Implications for small-system collectivity from a comprehensive set of soft physics measurements in 200 GeV p plus Au collisions by PHENIX

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Implications for small-system collectivity from a comprehensive set of soft physics measurements in 200 GeV p+Au collisions by PHENIX

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Abstract

Proton-nucleus (p+A) collisions play an important role as a control system for interpreting hot nuclear matter effects in nucleus-nucleus (A+A) collisions. There is a large amount of data from both RHIC and the LHC that indicate that collective effects are also present in small systems. Understanding the origin of these effects is still incomplete, since a variety of models with very different underlying physics have been shown to describe p+A data. We present a comprehensive set of measurements of soft-physics observables and comparisons with theoretical models. These measurements include multi-particle correlations as a function of event multiplicity, $v_2(p_T)$ and $v_3(p_T)$ for inclusive charged particles at mid-rapidity, $v_2(p_T)$ for hadrons at forward/backward rapidities, and the centrality and pseudorapidity dependence of inclusive v_2. The implications for the origin of collectivity in p+Au collisions at RHIC is discussed.

Keywords: QGP; collectivity; small system; multi-particle correlation

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1. Introduction

In heavy-ion collisions, proton-nucleus collisions have a crucial role in disentangling cold nuclear matter effects from final-state effects. In A+A collisions, signatures of collective behavior have been widely interpreted as arising from viscous hydrodynamics in the final state. As some typical collective phenomena have been observed in the highest-multiplicity proton-nucleus collisions and even proton-proton collisions [1, 2], it has become intriguing to discover the underlying mechanisms for this behavior. In order to explore the origin of the collectivity in p+A collisions, PHENIX has collected a large set of data from p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. PHENIX has published a paper on collectivity in p+Au at central rapidity [3]. We intend to extend the collectivity study to different kinematic ranges in p+A collisions. Thus, a set of comprehensive, wide-range soft physics observables have been measured.

2. Experimental Setup

In the PHENIX detector system, charged particles are reconstructed with the two central arm spectrometers, covering the pseudorapidity range $|\eta| < 0.35$ and $\pi/2$ in azimuthal angle each. The central arms consist

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of two drift chambers (DC) and multi-wire proportional pad chambers (PC). The drift chamber tracks are projected and matched to hits in the third layer of PC, to minimize the contribution from mis-reconstructed tracks. The beam-beam counters (BBC) consist of two arrays of 64 photomultiplier tubes (PMTs) each, covering 2π in azimuth and $3.1 < |\eta| < 3.9$ in pseudorapidity. The Forward Silicon Vertex Detector (FVTX) consists of two identical end-cap assemblies, covering $1.0 < |\eta| < 3.0$. The event planes are measured in the Au-going direction using the charge deposited in the south BBC (BBC-S), as well as the reconstructed clusters in the south end-cap of the FVTX (FVTX-S). Centrality classes are determined as a percentile of the total multiplicity measured in the BBC-S. Detailed description of the PHENIX detector and its subsystems can be found in [4].

3. Methods

We present two main methods for the flow analysis, the event plane method [5] and the multi-particle correlation method (cumulant method) [6].

The flow coefficient measured with the event plane method follows the equation: $v_n = \langle\cos(n(\phi - \Psi_{n,BBC_s}))\rangle / Res(\Psi_{n,BBC_s})$. The event plane is determined by detectors at large forward pseudorapidity, and the standard re-centering and flattering procedures are applied to calibrate the event-plane distributions. To determine the event plane resolution, the three sub-event method is used:

$$Res(\Psi_{n,BBC_s}) = \langle\cos(n(\Psi_{n,BBC_s} - \Psi_{RP}))\rangle = \sqrt{\frac{\langle\cos(n(\Psi_{n,BBC_s} - \Psi_{n,CNT}))\rangle\langle\cos(n(\Psi_{n,BBC_s} - \Psi_{n,FVTX_s}))\rangle}{\langle\cos(n(\Psi_{n,CNT} - \Psi_{n,FVTX_s}))\rangle}} \tag{1}$$

Here, $\Psi_{n,CNT}$ is the event plane angle determined by the central arm tracking detectors, Ψ_{n,BBC_s} represents the event plane angle determined by the BBC-S PMTs and FVTX-S clusters. $\Psi_{n,FVTX_s}$ is the event plane angle determined by the south end-caps of the FVTX.

The cumulant functions from k-particle correlation are denoted as $c_2\{k\}$. They are constructed to remove the potential contribution from lower order and self correlations. The cumulant $v_2\{k\}$ can be extracted directly from the $c_2\{k\}$. The k = 2-, and 4- particle correlations formulas are:

$$c_2\{2\} = \langle 2\rangle, \tag{2}$$

$$c_2\{4\} = \langle 4\rangle - 2\langle 2\rangle^2, \tag{3}$$

and

$$v_2\{2\} = (c_2\{2\})^{1/2}, \tag{4}$$

$$v_2\{4\} = (-c_2\{4\})^{1/4}. \tag{5}$$

4. Results and Discussions

4.1. Results of cumulant v_2 as a function of multiplicity

The multi-particle correlations method, especially when $k > 2$, is an efficient way to eliminate the contribution from non-flow correlations such as jet correlations or resonance decays. The event-by-event fluctuation in the flow contribution, σ_{v_2} can be also inferred by the formulas below:

$$v_2\{2\}[\eta\ gap] \approx v_2^2 + \sigma_{v_2}^2, \tag{6}$$

$$v_2\{4\} \approx v_2^2 - \sigma_{v_2}^2. \tag{7}$$

Fig. 1 shows the cumulant v_2 as a function of event multiplicity measured by the FVTX detector. As we can see, a positive $c_2\{4\}$ is presented with a real $v_2\{2\}[\eta\ gap]$. This indicates the small variance limit ($\sigma_{v_2} << v_2$) breaks in p+Au collisions at RHIC, which implies that the collectivity in p+Au collisions is dominated by fluctuations. AMPT (A Multi-phase transport model) [7] describes the sign change of $c_2\{4\}$. It is interesting to compare our results to the CMS p+Pb paper [8], where the $v_2\{4\}$ measured in small systems at LHC energies is positive, which implies that *p*+A at RHIC energy has more contributions from fluctuations than at LHC energies.

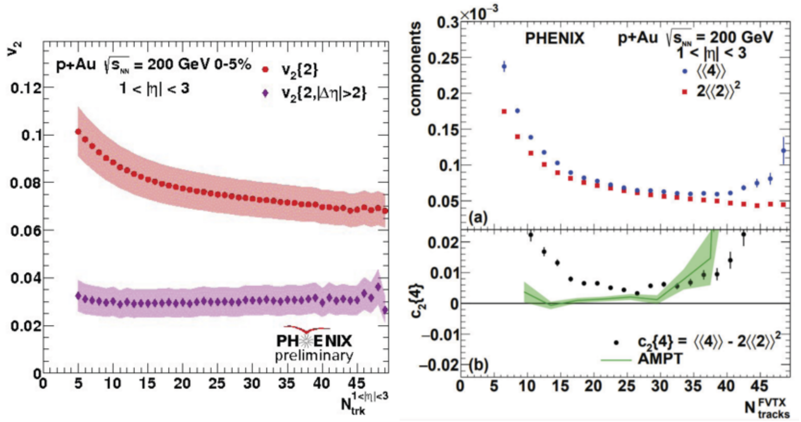

Fig. 1. Charged hadron v_2 vs multiplicity measured by the cumulant method in p+Au collisions. (Left) Two-particle cumulant with and without a large η gap. (Right) Four-particle cumulant with AMPT calculations.

4.2. Results of $v_2(p_T)$ and $v_3(p_T)$

To understand how initial geometry affects the final-state anisotropy, RHIC conducts an important geometry experiment by colliding $p/d/^3$He nuclei on Au nuclei. The high-multiplicity v_2 and v_3 results using the event plane method are shown in Fig. 2. We see a clear ordering of final state v_2 and v_3 according to the initial geometry configurations. A detailed discussion can be found in [9].

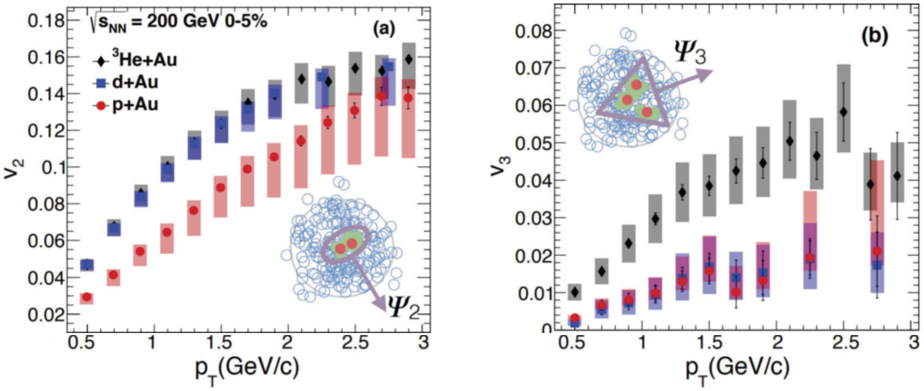

Fig. 2. Charged hadron v_2 and v_3 vs. transverse momentum, p_T, in high-multiplicity $p/d/^3$He+Au collisions.

4.3. The centrality and pseudorapidity dependence of v_2

The measurements of $v_2(\eta)$ yield the longitudinal dynamics in p+Au. The left panel of Fig. 3 shows the centrality dependence of the $v_2(\eta)$ distribution. Each panel in this figure represents a centrality interval. In each bin, flow is larger in the backward region than in the forward region. It is noticeable that the non-flow contributions are largely present in the v_2 calculation, which are quite sensitive to the centrality regions. We also present the comparison of the backward-forward shape of flow and longitudinal particle productions in the right panel of Fig. 3. They scale much better in p+Au in the forward region than in the backward region where the event plane detectors are located. The enhancement in the v_2 for η < -2.0 may be due to the non-flow contribution of short range correlations. Additionally, data are compared with the hydrodynamic model [10]. The model gives a reasonable description of the $dN_{ch}/d\eta$ and a good qualitative agreement of pseudorapdity dependence of v_2.

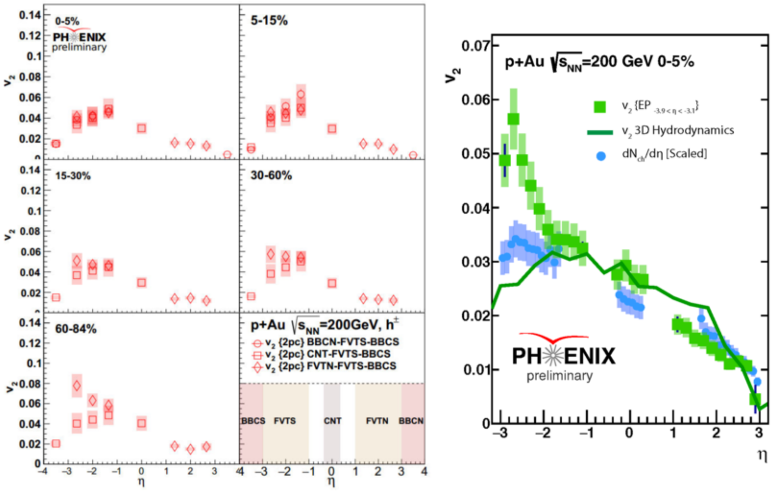

Fig. 3. (Left) v_2 as a function of pseudorapidity η in various centrality bins. (Right) Shape comparison between v_2 and the number of charge particle production.

5. Conclusions

In this proceeding, we presented the measurements of a wide range of soft observables in p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. By looking into the multi-particle correlations, we find that the $v_2\{4\}$ is imaginary which indicates that the fluctuations in p+Au are large. The geometry controlled experiments including p+Au results show strong evidence of initial geometry effects. Lastly, the 3D hydrodynamics model [10] can qualitatively describe the shape of $dN_{ch}/d\eta$ and v_2 as a function of pseudorapidity. In the longitudinal direction where the flow does not simply scale with particle production, we must re-consider non-flow effects when analyzing more peripheral events.

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