Recent Flow Results from PHENIX

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Abstract. The phenomenon of collective flow, as revealed through azimuthal anisotropies of the “bulk” of produced hadrons, has been one of the most information-rich sectors of observables measured in RHIC and LHC heavy-ion collisions. A new wealth of data on bulk azimuthal anisotropies is now becoming available, including measurements involving (i) higher-order harmonics, (ii) identified hadrons, (iii) forward and backward rapidities, and (iv) system and beam energy dependencies. The latest compendium of flow results from PHENIX is reviewed and their range of physics implications will be discussed.

1. Introduction

The hydrodynamic paradigm has been quite successful in describing and explaining the global patterns of the large majority of light hadrons produced in high-energy A+A collisions at RHIC (and also at the LHC), and is now a prominent feature of the emerging “standard picture” of these collisions. Within this paradigm we can identify three basic stages of the collision’s evolution:

(i) The energy of the incoming nuclei is transmuted into a localized energy density present at many different points over some three-dimensional volume.

(ii) The localized energy density exhibits some sufficiently well-defined pressure at each point, and thereafter evolves according to the laws of hydrodynamics along pressure gradients.

(iii) Whatever its composition, the fluid eventually expands and, with positive pressure, cools to the point where further expansion requires it to decay into color singlets, i.e. hadrons, which can spread out to a larger volume and eventually free-stream into their final states.

The hydro paradigm was able to explain the observation that the final states of RHIC collisions exhibited a large quadrupolar anisotropy in momentum, aka “elliptic flow”, as a consequence of a quadrupolar azimuthal spatial asymmetry in the initial energy deposit pattern, and so in the pattern of initial pressure gradients. Quantitative consideration of the magnitude of elliptic flow then implied that (a) the time for stage (i) leading to the hydro stage (ii) must be very short, $\lesssim 1 \text{ fm}/c$, and so occur at a high density, and (b) the evolution during the hydro stage (ii) must exhibit low dissipation, expressed as shear viscosity, in order to preserve the quadrupolar anisotropy so efficiently. These implications matched with the theoretical description, that thermalized nuclear matter at these densities should be described as a Quark Gluon Plasma (QGP) and that the QGP should have very low dissipation.

Thus, signatures of hydrodynamic (“flow”) behavior in the patterns of final-state hadron momenta now form the basis for arguing that the QGP as described by QCD is formed in
RHIC (and LHC) collisions, and for diagnosing both the hydrodynamic parameters of the QGP fluid and the shapes of the initial energy deposit pattern. This paper will exhibit a selection of recently published flow measurements made by the PHENIX experiment, and consider what they reveal about the hydro paradigm. To do this, we will address results which are relevant to the different stages described above, but in reverse time ordering: final-state description, diagnosing the hydro evolution, and investigating the initial-state energy deposit mechanism.

2. The Flowing Final State

Focusing on stage (iii) of the evolution as described above, the simplest picture is that, when a certain threshold density and temperature are reached, each element of the fluid is simply converted into a locally equilibrated gas of hadrons in accordance with the local temperature and chemical potentials. In this picture, the fact that the different species of hadrons all emerge from fluid elements with particular velocities will imprint particular “mass splitting” pattern on the elliptic flow strength for different species: stronger for the light mesons at lower transverse momenta then switching to be stronger for baryons at higher transverse momenta. When this pattern was observed at RHIC [1] it was taken as strong evidence for the hydro paradigm. The PHENIX experiment has now [2] extended the measurements of elliptic flow for identified charged hadrons out to much higher transverse momenta ($p_T$), as seen in Figure 1. The basic mass splitting is clearly seen, as well as the interesting turn down in the (anti-)proton elliptic flow at the higher $p_T$ in mid-central collisions.

An alternative is the coalescence picture, in which the hadrons emerge from the final state of the fluid through the re-combination of valence/constituent quarks, which are themselves following the fluid’s flow. This picture predicts a pattern in the $v_2$’s of hadrons not just according to mass but according to constituent quark number; roughly speaking, the elliptic flow modulation of a two- or three-quark hadron will be two or three times that of the flowing quarks. The lower panels of Fig. 1 illustrate the observables which would be predicted to show a common behavior across hadrons in two coalescence mechanisms; but with the new higher-$p_T$ data we can now see a unmistakeable departure from the trend for the (anti-)baryons.

3. The Evolution of Flow

If, as in the standard picture, the fluid is comprised of locally-equilibrated QGP during all or most of the hydro stage, then being able to diagnose or constrain what goes on in that stage offers the prospect for learning directly about the QGP itself, including its equation of state and transport properties.

A traditional probe for diagnosing the thermal properties of the early stages of nuclear collisions is direct photons, since photons radiated during all stages can survive nearly undisturbed to the final state. The PHENIX experiment has recently published – see Figure 2 – unique results showing a non-zero elliptic anisotropy of direct photons down to low $p_T \sim 1$ GeV/$c$, where thermal emission sources are expected [4] to dominate their production. In principle, then, these data should encode the history of when the elliptic flow was being built up during the hydrodynamic stage, or even at its start. However, the theoretical interpretation of the direct photon $v_2$ in terms of thermal fluid radiation is unclear at present, since the currently available predictions based on hydrodynamical pictures are seen to greatly underestimate the magnitude of the direct photon anisotropy. It remains to be determined whether this discrepancy can be resolved within the hydro paradigm, or whether a new ingredient will be called for, such as substantial momentum anisotropy at the start of the hydro stage (aka “pre-equilibrium flow”); or whether the identification of direct photons in this $p_T$ range with QGP radiation should be questioned.

Originally it was assumed that the quadrupolar anisotropy of elliptic flow would be aligned, collision by collision, with the direction of the reaction plane $\Psi_{RP}$ connecting the two nuclei:
Figure 1. Upper: Elliptic flow strengths for identified charged hadrons, with charge signs combined, in Au+Au collisions as measured by PHENIX [2]. Middle: observation of “quark number scaling”, where the $v_2$ amplitude is divided by the hadron's constituent quark number, plotted against the hadron’s transverse kinetic energy per constituent quark. Bottom: same, but plotted against transverse momentum per constituent quark. A common behavior for all the hadrons is often taken as validating a quark coalescence picture of hadron formation, but a clear departure can now be seen for the (anti-)baryons with the higher-$p_T$ data.
Figure 2. Elliptic flow strengths for $\pi^0$'s, inclusive photons (left) and direct photons (right) in Au+Au collisions, as measured by PHENIX [3]. The $v_2$ parameters are measured for pions and inclusive photons at mid-rapidity with reference to a second-order event plane $\Phi^\text{BBC}_2$ in the PHENIX Beam-Beam Counters (BBC) at high rapidities; the direct photon $v_2$ is then derived from a decomposition of the inclusive photons into decay and direct components.
\[ \frac{dN}{d\phi} (\phi; \Psi_{RP}) \propto 1 + 2 v_2 \cos(2(\phi - \Psi_{RP})) \]  

(1)

But if we allow for more general geometries, such as might be produced by initial-state spatial fluctuations, then we can in principle expect azimuthal modulations \( \{v_n\} \) at all harmonic orders, referenced to a set \( \{\psi_n\} \) of event plane directions at each order:

\[ \frac{dN}{d\phi} (\phi; \{\psi_n\}) \propto 1 + 2 v_1 \cos(\phi - \psi_1) + 2 v_2 \cos(2(\phi - \psi_2)) + 2 v_3 \cos(3(\phi - \psi_3)) + \ldots \]  

(2)

As mentioned in Section 1, the fact (within the hydro paradigm) that an initial-state quadrupolar spatial anisotropy can faithfully drive a corresponding final-state quadrupolar momentum anisotropy was interpreted as evidence for low dissipation in the hydro phase, and could quantitatively constrain transport/dissipation properties of the QGP such as the shear viscosity. If higher-order azimuthal momentum anisotropies are also being driven by higher-order initial spatial anisotropies, then these should show the effects of dissipation/shear viscosity even more prominently due to their shorter spatial wavelengths. As such, beyond the \( n = 2 \) “elliptic flow” there is now considerable interest in measuring the \( n = 3 \) “triangular” and \( n = 4 \) “cloverleaf” flow patterns of final-state hadrons.

Figure 3 shows recent results from the PHENIX experiment [5] for elliptic (\( v_2 \)) and triangular (\( v_3 \)) flow of inclusive charged hadrons, across centrality for two \( p_T \) bins. Also plotted are the predictions of several different theoretical hydrodynamical calculations, with different models of initial-state fluctuations and choices of shear viscosity; systematic comparison reveals that, as expected, the new \( v_3 \) data provide significant additional constraint on the models, beyond that of the \( v_2 \) data alone. Systematic comparisons of this kind may offer the best opportunity for detailed and quantitative characterization of the QGP state of nuclear matter.

4. The Initial Deposit of Energy

In a symmetric A+A collision the distribution of initial energy deposit in the transverse plane across mid-rapidity must, on average, be ”almond-shaped”: mirror- and \( 180^\circ \)- rotationally symmetric. Such an average distribution cannot, by symmetry, drive a final-state anisotropy of odd harmonic order at mid-rapidity, and will only drive relatively small \((v_4 \sim (v_2)^2)\) anisotropies at higher even orders. Within the hydro paradigm, then, the observation of measurable triangular flow at mid-rapidity in RHIC collisions provides strong evidence that the event-by-event initial states do not all conform to the average distribution, but must exhibit substantial fluctuations.

Specific models for initial-state fluctuations, coupled with simulations of the hydro and hadronization phases, can be compared to data across centralities and transverse momentum as in Fig. 3. But even without a specific model we can deduce some general trends directly from the data. The fuller set of PHENIX data on \( v_2 \), \( v_3 \) and \( v_4 \) for inclusive hadrons across centrality and \( p_T \) are shown in Figure 4. The elliptic flow strength \( v_2 \) grows dramatically from central to peripheral collisions, consistent with the average geometry of the nuclear overlap region becoming less round and more elliptical. However, even the ”roundest” central collisions exhibit a substantial \( v_2 \), consistent with a contribution to event-by-event non-roundness from fluctuations becoming visible. The \( v_3 \) strengths are nearly independent of centrality, which is qualitatively consistent with their origin lying entirely in fluctuations and having little or no connection to the average geometry. The \( v_4 \) trend, growing slowly from central to peripheral, fits the same picture, where it is driven largely by fluctuations but with some component tracking the average geometry as would be expected for an even-order moment.
The success of a picture with substantial initial-state fluctuations, which could in principle be measured and diagnosed, opens the way to a systematic investigation of how the initial deposit of energy density over space is achieved. The mechanism for this phase remains unknown at present, but understanding it would shed light on a whole new frontier of non-perturbative, non-thermal QCD physics.

Figure 5 shows another new PHENIX data set, which can bear directly on the question of what the initial hydro state looks like across three dimensions. On each event the PHENIX experiment measures, in several different detectors, the observable event plane orientation angles $\Phi_n$, at each order $n$; these are experimental proxies for the true event plane angles $\psi_n$ described in Eq. 2 above. What is shown in Fig. 5 is the azimuthal correlation between these measured event planes angles for combinations of detectors that span various ranges in rapidity. Each of these correlation strengths, measured as a function of centrality, provides information on the patterns of fluctuations in the initial state and how those are correlated across longitudinal space (initially) and across rapidity (finally).

To choose just one example, the blue points in panel (b) of Fig. 5 indicate that the triangular components of the final, and so presumably initial, state are positively correlated over a very wide separation in pseudorapidity, $\Delta \eta \sim 7$, which is to say that their triangular orientations are parallel on average. This is actually quite a surprising result! in that the average distribution over three dimensions would produce triangles whose axes should be anti-correlated between forward and backward rapidities; and so this may indicate the dominance of initial fluctuations in the transverse plane which are correlated over long initial distances longitudinally. The new
wealth of this kind of data holds great potential for understanding the initial state in three dimensions, and awaits detailed theoretical attention at present.

5. Conclusion
The PHENIX experiment has recently published a range of unique flow results with intriguing physics implications. Identified hadron elliptic flow out to very high transverse momentum (\(\sim 6 \text{ GeV}/c\)) reveals a breakdown in the quark coalescence scaling behavior seen at lower momenta. An elliptic flow pattern has been observed in direct photons in an energy range thought to have been dominated by thermal radiation from a QGP phase, but hydrodynamical calculations of QGP radiation greatly under-predict the measured strengths. Measurement of higher-order flow moments \(v_3\) and \(v_4\) confirm a picture in which the initial energy density pattern is dominated by fluctuations, and also allow tighter constraints to be placed on transport properties of QGP-phase matter.

6. References
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Figure 5. Correlation strengths between various combinations of measured event planes, as reconstructed in different PHENIX detectors at different harmonic orders (see [5] for full details). In particular, (i) the red triangles in panel (b) indicate that the third-order "triangular" event planes separated over a wide range in rapidity ($\Delta \eta \sim 7$) are positively correlated, i.e. they tend to have parallel orientations; while (ii) the blue squares in panel (d) indicate that the second-and third-order event planes are essentially uncorrelated over a slightly smaller separation.