Azimuthal anisotropy and correlations at large transverse momenta in $p+p$ and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

J. Adams, M.M. Aggarwal, Z. Ahammed, J. Amonett, B.D. Anderson, D. Arkhipkin, G.S. Averichev, S.K. Badyal, Y. Bai, J. Balewski, O. Baramnikova, L.S. Barnby, J. Baudot, S. Bekele, V.V. Belaga, R. Bellwied, J. Berger, B.I. Bezverkhny, S. Bharadwaj, A. Bhasin, A.K. Bhati, V.S. Bhatia, H. Bichsel, A. Billmeier, L.C. Bland, C.O. Bonner, M. Botje, A. Boucham, A.V. Brandin, A. Bravar, M. Bystrowsky, R.V. Cadman, X.Z. Cai, H. Caines, M. Calderón de la Barca Sánchez, J. Carroll, J. Castillo, D. Cebra, Z. Chajecki, P. Chaloupka, S. Chattopadhyay, H.F. Chen, Y. Chen, J. Cheng, A. Cherian, A. Christie, J.P. Coffin, T.M. Cormier, J.G. Cramer, H.J. Crawford, D. Das, S. Das, M.M. de Moura, A.A. Dersch, Lidenko, T. Dietel, S.M. Dogra, W.J. Dong, X. Dong, J.E. Draper, F. Du, A.K. Dubey, V.B. Dunin, J.C. Dunlop, M.R. Dutta Mazumdar, V. Eckardt, W.R. Edwards, L.G. Efimov, V. Emeljanov, J. Engelge, G. Eppley, B. Erasmus, M. Estienne, P. Fachini, J. Faivre, R. Fatemi, J. Fedorisin, K. Filimonov, P. Filip, E. Finch, V.F. Fine, Y. Fisyak, K.J. Foley, K. Fomenko, J. Fu, C.A. Gagliardi, J. Gans, M.S. Ganti, L. Gaudichet, F. Geurts, V. Ghazikhanian, P. Ghosh, J.E. Gonzalez, O. Grachov, G. Grebenyuk, D. Grusnick, S.M. Guertin, Y. Guo, A. Gupta, T.D. Gutierrez, T.J. Hallman, A. Hamed, D. Hardtke, J.W. Harris, M. Heinz, T.W. Henry, S. Heppleman, B. Hippolyte, A. Hirsch, E. Hjort, G.W. Hoffmann, H.Z. Huang, S.L. Huang, E.W. Hughes, T.J. Humanic, G. Igo, A. Ishihara, P. Jacobs, W.W. Jacobs, M. Janik, H. Jiang, P.G. Jones, E.G. Judi, S. Kabana, K. Kang, M. Kaplan, D. Keane, V.Yu. Khodyrev, J. Kiryluk, A. Kiselev, E.M. Kislov, J. Klay, S.R. Klein, A. Klyachko, D.D. Koetke, T. Kollegger, M. Kopytine, L. Kotchenda, M. Kramer, P. Kravtsov, V.I. Kravtsov, K. Krueger, C. Kuhn, A.I. Kulikov, A. Kumar, C.L. Kunz, R.K. Kutiev, A.A. Kuznetsov, M.A.C. Lamont, J.M. Landgraf, S. Lange, J. Laufer, A. Lebedev, R. Lednicky, S. Lechocka, M.J. LeVine, C. Li, Q. Li, Y. Li, S.J. Lindenbaum, M.A. Lisa, F. Liu, L. Liu, Q.J. Liu, Z. Liu, T. Ljubicic, W.J. Llope, H. Long, R.S. Longacre, M. Lopez-Noriega, W.A. Love, Y. Lu, T. Lundham, D. Lynn, G.L. Ma, J.G. Ma, Y.G. Ma, D. Magestro, S. Mahajan, D.P. Mahapatra, R. Majka, L.K. Mangotra, R. Manweiler, S. Margetis, C. Markert, L. Martin, J.N. Marx, H.S. Matis, Y. Yu, A. Matulecnko, C.J. McClain, T.S. McShane, F. Meissner, Yu. Melnick, A. Meschke, M.L. Miller, Z. Milosevich, N.G. Minaev, C. Mironov, A. Mischke, D.K. Misra, J. Mitchell, B. Mohanty, L. Molnar, C.F. Moore, D.A. Morozov, M.G. Munhoz, B.K. Nandi, S.K. Nayak, T.K. Nayak, J.M. Nelson, P.K. Netrakanti, V.A. Nikitin, L.V. Nagach, S.B. Nurushev, G. Odyniec, A. Ogawa, V. Okorokov, M. Oldenburg, D. Olson, S.K. Pal, Y. Panebratsev, S.Y. Panitkin, A.I. Pavlinov, T. Pawlak, T. Peitzmann, V. Perevozchikov, C. Perkins, W. Perry, V.A. Petrov, S.C. Phatak, R. Picha, M. Planinic, J. Pluta, N. Polire, J. Porter, A.M. Poskanzer, M. Potekhin, E. Potrebnow, B.V.S. Potukuchi, D. Prindle, C. Pruneau, J. Putschke, G. Rai, R. Rakness, R. Raniwala, S. Raniwala, O. Ravel, R.L. Ray, S.V. Razin, D. Reichhold, J.G. Reid, G. Renault, F. Retiere, A. Ridiger, H.G. Ritter, J.B. Roberts, O.V. Rogachevskiy, J.L. Romero, A. Rose, C. Roy, L. Ruan, R. Sahoo, I. Sakrejda, S. Salur, J. Sandweiss, P.S. Sazhin, J. Schambach, R.P. Scharenberg, N. Schmitz, L.S. Schroeder, K. Schwand, J. Seger, P. Seyboth, E. Shahaliev, M. Shao, W. Shen, K.E. Shestermanov, S.S. Shimansky, E. Sichtermann, F. Simon, R.N. Singaraju, G. Skoro, N. Smirnov, R. Snellings, G.S. Sood, P. Sorensen, J. Sowinski, J. Speltz, H.M. Spinka, B. Srivastava, A. Stadnik, T.D.S. Stanislaus, R. Stock, A. Stolpovsky, M. Strikhanov, J. Stringfellow, A.P. Suáide, E. Sugarbaker, C. Suire, M. Sunberla, B. Surrow, T.J.M. Symons, A. Szanto de Toledo, P. Szarwas, A. Tai, J. Takahashi, A.H. Tang, T. Tarnowsky, D. Thein, J.H. Thomas, S. Timoshenko, M. Tokarev, S. Trentalange, R.E. Tribble, O.D. Tsai, J. Uler, T. Ullrich, D.G. Underwood, A. Urkinbaev, G. Van Buren, M. van Leeuwen, A.M. Vander Molen, R. Varma, I.M. Vasilevski, A.N. Vasilev, R. Vernet, S.E. Viegard, J.P. Vigdor, Y.P. Viyogi, S. Vokal, S.A. Voloshin, M. Vznudza, W.T. Waggoner, F. Wang, G. Wang, G. Wang, X.L. Wang, Y. Wang, Z.M. Wang, H. Ward, J.W. Watson, J.C. Webb, R. Wells, G.D. Westfall, A. Wetzler, C. Whitten Jr., H. Wiemann, S.W. Wissink, R. Witt, J. Wood, J. Wu,
Results on high transverse momentum charged particle emission with respect to the reaction plane are presented for Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV. Two- and four-particle correlations results are presented as well as a comparison of azimuthal correlations in Au+Au collisions to those in $p+p$ at the same energy. Elliptic anisotropy, $v_2$, is found to reach its maximum at $p_t \sim 3$ GeV/c, then decrease slowly and remain significant up to $p_t \approx 7 - 10$ GeV/c. Stronger suppression is found in the back-to-back high-$p_t$ particle correlations for particles emitted out-of-plane compared to those emitted in-plane. The centrality dependence of $v_2$ at intermediate $p_t$ is compared to simple models based on jet quenching.

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In high energy heavy-ion collisions, a high density system consisting of deconfined quarks and gluons is expected to be created. Energetic partons, resulting from initial hard scatterings, are predicted to lose energy by induced gluon radiation when propagating through the medium. This energy loss is expected to depend strongly on the color charge density of the created system and the traversed path length of the propagating parton. At Brookhaven’s Relativistic Heavy Ion Collider (RHIC) three different observations related to parton energy loss have emerged: strong suppression of the inclusive hadron production, strong suppression of the back-to-back high-$p_t$ jet-like correlation, and large values of the elliptic flow at high $p_t$. In non-central heavy ion collisions, the geometrical overlap region has an almond shape in the transverse plane, with its short axis in the reaction plane. Depending on the emission azimuthal angle, partons traversing this system, on average, experience different path lengths and therefore different energy loss. It leads to (a) azimuthal anisotropy in high $p_t$ particle production with respect to the reaction plane (the second harmonic in the particle azimuthal distribution, elliptic flow, is characterized by $v_2 = \langle \cos(2(\phi - \Psi_R)) \rangle$) and (b) to the dependence of the high $p_t$ 2-particle back-to-back correlations on the orientation of the pair.

In this Letter, using higher-order cumulant analysis and comparing azimuthal correlations measured in $p+p$ collisions to those in Au+Au, we confirm strong elliptic flow in mid-central Au+Au collisions at least up to $p_t \approx 7$ GeV/c as qualitatively expected in the jet quenching scenario. We further investigate the influence of the jet quenching mechanism on high-$p_t$ particle production with respect to the reaction plane by studying $v_2$ centrality dependence in the intermediate $p_t$ region and two-particle azimuthal correlations at different angles with respect to the reaction plane.

The data set consists of about 2 million minimum bias and 1.2 million central trigger Au+Au events and 11 million $p+p$ events at $\sqrt{s_{NN}} = 200$ GeV. The measurements were made using the Time Projection Chamber (TPC) of the STAR detector, which covers pseudorapidity ($\eta$) from $-1.3$ to $1.3$. The event centrality in this paper is defined by the multiplicity measured at mid-rapidity by STAR. Tracks used to reconstruct the flow vector, or generating function, in the case of the cumulant method, were subject to the same quality cuts as used in the $\sqrt{s_{NN}} = 130$ GeV analysis, except for the low transverse momentum cutoff, which for this analysis is 0.15 GeV/c instead of 0.10 GeV/c.

One of the largest uncertainties in elliptic flow measurements in nuclear collisions is due to so-called non-flow effects – the contribution to the azimuthal correlations not related to the reaction plane orientation, such as resonance decays and inter- and intra-jet correlations. The importance of these effects can be investigated by comparing the azimuthal correlations measured in Au+Au to those in $p+p$ collisions, where all correlations are considered to be of non-flow origin. For such a comparison we evaluate the accumulative correlation of a particle from a given $p_t$ bin with all other particles in the region $0.15 < p_t < 2.0$ GeV/c and $|\eta| < 1.0$ by calculating the event average sum:

$$\langle \sum_i \cos(2(\phi_{p_t} - \phi_i)) \rangle = M v_2(p_t) \bar{v}_2 + \langle \text{non-flow} \rangle \quad (1)$$

where $\phi_{p_t}$ is the azimuthal angle of the particle from a given $p_t$ bin. The first term in the r.h.s. of Eq. 1 represents the elliptic flow contribution, where $v_2(p_t)$ is the elliptic flow of particles with a given $p_t$, and $\bar{v}_2$ is the average flow of particles used in the sum; $M$ is the multiplicity of particles contributing to the sum. The multiplicity in the sum changes with the centrality of the collision, but as long as the relative number of particles (per trigger particle) involved in non-flow effects does not change, the contribution due to these effects is a constant. Comparing $p+p$ and Au+Au collisions one indeed might expect some changes in particle correlations: there could be an increase in correlations due to a possible increase of jet multiplicities in Au+Au collisions, or conversely, some decrease due to the suppression of high $p_t$ back-to-back correlations. It is difficult to make an accurate estimate of possible modifications of non-flow effects. The fact that at very high $p_t$ the $p+p$ results are very close to central Au+Au (shown later by Figure 1), suggests that the modifications are relatively small.

Figure 1 shows the azimuthal correlation, Eq. 1, as a function of transverse momentum for three different centrality ranges in Au+Au collisions, as compared to minimum bias $p+p$ collisions. We observe that for the most peripheral Au+Au collisions, the azimuthal correlations are very similar to minimum bias $p+p$. In mid-central
Au+Au events, the azimuthal correlations are very different from those in $p+p$ collisions in both magnitude and $p_t$-dependence. Note that at $p_t = 7$ GeV/c, the azimuthal correlations in Au+Au collisions are still many standard deviations away from those observed in $p+p$ collisions, indicating significant elliptic flow up to these momenta. For the most central Au+Au collisions, at low-$p_t$ the magnitude of the correlations is also different from $p+p$. However, for particles with $p_t \geq 5$ GeV/c, the correlation in Au+Au collisions starts to follow that in $p+p$ collisions, suggesting that azimuthal correlations become dominated by non-flow effects and that the latter are rather similar in $p+p$ and Au+Au collisions at those momenta. The observed non-monotonic centrality dependence of the azimuthal correlation at low and moderate $p_t$ is strong evidence of elliptic flow. It is qualitatively different from that expected from intra-jet correlations among jet fragments [18].

We also perform a multi-particle cumulant analysis, which is much less sensitive to non-flow effects than the traditional approach based on two-particle correlations. Figure 2 shows $v_2$ as a function of transverse momentum for 20%-60% of the total cross-section. The $v_2$ obtained using the four-particle cumulant method, $v_2\{4\}$, is up to about 20% lower than the value of $v_2$ obtained from the two-particle cumulant method. This difference could be partially explained by non-flow effects, which are greatly suppressed in $v_2\{4\}$, and by the fluctuation of $v_2$ itself [17,18]. Flow fluctuations contribute to $v_2\{2\}$ and $v_2\{4\}$ with different signs. The true $v_2$ lies between $v_2\{4\}$ and approximately the average of $v_2\{2\}$ and $v_2\{4\}$. The systematic uncertainty is given by these two bounds. For the centrality range plotted in Fig. 2 we find significant $v_2$ at least up to $p_t \approx 7$ GeV/c, well within the region where particle production is expected to be dominated by parton fragmentation. Two-particle cumulant results extend to 12 GeV/c, although at high $p_t$ these might be dominated by non-flow contributions. Also shown in Fig. 2 by open circles are the 2-particle correlation results after subtracting the correlations measured in $p+p$ collisions. The comparison of these results to $v_2\{4\}$ in the region $p_t < 4$ GeV/c indicates that either the relative contribution of non-flow effects is larger in Au+Au collisions compared to $p+p$, or there is a significant flow fluctuation contribution that would increase the apparent $v_2\{2\}$ values and decrease $v_2\{4\}$. In general we observe that $v_2(p_t)$ reaches a maximum at about 3 GeV/c, confirming results obtained by PHENIX [21] and then slowly decreases.

The energy loss mechanism that leads to azimuthal anisotropy at high $p_t$ also leads to a distinct feature in two particle azimuthal correlations. At high transverse momenta, two-particle distributions in the relative azimuthal angle measured in $p+p$, d+Au, and Au+Au collisions at RHIC [6,7,8] exhibit a jet-like correlation characterized by the peaks at $\Delta \phi = 0$ (near-side correlations) and at $\Delta \phi = \pi$ (back-to-back). The back-to-back peak is found to be strongly suppressed in central Au+Au collisions [6]. In non-central collisions, the suppression should depend on the relative orientation of the back-to-back pair with respect to the reaction plane. In the analysis of the two-particle azimuthal correlations, we select trigger particles with $4 < p_t^{\text{trig}} < 6$ GeV/c emitted in the direction of the event plane angle $\Psi_2$ (in-plane, $|\phi^{\text{trig}} - \Psi_2| < \pi/4$ and $|\phi^{\text{trig}} - \Psi_2| > 3\pi/4$) and perpendicular to it (out-of-plane, $|\phi^{\text{trig}} - \Psi_2| < 3\pi/4$). The trigger particles are paired with associated particles satisfying $2$ GeV/c $< p_t < p_t^{\text{trig}}$. The tracks are restricted to $|\eta| < 1$. To reduce the effect of particles produced within a jet on the reaction plane reconstruction, all particles in a pseudorapidity region $|\Delta \eta| < 0.5$ around the highest $p_t$ particle in the event are excluded from the event plane determination. In the upper panel of Fig. 3 we show the azimuthal distributions of associated particles for trigger particles that are in-plane (squares) and out-of-plane (triangles) in midcentral Au+Au collisions. The distributions are corrected for the reconstruction efficiency. The measured distributions exhibit a strong elliptic flow pattern similar to that found in the recent analysis at the SPS [21].

In the presence of elliptic flow the in-plane and out-of-plane two-particle azimuthal distributions are given by [22]:

$$\frac{dN^{\text{in}}}{d\Delta \phi} = B \left[ 1 + 2v_2^{\text{assoc}} \left( \frac{p_t^{\text{trig}} + 2(\cos(2\Delta \Psi))}{\pi \pm 4v_2^{\text{assoc}} (\cos(2\Delta \Psi))} \right) \cos(2\Delta \phi) \right]$$

where $v_2^{\text{assoc}}$ and $v_2^{\text{trig}}$ are the elliptic flow of the associated and trigger particles, respectively, and $\langle \cos 2\Delta \Psi \rangle$ is the reaction plane resolution [11]. For the given centrality $\langle \cos(2\Delta \Psi) \rangle = 0.70$; $v_2^{\text{assoc}} = 0.20$, and $v_2^{\text{trig}} = 0.18$.

FIG. 2: (color online) $v_2$ of charged particles as a function of transverse momentum from the two-particle cumulant method (triangles) and four-particle cumulant method (stars). Open circles show the 2-particle correlation results after subtracting the correlations measured in $p+p$ collisions. Only statistical errors are shown.
measured via the reaction plane method. For the estimate of the systematic uncertainty in the determination of the flow contribution, we have varied $v_2^{\text{assoc}}$ and $v_2^{\text{tri}}$ between 0.167 and 0.213 ($v_2^4$) and $v_2^2$ [2] measured in the range $2<p_T<6$ GeV/c. To reduce the systematics, a z vertex cut of ±25 cm is applied to $p+p$ events to match that in $Au+Au$ events.

The distributions were fit to Eq. 2 in the region $0.75 < |\Delta \phi| < 2.24$ rad, with $B$ as the only free parameter, to determine the amount of background. For the in-plane distribution, $B = 0.649 \pm 0.004 (\text{stat.}) \pm 0.005 (\text{sys.})$, and for the out-of-plane, $B = 0.638 \pm 0.004 (\text{stat.}) \pm 0.002 (\text{sys.})$. The systematic errors were estimated from using different ranges of $\Delta \phi$ in the fit. We observe a strong excess of two-particle correlations over the correlation pattern generated by elliptic flow in the region $|\Delta \phi| < 0.75$ for both in-plane and out-of-plane distributions, characteristic of near-side intra-jet correlations. In the region around $\Delta \phi = \pi$, we observe an excess for the in-plane distribution, but no excess is found for the out-of-plane distribution. This is better illustrated in the lower panel of Fig. 3 where we show the flow-subtracted in-plane and out-of-plane distributions compared to that measured in $p+p$ collisions. The level of combinatorial background measured in $p+p$ collisions, 0.014 ± 0.001, has been subtracted. The near-side jet-like correlations measured in Au+Au are similar to those measured in $p+p$ collisions. The back-to-back (around $\Delta \phi = \pi$) correlations measured in Au+Au collisions for in-plane trigger particles are suppressed compared to $p+p$, and even more suppressed for the out-of-plane trigger particles. For the near angle correlations in the relative azimuthal region $|\Delta \phi| < 0.75$ rad, the integrals of the azimuthal distributions are $0.078 \pm 0.014 (\text{stat.}) \pm 0.031 (\text{sys.})$ in-plane and $0.081 \pm 0.014 (\text{stat.}) \pm 0.021 (\text{sys.})$ out-of-plane. For the back-to-back correlations in the relative azimuthal region $|\Delta \phi - \pi| < 0.75$ rad, the integrals are $0.048 \pm 0.014 (\text{stat.}) \pm 0.031 (\text{sys.})$ in-plane and $0.014 \pm 0.014 (\text{stat.}) \pm 0.021 (\text{sys.})$ out-of-plane. Note that the large systematic errors in Fig. 3 (lower panel), resulting from the uncertainty in the subtraction of elliptic flow contribution, are highly anti-correlated: assuming weaker (stronger) elliptic flow results in the upper (lower) systematic error bar for $dN/d|\Delta \phi|$ and lower (upper) systematic error bar for $dN/d(\Delta \phi)$ distributions.

A different approach to remove the elliptic flow contribution to the two-particle distributions is to subtract the raw away-side correlations from the near-side correlations measured in the same $|\Delta \phi|$ range (in this case, the elliptic flow contribution cancels out). The difference in the correlation strength, an integral over $\Delta \phi$ region, on the near-side ($|\Delta \phi| < 0.75$ rad) and the away-side ($|\Delta \phi - \pi| < 0.75$ rad) is measured to be $0.030 \pm 0.011 (\text{stat.})$ for the in-plane triggers and $0.067 \pm 0.011 (\text{stat.})$ for the out-of-plane triggers where the systematic uncertainty due to elliptic flow is canceled out, and the remaining systematic uncertainties are smaller than the statistical errors. Assuming similar strength of the near-side correlations in-plane and out-of-plane, the observed difference can be attributed to the suppression of away-side correlations which depends on the reaction plane orientation.

Although results presented above strongly support the jet-quenching scenario qualitatively, the amount of elliptic flow observed at high $p_t$ for collisions at $\sqrt{s_{NN}} = 130$ GeV seems to exceed the values expected in the case of complete quenching [23]. Extreme quenching leads to emission of high-$p_t$ particles predominantly from the surface, and in this case $v_2$ would be fully determined by the geometry of the collision. This hypothesis can be tested by studying the centrality dependence of $v_2$ for high-$p_t$ particles.

Figure 4 shows $v_2$ in the $p_t$-range of 3–6 GeV/c (where $v_2$ is approximately maximal and constant) versus impact parameter. The values of the impact parameters were obtained using a Monte Carlo Glauber calculation [24]. The measured values of $v_2^4$ are compared to various simple models of jet quenching. The upper curve corresponds to a complete quenching, in which particles are emitted from a hard shell [23,24]; this gives the maximum values of $v_2$ that are possible in a surface emission scenario. A more realistic calculation corresponds to a parameterization of jet energy loss in a static medium where the absorption coefficient is set to match the suppression of the inclusive hadron yields [2]. The density distributions of the

\[\text{FIG. 3: (color online) Upper panel: Azimuthal distributions of associated particles for trigger particles in-plane (squares) and out-of-plane (triangles) for $Au+Au$ collisions at centrality 20-60\%. Open symbols are reflections of solid symbols around $\Delta \phi = 0$ and $\Delta \phi = \pi$. Elliptic flow contribution is shown by dashed lines. Lower panel: Distributions after subtracting elliptic flow, and the corresponding measurement in $p+p$ collisions (histogram).}\]
FIG. 4: (color online) $v_2$ at $3 \leq p_t \leq 6$ GeV/c versus impact parameter, $b$, compared to models of particle emission by a static source (see text).

static medium are modeled using a step function (following [26]) and a more realistic Woods-Saxon distribution (following [27]). The corresponding $v_2$ values are shown as the upper and lower band, respectively. The lower and upper boundaries of bands correspond to an absorption that gives a suppression factor of 3 and 5, respectively, in central collisions. Over the whole centrality range, the measured $v_2$ values are much larger compared to calculations. Taking into account that this measurement is dominated by the lower $p_t$ side (3 GeV/c), the quark coalescence mechanism [28] might be responsible for the difference, but no quantitative explanation for the observed large elliptic flow exists at the moment.

In summary, we have shown that the charged particle elliptic anisotropy in midcentral Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV extends to large transverse momenta, at least up to $p_t \sim 7$ GeV/c, as expected in a jet quenching scenario. By performing multi-particle correlation analysis and comparing the azimuthal correlations in Au+Au collisions to those in $p+p$, we find the contribution of the effects not associated with the reaction plane orientation is relatively small in midcentral events but could be significant in peripheral and central collisions. We report stronger suppression of the back-to-back high $p_t$ correlations for out-of-plane triggers compared to in-plane triggers, again consistent with a jet quenching picture. $v_2$ integrated from moderate to high $p_t$, approximately in the region where it reaches a maximum, clearly exceeds the limits set for elliptic flow due to a simple jet quenching mechanism, and still waits for quantitative theoretical explanation.

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