System Size and Collision Energy Dependence of $v_2$ for Identified Charged Hadrons at RHIC-PHENIX

Maya Shimomura for the PHENIX Collaboration

Graduate School of Pure and Applied Sciences, Univ. of Tsukuba, Tenno-dai 1-1-1, Tsukuba, Ibaraki, Japan

Abstract

The transverse momentum ($p_T$) and centrality dependence of the azimuthal anisotropy ($v_2$) are measured for charged hadrons in different energies and collision species by the PHENIX experiment at RHIC. We find 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 $\sqrt{s_{\text{NN}}} = 62.4$ GeV. Taking the eccentricity and quark number scaling into account, there is a universal scaling for $v_2$ with different energies and collision sizes. The results indicate that $v_2$ is determined by more than just the geometrical eccentricity. It also depends on the size of collision. We also 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 way to create the quark-gluon plasma (QGP), 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. One of the most powerful probes for investigating the characteristics of the QGP is measuring the azimuthal anisotropy of the charged particles produced by the collisions. The strength of the elliptic anisotropy ($v_2$) reflects the initial geometrical anisotropy, which creates pressure gradients in the collision area. This pressure gradient transfers a spatial anisotropy into a momentum anisotropy since particles are pushed harder in the direction of the larger gradients. 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 ($\sim 4$ GeV/$c$), $v_2$ is consistent with quark number ($q_n$) 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 $\sqrt{s_{\text{NN}}} = 200$ and 62.4 GeV, and studied the dependence on collision energy, species and centrality. We expect that the $v_2$ is determined not only by the initial ellipticity, but is also influenced by a finite evolution time which can be related to the collision volume.
3. Results

3.1. Energy, System Size and Species Dependence

The left panel in Figure 1 shows $v_2$ vs. $N_{\text{part}}$ for two collision systems and two collision energies. The $v_2$ agrees well at $\sqrt{s_{\text{NN}}} = 200$ and 62.4 GeV, but there is a clear difference between the Cu+Cu and Au+Au results. Since Au+Au and Cu+Cu collisions have different initial geometrical eccentricities at the same $N_{\text{part}}$, applying the eccentricity ($\varepsilon$) scaling shows that the data follows a universal curve as shown in the middle panel in Figure 1. Here, we use the participant eccentricity, calculated with a long and short axis determined by the distribution of participants at each collision, using a Monte-Carlo simulation based on a Glauber model and including effects from participant fluctuations. The details of the participant eccentricity are described in [3]. One can see that $v_2/\varepsilon$ is not a constant and it depends on $N_{\text{part}}$. Therefore, $v_2$ can be normalized by $\varepsilon$ at the same $N_{\text{part}}$, but $\varepsilon$ is not enough to determine $v_2$. We newly found that $v_2/\varepsilon$ is proportional to $N_{\text{part}}^{1/3}$, and as shown in the right panel in Figure 1, $v_2/(\varepsilon \cdot N_{\text{part}}^{1/3})$ is independent of the collision system except for small $N_{\text{part}}$ in Cu+Cu at $\sqrt{s_{\text{NN}}} = 62.4$ GeV. This exception indicates this might be a region where the matter has not reached sufficient thermalization, although the errors are too large to discuss the difference. A scan of collision energies would be important to further study this effect. 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. Similar to the result in Au+Au at $\sqrt{s_{\text{NN}}} = 200$ GeV, $v_2$ in Au+Au at $\sqrt{s_{\text{NN}}} = 62.4$ GeV and in Cu+Cu at $\sqrt{s_{\text{NN}}} = 200$ GeV are mostly consistent with $q_n + KE_T$ 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 quark number + KE$_T$, eccentricity, and $N_{\text{part}}^{1/3}$ scaling follows a universal curve as shown in Figure 2. This figure includes the 45 curves for $p/\sqrt{N}$ in Au+Au at $\sqrt{s_{\text{NN}}} = 200$ GeV, in Au+Au at $\sqrt{s_{\text{NN}}} = 62.4$ GeV and in Cu+Cu at $\sqrt{s_{\text{NN}}} = 200$ GeV for the five centrality bins from 0 - 50% in 10% steps. The $\chi^2$/NDF of the polynomial fitting is 2.1.

3.2. Radial Flow Effect with Blast-Wave Fit

To understand the $N_{\text{part}}$ dependence and KE$_T$ scaling behavior for the $v_2$, we use a Blast-wave model to extract dynamical properties of the matter, especially at freeze-out. This model is a two-parameter model describing a boosted thermal source based on relativistic hydrodynamics [4].
The two parameters, the radial velocity ($\beta_T$) and the freeze-out temperature ($T_{fo}$), are extracted from the invariant cross section data according to the following equation:

$$ \frac{dN}{m_Tdm_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh \rho}{T_{fo}}\right) K_1\left(\frac{m_T \cosh \rho}{T_{fo}}\right), $$

(1)

where $I_0$ and $K_1$ represent modified Bessel functions with $\rho$ the transverse boost $\rho(r) = \tanh^{-1} \beta_T(r)$, $\beta_T(r) = \beta_s(\vec{r}/R)$, and $m_T = \sqrt{p_T^2 + m^2}$. Re-plotting the measured $p_T$ spectra, weighted by measured $v_2$, we obtain the $p_T$ spectra in and out-of-plane separately for $\pi/K/p$. We use two data sets: Cu+Cu and Au+Au at $\sqrt{s_{NN}} = 200$ GeV. Applying the Blast-wave fitting to the $p_T$ spectra in and out-of plane separately, the $\beta_T$ and $T_{fo}$ in and out-of plane are obtained separately. From these values, $\beta_{T2} = (\beta_{Tin} - \beta_{Tout})/(\beta_{Tin} + \beta_{Tout})/2$ and $T_{fo2} = (T_{fon} - T_{fout})/(T_{fon} + T_{fout})/2$ are calculated. $\beta_{T2} (T_{fo2})$ indicates the amplitude of the second harmonic of the $\beta_T (T_{fo})$ azimuthal distribution.
Figure 3 shows the $\beta_T$ vs. $N_{\text{part}}$ for in and out-of plane in Cu+Cu and Au+Au collisions. The magnitude of $\beta_T$ is clearly different between in and out-of plane, and it agrees well between Au+Au and Cu+Cu, especially for the in-plane data. The amplitude of the second harmonic, $\beta_{T2}$, is not the same at the same $N_{\text{part}}$ between Cu + Cu and Au + Au. When scaled by eccentricity, $\beta_{T2}/\varepsilon$ agrees between Au+Au and Cu+Cu and it is flat at $N_{\text{part}} \geq 40$ as shown in Figure 4. Since $v_2$ is proportional to $\beta_{T2}$ 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 $\beta_{T2}$ but includes other effects such as the freeze-out temperature ($T_{fo}$) of radial flow. Figure 5 shows the $T_{fo}$ vs. $N_{\text{part}}$ for both in and out-of plane. The magnitude of $T_{fo}$ agrees well between Au+Au and Cu+Cu collision at the same $N_{\text{part}}$. It can be seen that $T_{fo}$ depends on $N_{\text{part}}$, and it can influence $v_2$ since the larger $T_{fo}$ makes $p_T$ spectra flatter. Figure 6 shows $v_2/n_q$ vs. $T_{fo}$ obtained by the blast wave calculation, fixing parameters to reasonable values ($\langle \beta_T \rangle = 0.5, \beta_{T2} = 0.04, KE_T/n_q = 0.5 \text{ GeV/c}$) and changing only $T_{fo}$. In the freeze out temperature region ($0.10 \leq T_{fo} \leq 0.16 \text{ GeV}$), it can be seen that $KE_T$ scaling is approximately held by this calculation. In this figure, going from central to peripheral collisions, namely going from low $T_{fo}$ to high $T_{fo}$, finite deviations among $\pi/K/p$ are expected, and $v_2$ for protons becomes larger than that for pions. This deviation has the same tendency as the $v_2$ data.

Acknowledgements

I would like to express my great thanks to the organizers of this conference, Quark Matter 2009, for the opportunity to present these results. I am grateful to my PHENIX collaborators for many helpful discussions.

References

[1] S. S. Adler et al., Phys. Rev. Lett. 91, 182301 (2003)
[2] A. Adare et al., Phys. Rev. Lett. 98, 162301 (2007)
[3] B. Alver et al., Phys. Rev. Lett. 98, 242302 (2007)
[4] S. S. Adler et al., Phys. Rev. C72, 014903 (2005)