

Probing the Quark-Gluon Plasma through p_T -Differential Radial Flow of Heavy Quarks

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We introduce the p_T -differential radial flow $v_0(p_T)$ in the heavy-quark sector. Within an event-by-event Langevin framework, we show that this observable exhibits a strong sensitivity to the heavy quark-bulk interaction. It provides a powerful and novel tool to constrain the transport coefficients of heavy quarks in the quark-gluon plasma and, more generally, to assess the strength of the interaction of a Brownian particle in an expanding bulk medium. The results further indicate that heavy quarks exhibit collective behavior driven by the isotropic expansion of the quark-gluon plasma in heavy-ion collisions and, at low p_T , it offers a marked signature of the heavy-quark hadronization mechanism.

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Introduction—Strong evidence suggests that the quark-gluon plasma (QGP) [1,2], a hot and dense deconfined state of quarks and gluons, has been observed in ultrarelativistic heavy-ion collisions at the Relativistic Heavy-Ion Collider and the Large Hadron Collider (LHC). The evolution of the QGP is governed by strong pressure gradients that drive collective expansion, giving rise to various flow phenomena: anisotropic flows, originating from initial geometric asymmetries, and radial flow, resulting from the isotropic pressure-driven expansion of the medium. Over the years, differential measurements of particle azimuthal distributions have yielded strong evidence that the momentum distribution of final-state particles is a collective response to the initial pressure gradients. Radial flow has so far been extracted from the slope of the transverse momentum spectra and characterized by a p_T -integrated radial-flow parameter. Thus, p_T -dependent information on radial flow has been missing, even though it plays a crucial role in the expansion of the QGP fireball. The recently proposed observable $v_0(p_T)$ [3,4] allows a p_T -differential investigation of radial flow, opening the opportunity to probe collective dynamics in the QGP arising from isotropic expansion, which has only recently become accessible. The $v_0(p_T)$ quantifies the correlation between the fraction

of particles in a given p_T bin and the mean transverse momentum of all the produced particles within a single event. Results from the ATLAS [5] and ALICE [6] Collaborations in Pb-Pb collisions at 5.02 TeV demonstrate the sensitivity of this observable to key properties of the medium, such as the bulk viscosity and the QCD equation of state [4,5]. Furthermore, results from the ALICE Collaboration [6] (see also Refs. [7,8]) indicate the mass-dependent behavior of $v_0(p_T)$ at low p_T and reveal baryon-meson separation at intermediate p_T , a feature poorly explored theoretically until now.

Heavy quarks (HQs), produced in early stage of the collision due to their large masses, experience the entire space-time evolution of the QGP and, by retaining the memory of their interactions, serve as excellent probes of its transport properties [9–29]. Measurements of heavy-quark nuclear suppression factors R_{AA} [30] and elliptic flow v_2 [31] at both the Relativistic Heavy-Ion Collider and LHC provide constraints on the heavy-quark spatial diffusion coefficient D_s . Furthermore, the heavy meson-to-baryon ratio [32,33] serves as a probe of the hadronization mechanism, while the splitting in heavy-quark directed flow v_1 [26,34,35] is considered a probe of the initial electromagnetic field.

In this Letter, for the first time, we present a study of the p_T -differential radial flow of charm quarks in the QGP to probe the dynamics of their in-medium interactions. For HQs the $v_0(p_T)$ is no longer driven directly by their contribution to the bulk viscosity and equation of state of the bulk matter or the initial energy density fluctuations because their contribution is largely subdominant; hence, the novel aspect is to exploit the event-by-event fluctuations in p_T of a Brownian particle to determine the strength of its coupling to the expanding bulk medium, once the dynamics of the last is known. We study the $v_0(p_T)$ of the

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heavy quarks in QGP within a event-by-event Langevin transport approach. In order to investigate the sensitivity of $v_0(p_T)$ to the heavy quark-bulk interaction, we explore a range of scenarios spanning from a weakly coupled regime, as described by perturbative QCD (pQCD), to a strongly interacting medium, as suggested by quenched [36–39] and recent unquenched lattice QCD (lQCD) results [40–42]. The obtained p_T -differential radial flow is found to be highly sensitive to the underlying microscopic interaction dynamics, demonstrating that this observable, despite being independent of the mechanisms responsible for v_2 buildup, can be equally effective to provide quantitative constraints on the heavy-quark transport coefficient.

Event-by-event transport approach for charm and bulk dynamics—We use an event-by-event (ebe) relativistic transport framework where we couple the ebe relativistic Boltzmann at a fixed shear viscosity to entropy density ratio η/s with the Langevin equation [25,43–53]. The initial conditions of partons are described within a Monte Carlo Glauber model; see Refs. [52–55]. The soft partons are distributed in momentum space following an initial thermal equilibrium profile. We also consider a hard component consisting of minijets from initial binary pQCD collisions, with transverse momentum spectra at midrapidity taken from CUJET results for 5.02 TeV proton-proton collisions [56]. We notice that the evolution of the bulk dynamics corresponds to the one of viscous hydrodynamics [57–59] and the initial conditions have been set to reproduce the $dN/d\eta$ and the v_2 of charged particles [60,61]. Charm quarks are initialized in coordinate space using the binary collision profile N_{coll} from the Monte Carlo Glauber model. The momentum distribution of charm quarks is computed from the fixed-order next-to-leading-logarithm calculations that permit one to reproduce the D -meson spectra in proton-proton collisions after fragmentation [49,62]. In our approach, hadronization of charm quarks follows a hybrid model combining coalescence and fragmentation, detailed in Refs. [63–69].

Regarding the particles dynamics, we describe the evolution of gluons (g) and light quarks (q) with the following equation:

$$p_j^\mu \partial_\mu f_j(x, p) = \mathcal{C}[f_j, f_i](x, p) \text{ for } i, j = g, q, \quad (1)$$

where $\mathcal{C}[f_j, f_i](x, p)$ is the Boltzmann-like collision integral for elastic $2 \rightarrow 2$ scattering processes. Regarding the HQs' dynamics, we describe their propagation in the QGP in a Brownian motion by solving the following set of stochastic Langevin equations:

$$dx_j = \frac{p_j}{E} dt, \quad dp_j = -\Gamma p_j dt + \sqrt{dt} C_{j,k} \rho_k, \quad (2)$$

where Γ and $C_{j,k}$ govern the interaction between the HQ and the medium and they are directly connected to the *drag* and *diffusion* coefficients, respectively [70].

We can express $C_{j,k} = \sqrt{2D_p(E)}\delta_{jk}$, where D_p denotes the diffusion coefficient in momentum space. The fluctuation-dissipation theorem then simplifies to $D_p(p) = A(p)E(p)T$. Notice that the drag coefficient A and the momentum-space diffusion coefficient D_p depend on $T(x)$, the bulk temperature obtained from the Boltzmann equation through a coarse-graining procedure. In the static limit $p \rightarrow 0$, we recall that $A(p \rightarrow 0) = \gamma$, and the momentum-space diffusion coefficient D_p can be related to the spatial diffusion coefficient D_s by the following relation:

$$D_s = \frac{T^2}{D_p} = \frac{T}{M_{\text{HQ}}\gamma} = \frac{T}{M_{\text{HQ}}} \tau_{\text{th}}. \quad (3)$$

In this Letter, we consider three interaction scenarios between the charm quark and the bulk medium. The first case corresponds to a weak interaction between the HQ and the QGP, considering drag and diffusion coefficients coming from leading order pQCD with a running coupling taken from Ref. [71]. The corresponding $2\pi T D_s$ is shown in Fig. 1 by black solid line. The second case corresponds to an extreme scenario of strong interaction, with a momentum independent D_s , green dot-dashed line in Fig. 1, fitted to the new unquenched lQCD data [40–42]. These new lQCD data are significantly smaller than the ones in quenched approximation (yellow symbols in Fig. 1), also suggesting a small thermalization time for charm quark $\tau_{\text{th}} \approx 1.5 \text{ fm}/c$ at $T = 1.2T_c$ [40–42]. In this second case both drag and diffusion coefficient are momentum independent with $A = T/M_{\text{HQ}}D_s$, resulting in a thermalization time constant in momentum. In the third case, we consider the drag and diffusion evaluated in a recently developed quasiparticle model, QPM_p, see red dashed line in Fig. 1. The QPM_p, which incorporates momentum-dependent parton masses consistent with QCD asymptotic freedom, successfully describes lattice QCD equation of state and susceptibilities of light, strange, and charm quarks [72]. In the QPM_p, the effective vertex coupling $g(T)$ is derived

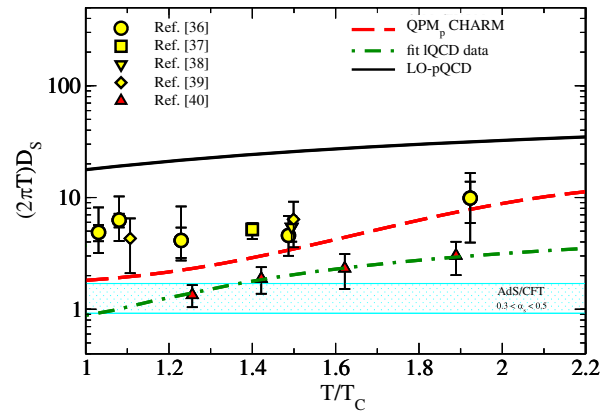


FIG. 1. Spatial diffusion coefficient $2\pi T D_s$ in QPM_p for charm quark compared to available lQCD data.

from a fit to IQCD thermodynamics and is notably larger than the one predicted by pQCD approach, leading to a smaller D_s especially as $T \rightarrow T_c$ (see details in Ref. [72]). QPM_p is also able to describe the R_{AA} and $v_{2,3}(p_T)$ of D mesons for different centralities at top LHC energies [53].

In this Letter, we study the fluctuation of the p_T spectrum of heavy hadrons associated with a fluctuation of the average heavy hadron transverse momentum $[p_T]$. Recently, in the light hadron sector a new observable called $v_0(p_T)$ has been introduced to measure this correlation; see Ref. [3]. It has been shown that the $v_0(p_T)$ in the light flavor sector depends on the bulk viscosity and also exhibits a mass ordering going from pions to protons. The main goal of this Letter is to compute v_0 in the HQ sector and to analyze how this newly proposed observable may be sensitive to the interaction between HQ and the medium. Following the definition of $v_0(p_T)$ in [3] we have

$$v_0(p_T) \equiv \frac{\langle \delta N(p_T) \delta p_T \rangle}{N_0(p_T) \sigma_{p_T}}, \quad (4)$$

which quantifies the event-by-event correlation between a fluctuation $\delta N(p_T)$ of the single-particle spectrum at transverse momentum p_T and the fluctuation δp_T of the mean transverse momentum per particle. For a given event, we denote by $N(p_T)$ the number of particles in a p_T bin, i.e., the p_T spectrum. For each event the spectrum $N(p_T)$ is decomposed as $N(p_T) = N_0(p_T) + \delta N(p_T)$, where $N_0(p_T)$ is the ensemble average. The eventwise mean transverse momentum is $[p_T] = N^{-1} \int_{p_T} p_T N(p_T) = \langle p_T \rangle + \delta p_T$, where $N = \int_{p_T} N(p_T)$ is the total multiplicity. The variance of these fluctuations is defined as $\sigma_{p_T}^2 \equiv \langle (\delta p_T)^2 \rangle$, where angular brackets represent averaging over events. By definitions, one can infer a characteristic behavior of $v_0(p_T)$ as a function of transverse momentum. Specifically, when the mean p_T in a given event exceeds the ensemble average, the spectrum shifts toward higher p_T , leading to a positive $v_0(p_T)$ at high transverse momentum. This shift simultaneously induces a depletion of particles at low p_T , resulting in a negative $v_0(p_T)$ in that region. Note that the formulas employed assume a constant particle multiplicity, i.e., $\delta N_{\text{charm}} = 0$. This condition is implemented in our approach for charm quarks, while the bulk medium is considered in its full realistic ebe fluctuations in the selected centrality class, hence $\delta N_{\text{bulk}} \neq 0$. We notice that, instead, when defining and measuring $v_0(p_T)$ for light hadrons one keeps constant the multiplicities of the bulk, $\delta N_{\text{bulk}} = 0$.

Results—First, we study the $v_0(p_T)$ at charm quark level for two centrality classes for Pb + Pb at $\sqrt{s} = 5.02$ TeV, which is shown in Fig. 2. Note that the curves in all the plots are shown with bands that represent the statistical uncertainty and, for the IQCD case, also the uncertainty associated with the quality of the fit of D_s . By construction,

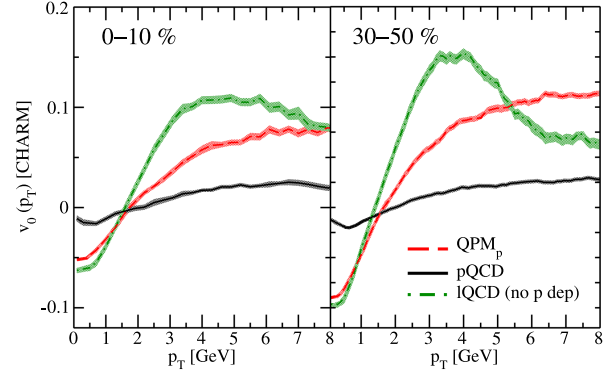


FIG. 2. $v_0(p_T)$ for charm quark at 0%–10% (left) and 30%–50% (right) in the different cases studied.

$v_0(p_T)$ is negative at low transverse momentum, as previously discussed, and changes sign around $p_T \approx M_c$. Specifically, we observe that in the 0%–10% centrality class, the $v_0(p_T)$ obtained within the QPM_p framework is approximately 3 times larger than in the weak interaction scenario at intermediate p_T . This enhancement becomes even more pronounced in the IQCD case, where $v_0(p_T)$ reaches values about 4 times higher than those predicted by pQCD, which instead exhibits a flat trend with only mild dependence on transverse momentum p_T . As anticipated $v_0(p_T)$ is a sensitive measure of the coupling of charm quarks to the medium: for a weak interaction corresponding to a large diffusion coefficient D_s (small drag of charm quark), as predicted by leading order pQCD (LO-pQCD), the medium ebe fluctuations are weakly transferred to the charm quarks, implying a small value of the $v_0(p_T)$. On the other hand, in a strongly interacting system such as that described by IQCD, the intense coupling leads to a more efficient transfer of bulk density fluctuations into the heavy-quark spectrum. As a result, the spectrum exhibits larger event-by-event deviations respect to the average, which manifest as a large v_0 . Furthermore, our results indicate that, going from central to semiperipheral collisions, $v_0(p_T)$ becomes increasingly sensitive to the differences in the spatial diffusion coefficient D_s across the various models. In order to provide predictions directly comparable to an experimental observable, we consider a hybrid hadronization mechanism combining coalescence and fragmentation to calculate the v_0 of D mesons and Λ_c baryons. The key ingredients of the hadronization approach are presented in detail in several papers [63–69]. It should be noted that an event-by-event coalescence-based hadronization mechanism still remains challenging at present, as it would require a fully dynamical, event-by-event coalescence approach. In order to get an approximate evaluation of the coalescence integral, we assume a δ -like Wigner function, an approximation that carries the main feature of the coalescence process [73–75]. Therefore, the hadron spectrum $f^H(p_T^H)$ in a single event can be written as the product of the spectra $f_i(x_i, p_T^H)$ of its N constituent quarks:

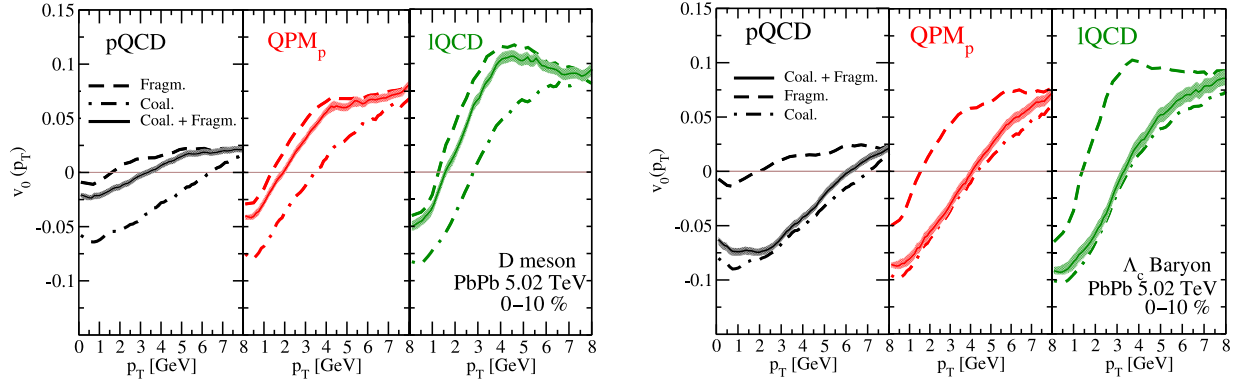


FIG. 3. $v_0(p_T)$ at 0%–10% centrality class for D meson (left) and Λ_c baryon (right) from fragmentation and coalescence for the different cases discussed.

$f^H(p_T^H) = C_H \prod_{i=1}^{N_q} f_i(x_i p_T^H)$. The quark momentum can be written as $p_T^i = x_i p_T^H$ with x_i the momentum fraction of quarks with respect to the hadron total momentum p_T^H , satisfying $\sum_{i=1}^N x_i = 1$. The spectrum of fluctuations take the form

$$\delta f^H(p_T^H) = C_H \prod_{i=1}^{N_q} f_i(x_i p_T^H) - \left\langle C_H \prod_{i=1}^{N_q} f_i(x_i p_T^H) \right\rangle, \quad (5)$$

which truncated at first order becomes

$$\delta f^H(p_T^H) = C_H \sum_{i=1}^{N_q} \delta f_i(x_i p_T^H) \prod_{j=1, j \neq i}^{N_q} \langle f_j(x_j p_T^H) \rangle. \quad (6)$$

We can write the hadron p_T fluctuation as $\delta p_T^H = \sum_{i=1}^{N_q} \delta p_T^i$ and $\sigma_{p_T^H}^2 \simeq \sum_{i=1}^{N_q} \sigma_{p_T^i}^2$. In our calculations, therefore assuming the off-diagonal terms $\langle \delta f_i(x_i p_T^H) \delta p_{T_j} \rangle \simeq 0$ for $i \neq j$, the final hadron $v_0^H(p_T^H)$ can be written as

$$v_0^H(p_T^H) = \sum_{i=1}^{N_q} v_0(x_i p_T^H) \frac{\sigma_{p_T^i}}{\sqrt{\sum_{i=1}^N \sigma_{p_T^i}^2}}. \quad (7)$$

Note that the v_0 of a hadron produced via coalescence results from a linear combination of the v_0 of its constituent quarks, in analogy with the sum rules derived for the v_n coefficients [76,77]. This implies that Λ_c baryons are more affected by the v_0 of the bulk light quarks at low p_T compared to D mesons. After the hadronization process, we observe that heavy flavor v_0 remains a sensitive observable to the interaction encoded in the D_s , as shown in Fig. 3, similarly to partonic level. It is worth noting that the dominant contribution to the v_0 of D mesons arises from fragmentation, whereas for Λ_c production, coalescence is expected to be the leading mechanism up to intermediate transverse momentum [63]. Regarding the v_0

of Λ_c , we observe a clear mass ordering at $p_T < 4$ GeV, as shown in the left and middle panels of Fig. 4, where we plot the $v_0(p_T)$ at 0%–10% and 30%–50% for both D meson and Λ_c baryon. Similarly to the pattern seen between pions and protons, charmed baryons exhibit a $v_0(p_T)$ that reaches zero crossing at higher transverse momentum compared to D mesons. Notice also that the magnitude and centrality dependence of the heavy hadron $v_0(p_T)$ is quite comparable to that of light hadron measured at ATLAS [5] and ALICE [6] Collaborations for small values of D_s (QPM_p and IQCD). This indicates that the bulk fluctuations of dN/dp_T in this case can be very efficiently transferred to the charm quark despite their large mass. The observed difference between heavy baryon and meson in $v_0(p_T)$ can provide insight into the hadronization process. A main key result finding is that at low $p_T \simeq 1$ GeV the v_0 is marginally dependent on the value of diffusion coefficient D_s , while it is marked the impact of the hadronization mechanism generating a difference of a factor of about 2 on the value of v_0 for Λ_c versus D . By complementing this observable

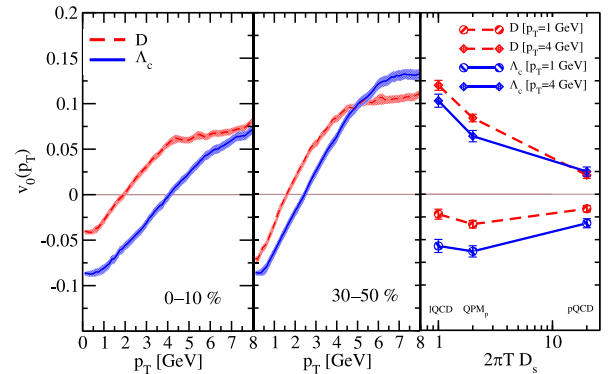


FIG. 4. $v_0(p_T)$ at 0%–10% (left) and 30%–50% (middle) for D meson (red dashed line) and Λ_c baryon (blue solid line) in QPM_p from coalescence plus fragmentation. Right: D meson (red dashed line) and Λ_c (blue solid line) $v_0(p_T)$ at 30%–50% centrality class for $p_T = 1$ GeV (circles) and $p_T = 4$ GeV (diamonds) as function of $2\pi T D_s$.

with v_2 , one can gain additional insight into the hadronization mechanism, since its sensitivity to the underlying dynamics differs across momentum ranges. Differently, for v_2 the hadronization effect is known to manifest predominantly at intermediate p_T , while it becomes almost negligible at low p_T , where instead coalescence is expected to be dominant. We have observed that $v_0(p_T)$ and $v_2(p_T)$ show different sensitivities to the D_s at intermediate p_T . In particular, the $v_2(p_T)$ in QPM_p and with a momentum dependence in the drag coming from the T -matrix approach discussed in Ref. [53] are similar, while $v_0(p_T)$ exhibits larger sensitivity than $v_2(p_T)$ in the same momentum range. This hints at a stronger discrimination power of $v_0(p_T)$ with regard to $v_2(p_T)$ along with a cleaner separation of transport and hadronization effect. A detailed investigation will be addressed in a forthcoming study. This can be considered a fingerprint of coalescence for heavy baryons that recombine with two light quarks at very low p_T hence carrying a quite negative v_0 that significantly decreases the v_0 of Λ_c with regard to the D meson one.

Summary and outlook—We have introduced, for the first time, a new observable, $v_0(p_T)$, in the heavy-quark sector. We have pointed out that for a Brownian particle like HQs, the differential radial flow measures the coupling to the QGP bulk medium and the effectiveness of the response to its event-by-event fluctuations. This leads to a strong sensitivity to both the underlying heavy-quark transport coefficients (at intermediate p_T) and the hadronization mechanism (at low p_T). Our Letter reveals that HQs in a strongly coupled regime should exhibit a collective behavior driven by the isotropic expansion of the QGP, with a magnitude comparable to that of light hadrons recently measured by the ALICE and ATLAS Collaborations. This paves the way for introducing this new observable to achieve a quantitative constraint on the extraction of the spatial diffusion coefficient D_s and a microscopic understanding of the underlying coupling to the bulk medium. Hence, its impact should also be investigated within a global Bayesian analysis. We highlight the contrast between weakly coupled and strongly coupled HQ-bulk interactions with a difference of about a factor of 5 for $v_0(p_T)$ at intermediate p_T . After hadronization, $v_0(p_T)$ not only remains a sensitive observable of the interactions encoded at the partonic level, but shows a specific pattern depending on the hadronization mechanism, particularly marked at low p_T . We have found that at low $p_T \simeq 1$ GeV the $v_0(\Lambda_c) \sim 2v_0(D)$, while a pure fragmentation would give $v_0(\Lambda_c) \sim v_0(D)$. This makes the measurement of the v_0 of Λ_c and D a unique observable for revealing the hadronization mechanisms.

This Letter represents a seminal work that opens several directions of investigation. Among them, we mention: the extension to proton–nucleus and light nucleus–nucleus systems down to oxygen–oxygen collisions, which

constitute a central focus of the High Luminosity LHC program; the extension to bottom quarks, which, despite their larger mass, exhibit a similar $2\pi TD_s$ as charm quarks according to IQCD, thereby allowing the extraction of pure mass effects. Furthermore, such studies would provide new insights into bottom hadronization in nucleus–nucleus collisions, which remains poorly understood. Another promising avenue involves exploring the relation between the momentum dependence of v_0 and that of the heavy-quark diffusion coefficient. Finally, we note that, more generally, $v_0(p_T)$ could be exploited to study the coupling of Brownian particles to an expanding mesoscopic systems. Because heavy-quark observables like v_2 still suffer from intrinsic ambiguities, v_0 provides a cleaner probe of dynamics distinct from the light sector. Confirming a large v_0 with the same D_s that reproduces v_2 would offer stronger evidence of charm-bulk coupling and help separate hydrodynamic effects from initial-state anisotropies, especially in small systems.

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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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