Directed flow at midrapidity in heavy-ion collisions

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It was recently shown by Teaney and Yan that fluctuations in the initial geometry of a heavy ion collision generally result in a dipole asymmetry of the distribution of outgoing particles. This asymmetry, unlike the usual directed flow, is expected to be present at a wide range of rapidity — including midrapidity. We show that first evidence of this phenomenon can be seen in recent two-particle correlation data by STAR, and propose a new direct measurement.

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I. INTRODUCTION

Analyses of correlations between particles emitted in heavy-ion collisions reveal azimuthal structure which is not seen in proton-proton or deuteron-gold collisions. These unique correlations are present even if the particles are separated by a large interval in rapidity. The largest component, known as elliptic flow, is one of the early observations at RHIC [1]. More recently, it has been realized that more detailed features of the correlation pattern known as "ridge" and "shoulder" can also be explained by a new phenomenon, dubbed "triangular flow", which comes from the hydrodynamic response to fluctuations in the initial geometry [2]. An analysis [3] of recent experimental data [4] shows that *all* the correlations observed at large relative pseudorapidities are likely to originate from collective flow (and global momentum conservation). Contributions from event-by-event fluctuations, which in the past have been neglected, are key to this understanding.

Teaney and Yan [5] have shown that such fluctuations in the initial geometry are expected to create a new type of directed flow in addition to elliptic and triangular flow. Fluctuations break the symmetry of the initial density profile, and as a result there is, in general, one direction where the profile is steepest. This effect can be quantified as a dipole asymmetry in the initial density [5]:

$$\varepsilon_1 e^{i\psi_1} = -\frac{\langle r^3 e^{i\phi}\rangle}{\langle r^3\rangle}. \tag{1}$$

where the averages in the right-hand side are taken over the initial transverse entropy density profile, and (r, ϕ) is a polar coordinate system around the center of the distribution, chosen such that $\langle re^{i\phi}\rangle = 0$. If one chooses ε_1 to be positive, then ψ_1 generally corresponds to the steepest direction for a smooth profile, and ε_1 is the magnitude of the dipole asymmetry. In general, ε_1 will differ from 0 — even at midrapidity — due to fluctuations.

This dipole asymmetry, followed by hydrodynamic expansion, creates a specific type of flow. Recall that particles with large momentum p_t are created where the fluid velocity is largest, and their momentum is parallel to the fluid velocity [6]. The fluid velocity scales like the gradients of the initial density profile, and so high-p_t particles are likely to be emitted along the steepest gradient, i.e., with azimuth ψ_1. This asymmetry can be characterized by the directed flow measured with respect to ψ_1:

$$v_1 \equiv \langle\cos(\phi - \psi_1)\rangle. \tag{2}$$

While v_1 is positive for high-p_t particles, the condition that the total net transverse momentum of the fluid approximately vanishes implies in turn that v_1 is negative for low-p_t particles, which results in a specific pattern for the p_t dependence of v_1 [5]. Although ψ_1 cannot be measured experimentally, the correlation of every particle to ψ_1 induces a correlation between pairs of particles, which can be measured even if ψ_1 is not known.

Unlike the usual directed flow, which is odd in rapidity [7–9], this new type of directed flow is expected to depend little on rapidity, since it is created by fluctuations in the initial geometry. In this paper, we argue that this phenomenon can already be seen in existing data, and we propose a method to measure it directly.

II. DIHADRON CORRELATIONS

The STAR collaboration has released an analysis of dihadron correlations at different angles with respect to the reaction plane [4]. They have measured the distribution of the relative angle $\Delta\phi$ between a high-p_t trigger particle and an associated particle in various p_t bins. The first Fourier harmonic of the correlation function, $\langle\cos\Delta\phi\rangle$, where brackets denote an average over pairs, gets contributions from transverse momentum conservation and from directed flow [3]:

$$\langle\cos\Delta\phi\rangle = \langle\cos\Delta\phi\rangle_{\rm p_t\ cons.} + v_1^{(t)} v_1^{(a)}, \tag{3}$$

where $v_1^{(t)}$ and $v_1^{(a)}$ are the directed flows of the associated and trigger particles. We assume that these are the only contributions at large relative pseudorapidity $\Delta\eta$. In practice, we use STAR data projected onto $|\Delta\eta| > 0.7$.

In order to isolate the flow contribution, one must quantitatively estimate the contribution of momentum conservation. Under fairly general assumptions, this contribution can be written as [10]

$$\langle \cos \Delta\phi \rangle_{\rm pt\ cons.} = -\frac{p_t^{(t)} p_t^{(a)}}{\langle \sum p_t^2 \rangle}, \quad (4)$$

where $p_t^{(t)}$ and $p_t^{(a)}$ are the transverse momenta of the trigger and associated particles, respectively, and the sum runs over all particles emitted in the event.

We estimate the denominator in the following way: we use the total pion and kaon multiplicities measured by BRAHMS in central collisions [11], and we rescale them to the 20%-60% centrality range assuming that the correlation (4) scales with centrality approximately like $1/N_{\rm part}$, which increases the correlation by a factor $\simeq 3.6$. We calculate $\langle p_t^2 \rangle$ for pions, kaons and nucleons assuming exponential m_t spectra, and using the inverse slopes of m_t spectra measured by PHENIX at mid-rapidity in the centrality range 40%-50% [12]. We further estimate that the effective inverse slopes, averaged over all rapidities, are 10% smaller than the inverse slopes at mid-rapidity, based on the observed decrease of $\langle p_t \rangle$ versus rapidity [11].

We thus obtain

$$\langle \cos \Delta\phi \rangle_{\rm p_t\ cons.} \simeq \frac{-0.00185}{({\rm GeV}/c)^2} p_t^{(t)} p_t^{(a)}. \quad (5)$$

Subtracting the contribution of momentum conservation from the measured $\cos\Delta\phi$, we extract $v_1^{(t)} v_1^{(a)}$ using Eq. (3). Since v_1 is defined as a correlation with a direction ψ_1 which is itself uncorrelated with the reaction plane [5], one expects that this quantity is independent of the orientation of the trigger particle, and this is indeed what is observed by analyzing STAR results [3]. In order to increase the statistics, we average the measured $\cos\Delta\phi$ over all orientations. We thus obtain 10 values of $\cos\Delta\phi$, corresponding to 5 intervals in p_t below 3 GeV/c for the associated particle, and 2 intervals in p_t for the trigger particle, namely, $3 < p_t^{(t)} < 4$ GeV/c and $4 < p_t^{(t)} < 6$ GeV/c.

Assuming some value of $v_1^{(t)}$, we can extract $v_1^{(a)}$ from the product $v_1^{(t)} v_1^{(a)}$. There is some arbitrariness in this procedure, but v_1 is expected to be a smooth function of p_t, so that it should have comparable values in the intervals $2 < p_t < 3$ and $3 < p_t < 4$. Any value of $v_1^{(t)}$ in the range 0.10–0.13 gives reasonable results for both sets of trigger particles, as shown in Fig. 1. In particular, we obtain similar curves for $v_1^{(a)}$ from both sets of trigger particles, which supports the validity of Eq. (3).

The variation of v_1 with p_t is as predicted by Teaney and Yan using ideal hydrodynamics below 2 GeV (see Fig. 12 of Ref. [5]). In particular, the absence of net transverse momentum implies that the sum of $p_t v_1(p_t)$ over all particles vanishes, which explains why v_1 changes sign near 0.8 GeV/c. Above 2 GeV, v_1 deviates from the linear rise predicted by ideal hydrodynamics and saturates or decreases, in the same way as elliptic flow [14].

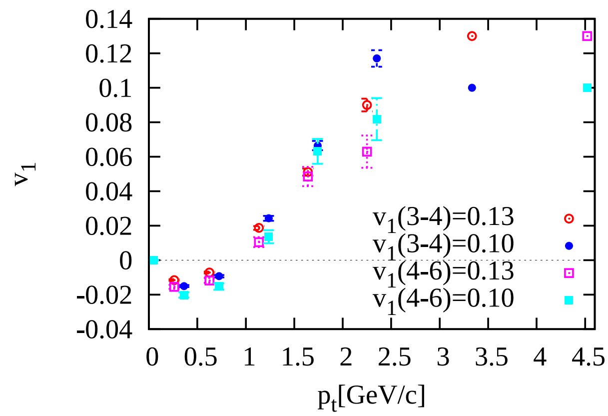

FIG. 1. (Color online) Differential v_1 of charged hadrons extracted from STAR correlation data [4]. Circles (squares) correspond to trigger particles with $3 < p_t^{(t)} < 4$ ($4 < p_t^{(t)} < 6$). Closed (open) symbols correspond to assumed values of $v_1^{(t)} = 0.1$ (0.13). Error bars are statistical only. The value of p_t on the horizontal axis is the average value in the corresponding bin. For $p_t > 0.5$ GeV/c, this value is obtained using p_t spectra measured by PHENIX [13] in the centrality bin 30-40%. For the lowest bin, it is obtained by assuming an exponential m_t spectrum. For sake of clarity, $\langle p_t \rangle$ has been shifted by -0.05 (0.05) for open (closed) symbols.

The magnitude of v_1 is also as expected: the initial dipole asymmetry ε_1 defined by Eq. (1) is predicted to be roughly 4 times smaller than the initial eccentricity ε_2 for Au-Au collisions [5]. In the momentum range $1.5 < p_t < 2$ GeV, hydrodynamics predicts $v_1/\varepsilon_1 \simeq v_2/\varepsilon_2$. Since $v_2 \simeq 0.2$ in this momentum range for the same centrality window [14], one expects $v_1 \simeq 0.05$, in good agreement with the value in Fig. 1.

The estimates in Fig. 1 have sizable statistical errors, because they are extracted from correlations involving a trigger particle with high transverse momentum, and there are few such particles. These errors, as well as significant errors coming from the estimation of the momentum conservation correlation, can be significantly reduced by carrying out a dedicated analysis.

III. NEW METHOD OF ANALYSIS

Directed flow is most often analyzed using an event-plane method, analogous to the one often used for elliptic flow [15, 16]. In every event, one defines the directed flow event plane $\psi_{EP,1}$ by

$$Q\cos\psi_{EP,1} = \sum w_j \cos\phi_j$$
$$Q\sin\psi_{EP,1} = \sum w_j \sin\phi_j \quad (6)$$

where the sum is over particles detected in the event, ϕ_j are the azimuthal angles of outgoing particles, and w_j is a weight, and $Q \geq 0$. Our new method is based on a new choice for the weight w_j. The weight of a particle is generally a function of its transverse momentum p_t and rapidity y. The desired conditions are that

- Correlations from momentum conservation should not bias the flow analysis. Since these correlations are proportional to p_t, this gives the condition $\langle w(p_t, y)p_t\rangle = 0$, where angular brackets denote an average over the detector acceptance.

- Particles with larger v_1 should be given more weight, the optimal choice being $w(p_t, y) \propto v_1(p_t, y)$ [17].

For smooth initial conditions, the symmetry between target and projectile implies that v_1 is an odd function of y. A standard choice is $w(p_t, y) = y$, which satisfies both requirements if the detector acceptance is symmetric with respect to midrapidity. By construction, this results in a measured v_1 that, on average, vanishes at midrapidity and is antisymmetric in y.

In this paper, we study the directed flow created by fluctuations in the initial geometry. These fluctuations are expected to depend weakly on rapidity [18]. Thus we choose a weight which depends on p_t only. The prescription

$$w(p_t) = p_t - \frac{\langle p_t^2\rangle}{\langle p_t\rangle}, \qquad (7)$$

where angular brackets denote an average over particles in the detector acceptance, satisfies the condition $\langle wp_t\rangle = 0$, so that momentum conservation does not bias the analysis. It also corresponds to the expected behavior of $v_1(p_t)$ in ideal hydrodynamics in the limit of low freeze-out temperature for massless particles [5].

Instead of the event-plane method, one can use any of its variants such as the scalar-product method [19]. All methods should give the same result provided that one only correlates particles, or subevents, separated by a gap in pseudorapidity in order to remove nonflow effects.

IV. CONCLUSIONS

We have shown that the first Fourier harmonic, $\langle\cos\Delta\phi\rangle$, of the two-particle correlation measured by STAR shows the first evidence for a sizable directed flow originating from fluctuations of the initial geometry. Unlike the usual directed flow, this phenomenon is predicted to have no correlation with the reaction plane and to depend weakly on rapidity. It changes sign around $p_t \simeq 0.8$ GeV, and may reach values as large as 10% at high p_t for mid-central collisions. We have proposed a specific method to analyze this new observable which eliminates correlations from momentum conservation.

This is an interesting new phenomenon that, like triangular flow, results from initial geometry fluctuations and subsequent hydrodynamic evolution, and provides the last element needed for a complete quantitative understanding of long-range dihadron correlations. Dedicated measurements of this new v_1 in heavy-ion collisions at RHIC and LHC will help constrain models of initial conditions and confirm the hydrodynamic behavior of the collision system.

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