Quadrupole Anisotropy in Dihadron Azimuthal Correlations in Central d plus Au Collisions at root s(NN)=200 GeV

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The PHENIX collaboration at the Relativistic Heavy Ion Collider (RHIC) reports measurements of azimuthal dihadron correlations near midrapidity in d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. These measurements complement recent analyses by experiments at the Large Hadron Collider (LHC) involving central p + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, which have indicated strong anisotropic long-range correlations in angular distributions of hadron pairs. The origin of these anisotropies is currently unknown. Various competing explanations include parton saturation and hydrodynamic flow. We observe qualitatively similar, but larger, anisotropies in d + Au collisions at RHIC compared to those seen in p + Pb collisions at the LHC. The larger extracted v_2 values in d + Au are consistent with expectations from hydrodynamic calculations owing to the larger expected initial-state eccentricity compared with that from p + Pb collisions. When both are divided by an estimate of the initial-state eccentricity the scaled anisotropies follow a common trend with multiplicity that may extend to heavy ion data at RHIC and the LHC, where the anisotropies are widely thought to arise from hydrodynamic flow.

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Proton- and deuteron-nucleus collisions at relativistic energies are studied to provide baseline measurements for heavy-ion collision measurements. In $p(d) + A$ collisions, initial-state nuclear effects are present; however, the formation of hot quark-gluon matter as created in heavy ion collisions is not commonly expected. Recently, there has been significant interest in the physics of high-multiplicity events in small collision systems, motivated by the observation of a small azimuthal angle ($\Delta\phi$) large pseudorapidity ($\Delta\eta$) correlation of primarily low p_T particles in very high multiplicity $p + p$ collisions at 7 TeV [1]. The correlation resembles the "near-side ridge" observed in Au + Au [2,3]. The initial $p + p$ result sparked considerable theoretical interest [4–6]. Recently, a similar effect was observed in p + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [7]. Subsequent work from ALICE [8] and ATLAS [9] removed centrality independent correlations (largely from jet fragmentation) by looking at the difference in correlations between central and peripheral events and has additionally uncovered similar long-range $\Delta\eta$ correlations at $\Delta\phi \approx \pi$ beyond those expected from fragmentation of recoiling jets. The effect appears as a longitudinally extended azimuthal modulation with a predominantly quadrupole component [i.e., $\cos(2\Delta\phi)$] and bears a qualitative resemblance in both magnitude and p_T dependence to elliptic flow measurements in heavy ion collisions, where the large quadrupole modulation is understood to be caused by the initial-state spatial anisotropy followed by a nearly inviscid hydrodynamic expansion [10]. A variety of physical mechanisms have been invoked to explain the observed anisotropies in p + Pb including gluon saturation [6,11–13], hydrodynamics [5,14,15], multiparton interactions [16], and final-state expansion effects [17].

Previous analyses involving two-particle correlations from d + Au collisions at Relativistic Heavy Ion Collider (RHIC) have not indicated any long-range features at small $\Delta\phi$ [2,18–20]. However, these measurements involved p_T selections that emphasize jetlike correlations, rather than the underlying event. Also, Refs. [19,20] were based on d + Au collisions recorded in 2003 with a small data sample, which limited the statistical significance of the results.

We present here the first analysis of very central d + Au events to measure hadron correlations between midrapidity particles at $\sqrt{s_{NN}} = 200$ GeV. The center of mass energy per nucleon is a factor of 25 lower than at the Large Hadron Collider (LHC). Another potentially key difference is the use of a deuteron as the projectile nucleus rather than a proton. In Ref. [14], within the context of a Monte Carlo-Glauber (MC-Glauber) model, the calculated initial spatial eccentricity of the participating nucleons, ε_2, for central (large number of participants) d + Pb is more than a factor of 2 larger than in central p + Pb collisions at LHC energies. We find the initial spatial eccentricity ε_2 from the MC-Glauber model [21] for d + Au at RHIC energies to be similar to the d + Pb calculations at LHC energies.

The results presented here are based on 1.56 billion minimum-bias d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV recorded with the PHENIX [22] detector in 2008. The event centrality in d + Au is determined from the integrated charge measured by a beam-beam counter facing the incoming Au nucleus [23]. Here, we isolate a more central sample than previously analyzed, to compare more closely to the LHC results. We use central and peripheral event samples comprising the top 5% and 50%–88% of the total charge distributions, respectively.

This analysis considers charged hadrons measured within the two PHENIX central arm spectrometers. Each arm covers nominally $\pi/2$ in azimuth and has a pseudorapidity acceptance of $|\eta| < 0.35$. Charged tracks are reconstructed using drift chambers with a hit association requirement in two layers of multiwire proportional chambers with pad readout; the momentum resolution is $0.7\% \oplus 1.1\% p(\mathrm{GeV}/c)$. Electrons are rejected with a veto in the ring-imaging Čerenkov counters.

All pairs satisfying the tracking cuts within an event are measured. The yield of pairs satisfying tracking and particle identification cuts is corrected for azimuthal acceptance through the use of mixed-event distributions. The conditional yield of pairs is determined by $(1/N^t) \times (dN^{\mathrm{pairs}}/d\Delta\phi) \propto (dN^{\mathrm{pairs}}_{\mathrm{same}}/d\Delta\phi/dN^{\mathrm{pairs}}_{\mathrm{mix}}/d\Delta\phi)$ where N^t is the number of trigger hadrons (trigger hadrons are those having the momenta required to begin the search for a pair of hadrons) and $N^{\mathrm{pairs}}_{\mathrm{same}}$ ($N^{\mathrm{pairs}}_{\mathrm{mix}}$) is the number of pairs from the same (mixed) events. Mixed pairs are constructed with particles from different events within the same 5% centrality class and with event vertices within 5 cm of each other. Because the focus of this analysis is on the shape of the distributions, no correction is applied for the track reconstruction efficiency, which has a negligible dependence on centrality for d + Au track multiplicities.

To make direct comparisons between our measurements and recent ATLAS p + Pb results [9], we follow a similar analysis procedure. Charged hadrons with $0.5 < p_T < 3.5$ GeV/c are used. For this analysis, each pair includes at least one particle at low p_T ($0.5 < p_T < 0.75$ GeV/c), which enhances the sensitivity to the nonjet phenomena. To minimize the contribution from small-angle correlations arising from resonances, Bose-Einstein correlations, and jet fragmentation, pairs are restricted to pseudorapidity separations of $0.48 < |\Delta\eta| < 0.7$. This $\Delta\eta$ gap is chosen to be as large as possible within the tracking acceptance, while still preserving an adequate statistical sample size. Unlike measurements at the LHC, this method is not sensitive to the pseudorapidity extent of the correlations.

The conditional yield owing to azimuthally uncorrelated background is estimated by means of the zero-yield-at-minimum (ZYAM) procedure [24]. This background contribution is obtained for both the central and peripheral samples by performing fits to the conditional yields using a functional form composed of a constant pedestal and two Gaussian peaks, centered at $\Delta\phi = 0$ and π. The minimum of this function, b_{ZYAM}, is subtracted from the conditional yields, and the result is: $Y(\Delta\phi) \equiv (1/N^t)(dN^{\mathrm{pairs}}/d\Delta\phi) - b_{\mathrm{ZYAM}}$ The conditional yields $Y_c(\Delta\phi)$ and $Y_p(\Delta\phi)$ (central and peripheral events, respectively) are shown in Fig. 1, along with their difference $\Delta Y(\Delta\phi) \equiv Y_c(\Delta\phi) - Y_p(\Delta\phi)$. As in Ref. [9], this subtraction removes any

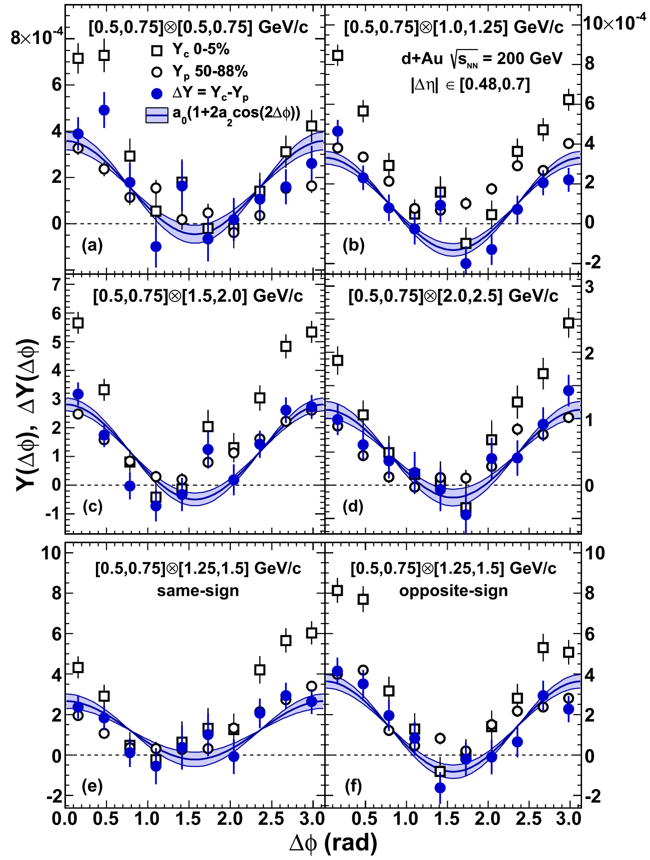

FIG. 1 (color online). Azimuthal conditional yields, $Y(\Delta\phi)$, for (open [black] squares) 0%–5% most central and (open [black] circles) peripheral (50%–88% least central) collisions with a minimum $\Delta\eta$ separation of 0.48 units. Difference $\Delta Y(\Delta\phi)$ (filled [blue] circles), which is ([blue] curve) fit to $a_0 + 2a_2\cos(2\Delta\phi)$, where a_0 and a_2 are computed directly from the data. (shaded [blue] band) Statistical uncertainty on a_2. The bottom left (right) panel shows the same quantity for same-sign (opposite-sign) pairs.

centrality independent correlations, such as effects from unmodified jet fragmentation, resonances and HBT. In the absence of any centrality dependence, $Y_c(\Delta\phi)$ and $Y_p(\Delta\phi)$ should be identical. It is notable that any signal in the peripheral events is subtracted from the central events. We see that $Y_c(\Delta\phi)$ is significantly larger than $Y_p(\Delta\phi)$ for $\Delta\phi$ near 0 and π.

We find that the difference with centrality is well described by the symmetric form: $\Delta Y(\Delta\phi) \approx a_0 + 2a_2\cos(2\Delta\phi)$ as demonstrated in Fig. 1. The coefficients a_n and their statistical uncertainties are computed from the $\Delta Y(\Delta\phi)$ distributions as: $a_n = \langle \Delta Y(\Delta\phi)\cos(n\Delta\phi)\rangle$. The $\cos(2\Delta\phi)$ modulation appears as the dominant component of the anisotropy for all p_T combinations.

To quantify the relative amplitude of the azimuthal modulation, we define $c_n \equiv a_n/(b^c_{\mathrm{ZYAM}} + a_0)$, where b^c_{ZYAM} is b_{ZYAM} in central events. c_2 and c_3 are shown as a function of associated p_T in Fig. 2 for central (0%–5%) collisions.

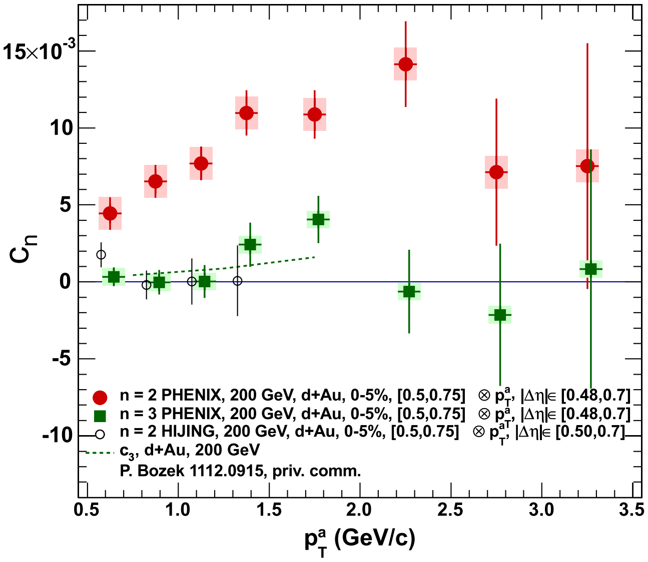

FIG. 2 (color online). The nth-order pair anisotropy, c_n, of the central collision excess as a function of associated particle p_T^a. c_2 (filled [red] circles) and c_3 (filled [green] squares) are for $0.5 < p_T^t < 0.75$ GeV/c, $0.48 < |\Delta\eta| < 0.7$. c_2 as extracted from d + Au HIJING events using the same procedure as in the data is also shown (open circles). c_3 as expected for our p_T selections from Ref. [31] is shown as a dashed line.

The dominant source of systematic uncertainty results from the inability to completely exclude the near-side jet peak in this analysis. The PHENIX central arm spectrometers lack sufficient $|\Delta\eta|$ acceptance to completely exclude the near-side jet peak. To assess the systematic influence of any residual unmodified jet correlations, we analyzed charge-selected correlations. Charge ordering is a known feature of jet fragmentation, which leads to enhancement of the jet correlation in opposite-sign pairs, and suppression in like-sign pairs, in the near side peak (e.g., Ref. [25]). A representative p_T selection of $Y(\Delta\phi)$ and $\Delta Y(\Delta\phi)$ distributions for like-sign and opposite-sign pairs are shown in Fig. 1 (bottom panels). Both $\Delta Y(\Delta\phi)$ distributions exhibit a significant $\cos(2\Delta\phi)$ modulation. The magnitude of the modulation at $\Delta\phi = 0$ is larger in the opposite-sign case. The root-mean-squared variation of the same-sign and opposite-sign c_n measurements relative to the combined value is included in the systematic uncertainties. This reflects the influence of possible remaining jet correlations and is applied symmetrically, because the influence of the jet contribution is not known. As an additional test, the minimum $\Delta\eta$ was varied from the nominal value of 0.48 to 0.36 (where sensitivity to jet contributions is enhanced) and 0.60 (where it is reduced). The 0.36 selection has some $\Delta\phi$ asymmetry in $\Delta Y(\Delta\phi)$; the 0.60 selection does not. In both cases the extracted c_2 values are consistent with the central $\Delta\eta$ selection. To assess the dependence of the results on our selection of peripheral events, we have extracted c2 values using 60%–88% and 70%–88% central events as alternate peripheral samples. No significant change was found in the c_2 values from the default peripheral subtraction. This is potentially different from the implications of Ref. [26] where a difference in low p_T hadron correlations between 40%–100% d + Au and $p + p$ collisions is observed. We observe a similar magnitude signal in both 0%–5% and 0%–20% central events. Other sources of uncertainty, such as occupancy and acceptance corrections, were found to have a negligible effect on these results.

In p + Pb collisions at the LHC, the signal is seen in long-range $\Delta\eta$ correlations. In this analysis, signal is measured at midrapidity, but it is natural to ask if previous PHENIX rapidity separated correlation measurements [18] would have been sensitive to a signal of this magnitude. The maximum c_2 observed here is approximately a 1% modulation about the background level. Overlaying a modulation of this size on the conditional yields shown in Fig. 1 of Ref. [18] shows that the modulation on the near side is small compared with the statistical uncertainties. With the current method we cannot determine whether the signal observed here persists for $\eta > 3$.

To test effects of the centrality determination or known jet modifications on this observable, we have applied the identical analysis procedure (including the centrality selection) to HIJING [27] (v1.383) d + Au events. As shown in Fig. 2, we find an average c_2 value of $(7.5 \pm 5.5) \times 10^{-4}$ for $0.5 < p_T^a < 1.5$ GeV/c with no significant p_T dependence.

The c_3 values, shown in Fig. 2, are small relative to c_2. Fitting the c_3 data to a constant yields $(6 \pm 4) \times 10^{-4}$ with a χ^2 per degree of freedom of 8.4/7 (statistical uncertainties only); no significant c_3 is observed.

A measure of the single-particle anisotropy, v_2, can be obtained under the assumption of factorization [28–30]: $c_2(p_T^t, p_T^a) = v_2(p_T^t)v_2(p_T^a)$. We have varied p_T^t and recomputed $v_2(p_T)$ and find no significant deviation from the factorization hypothesis. The calculated single particle v_2 is shown in Fig. 3, and also compared with the ATLAS [9] results, revealing qualitatively similar p_T dependence with a significantly larger magnitude. We also compare the v_2 results to a hydrodynamic calculation [14,31] and find good agreement between the data and the calculation. The v_2 reported here is the excess v_2 beyond any which is present in peripheral d + Au collisions. While we cannot extract v_3 from the current data, Fig. 2 shows that the measured c_3 values are in agreement with the values expected from v_3 as a function of p_T in the same model as the v_2 calculation [31]. The v_2 data are also in qualitative agreement with another hydrodynamic calculation [32] both with the MC-Glauber model and with impact-parameter glasma [33] initial conditions (note that these calculations are at a fixed $N_{\rm part}$, not the exact centrality range as in the data). These calculations have very different assumptions about the initial geometry and yet are all in qualitative agreement with the data.

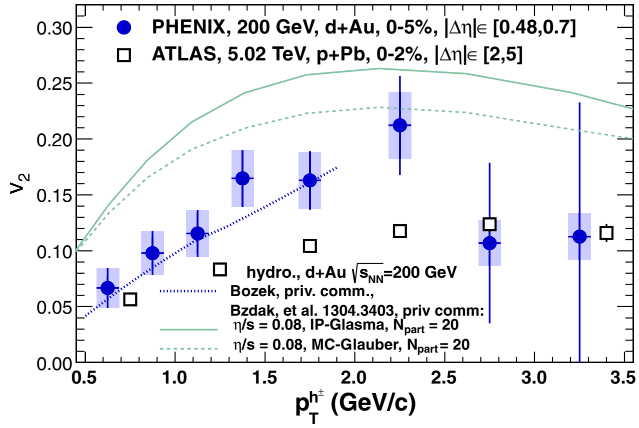

FIG. 3 (color online). Charged hadron second-order anisotropy, v_2, as a function of transverse momentum for (filled [blue] circles) PHENIX and (open [black] squares) ATLAS [9]. Also shown are hydrodynamic calculations from Bozek [14,31] (dotted [blue] curve) and Bzdak *et al.* [32,39] for impact-parameter glasma initial conditions (solid curve) and the MC-Glauber model initial conditions (dashed curve).

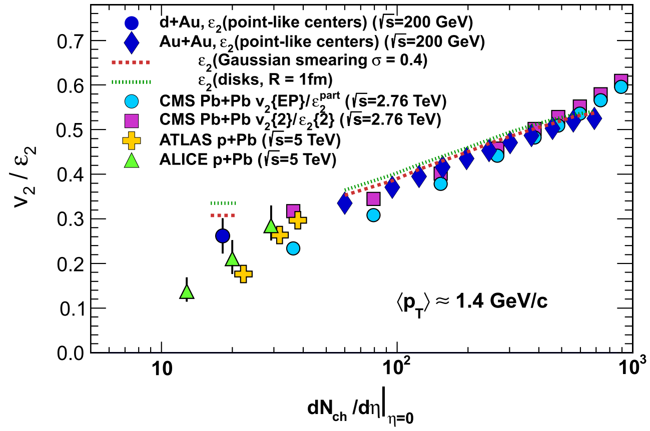

FIG. 4 (color online). The eccentricity-scaled anisotropy, v_2/ε_2, vs charged-particle multiplicity ($dN_{\rm ch}/d\eta$) for $d+A$ and $p+\rm Pb$ collisions [8,9]. Also shown are Au + Au data at $\sqrt{s_{NN}} = 200$ GeV [34–36] and Pb + Pb data at $\sqrt{s_{NN}} = 2.76$ TeV [37,38]. The v_2 are for similar p_T selections. The colored curves are for different nucleon representations in the ε_2 calculation in the MC-Glauber model. The errors shown are statistical only and only shown on the $d+\rm Au$ point with the pointlike centers ε_2 for clarity. Owing to the lack of available multiplicity data in $p+\rm Pb$ and $d+\rm Au$ collisions, the $dN_{\rm ch}/d\eta$ values for those systems are calculated from HIJING [27]. All $dN_{\rm ch}/d\eta$ values are in the center of mass system.

To further investigate the origin of this effect, we plot, in Fig. 4, the PHENIX results for both $d+\rm Au$ and Au + Au scaled by the eccentricity (ε_2), as calculated in a MC-Glauber model, as a function of the charged-particle multiplicity at midrapidity. Due to the lack of available multiplicity data for the $d+\rm Au$ centrality selection the $dN_{\rm ch}/d\eta$ value is calculated from HIJING [27]. The 0%–5% $d+\rm Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV have a $dN_{\rm ch}/d\eta$ similar to those of midcentral $p+\rm Pb$ collisions at the LHC, while the ε_2 values for $d+\rm Au$ collisions are about 50% larger than those calculated for the midcentral $p+\rm Pb$ collisions. The key observation is that the ratio v_2/ε_2 is consistent between RHIC and the LHC, despite the factor of 25 difference in collision center of mass energy. A continuation of this trend is seen by also comparing to v_2/ε_2 as measured in Au + Au [34–36] and Pb + Pb [37,38] collisions. The ε_2 values calculated depend on the nucleon representation used in the MC-Glauber model. In large systems, this uncertainty is small, but in small systems, such as $d+\rm Au$, this uncertainty becomes much more significant. For illustration, ε_2 has been calculated using three different representations of the participating nucleons, pointlike centers, Gaussians with $\sigma = 0.4$ fm, and uniform disks with $R = 1$ fm for the PHENIX data. The scaling feature is robust against these geometric variations, which leads to an approximately 30% difference in the extracted ε_2 in $d+\rm Au$ collisions (other models, e.g., Ref. [32], could produce larger variations).

In summary, a two-particle anisotropy at midrapidity in the 5% most central $d+\rm Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV is observed. The excess yield in central compared to peripheral events is well described by a quadrupole shape. The signal is qualitatively similar, but with a significantly larger amplitude than that observed in long-range correlations in $p+\rm Pb$ collisions at much higher energies. While our acceptance does not allow us to exclude the possibility of centrality dependent modifications to the jet correlations, the subtraction of the peripheral jetlike correlations has been checked both by varying the $\Delta\eta$ cuts and exploiting the charge sign dependence of jet-induced correlations. The observed results are in agreement with a hydrodynamic calculation for $d+\rm Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

We find that scaling the results from RHIC and the LHC by the initial second-order participant eccentricity from the MC-Glauber model [14] may bring the results to a common trend as a function of $dN_{\rm ch}/d\eta$. This may suggest that the phenomena observed here are sensitive to the initial state geometry, and that the same underlying mechanism may be responsible in both $p+\rm Pb$ collisions at the LHC and $d+\rm Au$ collisions at RHIC. It may also imply a relationship to the hydrodynamical understanding of v_2 in heavy ion collisions. The observation of v_2 at both RHIC and the LHC provides important new information. Models intended to describe the data must be capable of also explaining their persistence as the center of mass energy is varied by a factor of 25 from RHIC to the LHC.

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