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 $\sqrt{s_{NN}}$ = 200GeV are presented. The data were recorded by the PHENIX experiment at Relativistic Heavy Ion Collider(RHIC). Directed, elliptic and triangular flow 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 $1/(\epsilon_n N_{part}^{1/3})$. 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 Ψ_n[1],

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

where n is the order of the harmonic, ϕ is the azimuthal angle of produced particle. The event plane Ψ_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[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[3] and LHC[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 η/s by comparing the theory predictions and the experimental observables[3].

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Although the many experimental observables and theoretical predictions exist, the uncertainties of the initial condition and the value of η/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 Ψ_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.

$$v_n = \frac{\left\langle cos(n[\phi - \Psi_n^{obs}]) \right\rangle}{Res\{\Psi_n^{obs}\}} \tag{2}$$

where ϕ is the azimuthal angle of the produced particle and Ψ_n^{obs} as defined by the spectator neutrons for the 1st harmonic and the produced particles for the 2nd and 3rd harmoincs. The first order event plane Ψ_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 $\sqrt{s_{NN}} = 200$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 alight 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 pT 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

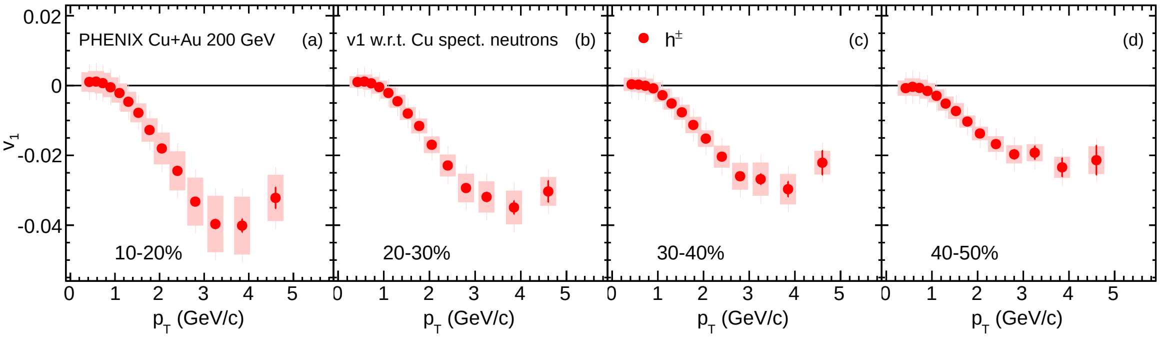

Figure 1. Charged hadron v_1 as a function of p_T for 4 centrality bins.

scaled with the initial spatial anisotropy ϵ_2 and $N_{part}^{1/3}$[8] for three collision systems are shown in Figure 3. Since the $N_{part}^{1/3}$ is proportional to the length of participant zone or expansion time, the $N_{part}^{1/3}$ 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.

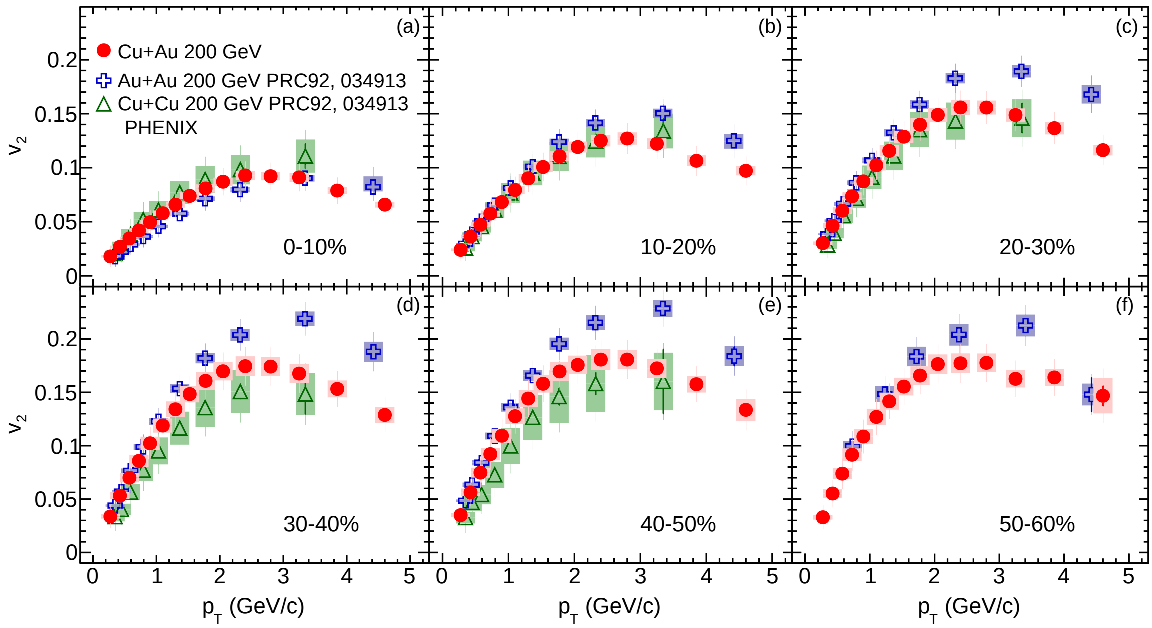

Figure 2. Charged hadron v_2 as a function of p_T in Cu+Au, Au+Au and Cu+Cu collisions for 6 centrality bins.

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 ϵ_3 dependence. The empirical scaling is perfomed to the v_3 using the ϵ_3 and $N_{part}^{1/3}$. 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.

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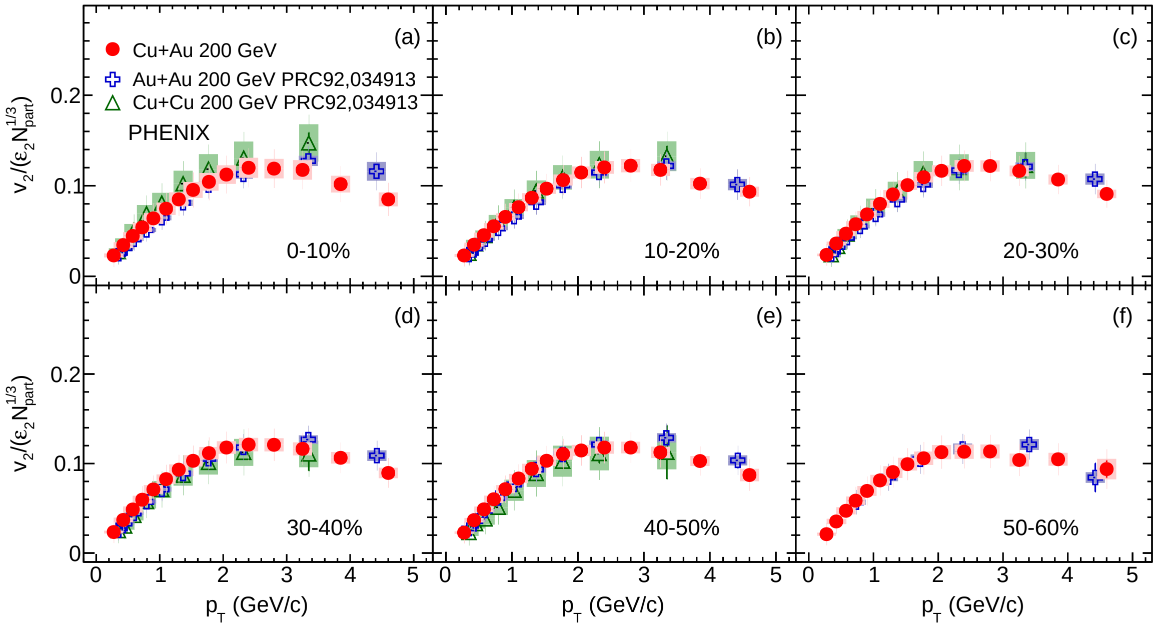

Figure 3. Scaled charged hadron v_2 as a function of p_T in Cu+Au, Au+Au,Cu+Cu for 6 centrality bins.

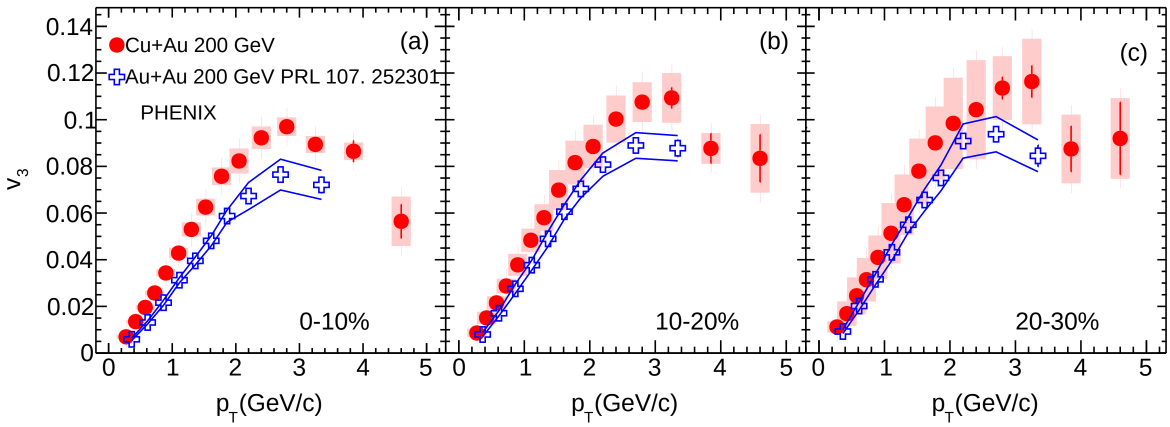

Figure 4. Charged hadron v_3 as a function of p_T in Cu+Au and Au+Au collisions for 3 centrality bins.

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 $\overline{p}$. 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 >2GeV/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.

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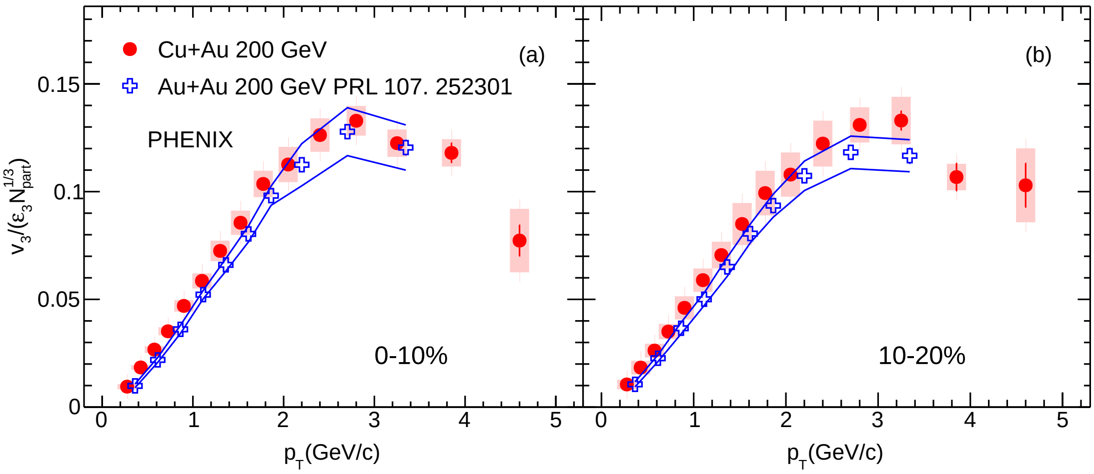

Figure 5. Scaled charged hadron v_2 as a function of p_T in Cu+Au and Au+Au for 2 centrality bins.

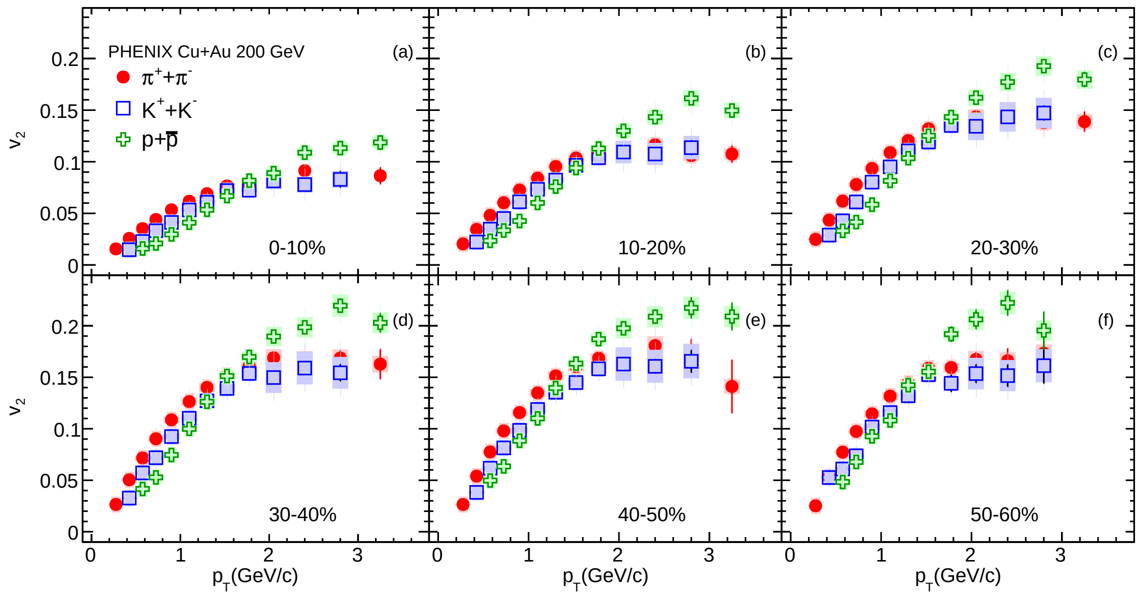

Figure 6. $\pi^{\pm}$,$K^{\pm}$, p v_2 as a function of p_T in Cu+Au collisions for 6 centrality bins

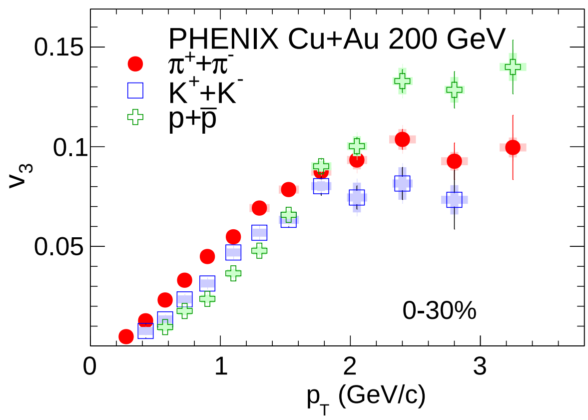

Figure 7. $\pi^{\pm}$,$K^{\pm}$, p v_3 as a function of p_T in Cu+Au collisions for 1 centrality bin

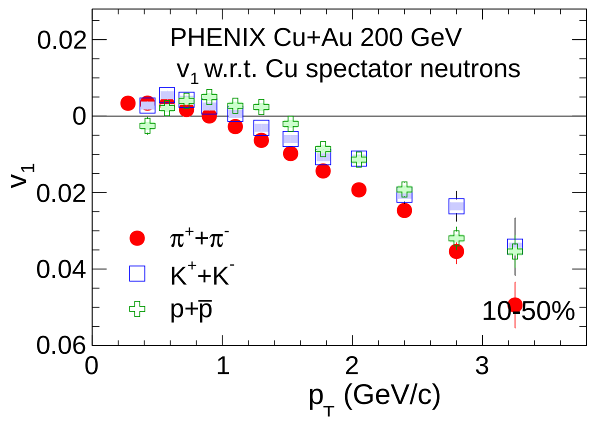

Figure 8. $\pi^{\pm}$,$K^{\pm}$, p v_1 as a function of p_T in Cu+Au collisions for 1 centrality bin

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 η/s case reproduce the our measurements well. In the 0-5% centrality bin, $\eta/s = 0.08$ case has better agreement with the experimental data.

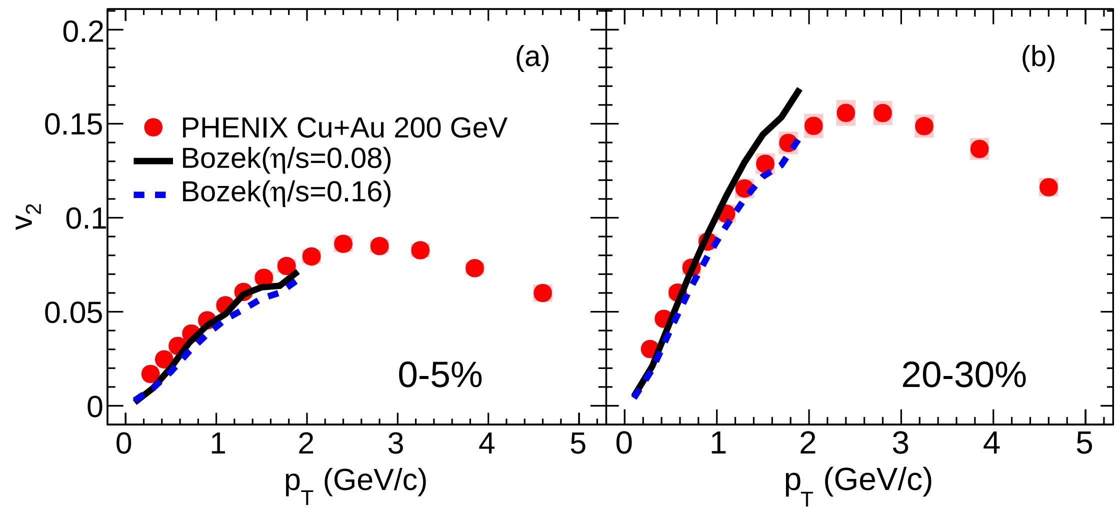

Figure 9. The charged hadron v_2 as a function of p_T in Cu+Au collisions in comparison to hydrodynamics calculations for two centrality bins

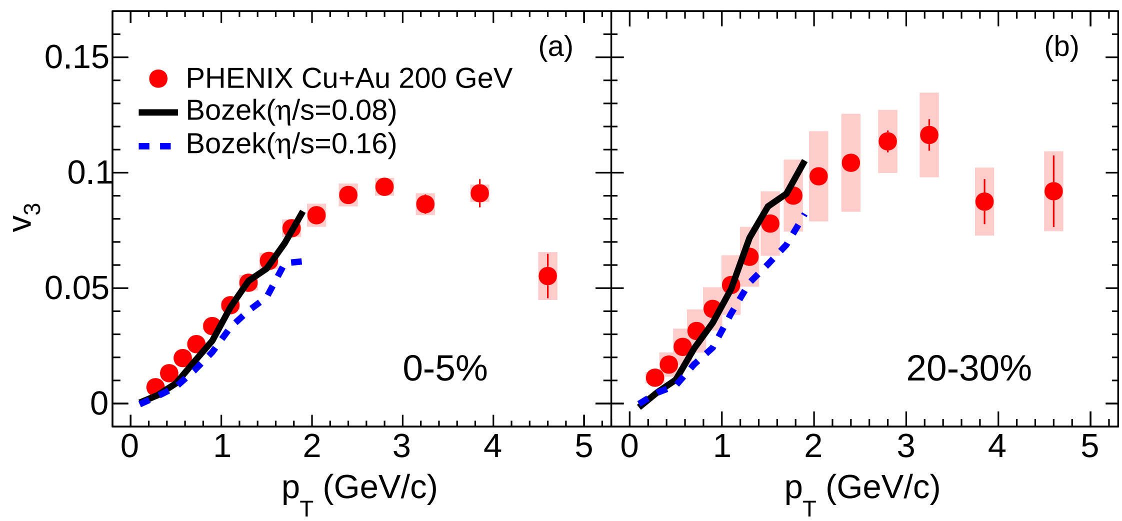

Figure 10. The charged hadron v_3 as a function of p_T in Cu+Au collisions in comparison to hydrodynamics calculations for two centrality bins

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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.

Reference

[1] S. Voloshin and Y. Zhang, Z. Phys. C 70, 665 (1996)
[2] K.Adcox et al.(PHENIX Collaboration) Nucl. Phys. A 757, 184 (2005)
[3] A. Adare et al. (PHENIX Collaboration), PhysRevLett.107.252301
[4] G. Aad et al. (ATLAS Collaboration), Phys. Rev. C 86 014907 (2012)
[5] K. Adcox et al.(PHENIX Collaboration) Nucl. Instrum. Methods Phys. Res. Sec. 499, 469(2003)
[6] C. Adler, A. Denisov, E. Garcia, M. Murray, H. Stro-bele, and S. White Nucl. Instrum. Methods Phys. Res. Sec. 499, 433(2003)
[7] A.M.Poskanzer, S.A. Voloshin PhysRevC.58.1671(1998)
[8] A. Adare el al.(PHENIX Collaboration) PhysRevC.92.034913
[9] A. Adare et al. (PHENIX Collaboration), arXiv:1412.1038
[10] Bozek Phys. Lett. B717, 287(2012)
[11] A. Adare et al (PHENIX Collaboration), arXiv:1509.07784