Kinematic dependence of azimuthal anisotropies in $p+Au$, $d+Au$, $^3He+Au$ at $\sqrt{s_{NN}} = 200$ GeV

U.A. Acharya, A. Adare, C. Aidala, N.N. Ajitanand, Y. Aikawa, M. Alfred, V. Andrieux, K. Aoki, N. Apadula, H. Asano, C. Ayuso, A. Aznoum, V. Babintsev, M. Bai, N.S. Bandara, B. Bannier, K.N. Barish, S. Bathe, A. Bazilevsky, M. Beaumier, S. Beckman, R. Belmont, A. Berdnikov, L. Berdnikov, B. Blankenship, D.S. Blau, M. Boer, J.S. Bok, V. Borisov, K. Boyle, M.L. Brooks, J. Brylowski, V. Bumazhnov, C. Butler, S. Campbell, V. Caoano Roman, R. Cervantes, C.-H. Chen, M. Chiu, C.Y. Choi, J.H. Choi, J.B. Choi, T. Chiu, Z. Citron, M. Connors, R. Corliss, N. Cronin, T. Csörgö, M. Csanád, L.D. Liu, T.W. Danley, A. Datta, M.S. Daugherity, G. David, K. DeBlasio, K. Dehmelt, A. Denisov, A. Deshpande, E.J. Desmond, A. Dion, P.B. Diss, D. Dixit, J.H. Do, A. Drees, K.A. Drees, M. Dumanec, J.M. Durham, T. Elder, H. En’yo, A. Enokizono, R. Esho, S. Esumi, F. Fadem, W. Fan, N. Fege, D.E. Fields, M. Finger, F. Fitzgerald, S.L. Fokin, J.E. Franitz, A. Franz, A.D. Frawley, Y. Fukuda, P. Gallus, C. Gal, P. Garg, H. Ge, M. Giles, F. Giordano, A. Glenn, Y. Goto, J.S. Haggerty, K.I. Hahn, H. Hamagaki, H.F. Hamilton, J. Hanks, S.Y. Han, M. Harvey, S. Hasegawa, T.O.S. Haseler, K. Hashimoto, T.K. Hemmick, X. He, J.C. Hill, K. Hill, A. Hodges, R.S. Hollis, K. Homma, B. Hong, T. Hoshino, N. Hotvedt, J. Huang, K. Imai, J. Inoue, M. Inaba, A. Iordanova, D. Isenhour, Y. Ito, D. Ivanishchev, B.V. Jacak, M. Jezhakh, X. Jiang, Z. Ji, B.M. Johnson, V. Jorjadv, D. D. Jumper, K. Kanda, J.H. Kang, D. Kapulkchian, S. Karthas, D. Kawall, A.V. Kazantzov, J.A. Key, V. Khachatryan, A. Khazadze, A. Khattab, B. Kimelman, C. Kim, D.J. Kim, E.-J. Kim, G.W. Kim, M. Kim, M.H. Kim, D. Kinseyes, K. Kinian, E. Kistenev, R. Kitamura, J.L. Klatzky, D. Kleinj, P. Kline, T. Koblesky, B. Komok, D. Kotov, L. Kovacs, S. Kudo, B. Kurgis, K. Kurita, M. Kuwaso, Y. Kwon, J.G. Lajoie, E.O. Lallow, D. Larionova, A. Lebedev, S. Lee, S.H. Lee, A.M. Leitch, Y.H. Leung, N.A. Lewis, S.H. Li, M.X. Li, T. Li, X. Li, V.R. Loggins, S. Lokeks, D.A. Loomis, K. Lovasz, D. Lynch, T. Majoros, Y.I. Makdisi, M. Makek, M. Malaev, A. Manion, V.I. Manko, E. Mannel, H. Masuda, M. MeCumber, P.L. McGaughy, D. McElhinney, C. McKinley, A. Meles, M. Mendosa, A.C. Mignerey, D.E. Mihalik, A. Milov, D.K. Mishra, J.T. Mitchell, M. Mitirankov, Iu. Mitirankov, G. Mitsuka, S. Miyasaka, S. Mizuno, A.K. Mohanty, M.M. Mondal, P. Montuenga, T. Moon, D.P. Morrison, S.I. Morrow, T.V. Moukhanov, B. Mullol, M. Murakami, J. Murata, I. Nagy, A. Mwai, K. Nagai, K. Nagashima, T. Nagashima, J.L. Nagle, M.I. Nagy, I. Nakagawa, H. Nakagomi, N. Nakano, C. Nattrass, S. Nelson, P.K. Nettakant, T. Niida, S. Nishimura, R. Nouicier, T. Novák, N. Novitzky, G. Nukazuka, A.S. Nyanin, E.O. Brien, C.A. Ogilvie, J.D. Orjuela Koop, J.D. Osborn, A. Oskarsson, G.J. Ottino, K. Ozawa, R. Pak, V. Pantuiev, V. Papavassiliou, J.S. Park, S. Park, M. Patel, S.F. Pate, J.C. Peng, W. Peng, D.V. Perepelitsa, G.D.N. Perera, Y. D. Yu, Peressounko, C.E. PerezLara, J. Perry, R. Petti, J. M. Phipps, T. Pinson, R.P. Pisani, M. Potekhin, A. Pun, M.L. Purschke, P.V. Radzhevich, I. Rak, N. Ramasubramanian, B.J. Ramson, I. Ravinovich, K.F. Read, D. Reynolds, V. Rjabov, Y. Rjabov, D.F. Richardson, T. Rinn, S.D. Rolnick, M. Rosati, Z. Rowan, J.G. Rubin, J. Runchev, A.S. Safonov, S. Sahlinmueller, N. Saito, T. Sakaguchi, S. Sako, V. Samsonov, A. Sarsour, K. Satô, S. Sato, B. Scharfe, B.K. Schmoll, K. Sedgwick, R. Seidl, A. Sen, R. Seto, A. Sexton, D. Sharma, I. Shein, T.A. Shibata, K. Shigaki, M. Shimomura, T. Shiroya, P. Shukla, A. Sickles, C.L. Silva, D. Silvermyr, B.K. Singh, C.P. Singh, V. Singh, M. Shneecole, K.L. Snowball, R.A. Soltz, W.E. Soudheim, S.P. Sorenson, I.V. Sourkova, J.W. Stankus, M. Stepanov, S.P. Stoll, T. Sugitate, A. Sukhanov, J. Sumita, Z. Sun, S. Sun, Z. Sun, S. Syed, J. Szklarz, A. Takeda, A. Takekita, K. Tanida, M.J. Tannenbaum, T. Tarafdar, A. Taranenko, G. Tarnai, R. Tieulient, A. Timilsina, T. Todoroki, S. Tompa, C. Towell, R. Towell, R.S. Towell, I. Tserruya, T. Ueda, B. Ujvari, H.W. van Hecke, S. Vazquez-Carson, J. Velkovska, M. Virtus, V. Vrba, N.V. Vukanov, X.R. Wang, Z. Wang, Y. Watanabe, Y.S. Watanabe, F. Wei, A.S. White, C.P. Wong, C.L. Woody, M. Wysocki, B. Xia, L. Xue, C. Xu, Y.Q. Xu, S. Yalcin, Y.L. Yamaguchi, H. Yamamoto, A. Yanovich, P. Yin, I. Yoon.
J.H. Yoo, I.E. Yushnov, H. Yu, W.A. Zajc, A. Zelenski, S. Zharko, S. Zhou, and L. Zou

(PhENIX Collaboration)

1 Abilene Christian University, Abilene, Texas 79699, USA
2 Department of Physics, Augusta University, Statesboro, Georgia 30460, USA
3 Department of Physics, Banaras Hindu University, Varanasi 221005, India
4 Bhabha Atomic Research Centre, Bombay 400 085, India
5 Baruch College, City University of New York, New York, New York, 10010 USA
6 Collider-Accelerator Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA
7 Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA
8 University of California-Riverside, Riverside, California 92521, USA
9 Charles University, Ovocný trh 5, Praha 1, 116 36, Prague, Czech Republic
10 Science and Technology on Nuclear Data Laboratory, China Institute of Atomic Energy, Beijing 102413, People’s Republic of China
11 Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
12 University of Colorado, Boulder, Colorado 80309, USA
13 Columbia University, New York, New York 10027 and Nevis Laboratories, Irvington, New York 10533, USA
14 Czech Technical University, Zikova 4, 166 36 Prague 6, Czech Republic
15 Debrecen University, H-4010 Debrecen, Egyetem tér 1, Hungary
16 ELTE, Eötvös Loránd University, H-1117 Budapest, Pázmány P. s. 1/A, Hungary
17 Eszterházy Károly University, Károly Robert Campus, H-3200 Gyöngyös, Mátrai út 36, Hungary
18 Ewha Womans University, Seoul 120-750, Korea
19 Florida A&M University, Tallahassee, FL 32307, USA
20 Florida State University, Tallahassee, Florida 32306, USA
21 Georgia State University, Atlanta, Georgia 30303, USA
22 Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan
23 Department of Physics and Astronomy, Howard University, Washington, DC 20059, USA
24 IHEP Protvino, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia
25 University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA
26 Institute for Nuclear Research of the Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia
27 Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic
28 Iowa State University, Ames, Iowa 50011, USA
29 Advanced Science Research Center, Japan Atomic Energy Agency, 2-4 Shirakata Shirane, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan
30 Jeonbuk National University, Jeonju, 54896, Korea
31 Helsinki Institute of Physics and University of Jyväskylä, P.O.Box 35, FI-40014 Jyväskylä, Finland
32 KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan
33 Korea University, Seoul 02841, Korea
34 National Research Center “Kurchatov Institute”, Moscow, 123098 Russia
35 Kyoto University, Kyoto 606-8502, Japan
36 Lawrence Livermore National Laboratory, Livermore, California 94550, USA
37 Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
38 Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden
39 IPNL, CNRS/IN2P3, Univ Lyon, Université Lyon 1, F-69622 Villeurbanne, France
40 University of Maryland, College Park, Maryland 20742, USA
41 Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003-9337, USA
42 Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040, USA
43 Muhlenberg College, Allentown, Pennsylvania 18104-5586, USA
44 Nara Women’s University, Kita-uoya Nishi-machi Nara 630-8506, Japan
45 National Research Nuclear University, MEPhI, Moscow Engineering Physics Institute, Moscow, 115409, Russia
46 University of New Mexico, Albuquerque, New Mexico 87131, USA
47 New Mexico State University, Las Cruces, New Mexico 88003, USA
48 Physics and Astronomy Department, University of North Carolina at Greensboro, Greensboro, North Carolina 27412, USA
49 Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA
50 Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
51 IPN-Orsay, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, BP1, F-91406, Orsay, France
52 Peking University, Beijing 100871, People’s Republic of China
53 PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia
54 Pusan National University, Pusan 46241, Korea
55 RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan
56 RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000, USA
57 Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan
58 Saint Petersburg State Polytechnic University, St. Petersburg, 195251 Russia
59 Department of Physics and Astronomy, Seoul National University, Seoul 151-742, Korea
There is strong evidence for the formation of small droplets of quark-gluon plasma in p/d/3He+Au collisions at the Relativistic Heavy Ion Collider (RHIC) and in p+p/Pb collisions at the Large Hadron Collider. In particular, the analysis of data at RHIC for different geometries obtained by varying the projectile size and shape has proven insightful. In the present analysis, we find excellent agreement with the previously published PHENIX at RHIC results on elliptical and triangular flow with an independent analysis via the two-particle correlation method, which has quite different systematic uncertainties and an independent code base. In addition, the results are extended to other detector combinations with different kinematic (pseudorapidity) coverage. These results provide additional constraints on contributions from nonflow and longitudinal decorrelations.

I. INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) was built and the Large Hadron Collider (LHC) heavy-ion program initiated to study the formation of nucleus-sized droplets of quark-gluon plasma (QGP) in the laboratory. This focused scientific enterprise has been remarkably successful. The now standard model of heavy-ion collisions includes the formation of QGP that expands hydrodynamically before the phase transition to hadrons with confined quarks and gluons. Refs. [1–3] provide useful reviews. Over the past ten years, experiments have employed multiple techniques to assess whether such QGP droplets are also formed in smaller collisions of p+A and even p+p collisions; see Ref. [4] for a recent review.

A specific proposal was to collide proton, deuteron, and helium-3 projectiles on nuclear targets at RHIC, utilizing the unique capabilities of that facility, to discern whether “flow-like” patterns are indeed attributable to mini-QGP droplet formation [5]. In the years 2014, 2015, and 2016, RHIC provided collisions of 3He+Au, p+Au, and d+Au at $\sqrt{s_{NN}} = 200$ GeV, extending earlier results from 2003 and 2008 d+Au running. The PHENIX Collaboration has published a suite of results on small systems including transverse momentum ($p_T$) spectra of identified particles (indicating “baryon anomaly” results in small collision systems) [6], pseudorapidity dependence of particle production and anisotropy coefficients [7, 8], multiparticle cumulants [9], and anisotropy coefficients at midrapidity as a function of $p_T$ for charged hadrons [10–13] and for identified particles [14, 15]. The full set of elliptic and triangular azimuthal anisotropy coefficients ($v_2$ and $v_3$, respectively) for all three collision geometries were published in Nature Physics [16].

The elliptical and triangular azimuthal anisotropy coefficients in all three collision geometries are quantitatively predicted by viscous hydrodynamic calculations published prior to the data [5, 17]. After intense theoretical work [18, 19] and intense scientific scrutiny [20], calculations with initial-state correlations in the color glass condensate framework are definitively ruled out as the dominant source of the observed correlations. More recent calculations indicate that prehydrodynamization evolution, either in the weak [21] or strong [22] coupling limit, may have a significant impact on the shortest lifetime systems—including the smallest systems or any size system at the lowest energies—particularly for triangular flow. Additionally, calculations within parton transport frameworks such as AMPT qualitatively reproduce the flow coefficient ordering [23]. Finally, the initial geometry has contributions from both intrinsic geometry and from geometric fluctuations (originating from nucleonic and subnucleonic position-space fluctuations), and from the statistics of particle production. As an example, the initial spatial eccentricities $\varepsilon_2$ and $\varepsilon_3$ for central collisions (impact parameter $b < 2$ fm) in different frameworks are given in Table I. Additional negative binomial distribution fluctuations in particle production and sub-nucleonic structure tend to increase the eccentricities overall and reduce the differences, i.e. reducing the relative contribution from intrinsic geometry; however, significant intrinsic contributions remain in almost all cases. Additional measurements and theoretical work are needed to gain insight on the relative contributions to the initial geometry and thus further constrain both the hydrodynamic and prehydrodynamization stages.

Given the importance of these results, the PHENIX
TABLE I. Summary of various initial geometry calculations quantified by the average eccentricities $\varepsilon_{2,3}$ in central (impact parameter $b < 2$ fm) $p+Au$, $d+Au$, and $^3He+Au$ events. The "Nucl. w/o NBD Fluc." column refers to Monte Carlo Glauber with nucleon position fluctuations [5]. The "Nucl. w/ NBD Fluc." column refers to Monte Carlo Glauber with nucleon position fluctuations and Negative Binomial Distribution (NBD) fluctuations in particle production [24]. The "Quarks w/ NBD Fluc." column refers to Monte Carlo Glauber with constituent quark position fluctuations and NBD fluctuations [24]. The last two columns use the IP-Glasma framework including gluon field fluctuations [25].

| $\varepsilon_{2,3}$ | Collision | Nucl. Fluc. | Nucl. Fluc. | Quarks Fluc. | IP-G Fluc. | IP-G Fluc. |
|---------------------|-----------|-------------|-------------|--------------|------------|------------|
| $\varepsilon_2$     | $p+Au$    | 0.23        | 0.32        | 0.38         | 0.10       | 0.50       |
|                     | $d+Au$    | 0.54        | 0.48        | 0.51         | 0.58       | 0.73       |
|                     | $^3He+Au$ | 0.50        | 0.50        | 0.52         | 0.55       | 0.64       |
| $\varepsilon_3$     | $p+Au$    | 0.16        | 0.24        | 0.30         | 0.09       | 0.32       |
|                     | $d+Au$    | 0.18        | 0.28        | 0.31         | 0.28       | 0.40       |
|                     | $^3He+Au$ | 0.28        | 0.32        | 0.35         | 0.34       | 0.46       |

Collaboration has carried out a new analysis of the same data sets using combinations of three sets of detector combinations to extract two-particle correlations (2PC), called the $3\times2$PC method, to check the published results [10] and to provide additional information via correlations between particles from different kinematic regions. Because this makes use of three different two-particle correlations, it is called the $3\times2$PC method. In addition, as the PHENIX experiment collected its final data in 2016, we provide an archival set of correlation function data for future examination. In this paper, we do not compare the experimental results with the latest theoretical calculations and rather focus solely on the measurements and their quantified uncertainties.

II. ANALYSIS METHOD

The following subsections detail the PHENIX detector and the correlation analysis.

A. Detector description

The PHENIX detector is composed of multiple spectrometers and detector subsystems [26, 27]. The detectors used in this analysis are highlighted in Fig. 1 and detailed here. The central arm spectrometers (CNT) measure charged hadrons with pseudorapidity $|\eta| < 0.35$. There are two CNT spectrometers, referred to as “east” and “west”, each subtending $\Delta \phi = \pi/2$. The beam-beam counters (BBC) [28] comprise two sets of 64 quartz Čerenkov radiators with photomultiplier readout, each set covering $3.1 < |\eta| < 3.9$—the BBC covering $-3.9 < \eta < -3.1$ is referred to as the “south” side (BBCS), and likewise the BBC covering $3.1 < \eta < 3.9$ is called the “north” side (BBCN). No individual particle information is available and the light output for each counter...
is normalized to the expected single charged particle response. We note that approximately half of the particles hitting the BBC are scattered from the beam pipe and the poles of the axial field magnet. The forward silicon vertex detector (FVTX) [29] comprises silicon strips oriented in the azimuthal direction and covers both forward and backward rapidity $1.0 < |\eta| < 3.0$. The FVTX can be used to count hits via clusters or via reconstructed tracks in the four-layers on each side. The acceptance for FVTX tracks is significantly more constrained than the acceptance for clusters, and has a strong dependence on the $z$-vertex of the collision (the direction along the beam line). Due to the orientation of the strips, there is no momentum information available with the FVTX tracks. The FVTX acceptance for tracks is shown in Fig. 2 and is dominated by tracks with $1.2 < |\eta| < 2.2$ and $p_T > 0.5$ GeV/c.

The BBC is used for triggering on minimum bias (MB) $p+Au$, $d+Au$, and $^3$He+$Au$ collisions by requiring a fast reconstructed $z$-vertex within $|z| < 10$ cm and at least one hit on each side of the collision point. Additionally, a high-multiplicity trigger was employed to enhance the 0%–5% highest BBC multiplicity events by more than an order of magnitude. The BBC information in the Au-going direction is also used offline to select events in the 0%–5% centrality category. Full details are available in Refs. [10, 11, 14, 16].

### B. Event plane method

Previous PHENIX publications, including Ref. [16], utilized the event plane method [30] for measuring azimuthal anisotropies. The second- and third-harmonic event planes are determined in the BBC in the Au-going direction (referred to as the BBC “south” or BBCS) and in the Au-going FVTX (referred to as the FVTX “south” or FVTXs). The standard Q-vector recentering and event plane flattening techniques [31] are applied. Because the collision system is asymmetric, one cannot determine the event plane resolutions by comparing forward and backward detectors alone. Thus, the event plane resolutions are determined utilizing the three-detector combination BBCS-FVTXs-CNT.

It was recently pointed out that the third-harmonic event plane resolutions for the BBCS and FVTXs published in Ref. [16] do not follow the expected simple scaling of $R(\psi_n) \propto v_n \sqrt{N_{\text{hit}}}$, where $N_{\text{hit}}$ is the number of particles striking the event plane detector and $v_n$ is the azimuthal anisotropy of those particles. We have carefully investigated this observation by running a full simulation of the event plane procedure, including the fact that the beam has nonzero angle and offset with respect to the detector coordinate system. The beam angles and offsets for the different running periods are given in Table II. An additional issue is that the PHENIX central carriages, which was moved between operation periods, has modest position offsets of order 1–2 mm relative to nominal. We find that the event plane flattening procedure in the rotated frame creates a distortion on the triangular anisotropy due to the elliptic anisotropy. The simulation qualitatively reproduced the event plane “bias” seen in real data; the effect largely cancels in the final $v_3$, because the bias is opposite between the BBCS and FVTXs. The effect is dependent on the size of the real signal $v_3$, the beam angle, beam offset, event multiplicity, and Q-vector recentering applied, and is much larger in $p+Au$ and $d+Au$, where the smaller $v_3$ induces higher sensitivity to these effects.

![Table II. System beam angles and offsets.](image)

| Year | System    | $x_{\text{offset}}$ (mm) | $y_{\text{offset}}$ (mm) | $x-z$ angle (mrad) |
|------|-----------|--------------------------|--------------------------|--------------------|
| 2014 | $^3$He+$Au$ | 3.9                      | 0.02                     | 1.8                |
| 2015 | $p+Au$    | 2.1                      | 0.5                      | 3.6                |
| 2016 | $d+Au$    | 3.0                      | 0.2                      | 1.0                |

Because the experimental results for $v_3$ in $p+Au$ and $d+Au$, where the distortion is largest, are important, we have carried out an independent analysis to examine the validity of the previous results. In the Monte Carlo simulation, two-particle correlation functions were successfully obtained when using an event-mixing acceptance correction in very fine bins in collision $z$-vertex. Thus, we have carried out a new analysis of all three collision systems using three sets of two-particle correlations ($3\times2$PC). In the limit of low event plane resolution, which is the case for all three systems, the event plane physics result and the $3\times2$PC physics result should agree [50]—this is because they are both estimators of $\langle v_3 \rangle^{1/2}$ in this case, which means the sensitivity to both fluctuations and nonflow is the same.

We highlight that the analysis is independent of the published event plane results in the following ways: (1) a completely different code base is used; (2) the FVTX clusters are used in the event plane result but only FVTX tracks with good quality are used in the $3\times2$PC analysis; (3) additional systematic uncertainty checks are carried out as detailed below. Note that a subset of these $3\times2$PC checks were carried out in the $d+Au$ published analyses detailed in Refs. [8, 11, 16]. In this paper, we also extend the kinematics from the original analysis to utilize different combinations of detectors in the $3\times2$PC method.

### C. 3×2PC method

Here we detail the methodology used for the $3\times2$PC method. The 2PC technique utilized here follows the standard methodology [50]; the difference only coming in requiring three such 2PC because the collision systems are asymmetric. We measure the $\Delta \phi$ distribution of three different sets of pairs. In each pair, one particle
is required to be in one subevent, and the other is required to be in another subevent. The manner in which the three different pairs of subevents are used is qualitatively very similar to the three subevent method for determining the event plane resolution. In the limit of small event plane resolution, the techniques should yield the same results as they are sensitive to flow, flow fluctuations, and nonflow in the same manner [33].

The correlation function $C(\Delta \phi)$ is defined by

$$C(\Delta \phi) = \frac{S(\Delta \phi) \int_0^{2\pi} M(\Delta \phi)}{M(\Delta \phi) \int_0^{2\pi} S(\Delta \phi)},$$

(1)

where $\Delta \phi$ is the difference in the azimuthal angles between the two particles in the pair; $S(\Delta \phi)$ is the signal distribution, which is constructed from pairs in which both particles are taken from the same event; and $M(\Delta \phi)$, which is the mixed event distribution, which is constructed from pairs of particles in which each particle is required to be from a different event. It is essential that particles from mixed events come from the same event category, which includes centrality class and collision $z$-vertex class (i.e. the collision $z$-vertices of both particles must be in the same collision $z$-vertex bin, typically 1 cm or 2 cm in width).

Once the correlation function is obtained, it can be decomposed via a Fourier series with coefficients $c_n$:

$$C(\Delta \phi) = 1 + \sum_{n=1}^\infty c_n \cos n \Delta \phi,$$

(2)

where $n$ is the harmonic number. Letting the superscripts denote subevents $A$, $B$, and $C$, the $c_n$ coefficients mathematically represent

$$c_n^{AB} = \langle \cos(n(\phi_A - \phi_B)) \rangle = \langle v_n^{A}v_n^{B} \rangle,$$

(3)

$$c_n^{AC} = \langle \cos(n(\phi_A - \phi_C)) \rangle = \langle v_n^{A}v_n^{C} \rangle,$$

(4)

$$c_n^{BC} = \langle \cos(n(\phi_B - \phi_C)) \rangle = \langle v_n^{B}v_n^{C} \rangle.$$  

(5)

Finally, the $v_n$ in a single subevent can be determined as

$$v_n^C(p_T) = \sqrt{\frac{c_n^{AC}(p_T)c_n^{BC}(p_T)}{c_n^{AB}}}. $$

(6)

Note that it is also possible to determine the $v_n$ in a different way, using only one correlation in the numerator and all three in the denominator:

$$v_n^C(p_T) = \sqrt{\frac{c_n^{AC}(p_T)}{c_n^{AB}/c_n^{AC}/c_n^{BC}}}, $$

(7)

$$v_n^C(p_T) = \sqrt{\frac{c_n^{BC}(p_T)}{c_n^{AB}/c_n^{BC}/c_n^{AC}}}, $$

(8)

where all of the correlations in the denominator are $p_T$-integrated. For the detectors without momentum information (BBCS, FVTXS, FVTXN), this simply means all tracks or hits. For the detectors with momentum information (CNT), this means all tracks in the momentum range considered (0.2 < $p_T$ < 3.0 GeV/c). Because this method is sometimes used by the LHC experiments, we will informally refer to it as the LHC-style $v_n$, in contrast to the PHENIX-style discussed previously. Note that the PHENIX-style $v_n$ is the geometric mean of the two possible LHC-style $v_n$. For that reason, the PHENIX-style presents certain advantages, particularly for reduced systematic uncertainties.

### D. Systematic uncertainties

The systematic uncertainties on the extracted $v_2$ and $v_3$ coefficients have multiple contributions. In previous analyses utilizing CNT tracks [10–12, 14, 16], contributions from variations in track quality criteria, run-to-run variations, etc. are quite modest and subdominant. The two dominant sources of systematic uncertainty result from comparing results with different collision $z$-vertex ranges and from comparing the two individual arms of the CNT. The uncertainty associated with the collision $z$-vertex is assessed by comparing the nominal result with $|z| < 10$ cm to cases with $+4.0 \text{ cm} < z < +10.0 \text{ cm}$ and $-10.0 \text{ cm} < z < -4.0 \text{ cm}$, because the changes in the FVTXS acceptance are significant over this range. We also consider the variation of only using “east” arm CNT tracks and only using “west” arm CNT tracks. The differences found in the systematic variations are taken to be the maximal possible deviations, representing asymmetric distributions about the central value. These differences are divided by $\sqrt{3}$ to give one standard deviation uncertainties, and then those individual uncertainties are added in quadrature.

For the results utilizing the FVTXS and FVTXN detectors, we have repeated the analyses using only one half, i.e. 1.2 < $|\eta|$ < 1.7, or the other half, i.e. 1.7 < $|\eta|$ < 2.2. These give similar results; however, we do not include the differences in the systematic uncertainties as the results may have differing contributions from nonflow and longitudinal decorrelations. These results are presented in the Appendix.

### III. RESULTS

The main physics results from the $3 \times 2$PC analysis are the extracted $v_{2,3}$ coefficients as a function of charged hadron $p_T$ at midrapidity $|\eta| < 0.35$. However, these values may depend on the other two detectors used in combination with the CNT tracks. A set of example two-particle correlations and a complete set of extracted Fourier coefficients ($c_2$, $c_3$, $c_4$, $c_6$, and $c_7$) and their statistical uncertainties are given in supplemental material [32].

We highlight that care should be employed when comparing $c_n$ coefficients directly as the $p_T$ acceptance of the BBCS and FVTXS differ, as well as their relative particle (direct and scattered) contributions. Thus, even though in principle one can extract $v_2$ and $v_3$ values in the BBCS
and FVTXS, by the same procedure as in the CNT, they do not have a straightforward physics interpretation. In the case of reconstructed, high quality FVTXS tracks, a full acceptance and efficiency correction as a function of collision $z$-vertex is possible, as done for example in Ref. [7]. However, a similar procedure has not been done for the BBCS, where approximately half the hits are from scattered particles.

### A. $v_2$ vs $p_T$ results

Figure 3 shows the elliptic $v_2$ coefficients as a function of $p_T$ from the 3×2PC method utilizing the three-detector combination BBCS-FVTXS-CNT. The results for the most central 0%-5% events are shown for all three collision geometries with statistical uncertainties as vertical lines and systematic uncertainties as open boxes. The systematic uncertainties have a high degree of point-to-point correlation. Also shown are the previously published $v_2$ coefficients [10] utilizing the event plane method. We highlight that the earlier publication includes an asymmetric systematic uncertainty estimate for nonflow based on a simple multiplicity scaling of coefficients from $p+p$ collisions at $\sqrt{s} = 200$ GeV; here we do not include this uncertainty, as we focus on what is directly measured from the correlation functions with all physics contributions included. The analysis presented...
here is in excellent agreement with the previously published results.

Figure 3 shows the third harmonic coefficient $v_3$ as a function of $p_T$. It is otherwise identical to the previous figure, showing a comparison between the present 3×2PC analysis and the previously published event plane analysis for the most central 0%–5% events for all three collision systems and, as before, the vertical lines represent the statistical uncertainties and the boxes indicate the point-to-point correlated systematic uncertainties. There is good agreement within uncertainties between the two analyses, with the $^3$He+Au $v_3$ values from the 3×2PC method slightly lower than the event plane results, though well within systematic uncertainties, which are largely independent between the two methods.

We highlight that the correlation coefficients $c_2$ and $c_3$ from all collision geometries follow the approximate expected scaling based on each detector’s multiplicity and $v_n$ using inputs from Ref. [7]. Thus the puzzle involving the nonscaling of the event plane values mentioned above is resolved.

**B. Additional kinematic ranges**

The above results are presented as $v_2$ and $v_3$ at midrapidity $|\eta| < 0.35$, but they can depend on the other two detectors used in the analysis, namely the BBCS and FVTXS. Nonflow contributions, longitudinal decorrelations, and potentially other effects can make the extraction dependent on the kinematic coverage of the other detectors – see for example Ref. [33]. The original motivation for utilizing the BBCS and FVTXS is based on their higher multiplicity and significant pseudorapidity gap from the CNT tracks. Note that the gap should be thought of not in simple terms of the extreme $|\Delta \eta| > X$ value, but rather the distribution of possible $|\Delta \eta|$ values. Thus, the average $\langle |\Delta \eta| \rangle \approx 3.5, 2.0, 1.8$ for the BBCS-CNT, FVTXS-CNT, BBCS-FVTXS detector combinations.

We have also analyzed the detector combination FVTXS-CNT-FVTXN for the 3×2PC. Note that now the average values are $\langle |\Delta \eta| \rangle \approx 2.0, 2.0, 3.4$ for the FVTXS-CNT, CNT-FVTXN, and FVTXS-FVTXN detector combinations. However, based on measurements as a function of pseudorapidity in Ref. [7], the $v_2$ values are less than half the magnitude in the FVTXN compared to FVTXS and the multiplicity of tracks is also less than half. Thus, nonflow contributions relative to flow contributions are expected to be substantially larger in the FVTXS.

Again, additional example correlation functions and the full set of extracted $c_n$ coefficients are given in the Appendix.

Tables III and IV list the pseudorapidity acceptances of the different detectors and two-detector combinations. In Fig. 8 the pseudorapidity acceptance of the BBCS-FVTXS-CNT combination is listed as $-3.0 < \eta < -1.0, |\eta| < 0.35, 1.0 < \eta < 3.0$. While the full FVTX acceptance for clusters is $1.0 < |\eta| < 3.0$, this analysis predominantly uses tracks that are from $1.2 < |\eta| < 2.2$.

**TABLE III.** Pseudorapidity acceptances of individual detectors.

| Detector     | $\eta_{\text{min}}$ | $\eta_{\text{max}}$ |
|--------------|---------------------|---------------------|
| BBCS (tubes) | -3.9                | -3.1                |
| FVTXS (clusters) | -3.0               | -1.0                |
| FVTXS (tracks) | -2.2                | -1.2                |
| CNT (tracks)  | -0.35               | 0.35                |
| FVTXN (clusters) | 1.0                 | 3.0                 |
| FVTXN (tracks) | 1.2                 | 2.2                 |

**TABLE IV.** Pseudorapidity acceptances of two-detector combinations.

| Detector combination | $|\Delta \eta|_{\text{min}}$ | $\langle |\Delta \eta| \rangle$ |
|----------------------|-----------------------------|-----------------------------|
| BBCS-FVTXS (clusters) | 0.1                         | 1.8                         |
| BBCS-FVTXS (tracks)  | 0.9                         | 1.8                         |
| BBCS-CNT (clusters)  | 0.65                        | 2.0                         |
| FVTXS-CNT (tracks)   | 0.85                        | 2.0                         |
| FVTXN-CNT (clusters) | 0.65                        | 2.0                         |
| FVTXN-CNT (tracks)   | 0.85                        | 2.0                         |
| FVTXS-FVTXN (clusters) | 2.0                      | 3.4                         |
| FVTXS-FVTXN (tracks) | 2.4                         | 3.4                         |

Figure 5 shows the elliptic $v_2$ coefficients as a function of $p_T$ from the 3×2PC method utilizing the three-detector combination FVTXS-CNT-FVTXN. The results for the most central 0%–5% events are shown for all three collision geometries with statistical uncertainties as vertical lines and systematic uncertainties as open boxes. The systematic uncertainties have a high degree of point-to-point correlation. For comparison, the 3×2PC values from the BBCS-FVTXS-CNT combination are shown. Shown in Figure 6 is the ratio of the $v_2$ in the FVTXS-CNT-FVTXN combination to the $v_2$ in the BBCS-FVTXS-CNT combination. We observe a modest 5%–15% difference in the $^3$He+Au case, growing to a 10%–20% difference in the $d$+Au case, and then a rather large 35%–80% difference in the $p$+Au case. Qualitatively this difference could result from substantially larger nonflow contributions in the FVTXS-CNT-FVTXN combination, and this would be expected to be largest in the $p$+Au system which has the smallest multiplicity as well as the lowest expected elliptic flow itself. Nonflow effects are also expected to play a larger role at larger $p_T$, and we observe a modest rise in the ratios with $p_T$.

Figure 7 shows the third harmonic coefficient $v_3$ as a function of $p_T$ from the 3×2PC using the FVTXS-
CNT-FVTXN method, shown in solid squares, and also the BBCS-FVTXS-CNT detector combination, shown in open circles, for comparison. The statistical uncertainties are shown as vertical lines and the systematic uncertainties as open boxes. In the case of $^3$He+Au, the results agree for the two detector combination sets within uncertainties. However, in the case of $p$+Au and $d$+Au, one of the $c_3$ coefficients is negative, and thus the mathematical calculation of $c_3$ results in an imaginary value. These imaginary values are shown along the negative $y$-axis in the figure.

These negative values of $c_3$ observed in the $p$+Au and $d$+Au systems are consistent with the observation that nonflow contributions in $p$+p collisions extrapolated to these systems drive $c_3$ towards negative values. This effect is consistent with nonflow dominance in the FVTXS-CNT-FVTXN result. It is striking how much larger the effect is in $p$+Au and $d$+Au compared to negligible in $^3$He+Au. Also, the difference in potential nonflow in the $v_2$ shown above is quite different between the systems and will also depend on the real triangular flow in these different geometries.

From the two-particle correlations and extracted coefficients (tabulated in the supplemental material [32]) one can examine the patterns between the two-particle kinematics and between collision systems. Access to the full suite of Fourier coefficients is critical to enable future analysis techniques to be applied and comparison with new theoretical tools that might more fully incorporate flow, nonflow, and longitudinal dynamics. Figure 8 shows the $c_2$ and $c_3$ coefficients from 0%-5% central $p$+Au, $d$+Au, $^3$He+Au collisions from left to right. The markers are located at the pseudorapidity average from the two detectors (i.e. $(\eta_1+\eta_2)/2$) and the associated horizontal line extends between the two detectors (i.e. from $\eta_1$ to $\eta_2$). Correlations involving tracks in the CNT (e.g. where one of the horizontal line end points is at $\eta = 0$) are for the inclusive range in $0.2 < p_T < 3.0$ GeV/c. As discussed in the supplemental material [32], the $c_n$ coefficients should not be viewed as strict physics quantities because the charge in the BBC and tracks in the FVTX are not corrected for variations in acceptance, efficiency, and backgrounds, all of which can vary between running periods.

Starting with the $c_2$ values, one observes significant variation amongst the values from the different detector combinations used for the two-particle correlations. This arises naturally from the pseudorapidity dependence of the flow $v_2$ itself, and also from the different $p_T$ coverage of the different detectors and different contributions from background, particularly in the BBCS. Overall one observes that the relative ordering of $c_2$ values from different combinations is qualitatively similar for the three collision systems, with the dominant feature that all of the $p$+Au values are lower.

For the $c_3$ values, the ordering of the detector combinations in $^3$He+Au collisions is qualitatively similar to that of the $c_2$ values. In striking contrast, all of the $c_3$ coefficients (so all detector combinations) are significantly lower in $p$+Au and $d$+Au compared with $^3$He+Au. This means that the conclusion of lower triangular flow in $p$+Au and $d$+Au is independent of any single detector used in the two-particle detector combination, i.e. it is seen in all combinations. In particular, $c_3$ values where the FVTXN is utilized, i.e. where the horizontal line extends to $\eta = +1.7$, are very low and in some cases actually negative, though with large statistical uncertainties. It is the negative value for $c_3$ between the CNT-FVTXN that results in the imaginary calculated $v_3$ in the FVTXS-CNT-FVTXN combination for $p$+Au and $d$+Au systems. Noting that the multiplicity is lowest in these systems at forward rapidity, i.e. the proton or deuteron-going direction, and the $v_3$ may be the smallest, the explanation may be from a large nonflow contribution toward negative values of $c_3$.

**IV. SUMMARY**

In this paper we have presented an independent analysis of the flow coefficients $v_2$ and $v_3$ as a function of $p_T$ in 0%-5% central $p$+Au, $d$+Au, and $^3$He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using the 3×2PC method. The results are in excellent agreement with the published Nature Physics results from the PHENIX Collaboration using the event plane method [10]. In addition, variations in the kinematic selection for the three detector combinations reveals a role for nonflow and longitudinal decorrelations, particularly at forward rapidity, i.e. in the small projectile direction. To support future analyses, this paper includes an archival documentation of correlation functions from $p$+p through $^3$He+Au systems.
FIG. 7. The extracted $c_3$ coefficient as a function of $p_T$ in 0%–5% central $p+Au$, $d+Au$, and $^3He+Au$ collisions from the $3\times2$PC method using the FVTXS-CNT-FVTXN detector combination are shown as solid squares. For comparison we also show the previously plotted results from the BBCS-FVTXS-CNT combination as open circles.

FIG. 8. Two-particle correlation $c_2$ and $c_3$ coefficients from 0%–5% central $p+Au$, $d+Au$, $^3He+Au$ collisions. The markers are located at the pseudorapidity average from the two detectors (i.e. $(\eta_1 + \eta_2)/2$) and the associated horizontal line extends between the two detectors (i.e. from $\eta_1$ to $\eta_2$). The vertical bars indicate the statistical uncertainties. See text for details.

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APPENDIX: $v_2$ COEFFICIENTS WITH TWO DIFFERENT SUBSETS OF FVTX ACCEPTANCE

We have repeated the analyses of $3\times 2$PC and dividing the FVTX and FVTXN into halves, either selecting tracks with $1.2 < |\eta| < 1.7$ or $1.7 < |\eta| < 2.2$. Thus, the detector combinations will have increased or decreased rapidity gaps from the default analysis.

Figures 9 and 10 show the comparison of $v_2$ as a function of $p_T$ at midrapidity using the two different FVTXN and FVTXS pseudorapidity ranges, in addition to the default use of the entire FVTX acceptance range. In all cases, the differences are modest. There is a general pattern that the $v_2$ calculated with the BBCS-FVTXS-CNT combination is slightly higher when using the FVTXS $1.2 < |\eta| < 1.7$ instead of FVTXS $1.7 < |\eta| < 2.2$. This may indicate a slight increase in nonflow contribution to the FVTXS-CNT correlation that dominates over a possible slight decrease in nonflow in the BBCS-FVTXS correlation. A similar effect is seen in the $v_2$ values with the FVTXS-CNT-FVTXN combination, which again may relate to slightly larger nonflow contributions due to all correlations having a smaller rapidity gap.

Figures 11 and 12 show the comparison of $v_3$ as a function of $p_T$ at midrapidity using the two different FVTXN and FVTXS pseudorapidity ranges, in addition to the default use of the entire FVTX acceptance range. In all cases, the differences are modest, though with larger statistical uncertainties when splitting the FVTX acceptance range. The larger statistical uncertainties preclude any strong conclusions regarding a pattern with the different selections.

We do not include these differences as systematic uncertainties in the default $v_2$ and $v_3$ results as modest differences are expected. We can however rule out any large uncertainty from detector effects in the FVTX from the lower and higher rapidity acceptances.

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FIG. 9. Calculated midrapidity $v_2$ as a function of $p_T$ for 0%-5% central $p+Au$, $d+Au$, $^3He+Au$ collisions. Shown are results from the BBCS-FVTXS-CNT combination including variations in the pseudorapidity selection of tracks in the FVTXS.

FIG. 10. Calculated midrapidity $v_2$ as a function of $p_T$ for 0%-5% central $p+Au$, $d+Au$, $^3He+Au$ collisions. Shown are results from the FVTXS-CNT-FVTXN combination including variations in the pseudorapidity selection of tracks in the FVTXS and FVTXN.

FIG. 11. Calculated midrapidity $v_3$ as a function of $p_T$ for 0%-5% central $p+Au$, $d+Au$, $^3He+Au$ collisions. Shown are results from the BBCS-FVTXS-CNT combination including variations in the pseudorapidity selection of tracks in the FVTXS.

FIG. 12. Calculated midrapidity $v_3$ as a function of $p_T$ for 0%-5% central $p+Au$, $d+Au$, $^3He+Au$ collisions. Shown are results from the FVTXS-CNT-FVTXN combination including variations in the pseudorapidity selection of tracks in the FVTXS and FVTXN.
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