EPJ Web of Conferences **339**, 02009 (2025)
Hard Probes 2024
https://doi.org/10.1051/epjconf/202533902009

Jet Drift in Heavy Ion Collisions

Joseph Bahder[1,*], *Hasan* Rahman[1,**], *Matthew* Sievert[1,***], and *Ivan* Vitev[2,****]

[1]New Mexico State University
[2]Los Alamos National Labs

Abstract. We introduce a sub-eikonal anisotropic contribution to jet-broadening, "jet drift", that couples to the flow of the medium, showing that this effect results in a deflection of hard partons, and thus jets, in the direction of the medium flow. Next, we study this effect in a full-fledged hybrid transport simulation of $\sqrt{s} = 5.02$ TeV PbPb collisions at the LHC, tracking trajectories of hard partons with perturbative energy loss and drift. We show that sub-eikonal anisotropic effects, including flow-mediated jet drift, are sensitive to properties of the medium that traditional eikonal isotropic effects are insensitive to, demonstrating that including these effects leads to modifications to jet and hard particle observables that survive averaging over events. We show that jet drift leads to an enhancement of the elliptic flow (v2) of hard particles.

1 Introduction

Hard probe tomography of the novel quark gluon plasma (QGP) produced in heavy ion collisions (see [1] for a review) has been a preeminent goal since the beginning of the heavy ion programs. Despite initial success [2] in calculating modifications to hard probes, the delivery of true tomography has stalled due to the inherent complexities of the problem. Standard measures of hard probe modification, like the nuclear modification factor

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

where $\langle n_{coll}\rangle$ is the number of binary collisions, can be reproduced by a wide variety of pQCD calculations and other models [3–8] (see e.g. [9] for a direct multi-model comparison).

This lack of discriminatory power results largely from the inherent generality of isotropic modifications to hard probes: many features of varying models result in highly similar phenomenological effects.

In previous work, the authors have shown that hard probes in the presence of a flowing medium have an $O(\mu/E)$ anisotropic component, μ being a medium scale and E the parton energy, preferencing broadening in the direction of the flow [10]. The preferred broadening amounts to a systematic deflection of hard probes in the direction of the flow, an effect dubbed “jet drift". Drift is unique in that it is *locally* anisotropic – it carries a preferred vector direction coupled to a local anisotropy in the medium. Drift is a unique type of phenomenological

---

[*] e-mail: joseph.bahder@gmail.com
[**] e-mail: hrrahman@nmsu.edu
[***] e-mail: msievert@nmsu.edu
[****] e-mail: ivitev@lanl.gov

modification to hard probes that has no parallel in other models and is highly sensitive to the medium geometry.

In principle, sensitivity to the flow of the QGP opens a new field of velocity tomography. 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.

To investigate the importance of this new flow effect, we present the first study of event-by-event jet drift via APE (Anisotropic Partonic Evolution), a new open-source Monte Carlo parton trajectory simulator, that incorporates a host of flexible model choices to survey the variability of the effect. Throughout, we make the most conservative model choices to set a reasonable lower bound on the size of the effect (Fig. 2). 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 Large Hadron Collider (LHC). Furthermore, we show that reasonable model choices can dramatically enhance the effect (Fig. 3).

2 APE Results

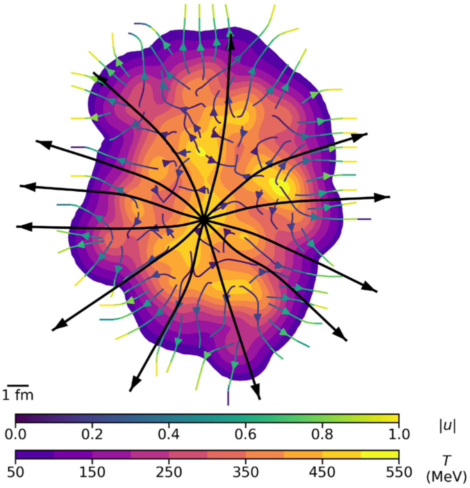

Figure 1. APE computed trajectories (black arrows) for an azimuthally uniform distribution of gluons originating at a hot spot in a mid-central $\sqrt{s_{NN}} = 5.02$ TeV PbPb event geometry. Note the coupling to the elliptic flow of the medium, attracting partons to the event plane. Parameters selected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

In APE, we implement the momentum transfer due to jet drift at the level of the first moment of the broadening distribution to sub-eikonal order in the presence of flow:

$$\left\langle \vec{q}_{drift} \right\rangle = \hat{e}_{\perp} \int d\ell \, \frac{3}{E} \frac{\mu^2}{\lambda} \ln \frac{E}{\mu} \frac{u_{\perp}}{1 - u_{\parallel}}, \tag{2}$$

neglecting fluctuations. Further details on our methodology are available in [11].

Our analysis reveals that the locally anisotropic drift effect conspires to enhance the global asymmetry of hard particles in the azimuthal plane, quantified by the hard flow vectors $v_n^{hard} = v_n e^{in\psi_n}$:

$$\frac{R_{AA}(p_T,\phi)}{R_{AA}(p_T)} \equiv 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n^{hard}(p_T))]\,. \tag{3}$$

We present a conservative lower bound estimate of the enhancement to the correlation between the soft (medium) and hard elliptic flow vectors

$$v_2^{exp}(p_T) = \frac{\left\langle \vec{v}_2^{\,hard} \cdot \vec{v}_2^{\,soft} \right\rangle}{\sqrt{\left\langle \left|\vec{v}_2^{\,soft}\right|^2 \right\rangle}}, \tag{4}$$

due to drift in Fig. 2. This closely approximates the enhancement to the experimentally measured hard $v_2\{SP\}$ [12].

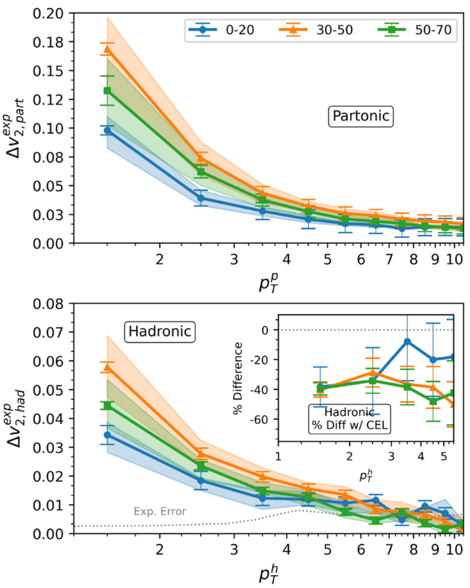

Figure 2. Δv_2^{exp} from flow-mediated jet drift as a function of leading-partonic p_T^p (upper panel) and leading-hadronic p_T^h (lower panels) in several centrality bins, including the percent difference of hadronic Δv_2^{exp} with collisional and radiative energy loss to only radiative (inset). Theoretical error is quantified by varied strength of drift from 75-125%, 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 [13], which is everywhere $\leq 1\%$. The p_T bin width is fixed to be 1 GeV.

Comparing against the experimental error, it is clear from these results alone that the effect of drift is both substantial and measurable. The hadronic results here rely on an implementation of pertubative fragmentation valid at high-p_T, resulting in preferences for extremely small framentation momentum fractions $z = p_T^h/p_T^p$. Furthermore, the medium model was deliberately selected to have large event-by-event fluctuations, effectively screening the global flow structure. Relaxing these two aggressive model choices results in a dramatic enhancement of the modification to v_2^{exp}, as shown via the implementation of a hybrid soft-hard coalescence hadronization mechanism [14] and smooth optical glauber initial conditions for the medium in Fig. 3.

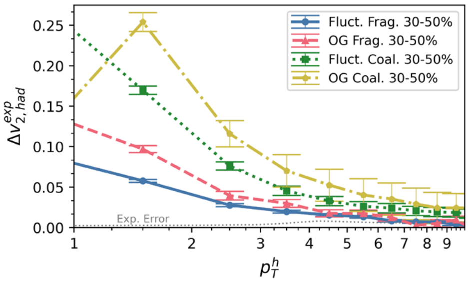

Figure 3. Comparison of Δv_2^{exp} in APE 30-50% centrality collisions for combinations of optical Glauber vs fluctuating initial conditions and coalescence vs fragmentation hadronization mechanisms. Bootstrap statistical error associated with the fluctuating event is shown in fences. Experimental error threshold is plotted for 30-40% centrality charged pions from CMS [13], which is everywhere ≤ 1%. The p_T bin width is fixed to be 1 GeV.

3 Conclusions

In this work, we show via a new Monte Carlo framework that the flow of the elliptic QGP enhances the elliptic flow of hard particles. Furthermore, we show that the space of reasonable models suggests this effect may be extremely large.

This study constitutes the first unambiguous demonstration of medium flow effects on hard probes, setting the stage for a new field of hard probe velocity tomography. While the current study is limited by the currently unconstrained theory at low- and intermediate-p_T, it motivates a systematic accounting of all sub-eikonal hard probe modification effects, with a special emphasis on those coupling to medium anisotropies.

In continuing work, we intend to focus on direct experimental measurements of drift-like couplings to the medium flow structure and the effect of jet drift on jet substructure.

References

[1] M. Connors, C. Nattrass, R. Reed, S. Salur, Jet measurements in heavy ion physics, Rev. Mod. Phys. **90**, 025005 (2018), `1705.01974`. 10.1103/RevModPhys.90.025005

[2] I. Vitev, M. Gyulassy, High p_T tomography of d + Au and Au+Au at SPS, RHIC, and LHC, Phys. Rev. Lett. **89**, 252301 (2002), `hep-ph/0209161`. 10.1103/PhysRevLett.89.252301

[3] J. Noronha-Hostler, B. Betz, J. Noronha, M. Gyulassy, Event-by-event hydrodynamics + jet energy loss: A solution to the $R_{AA} \otimes v_2$ puzzle, Phys. Rev. Lett. **116**, 252301 (2016), `1602.03788`. 10.1103/PhysRevLett.116.252301

[4] D. Molnar, D. Sun, High-pT suppression and elliptic flow from radiative energy loss with realistic bulk medium expansion (2013), `1305.1046`.

[5] W. Zhao, W. Ke, W. Chen, T. Luo, X.N. Wang, From Hydrodynamics to Jet Quenching, Coalescence, and Hadron Cascade: A Coupled Approach to Solving the

RAA⊗v2 Puzzle, Phys. Rev. Lett. **128**, 022302 (2022), `2103.14657`. 10.1103/PhysRevLett.128.022302

[6] X. Zhang, J. Liao, Jet Quenching and Its Azimuthal Anisotropy in AA and possibly High Multiplicity pA and dA Collisions (2013), `1311.5463`.

[7] B.Z. Kopeliovich, J. Nemchik, I.K. Potashnikova, I. Schmidt, Quenching of high-pT hadrons: Energy Loss vs Color Transparency, Phys. Rev. C **86**, 054904 (2012), `1208.4951`. 10.1103/PhysRevC.86.054904

[8] C. Andres, N. Armesto, H. Niemi, R. Paatelainen, C.A. Salgado, Jet quenching as a probe of the initial stages in heavy-ion collisions, Phys. Lett. B **803**, 135318 (2020), `1902.03231`. 10.1016/j.physletb.2020.135318

[9] A. Hayrapetyan et al. (CMS), Overview of high-density QCD studies with the CMS experiment at the LHC (2024), `2405.10785`.

[10] A.V. Sadofyev, M.D. Sievert, I. Vitev, Ab Initio Coupling of Jets to Collective Flow in the Opacity Expansion Approach (2021), `2104.09513`.

[11] J. Bahder, H. Rahman, M.D. Sievert, I. Vitev, Signatures of Jet Drift in QGP Hard Probe Observables (2024), `2412.05474`.

[12] M. Luzum, J.Y. Ollitrault, Eliminating experimental bias in anisotropic-flow measurements of high-energy nuclear collisions, Phys. Rev. C **87**, 044907 (2013), `1209.2323`. 10.1103/PhysRevC.87.044907

[13] A.M. Sirunyan et al. (CMS), Azimuthal anisotropy of charged particles with transverse momentum up to 100 GeV/ c in PbPb collisions at $\sqrt{s_{NN}}$=5.02 TeV, Phys. Lett. B **776**, 195 (2018), `1702.00630`. 10.1016/j.physletb.2017.11.041

[14] V. Greco, C.M. Ko, P. Levai, Parton coalescence and anti-proton / pion anomaly at RHIC, Phys. Rev. Lett. **90**, 202302 (2003), `nucl-th/0301093`. 10.1103/PhysRevLett.90.202302