

Signatures of jet drift in quark-gluon plasma hard-probe observables

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Hard-probe tomography of the quark-gluon plasma (QGP) in heavy ion collisions has long been a preeminent goal of the high-energy nuclear physics program. In service of this goal, the isotropic modification of jets and high-energy hadrons has been studied in great detail at the leading-power (eikonal) level, with effects originating from sub-eikonal $\mathcal{O}(\mu/E)$ anisotropic interactions presumed to be small. We present the first investigation of sub-eikonal, collective-flow-induced asymmetric jet broadening (jet drift) in event-by-event $\sqrt{s} = 5.02$ TeV PbPb collisions at the Large Hadron Collider using the Anisotropic Parton Evolution computational framework. We show that jet drift imparts a significant enhancement of elliptic flow (v_2) larger than the experimental resolution and increases the mean acoplanarity for low- and intermediate-energy particles ($p_T < 10$ GeV). Importantly, these modifications to hard-probe observables are shown to survive averaging over events and collision geometry. They couple to the collective flow of the medium seen by the jet and encode information about the QGP dynamics inaccessible to studies considering only isotropic, eikonal-level effects.

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Introduction. Hard probes are a cornerstone in the investigation of the form of nuclear matter—the quark-gluon plasma—produced in heavy ion collisions at the Relativistic Heavy Ion Collider and the Large Hadron Collider (LHC) (see Ref. [1] for a review). Following initial and acclaimed success [2], progress into hard-probe tomography, especially recently, has been limited by the inherent complexity of the problem. The standard measurement of the suppression of energetic particles and jets, the nuclear modification factor

$$R_{AA}(p_T) = \frac{dN^{AA}}{dyd^2p_T} \bigg/ \langle n_{\text{coll}} \rangle \frac{dN^{pp}}{dyd^2p_T}, \quad (1)$$

where $\langle n_{\text{coll}} \rangle$ is the number of binary collisions, is a robust quantity that can be reproduced by a wide variety of pQCD calculations and other models [3–8] (see Ref. [9] for a direct multimodel comparison). Other traditional hard-probe modifications like isotropic transverse momentum broadening measured in two-particle away-side correlations are also poorly discriminating, as they are complicated by competing background effects like energy-resolution smearing and medium response [1,10]. In contrast, there are few, if any, background effects that can mimic the anisotropic coupling of energetic partons to preferred directions in the medium.

Anisotropic modifications that go beyond the leading-power eikonal limit are thus more discriminating with respect to the microscopic Quantum Chromodynamics (QCD) interactions in the quark-gluon plasma (QGP) and encode unique tomographic information.

In previous work [11], as part of the effort to develop the full theoretical framework of QCD dynamics in matter, the authors have shown that the momentum broadening of a hard parton has an $\mathcal{O}(\mu/E)$ anisotropic component, μ being a medium scale and E the parton energy, which couples to the local collective flow velocity $\vec{u}$ in a thermal QGP. On average, this results in a net transverse momentum exchange $\langle \vec{q}_{\text{drift}} \rangle$ in the direction of the flow vector $\vec{u}_\perp$ transverse to the jet: the so-called “jet drift” effect (5). This direct anisotropic coupling to the flow [11] modifies the diagrammatic interferences and is a fundamentally quantum effect that is different from the one incorporated in Linearized Boltzmann Transport (LBT) and MARTINI [12,13] that results in a classical velocity dependence.

The aggregation of the locally anisotropic jet drift over the path length creates a global correlation between the inclusive azimuthal distribution of hard particles and the geometric anisotropy of the medium (the eccentricity ε_n). This enhances the corresponding anisotropic flow v_n^{hard} of hard particles [14], defined by standard Fourier decomposition as

$$\frac{R_{AA}(p_T, \phi)}{R_{AA}(p_T)} \equiv 1 + 2 \sum_{n=1}^{\infty} v_n^{\text{hard}} \cos[n(\phi - \psi_n^{\text{hard}}(p_T))], \quad (2)$$

where ψ_n^{hard} is the angle of the n th harmonic hard particle event plane [3]. We emphasize that jet drift represents an additional level of coupling to the medium geometry, distinct from the sensitivity to the path length dependence, although jet drift does nontrivially mix with these effects.

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However, sub-eikonal effects proportional to μ/E are small at large parton energy E , suggesting that modifications to hard-probe observables may be small. Furthermore, one may reasonably question whether anisotropies due to the medium velocity field survive averaging over fluctuating events. Thus, it is imperative to investigate this question on an event-by-event level. We note that power-suppressed (“sub-eikonal”) corrections like jet drift can modify every part of the jet production cross section including not only the medium interactions but also the hadronization process. Jet drift, which selects on locally *asymmetric* interactions that can only come from the medium, therefore provides a first window into effects that go beyond the well-understood, leading-power formalism. As we will show, the effects of jet drift on hard-probe observables are sensitive to different hadronization mechanisms.

In this work, we present the first study of event-by-event jet drift via APE (Anisotropic Parton Evolution), an open-source Monte Carlo parton trajectory simulator that incorporates a host of flexible model choices to survey the variability of the effect. We emphasize that the purpose of this work is *not* to fit the experimentally measured v_2 of hard particles; rather, it is to state with confidence a conservative lower bound on the *relative contribution* of the jet drift effect (Fig. 3) compared to energy loss. Therefore, we systematically make the most conservative model and parameter choices to minimize the relative effect of drift, which then underpredicts absolute v_2^{hard} . We demonstrate that despite these assumptions, the imprint of flow on hard probes is robust and survives averaging over many events on the example of $\sqrt{s} = 5.02$ TeV PbPb collisions at the LHC.

We also complement this rigorous lower bound with well-motivated alternative hadronization models like coalescence and alternative medium models (Fig. 4), which further enhance the effect of jet drift on hard observables below hadronic E of 10 GeV. Importantly, this framework differs substantially from most other similar hard particle and jet simulators (e.g., HIJING [15], HYDJET++ [16], JEWEL [17], DREENA-A [18], HYBRID [19]), including the JETSCAPE framework [20] and all existing plugins by tracking step-by-step average deflections to the trajectory of hard particles as they propagate through the evolving medium. In this work, we present the first rigorous, event-by-event simulation of flow effects from genuine power-suppressed corrections, which goes well beyond approaches that simply boost the leading-power (“eikonal”) scattering amplitudes to a moving frame [15,19,21].

Methodology. Our realistic event-by-event medium is a reimplementation of the open-source DukeQCD hybrid transport model [22], which consists of an initial condition from T_R ENTO [23,24], 2 + 1D viscous hydrodynamics, and Cooper-Frye particlization [25] followed by the UrQMD hadronic afterburner [26]. Consistent with the boost-invariant medium, we treat the production of hard partons near mid-rapidity as boost invariant for a given p_T [27]. We employ the maximum *A Posteriori* parameters for the model from Ref. [22], and we verify that our simulations quantitatively reproduce the soft $v_2\{2\}$, $v_3\{2\}$, and $v_4\{2\}$ flow harmonics as well as identified hadron multiplicities, mean p_T , and p_T fluctuations reported therein.

The seeds of jets in APE are modeled as single partons, for which we calculate the drift and energy loss. This approach effectively neglects splittings other than medium-induced soft gluon emission, under the assumption that the hard scattering, in medium interactions, and fragmentation are factorizable [2]. In many Monte Carlo simulations, a relatively small number $\sim \mathcal{O}(100)$ of QGP geometries are each seeded with many $\sim \mathcal{O}(10^6)$ hard-scattering events for computational efficiency (see, e.g., Refs. [3]). In contrast, we sample only $\sim \mathcal{O}(10^3)$ hard-scattering events per event geometry, but we simulate a much larger number $\sim \mathcal{O}(10^5)$ of unique events. This lower oversampling factor retains the correlations within an event geometry as much as possible, while performing a much finer sampling of the event phase space.

Hard $2 \rightarrow 2$ processes from $\sqrt{s} = 5.02$ TeV Pythia [28] pp collisions are sampled using an importance envelope of $(p_T^p/10 \text{ GeV})^4$ for a parton with momentum p_T^p . Equivalently, this assigns a weight $w_i = (10 \text{ GeV}/p_T^p)^4$ to each trajectory, allowing us to maintain controlled statistics in the high- p_T^p tail of the distribution. APE then embeds the unmodified partonic hard scattering products in the event geometry, distributed according to the binary collision density $n_{bc}(x, y) \propto s^2(x, y) \propto T^6(x, y)$ as in Refs. [14,29], computing trajectories for a fixed grid of initial azimuthal angles for the scattering axis at each production point. The partons are initially antiparallel by construction, as we include only the tree-level scattering in this work. This approximation does not affect single-inclusive distributions (R_{AA} , v_2) but does affect acoplanarity; we thus report the *enhancement* due to the impact of drift, which may be modified with a fluctuating treatment of the broadening.

Jet seeds in the plasma are evolved along a path parameterized by path length ℓ using the following kinematic workflow:

- (1) Propagate the parton over a small timestep of length $\Delta t = 0.1$ fm in the plasma center of mass rest frame.
- (2) Compute the momentum transferred to the parton over the small pathlength $\Delta \ell = \beta \Delta t$ due to enabled effects, updating parton momentum accordingly.
- (3) Repeat until the parton escapes the plasma perimeter at freezeout.

We keep the quark masses, noting that for the light flavors considered here $\beta \approx 1$. For every initial condition, we perform separate simulations with contributions of radiative energy loss, collisional energy loss, and jet drift effects switched on or off, resulting in fully correlated distributions of hard particles for each combination of effects. This minimizes Monte Carlo noise in relative comparisons between them, allowing extraction of statistics-hungry measures like the elliptic flow *enhancement* due to drift, Δv_2^{exp} (Fig. 3), in smaller sample sizes. Initial- and final-state properties of the hard partons are recorded before applying hadronization. We consider no medium response effects at this time.

Neglecting the running of α_s , we tune the coupling for the two energy loss cases (both including drift) via reduced χ^2 fit to Compact Muon Solenoid (CMS) R_{AA} data at 30%–50% centrality and $p_T \in [8 \text{ GeV}, 35 \text{ GeV}]$ [30]. To two significant figures, we find $g = \sqrt{4\pi\alpha_s} \approx 2.1$ with radiative energy loss alone and $g \approx 1.8$ with radiative and collisional energy loss, consistent with values from the literature [31]. We have also explored the use of various forms of cold nuclear matter effects, but

the observables reported here were found to be largely insensitive to their inclusion. Herein we choose to follow the perturbative treatment of Refs. [2,32,33] for the Cronin effect, isospin effects, and nuclear shadowing, but we neglect cold nuclear matter energy loss.

A perturbative calculation of parton drift and energy loss requires input for the mean free path λ and Debye screening mass μ . The latter reads $\mu \approx gT\sqrt{1+N_f/6}$, where we use $N_f = 2$, and by definition $\lambda^{-1} = \sigma_q \rho_q + \sigma_g \rho_g$, with $\sigma_q(\sigma_g)$ the total cross section for the hard parton to interact with a quark (gluon) in the plasma and $\rho_q(\rho_g)$ the density of quarks (gluons) in the medium. Here, we use the Gyulassy-Wang cross section modeled after static scattering centers in the medium [34], and the cross sections and partial quark and gluon densities are taken from Ref. [35], which approximates the medium as an ideal gas of gluons and quarks. It should be noted that the identified parton number densities $\rho_q(\rho_g)$ are not provided by the hydrodynamic equation of state and are necessary to compute the various flavor-dependent channels of jet-medium interactions. We set $\lambda \rightarrow \infty$ when the medium cools below the hadronization temperature, which is chosen to be $T_{\text{had}} = 155$ MeV. We note that this conservative assumption removes the potential effect of late-time interactions where collective flow, and thus drift, is strongest.

Calculations of the energy loss of high-energy partons due to stimulated gluon emission are computationally demanding. This has led to a range of approaches to evaluate energy loss in realistic media. Many of the traditional works select an analytic form for the plasma [36], others create effective lengths and temperatures as realistic envelopes on an analytic model [37], while others simplify or parametrize the energy loss form [3]. We elect to numerically compute the average single-emission Gyulassy-Levai-Vitev radiative energy loss at first order in opacity, including finite kinematic bounds for the momentum transfer to the medium and the radiated gluon momentum, using the Gyulassy-Wang form for the scattering potentials [36]. The behavior of the radiative energy loss is qualitatively different at low p_T for different choices of kinematic bounds, where sub-eikonal corrections become large. In a medium of effective length L , the mean energy loss rate is

$$\frac{dE}{d\ell} = -\frac{d}{dL} \left(\frac{2C_R \alpha_s}{\pi} \frac{L}{\lambda} E \int_{k_{\min}}^{k_{\max}} \frac{dk}{k} \int_0^{q_{\max}} dq q \int_0^{2\pi} d\phi \right. \\ \left. \times \frac{\mu^2}{\pi(q^2 + \mu^2)^2} \frac{2\mathbf{k} \cdot \mathbf{q}(\mathbf{k} - \mathbf{q})^2 L^2}{16x^2 E^2 + (\mathbf{k} - \mathbf{q})^4 L^2} \right)_{L=\ell}, \quad (3)$$

with $k_{\min} = \mu$, $k_{\max} = \min\{2Ex, 2E\sqrt{x(1-x)}\}$, and $q_{\max} = \sqrt{6ET}$ [36,38]. Here, C_R is the quadratic Casimir of the representation R of $SU(3)$ ($C_R = 3$ for gluons, $C_R = 4/3$ for quarks). We take $\tau_0 = 0.37$ fm for the thermalization time and do not treat the short-path-length corrections as derived in Ref. [39], which may be significant even for large collision systems. Thus, for massless partons, $L = \tau - \tau_0$, with τ the time relative to the collision in the plasma center of mass rest frame.

As described in Eq. (3), we evaluate the mean energy loss of a hard parton of energy E in a QGP of fixed length and temperature, and then compute the rate in L by central differences. This yields the tabulated instantaneous energy loss rate

$dE/d\ell$ we sample at run-time in each time step of the partonic propagation. This method preserves the quadratic path length dependence associated with the Landau-Pomeranchuk-Migdal effect [40,41] and the additional effects associated with the expanding medium, locally samples the properties of the QGP at each point of the partonic trajectory in a hydrodynamic geometry, and is computationally cheap at run-time. We implement an analytic calculation for the collisional energy loss [42] and can include it or neglect it in the computation, so as to estimate the effect on the phenomenology of drift:

$$\frac{dE}{d\ell} = -\frac{C_R \mu^2}{2} \ln \left(2^{\frac{N_f}{2(6+N_f)}} 0.920 \frac{\sqrt{ET}}{m_g} \right), \quad (4)$$

where $m_g = \mu/\sqrt{3}$ is the thermal gluon mass. A finite-temperature perturbative calculation [43] shows only minor corrections to Eq. (4). Likewise, the additional finite- L corrections to Ref. [43] were also shown to be small [44].

We treat only the first odd moment of the flow-mediated drift computed in Ref. [11]. The momentum transferred to the parton *transverse to its trajectory* is

$$\langle \vec{q}_{\text{drift}} \rangle = \hat{e}_\perp \int d\ell \frac{3}{E} \frac{\mu^2}{\lambda} \ln \frac{E}{\mu} \frac{u_\perp}{1 - u_\parallel}. \quad (5)$$

Here, λ is the mean free path, μ is the Debye screening mass, and $\vec{u}$ is the collective flow velocity, with components $\parallel$ and $\perp$ to the parton momentum vector, and $\hat{e}_\perp$ is the corresponding unit vector. Several recent works have extended the calculation of the impact of collective flow and gradients on medium-induced momentum broadening and radiation [45–49]; however, the moment we consider here has been shown to be exact to all orders in opacity [46].

The distribution of leading hadrons can be calculated from the distribution of leading partons by convolution with fragmentation functions (FFs) $D_p^h(z)$ [50]

$$\frac{d\sigma_{NN}^h}{dy dp_T^h} = \int dz \frac{1}{z} D_p^h(z) \frac{d\sigma_{NN}^p}{dy dp_T^p}. \quad (6)$$

In order to evaluate this expression for a discrete distribution of quarks and gluons, we perform an event-by-event fragmentation such that for a given parton with fixed flavor and p_T^p , we sample from a probability distribution function for hadronic momentum fraction $z = p_T^h/p_T^p$ proportional to the inclusive fragmentation function, $P_{p_T^p}^h(z) \propto D_p^h(z)$. We compute the distribution of inclusive charged hadrons, applying the JAM Collaboration's "JAM20-SIDIS" FF fits for charged hadrons [51] accessed through LHAPDF [52].

This treatment of the system as a whole takes the most conservative choices for each phase of the computation. The results represent a realistic lower bound on the effect size of flow-mediated drift. This energy regime, and especially the flow-mediated drift effect, is quite sensitive to model choices at every step. To study the impact of various other viable scenarios, we also implement a sharper, more anisotropic optical Glauber initial condition for the medium and formulate a simple treatment of hybrid coalescence effects. For the initial entropy density of the sharp optical Glauber medium model, we take the harmonic mean of two Woods-Saxon nuclear density profiles $T_{A,B}$ [23,24], $dS/dy \propto 2T_A T_B / (T_A + T_B)$. The

higher anisotropy and sharper gradients of these initial conditions produce larger deflections due to flow. The medium evolution is treated identically. Following Ref. [53], we presume that pions dominate the charged hadron distribution; thus, we take the distribution of hadrons formed from the hybrid coalescence of a hard parton and a thermal parton to be

$$\begin{aligned} \frac{dN_h}{dp_h d\phi_h} &= g_\pi \frac{6\pi^2}{V \Delta_p^3} \int dp_1 d\phi_1 dp_2 d\phi_2 \\ &\times \frac{dN_{\text{hard}}}{dp_1 d\phi_1} \frac{dN_{\text{thermal}}}{dp_2 d\phi_2} \delta^3(\vec{p}_h - \vec{p}_1 - \vec{p}_2) \\ &\times \Theta(\Delta_p - |p_{T,1} - p_{T,2}|/2), \end{aligned} \quad (7)$$

where we have taken the same model form for the Wigner distribution of the pion as Ref. [53] (with the momentum width of the pion $\Delta_p = 0.24$ GeV, V the volume of the QGP, and g_π the formation probability). Our thermal parton distribution is a simple Boltzmann distribution in the center-of-mass rest frame of the fluid with the appropriate boson or fermion statistics for the hard parton's color neutralizing counterpart, $dN_{\text{thermal}}/dp_1 d\phi_1 \propto 1/(e^{E/T_{\text{had}}} \pm 1)$.

Results. A simultaneous description of the suppression $R_{AA}(p_T)$ of jets and their elliptic modulation $v_2(p_T)$ has been one of the benchmark problems of jet physics in heavy ion collisions [3–8,54]. Various microscopic models and calculations can simultaneously capture both observables in the high-energy regime, $p_T > 10$ GeV, but perturbative calculations have not successfully described the intermediate- and low-energy regimes, $p_T < 10$ GeV, where elliptic flow is generally underpredicted [4,6,18] (the $R_{AA} \otimes v_2$ puzzle).

Recently, LBT simulations have shown an agreement in both R_{AA} and v_2 from low to high p_T using a highly flexible hybrid hadronization model [5]. While this demonstrates the impressive tunability of LBT and hybrid hadronization, such models cannot be relied on to rule out other sources of additional elliptic flow, as large corrections to their microscopic plasma-probe interaction models may be disguised by inherent freedom in parameter choice.

Jet drift is a perturbative correction to the transverse momentum distribution that naturally supplies some of the missing flow. While this sub-eikonal effect does not directly modify the energy loss, drift may indirectly affect the suppression by deflecting the paths toward regions of lower density. This deflection, however, directly modifies the azimuthal distribution of particles. The coupling of drift to the medium correlates leading hadrons to the event plane by dragging hard particles toward “attractors” at the minor axes of the elliptic medium geometry, as illustrated via sample trajectories in Fig. 1.

We report the suppression R_{AA} as computed from Eq. (1) in Fig. 2 and the enhancement of elliptic flow (the difference in elliptic flow with and without drift) in Fig. 3. We take the denominator of Eq. (1) as the number distribution of partons seeded from Pythia. The complex vector $\vec{v}_2^{\text{hard}}$ is computed via the Q-cumulant method [55] as a discrete sum over all trajectories i producing final state particles in the given

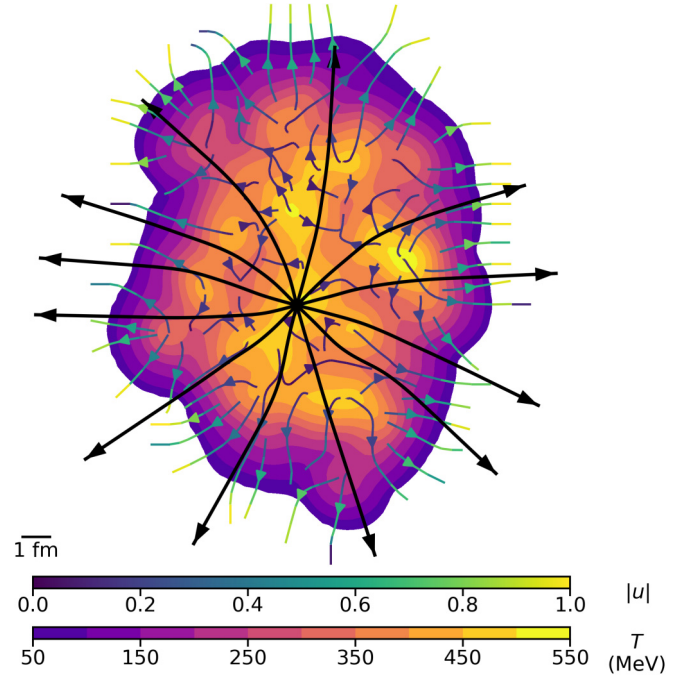


FIG. 1. APE computed trajectories (black arrows) for an azimuthally uniform distribution of gluons originating at a hot spot in a mid-central $\sqrt{s_{NN}} = 5.02$ TeV PbPb event geometry. Note the coupling to the elliptic flow of the medium, attracting partons to the event plane. Parameters selected for illustrative purposes.

p_T bin:

$$\vec{v}_n^{\text{hard}}(p_T) = \left\langle \frac{\sum_i w_i e^{in\phi_i}}{\sum_i w_i} \right\rangle, \quad (8)$$

where w_i is the weight associated with parton i and ϕ_i is the final azimuthal angle of the trajectory. Finally, the angle brackets represent an average over events. The soft elliptic flow $\vec{v}_2^{\text{soft}}$ is computed similarly to $\vec{v}_2^{\text{hard}}$ for thermal particles $p_T \in [0.2 \text{ GeV}, 5 \text{ GeV}]$ from UrQMD. The experimentally

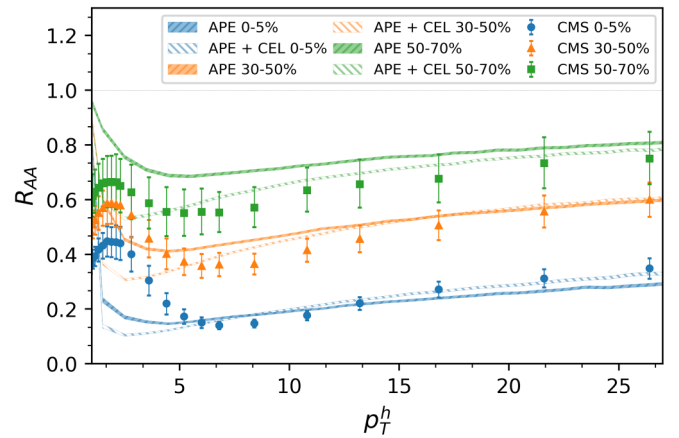


FIG. 2. APE results for radiative energy loss alone and radiative energy loss + collisional energy loss (labeled “+ CEL”) (bootstrap statistical error associated with the fluctuating event shown as hatched bands, with maximum value $\approx \pm 0.028$) plotted against CMS data for $R_{AA}(p_T^h)$ at different centralities [30].

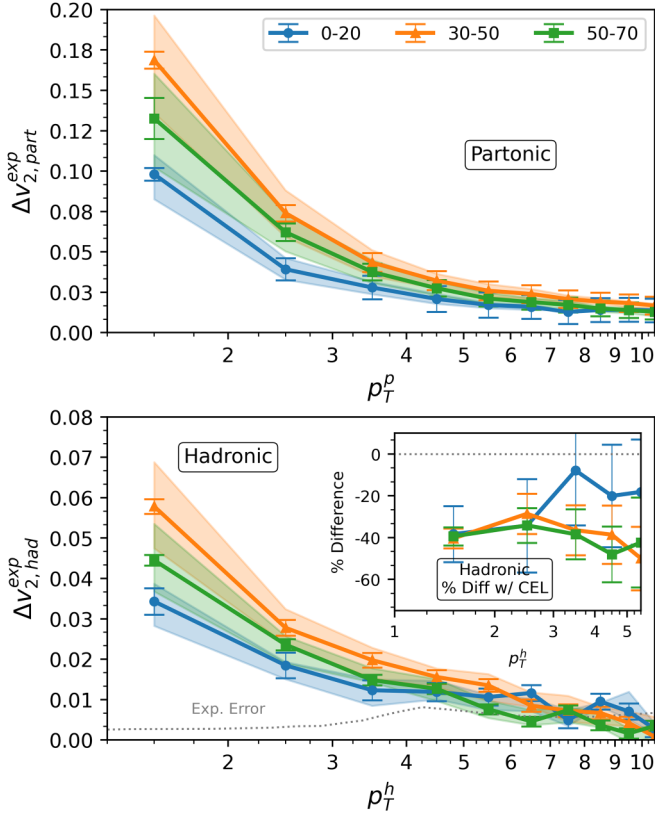


FIG. 3. Δv_2^{exp} from flow-mediated jet drift as a function of leading-partonic p_T^p (upper panel) and leading-hadronic p_T^h (lower panels) in several centrality bins, including the percent difference of hadronic Δv_2^{exp} with collisional and radiative energy loss to only radiative (inset). Theoretical error is quantified by varied strength of drift from 75% to 125%, and bootstrap statistical error associated with the fluctuating event is shown in fences. Experimental error threshold is plotted for 30%–40% centrality charged pions from CMS [56], which is everywhere $\leq 1\%$. The p_T bin width is fixed to be 1 GeV.

measured $v_n^{\text{exp}}(p_T)$ is the scalar product of the soft and hard flow vectors:

$$v_n^{\text{exp}}(p_T) = \frac{\langle \vec{v}_n^{\text{hard}} \cdot \vec{v}_n^{\text{soft}} \rangle}{\sqrt{\langle |\vec{v}_n^{\text{soft}}|^2 \rangle}}. \quad (9)$$

This treatment differs slightly from the experimental observable in that we restrict v_n^{hard} to be computed with only particles coming from the hard scattering. This affects the result only below $p_T \leq 2$ GeV (see the soft sector mean p_T in Ref. [22]). We retain the distribution of hard partons here, however, because it could still be informative for other observables after appropriate background subtraction.

Int intriguingly, we obtain a nuclear modification factor $R_{AA}(p_T)$ in Fig. 2, which is unmodified due to the effects of drift. This suggests that any systematic bias of trajectories toward lower density is not significant for the nuclear modification factor. We do, however, see the anticipated enhancement of the experimental elliptic flow shown in Fig. 3, which turns out to be sizable: an enhancement of several times the experimental uncertainty (e.g., APE $\Delta v_2^{\text{exp}} \approx 0.020 \pm$

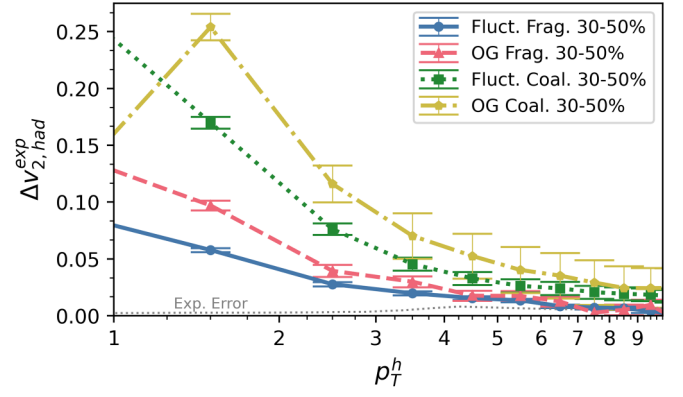


FIG. 4. Comparison of Δv_2^{exp} in APE 30%–50% centrality collisions for combinations of optical Glauber vs fluctuating initial conditions and coalescence vs fragmentation hadronization mechanisms. Bootstrap statistical error associated with the fluctuating event is shown in fences. Experimental error threshold is plotted for 30%–40% centrality charged pions from CMS [56], which is everywhere $\leq 1\%$. The p_T bin width is fixed to be 1 GeV.

0.004, compared to CMS $v_2^{\text{exp}} \approx 0.208 \pm 0.006$ for charged pion v_2 at 3.00–3.25 GeV in the 30%–40% bin [56]). Interestingly, the enhancement from drift qualitatively matches the excess in elliptic flow seen in experiment below 10 GeV [56]. While we make no claim that jet drift is *the* solution to the $R_{AA} \otimes v_2$ puzzle, it must nevertheless be an important *part* of the solution in the $p_T < 10$ GeV regime. We also note that the jet drift effect is strongest in semiperipheral collisions (30%–50% centrality), which balance a larger event eccentricity with the decreasing event temperatures in smaller-sized QGP. This demonstrates the interplay between energy loss and drift, whereby energy loss enhances the strength of drift, but strong energy loss extinguishes partons that have experienced strong drift. Likewise, the addition of collisional energy loss (and the refitting of the coupling) reduces the strength of the v_2^{hard} enhancement by about 50%, as shown in the ratio inset of Fig. 3. This occurs because a lower overall coupling is necessary to fit high- p_T suppression, and the relative strength of drift is reduced. The addition of more sources of energy loss (including from cold nuclear matter effects) generally reduces the relative strength of drift; however, a more realistic fluctuating treatment of collisional energy loss may not display this same behavior.

The strength of the anisotropic flow modification (Δv_2^{exp}) is significantly enhanced by the inclusion of coalescence or the use of a sharper initial condition for the medium evolution. As shown in Fig. 4, coalescence upshifts the p_T of strongly drifted partons, expanding the region of interest and dramatically increasing the magnitude of the enhancement. This implementation takes an isotropic distribution of thermal partons and thus does not include direct convolution with the azimuthal anisotropy of the medium, which is expected to have additional complex interplay with drift. The combination of both changes represents an optimistic, rational estimate, but is by no means an upper bound on the effect.

We further study acoplanarity in APE by embedding the pairs of partons from each hard process on exactly antiparallel trajectories at the same production point in a given event

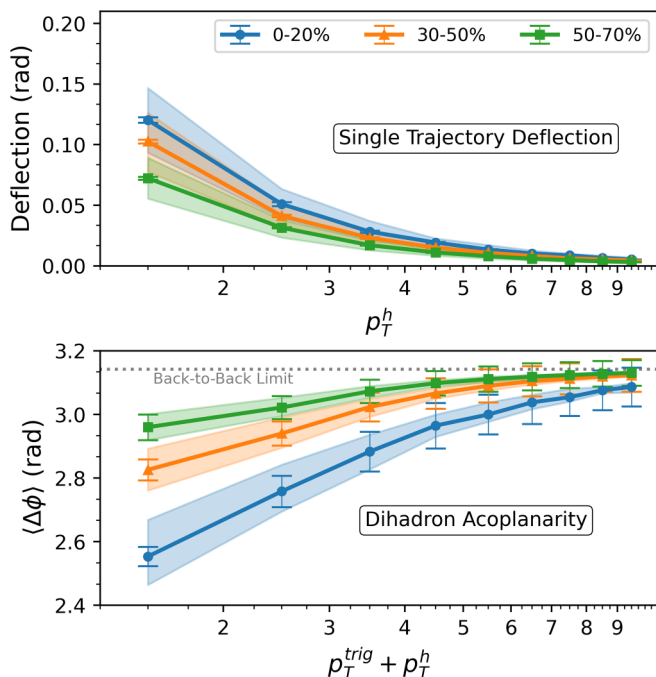


FIG. 5. Top: Mean angle of deflection due to drift as a function of p_T^h for charged hadrons. Bottom: Mean dihadron acoplanarity (deviation from π), including *only* anisotropic broadening and radiative energy loss as a function of $p_T^{\text{trig}} + p_T^h$. The p_T bin width is fixed to be 1 GeV. Bootstrap statistical error associated with the fluctuating event is shown in fences, with maximum deflection error value $\approx \pm 0.002$.

geometry. The resulting deflections of single partons, defined as the difference in initial and final trajectory angle, and acoplanarity, defined as the smallest angle between parton pairs from the same hard process in the final state, are plotted in Fig. 5.

The correlated deflections of particles from drifting in the same event geometry result in an enhancement of the acoplanarity (a deviation from back to back) (Fig. 5) between the hadrons. The additional contribution from drift can be easily understood from Fig. 1, in which widely separated parton trajectories are deflected toward the same “attractor” in the event geometry. While v_2^{hard} measures deflections correlated with the event plane, the azimuthally averaged acoplanarity provides a complementary measure of the *magnitude* of the deflections, independent of the event plane, although the strength of the enhancement varies azimuthally relative to the event plane.

Like the elliptic flow v_2 , the mean deflection angles and acoplanarity show sizable enhancements due to drift at low p_T , e.g., greater than 5-degree acoplanarity below 6 GeV. Importantly, however, the centrality dependence has changed between Figs. 3 and 5. The elliptic flow enhancement Δv_2^{exp} is largest for the intermediate 30%–50% centrality bin, while the deflections and acoplanarity are largest in the 0%–20% central bin. This is a reflection of the fact that acoplanarity are sensitive to the *magnitude* of drift, which is largest in central collisions but more weakly correlated with the event plane. The elliptic flow, on the other hand, reflects not only

the temperature but also the ellipticity, which is largest in peripheral collisions.

The results shown here do not include isotropic broadening effects by construction: The average momentum transfer $\langle \vec{p}_\perp \rangle$ due to isotropic broadening is zero; thus, there is no net deflection. Likewise, the antiparallel tree-level scatterings treated here do not include Next to Leading Order corrections to their acoplanarity. These effects will contribute to the correlated acoplanarity $\Delta\phi$, so the acoplanarity from average drift alone cannot be interpreted as an exact parallel of the experimental acoplanarity. However, it demonstrates the potentially large impact on experimental acoplanarity due to flow and, crucially, demonstrates the qualitative centrality ordering.

Conclusions. Flow-mediated drift, as studied here, belongs both to a family of sub-eikonal effects that extend the theory of jet quenching toward lower p_T and to a family of anti-symmetric effects that can generate azimuthal anisotropies of hard probes. This work shows that anisotropic effects modify hard observables in ways that survive event averaging, and sub-eikonal effects can systematically extend perturbative calculations to intermediate and low p_T . We have further demonstrated that inclusive measures like v_2 and correlations like acoplanarity exhibit different systematics in their response to drift. Jet drift and similar effects are sensitive to properties of the medium that neither isotropic measures of hard probes nor soft-sector anisotropies can capture, including local flow structure, flowing hot spots, and other internal structural differences. These properties of jet drift provide an additional dimension of sensitivity with which to expand the prospects of jet QGP tomography championed by the field.

Throughout this study, the main results intentionally presented a conservative estimate of the effect of jet drift (Fig. 3). Despite the unfavorable assumptions as described in our methodology section, we show here that jet drift nonetheless leaves substantial imprints of the flow on low- p_T^h particles, systematically enhancing elliptic flow above the experimental error threshold and increasing dijet acoplanarity. The reasonable inclusion of coalescence and use of a sharper medium model significantly enhances the effect (Fig. 4) and serves to emphasize how sensitive the results of an intermediate p_T simulation are to model choices, especially in regard to drift. Consequently, this study constitutes the first unambiguous demonstration of the importance of full velocity tomography in event-by-event heavy-ion collisions and the first comprehensive phenomenological investigation of the flow modification of hard probes.

A survey of candidate observables that more directly access the deflection due to drift is in progress using an improved version of APE. In the future, we plan to perform a combined R_{AA} and v_2 fit, which will correspondingly enhance the drift effect. We will also study the implications of drift for intrajet particle and energy distributions [57]. Previous work has suggested that gradients and flow may impact the distribution of radiation in the jet cone [11, 21, 58]; however, we expect jet substructure to be even more sensitive to flow than the inclusive observables considered here due to the *combination* of this asymmetric gluon radiation and deflections due to drift.

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Data availability. Some of the data that support the findings of this article are openly available [63]. All raw data corresponding to the findings in this manuscript are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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