Elliptic Flow and Initial Eccentricity in Cu+Cu and Au+Au Collisions at RHIC

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Abstract. We present a systematic study of elliptic flow as a function of centrality,
pseudorapidity, transverse momentum and energy for Cu+Cu and Au+Au collisions
from the PHOBOS experiment. New data on elliptic flow in Cu+Cu collisions at \( \sqrt{S_{NN}} = 22.4 \) GeV are shown. Elliptic flow scaled by participant eccentricity is found to be
similar for both systems when collisions with the same number of participants or the
same average area density are compared. This similarity is observed over a wide range
in pseudorapidity and transverse momentum, indicating that participant eccentricity is
the relevant quantity for generating the azimuthal asymmetry leading to the observed
elliptic flow.

PACS numbers: 25.75.-q

Submitted to: J. Phys. G: Nucl. Phys.

1. Introduction

The characterization of elliptic flow has proven to be one of the most fruitful probes
of the dynamics of heavy ion collisions at RHIC. It originates from the almond shape of
the overlap zone of the collision which produces, through unequal pressure gradients, an
anisotropy in the transverse momentum distribution [1]. The dominant contribution to
this anisotropy is due to elliptic flow and is measured by the second coefficient, $v_2$, of the Fourier expansion of the azimuthal distribution of produced particles. The large value of $v_2$ observed experimentally in semi-central Au+Au collisions at RHIC is consistent with non-viscous hydrodynamic expansion of quark gluon plasma (QGP) droplets \cite{2}. A strong pseudorapidity dependence of elliptic flow reported by PHOBOS \cite{3–5} provides useful information for constraining models of the full three-dimensional hydrodynamic evolution of the system.

In this paper, we present elliptic flow of charged hadrons in Cu+Cu and Au+Au collisions at $\sqrt{s_{\text{NN}}}$ = 19.6, 22.4, 62.4 and 200 GeV as a function of pseudorapidity, centrality and transverse momentum. The measurements of elliptic flow in 22.4 GeV Cu+Cu collisions are shown for the first time. This work completes our systematic study of elliptic flow measurements, providing an extensive and precise set of experimental data for Cu+Cu and Au+Au collisions at RHIC. Furthermore, the comparison of the data from Cu+Cu and Au+Au collisions measured by PHOBOS experiment provides new information on the interplay between initial state collision geometry and elliptic flow.

2. Results and Initial Eccentricity

The Cu+Cu and Au+Au data presented in this work were analyzed in the same way, using the “hit-based” and “track-based” analysis methods \cite{3}. Fig. 1 shows the preliminary results of the elliptic flow signal as a function of pseudorapidity ($\eta$) in the Cu+Cu collisions at $\sqrt{s_{\text{NN}}}$ = 22.4 GeV for 0-40% most central events. The Cu+Cu $v_2$ displays a strikingly similar shape in $\eta$ to Au+Au collisions at nearly the same energy (19.6 GeV) \cite{6}. The strength of Cu+Cu $v_2$ signal is surprising in light of
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Figure 2. $\varepsilon_{\text{part}}$ and $\varepsilon_{\text{std}}$ of the collision zone of Cu+Cu and Au+Au at $\sqrt{s_{NN}}=200$ GeV as function of $N_{\text{part}}$ from PHOBOS Glauber MC. The continuous and dashed lines correspond to the RMS of $\varepsilon_{\text{part}}(\sqrt{\varepsilon^2_{\text{part}}})$. The gray bands are discussed in the text.

Figure 3. Panel a) shows $v_2/(\langle \varepsilon_{\text{part}} \rangle)$ as function of mid-rapidity ($|\eta|<1$) particle area density $1/(S)\langle dN/dy \rangle$ for Cu+Cu and Au+Au collisions. Panel b) $v_2/(\langle \varepsilon_{\text{part}} \rangle)$ as a function of $p_T$ for Cu+Cu and Au+Au collisions at 200 GeV with the same area density (same $\langle N_{\text{part}} \rangle = 82$). The bars in the plots represent the statistical errors.

expectations that the smaller system size would result in a much smaller flow signal [7].

The dependence of $v_2$ on the transverse momentum ($p_T$) of charged hadrons in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}=62.4$ and 200 GeV for centrality bins 0-20% and 20-40% are presented on Figs. 1b, 1c, 1d and 1e. We observe that for both collision systems, the dependence of $v_2$ on $p_T$ is similar for the two measured centrality classes. For a given system, higher values of $v_2(p_T)$ are observed for more peripheral collisions.

In order to distinguish collision dynamics from purely geometrical effects, it has been suggested that the measured $v_2$ should be scaled by the eccentricity of the nuclear overlap area [8]. The standard definition of the eccentricity is, $\varepsilon_{\text{std}} = \frac{\sigma_x^2 - \sigma_y^2}{\sigma_x^2 + \sigma_y^2}$, where $\sigma_x^2$ ($\sigma_y^2$) are the variance of the participant nucleon distribution projected on the $x$ ($y$) axis, taken to be along (perpendicular to) the impact parameter direction.

It has been shown that the measured $v_2$ in Cu+Cu collisions at RHIC [4, 5] is surprisingly large even for most central collisions, for which the average eccentricity of the overlap region is small. The PHOBOS collaboration has shown that for small systems or small transverse overlap regions, event-by-event fluctuations in the shape of the initial collision region affect the elliptic flow. Monte Carlo (MC) Glauber studies

\[ F(z) = \int \left[ \int \frac{d^2q}{4\pi^2} \frac{1}{2\pi i} \left( \frac{1}{z - a + iq} + \frac{1}{z - a - iq} \right) \right] dz \]
have shown that the fluctuations in the nucleon positions frequently create a situation where the minor axis of the overlap ellipse of the participant nucleons is not aligned with the impact parameter vector. To account for this effect, PHOBOS has introduced the participant eccentricity defined as [4,5]:

$$\varepsilon_{\text{part}} = \sqrt{\left(\frac{\sigma_x^2 - \sigma_y^2}{\sigma_x^2 + \sigma_y^2}\right)^2 + 4\sigma_{xy}^2},$$

where $\sigma_{xy} = \langle xy \rangle - \langle x \rangle \langle y \rangle$ is the covariance. This definition accounts for the nucleon fluctuations by quantifying the eccentricity event-by-event with respect to the overlap region of the participants nucleons. Fig. 2 shows the Glauber model calculations of $\varepsilon_{\text{std}}$, $\varepsilon_{\text{part}}$ and $\sqrt{\langle \varepsilon_{\text{part}}^2 \rangle}$ as a function of $N_{\text{part}}$ for Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The gray bands correspond to systematic errors obtained by varying the Glauber model parameters such as the nuclear radius, nuclear skin depth, nucleon-nucleon inelastic cross-section and minimum nucleon separation. We observe that $\varepsilon_{\text{part}}$ and $\sqrt{\langle \varepsilon_{\text{part}}^2 \rangle}$ distributions are similar, within the small systematic errors, for both systems. The importance of the definition of eccentricity in comparing Cu+Cu and Au+Au results is presented on Figs. 3 and 4, showing the eccentricity scaled elliptic flow, $v_2/\langle \varepsilon_{\text{part}} \rangle$, for the two collision systems. For the comparison we selected centrality bins in Cu+Cu and Au+Au such that $\langle N_{\text{part}} \rangle$ are matched. For such centrality bins also the average area density, $1/\langle S \rangle \langle dN/d\eta \rangle$, is approximately the same. We observe in Fig. 3b that the $v_2$ scaled by $\varepsilon_{\text{part}}$ are similar for both Cu+Cu and Au+Au collisions at the same value of the average area density (similar $\langle N_{\text{part}} \rangle$). It should be noted that in Fig. 3b which has been introduced previously in Ref. [9], in the y-axis the $v_2(\eta)$ has been converted to $v_2(y)$ by scaling the data by factor 0.9 and also in the x-axis the $dN/d\eta = 1.15$ $dN/d\eta$ at mid-rapidity region, $|\eta| < 1$. This similarity between Cu+Cu and Au+Au collisions in Fig. 3b is also observed as a function of transverse momentum (see Fig. 3b) as well as in a wide pseudorapidity range as shown in Figs 4a and 4b. Furthermore, Fig. 4c shows that the Cu+Cu and Au+Au systems at 62.4 and 200 GeV exhibit the same extended longitudinal scaling when $\varepsilon_{\text{part}}$ and $\langle N_{\text{part}} \rangle$ are taken into consideration. It should be noted that within experimental errors, similar scaling properties should be observed using $\sqrt{\langle \varepsilon_{\text{part}}^2 \rangle}$, as advocated in Ref. [10].
3. Summary

In summary, we have performed a comprehensive examination of the elliptic flow of charged hadrons produced in Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 19.6, 22.4, 62.4$ and 200 GeV as a function of pseudorapidity, centrality and transverse momentum. The measurements of elliptic flow in 22.4 GeV Cu+Cu collisions are shown for the first time. The comparison of the data from Cu+Cu and Au+Au collisions provides new information illustrating that the participant eccentricity is the relevant geometric quantity for generating the azimuthal asymmetry leading to the observed elliptic flow.

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