Quark Coalescence for Charmed Mesons in Ultrarelativistic Heavy-Ion Collisions

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We investigate effects of charm-quark interactions in a Quark-Gluon Plasma on the production of D and J/ψ mesons in high-energy heavy-ion collisions. Employing a previously constructed coalescence model that successfully reproduces the transverse momentum (p_T) spectra and elliptic flow ($v_2(p_T)$) of light hadrons at RHIC from underlying light-quark distributions at the phase transition temperature T_c, D-meson and J/ψ p_T-spectra are evaluated. For the charm-quark distributions, we consider two limiting scenarios: (i) *no* rescattering, corresponding to perturbative QCD (pQCD) spectra and (ii) *complete* thermalization including transverse expansion. We find that D-mesons acquire a minimal v_2 inherited from their light-quark content and corresponding semileptonic decay spectra of single electrons practically preserve the v_2 of the parent particles, exhibiting marked differences between the pQCD and thermal scenarios for $p_T \geq 1$ GeV. Likewise, the p_T-spectra and yields of J/ψ's differ appreciably in the two scenarios.

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I. INTRODUCTION

Collisions of heavy nuclei at the Relativistic Heavy-Ion Collider (RHIC) are expected to provide conditions favorable for the creation of a deconfined and chirally symmetric Quark-Gluon Plasma (QGP). Among the promising probes of this phase are hadrons containing charm (c) quarks. On the one hand, the abundance of observed J/ψ mesons was predicted to be sensitive to QGP formation [1] due to Debye screening of the heavy-quark potential, leading to suppression of its production. On the other hand, spectra of open-charm states (mostly D-mesons) are believed to encode valuable information on charm-quark reinteractions in the hot and dense medium. Due to the relatively large charm-quark mass, $m_c \simeq 1.5$ GeV, $c\bar{c}$ production is presumably dominated by primordial N-N collisions [2], whereas thermalization of their momentum distributions is still an open issue, with important ramifications for charmonium production.

At RHIC energies, with an expected 10-20 $c\bar{c}$ pairs per central A-A collision, statistical models predict a substantial regeneration of J/ψ's by recombination of c and $\bar{c}$ quarks close to the phase transition [3, 4, 5, 6, 7, 8]. These estimates reside on the assumption that charm quarks are in thermal equilibrium with the surrounding medium. Recombination approaches have also been applied before with fair phenomenological success in studying flavor dependencies of open-charm production in elementary p-N and π-N collisions [9, 10, 11]. Again, the heavy quark serves as a probe for the (nonthermal) hadronization environment via coalescence-type processes with surrounding valence or sea quarks. Finally, parton coalescence within a hadronizing QGP has recently been put forward as a mechanism for light hadron production at intermediate $p_T \simeq$ 2-6 GeV in heavy-ion collisions at RHIC. The observed "anomalous" $\bar{p}/\pi$ ratio of ~ 1, as well as the apparent "constituent-quark" scaling of the hadron v_2, are naturally accounted for within this framework [12, 13, 14, 15, 16, 17].

In this paper, we employ quark coalescence to evaluate spectra of open- and hidden-charm mesons at RHIC, with the objective to address the following issues: (a) What is the sensitivity of the J/ψ abundance and p_T spectrum to the underlying momentum distribution of charm quarks? (b) How does the interplay of the charm- and light-quark distributions translate into the p_T-spectrum and elliptic flow of D-mesons? Point (a) lifts the assumption of complete c-quark thermalization common to statistical models, which is important to discriminate regeneration from suppression mechanisms. A first study of this kind has been performed in Ref. [7] where c-quark distributions from pQCD have been implemented into a kinetic rate equation solved in the background of an evolving QGP. For c-quark rapidity densities of $dN_{c\bar{c}}/dy \sim 2.5$ in central Au+Au collisions at RHIC, the final J/ψ number has been found to deviate from scenarios with thermalized c-quarks by $\sim 50\%$. Our results to be discussed below differ from these estimates. Concerning point (b), the recent study of Ref. [18] has shown that single-electron p_T spectra from decays of PYTHIA-generated and hydrodynamic D-meson distributions cannot by discriminated by current PHENIX data [19], extending to $p_T^e \simeq 3$ GeV. In the present work, D-mesons are formed from c-quark coalescence with thermal light quarks at hadronization, where the latter also carry the collective expansion characteristics (radial and elliptic flow) that underlies a satisfactory description of pion and baryon spectra in Refs. [12, 13]. An important point in the present study will be the evaluation of the elliptic flow of both D-mesons and their electronic decay spectra. For both (a) and (b) we will consider two limiting cases for the c-quark momentum spectra, i.e., (i) pQCD distributions from PYTHIA, representing no rescattering, and, (ii) complete thermalization including collective expansion.

II. COALESCENCE INTO CHARMONIUM

Let us start by recalling the basic elements of the coalescence model. In the Wigner formalism, the pertinent p_T-spectrum of a meson M takes the form

$$\frac{d^2N_M}{d\mathbf{p}_\mathrm{T}^2} = g_M \int \prod_{i=1}^{2} \frac{p_i \cdot d\sigma_i d^3\mathbf{p}_i}{(2\pi)^3 E_i}\ f_q(x_1,p_1)\ f_{\bar{q}}(x_2,p_2) \times f_M(x_1,p_1;x_2,p_2)\ \delta^{(2)}(\mathbf{p}_\mathrm{T}-\mathbf{p}_{1\mathrm{T}}-\mathbf{p}_{2\mathrm{T}})\ ,\ (1)$$

with $d\sigma_i$ denoting space-like hypersurface elements. $f_{q,\bar{q}}(x_i,p_i)$ are invariant distribution functions of anti-/quarks depending on their space-time position and 4-momentum, and including spin and color degeneracy. The statistical factor g_M accounts for the probability of forming a colorless meson of given spin from the underlying quark color and spin (e.g., g_ψ=1/12), whereas f_M encodes the dynamical part of the process. In the following, we will adopt plane-wave single-quark distribution functions, and neglect binding-energy corrections to f_M, in which case it becomes a Wigner distribution function.

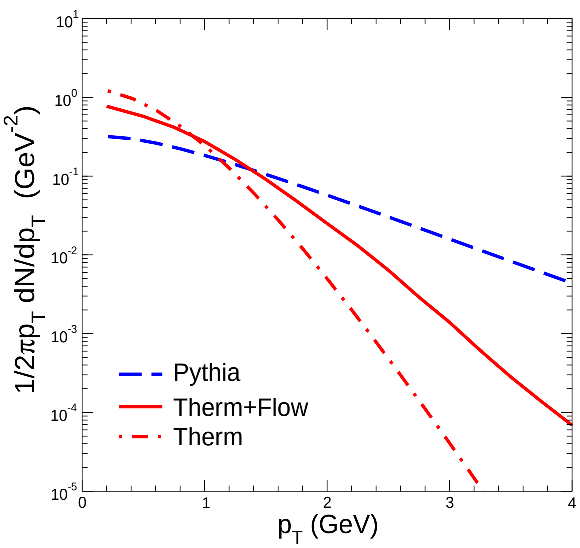

FIG. 1: Transverse-momentum spectra of charm quarks in central 200 AGeV Au+Au collisions at midrapidity for different scenarios: static thermal (dash-dotted line), thermal plus transverse flow (solid line) and primordial pQCD (dashed line).

Since the measured hadron distributions in heavy-ion collisions at RHIC energies are approximately uniform around midrapidity, we will assume this also for the anti-/quark distribution functions, $f_{q,\bar{q}}$, with an additional Bjorken-type correlation between longitudinal coordinate and momentum [20]. In the transverse direction, we follow Ref. [13] by employing light-quark momentum distributions that are a combination of thermal spectra with radial flow and quenched minijets according to the GLV approach [21] with an opacity parameter $L/\lambda = 3.5$. For the transverse momentum distribution of charm quarks, two possibilities will be investigated: (i) pQCD spectra as obtained from the PYTHIA event generator [22] and, (ii) thermal spectra at a temperature of T=170 MeV with radial flow. For the latter case, we take as an upper limit the same flow profile as determined in Ref. [12] for light quarks, i.e., a linear increase with the position in the transverse plane,

$$\beta(r) = \beta_\mathrm{max}\frac{r}{R} \quad (2)$$

with R= 8.1 fm, the radius of the firecylinder at hadronization, and β_max=0.5 or 0.65, representing inherent uncertainties within our approach. Since heavy quarks are expected to suffer less energy loss in the QGP than light quarks[23, 24], we neglect charm-quark energy loss in the PYTHIA spectra in present study. In Fig. 1, we show by the dashed line the charm-quark p_T-spectrum from the PYTHIA event generator and by the solid line that from the thermal scenario with collective flow. For comparison, Fig. 1 also contains a thermal c-quark spectrum without collective flow (dash-dotted line).

The wave functions of the charmonium states are taken to be of Gaussian form in coordinate space, implying that the corresponding Wigner function is a Gaussian as well, i.e.,

$$f_M = 8\ \exp(-x^2/\sigma^2)\ \exp(-q^2\sigma^2) \quad (3)$$

with $x = x_1 - x_2$, and $q^2 = (m_1-m_2)^2-(p_1-p_2)^2$, where x and p are 4-coordinate and -momentum (see Ref. [13] for details). The width of the Gaussians is related to the mean-square-radius $r_\mathrm{rms}^2 = < r^2 >$ via $r_\mathrm{rms}^2 = 3\sigma^2/8$. Typical values from Cornell-type potential models[25] amount to r_rms=0.47 fm for J/ψ, 0.74 fm for χ_c and 0.96 fm for ψ', which will constitute our baseline values.

To illustrate basic features of the coalescence approach in a transparent way we first employ thermal c-quark spectra without radial flow. Under these conditions, the momentum spectrum, Eq. (1), can be evaluated analytically upon invoking the non-relativistic Boltzmann approximation for the c-quark distribution functions, suitable for charmonia at low and moderate p_T. One finds

$$N_\psi \simeq g_M N_{c\bar{c}}^2 \left[\frac{(4\pi)^{\frac{3}{2}}\sigma^3}{V_H(1+m_cT_H\sigma^2)}\right]\left(\frac{\tau^2}{\tau^2+m_c^2\sigma^4}\right)^{1/2}, \quad (4)$$

with $N_{c\bar{c}}$ the total number of $c\bar{c}$ pairs within the rapidity range $|y| \leq 0.5$. The bulk system is characterized by the proper time τ, volume V_c and temperature T_c of the fireball at hadronization. Typical values for these quantities are τ=4.3 fm, T_c=170 MeV, and V_c=900 fm^3, as determined in Ref. [12] from numerical evaluations in the light-quark sector, which, after inclusion of transverse flow, reproduce well p_T-spectra of pions, protons, and kaons in central Au+Au collisions at 200 AGeV. The main features of Eq. (4) are: (a) a weak dependence on the hadronization time as long as $\tau \geq$ 2-3 fm/c and $r_\mathrm{rms} \leq 0.5$ fm; (b) a ratio $\sigma^3/V_c \sim V_\mathrm{hadron}/V_c$ of hadron eigenvolume over fireball volume, characteristic for coalescence (note, however, that the entailing increase of J/ψ production with σ is an artifact related to the neglection of binding energy effects; we will return to this issue below); (c) a dependence on the number of participants, A, as $N_\psi/N_{c\bar{c}} \propto N_{c\bar{c}}/V_c \propto A^{4/3}/A \propto A^{1/3}$, consistent with statistical models [3, 5, 6, 7].

III. CHARMONIUM SPECTRA

The numerical evaluation of Eq. (1) is performed along the lines of Ref.[12]. For each scenario, the total number of $c\bar{c}$ pairs is fixed to $N_{c\bar{c}} = 2.5$ over one unit of rapidity. This number follows from an extrapolation of charm production at fixed target energies to central Au+Au collisions at 200 AGeV, corresponding to leading-order pQCD calculations upscaled by an empirical K-factor of ∼5 [26], as well as the number of N-N collisions. With a charm-quark mass of $m_c = 1.4$ GeV, the resulting open-charm cross sections are consistent with first indirect measurements via single electrons in 130 and 200 AGeV Au+Au by PHENIX [19] at all centralities.

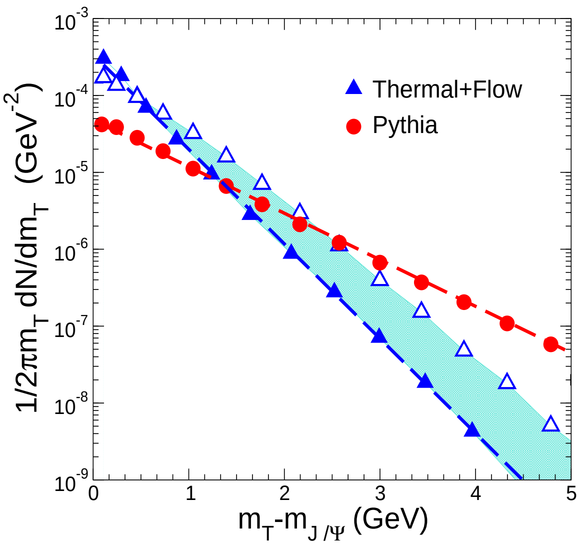

FIG. 2: J/ψ transverse-mass spectra for central Au+Au collisions at $\sqrt{s}$ = 200 AGeV from charm-quark coalescence: circles correspond to PYTHIA c-quark distributions, while filled and open triangles follow from thermal spectra with radial flow velocities of $\beta_{\rm max}$=0.5 and 0.65, respectively. Lines represent exponential fits where appropriate.

Fig. 2 displays our results for J/ψ m_T-distributions (without feeddown corrections); since, due to its large mass, the J/ψ is more sensitive to variations in the collective expansion then light hadrons, we indicated inherent uncertainties by using two values for the radial fireball-surface velocity at T_c, $\beta_{\rm max}$=0.5 and 0.65. We find that both pQCD-based (circles) and thermal c-quark spectra with $\beta_{\rm max}$=0.5 (filled triangles) exhibit approximately uniform slopes, which are quantified by the fitted lines to be $T_{\rm slope}$=720 MeV and $T_{\rm slope}$=350 MeV, respectively (for $\beta_{\rm max}$=0.65, $T_{\rm slope}$=550 MeV in the region $m_T - m_{J/\Psi} = 0 - 1.5$ GeV). The average $< p_T >$ decreases from 1.95 GeV for the pQCD-based case to a range of 1.29-1.60 GeV for the thermal one. Furthermore, the total $N_{J/\psi}$ obtained by employing c and $\bar{c}$ spectra from pQCD is smaller than that from the thermal model by about a factor of 3, as the flatter pQCD spectrum entails a substantial depletion of the probability in momentum space to form charmonia at low and moderate p_T where their yield is concentrated. Contrary to the single-electron spectra from heavy-meson decays, which appear to be relatively insensitive to the difference between pQCD and thermal+flow open-charm distributions [18] (at least up to $p_T \simeq 3$ GeV, and including "contaminations" from B-meson decays), J/ψ spectra exhibit a more pronounced sensitivity, which could enable it a rather direct window for studying the charm-quark behavior in the QGP.

TABLE I: Number of charmonia produced from charm-quark coalescence at mid-rapidity in central collisions of Au+Au at $\sqrt{s} = 200$ GeV.

	$N_{J/\psi}$	N_{χ_c}	$N_{\psi'}$
Thermal	2.6×10^{-3}	0.2×10^{-3}	0.7×10^{-4}
PYTHIA	0.8×10^{-3}	0.5×10^{-4}	0.2×10^{-4}

Let us briefly address the question of feeddown corrections from χ_c and ψ' resonances. A rigorous treatment of their formation requires the inclusion of in-medium effects on binding energies, charm-quark masses and radii in the coalescence probability, which is a much more involved problem. First studies in this direction, including formation and dissociation processes, have been undertaken in Refs. [7, 8, 27]. For simplicity, we take as a guideline thermal mass weights according to $(m_R/m_{J/\psi})^{3/2} \exp(-(m_R - m_{J/\psi})/T)$ for their production relative to that for J/ψ. The J/ψ numbers corresponding to the spectra in Fig. 2 are collected in Table I, together with estimated feeddown corrections. Despite the significantly larger radii of χ_c and ψ' states, their combined contribution to J/ψ is still only ∼10%. A more precise assessment is beyond the scope of this work. However, we expect the relative suppression of the J/ψ yield and its harder slope, as obtained with the pQCD charm-quark spectrum compared to the thermal+flow case, to be a rather robust result. It could prove valuable in, e.g., disentangling a transition from coalescence of soft c-$\bar{c}$ to hard ones (or even unsuppressed primordial charmonia) in p_T, as well as in probing the degree of thermalization of charm quarks in the QGP.

IV. D-MESON SPECTRA

The standard coalescence approach becomes unreliable if the phase space density of either one (or both) of the quarks is no longer small, such as in bulk hadron production at low p_T. For the case of interest here, i.e., D-meson spectra, we expect the following results to be trustworthy for $p_T \geq 1$ GeV. Again, our calculations proceed along the lines of Ref. [12], with the same fireball parameters as used above, i.e., a constituent light-quark mass of 300 MeV, and the two scenarios for charm quarks (pQCD vs. thermal+flow). The width of the Gaussian Wigner function for D's is taken to render their radius to 0.6 fm. We have again weighted the production of D^*'s with a thermal factor $(m_{D^*}/m_D)^{3/2}\exp(-(m_{D^*}-m_D)/T)$ relative to that of D mesons. Semileptonic decays of D-mesons have been computed assuming predominance of 3-body decays, $K\nu e$ and $K^*\nu e$, with a phase-space weighting according to the weak matrix element.

In Fig.3, the upper curves display the coalescence results for the p_T-spectra of charmed mesons D, D^*, D_s and D_s^*. Also for D-mesons, the pQCD c-quark distributions induce harder spectra (dashed line) than the thermal+flow ones, although somewhat less pronounced than for the charmonium case; the shaded bands in Fig.3 cover the range of flow velocities from $\beta_{\max}$=0.5 to 0.65). The lower curves show single-$e^{\pm}$ spectra from decays of all D- and D_s-mesons (including feeddown from D^*'s). Similar to Ref. [18], we find that, on the basis of the current experimental accuracy, also within a coalescence framework, underlying pQCD c-quark spectra cannot really be distinguished from thermalized ones with flow. Our coalescence spectrum from thermal c-quarks with flow indeed closely resembles the hydrodynamic D-meson spectra of Ref. [18] (implying that, modulo charmed baryons, essentially all c-quarks recombine). This is also true when comparing the pQCD-based c-quark coalesence with the fragmentation spectrum in Ref. [18] above $p_T \simeq 2$ GeV. Below $p_T \simeq 2$ GeV, however, there is a significant lack in the yield of the pQCD coalescence spectrum as compared to inclusive PYTHIA D-mesons, since no fragmentation contribution has been accounted for in the present study.

Concerning the coalescence yields for D_s mesons (including feeddown from D_s^*), we find for the two cases of thermal and pQCD c-quark spectra D_s/D ratios of 29% and 25%, respectively, with spectral shapes very similar to the inclusive ones of Fig. 3. These values are quite reminiscent to the 23% found within the coalescence approach of Ref. [11] for p-p collisions at RHIC.

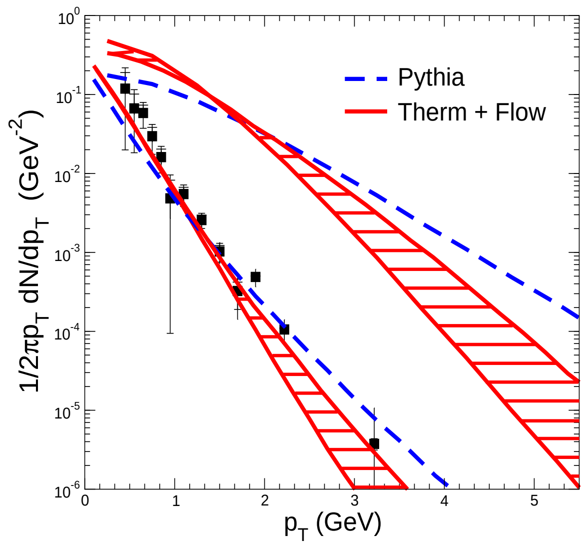

FIG. 3: Coalescence results for transverse-momentum spectra of all D-mesons (upper curves) and pertinent electron decays (lower curves) in central 200 AGeV Au+Au collisions at midrapidity. Dashed lines are obtained from pQCD c-quark distributions, while shaded bands correspond to thermal spectra with flow velocities between 0.5 and 0.65. "Non-photonic" single-$e^{\pm}$ data (squares with both statistical and systematic errors) are from PHENIX [19].

V. CHARM AND SINGLE-ELECTRON ELLIPTIC FLOW

Finally, we turn to the elliptic flow, v_2, of charmed particles, which is a well-established probe of the degree of thermalization in the (early) QGP as it vanishes in the absence of any rescattering. The coalescence model has been shown to quantitatively describe [13, 16, 28] the elliptic flow of light hadrons such as pions, protons, kaons and lambdas. Therefore, we believe that its pertinent predictions especially for D-mesons, and to a lesser extend for charmonia, are a rather reliable measure of charm-quark reinteractions. Even if c-quarks do not experience any final-state interactions, a lower limit for the v_2 of D-mesons from coalescence arises due to the v_2 of their light-quark component. On the contrary, an upper limit can be expected from the assumption that the charm quark has the same $v_2^{\max}$ as the light quarks.

Some specific features of charmed hadron $v_2(p_T)$ have already been pointed out within a schematic calculation in Ref. [29]. In particular, it has been shown that even if c quarks acquire the same $v_2(p_T)$ as light quarks, the large difference in the quark masses entails a smaller value of v_2 for D-mesons than for J/ψ at same p_T. This is so because the D-meson momentum is largely determined by the c-quark, and an equal velocity of c and light quark, as required for coalescence, implies the light quark to be at low momentum where its v_2 is relatively small. Here, we quantify this study by including more realistic quark distribution functions, especially through the inclusion of radial flow, which by itself affects light and heavy quarks in a different way, and extend it to the semileptonic decay electrons.

Fig. 4 summarizes our elliptic flow results. For the upper panel, we recall the underlying light-quark v_2 (solid circles), which has been fit (solid line) to reproduce the experimental data for pions and charged hadrons (filled

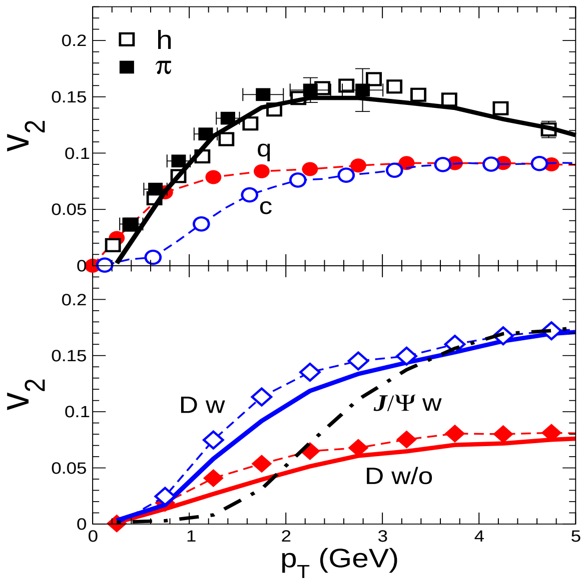

FIG. 4: Elliptic flow in minimum bias Au+Au collisions at $\sqrt{s}$= 200 AGeV. Upper panel: input parameterizations for light (solid circles) and charm quarks (open circles) together with the v_2 for pions (solid line) from coalescence plus fragmentation, as well as experimental data from PHENIX for π^+ (filled squares)[30] and charged particles (open squares) [31]. Lower panel: D-mesons (solid lines, lower: using pQCD charm-quark distributions, upper: for thermal+flow c-quark spectra at T_c) and respective decay electrons (diamonds), as well as J/ψ mesons (dash-dotted line).

and open squares, respectively) in Ref. [12], together with a charm-quark v_2 (open circles) saturating at the same maximal value (and with equal radial flow). The lower panel contains the ensuing results for D-mesons (solid lines) and their decay electrons (diamonds), as well as J/ψ's (dash-dotted line). For D-mesons, the elliptic flow from the two scenarios of complete thermalization and no reinteractions of the c-quarks deviates by about a factor of 2 for $p_T \geq 1.5$ GeV. The decay $e^\pm$ are found to essentially preserve the v_2 of their parent particles, which makes it a highly interesting observable for upcoming measurements. We note that B-meson contributions have not been included in present study. If these become significant for $e^\pm$ momenta above 2 GeV, caution needs to be exercised in drawing conclusions about c-quark elliptic flow.

For the elliptic flow of J/ψ's, which entirely stems from (thermalized) c-quarks, we observe a significant delay of its increase with p_T as compared to that for D-mesons, caused by the radial flow. Indeed, if the latter is absent, the v_2 of J/ψ's saturates faster than for D-mesons, see, e.g., Ref. [29]. We furthermore recall that, on the one hand, the v_2 of J/ψ's is zero for coalescence between pQCD charm quarks. On the other hand, we have not taken into account any primordially produced J/ψ's, for which suppression mechanisms, if active early in the evolution, can induce a nonzero v_2 [32]. However, the magnitude of such effects (which can arise from both nuclear absorption and QGP dissociation) has been estimated to be rather small, up to ∼2% (compared to 10% or more for coalescence between thermalized c-quarks). Nevertheless, in a more complete description, one expects an increasing fraction of (unsuppressed) primordial charmonia towards higher p_T, thus reducing v_2.

VI. SUMMARY

Within a coalescence approach as successfully applied earlier in the light-quark sector, we have evaluated transverse-momentum dependencies of charmed hadrons in central heavy-ion reactions at RHIC. For the charm-quark distributions at hadronization we have considered two limiting scenarios, i.e., no reinteractions (using spectra from PYTHIA) and complete thermalization with transverse flow of the bulk matter. The resulting J/ψ (m_T-) spectra differ in slope by up to a factor of 2 (harder for pQCD c-quarks), and the integrated yield is about a factor of 3 larger in the thermal case. For D-mesons, we found that the difference in the slope parameters of the p_T-spectra in the two scenarios is less pronounced, but their elliptic flow is about a factor of 2 larger for $p_T \geq 1.5$ GeV in the thermalized case. The elliptic flow pattern of D-mesons was found to be essentially preserved in the single-electron decay spectra, rendering the latter a very promising observable to address the strength of charm reinteractions in the QGP. The present study can be straightforwardly generalized to charmed baryons (Λ_c), which may serve as a complimentary probe for charm-quark reinteractions in the QGP.

VII. ACKNOWLEDGMENTS

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