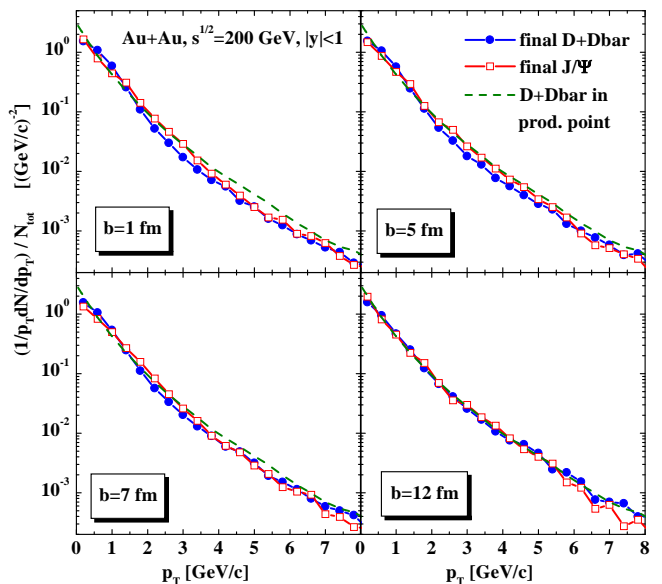


FIG. 1: The transverse  $p_T$  spectra of the final  $D + \bar{D}$ -mesons (solid lines with full dots, color: blue) and  $J/\Psi$  (solid lines with open squares, color: red) from Au + Au collisions at  $\sqrt{s} = 200 \text{ GeV}$  calculated for  $b = 1, 5, 7$  and 12 fm at midrapidity. The dashed lines correspond to the  $p_T$  spectra of  $D$ -mesons at the production point.

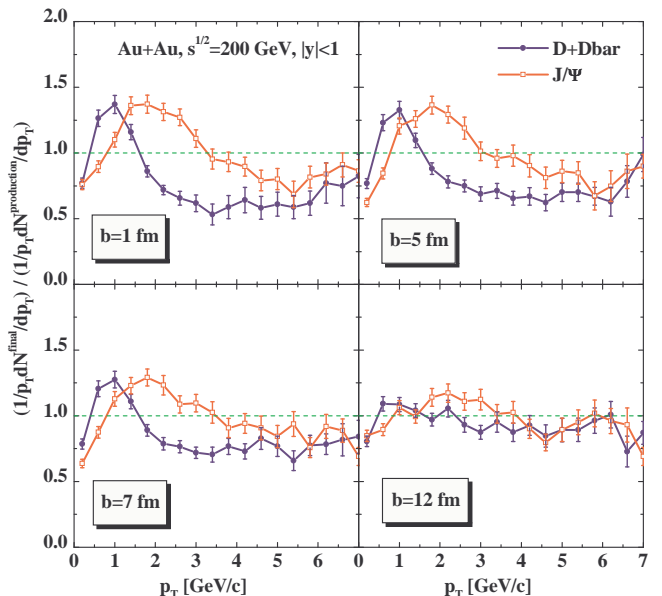


FIG. 2: The ratio of the final to the initial (i.e. at the production point) transverse  $p_T$  spectra of  $D + \bar{D}$ -mesons (solid lines with full dots, color: blue) and  $J/\Psi$  (solid lines with open squares, color: red) from Au + Au collisions at  $\sqrt{s} = 200 \text{ GeV}$  calculated for  $b = 1, 5, 7$  and 12 fm at midrapidity.

enhancement of the spectra at low and moderate  $p_T$  from Au+Au collisions as well as a modest suppression at high  $p_T$ .

In order to quantify the effect of final state interactions we show in Fig. 2 the ratio of the final to the initial (i.e. at the production point) transverse  $p_T$  spectra of  $D + \bar{D}$ -

mesons (solid lines with full dots, color: blue) and  $J/\Psi$  (solid lines with open squares, color: red) from the same reaction for impact parameter  $b = 1, 5, 7$  and  $12$  fm at midrapidity.

The actual ratios in Fig. 2 show an enhancement of  $D, \bar{D}$  mesons at low momenta with a maximum at  $p_T \approx 1$  GeV/c and a relative suppression for  $p_T > 2$  GeV/c. These effects increase with the centrality of the Au+Au collision. For the  $J/\Psi$  a maximum in the ratio shows up at  $\sim 2$  GeV/c while it drops below 1 for  $p_T > 3-4$  GeV/c.

In accordance with the ratios in Fig. 2 the averaged value of the transverse momentum  $p_T$ , which is displayed in Fig. 3 at midrapidity for  $D + \bar{D}$ -mesons (solid line with full dots, color: blue) and  $J/\Psi$  (solid line with open squares, color: red) from Au + Au collisions at  $\sqrt{s} = 200$  GeV, slightly increases (decreases) for  $J/\Psi$  ( $D, \bar{D}$  mesons) with decreasing impact parameter  $b$ . The  $D$ -meson spectrum is relatively 'hard' due to the large intrinsic charm quark mass. Through scatterings, the high  $p_T$   $D$ -mesons lose their energy and develop the collective shoulder at low  $p_T$ . This explains the dropping of  $D$ -meson  $\langle p_T \rangle$  in more central Au + Au collisions shown in Fig. 3. Such hadronic energy loss for  $D$ -mesons will complicate the analysis of the gluon radiative energy loss before hadronization [40]. These main trends should be readily tested experimentally in the near future.

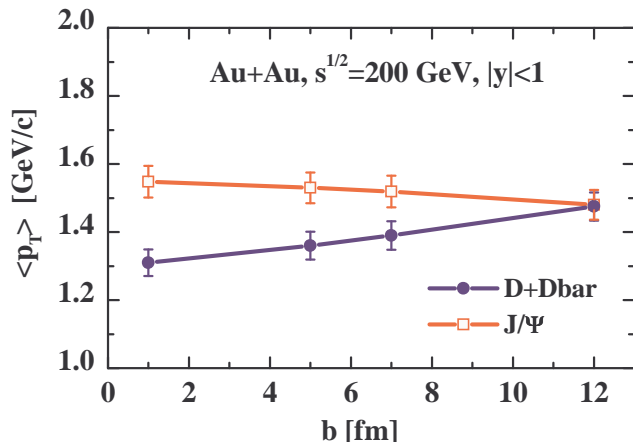


FIG. 3: The average value of the transverse momentum  $p_T$  at midrapidity for  $D, \bar{D}$ -mesons (solid line with full dots, color: blue) and  $J/\Psi$  (solid line with open squares, color: red) from Au + Au collisions at  $\sqrt{s} = 200$  GeV versus impact parameter  $b$ .

The question comes up how to interpret the findings in Figs. 1 to 3. We note that the maxima in the  $D + \bar{D}$  and  $J/\Psi$  ratios disappear when switching off the rescattering with mesons in the transport approach. Thus a collective acceleration of the  $D + \bar{D}$  mesons occurs dominantly via elastic scattering with mesons. This argument does not hold at first sight for the  $J/\Psi$ 's since their cross section with mesons is much lower and no strong collective acceleration by rescattering should be expected [27]. The answer comes about as follows: As known from Refs. [19, 22] the major fraction of final  $J/\Psi$ 's stems

from  $D + \bar{D} \rightarrow J/\Psi(\chi_c) + meson$  channels and not from the primary production by  $NN$  collisions. This finding is quantified in Fig. 4, where the channel decomposition for the final  $J/\Psi$ 's is shown as a function of the impact parameter  $b$  in Au+Au collisions at  $\sqrt{s} = 200$  GeV. Except for peripheral reactions ( $b > 9$  fm) the  $D + \bar{D}$  channel (solid line with full dots, color: red) dominates while the production in initial baryon-baryon ( $BB$ ) scattering (full line with open squares, color: blue) superceeds all other reaction channels for the most peripheral reactions. The contribution from meson-baryon ( $mB$ ) channels (solid line with full triangles, color: green) is seen to be low at all centralities.

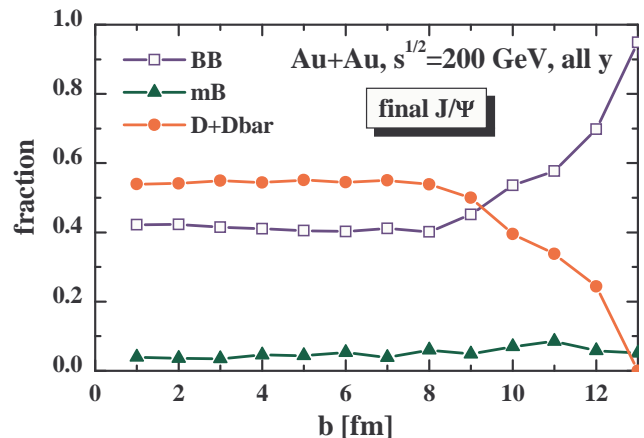


FIG. 4: The channel decomposition for the final  $J/\Psi$  in Au + Au collisions at  $\sqrt{s} = 200$  GeV within the transport approach as a function of the impact parameter  $b$ . The fraction of the final  $J/\Psi$  mesons produced in  $BB$  interactions is shown by the solid line with open squares (color: blue), the contribution from meson-baryon ( $mB$ ) interactions is given in terms of the solid line with full triangles (color: green) and the  $D\bar{D}$  annihilation fraction is displayed by the solid line with full circles (color: red).

According to Fig. 4 the bulk part of the  $J/\Psi$ 's thus stems from  $D + \bar{D}$  induced channels and their production happens somewhat delayed in time when the  $D, \bar{D}$  mesons have already picked up collective transverse momentum. In the  $D + \bar{D} \rightarrow J/\Psi(\chi_c) + meson$  reaction then the formed  $J/\Psi$  carries the collective momentum of both  $D$  and  $\bar{D}$  such that the charmonium appears to be accelerated even more than the  $D$ -mesons. On the other hand the  $J/\Psi$ 's with a high transverse momentum (in the power law tail) partly get dissociated with baryons of the target/projectile or with mesons in the expansion phase of the system. The probability to recreate a high  $p_T$  charmonium by the  $D + \bar{D}$  channel is lower than in the initial  $NN$  channel since the invariant energy  $\sqrt{s}$  in the  $D + \bar{D}$  reaction is lower by more than an order of magnitude and exponential (thermal)  $J/\Psi$  spectra become populated. This interpretation will, furthermore, be supported by the studies in the next Section.

#### IV. DIRECTED AND ELLIPTIC FLOW

Apart from the transverse flow that shows up as a 'shoulder' in the  $p_T$  spectra at low momentum or a maximum in the ratio relative to  $pp$  spectra (cf. previous Section) the directed flow

$$v_1(y, p_T) = \left\langle \frac{p_x}{p_T} \right\rangle_{y, p_T} \quad (4)$$

and the elliptic flow

$$v_2(y, p_T) = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle_{y, p_T} \quad (5)$$

provide additional information on the collective currents of hadrons in the complex reaction [41].

Fig. 5 shows the HSD predictions for the directed flow  $v_1$  (upper part) and elliptic flow  $v_2$  (lower part) of  $D + \bar{D}$ -mesons (solid lines with full dots) and  $J/\Psi$  (solid lines with open squares) from Au + Au collisions at  $\sqrt{s} = 200$  GeV for  $b = 7$  fm versus  $p_T$  for  $0 < y < 1$  (left part) and rapidity  $y$  (right part) integrated over  $p_T$ .

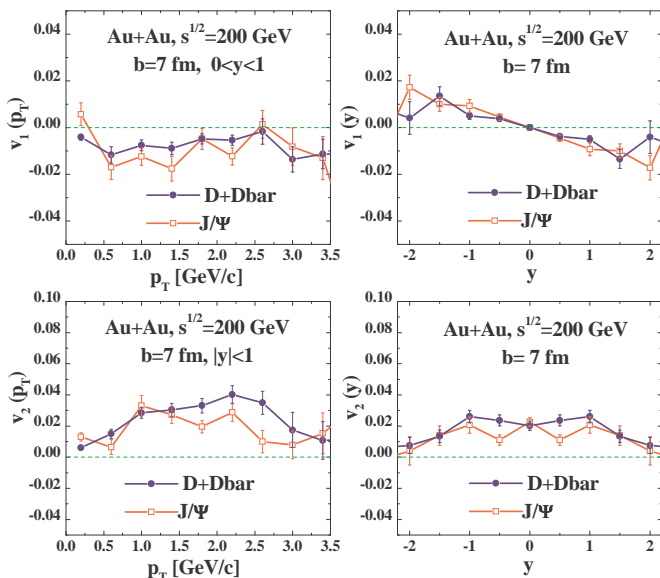


FIG. 5: The directed flow  $v_1$  (upper part) and elliptic flow  $v_2$  (lower part) of  $D + \bar{D}$ -mesons (solid lines with full dots, color: blue) and  $J/\Psi$  (solid lines with open squares, color: red) from Au + Au collisions at  $\sqrt{s} = 200$  GeV for  $b = 7$  fm versus  $p_T$  for  $0 < y < 1$  (left part) and rapidity  $y$  (right part) integrated over  $p_T$ .

The directed flow  $v_1$  is negative (within statistics up to  $p_T$  3.5 GeV/c) for both  $D + \bar{D}$  mesons and  $J/\Psi$ 's in the rapidity interval  $0 < y < 1$ . There is a tendency that  $v_1$  for  $J/\Psi$ 's is larger in magnitude for  $0.5 \text{ GeV/c} < p_T < 2 \text{ GeV/c}$  which supports the interpretation given in Section III that the final  $J/\Psi$ 's dominantly stem from  $D + \bar{D}$  channels where both open charm mesons already have picked up some collective flow. The pronounced 'antiflow'

of open charm mesons and  $J/\Psi$ 's becomes visible in the r.h.s. of Fig. 5 (upper part) where the slope  $dv_1/dy$  at midrapidity for  $J/\Psi$ 's is also slightly larger in magnitude than that for  $D + \bar{D}$  mesons.

The question now emerges how the 'bulk' of the light hadrons flows in this reaction. The answer is given in Fig. 6 where the HSD result for the directed flow  $v_1$  for charged hadrons from semi-central Au + Au collisions at  $\sqrt{s} = 200$  GeV is plotted versus pseudorapidity  $\eta$  and compared to the data from the STAR Collaboration [42] (solid dots) and the PHOBOS Collaboration [43] (solid triangles). Apparently the charged hadrons show a comparable flow  $v_1(\eta)$  as the open charm mesons and charmonia; consequently, the latter flow with the bulk of the lighter hadrons made up from  $u, d, s$  and  $\bar{u}, \bar{d}, \bar{s}$  quarks. We recall that the HSD calculations for the directed flow of charged hadrons match reasonably well with the data from Refs. [42, 43] for  $|\eta| < 3$  (cf. Ref. [44] for related UrQMD calculations).

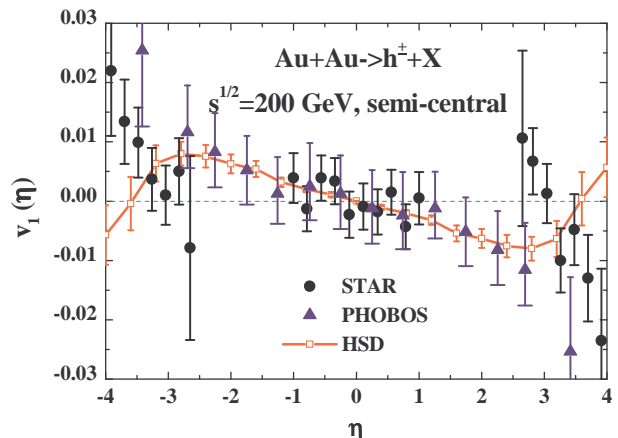


FIG. 6: The directed flow  $v_1$  for charged hadrons from semi-central Au + Au collisions at  $\sqrt{s} = 200$  GeV versus pseudorapidity  $\eta$  in comparison to the data from STAR [42] (solid dots) and PHOBOS [43] (solid triangles).

Coming back to the results for the elliptic flow  $v_2$  in the lower part of Fig. 5 we notice that both  $J/\Psi$ 's and  $D, \bar{D}$  mesons show in-plane flow since  $v_2(y, p_T) > 0$ . The elliptic flow of  $D, \bar{D}$  mesons is larger for  $1 \text{ GeV/c} < p_T < 3 \text{ GeV/c}$  than that for  $J/\Psi$ 's which indicates that the  $D, \bar{D}$  mesons are accelerated earlier than the  $J/\Psi$ 's. The elliptic flow  $v_2$  shows a maximum around midrapidity as the charged hadrons [43] and is also slightly larger for  $D, \bar{D}$  mesons than for  $J/\Psi$ 's. However, for impact parameter  $b = 7$  fm the elliptic flow of open charm mesons is  $\leq 3\%$  whereas the elliptic flow of charged hadrons reaches up to  $\sim 5\%$  at midrapidity. We recall that the HSD calculations underpredict the  $v_2$  of charged hadrons at midrapidity by about 30-35% [19]. Consequently one should expect also a larger elliptic flow for the open charm mesons and charmonia in experiment. We mention that in the quark coalescence model of Ref. [25] a significantly larger elliptic flow is obtained for both  $D, \bar{D}$  mesons and  $J/\Psi$ .

We now turn to the multiplicity of  $D, \bar{D}$  mesons and

$J/\Psi$  versus centrality in Au+Au collisions at  $\sqrt{s} = 200$  GeV. The left part of Fig. 7 shows the multiplicity of  $D + \bar{D}$  pairs (solid lines with full dots, color: red) and  $J/\Psi$  (solid lines with open squares, color: blue) from Au + Au collisions at  $\sqrt{s} = 200$  GeV integrated over rapidity versus impact parameter  $b$ , whereas the right part displays the ratio of the multiplicities of  $D + \bar{D}$  pairs over  $J/\Psi$  versus  $b$ . Note that the  $J/\Psi$  multiplicity on the l.h.s. has been multiplied by a factor of 100. Whereas we expect  $\sim 17$   $D + \bar{D}$  pairs in the top central collisions the  $J/\Psi$  multiplicity is only  $\sim 5 \times 10^{-2}$ , i.e. lower by a factor of  $\sim 300$ .

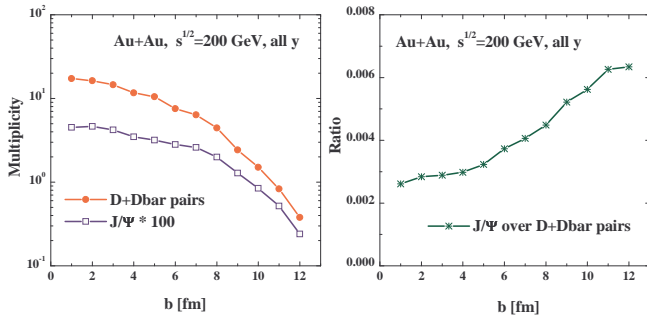


FIG. 7: Left part: the multiplicity of  $D + \bar{D}$  pairs (solid lines with full dots, color: red) and  $J/\Psi$  ( $\times 100$ , solid lines with open squares, color: blue) from Au + Au collisions at  $\sqrt{s} = 200$  GeV integrated over rapidity versus impact parameter  $b$ . Right part: the ratio of the multiplicity of  $D + \bar{D}$  pairs over  $J/\Psi$  versus  $b$ .

The r.h.s. of Fig. 7 shows the ratio of  $D + \bar{D}$  pairs over  $J/\Psi$  versus impact parameter  $b$ . Since the multiplicity of  $D + \bar{D}$  pairs scales directly with the number of binary (initial)  $NN$  collisions in the HSD transport approach [27] this ratio gives an information about  $J/\Psi$  suppression relative to binary scaled  $pp$  collisions. We find – in accordance with the previous studies in Refs. [19, 22] – that the  $J/\Psi$  suppression in very central collisions relative to very peripheral reactions is about a factor of  $\sim 2.5$ .

We now turn to the freeze-out properties of  $D + \bar{D}$  mesons and  $J/\Psi$ 's. The upper part of Fig. 8 presents the distribution in time of the last interaction for the final  $J/\Psi$  mesons ( $\times 100$ , solid line, color: blue) and  $D + \bar{D}$  mesons (dashed line, color: red) from Au + Au collisions for  $b = 2$  fm at  $\sqrt{s} = 200$  GeV at midrapidity ( $|y| \leq 1$ ). Here the production time is also recorded if the particles did not suffer from a further interaction (initial peaks up to 2 fm/c). The time  $t = 0$  is defined by the contact time of the heavy ions. Whereas the  $J/\Psi$  mesons freeze-out early due to their small cross section with light hadrons the  $D + \bar{D}$  mesons interact for a long time and freeze-out on average at 10 – 12 fm/c.

The lower part of Fig. 8 shows the collision rate of formed and leading particles from baryon-baryon ( $BB$ ), meson-baryon ( $mB$ ) and meson-meson ( $mm$ ) collisions from Au + Au collisions at  $b = 2$  fm and  $\sqrt{s} = 200$  GeV integrated over rapidity. Here leading diquarks are

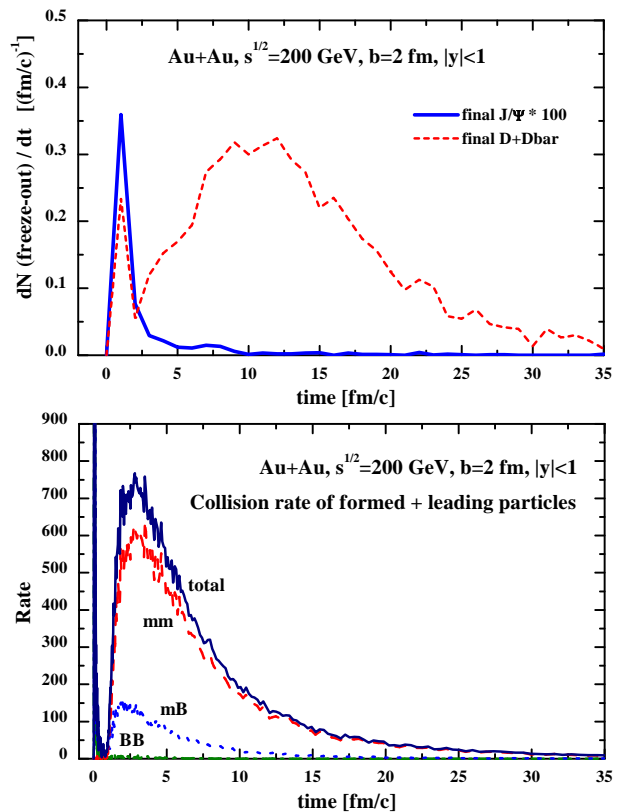


FIG. 8: Upper part: the distribution in time of the last interaction for the final  $J/\Psi$  mesons ( $\times 100$ , solid line, color: blue) and  $D + \bar{D}$  mesons (dashed line, color: red) from Au + Au collisions for  $b = 2$  fm at  $\sqrt{s} = 200$  GeV ( $|y| \leq 1$ ). Here the production time is also recorded if the particles did not suffer from a further interaction (initial peaks up to 2 fm/c). Lower part: the time evolution of the collision rate of formed and leading particles from baryon-baryon ( $BB$ ), meson-baryon ( $mB$ ) and meson-meson ( $mm$ ) collisions from Au + Au collisions for  $b = 2$  fm at  $\sqrt{s} = 200$  GeV integrated over rapidity. The time  $t = 0$  is defined by the contact time of the heavy ions.

counted as baryons ( $B$ ) whereas leading quarks and antiquarks are registered as mesons ( $m$ ). The rate of  $BB$  collisions shows a strong peak during the passage time of the heavy ions ( $< 0.2$  fm/c) and is almost negligible later on. The  $mB$  collision rate (apart from the initial peak for  $t < 0.2$  fm/c) shows a sizeable contribution only after a short time delay of  $\sim 1$  fm/c which is the scale of the hadron formation time for low momenta in the cms. We point out that the very early  $mB$  collisions ( $t < 0.4$  fm/c) correspond to pre-hadron interactions, where a quark from a struck nucleon – forming an endpoint of the excited string – interacts without time delay (cf. Ref. [45] for a detailed discussion of the pre-hadron concept in HSD). Furthermore, the early interactions of formed mesons (for  $1$  fm/c  $< t < 4$  fm/c) occur dominantly in the outer transverse region of the initial fireball where the energy density is below  $1$  GeV/fm<sup>3</sup>.

As seen from Fig. 8 the  $mm$  collision rate of formed mesons also starts with a short delay in the order of the

formation time  $\tau_f$  but superceeds the  $mB$  collision rate by more than a factor of 4. The maximum in the  $mm$  collision rate occurs for  $t \approx 3 - 4$  fm/c when the energy density in a sizeable volume drops below 1 GeV/fm<sup>3</sup> and the system is still very dense. We point out, furthermore, that the 'hadronic burning' by meson-baryon and meson-meson collisions persists up to rather long times since bunches of close-by hadrons may interact almost continuously if their relative momenta are low.

When comparing the upper part of Fig. 8 with its lower part one notices that the maximum in the  $mm$  collision rate occurs much earlier than the average freeze-out of  $D + \bar{D}$  mesons (at 9–12 fm/c). This further supports our conjecture in the end of Section III that the  $D + \bar{D}$  mesons suffer a couple of interactions with the light mesons and pick up collective flow before they freeze-out rather late on a time scale that is only slightly shorter (but comparable) to the freeze-out time for light hadrons if one discards the very late decay of resonances (e.g.  $\omega \rightarrow 3\pi's$ ,  $\Delta \rightarrow N\pi$ ,  $K^* \rightarrow K\pi$  etc.).

## V. SUMMARY

In this work we have extended our previous investigations within the HSD transport approach in Refs. [19, 22, 27] with respect to the collective dynamics of  $D, \bar{D}$  mesons and charmonia. Our detailed studies of Au+Au collisions at  $\sqrt{s} = 200$  GeV have shown that:

- Pre-hadronic and hadronic interactions generate a transverse collective flow of  $D, \bar{D}$  mesons and charmonia that shows up as a 'shoulder' in the low momentum spectra or as a maximum in the ratio relative to scaled  $pp$  collisions.
- The high  $p_T$  power law tail of the spectra is only moderately suppressed.
- The directed flow of  $D, \bar{D}$  mesons and charmonia is comparable to that of the light charged hadrons.
- The elliptic flow of  $D, \bar{D}$  mesons and charmonia is smaller than that of the light hadrons.
- The  $D, \bar{D}$  mesons freeze out on average at  $\sim 9 - 12$  fm/c which is shorter than the freeze-out time for light hadrons (when neglecting explicit resonance decays).

Whereas the collective acceleration of the  $D + \bar{D}$  mesons via elastic scattering with mesons in the expansion phase of the 'fireball' can be well understood on the basis of the rather large cross section of  $D, \bar{D}$  mesons with nucleons and mesons [21, 39] – in view of the light quark/antiquark content of these states – the collective dynamics of the  $J/\Psi$ 's cannot be explained in this way since the  $J/\Psi$  cross section with mesons is much lower. However, the dominant fraction ( $> 50\%$ ) of final  $J/\Psi$ 's in central and mid-central reactions stems from  $D + \bar{D} \rightarrow J/\Psi(\chi_c) + meson$  channels and to a lower extent from the primary production by  $NN$  collisions (cf. Fig. 4). Thus the production of the final charmonia happens delayed in time when the  $D, \bar{D}$  mesons have already picked up collective flow from interactions with light (and fast) hadrons. Furthermore, in the  $D + \bar{D} \rightarrow J/\Psi(\chi_c) + meson$  reaction the formed  $J/\Psi$  carries the collective momentum of both  $D$  and  $\bar{D}$  such that the charmonium appears to be accelerated even more than the  $D$ -mesons (cf. Figs. 2 and 5). On the other hand the elliptic flow of  $D, \bar{D}$  mesons is slightly larger than that of  $J/\Psi$ 's which indicates on average an earlier production of the open charm mesons.

The differential spectra, ratios as well as the differential flow analysis for  $v_1(y, p_T)$  and  $v_2(y, p_T)$  for open charm hadrons and charmonia is expected to be proved/disproved in the near future by the RHIC experiments. Our analysis and interpretation of the results has also paved the way to extract relevant time scales and possibly interaction rates or freeze-out times. Sensible deviations from our predictions will point towards a dynamical origin that is not included in our present calculations and should be addressed to explicit partonic interactions in a possibly colored medium.

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