

Spectra and azimuthal harmonic of charmed mesons in Pb+Pb collisions at energies available at the CERN Large Hadron Collider

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Using the recombination model extended to the heavy flavor scenario, we investigate the production of charmed mesons, i.e., D^0 , D_s^+ , and J/ψ , in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV at the CERN Large Hadron Collider including the heavy flavor energy loss inside the hot and dense medium. Soft, semihard, and hard partons all play important roles in our model and are uniformly treated for all mesons produced. The resulting transverse momentum spectra and the second azimuthal harmonic v_2 for these mesons are presented and compared with the available experimental data. The good agreement provides strong support again that the quark recombination mechanism is an effective model for hadronization in relativistic heavy-ion collisions.

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I. INTRODUCTION

The investigation of strongly interacting matter under extreme conditions of temperature and energy density is at the forefront of nuclear physics research, which is a formidable challenge to map out the phase structure of quantum chromodynamics (QCD) [1–3]. The experiments of high-energy heavy-ion collisions at the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC) provide a unique opportunity to create the hot, dense QCD matter and study its properties. Up to now, a fundamental question that remains open is how the quark hadron emerges from the underlying in-medium QCD force. The heavy quarks play a special role in this field [4,5]. Since the masses of heavy quarks are much higher than the pseudocritical temperature, they are retained through the hadronization transition in ultra-relativistic heavy-ion collisions. In addition, the energy loss is predicted to depend on the quark mass and to be smaller for heavy quarks [6]. Therefore, the hadrons containing charm quarks (c) or their antiquarks ($\bar{c}$) are excellent probes of the hadronization mechanism.

The production of charmed mesons in heavy-ion collisions have been widely experimentally measured at RHIC [7–9] and LHC [10–20]. To understand these results, several theoretical groups have developed transport approaches to

describe the dynamics of heavy quarks in their production at the initial state, their interactions with the quark-gluon plasma (QGP), the hadronization process, and the interactions of heavy hadrons in the hadronic phase. In those models, the hadronization of heavy quarks is modeled with fragmentation or a hybrid fragmentation plus recombination scenario [6,21–37]. Heavy quarks are produced in primary hard QCD scattering processes in the early stage of the nucleus-nucleus collisions [34], while the secondary thermal production in the QGP is expected to be negligible, unless the initial QGP temperature is much higher than that at RHIC or LHC [38]. Heavy quarks provide a cleaner probe for investigating the in-medium hadronization mechanism, not only for open mesons but also shedding light on the production of hidden charm mesons in high-energy nuclear-nuclear collisions. In our previous works, we studied the light hadron production in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$ –200 GeV and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV [39–41]. Those works established that the recombination model can nicely describe the light hadron production, which includes the effects of minijets. In particular, we have found compact formulas to describe the parton momentum distributions at the surface of the medium at midrapidity for any centrality, after the hard and semihard partons undergo momentum degradation when transversing the medium. Therefore, it is worth extending our study to the open- and hidden-charm mesons. In this paper, we employ the quark recombination model to investigate both the transverse momentum spectra and the second azimuthal harmonic coefficient of D^0 , D_s^+ , and J/ψ produced in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, respectively.

This paper is organized as follows. Section II briefly introduces the basic framework of the recombination model and the setups of the calculations. The formalisms of parton recombination for D^0 , D_s^+ , and J/ψ are shown in Sec. III. In Sec. IV, we show the results from our study on the cen-

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trality dependence of transverse momentum spectra and the second harmonic coefficient v_2 of D^0 , D_s^+ , and J/ψ at midrapidity in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. Finally, Sec. V summarizes the results and gives the conclusions from the present study.

II. RECOMBINATION OF CHARM QUARKS

To understand the transverse momentum distributions of charmed mesons, one can consider the one-dimensional formulation of recombination given in Refs. [39–44]. The invariant distribution of mesons is expressed as

$$p^0 \frac{dN^M}{dp_T} = \int \frac{dp_1}{p_1} \frac{dp_2}{p_2} F_{q_1 \bar{q}_2}(p_1, p_2) R_{q_1 \bar{q}_2}^M(p_1, p_2, p_T). \quad (1)$$

$R_{q_1 \bar{q}_2}^M$ is the recombination function (RF) for the formation of a meson with the transverse momentum p_T composed of a quark, q_1 , with momentum p_1 and an antiquark, $\bar{q}_2$, with momentum p_2 [45], and

$$R^M(p_1, p_2, p) = \frac{g_M}{B(a, b)} \left(\frac{p_1}{p} \right)^a \times \left(\frac{p_2}{p} \right)^b \delta \left(\frac{p_1}{p} + \frac{p_2}{p} - 1 \right), \quad (2)$$

where g_M is the statistical factor and $B(a, b)$ is the beta function. Having determined the RF, the natural question next is how to determine the parton distribution $F_{q_1 \bar{q}_2}$ just before hadronization. In the recombination model, the partons are divided into two types: thermal (T) and shower (S). The thermal partons contain the hot medium effect, while the shower partons are due to semihard and hard scattered partons. For mesons, the partons have the following recombination types,

$$F_{q_1 \bar{q}_2}(p_1, p_2) = \mathcal{T}\mathcal{T} + \mathcal{T}\mathcal{S} + \mathcal{S}\mathcal{S}, \quad (3)$$

where $\mathcal{T}$ and $\mathcal{S}$ are the thermal and shower partons invariant distributions, respectively.

For the thermal parton distribution, a simple exponential form is assumed,

$$\mathcal{T}_j = p_1 \frac{dN_j^T}{dp_1} = C_j p_1 e^{-p_1/T_j}, \quad (4)$$

where C_j has the dimension of inverse momentum and T_j refers to the inverse slope. T_j is different from the conventional temperature of thermalized systems. We use subscripts $j = \{q, s, c\}$ corresponding to light (u, d), strange, and charm quarks, respectively. The values of T_q and T_s for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV were obtained in our earlier work [41] and are listed in Table I, while T_c is discussed in Sec. IV.

The consideration of shower partons is a unique feature of the recombination model, which is empowered by the possibility to include the fragmentation process as $\mathcal{S}\mathcal{S}$ recombination for mesons. At a given centrality c , the shower-parton distribution after integration over the jet momentum q and summed over all jets is defined as [40,41,44]

$$S^j(p, c) = \int \frac{dq}{q} \sum_i \hat{F}_i(q, c) S_i^j(p, q). \quad (5)$$

TABLE I. Parameters T_q , T_s , and T_c in Eq. (4) as well as γ_0 and q_0 in Eq. (9) for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, respectively.

$\sqrt{s_{NN}}$ (TeV)	2.76	5.02
T_q (GeV)	0.39	0.415
T_s (GeV)	0.51	0.545
T_c (GeV)	0.57	0.79
γ_0	2.8	4.5
q_0 (GeV/c)	7	7

$S_i^j(p, q)$ is the unintegrated shower-parton distribution in a jet of type i fragmentating into a parton of type j with the momentum fraction p/q . It is determined by the fragmentation function (FF) on the basis that hadrons in a jet are formed by recombination of the shower partons in the same jet [42,45]. $\hat{F}_i(q, c)$ is the distribution of hard or semihard partons i at the medium surface after momentum degradation while transversing the medium but before fragmentation:

$$\hat{F}_i(q, c) = \frac{1}{2\pi} \int d\phi \int d\xi P_i(\xi, \phi, c) \times \int dk k f_i(k, c) G(k, q, \xi), \quad (6)$$

where $G(k, q, \xi)$ is the momentum degradation function due to energy loss. As discussed in Ref. [44], it is parametrized as

$$G(k, q, \xi) = q \delta(q - k e^{-\xi}). \quad (7)$$

$P_i(\xi, \phi, c)$ is the probability for parton i having a dynamical path length ξ at the angle ϕ initiated at the position (x_0, y_0) , weighted by the nuclear overlap function and integrated over all (x_0, y_0) . The dynamical path length ξ is proportional to the geometrical path length l , which is calculable from nuclear geometry [46]. Therefore, $P_i(\xi, \phi, c)$ can be written as

$$P_i(\xi, \phi, c) = \int dx_0 dy_0 Q(x_0, y_0, c) \delta[\xi - \gamma_i l(x_0, y_0, \phi, c)], \quad (8)$$

where $Q(x_0, y_0, c)$ is the probability that a hard (or semihard) parton is produced at (x_0, y_0) , which can be calculated from nuclear thickness functions [39,47]. The factor γ_i is introduced to account for the effects of jet quenching in the medium that results in additional parton degradation due to the soft partons created. Due to many more minijets being produced and the different geometrical configuration of the colliding system, the γ_i factor at LHC is different from that at RHIC. For Pb+Pb collisions, we parametrize γ_g for gluons as [40]

$$\gamma_g(q) = \frac{\gamma_0}{1 + (q/q_0)^2}. \quad (9)$$

The parameters γ_0 and q_0 are determined by fitting the spectra in the intermediate p_T region. As discussed before, the gluons lose about twice as much energy as the light quarks (u, d, s) [40], which directly implies that gluons on average lose the same fraction of momentum as quarks do in half the distance

of the transversal through the hot dense medium. The earlier work has shown that it is an important factor to reproduce the light hadron spectra [40]. The values of the two parameters for gluons for Pb+Pb collisions at 2.76 and 5.02 TeV are listed in Table I [40,41]. Their values for charm quarks are discussed in Sec. IV.

The minijets generate shower partons after emerging from the medium surface. Those shower partons recombine with themselves or with thermal partons in various combinations to form hadrons. In Ref. [48], the transverse momentum distributions of minijets $f_i(k, c)$ for gluons and light quarks as well as their antiquarks with the thickness functions contain the shadowing effect of the parton distribution in nuclear collisions. At central collisions, a simple parametrization is given as follows [48]:

$$f_i(k) = K \frac{A}{(1 + k/B)^n}, \quad (10)$$

where $K = 2.5$. For Pb+Pb collisions at 2.76 and 5.02 TeV, the parameters A , B , and n have been obtained by logarithmic interpolations of the parameters $\ln A$, B , and n between Au + Au collisions at 200 GeV and Pb+Pb collisions at 5.5 TeV [40,41], which are also shown in the Appendix. Taking into account the centrality dependence, the minijets distribution is assumed to be [41]

$$f_i(k, c) = \frac{T_{AA}(c)}{T_{AA}(0.05)} f_i(k, 0.05), \quad (11)$$

where $c = 0.05$ stands for 0–10% centrality. The values of the nuclear thickness function $T_{AA}(c)$ for Pb+Pb collisions are available in Ref. [49]. Since $f_i(k, c)$ has a power-law dependence on k , so does $\mathcal{S}^j(p, c)$ on p in contrast to the exponential behavior of the thermal partons. The introduction of shower partons is the way to bring the effects of hard scattering to the hadronization scale in the recombination model. At the same time, the formalism does not exclude fragmentation by a hard parton, since SS recombination at high p_T is equivalent to fragmentation.

For charm quarks, we extract the initial distribution directly from PYTHIA8 [50] generation using the Monash tune to derive the charm quark distribution in $p + p$ collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, respectively. To scale to Pb+Pb collisions, we employ the nuclear thickness function $\langle T_{PbPb} \rangle$ for any given centrality class C_1 – C_2 , as suggested in Ref. [51],

$$\frac{d^2 N_{c, C_1-C_2}^{AA}}{dp_T dy} = \langle T_{AA} \rangle_{C_1-C_2} \frac{d^2 \sigma_c^{pp}}{dp_T dy}.$$

Here, $\langle T_{PbPb} \rangle$, taken from Glauber model calculations [49], accounts for the shadowing effects and the spatial fluctuation. Therefore, this approach approximates the suppression of yields in Pb+Pb collisions through centrality-dependent geometric scaling rather than the nuclear parton distribution effects. Furthermore, a cut of $p_T > 3$ GeV/ c for charm quarks is applied in the following calculations since the hard parton distribution cannot be valid at low p_T .

III. TRANSVERSE MOMENTUM DISTRIBUTIONS OF CHARMED MESONS

The formulas for recombination of thermal and shower partons are well developed for central collisions in heavy-ion collisions at RHIC and LHC [39,40]. Up to now, we have successfully provided a coherent explanation for the centrality dependence of seven identified hadrons (π , p , K , Λ , ϕ , Ξ , Ω) produced in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV [41]. Now we turn our interest to the production of charmed mesons, such as D^0 , D_s^+ , and J/ψ using the quark recombination model.

A. D^0 production

Since the masses of charmed mesons are not negligible, we should replace p_0 in Eq. (1) by the transverse mass $m_T = (m^2 + p_T^2)^{1/2}$ at midrapidity. With the RF for D^0 [52] being

$$R_{D^0}(p_1, p_2, p_T) = \frac{5p_1 p_2^5}{p_T^5} \delta(p_1 + p_2 - p_T), \quad (12)$$

the four components for D^0 production are as follows:

$$\begin{aligned} \frac{dN_{D^0}^{TT}}{p_T dp_T} &= \frac{5C_q C_c}{m_T^{D^0} p_T^6} \int_0^{p_T} dp_1 p_1 e^{-p_1/T_q} \\ &\times (p_T - p_1)^5 e^{-(p_T - p_1)/T_c}, \end{aligned} \quad (13)$$

$$\begin{aligned} \frac{dN_{D^0}^{TS}}{p_T dp_T} &= \frac{5}{m_T^{D^0} p_T^6} \int_0^{p_T} dp_1 (p_T - p_1)^4 \\ &\times [p_1 C_q e^{-p_1/T_q} \mathcal{S}^c(p_T - p_1, c) \\ &+ C_c (p_T - p_1) e^{-(p_T - p_1)/T_c} \mathcal{S}^{\bar{u}}(p_1, c)], \end{aligned} \quad (14)$$

$$\frac{dN_{D^0}^{SS^{1j}}}{p_T dp_T} = \frac{1}{m_T^{D^0}} \int \frac{dq}{q^2} \sum_{i=g,c} \hat{F}_i(q, c) D_i^{D^0}(p_T, q), \quad (15)$$

$$\begin{aligned} \frac{dN_{D^0}^{SS^{2j}}}{p_T dp_T} &= \frac{5\Gamma}{m_T^{D^0} p_T^6} \int_0^{p_T} dp_1 (p_T - p_1)^4 \\ &\times \mathcal{S}^{\bar{u}}(p_1, c) \mathcal{S}^c(p_T - p_1, c). \end{aligned} \quad (16)$$

The shower-shower recombination from one jet (SS^{1j}) is equivalent to fragmentation, so the FF $D_i^{D^0}$ is directly used in Eq. (15). Γ in Eq. (16) is the probability that two parallel partons originating from two jets can recombine. Same as was done in Ref. [40], Γ was estimated as 0.1.

B. D_s^+ production

The four components of D_s^+ are very similar to those of D^0 . The differences are in the constituent quark masses between m_q and m_s and the different T_q value of light quarks and T_s value of s quarks. The RF of D_s^+ is taken to be [52]

$$R_{D_s^+}(p_1, p_2, p_T) = \frac{3p_1 p_2^3}{p_T^5} \delta(p_1 + p_2 - p_T). \quad (17)$$

Therefore, we have the following D_s^+ distributions:

$$\frac{dN_{D_s^+}^{\text{TT}}}{p_T dp_T} = \frac{3C_s C_c}{m_T^{D_s^+} p_T^4} \int_0^{p_T} dp_1 p_1 e^{-p_1/T_s} \times (p_T - p_1)^3 e^{-(p_T - p_1)/T_c}, \quad (18)$$

$$\frac{dN_{D_s^+}^{\text{TS}}}{p_T dp_T} = \frac{3}{m_T^{D_s^+} p_T^4} \int_0^{p_T} dp_1 (p_T - p_1)^2 \times [C_s p_1 e^{-p_1/T_s} S^c(p_T - p_1, c) + C_c (p_T - p_1) e^{-(p_T - p_1)/T_c} S^{\bar{s}}(p_1, c)], \quad (19)$$

$$\frac{dN_{D_s^+}^{\text{SS}^{1j}}}{p_T dp_T} = \frac{1}{m_T^{D_s^+}} \int \frac{dq}{q^2} \sum_{i=g,c} \hat{F}_i(q, c) D_i^{D_s^+}(p_T, q), \quad (20)$$

$$\frac{dN_{D_s^+}^{\text{SS}^{2j}}}{p_T dp_T} = \frac{3\Gamma}{m_T^{D_s^+} p_T^4} \int_0^{p_T} dp_1 (p_T - p_1)^2 \times S^{\bar{s}}(p_1, c) S^c(p_T - p_1, c). \quad (21)$$

C. J/ψ production

The mass of J/ψ is nearly at the threshold of the sum of the constituent quark masses, so loose binding means broad spatial distribution and thus narrow wave function in the momentum space. Considering the valon distribution for J/ψ is narrow enough so that it is not too far from the delta-function approximation, the RF of J/ψ can be written as

$$R_{J/\psi}(p_1, p_2, p_T) = g_{J/\psi} p_1 p_2 \prod_{i=1}^2 \delta(p_i - p_T/2), \quad (22)$$

with the statistical factor $g_{J/\psi}$, which will be fixed by the experimental data. It represents the medium effect on the recombination of $c\bar{c}$. Therefore, the four components for J/ψ are as follows:

$$\frac{dN_{J/\psi}^{\text{TT}}}{p_T dp_T} = \frac{g_{J/\psi} C_c^2 p_T}{4m_T^{J/\psi}} e^{-p_T/T_c}, \quad (23)$$

$$\frac{dN_{J/\psi}^{\text{TS}}}{p_T dp_T} = \frac{g_{J/\psi} C_c}{2m_T^{J/\psi}} e^{-p_T/2T_c} S^c(p_T/2, c), \quad (24)$$

$$\frac{dN_{J/\psi}^{\text{SS}^{1j}}}{p_T dp_T} = \frac{1}{p_T m_T^{J/\psi}} \int \frac{dq}{q^2} \sum_{i=g,c} \hat{F}_i(q, c) D_i^{J/\psi}(p_T, q), \quad (25)$$

$$\frac{dN_{J/\psi}^{\text{SS}^{2j}}}{p_T dp_T} = \frac{g_{J/\psi} \Gamma}{p_T m_T^{J/\psi}} S^c(p_T/2, c) S^{\bar{c}}(p_T/2, c). \quad (26)$$

IV. RESULTS AND DISCUSSION

In the present section, we show the results on the transverse momentum spectra and the second coefficient of azimuthal anisotropy v_2 for D^0 , D_s^+ , and J/ψ in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. The inverse slopes T_q and T_s and γ_0 and q_0 from Eq. (9) are shown in Table I. Furthermore, the normalization factor C_q of u and d quarks and the normalization factor C_s of strange quarks for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV were obtained in Ref. [41] and

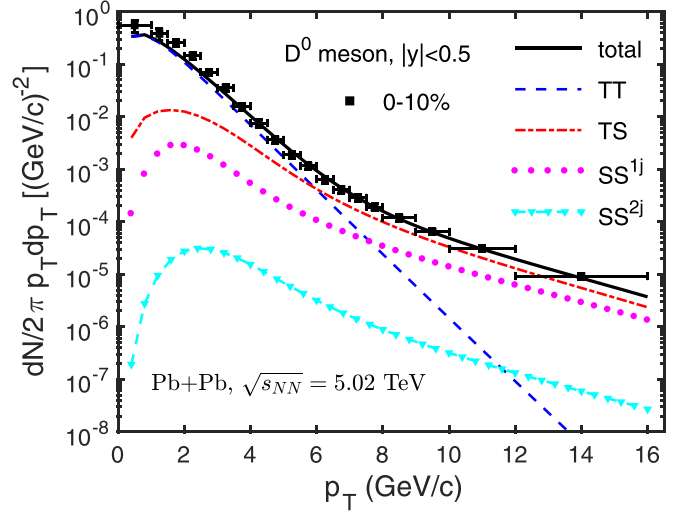


FIG. 1. Transverse momentum spectrum of D^0 at the centrality of 0–10% in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data are taken from Ref. [16].

are listed in Table II. Therefore, the unknown parameters are T_c and the centrality dependence of the normalization factor C_c for charm quarks.

A. Transverse momentum spectra

In Fig. 1, we show the transverse momentum spectra of D^0 (the black solid line) produced in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and a centrality of 0–10% at midrapidity. Also shown in the figure are experimental D^0 spectrum from the ALICE Collaboration at a centrality of 0–10% shown by black solid squares [16]. It is seen that the recombination model nicely describes the experimental data. The thermal and shower partons in various combinations are shown by different line types, which dominate at different p_T regions. The jet-medium interaction is taken into account at the hadronization stage by the TS component, which dominates at intermediate p_T . SS recombination from one jet becomes important at high p_T , which is equivalent to fragmentation but in a language that has dynamical content at the hadronization scale. The value of parameter γ_0 in the γ factor for charm quarks is 1.0 for $\sqrt{s_{NN}} = 5.02$ TeV, which is smaller than that for light quarks. It means that the effect of jet quenching in the medium for charm quarks is smaller than that for light quarks. In contrast to light quarks and gluons, which can be produced or annihilated during the entire evolution of the medium, heavy quarks are produced in the initial hard-scattering processes and their annihilation rate is small [53]. Therefore, heavy quarks preserve their flavor and mass identity while traversing the medium and can be tagged throughout all momentum ranges, from low to high p_T , through the measurement of heavy flavor hadrons in the final state of the collision. The inverse slope for charm quarks T_c is determined by fitting the transverse momentum spectrum of D^0 at low p_T , which is listed in Table I. A similar result is obtained for the transverse momentum spectrum of D_s^+ in central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The agreement be-

TABLE II. Parameters C_q , C_s , and C_c for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. The corresponding values of the impact parameter b (in fm) are also shown [49].

$\sqrt{s_{NN}}$ (TeV)	Centrality	$b_{\min}$ (fm)	$b_{\max}$ (fm)	C_q [(GeV/c) $^{-1}$]	C_s [(GeV/c) $^{-1}$]	C_c [(GeV/c) $^{-1}$]
2.76	0–10%	0.00	4.94	22.4	10.6	2.9
	20–40%	6.98	9.88	15.5	7.3	0.9
	20–50%	6.98	11.04	14.3	6.7	0.9
	30–50%	8.55	11.04	13.2	6.2	0.9
5.02	0–10%	0.00	4.94	23.8	8.0	1.1
	30–50%	8.55	11.04	15.0	4.0	0.39

tween the calculation results from the recombination model (RM) and the experimental data is quite good, as shown in Fig. 2.

Figure 3 shows the calculation result for J/ψ at a centrality of 0–10% in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. What is most noticeable is that the relative strengths of the components are unlike the cases for D^0 and D_s^+ . The TT component dominates for $p_T < 7$ GeV/c and the relative strength of the SS component is much lower. This means that J/ψ is produced thermally even at $p_T \sim 7$ GeV/c without any contribution from parton fragmentation which is the usual mechanism considered in perturbative QCD. This result is understandable. At earlier time, J/ψ is formed at higher density, and its survival in the hot medium is suppressed due to its dissociation through interaction with the plasma that is still active. By varying $g_{J/\psi}$ only for the overall normalization, we obtain the good description for the J/ψ spectrum at a centrality of 0–10% with $g_{J/\psi} = 0.28$. The small value of $g_{J/\psi}$ relative to g_{D^0} and $g_{D_s^+}$ being 1 is an indication of charmonium suppression after J/ψ is formed at a time much earlier than D^0 and D_s^+ , when the density of charm quarks is higher. Like the case of ϕ -meson production discussed in our earlier work [40], J/ψ also experiences the effects of dissociation by

the plasma as it traverses the remaining portion of the medium before it completely hadronizes.

Figure 4 includes the calculation results for the transverse momentum spectra of D^0 , D_s^+ , and J/ψ for the centralities of 0–10% and 30–50% at midrapidity in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Evidently, for D^0 , D_s^+ , and J/ψ the agreement with data for both central and noncentral collisions is excellent for all p_T where data exist. The corresponding impact parameter b for each centrality is listed in Table II [49]. After investigating the production of charmed mesons in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, it is natural to apply it to the lower colliding energy $\sqrt{s_{NN}} = 2.76$ TeV. The inverse slope T_c is determined by the D^0 distribution at central collisions shown in Table I. With the retuned parameters C_c , our calculation results can nicely reproduce the transverse momentum spectra of D^0 and D_s^+ for various centralities at $\sqrt{s_{NN}} = 2.76$ TeV, as shown in Fig. 5. From Table II, we can see that the normalization factor C_c at $\sqrt{s_{NN}} = 2.76$ TeV is higher than that at 5.02 TeV for each centrality. The parameter C_j ($j = q, s, c$) in the thermal parton distribution has been named as the normalization factor since the recombination model was officially proposed about two decades ago [42,43], but the overall normalizations of hadron distributions

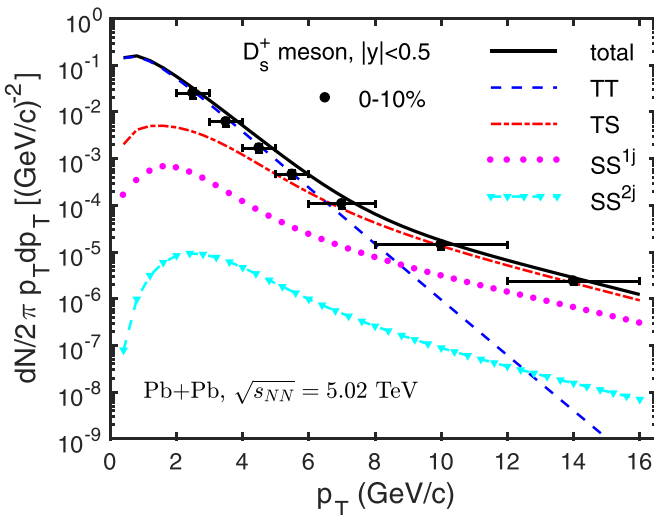


FIG. 2. Transverse momentum spectrum of D_s^+ at the centrality of 0–10% in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data are taken from Ref. [17].

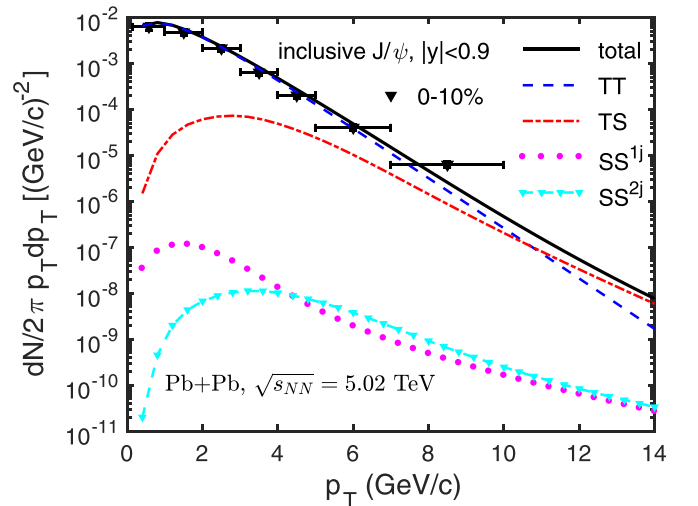


FIG. 3. Transverse momentum spectrum of J/ψ at the centrality of 0–10% in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data are taken from Ref. [18].

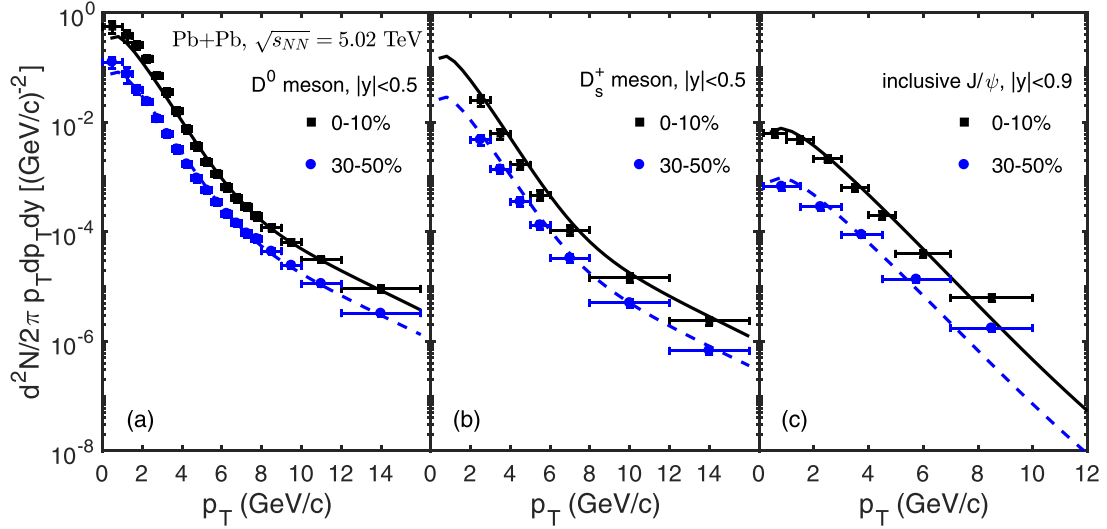


FIG. 4. Transverse momentum spectra of D^0 (a), D_s^+ (b), and J/ψ (c) from the recombination model at midrapidity in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for different centrality classes. The data are taken from Ref. [16] for D^0 , Ref. [17] for D_s^+ , and Ref. [18] for J/ψ .

are dependent on several parameters. For example, the D^0 distributions at low p_T are mutually determined by C_q , C_c , T_q , and T_c , not just C_c . What needs to be maintained is that the total multiplicity of a hadron increases with collision energy. Therefore, it is understandable that C_c at $\sqrt{s_{NN}} = 2.76$ TeV is higher than that at 5.02 TeV. The value of the parameter γ_0 in the γ factor is 1.2, which is a little bit larger than that for $\sqrt{s_{NN}} = 5.02$ TeV. The calculated distributions from the recombination model agree well with the experimental data of charmed mesons for both colliding energies at LHC.

Unfortunately, the experimental data for J/ψ at midrapidity in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are not available yet. We predict the transverse momentum distributions of J/ψ at the centralities of 0–20% and 20–40% in Fig. 5(c), which can be compared with experimental

measurements in the near future. From the above study, we can conclude that our results from the RM agree well with the measured data at all centralities and transverse momenta for the light hadrons and charmed mesons, which gives support to the reliability of the dynamical roles that minijets and their shower partons play in our model.

B. Second harmonic of azimuthal anisotropy

We now broaden our consideration to include the azimuthal angle ϕ dependence by considering the effects of semihard partons, which are created near the surface and directed outward. They can generate the minijets and give rise to ϕ anisotropy in the thermal component. As is done in Ref. [54], $\rho^h(p_T, \phi, b)$ denotes the single-particle distribution of hadron h produced at midrapidity in heavy-ion collisions at the impact

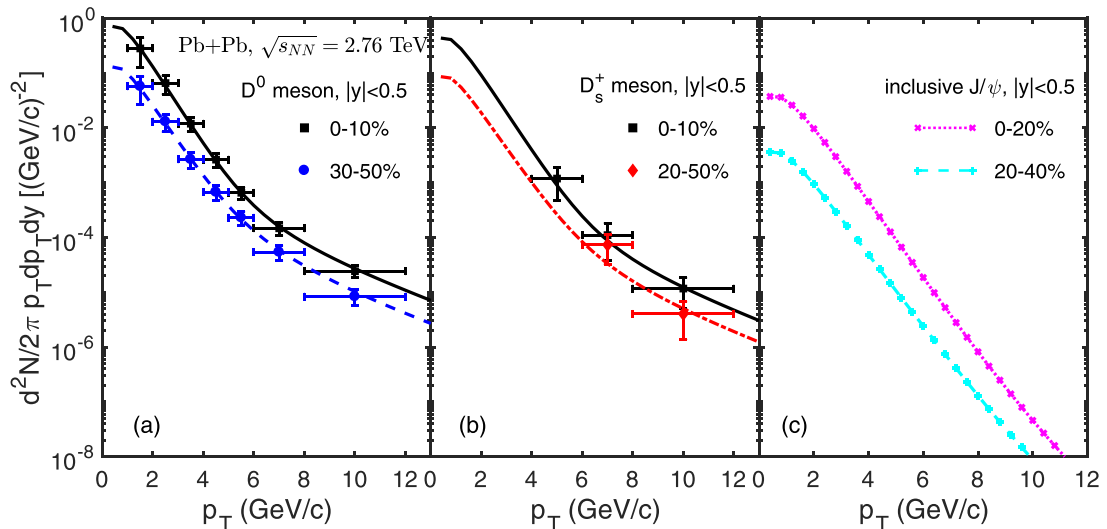


FIG. 5. Transverse momentum spectra of D^0 (a), D_s^+ (b), and J/ψ (c) from the recombination model at midrapidity in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for different centrality classes. The data are taken from Ref. [10] for D^0 and Ref. [11] for D_s^+ .

parameter b :

$$\rho^h(p_T, \phi, b) = \frac{dN_h}{p_T dp_T d\phi}(p_T, \phi, b). \quad (27)$$

At low p_T , ρ^h is assumed to consist of three components:

$$\rho^h(p_T, \phi, b) = B^h(p_T, b) + R^h(p_T, \phi, b) + M^h(p_T, \phi, b), \quad (28)$$

the base, ridge, and minijet components, respectively. The first two components are due to the recombination of thermal partons (TT), while the third one is dependent on the component of thermal-shower (TS) for mesons, which is dominant in the intermediate p_T region, but is still not negligible at low p_T . Therefore, the recombination of thermal partons has two components. One is the base component, which is azimuthally isotropic, while the other one is the ridge, which is ϕ dependent. On the other hand, in heavy-ion collisions, the density of minijets produced by semihard scattering of partons is so high that it is important to consider how they affect the azimuthal harmonics. After averaging over ϕ , we have

$$\bar{\rho}^h(p_T, b) = B^h(p_T, b) + \bar{R}^h(p_T, b) + \bar{M}^h(p_T, b). \quad (29)$$

With Eq. (28), the second harmonic coefficient can be expressed as

$$v_2^h(p_T, b) = \langle \cos n\phi \rangle_\rho^h = \frac{\int_0^{2\pi} d\phi \cos 2\phi \rho^h(p_T, \phi, b)}{\int_0^{2\pi} d\phi \rho^h(p_T, \phi, b)}. \quad (30)$$

The ϕ -independent base thermal component is expressed as

$$B^h(p_T, b) = \mathcal{N}_h(p_T, b) e^{-p_T/T_0}, \quad (31)$$

where $\mathcal{N}_h(p_T, b)$ is the normalization factor. T_0 is treated as a free parameter, which is colliding energy dependent. The second component $R(p_T, \phi, b)$ contains the ϕ dependence due to the initial elliptical spatial configuration through the $S(\phi, b)$. The physical meaning of $S(\phi, b)$ is that it is the segment on the initial ellipse through which semihard partons are emitted to contribute to a ridge particle at ϕ . In Ref. [46], it was found that the azimuthal correlation between a semihard parton and a ridge particle formed by TT recombination can be described by a Gaussian distribution in ϕ with a width of $\sigma = 0.33$ in order to reproduce the ridge data. Therefore, the possible semihard partons that can contribute to the fixed ridge particles at ϕ must have their azimuthal angles that deviate from ϕ by no more than σ [46,54]. This means the exit point of a semihard parton at the surface is restricted to a certain range $\phi \pm \sigma$. The derivation of $S(\phi, b)$ at the impact parameter b given in Ref. [55] is based on the geometry of the initial configuration taken to be an ellipse with width w and height h , where $w = 1 - b/2$ and $h = (1 - b^2/4)^{1/2}$ in units of nuclear radius R_A :

$$S(\phi, b) = h(b)[E(\theta_2, \alpha) - E(\theta_1, \alpha)], \quad (32)$$

where $E(\theta_i, \alpha)$ is the elliptic integral of the second kind with $\alpha = 1 - w^2/h^2$ and

$$\theta_i = \tan^{-1} \left(\frac{h}{w} \tan \phi_i \right), \quad \phi_1 = \phi - \sigma, \quad \phi_2 = \phi + \sigma. \quad (33)$$

It should be noted that $S(\phi, b)$ in Eq. (32) is not normalized. Since the elliptical axes may not coincide with the reaction plane that contains the impact parameter b , a tilt angle ψ_2 is introduced and averaged over,

$$\tilde{S}_2(\phi, b) = \frac{2}{\pi} \int_{\pi/4}^{\pi/4} d\psi_2 S_2(\phi - \psi_2, b). \quad (34)$$

So the normalized $\tilde{S}_2(\phi, b)$ can be expressed as

$$S_2(\phi, b) = \tilde{S}_2(\phi, b) \left/ \frac{1}{2\pi} \int_0^{2\pi} d\phi \tilde{S}_2(\phi, b) \right. \quad (35)$$

Then, the ridge component in Eq. (28) which responds to the minijets through TT recombination can be written as

$$R^h(p_T, \phi, b) = S(\phi, b) \bar{R}^h(p_T, b), \quad (36)$$

where $\bar{R}^h(p_T, b)$ is the second component of the recombination of thermal partons ($\frac{dN_h^{TT}}{p_T dp_T}$). The first component is the ϕ -independent $B^h(p_T, b)$. As done in Ref. [54], we write the third component of $\rho^h(p_T, \phi, b)$ as

$$M^h(p_T, \phi, b) = J(\phi, b) \bar{M}^h(p_T, b), \quad (37)$$

where $\bar{M}^h(p_T, b)$ refers to the recombination of thermal-shower partons ($\frac{dN_h^{TS}}{p_T dp_T}$), which is given in Sec. III. $J(\phi, b)$ describes the ϕ -dependent part of the minijet contribution, which is assumed as

$$J(\phi, b) = \tilde{J}(\phi, b) \left/ \frac{1}{2\pi} \int_0^{2\pi} d\phi \tilde{J}(\phi, b) \right., \quad (38)$$

where $\tilde{J}(\phi, b)$ contains all the harmonic components, $\cos n\phi$, averaged over the tilt angle ψ_n ,

$$\tilde{J}(\phi, b) = 1 + b \sum_{n=2}^{\infty} a_n \frac{n}{\pi} \int_{-\pi/2n}^{\pi/2n} d\psi_n \cos n(\phi - \psi_n), \quad (39)$$

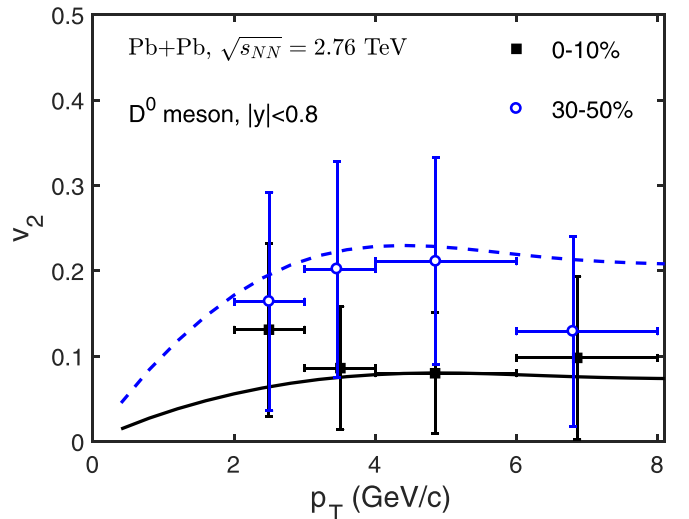


FIG. 6. The second harmonic coefficient v_2 of D^0 at the centralities of 0–10% and 30–50% in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The data are taken from Ref. [13].

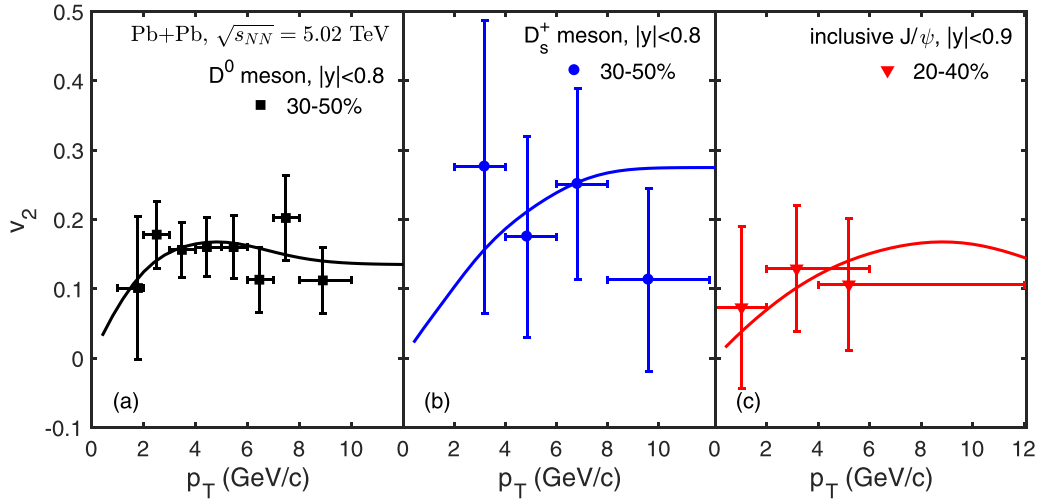


FIG. 7. The second harmonic coefficient v_2 of D^0 (a), D_s^+ (b), and J/ψ (c) as a function of transverse momentum in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for different centrality classes. The data are taken from Ref. [19] for D^0 , Ref. [17] for D_s^+ , and Ref. [20] for J/ψ .

where $a_n, n \geq 2$, are free parameters to be determined by fitting the experimental data of v_n .

With the three components of $\rho^h(p_T, \phi, b)$ shown in Eqs. (31), (36), and (37), a universal formula for the second azimuthal harmonic coefficient from Eq. (27) can be obtained as

$$v_2^h(p_T, b) = \frac{\langle \cos 2\phi \rangle_S \bar{K}^h(p_T, b) + \langle \cos 2\phi \rangle_J \bar{M}^h(p_T, b)}{\bar{\rho}^h(p_T, b)}, \quad (40)$$

where

$$\langle \cos 2\phi \rangle_S = \frac{1}{2\pi} \int_0^{2\pi} d\phi \cos 2\phi S(\phi, b), \quad (41)$$

$$\langle \cos 2\phi \rangle_J = \frac{1}{2\pi} \int_0^{2\pi} d\phi \cos 2\phi J(\phi, b). \quad (42)$$

In Fig. 6, we show the second harmonic coefficient v_2 of D^0 at the centralities of 0–10% and 30–50% in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from the recombination model, compared to the experimental data, shown by black solid squares for 0–10% and blue empty circles for 30–50%, from the ALICE Collaboration [13]. Similar results are also obtained for D^0 , D_s^+ , and J/ψ produced at midrapidity in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, as shown in Fig. 7. The solid lines reproduce very well the data from the ALICE Collaboration [17,19,20] for p_T almost up to 10 GeV/c at various centralities.

TABLE III. Parameter a_2 in Eq. (39) for D^0 , D_s^+ , and J/ψ in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV.

$\sqrt{s_{NN}}$ (TeV)	2.76	5.02
D^0	0.46	0.3
D_s^+		0.61
J/ψ		0.21

ties. The parameter a_2 is independent of the centrality, and its values are shown in Table III.

V. SUMMARY

In this paper, we have studied the transverse momentum distributions and azimuthal anisotropy of charmed mesons in relativistic heavy-ion collisions at LHC within the framework of the recombination model that includes the effects of minijets, which can generate azimuthal anisotropy both through energy loss to the medium and in creating shower partons that recombine with the thermal partons. With emphasis on the effects of minijets, calculated results agree well with the experimental data for p_T spectra and the second harmonic coefficient v_2 of D^0 , D_s^+ , and J/ψ in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV. The geometry and the nuclear medium produced in heavy-ion collisions are complex, but the agreement between our model calculations and available data indicates that the current recombination model supports the picture that the centrality dependence of the production of light hadrons and charmed mesons for the whole p_T region can be described by the recombination of thermal and shower partons in relativistic heavy-ion collisions. In this case, it is of great interest to study the production of Λ_c^+ baryons with the recombination model which we will discuss in a following paper.

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TABLE IV. Parameters A , B , and n for $f_i(k, 0.05)$ in Eq. (10) for central Pb+Pb collisions at $\sqrt{s} = 2.76$ and 5.02 TeV [40,41].

$\sqrt{s_{NN}}$ (TeV)		A ($10^4/\text{GeV}^2$)	B (GeV)	n
2.76	g	6.2	0.98	6.22
	u	1.138	0.687	5.67
	d	1.266	0.677	5.66
	$\bar{u}$	0.24	0.87	5.97
	$\bar{d}$	0.23	0.88	5.99
	$s, \bar{s}$	0.093	1.05	6.12
5.02	g	11.2	0.80	5.68
	u	2.02	0.59	5.31
	d	2.28	0.58	5.29
	$\bar{u}$	0.42	0.75	5.52
	$\bar{d}$	0.40	0.76	5.53
	$s, \bar{s}$	0.154	0.93	5.63

DATA AVAILABILITY

The data that support the findings of this article are openly available [10,11,13,16–20].

APPENDIX: PARAMETERS

Some parameters used in the paper are listed in Table IV, which are referenced from previous publications.

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