

Heavy hadron production in Au + Au collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 200$ GeV

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Using the Monte Carlo HYDJET++ model, we investigate the transverse momentum (p_T) spectra of heavy-flavor hadrons, namely D^0 , $\bar{D}^0$, D^+ , D^- , and Λ_c , along with the nuclear modification factors of D^0 and $D^\pm$ in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV RHIC energy across various centrality bins. This work extends the earlier study by relaxing the assumption of identical chemical and thermal freezeout and by exploring the effect of a higher chemical freezeout temperature relative to thermal freezeout. The study also explores the centrality and mass dependence of the charm enhancement factor (γ_c). Furthermore, we investigate medium-induced energy loss, particle-antiparticle asymmetry, and the role of fragmentation in the hadronization process. The HYDJET++ model, with its default parameters, is unable to reproduce heavy hadron yields due to their early thermal freezeout and initial state production of heavy quarks. Therefore, a systematic tuning of model parameters is performed to improve the overall agreement with experimental data. Additionally, to assess the performance of the HYDJET++ model relative to other theoretical approaches, its results are compared with the TAMU, SUBATECH, Torino, and Duke models, for which corresponding simulation data are available. This study shows a decreasing trend in γ_c from central to peripheral collisions. Moreover, γ_c increases with increasing charm-hadron mass. The model approximately reproduces the experimental data of p_T spectra at low and intermediate p_T . However, it overestimates the data at high p_T , indicating a need for improvements in modeling the energy loss of heavy quarks. The nuclear modification factors (R_{AA} and R_{CP}) for D^0 mesons exhibit significant suppression at high p_T . At low p_T , R_{AA} results show deviations from the data, reflecting limitations in the model where coalescence becomes important. The antiparticle-to-particle ratios are consistent with experimental data, whereas mixed-particle ratios are underestimated, revealing the model's limitation in estimating the baryon-to-meson enhancement.

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I. INTRODUCTION

The curiosity to deeply understand the strong interaction and the formation of matter in the earliest stage of the universe requires the study of quark-gluon plasma (QGP) [1]. QGP is the deconfined, hot and dense color-conducting state of matter, which is formed just a few microseconds after the Big Bang. Thus, the study of QGP is an important tool for understanding the properties of nuclear matter under extreme conditions. In the laboratory, QGP is created at extremely high temperatures and nearly zero baryon chemical potential through ultrarelativistic heavy-ion collisions. As the temperature decreases, the QGP phase rapidly transitions into the hadronic phase, where new particles are produced due to hadronic interactions. On further decrease of temperature,

inelastic hadronic interactions cease, fixing particle abundances and types; this particular temperature is known as the chemical freezeout temperature (T_{ch}). At a later stage, elastic interactions also cease, defining the temperature as the kinetic (thermal) freezeout temperature (T_{th}). Since QGP is formed for a very short time, its properties cannot be studied directly; they are inferred from the particles emerging from the QGP after interaction with the medium. These particles are light hadrons, dileptons, photons, heavy hadrons, and so on.

Heavy quarks (charm and bottom) play a vital role in studying QGP. They are produced during the initial hard scattering due to their larger masses ($m_b \approx 4.7$ GeV, $m_c \approx 1.3$ GeV [2]) [3,4] and propagate through the QGP medium throughout its evolution. Heavy quarks gain their mass primarily through coupling with the Higgs field in the electroweak sector, which allows them to remain massive even within the QGP, where chiral symmetry is restored. In contrast, the masses of light quarks (u, d, s) arise predominantly from the spontaneous breaking of chiral symmetry in quantum chromodynamics (QCD) [5]. The dynamically generated masses of light quarks vanish on chirality restoration, which may affect their ability to retain information about the QGP formation. Thus, heavy quarks are valuable probes for investigating the

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pre-equilibrium phase and transport properties of QGP through perturbative calculations of their production cross sections [6].

To investigate the heavy hadron production within the QGP, we examine observables such as the transverse momentum (p_T) spectra, nuclear modification factors (R_{AA} and R_{CP}), the antiparticle-to-particle ratios ($\bar{h}/h$), and mixed particle ratios (h_1/h_2). The slope of the p_T spectra at low p_T is sensitive to the kinetic freezeout temperature and radial collective flow [7], providing insights into the thermal and hydrodynamic behavior of the QGP medium. At high p_T , heavy quarks interact with the highly excited particles of the QGP medium; thereby losing their energy and momentum, creating a wake. This phenomenon is known as jet quenching, where jets are collimated sprays of highly excited hadrons. The energy loss occurs either through elastic interactions with the medium constituents or via inelastic processes such as gluon radiation [8].

This energy loss can be quantified through nuclear modification factors (R_{AA} and R_{CP}). R_{AA} is defined as the ratio of the yield of heavy-flavored hadrons in Au + Au collisions to that in p + p collisions (where QGP is not formed), scaled by the mean number of binary nucleon-nucleon collisions, while R_{CP} represents the ratio of heavy hadron yields in central to peripheral Au + Au collisions, normalized by the number of binary collisions.

Charm and bottom quarks experience different energy losses when colliding with the QGP medium [9]. The energy loss of heavy quarks via gluon radiation is smaller than that of light quarks at angles ($\theta < \theta_0$), where θ_0 is the critical angle defined as the ratio of the quark mass (M) to its energy (E). Consequently, heavy hadron yields are enhanced relative to light hadrons [10]. This suppression of small-angle gluon radiation from heavy quarks is referred to as the dead cone effect [10]. The suppression factor quantifying this difference is given by the following equation [10]:

$$dP_{HQ} = dP_0 \left(1 + \frac{\theta_0^2}{\theta^2} \right)^{-2}, \quad \theta_0 \equiv \frac{M}{E}. \quad (1)$$

Here, dP_{HQ} represents the distribution of soft gluons radiated by heavy quarks, and dP_0 denotes the standard bremsstrahlung distribution of light quarks.

After the in-medium evolution of heavy quarks, when the QGP cools down, charm quarks hadronize into various open charm hadrons, such as D^0 , $D^\pm$, $D_s^\pm$, and $\Lambda_c^\pm$. The hadronization process involves two primary mechanisms: coalescence and fragmentation. In the coalescence mechanism, hard partons combine with nearby soft partons within the QGP to form hadrons. This mechanism was first described by TAMU group [11] and is known to dominate in the intermediate p_T region ($2 < p_T < 6$ GeV/c) [12,13]. At higher transverse momentum ($p_T > 6$ GeV/c), the fragmentation mechanism becomes dominant [14]. In this mechanism, a high-energy parton hadronizes by breaking the color string and creating quark-antiquark pairs from the vacuum, as described by the fragmentation function [14].

Further, the antiparticle-to-particle ratio ($\bar{h}/h$) should be balanced to produce a low baryon density, as expected within

the QGP medium. This ratio is useful for gaining insights into the baryon chemical potential (μ_B) because the mass term in the particle and antiparticle partition functions is the same [15]. The relation between μ_B and $\bar{h}/h$ is given by:

$$\bar{h}/h \propto \exp[-2(B\mu_B + S\mu_S)/T_{ch}], \quad (2)$$

where B is baryon quantum number, S is the strange quantum number, μ_S is the strange chemical potential, and T_{ch} is the chemical freezeout temperature. Since this study focuses on heavy hadrons except strange-charm hadrons, the ratio considered here depends on μ_B and T_{ch} only. For small values of μ_B , the ratio exhibits negligible sensitivity to temperature, making the antiparticle-to-particle ratio an ineffective probe for studying T_{ch} . However, it remains an important observable for studying μ_B .

The mixed particle ratio (h_1/h_2) serves as an effective thermometer for determining T_{ch} . Its relation with T_{ch} is given by [15]:

$$\frac{h_1}{h_2} \propto \left(\frac{m_{h_1}}{m_{h_2}} \right)^{(3/2)} \exp \left[-\frac{(m_{h_1} - m_{h_2})}{T_{ch}} \right] \exp \left[-\frac{\mu_S}{T_{ch}} \right], \quad (3)$$

where h_1 and h_2 are the yields of two different hadrons; m_{h_1} and m_{h_2} are the masses of the two hadrons. The absence of strange particles in this study reduces the second exponential term to unity. Therefore, T_{ch} depends only on the masses of the two hadrons.

The production of hadrons containing charm quarks has been observed in Au + Au collisions at a center-of-mass energy of 200 GeV by the STAR collaboration [16]. It has been observed that D^0 mesons undergo kinetic freezeout earlier than light hadrons (pions and protons) due to their weaker interactions with the QGP medium [17]. However, the kinetic freezeout of D^0 mesons occurs on a similar timeline as strange hadrons ($K^\pm$, Λ), owing to their comparable radial flow [17]. At high p_T ($p_T > 4$ GeV/c), charm quarks experience energy loss as they traverse through the QGP medium, resulting in suppression of the D^0 meson yield. While at low p_T , they exhibit strong interaction with the light quarks that participate in the collective flow. This partial thermalization of charm quarks [18], combined with the collective motion of light quarks, enhances the probability of coalescence, thereby enhancing the D^0 meson yield [19].

The production of charm baryon (Λ_c) was first observed in Au + Au collisions with $\sqrt{s_{NN}} = 200$ GeV at midrapidity [20]. The experimental observation indicates that the Λ_c/D^0 ratio in Au + Au collisions is greater than the predictions from PYTHIA 6 simulations for p + p collisions [21], suggesting a significant contribution of coalescence between charm and light quarks. Furthermore, charm-strange mesons ($D_s^\pm$) were first observed at midrapidity in the same collision system and energy, resulting from the coalescence of charm quarks with strange quarks [22]. Other hadrons from the total charm hadron production include $D^\pm$ mesons, which follow a production mechanism similar to that of D^0 mesons [23].

Several theoretical models, such as TAMU [24], SUBATECH [25], Torino [26], Duke [27], LANL [28], PHSD [29], LBT [30], BAMPS [31], and HYDJET++ [32], are available to explain the experimental observations.

In the present study, the performance of the HYDJET++ model is assessed by comparing its results with those from the TAMU, SUBATECH, Torino, and Duke models, based on the availability of corresponding results. The TAMU model [24] uses nonperturbative T-matrix methods [33,34] and Fokker-Planck-Langevin dynamics to describe heavy quark transport in a hydrodynamic QGP medium. This model explains the flow bump in the R_{AA} of D^0 mesons but does not account for hadronic rescattering and the radiative energy loss of heavy quarks. SUBATECH [25] incorporates hard thermal loop (HTL)-based calculation for charm-medium interactions with collisional and radiative energy loss. This model reproduces R_{AA} and elliptic flow (v_2), but does not clarify the individual contributions of collisional and radiative energy loss. The Torino group [26] combines POWHEG-based initial production [35] with HTL + pQCD transport [36] and Langevin evolution [37] but omits coalescence. This model reproduces R_{AA} results at high p_T ($p_T \gtrsim 3$ GeV/c), but fails at low- p_T ($p_T \lesssim 3$ GeV/c) and in peripheral collisions. The Duke group [27] employs leading-order pQCD [38] with shadowing (EPS08 parametrization) [39]. They use Langevin dynamics augmented with a recoil force term to include the effects of gluon radiation via higher-twist energy loss calculations [40–43]. Additionally, the model includes a fragmentation-plus-recombination hadronization scheme [44–47] based on viscous hydrodynamics [48]. This model highlights the role of medium-induced gluon radiation in the R_{AA} at high p_T and shows the effect of nuclear shadowing across the entire p_T range.

The HYDJET++ model [32] combines thermal and nonthermal components with the FAST MC [49,50] and PYQUEN generators [51], respectively, modeling a longitudinally expanding QGP. This model is described in detail in Sec. II. The HYDJET++ model has been used to describe strange hadron production [52–54]. At RHIC energy, the model describes the early thermal freezeout of charmed mesons compared to light hadrons, assuming $T_{th} = T_{ch}$ [55]. At LHC energy, D mesons (D^0 , $D^\pm$ and $D^{*\pm}$) thermalize simultaneously with light hadrons, whereas the J/ψ meson undergoes thermal freezeout earlier than light hadrons. This behavior of thermalization in D mesons is exhibited due to their increased interaction cross section [55]. Although the previous study [55] has achieved notable successes for heavy hadron production, it does not capture the effects of $T_{th} < T_{ch}$, the centrality and mass dependence of the charm enhancement factor (γ_c), medium induced energy loss, particle-antiparticle asymmetry, and the role of fragmentation mechanism in hadronization. In this article, we address all of these aspects. This study is helpful in defining the dependence of charm quark production on the size of the QGP fireball and the contribution of the fragmentation mechanism of hadronization to the formation of various charm hadrons.

This article is structured as follows. Section II describes the model framework used to produce heavy hadron spectra, starting from the initial production of partons through their in-medium evolution, leading to hadronization and decay. In Sec. III, we present the invariant yields of D^0 , $\bar{D}^0$, $D^\pm$, and Λ_c at midrapidity ($|y| < 1$) as a function of p_T for various centrality classes. We also discuss R_{AA} of D^0 and $D^\pm$ mesons

and R_{CP} of D^0 meson, their variation from central to peripheral collisions, the antiparticle-to-particle ratio, and the mixed particle ratio as a function of p_T . The results from the HYDJET++ model are compared with other models and with STAR measurements of D^0 , $\bar{D}^0$ [17], $D^\pm$ [23] and Λ_c [20] production in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Finally, we summarize the key findings in Sec. IV.

II. HYDJET++ MODEL FRAMEWORK

The heavy-ion event generator HYDJET++ (the successor of HYDJET [51]) combines the description of the soft hydrotype state (thermal component) with the hard state (non-thermal component). In this model, the soft and hard states are treated independently.

The soft component of the HYDJET++ model represents the thermal hadronic state produced on the chemical and thermal freezeout hypersurfaces. It is derived from a parameterized relativistic hydrodynamic model with predefined freezeout conditions, using the FASTMC event generator [49,50]. The statistical hadronization approach [56,57] is employed to define the thermal production of charm hadrons. This approach does not describe microscopic mechanisms of hadron production [58,59]. It neglects color field dynamics and may not capture baryon-to-meson enhancement at intermediate p_T (where coalescence matters) [58,60].

The production of thermal hadrons involves the following steps: first, the four-momentum of hadrons is generated within the rest frame of the quark-gluon liquid using the equilibrium distribution function [61]. Next, the spatial position and four-momentum of the fluid element are generated. This is followed by the generation of the boost for the four-momentum of a hadron within the event's center-of-mass frame. Finally, two- and three-body resonance decays are taken from the SHARE particle decay table [62].

The (partially) equilibrated Lorentz-invariant distribution function (f_{oh}) of open charm hadrons is defined as [61]:

$$f_{oh}(p_0^*; T_{ch}, \gamma_c) = \frac{(\gamma_c)^{n_c} g_h}{\exp(p_0^*/T_{ch}) \pm 1}, \quad (4)$$

Here, p_0^* is the charm hadron energy and T_{ch} is the freezeout temperature. The factor γ_c is the charm enhancement factor, or charm fugacity, and it is the free parameter of the model. The parameter n_c defines the number of charm quark pairs present in a hadron, while g_h is the spin degeneracy factor ($g_h = 2J_h + 1$). The $+$ sign in the denominator applies to fermions, whereas the $-$ sign applies to bosons. Additionally, γ_c quantifies the enhancement of the charm-hadron multiplicity relative to its value at chemical equilibrium, i.e., $\gamma_c \geq 1$. In other words, γ_c ensures the charm conservation within the thermal medium. The mean multiplicity of charm hadrons (N_{oh}^{th}) propagating through the QGP medium in Minkowski space is calculated using the thermal volume approximation and is given by the following equation [61,63]:

$$N_{oh}^{th} = \rho_{oh}^{eq}(T_{ch}) V_{eff}, \quad \rho_{oh}^{eq}(T_{ch}) = \int d^3p^* f_{oh}(p_0^*; T_{ch}, \gamma_c), \quad (5)$$

where ρ_{oh}^{eq} is the charm hadron number density at the freezeout temperature T_{ch} and V_{eff} is the effective volume from which

charm hadrons are emitted. V_{eff} depends on the impact parameter (b) of the heavy-ion collision as [61]:

$$V_{\text{eff}} = \tau \int_0^{2\pi} d\phi \int_0^{R(b,\phi)} \sqrt{1 + \delta(b) \tanh^2 Y_T(r, b) \cos 2\phi} \\ \times \cosh Y_T(r, b) r dr \int_{\eta_{\min}}^{\eta_{\max}} Y_L \eta d\eta, \quad (6)$$

where τ is the constant proper time of freezeout, $R(b, \phi)$ is the transverse radius of the fireball in the ϕ direction, $\delta(b)$ defines the momentum anisotropy, Y_T represent the linear profile of transverse flow rapidity, and Y_L denotes the Gaussian profile of longitudinal flow rapidity. In HYDJET++, different chemical freezeout (T_{ch}) and thermal freezeout (T_{th}) temperatures are used. At temperature T_{ch} , particle number ratios are fixed. Then the effective volume and momentum spectra of hadrons are computed at temperature T_{th} , indicating that $T_{\text{th}} < T_{\text{ch}}$. This formulation of the soft part of the model allows us to incorporate thermal and collective flow effects in charm hadron production. It is expected to provide a partial description of the low to intermediate p_T spectra in the absence of an explicit coalescence mechanism.

The hard part of the HYDJET++ model is the same as in the HYDJET model [51,64]. It is based on the PYTHIA 6 [65] and PYTHIA QUENCHED (PYQUEN) [51] event generators. PYTHIA 6 generates the initial parton spectra in hard nucleon-nucleon (NN) collisions. The PYQUEN partonic energy loss model uses the Glauber model approach [66] to generate impact parameter-dependent binary nucleon-nucleon collision vertices. The impact parameter-dependent mean number of jets ($\overline{N}_{AA}^{\text{jet}}$) [61] (which includes heavy quarks) produced in heavy-ion collisions in the presence of shadowing is defined as:

$$\overline{N}_{AA}^{\text{jet}}(b, \sqrt{s}, p_T^{\min}) = \int_{p_T^{\min}} d p_T^2 \int B dy \int_0^{2\pi} d\psi \int_0^\infty C dr, \quad (7)$$

$$B = \frac{d\sigma_{NN}^{\text{hard}}(p_T, \sqrt{s})}{d p_T^2 dy}, \text{ and} \quad (8)$$

$$C = r T_A(r_1) T_A(r_2) S(r_1, r_2, p_T, y). \quad (9)$$

Here, $p_T^{\min}$ is the minimum transverse momentum transfer in nucleon-nucleon collisions. The term $d\sigma_{NN}^{\text{hard}}(p_T, \sqrt{s})/d p_T^2 dy$ represents the differential cross section of the hard process in NN collision at the center of mass energy ($\sqrt{s}$) of the colliding beams, evaluated at $p_T^{\min}$. The quantities r_1 and r_2 are the transverse distances from the centers of the two nuclei to the jet production vertex, such that $r_1 + r_2 = b$. T_A denotes the nuclear thickness function [51]. S is the shadowing factor, which can be further represented as [32]:

$$S(r_1, r_2, p_T, y) = S_A^i(x_1, Q^2, r_1) S_A^j(x_2, Q^2, r_2). \quad (10)$$

Here, S_A^i and S_A^j are the ratios of nuclear to nucleon parton distribution functions (PDFs) for partons i and j , respectively. The variables x_1 and x_2 are the momentum fractions of the initial partons from the participating nuclei in the hard scattering. These momentum fractions satisfy the relation $Q^2 = x_1 x_2 s$,

where

$$s = 2m_0 E + m_0^2 + m_q^2. \quad (11)$$

Here, E and m_q are the energy and mass of the heavy quark, respectively, and m_0 is the effective mass of the thermal parton. The shadowing factor $S \leq 1$ corresponds to the nuclear shadowing effect on the PDF.

Subsequently, the rescattering of partons within the dense QGP medium is simulated using a parton path algorithm [67], which includes both collisional and radiative energy losses. The collisional energy loss is due to elastic scattering among the partons and is calculated only in the high-momentum transfer limit [32,51,68,69]. This energy loss is defined as [61]:

$$\frac{dE^{\text{coll}}}{dl} = \frac{1}{4T_{\text{ch}}\lambda\sigma} \int_{\mu_D^2}^{t_{\max}} dt \frac{d\sigma}{dt} t, \quad \frac{d\sigma}{dt} \cong C' \frac{2\pi\alpha_s^2(t)}{t^2} \frac{E^2}{E^2 - m_q^2}, \quad (12)$$

where $\lambda = 1/(\sigma\rho)$ is the mean-free path within the medium, σ is the integral cross section of parton interaction, and $C' = 9/4, 1$, and $4/9$ is the multiplication factor corresponding to gg, qq, and qq scatterings, respectively. ρ is the medium density at temperature T_{ch} , with $\rho \propto (T_{\text{ch}})^3$. The Debye screening mass squared (μ_D^2) is defined as $\mu_D^2(T_{\text{ch}}) \simeq 4\pi\alpha_s T_{\text{ch}}^2 (1 + N_f/6)$, where N_f represents the number of active quark flavors and α_s is the QCD running coupling constant. The maximum momentum transfer ($t_{\max}$) is given by the following equation [67]:

$$t_{\max} = [s - (m_q + m_0)^2][s - (m_q - m_0)^2]/s. \quad (13)$$

The radiative energy loss is described within the Baier-Dokshitzer-Mueller-Schiff (BDMS) framework [70,71], and its generalization to the heavy-quark case is based on the dead-cone approximation [61]. It is given by:

$$\frac{dE^{\text{rad}}}{dl} \Big|_{m_q \neq 0} = \frac{1}{(1 + (\beta\omega)^{3/2})^2} \frac{dE^{\text{rad}}}{dl} \Big|_{m_q = 0}, \quad (14)$$

$$\beta = \left(\frac{\lambda}{\mu_D^2} \right)^{1/3} \left(\frac{m_q}{E} \right)^{4/3}, \quad (15)$$

where

$$\frac{dE^{\text{rad}}}{dl} \Big|_{m_q = 0} = \frac{2\alpha_s \mu_D^2 C_R}{\pi L} \int_{\mu_D^2 \lambda_g}^E d\omega \left[1 - x + \frac{x^2}{2} \right] \\ \times \ln |\cos(\omega_1 \tau_1)|, \quad (16)$$

$$\omega_1 = \sqrt{i \left(1 - x + \frac{C_R}{3} x^2 \right) \bar{\kappa} \ln \frac{16}{\bar{\kappa}}}, \quad (17)$$

$$\bar{\kappa} = \frac{\mu_D^2 \lambda_g}{\omega(1-x)}, \quad (18)$$

where $C_R = 4/3$ is the quark color factor, L is the path length, x is the ratio of radiated gluon energy to quark energy, defined as $x = \omega/E$, and τ_1 is defined as $\tau_1 = L/(2\lambda_g)$, where λ_g is the gluon mean-free path.

During the in-medium partonic evolution, additional gluons are emitted via radiative and collisional energy loss mechanisms. The color information of quarks and gluons is

TABLE I. Tuned parameters of HYDJET++ for modeling heavy hadron production.

Particle type	T_{ch}	T_{th}	Y_l^{max}	Y_T^{max}	p_T^{min}	μ_c
Heavy Hadrons	165 MeV	125 MeV	2.9	0.78	4.8 GeV/c	-0.004 GeV

tracked through PYTHIA 6 color tags. These gluons are appended to the event record, and the string topology is updated accordingly. This is done by assigning them to the same color string as their emitter using routine PYJOIN, maintaining approximate color coherence based on longitudinal ordering [32,51]. Heavy quarks are not connected to light quarks via strings, due to the absence of a coalescence mechanism in the model. The final hadronization is described via string fragmentation among the partons generated in the hard scattering and in-medium emitted gluons using the Lund string model [72].

The default input parameters of the HYDJET++ model for light hadron production [32] in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV are $T_{\text{ch}} = 165$ MeV, $T_{\text{th}} = 100$ MeV, $Y_l^{\text{max}} = 3.3$, $Y_T^{\text{max}} = 1.1$, charm chemical potential (μ_c) = 0 GeV, and $p_T^{\text{min}} = 3.55$ GeV/c. However, these default parameters fail to describe heavy hadron production, as they thermalize earlier than light hadrons [55]. Consequently, the parameters are optimized to improve the description of heavy hadrons while ensuring that the charged hadron spectra remain unaffected [54,61,73].

We have systematically tuned these parameters based on the following considerations. Heavy hadrons are less likely to attain complete chemical equilibrium within the medium due to their large masses [57]. Therefore, their hadronization is assumed to occur at the same T_{ch} as that of light hadrons, consistent with the statistical hadronization model [57]. In addition, T_{th} is considered lower than T_{ch} , since thermal equilibrium is achieved later than chemical equilibrium [51]. The early thermal freezeout of heavy hadrons requires higher T_{th} and smaller collective flow rapidities (Y_l^{max} , Y_T^{max}) [74]. Furthermore, μ_c is negative and shows a negative correlation with μ_B , as suggested by theoretical studies [75,76]. Since the default model uses a small value of μ_B , we accordingly adopt a small negative value for μ_c . Further, as charm quarks are primarily produced in initial hard scatterings, a slightly higher p_T^{min} value is employed to better describe the hard component of heavy hadron production. Our approach of tuning these parameters is physically motivated and consistent with the previous HYDJET++ study on charm hadron production in Au + Au collisions at RHIC energy [55]. The optimized parameters are summarized in Table I. The remaining parameters of the soft and hard components are kept at their default values for inclusive hadron production [32] since they primarily depend on the collision system and energy, and have a negligible effect on the production of specific hadron species.

After tuning the parameters that define charm-hadron production within the medium, it is also necessary to ensure that the total number of charm and anticharm quarks is conserved.

To achieve this, the charm fugacity (γ_c) is tuned. γ_c is defined through the charm balance equation within the statistical hadronization model [56,57,77]:

$$N_{c\bar{c}}^{\text{dir}} = \frac{1}{2} \gamma_c N_{\text{oh}}^{\text{th}} \frac{I_1(\gamma_c N_{\text{oh}}^{\text{th}})}{I_0(\gamma_c N_{\text{oh}}^{\text{th}})} + \gamma_c^2 N_{hh}^{\text{th}}. \quad (19)$$

Here, $N_{c\bar{c}}^{\text{dir}}$ is the number of charm quark pairs directly produced in initial hard scatterings. $N_{\text{oh}}^{\text{th}}$ and N_{hh}^{th} are the total numbers of open and hidden charm hadrons, respectively, produced from the effective fireball volume (V_{eff}). $I_{0,1}$ denotes the modified Bessel functions. Since this study focuses on open-charm hadron production, the second term in Eq. (19) can be ignored. Hence, Eq. (19) can be rewritten as:

$$N_{c\bar{c}}^{\text{dir}} = \frac{1}{2} \gamma_c N_{\text{oh}}^{\text{th}} \frac{I_1(\gamma_c N_{\text{oh}}^{\text{th}})}{I_0(\gamma_c N_{\text{oh}}^{\text{th}})}. \quad (20)$$

According to Eq. (5), $N_{\text{oh}}^{\text{th}}$ linearly depends on $\rho_{\text{oh}}^{\text{eq}}$ and V_{eff} . $\rho_{\text{oh}}^{\text{eq}}$ remains constant at a given collision energy, while V_{eff} depends on centrality. Thus, Eq. (20) can be rewritten as:

$$N_{c\bar{c}}^{\text{dir}} = \frac{1}{2} \gamma_c \rho_{\text{oh}}^{\text{eq}} V_{\text{eff}} \frac{I_1(\gamma_c N_{\text{oh}}^{\text{th}})}{I_0(\gamma_c N_{\text{oh}}^{\text{th}})}. \quad (21)$$

The ratio of the Bessel functions (I_1/I_0) also varies with centrality. For most central collisions, where $\gamma_c N_{\text{oh}}^{\text{th}} > 1$ [57,78], this ratio can be approximated as:

$$\frac{I_1(\gamma_c N_{\text{oh}}^{\text{th}})}{I_0(\gamma_c N_{\text{oh}}^{\text{th}})} \approx 1 - \frac{1}{2\gamma_c N_{\text{oh}}^{\text{th}}} \approx 1 - \frac{1}{2\gamma_c \rho_{\text{oh}}^{\text{eq}} V_{\text{eff}}}, \quad (22)$$

while for peripheral collisions, where $\gamma_c N_{\text{oh}}^{\text{th}} \ll 1$ [57,78], the ratio reduces to:

$$\frac{I_1(\gamma_c N_{\text{oh}}^{\text{th}})}{I_0(\gamma_c N_{\text{oh}}^{\text{th}})} \approx \frac{1}{2} \gamma_c N_{\text{oh}}^{\text{th}} \approx \frac{1}{2} \gamma_c \rho_{\text{oh}}^{\text{eq}} V_{\text{eff}}. \quad (23)$$

Therefore, Eq. (21) simplifies to:

$$N_{c\bar{c}}^{\text{dir}}(\text{central}) = \frac{1}{2} \gamma_c \rho_{\text{oh}}^{\text{eq}} V_{\text{eff}} - \frac{1}{4}, \quad (24)$$

$$N_{c\bar{c}}^{\text{dir}}(\text{peripheral}) = (\frac{1}{2} \gamma_c \rho_{\text{oh}}^{\text{eq}} V_{\text{eff}})^2. \quad (25)$$

According to the Glauber model [79],

$$N_{c\bar{c}}^{\text{dir}} \propto N_{\text{coll}} \propto (N_{\text{part}})^{4/3} \text{ and } V_{\text{eff}} \propto N_{\text{part}}. \quad (26)$$

Therefore, Eq. (24) can be defined as:

$$(N_{\text{part}})^{4/3} \propto \gamma_c(\text{central}) N_{\text{part}}, \quad (27)$$

$$\gamma_c(\text{central}) \propto (N_{\text{part}})^{1/3}. \quad (28)$$

Similarly, Eq. (25) can be defined as:

$$(N_{\text{part}})^{4/3} \propto (\gamma_c(\text{peripheral}) N_{\text{part}})^2, \quad (29)$$

$$\gamma_c(\text{peripheral}) \propto (N_{\text{part}})^{-1/3}. \quad (30)$$

Equations (28) and (30) indicate that γ_c depends on the number of participant nucleons (N_{part}). In central collisions, γ_c increases with N_{part} , while in peripheral collisions, it decreases with N_{part} . Overall, as the collision system evolves from central to peripheral, both N_{part} and γ_c decrease correspondingly.

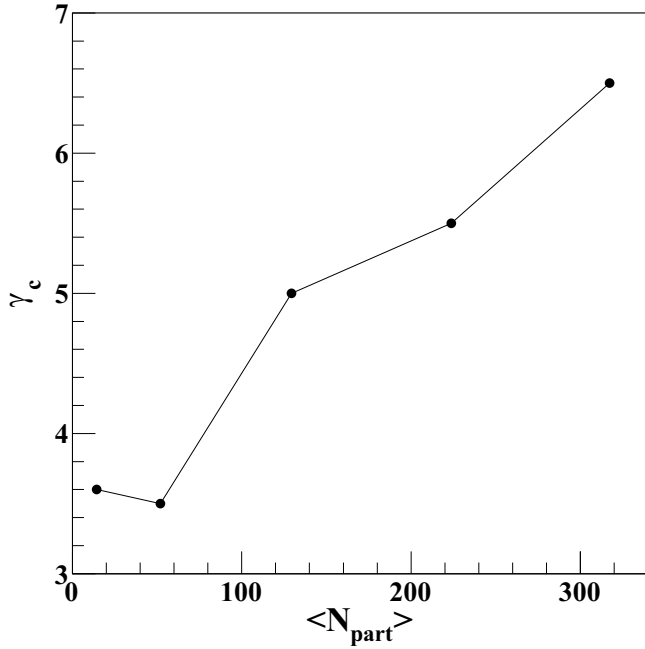


FIG. 1. Dependence of the charm fugacity (γ_c) on the average number of participants ($\langle N_{\text{part}} \rangle$) obtained from the HYDJET++ model.

This centrality dependence of γ_c is clearly observed in this study, as shown in Fig. 1. Further, from Eq. (21), γ_c depends

on $\rho_{\text{oh}}^{\text{eq}}$ as:

$$\gamma_c \propto \frac{1}{\rho_{\text{oh}}^{\text{eq}}}. \quad (31)$$

The mass dependence of $\rho_{\text{oh}}^{\text{eq}}$ is defined as [56]:

$$\rho_{\text{oh}}^{\text{eq}} \propto \exp(-m_{c_h}/T_{\text{ch}}). \quad (32)$$

Hence, Eq. (31) can be rewritten as:

$$\gamma_c \propto \exp(m_{c_h}/T_{\text{ch}}). \quad (33)$$

Here, m_{c_h} is the mass of the charm hadron. Equation (33) shows that heavier charm hadrons require a larger value of γ_c to satisfy charm conservation. Thus, the γ_c value increases with hadron mass. This mass dependence is also evident in our study: for the most central (0–10 %) collisions, $\gamma_c = 6.5$ for the D^0 meson and 10 for the Λ_c baryon.

Additionally, in various MC event generators and experiments, the geometrical quantities ($\langle N_{\text{part}} \rangle$ and $\langle N_{\text{coll}} \rangle$) are calculated from the Monte Carlo Glauber model [66]. These geometrical quantities are unaffected by tuning input parameters such as T_{th} and T_{ch} . Therefore, the $\langle N_{\text{part}} \rangle$ and $\langle N_{\text{coll}} \rangle$ values obtained from the modified HYDJET++ model remain consistent with the STAR experimental data [17].

Au+Au at $\sqrt{s_{NN}} = 200$ GeV

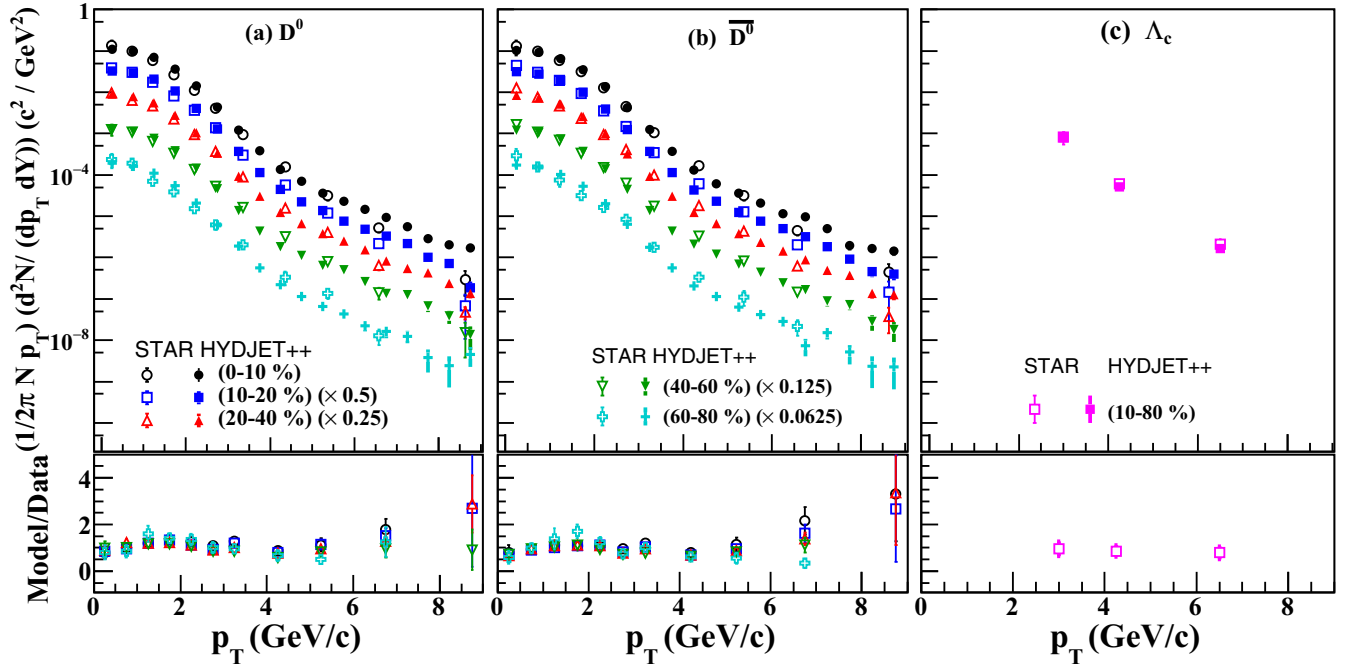


FIG. 2. Transverse momentum spectra of (a) D^0 , (b) $\bar{D}^0$ mesons, and (c) Λ_c baryons at mid-rapidity ($|y| < 1$) for various centrality classes. Open markers represent data from STAR [17,20], while solid markers denote results from the HYDJET++ model. For better visibility, the p_T spectra for 10–20 %, 20–40 %, 40–60 %, and 60–80 % centrality bins are scaled by 0.5, 0.25, 0.125, and 0.0625, respectively. The lower panel shows the model-to-data ratio.

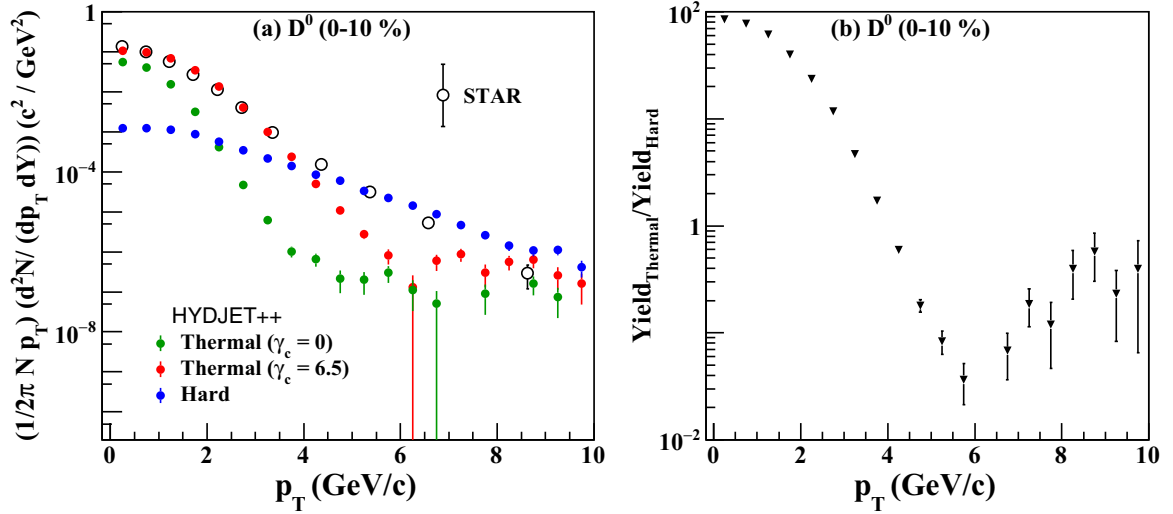


FIG. 3. (a) Transverse momentum spectra of D^0 mesons from thermal and hard collisions at midrapidity ($|y| < 1$) for 0–10% centrality class. Open markers represent data from STAR measurements [17], while closed markers indicate results from the HYDJET++ model, (b) Ratio of thermal to hard yields as a function of transverse momentum.

III. RESULTS

A. Transverse momentum (p_T) spectra

Figures 2(a) and 2(b) present the transverse momentum spectra of D^0 and $\bar{D}^0$ mesons, respectively, at midrapidity ($|y| < 1$) for the 0–10%, 10–20%, 20–40%, 40–60%, and 60–80% centrality classes. Figure 2(c) presents the transverse momentum spectra of the Λ_c baryon in the 10–80% centrality bin. For better visibility, the p_T spectra for 10–20%, 20–40%, 40–60%, and 60–80% centrality bins are scaled by 0.5, 0.25, 0.125, and 0.0625, respectively, as indicated in the legend. The simulated results are compared with the experimental data from the STAR experiment [17,20]. We also present the model-to-data ratio in the bottom panel of Fig. 2. From these plots, it is evident that the HYDJET++ model describes the p_T spectra of D^0 and $\bar{D}^0$ mesons at low and intermediate p_T . However, at high p_T , the model overpredicts the experimental data across all centrality bins. This overprediction shows the need for refinement of the energy loss of charm quarks at high p_T . Moreover, the p_T spectrum of the Λ_c baryon is consistent with the STAR result [20]. Further, the simulated p_T spectra show a similar centrality dependence to that reported by the STAR collaboration [17], where the slope of the spectra serves as a proxy for the effective temperature of the QGP fireball. The slope of the p_T spectra is inversely proportional to the effective temperature [17], and it decreases from peripheral to central collisions. This behavior indicates that central collisions have a higher QGP temperature than noncentral collisions, which is consistent with the STAR experimental data [17,20]. The experimental data [17] also show that the p_T spectra follow an exponential distribution at low p_T , while at high p_T (typically above 4 GeV/c), the spectra transition from an exponential to a power-law behavior due to contributions from hard scatterings [80].

Additionally, the yield of D^0 mesons from thermal and hard production mechanisms in central collisions is presented

in Fig. 3(a), and the ratio of thermal to hard yield as a function of transverse momentum is presented in Fig. 3(b). These figures show that both thermal and hard processes may contribute to the production of D^0 mesons. Thermal production dominates in the low and intermediate p_T regions, while hard production dominates at high p_T . This trend indicates that thermalized charm quarks primarily produce lower p_T hadrons, while hard-scattered partons produce higher- p_T hadrons through fragmentation, which is consistent with theoretical expectations [55]. Figure 3(a) also shows the thermal freezeout component at low to intermediate p_T corresponding to the absence of thermal charm production ($\gamma_c = 0$). The deviation between the spectra with or without the γ_c factor quantifies the contribution of thermal charm production.

Since the simulated results reasonably describe the p_T spectra of D^0 mesons from the STAR experiment, the model is further used to predict the p_T spectra of $D^\pm$ mesons. Fig. 4 shows the p_T spectra of $D^\pm$ mesons at mid-rapidity ($|y| < 1$) for the 0–10%, 10–20%, 20–40%, 40–60%, and 60–80% centrality classes in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The scaling factors for better visibility are indicated in the legend. Since experimental data for $D^\pm$ mesons are unavailable; therefore, only the HYDJET++ model results are presented. It is observed that $D^\pm$ mesons follow similar centrality dependence as D^0 mesons, indicating that $D^\pm$ mesons might thermalize at the same time as D^0 mesons.

The average transverse momentum ($\langle p_T \rangle$) of D^0 meson for all centrality bins is listed in Table II. It is observed that $\langle p_T \rangle$ has minimal dependence on collision centrality. In central collisions, $\langle p_T \rangle$ is larger than in peripheral ones because high QGP temperature corresponds to a longer lifetime of the fireball. This longer lifetime produces a large pressure gradient in an outward direction, resulting in sizable radial flow [81].

In the HYDJET++ model, radial flow is implemented in the soft (thermal) component through a parameterized transverse flow rapidity profile, which mimics collective expansion

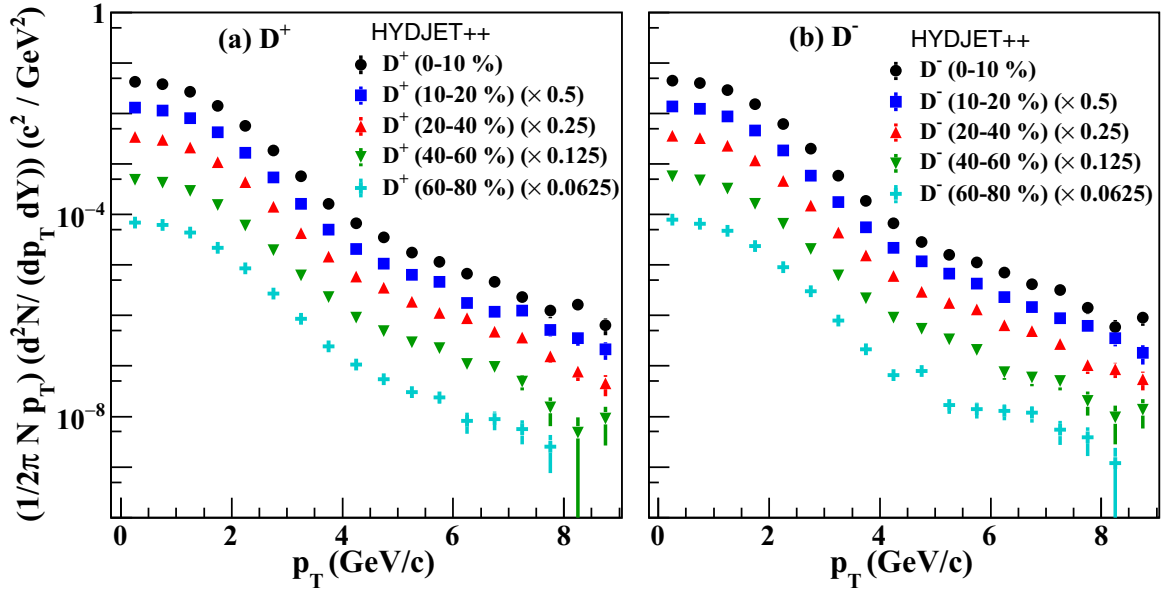


FIG. 4. Transverse momentum spectra of (a) D^+ and (b) D^- mesons at midrapidity ($|y| < 1$) for various centrality classes using the HYDJET++ model. For better visibility, the p_T spectra for 10–20 %, 20–40 %, 40–60 %, and 60–80 % centrality bins are scaled by 0.5, 0.25, 0.125, and 0.0625, respectively.

of the QGP [32]. This flow boosts thermal particles in the transverse direction and significantly influences the shape of the p_T spectra at low to intermediate momentum. The agreement between model and data in the low- and intermediate- p_T regions for D^0 , $\bar{D}^0$, and Λ_c hadrons indicates that the radial flow encoded in HYDJET++ can capture key aspects of the medium's collective behavior. The observed centrality dependence of $\langle p_T \rangle$ further supports the presence of radial flow in Au + Au collisions.

B. Nuclear modification factors (R_{AA} and R_{CP})

R_{AA} is a tool for investigating parton-medium interactions, since it is primarily sensitive to the energy loss mechanism itself, and relatively less sensitive to the details of the medium's space-time evolution [82]. Figure 5 shows the R_{AA} of D^0 and $D^\pm$ mesons for different centrality bins: 0–10 %, 10–40 %, and 40–80 %, with reference to the D^0 meson yield in p + p collisions. To estimate R_{AA} , the heavy hadron yield in Au + Au collisions is simulated using the HYDJET++ model, while the yield in p + p collisions is simulated using PYTHIA 8 Tune 5 with the same parameters as discussed in these references [83,84]. Figure 6 shows the

p_T spectra of the D^0 meson from PYTHIA 8 along with its comparison with the STAR experimental data [19,83]. The PYTHIA 8 results are consistent with the experimental data, indicating that the generated sample provides a reliable p + p baseline. The normalization factor ($\langle N_{coll} \rangle$) for R_{AA} estimation is taken from Table II. Further, Fig. 5 shows that the R_{AA} results for the D^0 meson from this study follow the same trend as the experimental data [17] for $p_T > 2$ GeV/c. For $p_T < 2$ GeV/c, the simulated results show deviation from the data due to the lack of a coalescence. In this p_T region ($p_T < 2$ GeV/c), collisional energy loss dominates over radiative loss. As the momentum of heavy quarks increases, collisional energy loss decreases while radiative loss increases. Thus, at high p_T , the dominant contribution to the energy loss shifts from collisional to radiative loss [85,86].

For central (0–10 %) collisions, there is significant suppression in the calculated R_{AA} at $p_T > 2.5$ GeV/c. This suppression decreases as we move from central to peripheral collisions. This trend is expected due to the smaller size of QGP in peripheral collisions compared to central collisions. In peripheral collisions, the R_{AA} value approaches unity, while in most central collisions, this value is around 0.5 at $p_T > 3$ GeV/c. This suppression is attributed to radiative energy loss for all centralities. At higher p_T , the suppression is comparable to that of light hadrons [87,88] as well as electron decays from heavy-flavor hadrons [89,90]. Across all centralities, a peak appears when moving from low to intermediate p_T , indicating the collective motion of charm quarks as they traverse the QGP medium [24].

Furthermore, we compare our results with TAMU [24], SUBATECH [25], Torino [26], and Duke [27] models for the most central collisions. The HYDJET++ model results follow the same trend as the TAMU, SUBATECH, and Duke

TABLE II. Average number of collisions ($\langle N_{coll} \rangle$), average number of participants ($\langle N_{part} \rangle$), charm fugacity (γ_c), and average transverse momentum ($\langle p_T \rangle$) from the modified HYDJET++ model.

Centrality	0–10%	10–20%	20–40%	40–60%	60–80%
$\langle N_{coll} \rangle$	895.8	562.6	272.2	79.49	14.98
$\langle N_{part} \rangle$	317.3	223.8	129.3	51.76	14.25
γ_c	6.5	5.5	5.0	3.5	3.6
$\langle p_T \rangle$	1.364	1.358	1.353	1.352	1.333

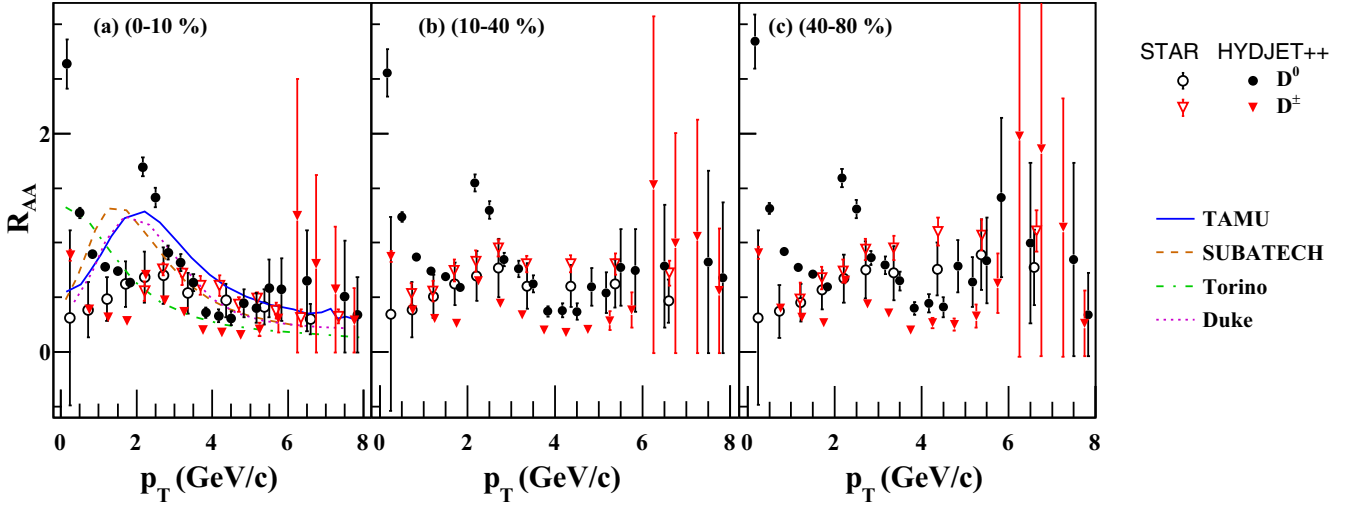


FIG. 5. Nuclear modification factor (R_{AA}) of D^0 and $D^\pm$ mesons as a function of p_T for (a) 0–10 %, (b) 10–40 %, and (c) 40–80 % centrality classes in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Open markers represent STAR data [17,23], while closed markers indicate HYDJET++ model results. Colored lines show the results from the TAMU [24], SUBATECH [25], Torino [26], and Duke [27] models for D^0 meson R_{AA} in the most central collisions, as indicated in the legend.

models across the entire p_T range, except at low p_T . This similarity is attributed to the parameterized treatment of partonic energy loss and hydrodynamic flow in the HYDJET++ model, which effectively reproduces the combined effect of radiative and collisional energy loss mechanisms. These mechanisms are also implemented microscopically in the TAMU, SUBATECH, and Duke models. At low p_T , the HYDJET++ model results follow the same trend as the Torino model, due to the common limitation in incorporating the coalescence mechanism. Although the HYDJET++ model omits the coalescence mechanism, it includes thermal charm production and collective flow effects, resulting in a slightly improved description of R_{AA} at low p_T as compared to the Torino model.

We also present the R_{AA} of the $D^\pm$ meson for the same three centrality intervals in Fig. 5. These results are compared with the preliminary data from the STAR experiment [23].

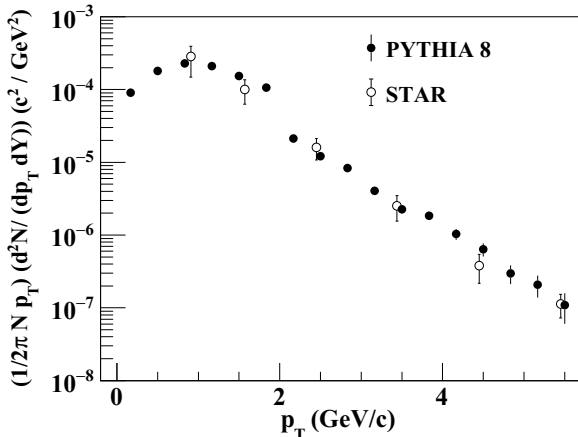


FIG. 6. p_T spectra of the D^0 meson in p + p collisions at 200 GeV from PYTHIA 8. Open markers show the STAR results [19,83], and solid markers show the PYTHIA 8 results.

The simulated results underestimate the experimental data but exhibit the same overall trend. The model effectively describes the peak in the intermediate p_T region, indicating the collective behavior of quarks within the QGP medium. The $D^\pm$ meson exhibits similar suppression as the D^0 meson at high p_T . This suppression decreases as we move from the most central to midcentral and peripheral collisions. At low p_T , the $D^\pm$ mesons are more suppressed than the D^0 meson.

The HYDJET++ model cannot simulate p + p collisions, as it is optimized for describing symmetric heavy-ion (AA) collisions with $A \geq 40$ at high energies [91]. Therefore, suppression effects can be more effectively studied using R_{CP} . R_{CP} provides insights into medium-induced modifications without relying on p + p reference data. Figure 7 presents the R_{CP} of D^0 mesons obtained using the HYDJET++ model and compared with the STAR experimental data [17] for different centrality bins: 0–10 %, 10–20 %, and 20–40 %, with reference to the 40–60 % peripheral centrality bin in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The HYDJET++ model results are nearly consistent with the experimental data [17] for all centrality bins. At low p_T ($p_T < 1$ GeV/c), the R_{CP} of D^0 mesons approaches unity due to the dominance of soft processes such as thermalized charm quark hadronization and radial flow. These soft processes scale approximately with N_{part} rather than N_{coll} , and exhibit weaker centrality dependence [92]. As a result, the yields per binary collision in central and peripheral events become comparable, leading to $R_{CP} \approx 1$. However, at high p_T , there is significant suppression in the R_{CP} value. This suppression decreases as we move from the most-central to the peripheral collisions. It might occur due to the dominance of radiative energy loss. The level of suppression in R_{CP} at high p_T is similar to that observed in light hadrons [87]. However, a small suppression from unity is also observed at low p_T [93], for light hadrons. This behavior observed in light hadrons can be attributed to collective effects such as radial flow, shadowing due to nuclear parton

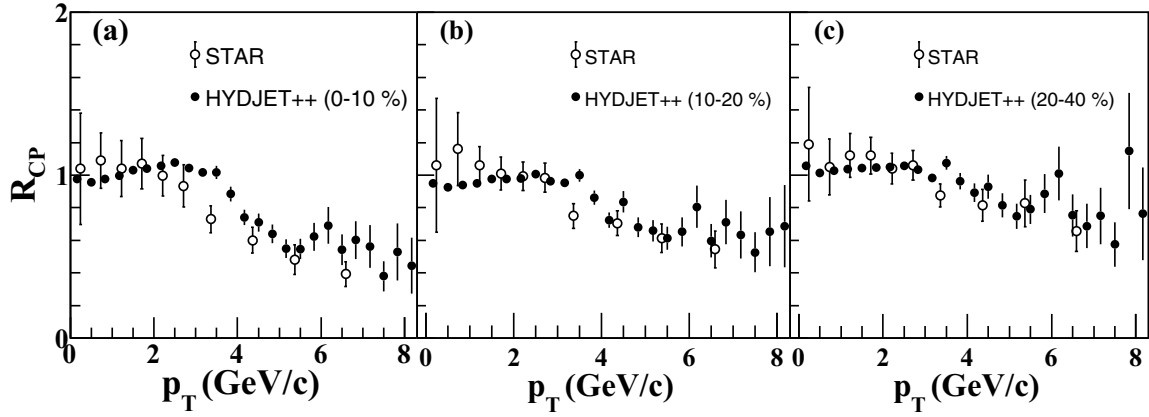


FIG. 7. R_{CP} of D^0 meson as a function of p_T , using the 40–60 % centrality bin as the reference, for the (a) 0–10 %, (b) 10–20 %, and (c) 20–40 % centrality classes in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Open markers represent STAR data [17], while closed markers indicate results from the HYDJET++ model.

distribution functions, and the dominance of soft physics processes in central collisions.

C. Antiparticle-to-particle ratio

In Fig. 8, the $\bar{D}^0/D^0$ meson ratio is shown for different centrality bins: 0–10 %, 10–20 %, 20–40 %, 40–60 %, and 60–80 %. The solid line represents a constant function fit. The fitted values of the $\bar{D}^0/D^0$ invariant yield, obtained from the HYDJET++ model and the STAR experiment [17], are listed in Table III. The model results follow a trend similar to the experimental data and show a minimal deviation from unity

for all centrality bins. Since charm and anticharm quarks are produced in pairs, their total amount should be the same. To further explore the charm and anticharm conservation, it is also essential to calculate other charm hadron ratios.

Hence, the D^-/D^+ , D_s^-/D_s^+ , and Λ_c^-/Λ_c^+ ratios as a function of transverse momentum at midrapidity ($|y| < 1$) are presented in Fig. 9 for the most central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The constant-fit value of the D^-/D^+ ratio is 1.076. This value is attributed to the charm chemical potential (μ_c) of -0.004 GeV and medium-induced mass shifts [96], which together indicate a slight enhancement in the production of anticharm-charged mesons relative to charm-charged

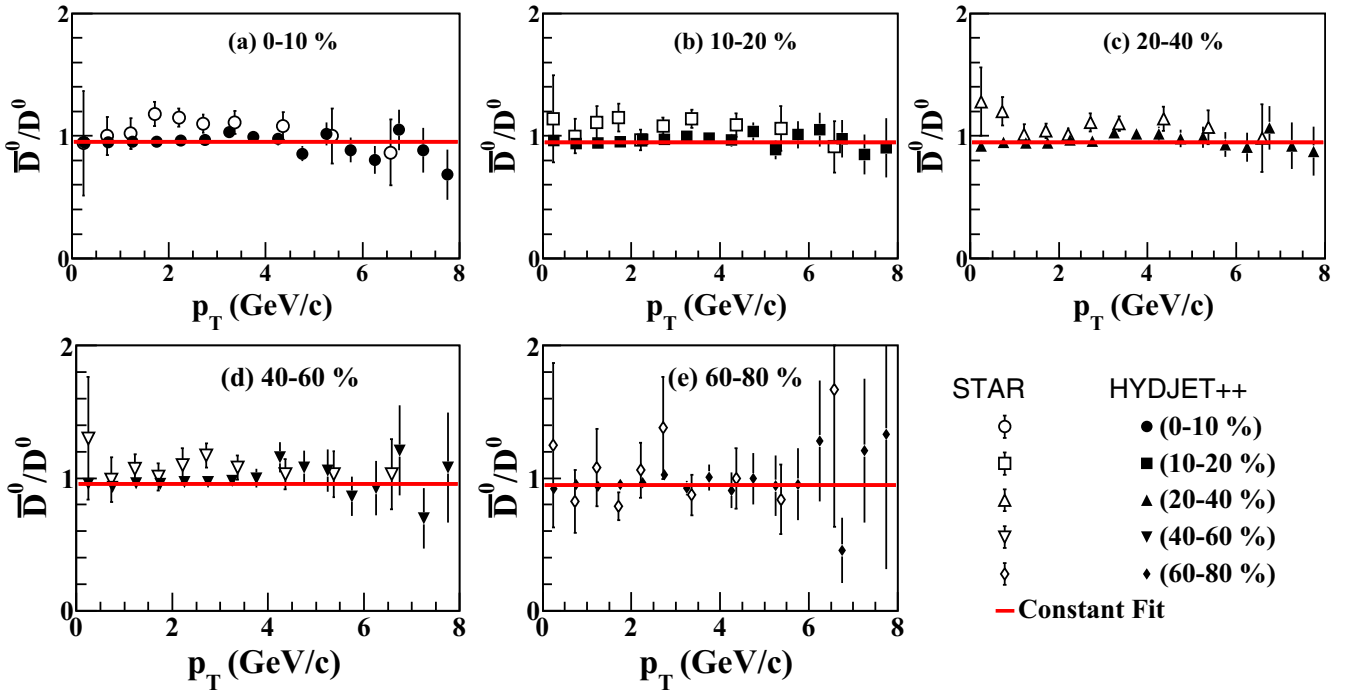


FIG. 8. Ratio of $\bar{D}^0$ to D^0 invariant yield as a function of p_T at mid-rapidity ($|y| < 1$) for (a) 0–10 %, (b) 10–20 %, (c) 20–40 %, (d) 40–60 %, and (e) 60–80 % centrality classes in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Open markers represent STAR data [17], while closed markers indicate HYDJET++ model results. The red line indicates a constant fit to the $\bar{D}^0/D^0$ ratios.

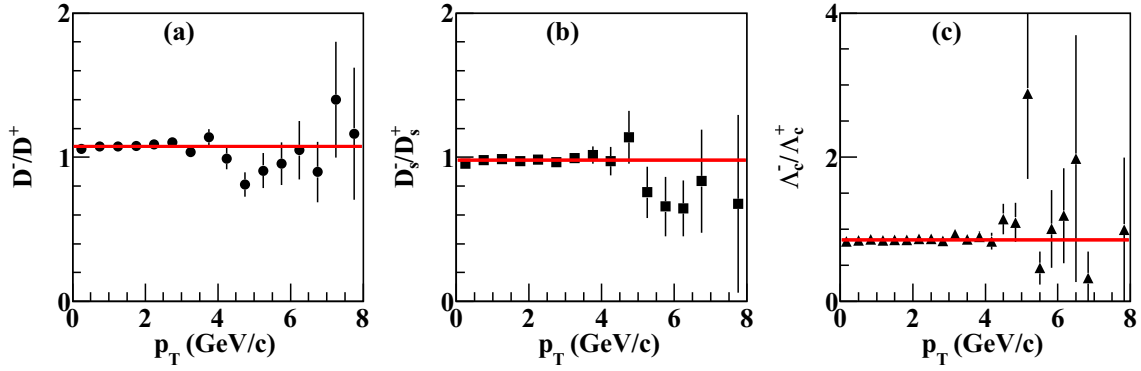


FIG. 9. (a) D^-/D^+ , (b) D_s^-/D_s^+ , and (c) Λ_c^-/Λ_c^+ as a function of p_T at midrapidity ($|y| < 1$) for the 0–10 % centrality class in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, as predicted by the HYDJET++ model. The red line shows the constant function fit.

mesons. The complete behavior of the D^-/D^+ and $\bar{D}^0/D^0$ ratios also depends on the quark content, light quark chemical potentials, and in-medium mass modifications of the charm hadrons. These combined effects influence the thermal yields differently for charged and neutral D mesons. This behavior is in line with thermal model expectations [96]. The D_s^-/D_s^+ ratio has a constant fit value of 0.979, which is due to the strange chemical potential (μ_s) of 0.007 GeV (default value [32]). This may indicate strangeness enhancement within the QGP, which is one of the key signatures of the QGP medium [97]. Similarly, the constant fit value of the Λ_c^-/Λ_c^+ ratio is 0.856. This results from the baryon chemical potential (μ_B) of 0.0285 GeV (default value [32]), indicating a baryon-rich region, which is expected to exist at RHIC energy [98].

D. Mixed particle ratios

Figure 10(a) shows the $D^\pm/(D^0 + \bar{D}^0)$ yield ratio in the 0–10 % centrality bin. Our model results are consistent with the experimental data [23] and PYTHIA 8 calculations [94] at high p_T . This behavior indicates that both mesons may follow the same suppression and hadronization mechanisms in Au + Au and p + p collisions.

Figure 10(b) shows the baryon-to-meson ratio for the 10–80 % centrality bin in Au + Au collisions for both heavy and strange hadrons. The simulated model results for heavy hadrons exhibit the same p_T dependence (a decreasing trend) as strange hadrons. Similarly, the STAR experimental data also show a decreasing trend with increasing p_T [95]. The baryon-to-meson yield ratio for all hadrons from the

HYDJET++ model is enhanced compared to PYTHIA 6 predictions for p + p collisions [65]. This enhancement can be attributed to thermal and collective flow effects within the QGP medium for both light and heavy hadrons. However, the HYDJET++ results for heavy hadrons underestimate the STAR experimental data [95]. This discrepancy can be partially explained by the absence of a quark coalescence mechanism in HYDJET++, which plays a significant role in baryon enhancement. Additionally, in this study, the charm quark fugacity (γ_c) was not specifically tuned for the 10–80% D^0 meson yield, due to the lack of corresponding spectral data. Instead, an average γ_c value obtained from narrower centrality bins (0–10 %, 10–20 %, 20–40 %, 40–60 %, and 60–80 %) was used. Since γ_c is centrality dependent and crucial for charm conservation, the approximation of average γ_c may also contribute to the observed deviation in the Λ_c/D^0 ratio.

The distinct nature of $D^\pm/(D^0 + \bar{D}^0)$ and Λ_c/D^0 , indicates that the QGP medium may modify the hadronization process, leading to a redistribution of charm quarks among different open-charm hadron species [23].

IV. SUMMARY AND OUTLOOK

In this study, the production of heavy hadrons (D^0 , $\bar{D}^0$, Λ_c , D^+ , and D^-) in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for different centrality bins has been investigated using the HYDJET++ model. This analysis predicts an increasing trend of γ_c with N_{part} in central collisions, but a decreasing trend in peripheral collisions. Overall, γ_c decreases from central to peripheral collisions, reflecting the reduced fireball volume in peripheral collisions. Additionally, γ_c shows mass dependence, with higher values for heavier charm hadrons in central collisions. Moreover, the p_T spectra results demonstrate that the model describes the experimental data reasonably at low and intermediate p_T , capturing the essential features of charm hadron production in a QGP medium. At high p_T ($p_T > 4$ GeV/c), the model overpredicts the experimental data across all centrality bins, indicating that further refinements are needed to improve the description of charm quark energy loss. The p_T spectra further indicate that central collisions produce a hotter and denser QGP compared

TABLE III. Invariant yield ratios ($\bar{D}^0/D^0$) obtained from the HYDJET++ model and STAR data [17], fitted with a constant function for various centrality bins.

Centrality	$\bar{D}^0/D^0$ (HYDJET++)	$\bar{D}^0/D^0$ (STAR)
0–10%	0.953 ± 0.0023	1.104 ± 0.021
10–20%	0.949 ± 0.0024	1.071 ± 0.019
20–40%	0.949 ± 0.0026	1.060 ± 0.015
40–60%	0.956 ± 0.0049	1.073 ± 0.022
60–80%	0.949 ± 0.0065	0.943 ± 0.039

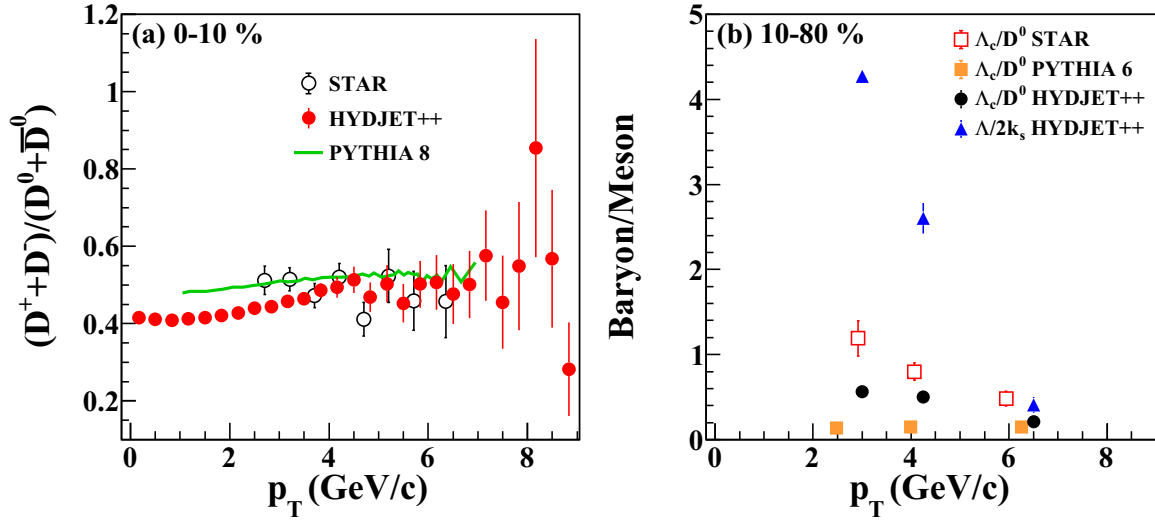


FIG. 10. (a) $D^\pm/(D^0 + \bar{D}^0)$ ratio for the 0–10 % centrality as a function of p_T at midrapidity ($|y| < 1$) in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV obtained from the HYDJET++ model and compared with data from STAR measurements [23] along with PYTHIA 8 results [94]. Open markers represent data from STAR measurements, while closed markers indicate results from the HYDJET++ model. The green line shows the PYTHIA 8 result [94]. (b) The baryon-to-meson ratio for the 10–80 % centrality class as a function of p_T at midrapidity ($|y| < 1$) in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, obtained from the HYDJET++ model and compared with data from STAR measurements [95]. Blue and black markers show the $\Lambda/2K_s$ and Λ_c/D^0 ratio from the HYDJET++ model, while orange markers show the results from PYTHIA 6 [65].

to peripheral collisions. Furthermore, p_T spectra indicate that heavy hadrons experience earlier kinetic freezeout than light hadrons due to their larger mass. Additionally, the nuclear modification factors (R_{AA} and R_{CP}) as a function of p_T for D^0 mesons are consistent with experimental measurements. In the R_{AA} and R_{CP} results, significant suppression is observed in central collisions compared to peripheral collisions, which is consistent with experimental findings. The suppression at high p_T confirms the dominance of radiative energy loss mechanisms, while the suppression at low p_T is attributed to collective effects, such as radial flow. Comparisons of HYDJET++ results with other theoretical models, such as TAMU, SUBATECH, and Duke, show reasonable agreement in most cases, except at low p_T . At low p_T , the results from HYDJET++ and the Torino model follow a similar trend, as both models omit the coalescence mechanism. The study of antiparticle-to-particle ratios demonstrates that the model results are consistent with experimental data, reaffirming the chemical potential within the QGP medium. Additionally, the $D^\pm/(D^0 + \bar{D}^0)$ yield ratio in most central collisions aligns well with experimental data and PYTHIA 8 at high p_T , indicating similar suppression and hadronization processes in both Au + Au and p + p collisions. Further, the baryon-to-meson ratio for heavy hadrons follows a similar trend as observed for light hadrons and experimental data, but underestimates the observed values from the STAR experiment due to the absence of heavy quark coalescence within the HYDJET++ model. This underestimation highlights the importance of incorporating coalescence mechanisms into theoretical models to improve their ability to describe baryon production in the QGP.

Overall, this study demonstrates the capability of the HYDJET++ model to describe the production of charm

hadrons, centrality dependence, R_{AA} and R_{CP} behavior, antiparticle-to-particle ratios, and baryon-to-meson ratios in heavy-ion collisions. However, the overprediction at high p_T indicates the need for further improvements in modeling energy loss mechanisms. We plan to address this by incorporating a dynamically evolving QCD medium, specifically by replacing the preset freezeout parametrization with a hydrodynamic module that evolves temperature, flow, and density with time. Additionally, PYTHIA 8 could also be adopted for more realistic modeling of the hard parton production in the initial stage. These findings motivate future investigations into other QGP signals, including elliptic flow, which will be the focus of our next work. This study also encourages further exploration of heavy quarkonia, such as J/ψ , ψ' , and χ_c , by readjusting the charm enhancement factor (γ_c) in the HYDJET++ model at RHIC and LHC energies. The study of quarkonia production might provide deeper knowledge of the dynamics of heavy quarks in the QGP medium and enhance our understanding of jet quenching and other in-medium effects.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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