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Elliptic Flow, Initial Eccentricity and Elliptic Flow Fluctuations in Heavy Ion Collisions at RHIC

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ELLIPTIC FLOW, INITIAL ECCENTRICITY AND ELLIPTIC FLOW FLUCTUATIONS IN HEAVY ION COLLISIONS AT RHIC

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We present measurements of elliptic flow and event-by-event fluctuations established by the PHOBOS experiment. 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 particle area density are compared. The agreement of elliptic flow between Au+Au and Cu+Cu collisions provides evidence that the matter is created in the initial stage of relativistic heavy ion collisions with transverse granularity similar to that of the participant nucleons. The event-by-event fluctuation results reveal that the initial collision geometry is translated into the final state azimuthal particle distribution, leading to an event-by-event proportionality between the observed elliptic flow and initial eccentricity.

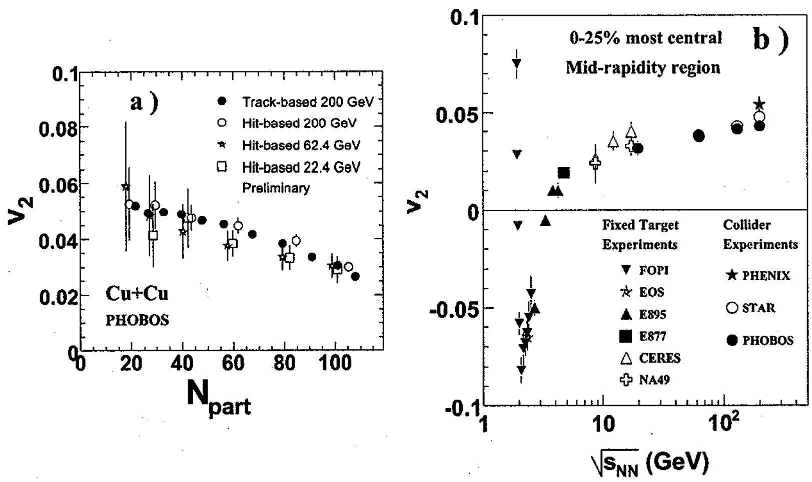


Figure 1. Panel a) v_2 versus N_{part} for Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}$ = 22.4, 62.4 and 200 GeV. Panel b) the dependence of v_2 on beam energy for mid-central Au+Au collisions. We add to this plot PHOBOS published data for Au+Au at $\sqrt{s_{NN}}$ = 19.6, 62.4, 130 and 200 GeV. The bars in the plots represent statistical errors.

1. Introduction

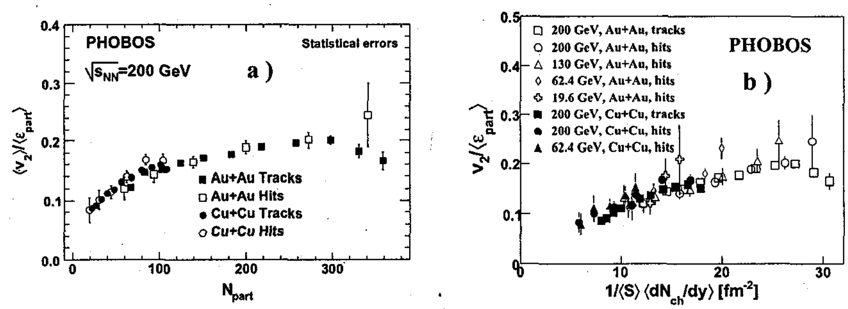
Elliptic flow has been studied extensively in nucleus-nucleus collisions at SPS and RHIC as a function of pseudorapidity, centrality, transverse momentum and center-of-mass energy [1,2]. One of the most striking observations at RHIC is a strong event anisotropy in non-central collisions [3], which is generated through the elliptically deformed overlap region of the colliding nuclei, resulting in an eccentric distribution of matter and anisotropic pressure gradients in the early stages of the expansion [4]. From a microscopic point of view this strong collective anisotropy is best described under the assumption of extremely strong rescattering [5], strong enough in fact to reach the limit of continuum dynamics. To achieve such a strong conversion of anisotropies from coordinate to momentum space, rescattering has to be strong at very early times and local thermalization has to occur while the geometric deformation of the source is still large [6]. In this work, the comparison of the data from Cu+Cu and Au+Au collisions measured by PHOBOS experiment at RHIC provides new information on the interplay between initial collision geometry (initial eccentricity) and initial particle density in determining the observed final state flow pattern. Studies from PHOBOS have pointed out the importance of fluctuations in the initial-state geometry for understanding the large Cu+Cu v2 value.

2. Elliptic Flow

PHOBOS has measured elliptic flow as a function of pseudorapidity, centrality, transverse momentum, center-of-mass energy [7,8,9] and, recently, nuclear species [10]. In particular, the measurements of elliptic flow as a function of centrality provide information on how the azimuthal anisotropy of the initial collision region drives the azimuthal anisotropy in particle production. In figure 1a, we show the centrality dependence of v_2 at midrapidity ($|\eta| < 1$) for Cu+Cu at $\sqrt{s_{NN}} = 22.4$, 62.4 and 200 GeV collision energies, as obtained from our hit-based and track-based analysis methods [8,10]. A substantial flow signal is measured in Cu+Cu at three energies, even for the most central events. The strength of Cu+Cu v_2 signal is surprising in light of expectations that the smaller system size would result in a much smaller flow signal [11]. Figure. 1b shows the dependence of v_2 on beam energy [12]. We add to this plot PHOBOS published data for Au+Au at $\sqrt{s_{NN}}$ = 19.6, 62.4, 130 and 200 GeV [8]. At low fixed target energies ($\sqrt{s_{NN}} \sim 3$ GeV), particle production is enhanced in the direction orthogonal to the reaction plane, and v_2 is negative. This is due to the effect that the spectator parts of the nuclei block the matter in the direction of the reaction plane. At higher center of mass energies, these spectator components move away sufficiently quickly, and therefore particle production is enhanced in the reaction plane, leading to $v_2 > 0$. This phenomenon is expected in hydrodynamic scenarios in which the large pressure gradients within the reaction plane drive a stronger expansion. However, the most important observation is that, up to the highest center of mass energies at RHIC, the observed asymmetry v_2 continues to grow. It would be interesting to see whether this tendency is confirmed by the LHC data.

3. Initial Eccentricity

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 [13]. 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 Glauber (MCG) studies 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



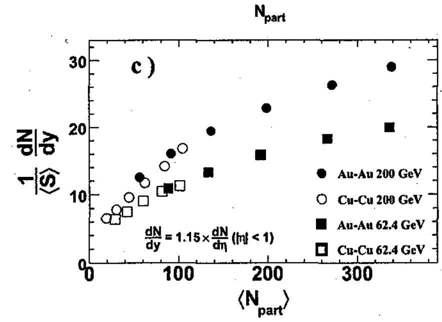


Figure 2. Panel a) $v_2/\langle\varepsilon_{\rm part}\rangle$ versus $N_{\rm part}$ for Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}$ = 200 GeV. Panel b) shows $v_2/\langle\varepsilon_{\rm part}\rangle$ as function of mid-rapidity ($|\eta| < 1$) particle area density $1/\langle S\rangle\langle dN/dy\rangle$ for Cu+Cu and Au+Au collisions. The bars in the plots represent the statistical errors. Panel c) correlation plot of midrapidity particle area density $1/\langle S\rangle\langle dN/dy\rangle$ as function of $N_{\rm part}$ calculated in Glauber MC for Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}$ = 62.4 and 200 GeV.

impact parameter vector. To account for this effect, PHOBOS has introduced the participant eccentricity defined as [10]: $\varepsilon_{\rm part} = \frac{\sqrt{(\sigma_y^2-\sigma_x^2)^2+4\sigma_{xy}^2}}{\sigma_x^2+\sigma_y^2}$, 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 participant nucleons. For comparison of Au+Au and Cu+Cu collisions at several energies, figure 2a and 2b show $v_2/\langle\varepsilon_{\rm part}\rangle$ as a function of $N_{\rm part}$ and midrapidity particle area density, $1/\langle S\rangle\langle dN/dy\rangle$, respectively. Figure 2c shows that at given energy, 62.4 or 200 GeV, the Au+Au and Cu+Cu collisions selected for the same value of $N_{\rm part}$ leads to the same value of midrapidity particle area density $1/\langle S\rangle\langle dN/dy\rangle$ calculated in MCG. We observe in figure. 2a (2b) that the v_2 scaled by $\varepsilon_{\rm part}$ are similar for both Cu+Cu and Au+Au collisions at the same value of $N_{\rm part}$ ($1/\langle S\rangle\langle dN/dy\rangle$). It should be noted that in figure 2b which has been introduced previously in Ref. [14], 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/dy = 1.15 dN/dη at midrapidity region, $|\eta| < 1$. This similarity between Cu+Cu and Au+Au collisions is also observed as a function of transverse momentum as well as in a wide pseudorapidity range [15].

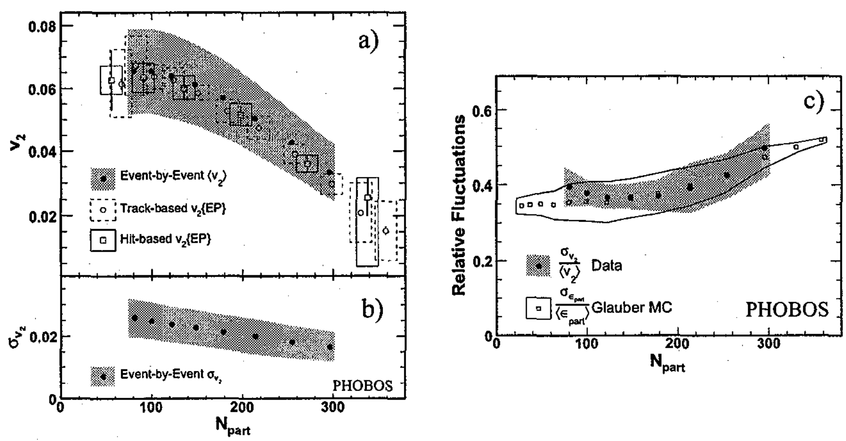


Figure 3. Panel a) $\langle v_2 \rangle$ and panel b) σ_{v_2} versus N_{part} for Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV. Boxes and gray bands show 90% C.L. systematic errors and the error bars represent 1-σ statistical errors. The results are for $0 < \eta < 1$ for the track-based method and $|\eta| < 1$ for hit-based and event-by-event methods. Panel c) $\sigma_{v_2}/\langle v_2 \rangle$ versus N_{part} for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Open squares show $\sigma_{\epsilon_{\text{part}}}/\langle \epsilon_{\text{part}} \rangle$ calculated in a Glauber MC. The bands show 90% C.L. systematics errors.

4. Elliptic Flow Fluctuations

The apparent relevance of the participant eccentricity model in unifying the average elliptic flow results for Cu+Cu and Au+Au collisions leads naturally to consideration of the dynamical fluctuations of both the participant eccentricity itself as well as in the elliptic flow signal from data. Simulations of the expected dynamical fluctuations in participant eccentricity as a function of N_{part} were performed using the PHOBOS Monte Carlo Glauber based participant eccentricity model. Figure. 3a shows the mean, $\langle v_2 \rangle$, and the standard deviation, σ_{v_2}, of the elliptic flow parameter v_2 at midrapidity as a function of the number of participating nucleons, in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for 6–45% most central events [17]. The results for $\langle v_2 \rangle$ are in agreement with the previous PHOBOS v_2 measurements [8], which were obtained with the event-plane method for charged hadrons within $|\eta| < 1$. The uncertainties in $dN/d\eta$ and $v_2(\eta)$, as well as differences between HIJING and the data in these quantities, introduce a large uncertainty in the overall scale in the event-by-event analysis due to the averaging procedure over the wide pseudorapidity range. The event-plane method used in the previous PHOBOS measurements has been proposed to be sensitive to the second moment, $\sqrt{\langle v_2^2 \rangle}$, of elliptic flow [16].

The fluctuations presented in this work would lead to approximately 10% difference between the mean, $\langle v_2 \rangle$, and the RMS, $\sqrt{\langle v_2^2 \rangle}$, of elliptic flow at a fixed value of $N_{\rm part}$. Most of the scale errors cancel in the ratio, $\sigma_{v_2}/\langle v_2 \rangle$, which defines "relative flow fluctuations", shown in figure. 3b as a function of the number of participating nucleons [17]. We observe large relative fluctuations of approximately 40%. MC studies show that the contribution of non-flow correlations to the observed elliptic flow fluctuations is less than 2%. Figure 3c shows $\sigma_{\epsilon_{\rm part}}/\langle \epsilon_{\rm part} \rangle$ at fixed values of N_{part} obtained in a MC Glauber simulation. The 90% confidence level systematic errors are estimated by varying Glauber parameters as discussed in Ref. [10]. A striking agreement between the relative fluctuations in the Glauber model participant eccentricity predictions and the observed elliptic flow fluctuations is seen over the full centrality range under study. The observed agreement suggests that the fluctuations of elliptic flow primarily reflect fluctuations in the initial state geometry and are not affected strongly by the later stages of the collision.

5. 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, 64.4 and 200 GeV. We also presented the measurements of event-by-event fluctuations for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. 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 flow. The magnitude of event-by-event fluctuations agree with predictions for fluctuations of the initial shape of the collision region based on the Glauber model. These results provide qualitatively new information on the initial conditions of heavy ion collisions and the subsequent collective expansion of the system.

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