A BIG SURPRISE IN SMALL DROPS OF QUARK-GLUON PLASMA
OR: FLOW IN D+AU AT RHIC?

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In the collisions of small systems, p(d)+A, it was previously believed that the production of a thermalized quark-gluon plasma would not be permitted due to a limited density and small spatial extent. However, recent studies of small collisions at RHIC and the LHC are now challenging that set of assumptions by showing some features consistent with hydrodynamic flow. These proceedings are a review of results from PHENIX in d+Au collisions which show signatures of hydrodynamic evolution are present at RHIC energies.

1 Introduction

Proton- and deuteron-nucleus collisions at the collider energies of the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) provide useful baseline measurements of initial-state nuclear effects that can also influence the outcome of heavy ion collisions. Proper modeling of these initial-state nuclear effects is important in providing a detailed understanding of the quark-gluon plasma. The energy density left behind in p(d)+A collisions was generally considered too small to create significant quantities of quark-gluon plasma. Recent measurements at the LHC within p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV have challenged the extent to which that assumption applies.\textsuperscript{1,2,3} In these studies, the strength of the azimuthal angular correlations between particles with a large pseudorapidity separation, examined as a Fourier coefficient series, $v_\ell$, are reproduced by theoretical models assuming a hydrodynamic evolution of deposited energy.\textsuperscript{4,5,6} An alternative explanation from Color Glass Condensate “glasma” diagrams has also been proposed to produce these correlations.\textsuperscript{7} The two frameworks predict different correlation strengths at lower collider energy and selection of light projectile: proton versus deuteron.

These proceedings review a set of results made by the PHENIX Collaboration which demonstrate that these azimuthal correlations are present in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The correlations are influenced by the larger eccentricity in the initial state of this system. The correlations also exhibit a mass ordering in the magnitude of the second order coefficient, $v_2$, consistent with the effects of hydrodynamic expansion and freeze-out.\textsuperscript{8,9}

2 Results

The strength of the azimuthal anisotropies are studied via correlations between particles separated in pseudo-rapidity to minimize contributions from hard processes. Figure 1 shows a set of example correlations between mid-rapidity charged particles measured by a set of drift chambers and additional layers of pad chambers, and electromagnetic energy in a set of large rapidity
calorimeter towers. The correlations within p+p collisions exhibit a peak at $\Delta \phi \sim \pi$ from particle production within azimuthally back-to-back jets. A corresponding peak at $\Delta \phi \sim 0$ would be present from particle production within a single jet but is eliminated by the pseudorapidity separation between the particles. The 0-5% most central d+Au collisions also contain a peak at $\Delta \phi \sim \pi$, but unlike p+p collisions also contains a significant enhancement above baseline at $\Delta \phi \sim 0$. This observation is direct evidence that the angular correlation structure of d+Au correlations is modified from the expectation in p+p collisions at RHIC.

The correlation strength of the second moment, $v_2$, in d+Au collisions has been extracted using two methods. The first approach employs a two particle methodology within the mid-rapidity charged particle sample. Because only a small pseudorapidity separation can be made within the detector coverage, a follow up subtraction is used to remove the contribution from jets using peripheral collisions as a model of the (di-)jet contribution. The second approach employs an event plane reconstruction using the calorimeter at large pseudorapidity and correlates this to mid-rapidity charged particles. In this case, the jet contribution is minimal and no follow-up subtraction is needed, but the event plane reconstruction resolution is limited and a correction is applied to remove the effect of this smearing.

Figure 2 shows the resulting extracted values for the second moment of the correlation strength as a function of transverse momentum from 0.5 to 4.5 GeV/c. Both analyses show a large second order modulation in central d+Au collisions that rises with transverse momentum. The small $\eta$ separation study has a sizable correlated systematic uncertainty that results from the removal of the jet contribution. The large $\eta$ separation study is largely free of this uncertainty and gives a more precise determination of the correlation strength. The two methods agree at low momentum and differ by less than a significance of two sigma at large momentum.

The $v_2$ in d+Au generally lies above a variety of central p+Pb results from the LHC. This ordering is predicted within hydrodynamic models as the initial energy density eccentricity driving the expansion is larger for collisions with a deuteron projectile. A comparison of the magnitude of $v_2$ for $p_T \sim 1.4$ GeV/c after scaling by the initial eccentricity, $\varepsilon_2$, is shown as a function of final state particle density in Figure 3. The world data falls on a similar trend though some differences exist for the least dense systems. The d+Au result falls near the scatter of the world data and implies that the initial state eccentricity can account for the larger values of $v_2$ measured at RHIC.

Another further test of hydrodynamic evolution with a larger eccentricity is shown in the right panel of Figure 3. The RHIC data is compared with a series of hydrodynamic theory comparisons for d+Au. The cases of ideal non-viscous hydrodynamics provided by Bozek
and Qin & Mueller\textsuperscript{6} give values similar to the data at low momentum and begin to differ at large momentum where viscous corrections become important. This evidence confirms that hydrodynamics is capable of reproducing the size of the measured signal with the expected eccentricity. The other pair of models show a prediction using a viscous hydrodynamic model, but are estimated for a different centrality selection. Here the overall value differs due to the centrality selection, but the trend of the model is shown to be similar to the data at large momentum when the viscous terms are included.

An additional test of the hydrodynamic generation of the $v_2$ moment is shown in Figure 4. Hydrodynamics predicts different values in the flow pattern for pions and protons. The data in d+Au collisions shows a very similar trend with the pion $v_2$ above the proton $v_2$ at low momentum and below the proton $v_2$ after a transition at $\sim 1.5$ GeV/c. A similar trend has been found in p+Pb collisions at the LHC by ALICE.\textsuperscript{10} This mass ordering has traditionally been viewed as strong evidence of hydrodynamic behavior in heavy ion collisions.

Figure 2 – Transverse momentum dependence of the second moment, $v_2$, for mid-rapidity particles via two-particle correlations with a small $\eta$ gap and via an event-plane method with a large $\eta$ gap compared with LHC results from ATLAS, ALICE, and CMS.

Figure 3 – The second moment, $v_2$, scaled by the system eccentricity, $\varepsilon_2$, versus charged particle density, $dN_{ch}/d\eta$, a mid-rapidity (left). The transverse momentum dependence of $v_2$ is compared with hydrodynamic models (right).
Figure 4 – The second moment, $v_2$, by transverse momentum for pions and protons compared to a hydrodynamic model (left). LHC results from ALICE are shown for comparison (right).

Higher order moments, namely $v_3$, were examined in both analyses and were found to be consistent with zero within the uncertainties of the measurements. Collisions of d+Au have very little initial 3rd order eccentricity as this source arises through fluctuations in the positions of struck nucleons within the target nucleus. Thus hydrodynamic models expect little $v_3$ to result from these collisions. A proposal\textsuperscript{11} has been made to collide He$^3$+Au at RHIC to enhance the 3rd order eccentricity and further test a hydrodynamic understanding of these large pseudorapidity correlations. He$^3$+Au collisions are now expected to begin at RHIC this year and first results could be available for this system relatively soon. In 2015 the PHENIX experiment is requesting collisions of p+p, p+Au, and p+Si. This additional data will allow measurements of the correlations in p+A with a large and a small target nucleus.

3 Summary

PHENIX has observed a significant 2nd order azimuthal anisotropy in d+Au. This feature extends across rapidity and is larger than that found in p+Pb at LHC energies, apparently due to the larger intrinsic eccentricity of the d+Au collision. The signal is largely consistent with the expectation from hydrodynamic modeling of the collisions. RHIC is planning a run of He$^3$+Au collisions in 2014 and a set of p+A data in 2015. These various collision systems within the same experimental apparatus and beam energy will provide stringent tests of the hydrodynamic modeling of small collision systems.

References