

Bottom energy loss and nonprompt J/ψ production in relativistic heavy ion collisionsMeimei Yang,¹ Shiqi Zheng,² Bo Tong,¹ Jiaying Zhao,^{3,*} Wenyuan Ouyang^{1,†}, Kai Zhou,^{4,‡} and Baoyi Chen^{1,§}¹*Department of Physics, Tianjin University, Tianjin 300354, China*²*University of North Carolina at Chapel Hill, North Carolina 27599, USA*³*SUBATECH, Université de Nantes, IMT Atlantique, IN2P3/CNRS, 4 rue Alfred Kastler, 44307 Nantes Cedex 3, France*⁴*Frankfurt Institute for Advanced Studies, Giersch Science Center, D-60438 Frankfurt am Main, Germany*

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We study the momentum and centrality dependence of the nonprompt J/ψ nuclear modification factors (R_{AA}), which come from the B hadron decay, in Pb-Pb collisions at the Large Hadron Collider. Bottom quarks are produced in the parton hard scatterings and suffer energy loss in the quark-gluon plasma and the hadronic gas, where the spatial and time evolution of the medium is described with the hydrodynamic equations. Medium-induced elastic scatterings and the radiation in bottom quarks are included in the energy loss of bottom quarks. The hadronization process of bottom quarks is described with the instantaneous coalescence model. After considering both cold and hot nuclear matter effects in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, we calculated the R_{AA} and also the elliptic flows of nonprompt J/ψ from the decay of B mesons at different centralities and transverse momentum bins. The R_{AA} and v_2 of nonprompt J/ψ sensitive to the hot medium reflect and centrality supply an opportunity to study the bottom quarks energy loss in the hot medium.

DOI: [10.1103/PhysRevC.107.054917](https://doi.org/10.1103/PhysRevC.107.054917)**I. INTRODUCTION**

A state of matter consisting of quarks and gluons called quark-gluon plasma (QGP) is believed to be produced in the nucleus-nucleus collisions [1] performed at the Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC). Studying the properties of the deconfined medium helps to understand quantum chromodynamics (QCD) at finite temperatures [2–5]. Heavy quarks and quarkonium which are produced in the initial parton hard scatterings are sensitive to not only properties of the QGP [6–17] but also the early stage of heavy ion collisions [18–21]; see recent review papers [22,23]. Heavy quarks dump energy to the medium via radiation and the random elastic scatterings with thermal partons when they move inside the QGP [24–33]. The magnitude of the medium-induced energy loss depends on the coupling strength between heavy quarks and the medium and also the initial medium energy density, which are all encoded in the heavy quark transport coefficients [34–42]. When the local temperature of the medium drops to a critical value, heavy quarks hadronize into mesons or baryons via the recombination with light quarks or the fragmentation [43–46]. In the hadronic phase, open heavy flavor hadrons continue losing energy via collisions with thermal light hadrons [47,48]. Therefore, the nuclear modification factors of B and D mesons

have been used to extract the transport coefficients in phenomenological studies [34,49,50].

In experiments, the nuclear modification factor and the elliptic flow of D mesons have been measured [51–53], which indicates a strong coupling between heavy quarks and the QGP, which is created in the heavy ion collisions at the LHC. Except for the b -decayed electrons or muons, there is no direct observation of the nuclear modification factor and the elliptic flow of B mesons in heavy ion collisions. However, the nonprompt J/ψ from the decay of B hadrons has been measured by the CMS and ATLAS Collaboration [54,55]. This supplies a way to study bottom quark energy loss and hadronization in the QGP. Due to the energy loss, the high transverse momentum bottom quark will shift to the low transverse momentum region. This will suppress the final spectrum of bottom quarks at high p_T while enhancing the yield in the low p_T . At LHC energies, there is a sizable modification in the parton distribution function in the nucleus [56], which affects the production of bottom quarks directly. This is called the shadowing effect and is cast into the cold nuclear matter effect. It suppresses the initial production of bottom quarks and changes the nuclear modification factors of B hadrons or nonprompt J/ψ .

In this work, we take the momentum distribution of the initial distribution of bottom quarks given by the fixed-order-next-to-leading-log (FONLL) calculation [57,58]. The cold nuclear matter effect is considered by modifying the initial distribution before the start of Langevin dynamics for heavy quark diffusion in the QGP. The parameters in the Langevin equation such as the transport coefficients are determined in previous works [59]. When the local temperature of the bottom quark is smaller than the critical temperature, the

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bottom quark will hadronize into B hadrons. These B hadrons continue to lose energy in the hadronic phase and finally decay into the nonprompt J/ψ after the kinetic freeze-out.

This paper is organized as follows. In Sec. II, we will describe the theoretical framework of heavy quark evolution and hadronization. In Sec. III, hydrodynamic equations are presented to simulate the realistic expansion of the hot medium created in heavy ion collisions. This is treated as a background medium of the heavy quark diffusion. Numerical results about the nuclear modification factor R_{AA} and elliptic flow v_2 of non-prompt J/ψ in different centralities and transverse momentum are calculated and shown in Sec. IV. We summarize in Sec. V.

II. DYNAMICAL EVOLUTIONS OF BOTTOM QUARKS AND HADRONIZATION

In the QGP, bottom quarks will scatter with thermal partons. With a small momentum transfer in each collision, the dynamical evolution of bottom quarks can be treated as Brownian motion. The stochastic evolution of heavy quark momentum has been well described by the Langevin equation [37,43,59,60]. The medium-induced gluon radiation is also included in the energy loss of heavy quarks, which becomes dominant for heavy quarks with large momentum. Correspondingly the Langevin equation for bottom quark dynamics can be written as [43,61]

$$\frac{d\mathbf{p}}{dt} = -\eta(p)\mathbf{p} + \xi + \mathbf{f}_g, \quad (1)$$

where \mathbf{p} is the bottom quark momentum. The drag term $\eta(p)$ is connected with the momentum diffusion coefficient via the fluctuation-dissipation relation, $\eta(p) = \kappa/(2TE_b)$, where the bottom quark energy is $E_b = \sqrt{m_b^2 + \mathbf{p}^2}$ and $m_b = 4.5$ GeV is the bottom quark mass. The momentum diffusion coefficient κ is related to the spatial diffusion coefficient \mathcal{D}_s through $\kappa\mathcal{D}_s = 2T^2$. In the QGP and the hadronic medium, the spatial diffusion coefficient is used as $\mathcal{D}_s(2\pi T) = 7$ and 9 in this study respectively [50]. The stochastic term ξ is treated as white noise. If we neglect the momentum dependence in the ξ , it satisfies the relation

$$\langle \xi^i(t)\xi^j(t') \rangle = \kappa\delta^{ij}\delta(t-t'), \quad (2)$$

where the index i, j represents three dimensions. The noise terms are uncorrelated at different time points. Gluon radiation contribution is represented by $\mathbf{f}_g = -d\mathbf{p}_g/dt$ with \mathbf{p}_g the momentum of the emitted gluon. The number of emitted gluons in the time interval $t \sim t + \Delta t$ is [43]

$$P_{\text{rad}}(t, \Delta t) = \langle N_g(t, \Delta t) \rangle = \Delta t \int dx dk_T^2 \frac{dN_g}{dx dk_T^2 dt}. \quad (3)$$

In the numerical simulation with small Δt , the number of the emitted gluon in the period is smaller than the unit and P_{rad} can be treated as the radiation probability. The variable $x = E_g/E_b$ is the ratio of the energies of the emitted gluon and the bottom quark. $dN_g/dx dk_T^2 dt$ is the spectrum of emitted gluon given by perturbative QCD calculations [30,32]. k_T is the transverse momentum of the gluon. At each time step, the bottom quark momentum is updated with the Langevin equation.

The initial momentum distribution of bottom quarks in heavy ion collisions can be simulated via the FONLL model [57,58]. For the initial spatial distribution of bottom quarks, as they are produced in the parton hard scatterings, the initial spatial density of bottom quarks is proportional to the product of two thickness function $T_A(\mathbf{x}_T + \mathbf{b}/2)T_B(\mathbf{x}_T - \mathbf{b}/2)$, where \mathbf{b} is the impact parameter. In heavy ion collisions, the parton density in the nucleus is changed relative to the distribution in the free nucleon, where the bottom yield is also changed. The ratio of the parton density in the nucleus f_A and the free nucleon f_n is defined as $\mathcal{R} = f_A(x, \mu_F)/[Af_n(x, \mu_F)]$. The longitudinal momentum fractions of the two initial gluons are defined as $x_{1,2} = e^{\pm y}\sqrt{m_{b\bar{b}}^2 + (2p_T)^2}/\sqrt{s_{NN}}$ in nuclei A and B respectively. p_T and y are the transverse momentum and the rapidity of one bottom quark. $m_{b\bar{b}}$ is the total mass of bottom and antibottom quarks. $\mu_F = \sqrt{m_{b\bar{b}}^2 + (2p_T)^2}$ is the factorization scale. The shadowing modification factor of bottom quarks is calculated with the EPS09 package [56] in this work. The global shadowing factor of bottom quarks is calculated to be 0.86–0.95 in the nucleus. The spatial dependence of the shadowing factor is included which is proportional to the nuclear thickness function $T_{A(B)}(\mathbf{x}_T)$ [10], which are calculated from optical Glauber model [62]. The initial distribution of bottom quarks in the Pb-Pb collisions with the modification of the shadowing effect is written as

$$\frac{d^3 N_{AA}^{b\bar{b}}}{d\mathbf{x}_T dy d p_T} = \frac{d^2 \sigma^{b\bar{b}}}{dy d p_T} T_A(\mathbf{x}_T + \mathbf{b}/2) T_B(\mathbf{x}_T - \mathbf{b}/2) \times \mathcal{R}_A(\mathbf{x}_T, x_1, \mu_F) \mathcal{R}_B(\mathbf{x}_T, x_2, \mu_F). \quad (4)$$

In the event-by-event numerical simulations, we randomly generate a large set of bottom quarks based on Eq. (4) with different positions and momentum. Each bottom quark is evolved under the Langevin equation, Eq. (1).

When the bottom quark travel across the hadronization boundary, which is defined by the local temperature equaling the critical temperature, $T = T_c$, the bottom quark will convert to B hadrons. The hadronization mechanism used in this study is the coalescence model. The momentum of bottom quarks at the hadronization is determined by the Langevin equation. The the momentum of thermal light quarks used in the coalescence process is generated with the Fermi distribution. The coalescence probability of bottom quarks and light quarks to form B mesons can be described with [63]

$$\mathcal{P}_{b+\bar{q}\rightarrow B}(\mathbf{p}_B) = \int \frac{d\mathbf{p}_1}{(2\pi)^3} \frac{d\mathbf{p}_2}{(2\pi)^3} \frac{dN_1}{d\mathbf{p}_1} \frac{dN_2}{d\mathbf{p}_2} f_B^W(\mathbf{q}_r) \delta^{(3)}(\mathbf{p}_B - \mathbf{p}_1 - \mathbf{p}_2), \quad (5)$$

where $dN_1/d\mathbf{p}_1$ is the normalized momentum distribution of bottom quarks at the hadronization hypersurface. $dN_2/d\mathbf{p}_2$ is the normalized Fermi distribution of light quarks in the local rest frame (LRF) of the expanding medium. It is $f(\mathbf{p}_2^{\text{lrf}}) = N_0/(e^{\sqrt{(m_2^2 + |\mathbf{p}_2^{\text{lrf}}|^2)/T_c}} + 1)$ with N_0 is the normalization factor. The thermal mass of light quarks is set to be $m_2 = 0.3$ GeV [63]. In this setup, $\mathcal{P}_{b+\bar{q}\rightarrow B}(\mathbf{p}_B)$ is understood as the coalescence probability of one bottom quark with the momentum \mathbf{p}_1 turning into a B meson with the momentum \mathbf{p}_B . The δ

function ensures the momentum conservation in the reaction, where the momentum of emitted gluon has been neglected to get the simplified relation $\mathbf{p}_B = \mathbf{p}_1 + \mathbf{p}_2$. The Wigner function $f_B^W(\mathbf{q}_r)$ depends on the relative momentum between the bottom and the thermal light quark. In the center-of-mass (c.m.) frame of the formed B meson, $\mathbf{q}_r = (E_2^{c.m.} \mathbf{p}_1^{c.m.} - E_1^{c.m.} \mathbf{p}_2^{c.m.}) / (E_1^{c.m.} + E_2^{c.m.})$. $\mathbf{p}_1^{c.m.}$ and $\mathbf{p}_2^{c.m.}$ are the momentum of the bottom quark and the light quark in the c.m. frame. $E_1^{c.m.}$ and $E_2^{c.m.}$ are the corresponding energies. The Wigner function is taken as a Gaussian function with the width determined by the mean square radius of the B meson, $\sigma^2 = \frac{4}{3} \frac{(m_1 + m_2)^2}{m_1^2 + m_2^2} \langle r^2 \rangle_B$ [64]. We approximate the root-mean-square radius of B meson as $\sqrt{\langle r^2 \rangle_B} = 0.43$ fm. B meson production is dominated by the coalescence process at low- p_T regions. From model calculations [61] about bottom quark hadronization, the coalescence probability is much larger than the fragmentation in the low region, such as $p_T \lesssim 5$ GeV/c. In this work, we take a simplification and assume that all B mesons are produced via the coalescence process in this low- p_T region. While at higher p_T , all B mesons are produced via the fragmentation where the momentum of the B meson is assumed to be the momentum of bottom quark.

After the hadronization, the B meson will evolve in the hadronic phase and finally decay weakly into various hadrons. Many of the decay channels are difficult to be observed in the heavy ion collisions except the $B \rightarrow J/\psi$. This component is named nonprompt J/ψ , which makes a significant contribution to the inclusive J/ψ , especially at high- p_T regions [54,55]. This offers the opportunity to study the bottom quark energy loss and hadronization in the QGP. In the real case, the bottom quark will convert to various B hadrons, such as $B^{0,\pm}$, B_s , Λ_b , and so on. Based on the thermal model [65], a simple estimation shows more than 60% bottom quarks become B mesons, including $B^{0,\pm}$ and B_s . The observed data show the branching ratio of B meson to J/ψ is larger than bottom baryons [66]. So, as a first approximation, we force all bottom quarks to convert to B mesons and multiply a 60% factor to the final B meson spectra in this study.

The unknown thing is the decay branch fraction \mathcal{F} of B mesons to J/ψ . We estimate this fraction in A - A collisions is the same as the p - p collisions. So, it can be extracted from p - p data that

$$\mathcal{F}(p_T) = \frac{dN_{J/\psi}^{\text{nonprompt}}/dp_T}{dN_B/dp_T}, \quad (6)$$

where the B meson spectra dN_B/dp_T in p - p collisions are observed by the ALICE [67] and CMS [68] Collaborations. The differential cross section of nonprompt J/ψ in 5.02-TeV pp collisions have been measured by the ALICE [69], CMS [70], and ATLAS [71] Collaborations. The transverse momentum distribution can be fitted with the formulas [11]

$$\begin{aligned} \frac{d^2\sigma}{dydp_T} &= \frac{dN^{\text{norm}}}{dp_T} \frac{d\sigma}{dy}, \\ \frac{dN^{\text{norm}}}{dp_T} &= \frac{2\pi p_T (n-1)}{\pi(n-2)\langle p_T^2 \rangle_{pp}} \left[1 + \frac{p_T^2}{(n-2)\langle p_T^2 \rangle_{pp}} \right]^{-n}, \end{aligned} \quad (7)$$

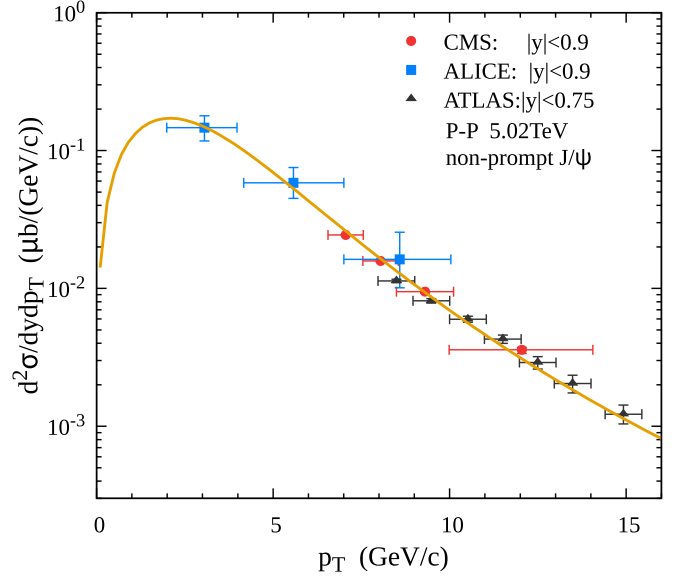


FIG. 1. The transverse momentum spectrum $d^2\sigma/dydp_T$ of nonprompt J/ψ in the central rapidity of proton-proton collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The experimental data are cited from the ALICE [69], CMS [70], and ATLAS [71] Collaborations.

where dN^{norm}/dp_T is the normalized transverse momentum distribution. Rapidity differential cross section $d\sigma/dy$ will be eliminated in the calculation of R_{AA} . The parameters n and $\langle p_T^2 \rangle_{pp}$ control the the shape of the line. They are determined as $n = 3.2$ and $\langle p_T^2 \rangle_{pp} = 19.5$ (GeV/c)². The data and fitted curve are shown in Fig. 1. The yield of nonprompt J/ψ in heavy ion collisions can be obtained by multiplying the branch fraction \mathcal{F} to the B -meson spectra after the evolution.

III. HOT MEDIUM EVOLUTION

The deconfined medium produced in heavy ion collisions turns out to be a strongly coupled matter. Its dynamical evolution has been extensively studied with hydrodynamic equations [72–74]. We employ the (2+1)-dimensional ideal hydrodynamic equations to describe the medium expansion on the transverse plane. Along the longitudinal direction defined as the direction of nuclear acceleration, there is a flat pattern in the initial rapidity distribution of the charged hadron multiplicities [72]. With this feature, the longitudinal evolution of the hot medium is treated to be a Bjorken expansion. The hydrodynamic equation is written as

$$\partial_{\mu\nu} T^{\mu\nu} = 0, \quad (8)$$

where the energy-momentum tensor is $T^{\mu\nu} = (e + p)u^\mu u^\nu - g^{\mu\nu} p$. u^μ is the four-velocity of the fluid. e and p are the energy density and the pressure of the medium. The equation of state (EoS) of the deconfined matter is taken to be the EoS of the ideal gas. While the EoS of the hadronic matter is taken from the hadron resonance gas model [75]. The hadronization phase transition is first order, with the critical temperature $T_c = 165$ MeV. This value is determined by selecting the mean field repulsion parameter and the bag parameter to be $K = 450$ MeV fm³ and $B^{1/4} = 236$ MeV at the zero baryon

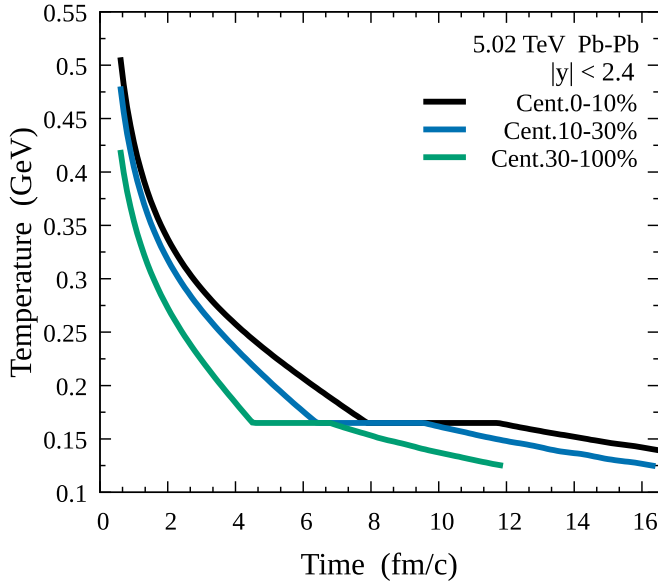


FIG. 2. The time evolution of the temperature at the center of the medium ($\mathbf{x}_T = 0$) in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Temperatures in different collision centralities are plotted with different color lines. The critical temperature of the deconfined phase transition is $T_c = 165$ MeV.

number density [75]. The initial entropy density comes from both soft and hard processes. The profile of the entropy density is assumed to be proportional to the number of nucleon participants $n_{\text{part}}(\mathbf{x}_T)$ and the number of binary collisions $n_{\text{coll}}(\mathbf{x}_T)$. The entropy density is determined by the charged hadron multiplicities, where the maximum temperature at the center of the medium is $T_0(\mathbf{x}_T = 0, \tau_0) = 510$ MeV [11] at the time τ_0 . τ_0 is the timescale of the medium reaching local equilibrium. Its value is fitted as $\tau_0 = 0.6$ fm/c by the collective flows of light hadrons observed in Pb-Pb collisions [73]. The time evolutions of the medium temperature in different centralities are plotted in Fig. 2.

IV. RESULTS

With hydrodynamic equations for the medium expansion and the Langevin equation for the evolution of bottom quarks and B mesons, one can get the final spectrum and the nuclear modification factor R_{AA} of nonprompt J/ψ in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The spatial diffusion coefficient of bottom quarks and B meson are taken as $\mathcal{D}_s(2\pi T) = 7$ and 9 respectively as explained before. Nonprompt J/ψ R_{AA} as a function of the number of participants N_{part} are plotted in Fig. 3. Bottom quarks with large momentum lose energy in the hot medium. They are moved to the low- p_T regions after they travel through the hot medium. This results in a significant suppression in the R_{AA} at $6.5 < p_T < 50$ GeV/c. In this high- p_T bin, the medium-induced radiation dominates the energy loss of bottom quarks. At low p_T , the R_{AA} becomes larger where the effect of the energy loss is not evident compared with the situation at high p_T . The shadowing effect reduces the bottom quark production and R_{AA} at different p_T bins in Fig. 3. The band in the figure is due to the uncertainty in

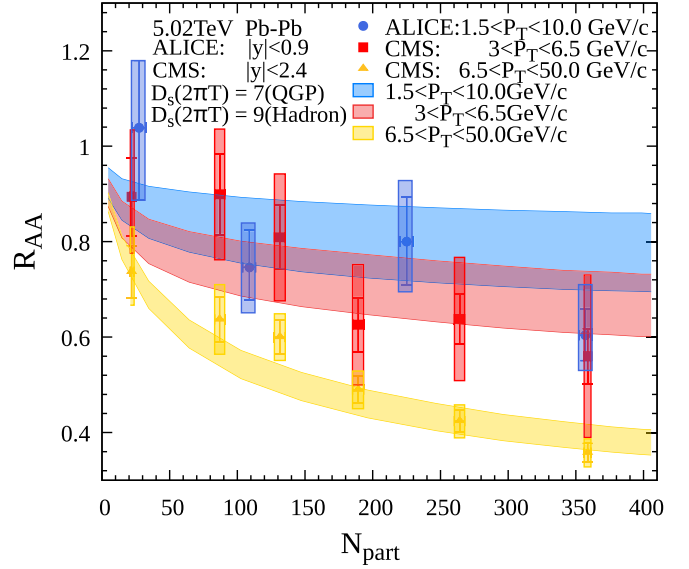


FIG. 3. Nuclear modification factor of nonprompt J/ψ as a function of N_{part} in the central rapidity at $\sqrt{s_{NN}} = 5.02$ TeV Pb-Pb collisions. Different p_T bins are calculated: $1.5 < p_T < 10$, $3 < p_T < 6.5$, and $6.5 < p_T < 50$ GeV/c. The theoretical bands are induced by the uncertainty in the shadowing factors. Experimental data are taken from the CMS [54] and ALICE [76] Collaborations.

the shadowing effect. Besides, the band becomes smaller at high p_T because both the central value and the uncertainty of the shadowing effect depend on p_T . This feature is reflected in both $R_{AA}(N_{\text{part}})$ and also $R_{AA}(p_T)$. As one can see in Fig. 3, theoretical calculations qualitatively explain well the data from the CMS and ALICE Collaborations.

In Fig. 4, the p_T -differential nuclear modification factor at fixed collision centralities is plotted. Bottom quarks lose energy in the hot medium. They are shifted from high to low p_T , which results in a significant suppression in R_{AA} at high p_T and a corresponding enhancement at low p_T . This modification becomes more evident in the central collisions compared with the peripheral collisions. The band in theoretical calculations is induced by the uncertainty in the shadowing factor. When the shadowing effect is strong, R_{AA} becomes smaller than the unit even at low p_T .

We also calculated the elliptic flows v_2 of nonprompt J/ψ as a function of N_{part} and p_T in Pb-Pb collisions. In Fig. 5, nonprompt J/ψ with high p_T are selected. In the most central collisions, the initial energy density of the hot medium produced in nuclear collisions are nearly isotropic on the transverse plane when neglecting the event-by-event fluctuations. Collective expansion of the medium is isotropic on the transverse plane due to the same pressure gradients along x and y directions. In semicentral collisions, the accelerations of the medium become different along x and y directions on the transverse plane. This anisotropic expansion will be inherited by heavy quarks due to the strong coupling strength. The theoretical results are slightly below the experimental data at high p_T , possibly due to the absence of event-by-event fluctuations in theoretical calculations. In Fig. 6, elliptic flows of nonprompt J/ψ as a function of transverse momentum are

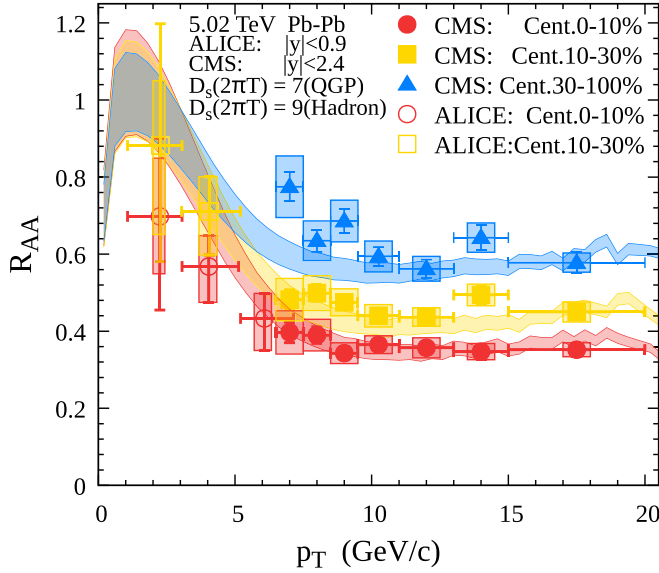


FIG. 4. The nuclear modification factor of nonprompt J/ψ as a function of p_T in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The collision centralities are 0–10%, 10–30%, and 30–100%. The band in theoretical calculations comes from the uncertainty in the shadowing factor. Experimental data are taken from the CMS [54] and ALICE [76] Collaborations.

also calculated in centralities 0–60% and 10–60%. Theoretical calculations qualitatively explain most of the data points at middle and low p_T , while underestimating the data at high p_T but still within the large error bars. In the theoretical

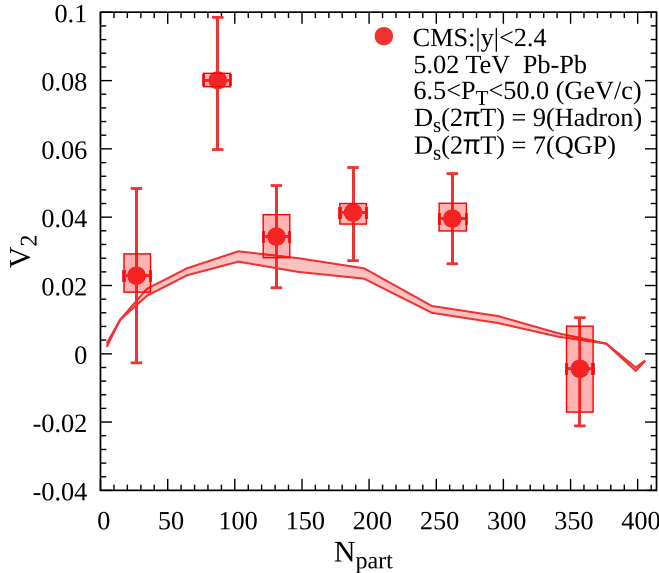


FIG. 5. Elliptic flows of nonprompt J/ψ as a function of number of participants N_{part} in $\sqrt{s_{NN}} = 5.02$ TeV Pb-Pb collisions. The selected p_T bin is 6.5–50 GeV/c. The spatial diffusion coefficient is taken to be $D_s(2\pi T) = 7$ and 9 respectively in the QGP and the hadronic gas. The theoretical band represents the uncertainty in the shadowing factor. Experimental data is cited from the CMS Collaboration [77].

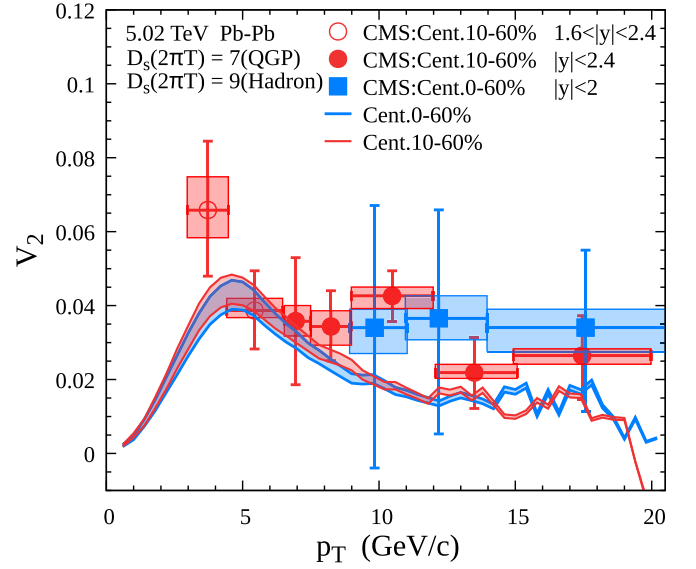


FIG. 6. Elliptic flows of nonprompt J/ψ as a function of p_T in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The collision centralities are 0–60% and 10–60%. Theoretical bands represent the uncertainty in the shadowing factor. Experimental data is cited from the CMS and ATLAS Collaborations [55,77].

calculations, the momentum dependence has been neglected in the value of $D_s(2\pi T)$, which may underestimate the v_2 of heavy quarks at high p_T . When the value of $D_s(2\pi T)$ becomes smaller at high p_T , the coupling strength between heavy quarks and the medium is also stronger, where v_2 is enhanced at high p_T . The detailed momentum dependence in $D_s(2\pi T)$ will be left for future works.

V. SUMMARY

In this paper, we employ the Langevin equation to study the energy loss of bottom quarks in the quark-gluon plasma and B mesons in the hadronic medium. Both contributions of elastic collisions and the medium-induced radiation are included in the bottom quark evolution. At the hadronization hypersurface, B mesons are produced via the coalescence between the bottom quark and a thermal light quark, which finally decay into nonprompt J/ψ after B mesons move out of the hadronic medium. The cold nuclear matter effect is also considered by modifying the initial distribution of bottom quarks in the Pb-Pb collisions. The space and time evolution of the hot medium is given by the hydrodynamic equations. With realistic treatment of heavy quarks and the thermal medium, we calculated the nuclear modification factor and elliptic flow of nonprompt J/ψ in different collision centralities and transverse momentum. Theoretical results explain the experimental data well with the proper values of the spatial diffusion coefficients determined in previous works. The spectra and elliptic flow of nonprompt J/ψ reflect the energy loss of bottom quarks in the hot medium. This offers the opportunity to study the bottom quark energy loss mechanism in experiments.

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- [1] A. Bazavov, T. Bhattacharya, M. Cheng, C. DeTar, H. T. Ding, S. Gottlieb, R. Gupta, P. Hegde, U. M. Heller, F. Karsch *et al.*, *Phys. Rev. D* **85**, 054503 (2012).
- [2] H. Satz, *Rep. Prog. Phys.* **63**, 1511 (2000).
- [3] S. A. Bass, M. Gyulassy, H. Stoecker, and W. Greiner, *J. Phys. G: Nucl. Part. Phys.* **25**, R1 (1999).
- [4] W. Cassing and E. L. Bratkovskaya, *Phys. Rep.* **308**, 65 (1999).
- [5] E. V. Shuryak, *Phys. Rep.* **115**, 151 (1984).
- [6] T. Matsui and H. Satz, *Phys. Lett. B* **178**, 416 (1986).
- [7] X. Zhao and R. Rapp, *Phys. Rev. C* **82**, 064905 (2010).
- [8] X. Du and R. Rapp, *Nucl. Phys. A* **943**, 147 (2015).
- [9] Y. Liu, B. Chen, N. Xu, and P. Zhuang, *Phys. Lett. B* **697**, 32 (2011).
- [10] K. Zhou, N. Xu, Z. Xu, and P. Zhuang, *Phys. Rev. C* **89**, 054911 (2014).
- [11] B. Chen, *Chin. Phys. C* **43**, 124101 (2019).
- [12] J. Zhao and B. Chen, *Phys. Lett. B* **776**, 17 (2018).
- [13] X. Yao and T. Mehen, *J. High Energy Phys.* 02 (2021) 062.
- [14] J.-P. Blaizot, D. De Boni, P. Faccioli, and G. Garberoglio, *Nucl. Phys. A* **946**, 49 (2016).
- [15] N. Brambilla, M. A. Escobedo, M. Strickland, A. Vairo, P. Vander Griend, and J. H. Weber, *J. High Energy Phys.* 05 (2021) 136.
- [16] S. Delorme, T. Gousset, R. Katz, and P.-B. Gossiaux, *EPJ Web Conf.* **258**, 05009 (2022).
- [17] T. Miura, Y. Akamatsu, M. Asakawa, and Y. Kaida, *Phys. Rev. D* **106**, 074001 (2022).
- [18] W. Zha, L. Ruan, Z. Tang, Z. Xu, and S. Yang, *Phys. Lett. B* **789**, 238 (2019).
- [19] W. Shi, W. Zha, and B. Chen, *Phys. Lett. B* **777**, 399 (2018).
- [20] J. Zhao, B. Chen, and P. Zhuang, *Phys. Rev. C* **105**, 034902 (2022).
- [21] B. Chen, M. Hu, H. Zhang, and J. Zhao, *Phys. Lett. B* **802**, 135271 (2020).
- [22] A. Rothkopf, *Phys. Rep.* **858**, 1 (2020).
- [23] J. Zhao, K. Zhou, S. Chen, and P. Zhuang, *Prog. Part. Nucl. Phys.* **114**, 103801 (2020).
- [24] M. Djordjevic and M. Gyulassy, *Nucl. Phys. A* **733**, 265 (2004).
- [25] S. Wicks, W. Horowitz, M. Djordjevic, and M. Gyulassy, *Nucl. Phys. A* **784**, 426 (2007).
- [26] E. Braaten and M. H. Thoma, *Phys. Rev. D* **44**, R2625 (1991).
- [27] G. D. Moore and D. Teaney, *Phys. Rev. C* **71**, 064904 (2005).
- [28] M. Gyulassy, P. Levai, and I. Vitev, *Phys. Rev. Lett.* **85**, 5535 (2000).
- [29] P. B. Arnold, G. D. Moore, and L. G. Yaffe, *J. High Energy Phys.* 01 (2003) 030.
- [30] B.-W. Zhang, E. Wang, and X.-N. Wang, *Phys. Rev. Lett.* **93**, 072301 (2004).
- [31] G.-Y. Qin, J. Ruppert, C. Gale, S. Jeon, G. D. Moore, and M. G. Mustafa, *Phys. Rev. Lett.* **100**, 072301 (2008).
- [32] A. Majumder, *Phys. Rev. D* **85**, 014023 (2012).
- [33] H. Berrehrah, P.-B. Gossiaux, J. Aichelin, W. Cassing, and E. Bratkovskaya, *Phys. Rev. C* **90**, 064906 (2014).
- [34] S. Cao *et al.*, *Phys. Rev. C* **99**, 054907 (2019).
- [35] A. Beraudo *et al.*, *Nucl. Phys. A* **979**, 21 (2018).
- [36] P. B. Gossiaux, J. Aichelin, T. Gousset, and V. Guiho, *J. Phys. G: Nucl. Part. Phys.* **37**, 094019 (2010).
- [37] M. He, R. J. Fries, and R. Rapp, *Phys. Rev. Lett.* **110**, 112301 (2013).
- [38] S. K. Das, V. Chandra, and Jan-e Alam, *J. Phys. G: Nucl. Part. Phys.* **41**, 015102 (2013).
- [39] S. Mazumder, T. Bhattacharyya, and Jan-e Alam, *Phys. Rev. D* **89**, 014002 (2014).
- [40] T. Song, P. Moreau, J. Aichelin, and E. Bratkovskaya, *Phys. Rev. C* **101**, 044901 (2020).
- [41] M. Kurian, M. Singh, V. Chandra, S. Jeon, and C. Gale, *Phys. Rev. C* **102**, 044907 (2020).
- [42] J. Prakash, M. Kurian, S. K. Das, and V. Chandra, *Phys. Rev. D* **103**, 094009 (2021).
- [43] S. Cao, G.-Y. Qin, and S. A. Bass, *Phys. Rev. C* **88**, 044907 (2013).
- [44] M. He and R. Rapp, *Phys. Rev. Lett.* **124**, 042301 (2020).
- [45] P. B. Gossiaux, R. Bierkant, and J. Aichelin, *Phys. Rev. C* **79**, 044906 (2009).
- [46] S. Plumari, V. Minissale, S. K. Das, G. Coci, and V. Greco, *Eur. Phys. J. C* **78**, 348 (2018).
- [47] C. Fuchs, B. V. Martemyanov, A. Faessler, and M. I. Krivoruchenko, *Phys. Rev. C* **73**, 035204 (2006).
- [48] M. He, R. J. Fries, and R. Rapp, *Phys. Lett. B* **701**, 445 (2011).
- [49] F. Scardina, S. K. Das, V. Minissale, S. Plumari, and V. Greco, *Phys. Rev. C* **96**, 044905 (2017).
- [50] X. Dong and V. Greco, *Prog. Part. Nucl. Phys.* **104**, 97 (2019).
- [51] B. Abelev *et al.* (ALICE Collaboration), *Phys. Rev. Lett.* **111**, 102301 (2013).
- [52] S. Acharya *et al.* (ALICE Collaboration), *Phys. Lett. B* **813**, 136054 (2021).
- [53] A. M. Sirunyan *et al.* (CMS Collaboration), *Phys. Lett. B* **816**, 136253 (2021).
- [54] A. M. Sirunyan *et al.* (CMS Collaboration), *Eur. Phys. J. C* **78**, 509 (2018).
- [55] M. Aaboud *et al.* (ATLAS Collaboration), *Eur. Phys. J. C* **78**, 784 (2018).
- [56] K. J. Eskola, H. Paukkunen, and C. A. Salgado, *J. High Energy Phys.* 04 (2009) 065.
- [57] M. Cacciari, M. Greco, and P. Nason, *J. High Energy Phys.* 05 (1998) 007.
- [58] M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, and G. Ridolfi, *J. High Energy Phys.* 10 (2012) 137.
- [59] B. Chen and J. Zhao, *Phys. Lett. B* **772**, 819 (2017).
- [60] S. K. Das, F. Scardina, S. Plumari, and V. Greco, *Phys. Lett. B* **747**, 260 (2015).
- [61] S. Cao, G.-Y. Qin, and S. A. Bass, *Phys. Rev. C* **92**, 024907 (2015).
- [62] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, *Annu. Rev. Nucl. Part. Sci.* **57**, 205 (2007).

- [63] B. Chen, L. Jiang, X.-H. Liu, Y. Liu, and J. Zhao, *Phys. Rev. C* **105**, 054901 (2022).
- [64] T. Song and H. Berrehrah, *Phys. Rev. C* **94**, 034901 (2016).
- [65] A. Andronic, P. Braun-Munzinger, M. K. Köhler, A. Mazeliauskas, K. Redlich, J. Stachel, and V. Vislavicius, *J. High Energy Phys.* **07** (2021) 035.
- [66] P. A. Zyla *et al.* (Particle Data Group), *Prog. Theor. Exp. Phys.* **2020**, 083C01 (2020).
- [67] G. Aad *et al.* (ATLAS Collaboration), *J. High Energy Phys.* **10** (2013) 042.
- [68] V. Khachatryan *et al.* (CMS Collaboration), *Phys. Rev. Lett.* **106**, 112001 (2011).
- [69] S. Acharya *et al.* (ALICE Collaboration), *J. High Energy Phys.* **03** (2022) 190.
- [70] A. M. Sirunyan *et al.* (CMS Collaboration), *Eur. Phys. J. C* **77**, 269 (2017).
- [71] M. Aaboud *et al.* (ATLAS Collaboration), *Eur. Phys. J. C* **78**, 171 (2018).
- [72] B. Schenke, S. Jeon, and C. Gale, *Phys. Rev. Lett.* **106**, 042301 (2011).
- [73] C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass, and U. Heinz, *Comput. Phys. Commun.* **199**, 61 (2016).
- [74] L. Pang, Q. Wang, and X.-N. Wang, *Phys. Rev. C* **86**, 024911 (2012).
- [75] J. Sollfrank, P. Huovinen, M. Kataja, P. V. Ruuskanen, M. Prakash, and R. Venugopalan, *Phys. Rev. C* **55**, 392 (1997).
- [76] ALICE, <https://alice-figure.web.cern.ch/node/22314>.
- [77] CMS, CMS-PAS-HIN-21-008.