Latest results of charged hadron flow measurements in CuAu collisions at RHIC-PHENIX

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Abstract.
Measurements of azimuthal anisotropic flow $v_n$ for inclusive charged hadrons and identified particles at mid rapidity in Cu+Au collisions at $p_{NN} = 200$GeV are presented. The data were recorded by the PHENIX experiment at Relativistic Heavy Ion Collider(RHIC). Directed, elliptic and triangular $v_n$ as a function of transverse momentum $p_T$ are measured with respect to event planes. The inclusive charged hadron $v_1$ shows the negative value at high $p_T$. The $v_2$ and $v_3$ are compared to those in Au+Au and Cu+Cu collisions. We find the $v_2$ and $v_3$ follow an empirical scaling with $1/(\epsilon_n N_{part}^{2/3})$. We also compare the $v_2$ and $v_3$ to hydrodynamical predictions. The identified particles $v_2$ and $v_3$ show a mass ordering in low $p_T$ region and baryon and meson splitting in high $p_T$ region. However the identified hadron $v_1$ only shows mass ordering in mid $p_T$ region.

1. Introduction

Azimuthal anisotropies of particle production in relativistic heavy ion collisions have been measured for the investigating the properties of the quark gluon plasma(QGP). The magnitude of these anisotropies can be evaluated by $v_n$ which are the coefficients of the Fourier serious of the particle emission angle distributions with respect to the event planes $\Psi_n$\cite{1},

$$\frac{dN}{d\phi} = 1 + \sum_{n=1}^{2} 2v_n \cos(n(\phi - \Psi_n))$$ \hspace{1cm} (1)

where $n$ is the order of the harmonic, $\phi$ is the azimuthal angle of produced particle. The event plane $\Psi_n$ is determined for each of the harmonics $n$ on event by event basis. Until now the second harmonic coefficient $v_2$ has been studied well and concluded the QGP state is the nearly perfect fluid\cite{2}. Initial spatial anisotropy of the nuclear overlap region, which is a rugby ball shape in A+A collisions, is considered to be the origin of the elliptic flow. The initial spatial anisotropy is converted to an anisotropy in momentum space.

In symmetric nuclear - nuclear collisions, when the nuclei are considered to be smooth spheres, odd harmonics have to vanish at mid-rapidity. If the participant nucleons fluctuate on event by event, the initial condition could make odd harmonic anisotropic particle production at mid rapidity. Indeed, sizeable odd harmonics have been observed at RHIC\cite{3} and LHC\cite{4}. In order for theory calculation to reproduce even and odd harmonics spontaneously, the experimental measurements of even and odd harmonics strongly constrain the initial condition and the value of $\eta/s$ by comparing the theory predictions and the experimental observables\cite{3}.

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Although the many experimental observables and theoretical predictions exist, the uncertainties of the initial condition and the value of $\eta/s$ remains. In 2012, the first asymmetric collisions, Cu+Au were operated at RHIC in Brook Haven National Laboratory to control the initial condition because the asymmetric collisions may lead to larger odd harmonics at mid rapidity.

2. Experimental details

In our analysis, drift chamber (DC), three layers of pad chamber (PC1, PC2 and PC3), the time of flight East and West (TOF.E, TOF.W) and the electromagnetic calorimeter (EMCal) are employed for Central arm particle tracking and identification [5]. The global detectors, the beam-beam counters (Bbc), the zero degree calorimeter and the shower max detectors (Smd) are employed for centrality and event plane determination [5], [6].

The event plane method [7] is used in the measurements of azimuthal anisotropies of emitted particle distributions in Cu+Au collisions. The event plane $\Psi_n^{obs}$ is determined on event by event base for each harmonic order. The Fourier coefficients $v_n$ are measured with respect to the $n$ – th order event plane and divided by the event plane resolution.

$$v_n = \frac{\langle \cos(n(\phi - \Psi_n^{obs})) \rangle}{\text{Res}\{\Psi_n^{obs}\}}$$  

(2)

where $\phi$ is the azimuthal angle of the produced particle and $\Psi_n^{obs}$ as defined by the spectator neutrons for the 1st harmonic and the produced particles for the 2nd and 3rd harmonics. The first order event plane $\Psi_1$ (directed plane) is determined by the Smd South (SmdS). The SmdS measures the center of shower profile given by Au spectator neutrons to determine the spectator plane. For the directed flow measurement, the spectator neutrons are preferred because they are insensitive to momentum conservation effect. The measurements of the charged hadron and identified hadron $v_1$ are with respect to the Au spectator event plane. Since the number of neutrons in Au spectator is larger than that in Cu spectator, the event plane resolution of the SmdS is greater than that of the SmdN. The combination of the Bbc South (BbcS) and the Bbc North (BbcN) are used to determine the second and third order event planes.

3. Results

3.1. Charged hadron $v_n$

Figure 1 shows the charged hadron $v_1$ at mid-rapidity as a function of $p_T$ for 4 centrality bins in Cu+Au collisions at $\sqrt{s_{NN}} = 200\text{GeV}$. The red solid circles correspond to the $v_1$ data points and the shaded boxes are systematic uncertainties. The $v_1$ is measured with respect to the Au spectator event plane as described previous section. However, we flip the sign of $v_1$ to align with previous conventions by taking smaller size (Cu in this case) spectator as forward going spectator. In all centrality classes, high $p_T$ particles at mid rapidity are emitted towards the Au side as indicated by the negative $v_1$. Considering the momentum balance between the high and low $p_T$ particles due to the momentum conservation effect, the $v_1$ of the low $p_T$ charged particles could be slightly negative, however the data points are consistent with zero in the low $p_T$ region below 1GeV/c within large systematic uncertainties. At high $p_T$ region, the magnitude of the $v_1$ decreases from central to peripheral collisions.

Figure 2 shows the charged hadron $v_2$ as a function of $p_T$ in Cu+Au collisions compared with those in Au+Au and Cu+Cu collisions [8]. The $v_2$ component in Cu+Au collisions shows similar $p_T$ and centrality dependence as seen in symmetric collision systems. We observed the $v_2$ in Cu+Au collisions are always between those in Au+Au and Cu+Cu. Except for 0-10% centrality bin, the $v_2$ in Au+Au collisions are higher than those in Cu+Au and Cu+Cu. This trend is not ordered according to system size dependence of second order initial spatial anisotropy. The $v_2$
scaled with the initial spatial anisotropy $\epsilon_2$ and $N_{\text{part}}^{1/3}$ [8] for three collision systems are shown in Figure 3. Since the $N_{\text{part}}^{1/3}$ is proportional to the length of participant zone or expansion time, the $N_{\text{part}}^{1/3}$ could be responsible for the system size contribution to $v_2$. In Figure 3, it is shown that the empirical scaling works well also in Cu+Au collisions as well as in the other collision systems.

In Figure 4, the $v_3$ as a function of $p_T$ at mid-rapidity in Cu+Au and Au+Au[3] collisions for three centrality bins are shown. The $v_3$ in Cu+Au collisions has similar centrality and $p_T$ dependence as seen Au+Au collisions. Unlike the $v_2$, the trend of system size dependence of the $v_3$ are ordered according to the third order initial spatial anisotropy $\epsilon_3$ dependence. The empirical scaling is performed to the $v_3$ using the $\epsilon_3$ and $N_{\text{part}}^{1/3}$. The scaled $v_3$ are shown in Figure 5 which also hold a universal behavior like the scaled $v_2$. The empirical scaling is successfully extended to the third order azimuthal anisotropy.
3.2. Identified particle $v_n$

Figure 6, 7 and 8 show the identified particle $v_2$, $v_3$ and $v_1$ in Cu+Au collisions. The symbols are represented charge combined $\pi^{\pm}, K^{\pm}$, $p$ and $\bar{p}$. For the $v_1$ and $v_3$ results, centrality bins are combined to improve statistical uncertainties. There are two trends for the $v_2$ and $v_3$ in Figure 6 and 7. In the low $p_T$ region, the anisotropy becomes larger as hadron mass decreases. Hydrodynamics predicts similar mass dependence caused by radial flow effect. Above $p_T > 2$ GeV/c, this mass ordering becomes reversed. The anisotropy for baryons is larger than that for mesons. These particle species dependencies have been seen in symmetric collision systems[9]. Unlike the $v_2$ and $v_3$, the $v_1$ shown in Figure 8 have the mass ordering in the mid $p_T$ region and don’t show baryon and meson splitting at the higher $p_T$. 

Figure 3. Scaled charged hadron $v_2$ as a function of $p_T$ in Cu+Au, Au+Au, Cu+Cu for 6 centrality bins.

Figure 4. Charged hadron $v_3$ as a function of $p_T$ in Cu+Au and Au+Au collisions for 3 centrality bins.
**Figure 5.** Scaled charged hadron $v_2$ as a function of $p_T$ in Cu+Au and Au+Au for 2 centrality bins.

**Figure 6.** $\pi^\pm, K^\pm, p$ $v_2$ as a function of $p_T$ in Cu+Au collisions for 6 centrality bins.

**Figure 7.** $\pi^\pm, K^\pm, p$ $v_3$ as a function of $p_T$ in Cu+Au collisions for 1 centrality bin.

**Figure 8.** $\pi^\pm, K^\pm, p$ $v_1$ as a function of $p_T$ in Cu+Au collisions for 1 centrality bin.
3.3. Theory comparisons

Event by event 3D+1 viscous hydrodynamic predictions are available[10]. In Figure 9 and 10, the hydrodynamic calculations with $\eta/s = 0.08$ and $\eta/s = 0.16$ for the $v_2$ and $v_3$ are compared to the PHENIX experimental data. In the 20-30% centrality bin, both $\eta/s$ case reproduce our measurements well. In the 0-5% centrality bin, $\eta/s = 0.08$ case has better agreement with the experimental data.

![Figure 9](image-url)  
**Figure 9.** The charged hadron $v_2$ as a function of $p_T$ in Cu+Au collisions in comparison to hydrodynamics calculations for two centrality bins

![Figure 10](image-url)  
**Figure 10.** The charged hadron $v_3$ as a function of $p_T$ in Cu+Au collisions in comparison to hydrodynamics calculations for two centrality bins
4. Conclusion

We have presented directed, elliptic and triangular azimuthal anisotropies for inclusive charged hadrons and identified hadrons at mid-rapidity in Cu+Au collisions at $\sqrt{s_{NN}} = 200$GeV observed by PHENIX experiment at RHIC using event plane method. The $v_1$ coefficients for charged hadrons indicate high $p_T$ particles are emitted to the Au side. For the system size dependence of the $v_2$ and $v_3$ measurements, the empirical scaling for the $v_2$ works well in Cu+Au, Au+Au and Cu+Cu and is extended for the $v_3$ measurements in Cu+Au and Au+Au. The identified hadron $v_2$ and $v_3$ show the mass ordering in the low $p_T$ region and baryon and meson splitting in the high $p_T$ region. These trends have been seen in the previous symmetric collisions. The identified hadron $v_1$ shows the mass ordering in the mid $p_T$ region and doesn’t show baryon and meson splitting in the high $p_T$ region.

The inclusive charged hadron $v_2$ and $v_3$ for the 0-5% and 20-30% centrality bins are compared to the event by event 3D+1 viscous hydrodynamics calculations. The hydrodynamics calculations with \( \eta/s = 0.08 - 0.16 \) reproduce the experimental data $v_2$ and $v_3$.

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