

System-size dependence of the D^0 - D_s^+ flow splitting from early D_s^+ formation at $\sqrt{s_{NN}} = 5.36$ TeV

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We investigate the elliptic-flow splitting between prompt D^0 and D_s^+ mesons within a heavy-quark transport framework with sequential hadronization, in which D_s^+ forms at $1.2 T_c$ and D^0 at T_c . We present model calculations for the p_T -differential v_2 and predictions for the D_s^+/D^0 yield ratio in O-O 0–20% collisions at $\sqrt{s_{NN}} = 5.36$ TeV, where preliminary ALICE data are available. The sequential scenario reproduces the observed $v_2(D^0) > v_2(D_s^+)$ ordering and predicts an enhanced D_s^+/D^0 ratio at low p_T , whereas a simultaneous baseline yields the opposite ordering. Decomposing the hadronic splitting into its partonic components, we show that the v_2 ordering is driven by the late-stage flow accumulated by D^0 -parent charm quarks during the $1.2 T_c \rightarrow T_c$ interval, with hadronic rescattering essential to preserve the signal in small systems. A systematic scan across nine collision configurations spanning O-O and Pb-Pb centralities reveals a universal linear scaling between the hadronic splitting and the partonic flow increment accumulated during this window. This establishes the D^0 - D_s^+ flow splitting as a hadronization chronometer of the QGP at $\sqrt{s_{NN}} = 5.36$ TeV.

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I. INTRODUCTION

The production of heavy-flavor hadrons in ultrarelativistic heavy-ion collisions offers a calibrated probe of the hadronization mechanism in the quark-gluon plasma (QGP) [1]. Among open-charm mesons, the comparison between D^0 and D_s^+ is informative. The D_s^+/D^0 yield ratio is significantly enhanced in nucleus-nucleus collisions relative to proton-proton and proton-nucleus collisions, as established

by the ALICE Collaboration in Pb-Pb measurements at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV [2,3]. This enhancement arises because the abundant strangeness produced in the deconfined medium enables charm quarks to form D_s^+ via coalescence with thermal strange quarks, a channel that is presumed to be negligible in proton-proton collisions [2–4]. Coalescence-plus-fragmentation model calculations predict a monotonic increase in the D_s^+/D^0 ratio with increasing system size, from small to large collision systems [4,5]. A systematic scan across collision systems—from small O-O to large Pb-Pb—is essential to isolate the hadronization dynamics from system-specific initial geometry and lifetime effects.

Alongside the yield enhancement phenomenon, a characteristic ordering has emerged recently in the elliptic flow observable of charmed mesons: ALICE measurements in Pb-Pb collisions reveal $v_2(D_s^+) < v_2(D^0)$ at intermediate transverse momentum (p_T) [6]. In most phenomenological approaches, all charmed hadrons are assumed to form on a

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single universal freezeout hypersurface at the critical temperature T_c [7–24]. Within this simultaneous-hadronization framework, however, coalescence kinematics favor the opposite ordering. Owing to the distinct thermal momentum distributions of strange and light quarks, the phase-space selection inherent to the recombination process preferentially picks charm quarks with larger v_2 to form D_s^+ mesons, leading to $v_2(D_s^+) > v_2(D^0)$ —in direct contradiction with the experimental observations. Resolving this ordering reversal is therefore a challenge for heavy-flavor hadronization theory.

An alternative paradigm is provided by the sequential hadronization scenario [25,26]. Based on the distinct binding energies of heavy-flavor hadrons obtained by solving the Dirac equation with an in-medium lattice potential [25,27], we predicted that D_s^+ mesons are to form on an earlier hypersurface, presumably at $T \simeq 1.2 T_c$, while D^0 and other charmed hadrons freeze out later at T_c . This time separation defines a finite late-stage evolution window, $\Delta\tau_{\text{had}}$, during which the parent charm quarks destined for D^0 continue to accumulate momentum anisotropy from the expanding bulk medium. The natural consequence is $v_2(D_s^+) < v_2(D^0)$, with the splitting magnitude governed by the duration of the $1.2 T_c \rightarrow T_c$ cooling phase. Our earlier analysis of Pb-Pb collisions at 30–50 % centrality identified this very signal and demonstrated quantitative agreement with ALICE data within the sequential framework [28]. While this earlier study established the viability of the sequential scenario in Pb-Pb, the microscopic mechanism—how the partonic flow increment during $\Delta\tau_{\text{had}}$ translates into the hadronic v_2 reversal, and how this picture survives when the time window is compressed—remains to be fully dissected.

O-O collisions, with their far shorter QGP lifetime, provide a particularly stringent test of whether the sequential-hadronization picture holds across system sizes: they probe whether signatures of distinct hadronization timescales survive when the late-stage evolution window is severely compressed [29,30]. The recent availability of ALICE Run-3 O-O collision data at $\sqrt{s_{NN}} = 5.36$ TeV [31] now makes this test possible. The preliminary data reveal that $v_2(D_s^+) < v_2(D^0)$ indeed persists in O-O, albeit with a markedly smaller magnitude than in Pb-Pb. These observations motivate a comprehensive investigation that dissects the microscopic origin of the v_2 ordering and maps its dependence on system size.

The present work is driven by two interconnected goals. First, we aim to uncover the microscopic mechanism by which sequential hadronization generates the observed $v_2(D^0) > v_2(D_s^+)$ ordering, and to contrast it with the reversed baseline expected from simultaneous coalescence kinematics. Second, by systematically scanning collision systems from O-O to Pb-Pb, we identify the experimental conditions—system size and centrality—under which the sequential-hadronization signal is maximized. Toward these ends, we compare our calculated p_T -differential v_2 with the preliminary ALICE data and present predictions for the D_s^+/D^0 yield ratio in O-O 0–20 % collisions, contrast the sequential and simultaneous scenarios against preliminary ALICE data, and compare the splitting across O-O and Pb-Pb systems. In Sec. IV, we decompose the hadronic flow splitting into its partonic components by examining the parent charm-quark v_2 at the

$1.2 T_c$ and T_c hypersurfaces in both O-O and Pb-Pb systems, isolating the roles of coalescence kinematics, fragmentation mixing, and hadronic rescattering. Finally, in Sec. V, we perform a systematic scan across nine collision configurations spanning O-O and Pb-Pb and test whether the hadronic splitting obeys a universal linear scaling with the partonic flow increment accumulated during the sequential-hadronization window, establishing the D^0 – D_s^+ splitting as a chronometer of the late-stage QGP evolution.

II. THEORETICAL FRAMEWORK

In this section, we present the multistage theoretical framework employed to simulate the heavy-quark evolution and hadronization. The framework integrates initial state generation, (3 + 1)-dimensional [(3 + 1)D] viscous hydrodynamic expansion, an improved Langevin transport approach, and a hybrid hadronization scheme.

A. Initial conditions of the O-O system and hydrodynamic description

The space-time evolution of the bulk medium is simulated by coupling an initial-state generator with (3 + 1)D relativistic viscous hydrodynamics. For the initial geometry, we employ the T_RENTo model [32]. For the O-O system, the nucleonic density profiles are taken from the projected generator coordinate method (PGCM) configurations in Ref. [30] to account for the intrinsic α -clustering structure of the oxygen nucleus.

Within the T_RENTo framework, the initial entropy density is deposited proportionally to the reduced thickness, constructed from the participant nuclear thickness functions. Each thickness function is modeled as a superposition of fluctuating Gaussian nucleons with an effective width w , and subnucleonic multiplicity fluctuations are incorporated by independently sampling the weight of each nucleon from a Gamma distribution with shape parameter k . We set $k = 1.5$ and $w = 0.43$ fm. The initial condition used in this work is constructed from a two-dimensional transverse profile supplemented by a longitudinal envelope function. Specifically, the transverse entropy-density distribution in the x – y plane is generated with the T_RENTo model, while the rapidity dependence is introduced through a plateau-plus-Gaussian-tail envelope in the longitudinal direction. We employ a smooth one-shot initialization: for each centrality class, 2000 independent T_RENTo events are generated and averaged in the transverse plane to obtain a smooth initial entropy-density profile, which is then used for the subsequent hydrodynamic evolution.

The hydrodynamic expansion of the QGP is described by the (3 + 1)D CLVisc framework [33,34], starting at an initial proper time $\tau_0 = 0.6$ fm/c. The equation of state is taken from the HotQCD2014 lattice result [35]. The medium’s dissipative properties are parametrized by temperature-dependent shear and bulk viscosities. For the shear viscosity, $\eta/s(T)$ maintains a minimum of 0.08 in the high-temperature phase and increases linearly below $T_c = 0.154$ GeV. For the bulk viscosity, $\zeta/s(T)$ is parametrized as a skewed double-exponential

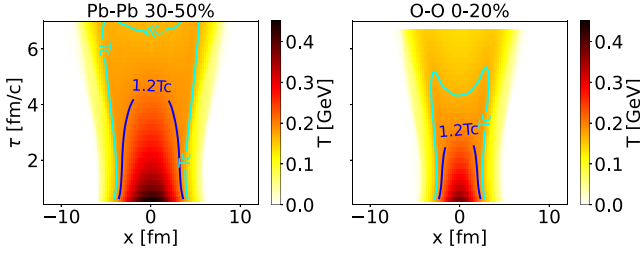


FIG. 1. Spatial profiles of the isothermal hypersurfaces at $T = 1.2 T_c$ (blue) and $T = T_c$ (cyan) in the τ - x plane, evaluated at midrapidity for O-O 0–20 % (right) and Pb-Pb 30–50 % (left) collisions. The separation between the two hypersurfaces 30–50 % defines the late-stage evolution window probed by the sequential hadronization scenario.

peak centered at T_c , whose shape and magnitude were determined through Bayesian model-to-data comparisons [36,37]. The hydrodynamic evolution continues until the system cools below the freezeout hypersurface, which defines the spacetime boundary at which heavy-flavor hadronization takes place. In the sequential hadronization scenario, however, D_s^+ mesons are formed on an earlier hypersurface at $T \simeq 1.2 T_c$, while D^0 mesons freeze out at T_c . Figure 1 illustrates this geometry by comparing the isothermal contours at $T = 1.2 T_c$ and $T = T_c$ in the τ - x plane for both O-O and Pb-Pb collisions. The figure highlights two distinct sources of system-size dependence: the overall space extent differs between the two collision systems, and within each system the time interval between the two hypersurfaces provides the late-stage evolution window that drives the D_s^+ - D^0 flow splitting, as will be quantified in Secs. III–V.

B. Heavy quark transport

The space-time evolution of charm quarks within the dynamically expanding QGP is described by a Langevin approach that accounts for both quasi-elastic scattering and radiative energy loss [15,38,39]. To initialize this evolution, the space coordinates of charm quarks are sampled according to the binary nucleon-nucleon collision (N_{coll}) profile, while their initial momentum spectra are taken from fixed-order-plus-next-to-leading-logarithms (FONLL) calculations [40]. To account for cold nuclear matter effects in the O-O system, the EPPS21 nuclear parton distribution functions (nPDFs) [41] are explicitly incorporated, which yield a sizable shadowing suppression of the initial charm-quark production cross section at low p_T . The numerical simulation tracks these heavy quarks as they propagate through the hydrodynamic cells provided by the CLVisc background. For a charm quark with energy $E = \sqrt{p^2 + M^2}$, the updates of its space coordinates x_j and momentum p_j in each time step dt are described by the following set of equations [39,42–45]:

$$dx_j = \frac{p_j}{E} dt, \quad (1)$$

$$dp_j = -\Gamma p_j dt + \sqrt{\kappa dt} \rho_j - \vec{p}_g, \quad (2)$$

where the terms on the right-hand side of the momentum update represent the deterministic drag force, the stochastic

thermal force, and the momentum change due to radiated gluons, respectively. These Langevin equations are implemented in the local rest frame of the background fluid. At each time step, the charm-quark momentum is boosted to the local fluid rest frame before the Langevin update and boosted back to the laboratory frame afterward.

In this formulation, Γ is the drag coefficient and κ denotes the momentum diffusion coefficient. The stochastic variable ρ_j represents an independent Gaussian noise following a normal distribution with zero mean and unit variance, satisfying $\langle \rho_j \rangle = 0$ and $\langle \rho_j(t) \rho_k(t') \rangle = \delta_{jk} \delta_{tt'}$. The drag and diffusion coefficients are intrinsically linked through the fluctuation-dissipation relation, $\kappa = 2\Gamma E T$ [46], which is further related to the spatial diffusion coefficient of charm quarks via $D_s = 2T^2/\kappa$. Guided by 2+1 flavor lattice QCD calculations [47,48] and taking the parameters from previous Pb-Pb studies [28,45] as a reference benchmark, we vary the spatial diffusion coefficient around a comparable baseline, setting $2\pi T D_s = 2.1 \pm 0.4$ for the O-O system, and treat it as temperature-independent. In the present implementation, the momentum diffusion coefficient κ is taken to be momentum independent and is related to the spatial diffusion coefficient D_s through $\kappa = 2T^2/D_s$. Since the lattice QCD input for D_s is the static, momentum-independent value, κ is correspondingly momentum independent. The drag coefficient Γ , however, acquires a momentum dependence through the fluctuation-dissipation relation $\kappa = 2\Gamma E T$, where $E = \sqrt{m^2 + p^2}$. Thus the collisional part of the Langevin evolution has a momentum-independent diffusion term and a momentum-dependent drag term. The additional radiative term $-\vec{p}_g$ in Eq. (3) accounts for high- p_T gluon radiation and is intrinsically momentum dependent.

The term $-\vec{p}_g$ accounts for the recoil momentum exerted on the heavy quark during each gluon radiation event. The radiation process is implemented based on the medium-induced gluon distribution within the higher-twist approach [38,49–52]:

$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_s P(x) \hat{q}}{\pi k_\perp^4} \sin^2 \left(\frac{t - t_i}{2\tau_f} \right) \left[\frac{k_\perp^2}{k_\perp^2 + (xM)^2} \right]^4, \quad (3)$$

where x and $k_\perp$ denote the energy fraction and transverse momentum of the emitted gluon, α_s is the strong coupling constant, C_s is the quadratic Casimir in color representation, $P(x)$ is the vacuum splitting function [53], and $\tau_f = 2Ex(1-x)/[k_\perp^2 + (xM)^2]$ is the formation time. The jet quenching parameter is parametrized as $\hat{q} = \hat{q}_0(T^3/T_c^3)(p_\mu u^\mu/p^0)$. Guided by previous Pb-Pb studies [28,54], we set the quenching strength for the O-O system to $\hat{q}_0 = 1.4 \pm 0.3 \text{ GeV}^2/\text{fm}$, where the variation range explicitly accounts for systematic uncertainties when extrapolating the transport framework to smaller collision volumes. For Pb-Pb collisions, the central values of the transport parameters are taken from our previous study [28,45], whereas the uncertainty bands are shown only for the O-O system.

After hadronization, the formed D mesons undergo rescattering in the hadronic phase. This stage is also described by a Langevin equation, with a temperature-dependent spatial diffusion coefficient for D -meson interactions with the

light-flavor hadron gas [18,55,56]. The hadronic rescattering continues until the system reaches a fixed kinetic freezeout temperature of 137 MeV [33].

The elliptic-flow coefficient is evaluated from the azimuthal distribution of particles relative to the event plane,

$$v_2(p_T) = \langle \cos[2(\phi - \Psi_{EP})] \rangle_{p_T} = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle_{p_T}. \quad (4)$$

Here, ϕ denotes the azimuthal angle of each particle, and Ψ_{EP} is the event-plane angle determined from the initial-state geometry. The x axis is aligned with Ψ_{EP} . The same definition is used for final charmed hadrons and for the parent charm quarks shown in Fig. 6.

C. Hadronization

This section describes the hadronization of charm quarks into charmed hadrons via a hybrid coalescence-plus-fragmentation model [10,11,57]. Charm quarks first hadronize through coalescence with thermal light and strange quarks at the hadronization hypersurface; those that do not coalesce are subsequently converted via fragmentation. The momentum distribution of hadrons produced from quark coalescence is given by

$$\begin{aligned} \frac{dN}{d^3\mathbf{P}} &= g_H \int \prod_{i=1}^n \frac{d^3x_i d^3p_i}{(2\pi)^3 E_i} f_i(\mathbf{x}_i, \mathbf{p}_i) \\ &\times W_h(\mathbf{x}_1, \dots, \mathbf{x}_n, \mathbf{p}_1, \dots, \mathbf{p}_n) \delta^{(3)}\left(\mathbf{P} - \sum_{i=1}^k \mathbf{p}_i\right), \end{aligned} \quad (5)$$

where i indexes the constituent quarks and g_H is the spin-color degeneracy factor. The phase-space distribution $f_i(x_i, p_i)$ of each constituent quark is evaluated at the hadronization hypersurface. For thermal light quarks, a thermal distribution is taken, $f_q(x_i, p_i) = N_q / (e^{u_\mu p_i^\mu / T} + 1)$ with degeneracy $N_q = 6$.

The Wigner function W_h represents the probability density for the parton pair to form a specific hadron state. Taking charmed mesons as an example, the phase-space Wigner functions for the specific wave states involved in this model read [58–60]:

$$\begin{aligned} W_{1S}(\mathbf{r}, \mathbf{p}) &= 8e^{-\xi}, \\ W_{1P}(\mathbf{r}, \mathbf{p}) &= \frac{8}{3}e^{-\xi}(2\xi - 3), \\ W_{1D}(\mathbf{r}, \mathbf{p}) &= \frac{8}{15}e^{-\xi}(15 + 4\xi^2 - 20\xi + 8\eta), \\ W_{2S}(\mathbf{r}, \mathbf{p}) &= \frac{8}{3}e^{-\xi}(3 + 2\xi^2 - 4\xi - 8\eta), \\ W_{2P}(\mathbf{r}, \mathbf{p}) &= \frac{8}{15}e^{-\xi}(-15 + 4\xi^3 - 22\xi^2 + 30\xi \\ &\quad - 8(2\xi - 7)\eta), \end{aligned} \quad (6)$$

where we define $\xi \equiv r^2/\sigma^2 + p^2\sigma^2$ and $\eta \equiv p^2r^2 - (\mathbf{p} \cdot \mathbf{r})^2$. Here, $\mathbf{r}$ and $\mathbf{p}$ denote the relative coordinate and relative momentum of the two constituent quarks in their center-of-mass (CM) frame. For charmed mesons, the relative momentum is

given by:

$$\mathbf{p} = \frac{m_l \mathbf{p}_c - m_c \mathbf{p}_l}{m_l + m_c}. \quad (7)$$

The Gaussian width parameter σ encoding the spatial extension of the wave function is determined by the average radius of the meson:

$$\langle r \rangle = \int \frac{d^3r d^3p}{(2\pi)^3} W_h(\mathbf{r}, \mathbf{p}) r. \quad (8)$$

The averaged radius of the ground state for charmed mesons and baryons is calculated by solving the Dirac equation with a lattice quark potential [25,27]. To simplify the subsequent calculations, we integrate out the coordinate-space degrees of freedom from the Wigner function and retain only the momentum-space distribution in this study. The coalescence probabilities of various charmed hadrons are evaluated in a thermal box at a given temperature using a formula analogous to Eq. (5), with the charm-quark distribution approximated by a delta function $\delta^{(3)}(\mathbf{p} - \mathbf{p}_c)$.

Based on the distinct binding energies of heavy-flavor hadrons, we implement a sequential hadronization scenario governed by the temperature ordering [25]:

$$T_{D_s} \simeq 1.2T_c > T_{D^0}, \quad T_{\Omega_c}, \quad T_{\Xi_c}, \quad T_{\Lambda_c} \simeq T_c. \quad (9)$$

In this approach, when a charm quark with momentum p (determined by the Langevin evolution) reaches the earlier coalescence hypersurface at T_{D_s} , its probability P_{D_s} to form a D_s^+ meson is computed from the coalescence integral, Eq. (5), evaluated at that hypersurface. If coalescence occurs, the charm quark hadronizes into D_s^+ and exits the partonic evolution. If not, it continues to transport through the QGP until reaching the T_c hypersurface, where it undergoes a second coalescence stage into other charmed hadrons, with the available probability rescaled by $1 - P_{D_s}$.

After these two coalescence stages at T_{D_s} and T_c , if the charm quark still survives, it hadronizes via fragmentation. The momentum distribution of the final-state hadron is then governed by the Peterson fragmentation function [61]:

$$\mathcal{D}_{c \rightarrow H}(z) \propto \frac{1}{z \left(1 - \frac{1}{z} - \frac{\epsilon}{1-z}\right)^2}, \quad (10)$$

where z is the momentum fraction of the charmed hadron fragmented from the parent charm quark. We adopt $\epsilon = 0.01$ for charmed mesons and $\epsilon = 0.02$ for charmed baryons [23]. The relative fragmentation fractions of a charm quark into various specific charmed hadrons are constrained by experimental data from $p + p$ collisions [62].

The sequential formation temperatures used here apply to the heavy-flavor sector. Light-flavor hadrons may also exhibit formation-temperature differences in lattice QCD calculations, but the effect is expected to be much weaker than for heavy-flavor states because of their smaller binding-energy splittings and is not included in the present study [63].

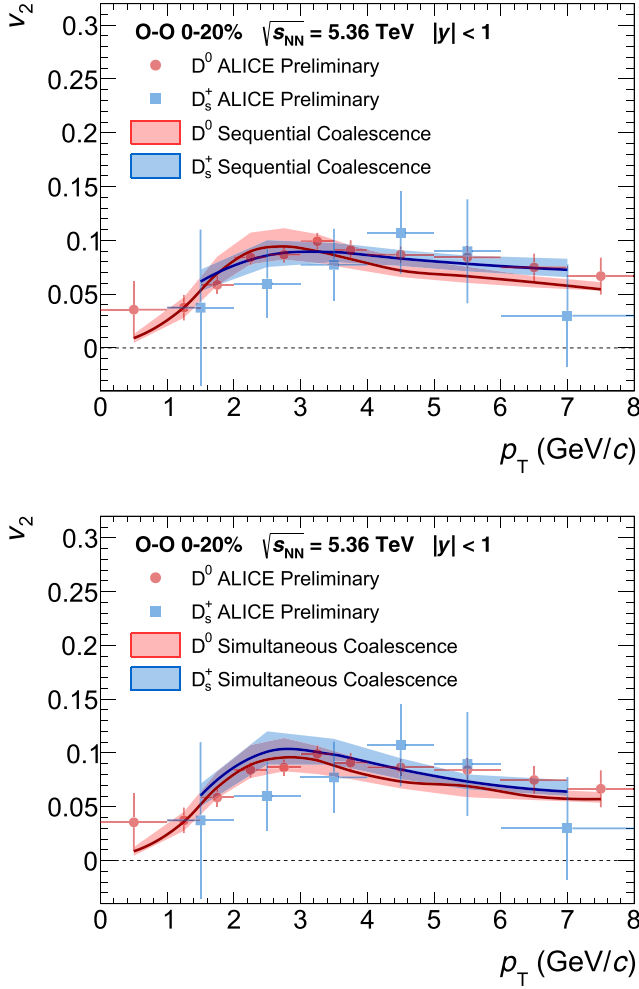


FIG. 2. Elliptic flow v_2 of prompt D^0 and D_s^+ as a function of p_T in 0–20% central O–O collisions at $\sqrt{s_{NN}} = 5.36$ TeV. Bands reflect variations of $2\pi T D_s = 2.1 \pm 0.4$ and $\hat{q}_0 = 1.4 \pm 0.3$ GeV²/fm; solid lines show central values. Top and bottom panels correspond to the sequential and simultaneous hadronization scenarios, respectively.

III. PREDICTIONS FOR O-O COLLISIONS AND SYSTEM-SIZE COMPARISON

We present theoretical calculations for the p_T -differential v_2 of prompt D^0 and D_s^+ mesons and predictions for their yield ratio in 0–20% central O–O collisions at $\sqrt{s_{NN}} = 5.36$ TeV, and compare the calculated v_2 with preliminary ALICE data.

Figure 2 (top panel) presents the p_T -differential v_2 of prompt D^0 and D_s^+ mesons calculated within the sequential hadronization scenario. The calculations reproduce the $v_2(D^0) > v_2(D_s^+)$ ordering observed in the data at intermediate p_T , with the theoretical uncertainty bands—reflecting variations of $2\pi T D_s = 2.1 \pm 0.4$ and $\hat{q}_0 = 1.4 \pm 0.3$ GeV²/fm—in good overall agreement with the measurements. In the sequential scenario, D_s^+ mesons freeze out on the earlier $T \simeq 1.2 T_c$ hypersurface with less accumulated momentum anisotropy, while D^0 -parent charm quarks continue to acquire v_2 throughout the $1.2 T_c \rightarrow T_c$ cooling phase,

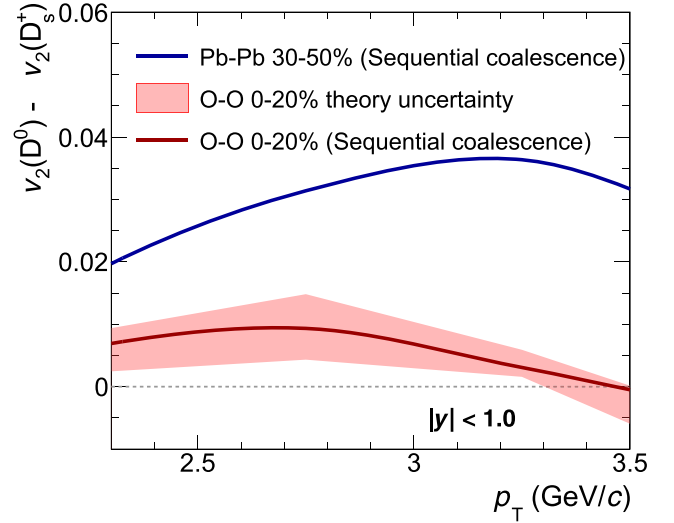


FIG. 3. Hadronic flow splitting $v_2(D^0) - v_2(D_s^+)$ as a function of p_T within the sequential hadronization framework, comparing 0–20% O–O at $\sqrt{s_{NN}} = 5.36$ TeV and 30–50% Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV collisions. The solid line and shaded band show the central prediction and theoretical uncertainty for O–O.

naturally producing the correct ordering even within the short-lived QGP of O–O collisions.

Figure 2 (bottom panel) presents the simultaneous scenario, in which both species are forced to form at T_c . While the D^0 v_2 remains well described, the predicted D_s^+ v_2 deviates noticeably from the data, yielding an inverted $v_2(D_s^+) > v_2(D^0)$ ordering at $p_T \lesssim 4$ GeV/c. Without the earlier D_s^+ freezeout, the coalescence phase space preferentially selects charm quarks with larger v_2 to form D_s^+ mesons—a kinematic bias that drives the reversed ordering. The fact that only the sequential scenario reproduces the data indicates that the time separation between the two hadronization hypersurfaces is the essential ingredient for describing heavy-flavor flow in O–O collisions. If the v_2 splitting is controlled by the duration of the $1.2 T_c \rightarrow T_c$ window, its magnitude should be sensitive to the fireball lifetime, which varies with system size. We quantify this dependence in Fig. 3, which compares the hadronic flow splitting $v_2(D^0) - v_2(D_s^+)$ from the sequential scenario for O–O (0–20%) and Pb–Pb (30–50%) collisions. The peak Δv_2 in Pb–Pb is substantially larger than in O–O, reflecting the extended QGP lifetime in the heavier system. In the shorter-lived O–O system, the late-stage accumulation is compressed, yielding a reduced but still positive Δv_2 .

In this comparison, the Pb–Pb result uses the central values of the transport parameters from our previous study [28,45], while an uncertainty band is introduced for O–O to account for extrapolation of the transport coefficients to a smaller collision system. The positive Δv_2 persists across the explored parameter range, confirming that the sequential signal survives even under the compressed conditions of small systems. This sensitivity to the macroscopic space-time scale demonstrates that Δv_2 directly reflects the late-stage QGP evolution.

Figure 4 shows the D_s^+/D^0 yield ratio as a function of p_T for O–O and Pb–Pb collisions under both hadronization

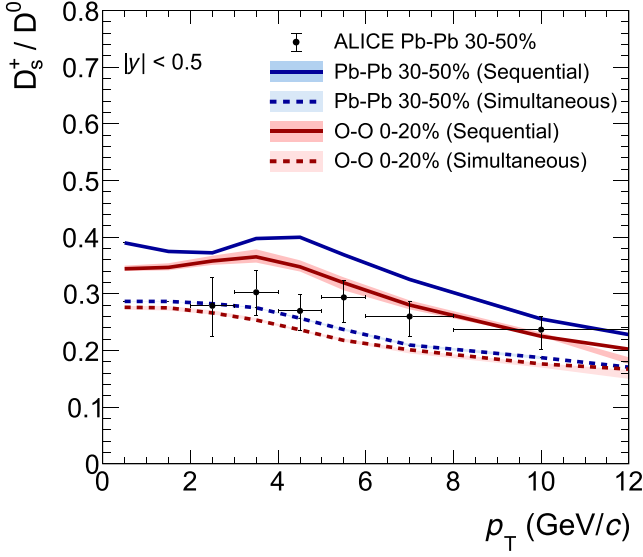


FIG. 4. D_s^+/D^0 yield ratio as a function of p_T in 0–20% O-O at $\sqrt{s_{NN}} = 5.36$ TeV and 30–50% Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV, shown for both the sequential and simultaneous hadronization scenarios.

scenarios. In both systems, the sequential scenario yields a larger D_s^+/D^0 ratio than the simultaneous scenario at low p_T . Comparing the two systems, the D_s^+/D^0 ratio is systematically higher in Pb-Pb than in O-O across the full p_T range.

The enhancement of the D_s^+/D^0 ratio in the sequential scenario reflects the higher coalescence probability for D_s^+ on the earlier $1.2 T_c$ hypersurface, where the strange-quark phase-space density is larger than at T_c . The systematic increase from O-O to Pb-Pb is driven by the stronger partonic energy loss in the heavier system, which shifts the parent charm-quark spectrum to lower p_T and thereby enhances the coalescence probability at the $1.2 T_c$ hypersurface. Together with the v_2 results discussed above, these trends demonstrate that the hadronization scheme and the collision system size jointly govern both the kinematic and chemical properties of open-charm hadrons.

IV. PARTONIC ORIGIN OF THE FLOW SPLITTING

To identify the partonic origin of the D^0 – D_s^+ flow splitting, we examine the dynamics at the level of the parent charm quarks prior to hadronization. The key quantity is the time separation between the two formation hypersurfaces, $\Delta\tau_{\text{had}} = \langle\tau_{D^0}\rangle - \langle\tau_{D_s^+}\rangle$, extracted from the sequential hadronization scenario.

Figure 5 illustrates the transverse-momentum (p_T) dependence of $\Delta\tau_{\text{had}}$, evaluated across nine distinct configurations encompassing various centrality classes in both Pb-Pb and O-O collisions. The calculations reveal a pronounced sensitivity to the system size, event centrality, and p_T . Specifically, $\Delta\tau_{\text{had}}$ is maximized at low p_T and exhibits a monotonic decrease toward higher p_T . Macroscopically, this time difference reflects the overall lifetime of the dynamically expanding fireball; in midcentral Pb-Pb collisions, $\Delta\tau_{\text{had}}$ reaches 2–3 fm/c at low

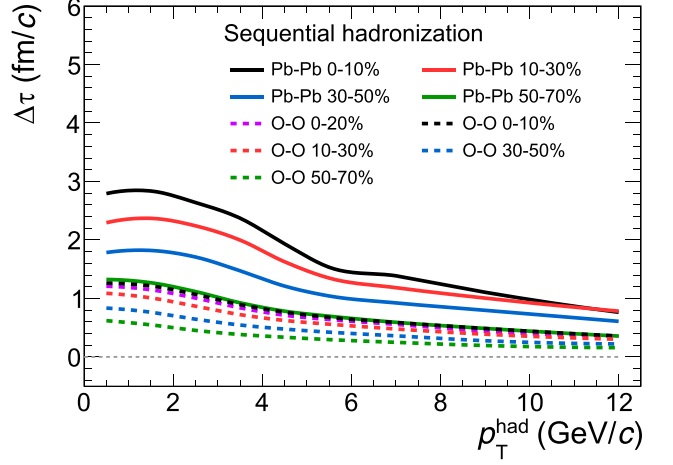


FIG. 5. Average hadronization time difference $\Delta\tau_{\text{had}} = \langle\tau_{D^0}\rangle - \langle\tau_{D_s^+}\rangle$ as a function of hadronic p_T^{had} , extracted from the sequential hadronization scenario across nine collision configurations in Pb-Pb and O-O systems.

p_T , whereas the rapid expansion characteristic of the smaller O-O systems significantly compresses this temporal window. Physically, this finite $\Delta\tau_{\text{had}}$ corresponds to the macroscopic cooling interval between the $T = 1.2 T_c$ and $T = T_c$ hypersurfaces. During this extended late-stage evolution, the parent charm quarks of the D^0 mesons continue to scatter within the hydrodynamically expanding medium, thereby accumulating additional momentum anisotropy. We demonstrate that this late-time partonic flow acquisition is the fundamental driver of the observed hadronic flow splitting, $\Delta v_{2,\text{had}} \equiv v_{2,\text{had}}(D^0) - v_{2,\text{had}}(D_s^+)$.

Figure 6 displays the partonic v_2 of parent charm quarks ($v_{2,c}$) in the coalescence channel evaluated just before hadronization. In the sequential scenario (top panel), D_s^+ parent charm quarks (red) freeze out earlier at $1.2 T_c$ with less accumulated $v_{2,c}$, while those destined for D^0 (blue) continue to gain anisotropy down to T_c , yielding $v_{2,c}(D^0) > v_{2,c}(D_s^+)$ in both Pb-Pb and O-O. In the simultaneous limit (bottom panel), coalescence phase-space selection instead produces $v_{2,c}(D_s^+) > v_{2,c}(D^0)$; the sequential time separation must therefore supply sufficient partonic flow to overcome this inverted baseline [19,64].

Beyond the coalescence channel, a fraction of charm quarks hadronize via fragmentation. The partonic $v_{2,c}$ inherited through fragmentation is substantially smaller than that from coalescence, and is identical between the sequential and simultaneous scenarios because fragmentation occurs at the same T_c hypersurface in both schemes. The parent charm $v_{2,c}$ is therefore a mixture of the two contributions. Since D_s^+ has a higher final state coalescence contribution fraction than D^0 , the total parent-charm $v_{2,c}$ of D^0 receives a larger suppression from the low- $v_{2,c}$ fragmentation component than that of D_s^+ . Due to this complication, the parton-level $v_{2,c}$ gap between D^0 and D_s^+ parent charm quarks is further narrowed in Pb-Pb collisions. In O-O collisions, where the $1.2 T_c \rightarrow T_c$ window is severely compressed, the contribution mixing can even invert the partonic ordering, risking

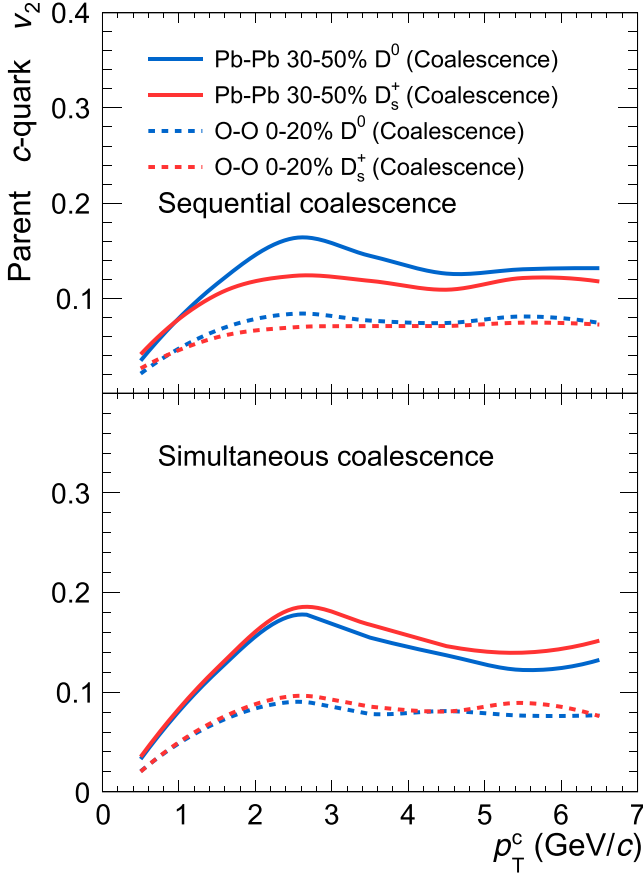


FIG. 6. Elliptic flow $v_{2,c}$ of parent charm quarks immediately before hadronization as a function of partonic p_T^c , for Pb-Pb 30–50 % (solid) and O-O 0–20 % (dotted) collisions. Top and bottom panels correspond to the sequential and simultaneous hadronization scenarios, respectively. Red and blue curves correspond to charm quarks destined for D_s^+ and D^0 , respectively.

$v_{2,c}(D_s^+) > v_{2,c}(D^0)$ at the parton level. The hadronic rescattering phase, in which D^0 acquires a larger v_2 boost than D_s^+ , is therefore essential to restore the $v_2(D^0) > v_2(D_s^+)$ ordering in small systems.

This rescattering phase at the hadron level means: D^0 mesons, with their larger hadronic cross sections, acquire an additional positive v_2 boost relative to D_s^+ . Since this hadronic amplification is proportional to the partonic flow increment acquired during $1.2T_c \rightarrow T_c$, it acts as a dynamical amplifier that steepens the correlation between the final hadronic splitting and the late-stage partonic accumulation, as will be quantified in Sec. V. Taking into account all these effects, we choose the D^0 -parent increment rather than the difference $v_{2,c}(D^0) - v_{2,c}(D_s^+)$ because the latter is contaminated by the coalescence phase-space baseline and by species-dependent fragmentation mixing, whereas the former isolates the flow accumulated solely during the sequential-hadronization window. In the subsequent mechanism study, we therefore adopt the partonic v_2 increment $\Delta v_{2,c}$ accumulated by D^0 parent charm quarks during the $1.2T_c \rightarrow T_c$ interval as a proxy for the effective evolution time difference between the two hadronization hypersurfaces.

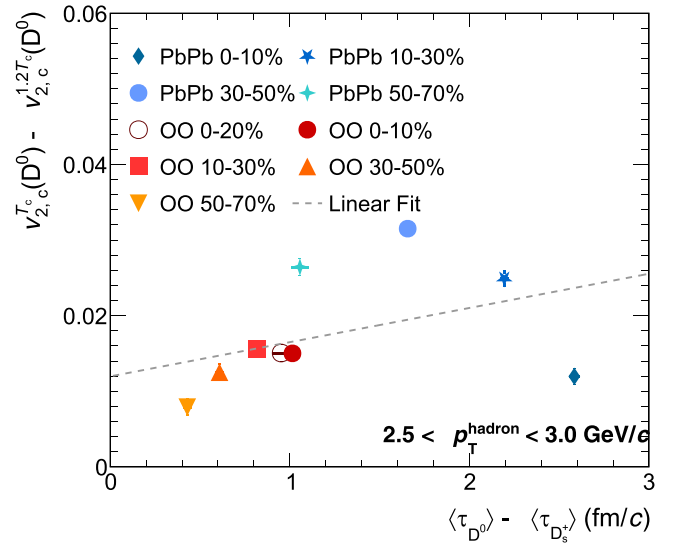


FIG. 7. Partonic flow increment $\Delta v_{2,c}$ accumulated by parent charm quarks during $1.2T_c \rightarrow T_c$ as a function of $\Delta\tau_{\text{had}}$, integrated over $2.5 < p_T^{\text{had}} < 3.0$ GeV/c. Data points correspond to nine collision configurations—Pb-Pb 0–10 %, 10–30 %, 30–50 %, 50–70 %, and O-O 0–10 %, 10–30 %, 30–50 %, 50–70 %, together with O-O 0–20 %—all evaluated under the sequential scenario.

V. UNIVERSAL SCALING OF LATE-STAGE EVOLUTION

The preceding analysis establishes that $\Delta\tau_{\text{had}}$ is the primary driver behind the D^0 - D_s^+ flow splitting. To test whether this connection is universal, we perform a systematic scan across nine LHC collision configurations at 5.36 TeV—spanning Pb-Pb and O-O centralities—all evaluated under the sequential hadronization scenario. We examine whether the hadronic flow splitting and the partonic flow increment obey a common scaling relation across this wide range of system sizes and initial geometries. All observables in this section are integrated over the transverse momentum window $2.5 < p_T^{\text{had}} < 3.0$ GeV/c, which corresponds to the intermediate- p_T region where coalescence is the dominant hadronization channel and the D^0 - D_s^+ flow splitting is most pronounced.

Figure 7 shows $\Delta v_{2,c}$ as a function of $\Delta\tau_{\text{had}}$ for the nine collision configurations. As expected, $\Delta\tau_{\text{had}}$ increases with system size and centrality: Pb-Pb collisions span $\Delta\tau_{\text{had}} \approx 1.5$ –3 fm/c, while all O-O configurations are concentrated below 1 fm/c. Although a clear positive correlation is observed between $\Delta v_{2,c}$ and $\Delta\tau_{\text{had}}$, the relationship is not strictly monotonic. The largest $\Delta v_{2,c}$ is found in Pb-Pb 30–50 % rather than in the most central 0–10 % bin, despite the latter having a longer $\Delta\tau_{\text{had}}$. This reflects the critical interplay between the initial geometric eccentricity of the collision zone, which decreases toward central collisions, and the duration of the $1.2T_c \rightarrow T_c$ window, which increases with centrality. The 30–50 % class strikes an optimal balance between a sufficient initial spatial anisotropy and an adequate evolution time to convert it into momentum anisotropy. For the O-O systems, all configurations are confined to $\Delta\tau_{\text{had}} < 1$ fm/c and yield correspondingly small $\Delta v_{2,c}$. Here, the dynamics are dominated by the severely compressed time window: even though the

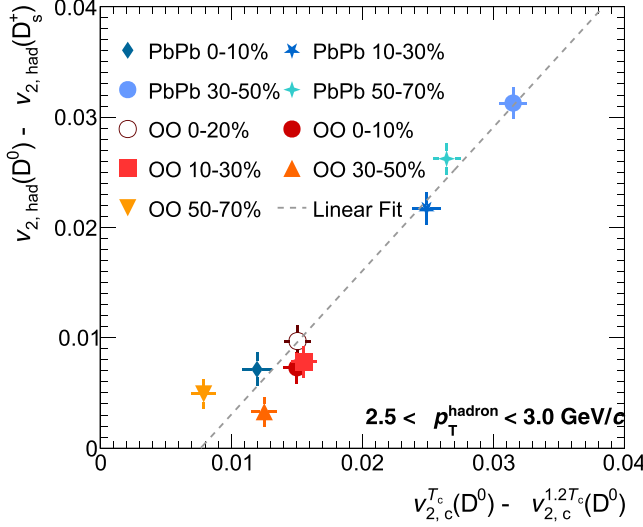


FIG. 8. Hadronic flow splitting $\Delta v_{2, \text{had}}$ versus partonic increment $\Delta v_{2, c}$, integrated over $2.5 < p_T^{\text{hadron}} < 3.0 \text{ GeV}/c$. Data points correspond to nine distinct collision configurations evaluated under the sequential scenario, spanning Pb-Pb 0–10 %, 10–30 %, 30–50 %, 50–70 %, and O-O 0–10 %, 10–30 %, 30–50 %, 50–70 %, together with O-O 0–20 %.

initial eccentricity is larger in peripheral O-O collisions, the system lacks sufficient time to translate this spatial asymmetry into additional charm-quark flow. Consequently, the differences among the O-O configurations are marginal; $\Delta v_{2, c}$ in the 10–30 % bin is only slightly higher than in 0–10 % and 0–20 %, rather than following a monotonic trend with eccentricity. Ultimately, $\Delta v_{2, c}$ is governed not by the cooling time alone, but by the combined influence of the initial collision geometry and the late-stage QGP lifetime. As will be shown in Fig. 8, this partonic mapping is directly imprinted onto the final hadronic splitting. Figure 8 shows $\Delta v_{2, \text{had}}$ versus $\Delta v_{2, c}$ for all nine evaluated LHC configurations. The data points follow a clear linear trend. This linearity is a product of mixing the coalescence and fragmentation contributions across different collision configurations: the individual coal and frag channels for D_s^+ and D^0 are not strictly linear in $\Delta v_{2, c}$ when taken separately, but their superposition—sampled over these diverse systems with distinct coal-to-frag ratios—collapses onto a single line. Hadronic rescattering further amplifies the splitting on top of this baseline.

The collapse of all nine data points onto a single line, despite spanning widely different initial eccentricities and system sizes, establishes that $\Delta v_{2, \text{had}}$ is not controlled by the global collision history prior to $1.2 T_c$, but is dictated entirely by the partonic anisotropy accumulated during the sequential hadronization window. We therefore propose the D^0 – D_s^+ flow splitting as a “hadronization chronometer” of the QGP.

The O-O configurations occupy the small- $\Delta v_{2, c}$ limit of the universal line in Fig. 8, reflecting their severely compressed $1.2 T_c \rightarrow T_c$ window; Pb-Pb systems extend the trend to correspondingly larger values. This unified behavior provides a natural explanation for the system-size ordering reported in Sec. III: the substantially smaller Δv_2 observed in O-O

0–20 % relative to Pb-Pb 30–50 % is a direct consequence of O-O occupying the small- $\Delta v_{2, c}$ end of the universal line. On this line, O-O 0–20 % lies close to Pb-Pb 0–10 %, illustrating that a severely compressed $1.2 T_c \rightarrow T_c$ window can place a small system in the same kinematic regime as the most central heavy-ion collisions. The optimal splitting is found in Pb-Pb 30–50 % rather than in the more peripheral 50–70 % bin, consistent with the competition between the initial geometric eccentricity ε_2 and the duration of the late-stage cooling window $\Delta \tau_{\text{had}}$, as demonstrated in Fig. 7. Rather than signaling a breakdown of the sequential mechanism in small systems, the system-size ordering is a natural outcome of a universal mapping from the partonic to the hadronic sector. We emphasize that this scaling is established at $\sqrt{s_{NN}} = 5.36 \text{ TeV}$ and remains a phenomenological observation; whether it extends to different collision energies is an open question for future measurements.

VI. SUMMARY

In summary, we have investigated the elliptic-flow (v_2) splitting between D^0 and D_s^+ mesons using a Langevin transport model coupled to a hybrid coalescence-plus-fragmentation framework. We contrasted two hadronization paradigms—simultaneous versus sequential freezeout—across collision configurations in O-O and Pb-Pb collisions.

For O-O 0–20 % collisions at $\sqrt{s_{NN}} = 5.36 \text{ TeV}$, we calculated the p_T -differential elliptic flow and predicted the D_s^+/D^0 yield ratio. The sequential scenario reproduces the $v_2(D^0) > v_2(D_s^+)$ ordering observed in the preliminary ALICE data, whereas the simultaneous baseline yields the opposite ordering. The sequential scenario also predicts an enhanced D_s^+/D^0 yield ratio at low p_T relative to the simultaneous case, and a systematic increase of this ratio from O-O to Pb-Pb, driven by the stronger partonic energy loss in the heavier system.

By decomposing the flow splitting into its partonic components, we showed that the simultaneous ordering arises from a phase-space selection effect in the coalescence channel, which cannot be reconciled with the experimental data even after hadronic rescattering. The sequential scenario reverses this ordering through the late-stage partonic flow accumulated by D^0 -parent charm quarks during the $1.2 T_c \rightarrow T_c$ interval.

In O-O collisions, the severe compression of the $1.2 T_c \rightarrow T_c$ interval restricts the late-stage partonic v_2 buildup, potentially inducing an inverted ordering of $v_{2, c}(D_s^+) > v_{2, c}(D^0)$ at the parton level. Consequently, the hadronic rescattering phase—which imparts a larger flow increment to the D^0 —proves critical for restoring the physical $v_2(D^0) > v_2(D_s^+)$ ordering in small collision systems.

To quantify this dynamical response, we performed a systematic scan across nine collision configurations spanning O-O and Pb-Pb, and identified a universal linear scaling between the final hadronic splitting $\Delta v_{2, \text{had}}$ and the partonic flow increment $\Delta v_{2, c}$. All nine configurations collapse onto the same line despite spanning widely different system sizes and initial eccentricities, demonstrating that Δv_2 is dictated by the partonic anisotropy accumulated during the $1.2 T_c \rightarrow T_c$ window rather than by the global collision history. We further found that $\Delta v_{2, c}$ is governed by the competition

between the initial geometric eccentricity and the duration of the $1.2 T_c \rightarrow T_c$ window. In Pb-Pb, this competition selects the 30–50 % centrality class as the optimal balance; in O-O, the time window is so short that it dominates over eccentricity, confining all O-O configurations to the low-response end of the universal trend.

We therefore establish the D^0 - D_s^+ flow splitting as a hadronization chronometer of the QGP at $\sqrt{s_{NN}} = 5.36$ TeV. O-O systems populate the low-response limit of this universal line, while Pb-Pb systems extend the trend to larger values, providing a natural explanation for the system-size ordering reported in this work. Whether this phenomenological scaling persists at different collision energies or with different ion species remains an open question for future measurements.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this paper. Requests for further information or data should be sent to the authors.

- [1] A. Andronic, P. Braun-Munzinger, M. K. Köhler, A. Mazeliauskas, K. Redlich, J. Stachel, and V. Vislavicius, The multiple-charm hierarchy in the statistical hadronization model, *J. High Energy Phys.* **07** (2021) 035.
- [2] J. Adam *et al.* (ALICE Collaboration), Measurement of d_s^+ production and nuclear modification factor in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, *J. High Energy Phys.* **03** (2016) 082.
- [3] S. Acharya *et al.* (ALICE Collaboration), Measurement of d^0 , d^+ , d^{*+} and d_s^+ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *J. High Energy Phys.* **10** (2018) 174.
- [4] V. Minissale, S. Plumari, Y. Sun, and V. Greco, Multi-charmed and singled charmed hadrons from coalescence: Yields and ratios in different collision systems at LHC, *Eur. Phys. J. C* **84**, 228 (2024).
- [5] Y.-F. Liu, W.-J. Xing, X.-Y. Wu, S. Cao, G.-Y. Qin, and S.-Q. Li, Charmed hadron chemistry and flow in heavy and light ion collisions at the LHC, [arXiv:2402.03622](https://arxiv.org/abs/2402.03622).
- [6] D. Ali Hassan Abdallah *et al.* (ALICE Collaboration), Evidence of different Λ_c -baryon and D-meson elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV with ALICE at the LHC, [arXiv:2603.18966](https://arxiv.org/abs/2603.18966).
- [7] R. Katz, Caio A. G. Prado, J. Noronha-Hostler, and Alexandre A. P. Suaide, System-size scan of D meson R_{AA} and v_n using PbPb, XeXe, ArAr, and OO collisions at energies available at the CERN Large Hadron Collider, *Phys. Rev. C* **102**, 041901(R) (2020).
- [8] S.-Q. Li, W.-J. Xing, X.-Y. Wu, S. Cao, and G.-Y. Qin, Scaling behaviors of heavy flavor meson suppression and flow in different nuclear collision systems at the LHC, *Eur. Phys. J. C* **81**, 1035 (2021).
- [9] J. Zhao, J. Aichelin, P. B. Gossiaux, and K. Werner, System-size dependence of energy loss and correlations of heavy mesons at energies available at the CERN Large Hadron Collider, *Phys. Rev. C* **111**, 014907 (2025).
- [10] R. J. Fries, B. Muller, C. Nonaka, and S. A. Bass, Hadron production in heavy ion collisions: Fragmentation and recombination from a dense parton phase, *Phys. Rev. C* **68**, 044902 (2003).
- [11] V. Greco, C. M. Ko, and P. Levai, Parton coalescence at RHIC, *Phys. Rev. C* **68**, 034904 (2003).
- [12] M. He and R. Rapp, Hadronization and charm-hadron ratios in heavy-ion collisions, *Phys. Rev. Lett.* **124**, 042301 (2020).
- [13] M. He, H. van Hees, and R. Rapp, Heavy-quark diffusion in the quark-gluon plasma, *Prog. Part. Nucl. Phys.* **130**, 104020 (2023).
- [14] V. Greco, H. van Hees, and R. Rapp, Phase-space coalescence for heavy and light quarks at RHIC, *Eur. Phys. J. Spec. Top.* **155**, 45 (2008).
- [15] S. Cao, G.-Y. Qin, and S. A. Bass, Energy loss, hadronization and hadronic interactions of heavy flavors in relativistic heavy-ion collisions, *Phys. Rev. C* **92**, 024907 (2015).
- [16] S. Cao, K.-J. Sun, S.-Q. Li, S. Y. F. Liu, W.-J. Xing, G.-Y. Qin, and C. M. Ko, Charmed hadron chemistry in relativistic heavy-ion collisions, *Phys. Lett. B* **807**, 135561 (2020).
- [17] P. B. Gossiaux, R. Bierkandt, and J. Aichelin, Tomography of a quark gluon plasma at RHIC and LHC energies, *Phys. Rev. C* **79**, 044906 (2009).
- [18] M. He, R. J. Fries, and R. Rapp, D_s -meson as quantitative probe of diffusion and hadronization in nuclear collisions, *Phys. Rev. Lett.* **110**, 112301 (2013).
- [19] A. Beraudo, A. De Pace, M. Monteno, M. Nardi, and F. Prino, Heavy flavors in heavy-ion collisions: Quenching, flow and correlations, *Eur. Phys. J. C* **75**, 121 (2015).
- [20] J. Zhao, J. Aichelin, P. B. Gossiaux, V. Ozvenchuk, and K. Werner, Heavy-flavor hadron production in relativistic heavy ion collisions at energies available at BNL RHIC and at the CERN LHC in the EPOS4HQ framework, *Phys. Rev. C* **110**, 024909 (2024).
- [21] T. Song, H. Berrehrah, D. Cabrera, J. M. Torres-Rincon, L. Tolos, W. Cassing, and E. Bratkovskaya, Tomography of the quark-gluon-plasma by charm quarks, *Phys. Rev. C* **92**, 014910 (2015).
- [22] S. Plumari, V. Minissale, S. K. Das, G. Coci, and V. Greco, Charmed hadrons from coalescence plus fragmentation in relativistic nucleus-nucleus collisions at RHIC and LHC, *Eur. Phys. J. C* **78**, 348 (2018).
- [23] S. K. Das, J. M. Torres-Rincon, L. Tolos, V. Minissale, F. Scardina, and V. Greco, Propagation of heavy baryons in heavy-ion collisions, *Phys. Rev. D* **94**, 114039 (2016).
- [24] V. Minissale, S. Plumari, and V. Greco, Charm hadrons in pp collisions at LHC energy within a coalescence plus fragmentation approach, *Phys. Lett. B* **821**, 136622 (2021).
- [25] S. Shi, J. Zhao, and P. Zhuang, Heavy flavor dissociation in framework of multi-body Dirac equations, *Chin. Phys. C* **44**, 084101 (2020).
- [26] J. Zhao, S. Shi, N. Xu, and P. Zhuang, Sequential hadronization in heavy ion collisions, *Nucl. Phys. A* **1005**, 121898 (2021).
- [27] S. Shi, X. Guo, and P. Zhuang, Flavor dependence of meson melting temperature in relativistic potential model, *Phys. Rev. D* **88**, 014021 (2013).

- [28] Z.-X. Xu, W. Dai, B.-W. Zhang, J. Zhao, and P. Zhuang, D-meson production via sequential hadronization in high-energy nuclear collisions, *Phys. Rev. Lett.* **136**, 232301 (2026).
- [29] S. Pucillo (ALICE Collaboration), Recent results on strangeness enhancement in small collision systems with ALICE, [arXiv:2504.02527](https://arxiv.org/abs/2504.02527).
- [30] G. Giacalone *et al.*, Exploiting ^{20}Ne isotopes for precision characterizations of collectivity in small systems, *Phys. Rev. Lett.* **135**, 012302 (2025).
- [31] ALICE Collaboration (unpublished).
- [32] J. S. Moreland, J. E. Bernhard, and S. A. Bass, Alternative ansatz to wounded nucleon and binary collision scaling in high-energy nuclear collisions, *Phys. Rev. C* **92**, 011901(R) (2015).
- [33] L.-G. Pang, H. Petersen, and X.-N. Wang, Pseudorapidity distribution and decorrelation of anisotropic flow within the open-computing-language implementation CLVisc hydrodynamics, *Phys. Rev. C* **97**, 064918 (2018).
- [34] X.-Y. Wu, G.-Y. Qin, L.-G. Pang, and X.-N. Wang, (3+1)-D viscous hydrodynamics at finite net baryon density: Identified particle spectra, anisotropic flows, and flow fluctuations across energies relevant to the beam-energy scan at RHIC, *Phys. Rev. C* **105**, 034909 (2022).
- [35] A. Bazavov *et al.* (HotQCD Collaboration), Equation of state in (2+1)-flavor QCD, *Phys. Rev. D* **90**, 094503 (2014).
- [36] J. E. Bernhard, J. S. Moreland, S. A. Bass, J. Liu, and U. Heinz, Applying Bayesian parameter estimation to relativistic heavy-ion collisions: Simultaneous characterization of the initial state and quark-gluon plasma medium, *Phys. Rev. C* **94**, 024907 (2016).
- [37] S. Ryu, J. F. Paquet, C. Shen, G. S. Denicol, B. Schenke, S. Jeon, and C. Gale, Importance of the bulk viscosity of QCD in ultrarelativistic heavy-ion collisions, *Phys. Rev. Lett.* **115**, 132301 (2015).
- [38] S. Cao, G.-Y. Qin, and S. A. Bass, Heavy-quark dynamics and hadronization in ultrarelativistic heavy-ion collisions: Collisional versus radiative energy loss, *Phys. Rev. C* **88**, 044907 (2013).
- [39] W. Dai, S. Wang, S.-L. Zhang, B.-W. Zhang, and E. Wang, Transverse momentum balance and angular distribution of $b\bar{b}$ dijets in Pb+Pb collisions, *Chin. Phys. C* **44**, 104105 (2020).
- [40] M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, and G. Ridolfi, Theoretical predictions for charm and bottom production at the LHC, *J. High Energy Phys.* **10** (2012) 137.
- [41] K. J. Eskola, P. Paakkinen, H. Paukkunen, and C. A. Salgado, EPPS21: A global QCD analysis of nuclear PDFs, *Eur. Phys. J. C* **82**, 413 (2022).
- [42] S. Wang, W. Dai, B.-W. Zhang, and E. Wang, Diffusion of charm quarks in jets in high-energy heavy-ion collisions, *Eur. Phys. J. C* **79**, 789 (2019).
- [43] S. Wang, W. Dai, B.-W. Zhang, and E. Wang, Z^0 boson associated b-jet production in high-energy nuclear collisions*, *Chin. Phys. C* **47**, 054102 (2023).
- [44] S. Wang, W. Dai, B.-W. Zhang, and E. Wang, Radial profile of bottom quarks in jets in high-energy nuclear collisions, *Chin. Phys. C* **45**, 064105 (2021).
- [45] X.-F. Xue, Z.-X. Xu, W. Dai, J. Zhao, and B.-W. Zhang, Bayesian inference of heavy-quark dissipation and jet transport parameters from D-meson observables in heavy-ion collisions at energies available at the CERN Large Hadron Collider, *Phys. Rev. C* **113**, 054902 (2026).
- [46] R. Kubo, The fluctuation-dissipation theorem, *Rep. Prog. Phys.* **29**, 255 (1966).
- [47] L. Altenkort, O. Kaczmarek, R. Larsen, S. Mukherjee, P. Petreczky, H.-T. Shu, and S. Stendebach (HotQCD Collaboration), Heavy quark diffusion from 2+1 flavor lattice QCD with 320 MeV pion mass, *Phys. Rev. Lett.* **130**, 231902 (2023).
- [48] P. Petreczky, Quarkonium in hot medium, *J. Phys. G: Nucl. Part. Phys.* **37**, 094009 (2010).
- [49] X. Guo and X.-N. Wang, Multiple scattering, parton energy loss and modified fragmentation functions in deeply inelastic eA scattering, *Phys. Rev. Lett.* **85**, 3591 (2000).
- [50] B.-W. Zhang, E. Wang, and X.-N. Wang, Heavy quark energy loss in nuclear medium, *Phys. Rev. Lett.* **93**, 072301 (2004).
- [51] B.-W. Zhang, E.-k. Wang, and X.-N. Wang, Multiple parton scattering in nuclei: Heavy quark energy loss and modified fragmentation functions, *Nucl. Phys. A* **757**, 493 (2005).
- [52] A. Majumder, Hard collinear gluon radiation and multiple scattering in a medium, *Phys. Rev. D* **85**, 014023 (2012).
- [53] W.-T. Deng and X.-N. Wang, Multiple parton scattering in nuclei: Modified DGLAP evolution for fragmentation functions, *Phys. Rev. C* **81**, 024902 (2010).
- [54] M. Xie, S.-Y. Wei, G.-Y. Qin, and H.-Z. Zhang, Extracting jet transport coefficient via single hadron and dihadron productions in high-energy heavy-ion collisions, *Eur. Phys. J. C* **79**, 589 (2019).
- [55] M. He and R. Rapp, Charm-baryon production in proton-proton collisions, *Phys. Lett. B* **795**, 117 (2019).
- [56] J. M. Torres-Rincon, G. Montaña, À. Ramos, and L. Tolos, In-medium kinetic theory of D mesons and heavy-flavor transport coefficients, *Phys. Rev. C* **105**, 025203 (2022).
- [57] R. J. Fries, V. Greco, and P. Sorensen, Coalescence models for hadron formation from quark gluon plasma, *Annu. Rev. Nucl. Part. Sci.* **58**, 177 (2008).
- [58] J. Zhao, S. Shi, N. Xu, and P. Zhuang, Sequential coalescence with charm conservation in high energy nuclear collisions, [arXiv:1805.10858](https://arxiv.org/abs/1805.10858).
- [59] J. Zhao *et al.*, Hadronization of heavy quarks, *Phys. Rev. C* **109**, 054912 (2024).
- [60] J. Zhao, J. Aichelin, P. B. Gossiaux, and K. Werner, Correlations between heavy mesons and the creation of the charmonia, bottomonia, and B_c mesons in high energy pp collisions, *Phys. Rev. D* **113**, 116022 (2026).
- [61] C. Peterson, D. Schlatter, I. Schmitt, and P. M. Zerwas, Scaling violations in inclusive e^+e^- annihilation spectra, *Phys. Rev. D* **27**, 105 (1983).
- [62] M. Lisovyi, A. Verbytskyi, and O. Zenaiev, Combined analysis of charm-quark fragmentation-fraction measurements, *Eur. Phys. J. C* **76**, 397 (2016).
- [63] R. Bellwied, S. Borsanyi, Z. Fodor, S. D. Katz, and C. Ratti, Is there a flavor hierarchy in the deconfinement transition of QCD?, *Phys. Rev. Lett.* **111**, 202302 (2013).
- [64] A. Beraudo, A. De Pace, M. Monteno, M. Nardi, and F. Prino, Development of heavy-flavour flow-harmonics in high-energy nuclear collisions, *J. High Energy Phys.* **02** (2018) 043.