Anisotropic Flow in $\sqrt{s_{NN}} = 200$ GeV Cu+Cu and Au+Au collisions at PHENIX

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We report the measurement of anisotropic flow at RHIC - PHENIX experiment. We present the v_4 results at $\sqrt{s_{NN}} = 200$ GeV in Au+Au collision. The scaling ratio of $v_4/(v_2)^2$ is about 1.5 and it is found to be smaller than the prediction from simple coalescence model. The v_2 for high p_T identified particles ($\sim$ 5 GeV/c) measured with Aerogel Cherenkov Counter are presented. We discuss the constituent quark scaling of v_2 for identified particles. We also report the first observation of v_2 for inclusive charged hadrons as well as identified hadrons at $\sqrt{s_{NN}} = 200$ GeV in Cu+Cu collisions. The system size dependence of v_2 and scaling properties are discussed.

1. Introduction

Anisotropic Flow, an anisotropy of the azimuthal distribution of emitted particles in momentum space with respect to the reaction plane, is a sensitive tool to study the early stage of high energy heavy ion collisions at RHIC. It is commonly studied by measuring the Fourier harmonics (v_n) of this distribution [1]. Elliptic Flow (v_2) in Au+Au collisions is well studied at RHIC and is thought to reflect conditions from the early stage of the collision.

It has been reported that anisotropic flow can be reasonably described by the hydrodynamical model up to 2 GeV/c [2]. Hydrodynamics also predict several scaling relations, such as the scaling of $v_4/(v_2)^2$, eccentricity scaling and the scaling with system size. It is crucial to test these scaling in order to investigate the properties of the hot and dense matter which created at the early stage of the heavy ion collisions.

2. Analysis

The data taken by the PHENIX central arm for Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}$ = 200 GeV were used in this analysis. The PHENIX central arm covered half of azimuth, pseudorapidity (η) from -0.35 to 0.35 and the low transverse momentum (p_T) cut off was 0.2 GeV/c. Identified hadrons are measured by the high resolution Time-of-Flight (TOF) and the threshold type Aerogel Cherenkov Counter.

We used event plane method [1] for anisotropic flow measurement. Event plane was determined at Beam-Beam Counter (BBC) [3] which covered full azimuth and $|\eta|$ from

*For the full list of PHENIX authors and acknowledgements, see Appendix 'Collaborations' of this volume.

3.0 to 3.9. The large rapidity gap between the PHENIX central arm and BBC ($\Delta\eta \sim 3$) reduces the non-flow contribution to the two-particle azimuthal correlations.

3. $v_4\{EP_2\}$

Figure 1 shows the v_4 for charged pions and protons with respect to the second harmonic BBC event plane in minimum bias event (0 - 93 % centrality). The p_T dependence of v_4

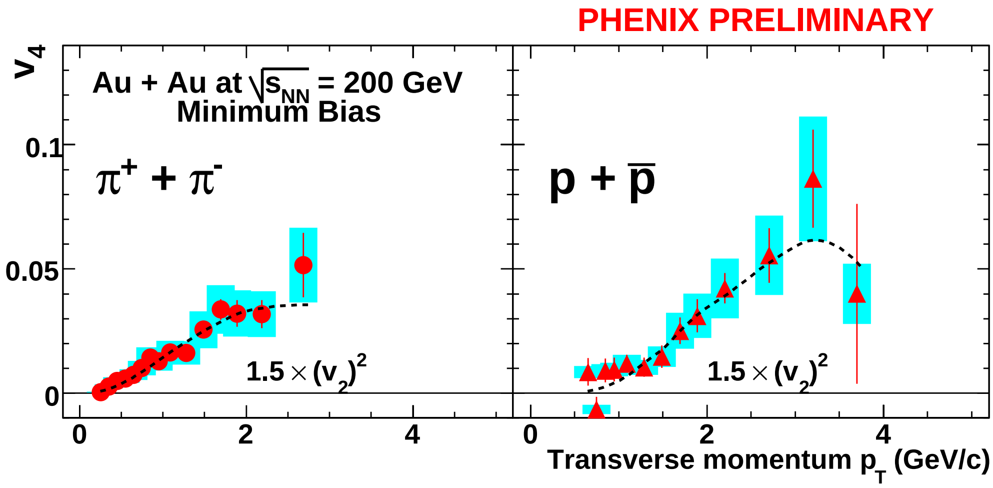

Figure 1. The minimum bias v_4 for identified pion (left) and proton (right) in Au+Au collision with respect to the second harmonic event plane as a function of p_T. The error bars are statistical error, and shaded boxes are systematic error. The dashed curves are $1.5 \times (v_2)^2$.

is very similar to the v_2, that is, proton v_4 is smaller than pions in low p_T and in higher p_T the magnitude of proton v_4 is same as or larger than pions. The ratio, $v_4/(v_2)^2$, has been found to be scaled with the proportionality constant 1.2 by STAR collaboration [4]. We observe the ratio $v_4/(v_2)^2$ is scaled by 1.5 but this result is consistent with that of [4] within systematic uncertainties. A simple parton coalescence model predicts the ratio $v_4/(v_2)^2$ for both mesons and baryons as [5]:

$$v_4^m/(v_2^m)^2 \approx 1/4 + 1/2(v_4^q/(v_2^q)^2), \qquad v_4^b/(v_2^b)^2 \approx 1/3 + 1/3(v_4^q/(v_2^q)^2) \tag{1}$$

where v_2^m, v_2^b and v_2^q are meson, baryon and parton v_2, respectively. If one assume that the following scaling relation [6] for higher order parton anisotropic flow, $v_4^q \sim (v_2^q)^2$, then one get $1/4 + 1/2 = 3/4$ for mesons, $1/3 + 1/3 = 2/3$ for baryons. These predictions underestimate the experimental results, and this would indicate the v_4^q is larger than simple parton $(v_2^q)^2$. Recently, ideal-fluid model suggests that $v_4/(v_2)^2 = 0.5$ and this should become more and more accurate for higher p_T [7]. Further study of higher harmonics at RHIC would be very interesting to understand the system properties.

4. Identified hadron v_2

Figure 2 shows v_2 for identified pion and proton measured by Aerogel as a function of p_T. We extended the p_T reach by Aerogel counter up to 5 GeV/c for identified pion

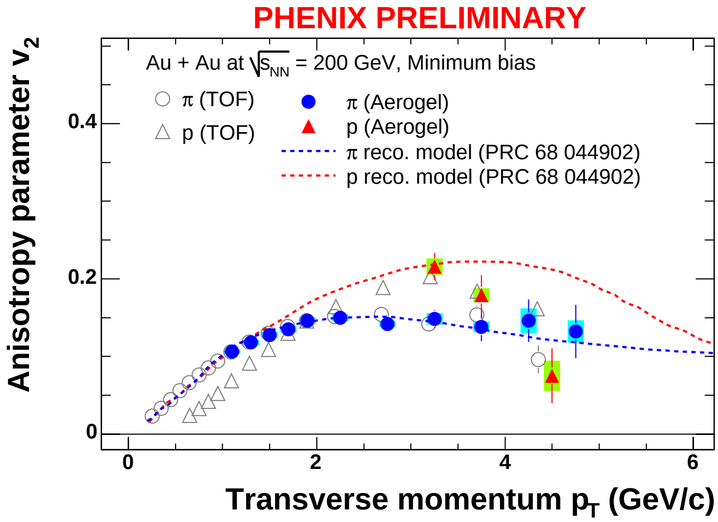

Figure 2. $v_2(p_T)$ for identified pion (circles) and proton (triangles) measured by Aerogel Cherenkov Counter. v_2 measured by Time-of-Flight are also plotted by open data points for comparison. The dashed curves are the calculation from recombination model [8].

and proton. Pion v_2 is quite consistent with the prediction of recombination model [8] as shown by dashed curves in figure 2. The proton v_2, however, seems to decrease for p_T = 4 - 5 GeV/c and clearly deviate from recombination model. The mass splitting of v_2 at low p_T ($p_T < 2$ GeV/c) are also not described by the recombination model. The similar trend can also see in TOF data. We still need further study in this p_T and higher with Aerogel to investigate the production mechanism of proton.

5. System size dependence of v_2: Cu+Cu vs Au+Au

The inclusive charged hadron $v_2(p_T)$ in Cu+Cu collisions compared to that in Au+Au are shown in figure 3. The p_T dependence of v_2 in Cu+Cu is similar to that in Au+Au and the magnitude of v_2 is smaller than in Au+Au about 15 % in minimum bias event. One of the parton cascade model, AMPT, predicts that the v_2 in Cu+Cu is scaled with the system size linearly so that v_2(Cu)$\sim 0.3 \cdot v_2$(Au) [9]. However, the data seems to not scale with the system size linearly. The difference between data and model prediction might be due to non-flow contribution but it is necessary to have more study to understand the system size dependence of v_2.

Figure 4 shows the scaling of v_2, which is the ratio of differential v_2 to integrated one, for charged hadrons in Cu+Cu and Au+Au collisions as a function of p_T. We use the fact that integrated v_2 ($v_2(N_{part})$) approximately scales with eccentricity (ϵ). Thus the scaling of v_2 is approximately equal to v_2/ϵ. This scaling has advantages which could reduce the systematic errors related to eccentricity calculation and event plane resolution. One can see that the scaling of v_2 is roughly independent of the system size from central to mid-central collisions. This would suggest that hydrodynamical regime is reached in central

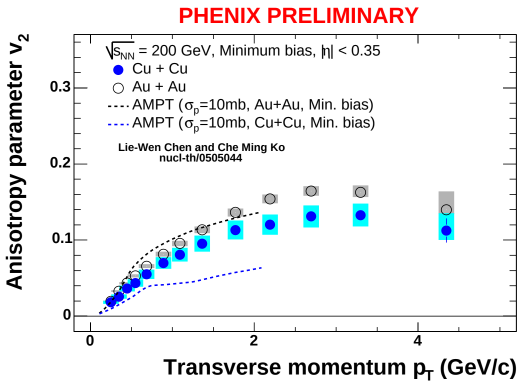

Figure 3. v_2 for inclusive charged hadrons in Cu+Cu and Au+Au collisions for minimum bias event as a function of p_T. The dashed curves are predictions by AMPT model [9].

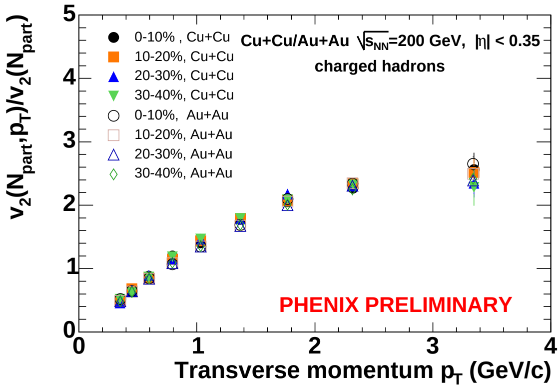

Figure 4. Eccentricity scaling (the ratio of differential $v_2(p_T)$ to integrated $v_2(p_T)$) for inclusive charged hadrons in Cu+Cu and Au+Au collisions for 0-10 %, 10-20 %, 20-30 % and 30-40 %.

to mid-central Cu+Cu collisions.

6. Conclusions

We measure the anisotropic flow for various particle species in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC-PHENIX experiment. The scaling ratio $v_4/(v_2)^2$ for both unidentified and identified hadrons are 1.5 and it is consistent with the previous measurement by STAR experiment. Proton v_2 seems to decrease and deviate from recombination model for $p_T = 4$ - 5 GeV/c, while pion v_2 has good agreement with recombination model. The v_2 in Cu+Cu is smaller than that in Au+Au. The eccentricity scaling of v_2 for Cu+Cu and Au+Au is roughly independent of the system size and this suggest that hydro regime is reached in central to mid-central Cu+Cu collisions at RHIC.

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