

Hadronization of Λ_c^+ baryons from a recombination model in Pb + Pb collisions at energies available at the CERN Large Hadron Collider

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The production of Λ_c^+ baryons in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is investigated within the quark recombination framework, including the energy loss of light and charm quarks inside the hot and dense medium. The model simultaneously describes the transverse momentum (p_T) spectra of Λ_c^+ baryons, Λ_c^+/D^0 yield ratio, which is attributed to the dominance of the quark recombination mechanism in the quark-gluon plasma, and the second harmonic coefficient of Λ_c^+ baryons with emphasis on the effects of minijets on the azimuthal anisotropy. Furthermore, we extend the theoretical calculation to Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and make predictions for Λ_c^+ baryons and Λ_c^+/D^0 yield ratio. The simultaneous description of the yield, baryon-to-meson ratio, and azimuthal anisotropy further validates that the recombination model is an effective hadronization mechanism in heavy-ion collisions.

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I. INTRODUCTION

Ultrarelativistic heavy-ion collisions provide a unique laboratory for probing quantum chromodynamics (QCD) under extreme conditions of temperature and energy density [1,2]. The hadronization of heavy quarks constitutes one of the most compelling probes of the quark-gluon plasma (QGP) created in ultrarelativistic heavy-ion collisions. Due to their large masses, heavy quarks are predominantly produced in the initial hard scatterings and subsequently propagate through the strongly interacting medium. During the past decade, experimental advances at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) have enabled the precise measurement of not only open-charm mesons but also charmed baryons [3–11]. A striking observation is the significant enhancement of the Λ_c^+/D^0 yield ratio at intermediate transverse momentum in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [6], which contradicts the expectation from vacuum fragmentation functions and resembles the “baryon anomaly” observed for light flavors such as p/π and Λ/K_s^0 [12–14]. This enhancement can be used to probe the in-medium hadronization dynamics of heavy quarks and put

stronger constraints on the heavy quark hadronization mechanism in heavy-ion collisions.

Several theoretical approaches have been developed to describe the production of charmed hadrons in heavy-ion collisions, such as the statistical model [15,16], transport model [17,18], and quark recombination or coalescence (ReCo) model [19–22]. Specifically, the ReCo model offers a natural explanation for baryon-to-meson enhancement and has also successfully described the production of light hadrons [23–25]. Furthermore, its extension to charm quarks has attracted significant attention. More than a decade ago, the ReCo model was already employed to study the heavy-flavor hadron ratios Λ_c^+/D^0 and $\Lambda_b/\bar{B}^0$ produced in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV [26]. Although several theoretical approaches exist, a unified framework that simultaneously describes the transverse momentum spectra, Λ_c^+/D^0 yield ratio, and the azimuthal anisotropy across different centralities within a single set of physical parameters remains a challenge. In this work we present a systematic study of the production of Λ_c^+ baryons in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV within the quark recombination model. Our approach explicitly incorporates the recombination of thermal partons with shower partons generated by energetic partons losing energy in the hot medium. We demonstrate that this mechanism not only reproduces the transverse momentum distributions of Λ_c^+ baryons and Λ_c^+/D^0 yield ratio but also provides a natural explanation for the observed second harmonic of azimuthal anisotropy v_2 of Λ_c^+ . Our results emphasize the essential role of minijets in bridging the soft and hard sectors of the collision system and support the dominance of recombination in the hadronization of charm quarks produced in heavy-ion collisions.

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This paper is organized as follows. In Sec. II we introduce the recombination model, which incorporates both thermal and shower parton distributions, and present the formalism for Λ_c^+ baryons via parton recombination. In Sec. III we establish the theoretical calculations of transverse momentum spectra of Λ_c^+ baryons at central and midcentral collisions, Λ_c^+/D^0 yield ratio, and the second harmonic coefficient of Λ_c^+ baryons in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. These results are compared with available experimental data. The predictions for the transverse momentum spectra of Λ_c^+ baryons and Λ_c^+/D^0 yield ratio in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are also provided, without introducing any additional free parameters. A summary and outlook are given in Sec. IV.

II. QUARK RECOMBINATION FOR Λ_c^+ BARYONS

In the quark recombination model, hadron production is described as the coalescence of constituent quarks that are close in phase space. For baryons composed of quarks (q_1, q_2, q_3) with momenta (p_1, p_2, p_3) , the invariant distribution at midrapidity can be expressed as [27,28]

$$p^0 \frac{dN^B}{dp_T} = \int \prod_{i=1}^3 \frac{dp_i}{p_i} F_{q_1 q_2 q_3}(p_1, p_2, p_3) R_{q_1 q_2 q_3}^B(p_1, p_2, p_3, p_T), \quad (1)$$

where $R_{q_1 q_2 q_3}^B$ is the recombination function (RF) for baryons. For Λ_c^+ we have the following parametrization [29,30]:

$$R_{\Lambda_c^+}(p_1, p_2, p_3, p_T) = g_{st}^{\Lambda_c^+} \frac{p_1 p_2 p_3}{p_T^3} \delta\left(\frac{p_1}{p_T} + \frac{p_2}{p_T} + \frac{p_3}{p_T} - 1\right), \quad (2)$$

where $g_{st}^{\Lambda_c^+}$ is the statistical factor, and the δ function enforces momentum conservation. $F_{q_1 q_2 q_3}$ is the parton distribution before hadronization. In the recombination model, the partons are divided into two types: thermal (T) and shower (S). Taking into account the recombination of different types of partons, we thus have

$$F_{q_1 q_2 q_3} = TTT + TTS + TSS + SSS, \quad (3)$$

where T and S are used to denote the invariant distributions for thermal and shower partons, respectively. For a visualization of the various components, the schematic diagrams are presented in Ref. [27]. The shower partons in TSS can come from one or two jets. The case for SSS is more complicated. In this work only the contributions from SSS^{1j} and SSS^{2j} are retained, since the component SSS^{3j} , which corresponds to three shower partons originating from three distinct jets, is strongly suppressed.

The soft partons generated by multiple partonic scattering and radiation in the medium interact with the bulk partons and cannot be distinguished from the latter by the time the density of all soft partons is low enough for hadronization. They are all referred to here as thermal partons in the final stage of the quark matter as they move out of the deconfinement phase. The thermal parton distribution is assumed to follow a

TABLE I. Parameters C_q , C_c , T_q , and T_c in Eq. (4) for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Centrality	0%–10%	30%–50%
C_q [(GeV/c) $^{-1}$]	23.8	15
C_c [(GeV/c) $^{-1}$]	1.1	0.39
T_q (GeV)	0.42	0.42
T_c (GeV)	0.79	0.79

simple exponential form [27,28],

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

where C_j and T_j are the normalization constant and inverse slope parameter, respectively, which have already been determined in our previous study on the production of charmed mesons in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [22]. Their values are listed in Table I for the convenience of readers.

As discussed in Refs. [22,28], the shower parton distribution at centrality c is written as

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

where $S_i^j(p, q)$ is the shower parton distribution (SPD) of a parton of type j fragmenting from a jet of type i with momentum fraction p/q , determined through the fragmentation function (FF) as described in Refs. [31,32]. $\hat{F}_i(q, c)$ is given by

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

where $G(k, q, \xi)$ represents the momentum degradation due to parton energy loss parametrized as [27]

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

relating the initial parton momentum k to the final momentum q at the medium surface by an exponential decay via the dynamical path length ξ . $P_i(\xi, \phi, c)$ denotes the probability for parton i to traverse the path length ξ at an azimuthal angle ϕ in collisions with centrality c . The probability is initiated from position (x_0, y_0) and weighted by the nuclear overlap function integrated over all (x_0, y_0) . The intrinsic connection between the collision geometry and the parton dynamics is imbedded in $P_i(\xi, \phi, c)$, where the dynamical path length ξ is proportional to the geometrical path length l . The detailed explanation of l has been presented in our earlier work [27] and is not repeated here. Hence, $P_i(\xi, \phi, c)$ can be calculated by [33]

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

where $Q(x_0, y_0, c)$ is the probability for a hard (or semihard) parton to be produced at (x_0, y_0) . The factor γ_i accounts for the jet-quenching effects in the medium, which enhance the parton energy degradation due to soft parton creation. For

TABLE II. Parameters A , B , and n for $f_i(k, 0.05)$ in Eq. (10) for central Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV [28].

$\sqrt{s_{NN}}$ (TeV)		A ($10^4/\text{GeV}^2$)	B (GeV)	n
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

Pb + Pb collisions, γ_g for gluons is parameterized as [27]

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

with $q_0 = 7$ GeV/c and $\gamma_0 = 4.5$ for gluons and 1.0 for charm quarks, as determined in our previous works [22,28] for the production of light hadrons and charmed mesons in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. As discussed before, light quarks ($i = u, d, s$) are assumed to undergo approximately half the energy loss experienced by gluons [27]. Charm quarks are produced in the initial hard-scattering process and their annihilation rate is small, so the effect of jet quenching in the medium for charm quarks is smaller than that for light quarks.

For light quarks the centrality dependence of the minijet distribution $f_i(k, c)$ is assumed to be [28]

$$f_i(k, c) = \frac{T_{AA}(c)}{T_{AA}(0.05)} \times K \frac{A}{(1 + k/B)^n}, \quad (10)$$

where $K = 2.5$, and $c = 0.05$ represents the centrality of 0%–10%. T_{AA} is the nuclear thickness function, which accounts for

shadowing effects and spatial fluctuations [34]. The parameters A , B , and n for Pb + Pb collisions at 5.02 TeV 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 [27,28], which are shown in Table II. As done in our previous work [22], the initial momentum distribution of charm quarks for $p + p$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV can be extracted from PYTHIA8 [35] simulations using the Monash tune. Then for charm quarks produced in Pb + Pb collisions, we employ the nuclear thickness function T_{PbPb} for each centrality [36]:

$$\frac{d^2 N^{\text{PbPb}}(c)}{dp_T dy} = T_{\text{PbPb}}(c) \frac{d^2 \sigma^{pp}}{dp_T dy}. \quad (11)$$

From the essential points discussed above, the thermal-thermal-thermal (TTT), thermal-thermal-shower (TTS), thermal-shower-shower (TSS), and shower-shower-shower (SSS) recombination for Λ_c^+ baryons can be written as

$$\frac{dN_{\Lambda_c^+}^{\text{TTT}}}{p_T dp_T} = \frac{g_{st}^{\Lambda_c^+} C_q^2 C_c}{m_T^{\Lambda_c^+} p_T^{2\alpha+\beta}} \int_0^{p_T} dp_1 \int_0^{p_T-p_1} dp_2 p_1 p_2 e^{-(p_1+p_2)/T_q} (p_T - p_1 - p_2) e^{-(p_T-p_1-p_2)/T_c}, \quad (12)$$

$$\begin{aligned} \frac{dN_{\Lambda_c^+}^{\text{TTS}}}{p_T dp_T} &= \frac{g_{st}^{\Lambda_c^+}}{m_T^{\Lambda_c^+} p_T^{2\alpha+\beta}} \int_0^{p_T} dp_1 \int_0^{p_T-p_1} dp_2 \{ C_q^2 p_1 p_2 e^{-(p_1+p_2)/T_q} \mathcal{S}^c(p_T - p_1 - p_2, c) \\ &\quad + 2C_q C_c p_1 e^{-p_1/T_q} p_2 e^{-p_2/T_c} \mathcal{S}^u(p_T - p_1 - p_2, c) \}, \end{aligned} \quad (13)$$

$$\begin{aligned} \frac{dN_{\Lambda_c^+}^{\text{TSS}^{1j}}}{p_T dp_T} &= \frac{g_{st}^{\Lambda_c^+}}{m_T^{\Lambda_c^+} p_T^{2\alpha+\beta}} \int_0^{p_T} dp_1 \int_0^{p_T-p_1} dp_2 \{ C_c p_1 e^{-p_1/T_c} \mathcal{S}^{ud}(p_2, p_T - p_1 - p_2, c) \\ &\quad + 2C_q p_1 e^{-p_1/T_q} \mathcal{S}^{dc}(p_2, p_T - p_1 - p_2, c) \}, \end{aligned} \quad (14)$$

$$\begin{aligned} \frac{dN_{\Lambda_c^+}^{\text{TSS}^{2j}}}{p_T dp_T} &= \frac{g_{st}^{\Lambda_c^+} \Gamma}{m_T^{\Lambda_c^+} p_T^{2\alpha+\beta}} \int_0^{p_T} dp_1 \int_0^{p_T-p_1} dp_2 \{ C_c p_1 e^{-p_1/T_c} \mathcal{S}^u(p_2, c) \mathcal{S}^d(p_T - p_1 - p_2, c) \\ &\quad + 2C_q p_1 e^{-p_1/T_q} \mathcal{S}^d(p_2, c) \mathcal{S}^c(p_T - p_1 - p_2, c) \}, \end{aligned} \quad (15)$$

$$\frac{dN_{\Lambda_c^+}^{\text{SSS}^{1j}}}{p_T dp_T} = \frac{1}{m_T^{\Lambda_c^+}} \int \frac{dq}{q^2} \hat{F}(q, c) D_c^{\Lambda_c^+}(p_T, q), \quad (16)$$

$$\begin{aligned} \frac{dN_{\Lambda_c^+}^{\text{SSS}^{2j}}}{p_T dp_T} &= \frac{g_{st}^{\Lambda_c^+} \Gamma}{m_T^{\Lambda_c^+} p_T^{2\alpha+\beta}} \int_0^{p_T} dp_1 \int_0^{p_T-p_1} dp_2 \{ \mathcal{S}^c(p_1, c) \mathcal{S}^{ud}(p_2, p_T - p_1 - p_2, c) \\ &\quad + 2\mathcal{S}^u(p_1, c) \mathcal{S}^{dc}(p_2, p_T - p_1 - p_2, c) \}, \end{aligned} \quad (17)$$

where

$$\mathcal{S}^{qq}(p_2, p_3, c) = \int \frac{dq}{q} \sum_i \hat{F}_i(q, c) S_i^q(p_2, q, c) S_i^q(p_3, q - p_2, c). \quad (18)$$

The shower-shower-shower recombination from one jet is equivalent to the fragmentation process, so we can use fragmentation functions (FFs) $D_i^{\Lambda_c^+}$ in Eq. (16). Following Ref. [37], when calculating the component $\mathcal{SSS}^{1j}$, we only consider the contribution from charm quark $D_c^{\Lambda_c^+}$. The corresponding FFs for gluon and light quarks are set to zero at the initial scale [37]. In Eqs. (15) and (17), Γ is the probability of recombination between two parallel partons originating from different jets. Given that these partons are emitted from the medium at early times, the emitting system can be approximated as a thin, almond-shaped overlap region viewed edge-on in the transverse plane at midrapidity. From this perspective, the source effectively constitutes a one-dimensional system with a width of ~ 10 fm. Within this framework, the two parallel shower partons are treated as points on this line separated by a distance not greater than the diameter of a hadron (~ 1 fm). Consequently, we estimate $\Gamma = 0.1$, which corresponds to the ratio of hadron diameter to nuclear diameter [27,28].

III. RESULTS AND DISCUSSION

In this section we show the results on the transverse momentum spectra of Λ_c^+ baryons, Λ_c^+/D^0 yield ratio, and the second coefficient of azimuthal anisotropy v_2 for Λ_c^+ baryons in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The inverse slopes T_q and T_c as well as the normalization factors C_q and C_c for Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV determined in Ref. [22] are listed in Table I. The values of parameters γ_0 and q_0 in Eq. (9) are also shown in Sec. II. Therefore the only

one unknown parameter is the statistical factor of $g_{st}^{\Lambda_c^+}$, which will be determined by the transverse momentum spectra of Λ_c^+ baryons.

A. Transverse momentum spectra and Λ_c^+/D^0 ratio

The transverse momentum spectrum of Λ_c^+ baryons produced in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and the centrality of 0%–10% at midrapidity is shown by black line in Fig. 1. The recombination model reproduces very well the experimental data from the ALICE Collaboration, shown by black solid squares [22]. The thermal and shower partons in various combinations are shown by different line types, which dominate at different p_T regions. At low and intermediate p_T , the Λ_c^+ yield is dominated by the $\mathcal{T}\mathcal{T}\mathcal{T}$ component. The $\mathcal{T}\mathcal{T}\mathcal{S}$ and $\mathcal{T}\mathcal{S}\mathcal{S}$ components contain the jet-medium interaction at the hadronization stage, which is important at the region of $p_T > 4$ GeV/c. $\mathcal{SSS}^{1j}$ recombination becomes important at high p_T , which is equivalent to fragmentation. At the same time, the contributions from two jets $\mathcal{T}\mathcal{S}\mathcal{S}^{2j}$ and $\mathcal{SSS}^{2j}$ are relatively small and can be neglected in the current analysis. The smooth transition from soft to hard regimes demonstrates that the unified recombination framework can consistently describe Λ_c^+ production across the entire p_T range. A similar result is obtained for the transverse momentum distribution of Λ_c^+ baryons at the centrality of 30%–50%. The agreement between the calculation results from the recombination model and the experimental data is quite good, as shown in Fig. 2. It should be emphasized that all parameters are fixed in our

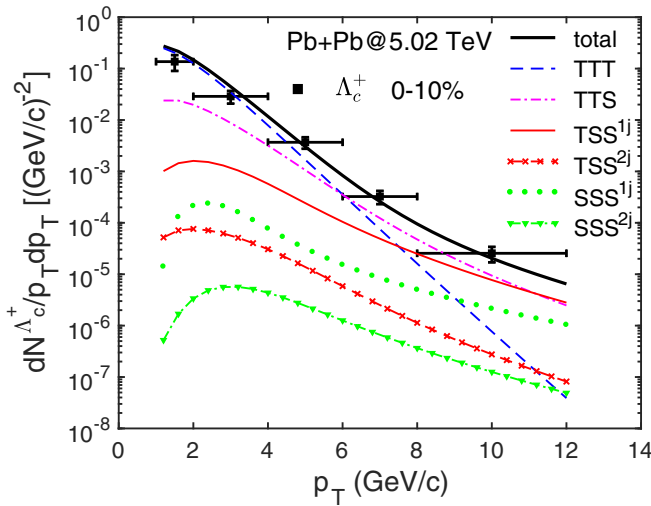


FIG. 1. Transverse momentum spectrum of Λ_c^+ baryons at centrality of 0%–10% in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data are taken from Ref. [6].

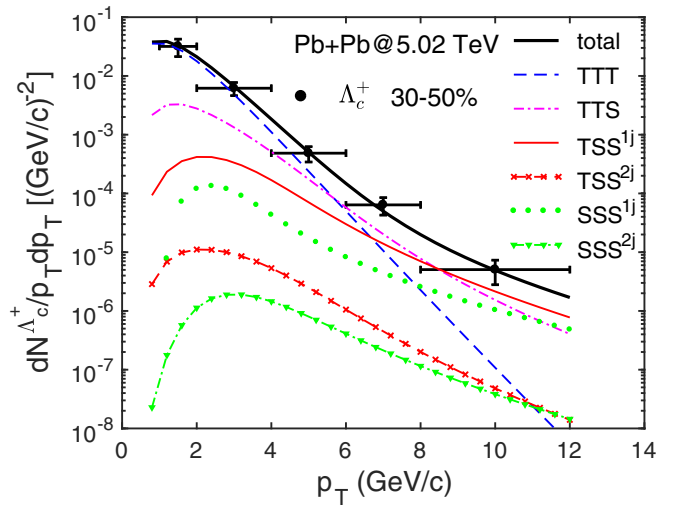


FIG. 2. Transverse momentum spectrum of Λ_c^+ baryons at centrality of 30%–50% in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data are taken from Ref. [6].

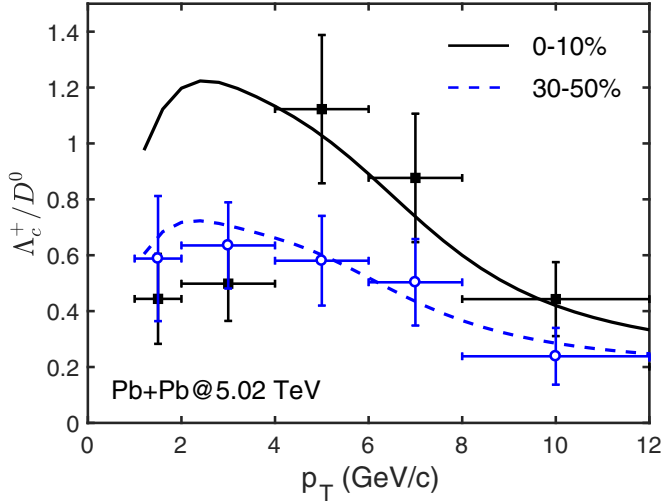


FIG. 3. The Λ_c^+/D^0 yield ratio as a function of p_T in central and midcentral Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The experimental data for 0%–10% (black solid squares) and 30%–50% (blue open circles) are taken from Ref. [6].

earlier work except for the statistical factor $g_{st}^{\Lambda_c^+}$, whose value is equal to 0.24.

In our earlier work [22], the production of D^0 mesons in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV has been studied within the recombination model. Therefore, it is natural to consider the Λ_c^+/D^0 yield ratio, which serves as a critical probe for testing our model. Figure 3 displays the Λ_c^+/D^0 yield ratio as a function of transverse momentum in central (0%–10%) and midcentral (30%–50%) Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The experimental data from the ALICE Collaboration are represented by black solid squares (0%–10%) and blue open circles (30%–50%) [6], while the results of the quark recombination model are shown by the solid black line (0%–10%) and short-dashed blue line (30%–50%), respectively. It is established that the recombination model can nicely describe the Λ_c^+/D^0 yield ratio in midcentral collisions, which confirms that the QGP density at midcentral collisions optimally supports charmed baryon enhancement via quark recombination. The situation for central collisions is a little bit different. The theoretical calculation for central collisions provides a good description of the ratio at $p_T > 4$ GeV/c but overestimates at $p_T < 4$ GeV/c. This is expected, as the D^0 yield did not include the contributions from resonance decays in Ref. [22]. Consequently, the calculated transverse momentum distribution for D^0 mesons is lower than the experimental data at $p_T < 4$ GeV/c, leading to an overestimated Λ_c^+/D^0 ratio in this range. Including the feed-down contributions from D^* meson decays can significantly increase the D^0 yield, thereby reducing the Λ_c^+/D^0 ratio at low p_T and bringing the model into better agreement with the experimental data.

The statistical factor for Λ_c^+ baryons has been fixed by its transverse momentum spectra produced in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as shown in Figs. 1 and 2. All other parameters, γ_0 and q_0 in γ factor, inverse slopes T_q and T_c ,

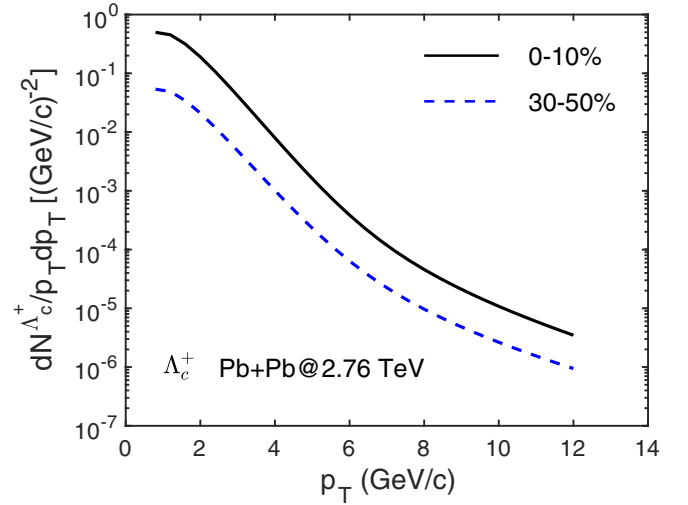


FIG. 4. The predictions of transverse momentum spectra of Λ_c^+ baryons from the recombination model at centralities of 0%–10% and 30%–50% in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

and normalization factors C_q and C_c for Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, were determined in Ref. [22]. Therefore we extend the investigation to $\sqrt{s_{NN}} = 2.76$ TeV and present predictions for transverse momentum spectra of Λ_c^+ baryons and Λ_c^+/D^0 ratio in Figs. 4 and 5, respectively, which can be tested once the experimental data become available.

B. Second harmonic of azimuthal anisotropy of Λ_c^+

In Refs. [22,38] we investigated the second azimuthal harmonic coefficient v_2 for π and charmed mesons by including the effects of semihard partons, which can generate the mini-jets and give rise to ϕ anisotropy in the thermal component. It is worth extending the study to Λ_c^+ baryons. Since the detailed formulations have been presented in previous studies [22,38],

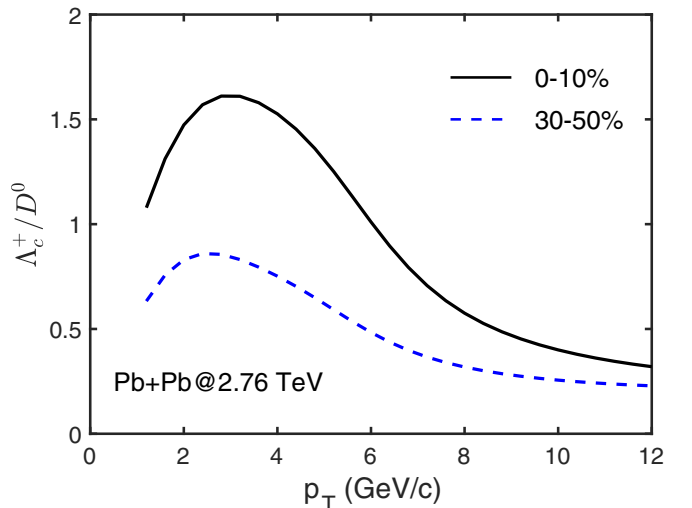


FIG. 5. Predictions of the Λ_c^+/D^0 yield ratio from the recombination model at centralities of 0%–10% and 30%–50% in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

we focus on the key computational steps in this work. Let us use $\rho(p_T, \phi, b)$ to denote the Λ_c^+ distribution produced at midrapidity with impact parameter b , which is assumed to consist of three components: the base, ridge, and minijet contributions at low and intermediate p_T :

$$\rho(p_T, \phi, b) = B(p_T, b) + R(p_T, \phi, b) + M(p_T, \phi, b). \quad (19)$$

The component $B(p_T, b)$ is azimuthally isotropic, while $R(p_T, \phi, b)$ and $M(p_T, \phi, b)$ exhibit ϕ dependence. The base and ridge terms originate from recombination among thermal partons (TTT), while the minijet component arises from thermal-thermal-shower recombination (TTS). After averaging over ϕ , we have

$$\bar{\rho}(p_T, b) = B(p_T, b) + \bar{R}(p_T, b) + \bar{M}(p_T, b). \quad (20)$$

The ridge component $R(p_T, \phi, b)$ incorporates azimuthal anisotropy that stems from the initial spatial eccentricity through the function $S_2(\phi, b)$, which converts spatial asymmetry into momentum anisotropy. The function $S_2(\phi, b)$ represents the segment of the medium surface through which a semihard parton can be emitted to produce a ridge particle at azimuthal angle ϕ . When two nuclei of radius R_A collide at impact parameter b , the almond-shaped overlap has width and height given by

$$w = 1 - b/2, \quad h = (1 - b^2/4)^{1/2}, \quad (21)$$

where all lengths are normalized by R_A . The appropriate geometry that can describe the initial configuration is the ellipse

$$\left(\frac{x}{w}\right)^2 + \left(\frac{y}{h}\right)^2 = 1. \quad (22)$$

Therefore, from the geometry of the ellipse, $S(\phi, b)$ can be determined by [39]

$$\begin{aligned} S(\phi, b) &= \int_{\theta_1}^{\theta_2} [w^2 \sin^2 \theta + h^2 \cos^2 \theta]^{1/2} d\theta \\ &= h(b)[E(\theta_2, \alpha) - E(\theta_1, \alpha)], \end{aligned} \quad (23)$$

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

$$\theta_i = \tan^{-1} \left(\frac{h}{w} \tan \phi_i \right), \quad \phi_1 = \phi - \sigma, \quad \phi_2 = \phi + \sigma. \quad (24)$$

Therefore the ridge component in Eq. (19), which responds to the minijets through TTT recombination, can be expressed as

$$R(p_T, \phi, b) = S(\phi, b) \bar{R}(p_T, b). \quad (25)$$

Similarly, the third component of $\rho(p_T, \phi, b)$ is written as

$$M(p_T, \phi, b) = J(\phi, b) \bar{M}(p_T, b), \quad (26)$$

where $J(\phi, b)$ describes the azimuthal dependence of the minijet contribution and is defined as

$$J(\phi, b) = \tilde{J}(\phi, b) / \left[\frac{1}{2\pi} \int_0^{2\pi} d\phi \tilde{J}(\phi, b) \right]. \quad (27)$$

Since minijets are produced in any given event in unpredictable directions, the average ϕ distribution can have all terms in a harmonic analysis. Hence, the unnormalized

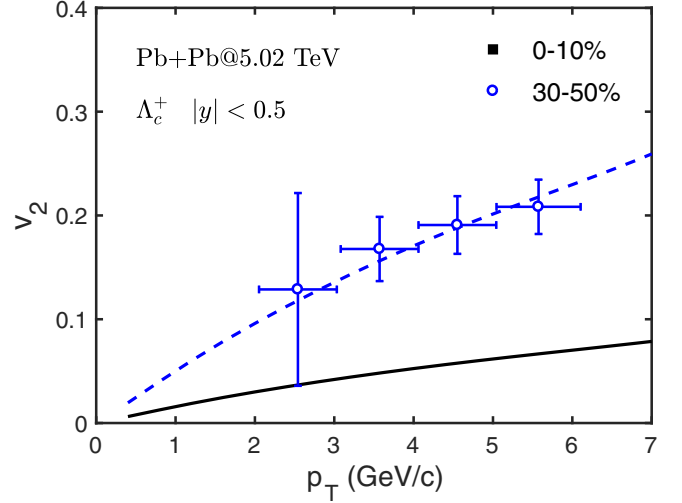


FIG. 6. The second harmonic coefficient v_2 of Λ_c^+ baryons at centralities of 0%–10% and 30%–50% in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data are taken from Ref. [7].

function $\tilde{J}(\phi, b)$ includes all harmonic components $\cos(n\phi)$, averaged over the angle ψ_n :

$$\tilde{J}(\phi, b) = 1 + b \sum_{n=2}^{\infty} a_n \frac{n}{\pi} \int_{-\pi/2\pi}^{\pi/2\pi} d\psi_n \cos[n(\phi - \psi_n)], \quad (28)$$

where a_n are free parameters determined by fitting to the experimental data of v_n . Here we only consider the second harmonic of azimuthal anisotropy of Λ_c^+ , so we can get [39]

$$v_2(p_T, b) = \frac{\langle \cos 2\phi \rangle_S \bar{R}(p_T, b) + \langle \cos 2\phi \rangle_J \bar{M}(p_T, b)}{\bar{\rho}^h(p_T, b)}, \quad (29)$$

where

$$\langle \cos 2\phi \rangle_S = \frac{1}{2\pi} \int_0^{2\pi} d\phi \cos 2\phi S(\phi, b), \quad (30)$$

$$\langle \cos 2\phi \rangle_J = \frac{1}{2\pi} \int_0^{2\pi} d\phi \cos 2\phi J(\phi, b). \quad (31)$$

Figure 6 presents the second harmonic coefficient v_2 for Λ_c^+ baryons at centralities of 0%–10% and 30%–50% in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The model calculation reproduces the data very well for the centrality of 30%–50% from the ALICE Collaboration [7]. The parameter a_2 is equal to 3.3. Unfortunately, the experimental data of v_2 for Λ_c^+ baryons at central collisions are not available yet. The theoretical prediction is shown in Fig. 6, which can be compared with experimental measurements in the near future. From the above study, we can conclude that the recombination model successfully describes the azimuthal anisotropy of mesons and baryons, which gives support to the essential dynamical role of minijets in the hadronization process [22,38].

IV. SUMMARY

In this work we investigate the production of Λ_c^+ baryons in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the quark recombination model that emphasizes the crucial role of

minijets, which generate azimuthal anisotropy both through partonic energy loss in the hot medium and by producing shower partons that recombine with thermal partons. The model provides a unified description of three key experimental observables: the transverse momentum spectra of Λ_c^+ baryons, the enhanced Λ_c^+/D^0 yield ratio, and the second harmonic coefficient v_2 for Λ_c^+ baryons. The successful reproduction of the centrality dependence of observables demonstrates that the interplay between charm quarks and the dense partonic medium is essential for understanding charmed baryon formation. The results strongly support the dominance of quark recombination as the primary hadronization mechanism for charm quarks at intermediate transverse momenta. The inclusion of shower partons is indispensable for simultaneously accounting for the enhancement of the baryon-to-meson and the development of azimuthal anisotropy, thereby bridging the dynamics of soft and hard processes in heavy-ion collisions. Furthermore, the model provides quantitative predictions for the transverse momentum distributions of Λ_c^+ baryons and

the Λ_c^+/D^0 yield ratio in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for future measurements. This work provides compelling support for the picture that quark recombination is an effective hadronization mechanism for charm quarks in the hot and dense medium created at the LHC. This framework can be readily extended to make predictions for other charmed baryons, such as Ξ_c and Ω_c baryons, which will provide further stringent tests of our understanding of heavy-flavor hadronization in the future.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [6,7].

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