Systematic study of $v_2$ at 62.4 and 200 GeV in Cu + Cu and Au + Au Collisions at RHIC-PHENIX

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Abstract. The transverse momentum ($p_T$) and centrality dependence of the azimuthal anisotropy ($v_2$) are measured for charged hadron species at 62.4 and 200 GeV in Cu + Cu and Au + Au collisions by the PHENIX experiment at RHIC. The results are consistent with eccentricity scaling and with quark number ($n_q$) + transverse kinetic energy ($KE_T$) scaling. Also, we found that $v_2$ divided by the participant eccentricity of the initial geometry proportionally increases with the number of participants to the 1/3 power except at small $N_{\text{part}}$ in Cu+Cu at $\sqrt{s_{NN}} = 62.4$ GeV. Taking these scalings ($n_q$, KE$_T$, eccentricity and $N_{\text{part}}^{1/3}$) into account, there is a universal scaling for $v_2$ with different energies, collision sizes and particle species. The results indicate that $v_2$ is determined by more than just the geometrical eccentricity and also depends on the size of the collision. Moreover, using blast wave fitting, we report that both the behaviors of $v_2$ and $p_T$ distributions can be understood from the thermal nature of produced particles based on hydro-dynamical behavior.

1. Introduction
Relativistic heavy ion collisions have been considered as a unique way to create the quark-gluon plasma (QGP), which is the phase of de-confined quarks and gluons. The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory was constructed to create and study the QGP. Azimuthal anisotropy of particles produced in relativistic heavy ion collisions is the one of the most powerful probes for investigating the characteristics of the QGP. Especially the strength of the elliptic anisotropy ($v_2$), which is defined by the second harmonics of Fourier expansion for the azimuthal distribution of produced particles with respect to the reaction plane, is expected to be sensitive to the early stage of heavy ion collisions. The anisotropy in the momentum phase space is transferred from the geometrical anisotropy of the initial collisional region because of the pressure gradient. Thus, the measured $v_2$ reflects the dynamical properties of the dense matter produced in the collisions.

2. Motivation
One of the most remarkable findings at RHIC is that the strength of $v_2$ can be described well by hydro-dynamical models in the low transverse momentum region ($\sim 1$ GeV/c) [1]. In the intermediate transverse momentum region (1 $\sim$ 4 GeV/c), $v_2$ is consistent with $n_q$ and $KE_T$ ($= m_T - m_0$) scaling, and the result supports a quark-recombination model [2]. For a more comprehensive understanding of $v_2$, we have carried out systematic measurements of $v_2$, by measuring $v_2$ for identified charged hadrons in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$...
and 62.4 GeV, and studied the dependence on collision energy, size and species of the produced particles. We expect that the $v_2$ is determined not only by the initial ellipticity, but also by the collision volume [3].

3. Results

3.1. Collision Energy, System Size and Species Dependence

The left panel in Figure 1 shows the comparison of $v_2$ in Au+Au and Cu+Cu at $\sqrt{s_{NN}} = 200$ and 62.4 GeV as a function of $N_{part}$. The values of $v_2$ agree well at $\sqrt{s_{NN}} = 200$ and 62.4 GeV in the errors, but have clear differences between the Cu+Cu and Au+Au. Since Au+Au and Cu+Cu collisions have different initial geometrical eccentricities at the same $N_{part}$, normalizing $v_2$ by eccentricity, $\varepsilon$, (eccentricity scaling) shows that the data follows a universal curve between Cu + Cu and Au + Au as shown in the middle panel in Figure 1. Here, we use the participant eccentricity, which includes the effect of participant fluctuations [4]. One can see that $v_2/\varepsilon$ is not a constant and it depends on $N_{part}$. Therefore, $v_2$ can be normalized by $\varepsilon$ at the same $N_{part}$, but $\varepsilon$ is not enough to determine $v_2$. We found that $v_2/\varepsilon$ is proportional to $N_{part}^{1/3}$ as shown in the right panel of Figure 1. $v_2/(\varepsilon \cdot N_{part}^{1/3})$ is independent of the collision system except for small $N_{part}$ in Cu+Cu at $\sqrt{s_{NN}} = 62.4$ GeV. This exception might indicate that this is a region where the matter has not reached sufficient thermalization, although the errors are too large to discuss the difference. Therefore, a scan of collision energies and sizes would be very important for further study of this exception. Figure 1 is for $p_T = 0.2 - 1.0$ GeV/c. The results for $p_T = 1.0 - 2.0$ and 2.0 - 4.0 GeV/c have the same tendency as well.

3.2. Quark number($n_q$) + K$E_T$ scalings and Universal $v_2$

The left panel of Figure 2 shows that various particle species are mostly consistent with $n_q + K E_T$ scaling in Au+Au at at $\sqrt{s_{NN}} = 200$ GeV. From the systematic study, it is found that $v_2$ in Au+Au at $\sqrt{s_{NN}} = 62.4$ GeV and in Cu+Cu at $\sqrt{s_{NN}} = 200$ GeV are also consistent with $n_q + K E_T$ scaling for centralities 0 - 50%. In addition to the fact that $v_2(p_T)$ does not depend on collision energy at RHIC energies, $v_2$ normalized by $n_q + K E_T$, eccentricity, and $N_{part}^{1/3}$ scaling follows a universal curve as shown in the right panel of Figure 2. This figure includes the 45 curves for $\pi/K/p$ in Au+Au at $\sqrt{s_{NN}} = 200$ GeV, in Au+Au at $\sqrt{s_{NN}} = 62.4$ GeV.
extracted from the invariant cross section data according to the following equation: [5].

The two parameters, the radial velocity ($v_{rad}$) and the freeze-out temperature ($T_{fo}$), are obtained separately. From these values, the radial velocity ($v_{rad}$) is proportional to $T_{fo}$, the freeze-out temperature ($T_{fo}$) of radial flow. The right panel of Figure 4 shows the $v_{2}$ vs. $T_{fo}$ for in and out-of-plane, and it agrees well between Au+Au and Cu+Cu collision at the same $N_{part}$. However, it was found that $v_{2}$ is proportional to $\beta_{T}$ in this model, $v_{2}$ should be scaled by participant eccentricity. However, as shown in Figure 1, this is not what is seen in the measured $v_{2}$ results. Therefore, this implies that $v_{2}$ is not determined by only $\beta_{T}$ but also other effects such as the freeze-out temperature ($T_{fo}$) of radial flow. The right panel of Figure 4 shows the $T_{fo}$ vs. $N_{part}$ for both in and out-of-plane. The magnitude of $T_{fo}$ agrees well between Au+Au and Cu+Cu collision at the same $N_{part}$. It can be seen that $T_{fo}$ depends on $N_{part}$, and it can influence $v_{2}$ since the larger $T_{fo}$ makes $p_T$ spectra flatter. Thus, the size dependence of $v_{2}$
Figure 3. $\beta_{T2}/\varepsilon$ vs. $N_{\text{part}}$ in Cu+Cu and Au+Au at 200 GeV. This result is obtained by fitting to PHENIX PRELIMINARY results.

Figure 4. Left panel shows that $\beta_T$ vs. $N_{\text{part}}$ for in and out-of plane in Cu+Cu and Au+Au at 200 GeV. This result is obtained by fitting to PHENIX PRELIMINARY results. Right panel shows that $T_{fo}$ vs. $N_{\text{part}}$ for in and out-of plane in Cu+Cu and Au+Au at 200 GeV. This result is obtained by fitting to PHENIX PRELIMINARY results.

can be understood as thermal freeze-out nature of produced particles based on hydrodynamical behavior, which is different from that of chemical freeze-out.

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