Elliptic flow for φ mesons measured by PHENIX

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Abstract. The systematic study of hadronic elliptic flow in various relativistic heavy ion collisions is important for the investigation of the initial geometry influence on the quark gluon plasma characteristics. The φ meson consists of strange and antistrange quarks and has a small interaction cross section with non-strange hadrons. Therefore, φ mesons are barely affected by late hadronic stage and reflect detailed information about hot and dense matter properties. Additionally, the comparison of elliptic flow for φ mesons to those of charged hadrons will provide additional information on the flavor dependence of flow. PHENIX has measured second order azimuthal anisotropy coefficients for φ mesons in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and in U+U collisions at $\sqrt{s_{NN}} = 193$ GeV at midrapidity ($|\eta| < 0.35$). The obtained data suggest scaling of elliptic flow for φ mesons with eccentricity of participant nucleons in Cu+Au, U+U, and Au+Au collisions. Viscous hydrodynamic model iEBE-VISHNU provides a simultaneous description of the obtained data.

1 Introduction

One of the most important goals of the current ultra-relativistic heavy ion research is the investigation of the quark gluon plasma (QGP) [1] properties. Study of second order azimuthal anisotropy has played a key role in the establishment of the QGP formation at the Relativistic Heavy Ion Collider [2]. Elliptic flow is commonly quantified by the second Fourier moment $v_2 \equiv \langle \cos 2(\phi - \Psi_{RP}) \rangle$ of the azimuthal momentum distribution [3]. The detailed dependencies of v_2 on centrality, transverse momentum p_T, and particle species can lend insight on reaction dynamics and are important for defining parameters of viscous hydrodynamic, which may describe QGP behavior [4].

According to the Okubo-Zweig-Iizuka (OZI) rule φ-mesons have a relatively large mean free path, compared to the transverse size of the emitting system and those of $\pi^{\pm}$-meson [5, 6]. Also, the φ-mesons mostly decay after the QGP phase [1, 5], therefore φ kinematic properties are not affected by hadronic stage and bring detailed information of the QGP properties. Since the φ-meson mass is comparable to the (anti)protons $(p + \bar{p})/2$ mass, the comparisons of φ-meson, $\pi^{\pm}$-meson and $(p + \bar{p})/2$ provide an investigation of v_2 dependence on quark content and hadron mass. If the hadronic v_2 is proportional to the number of valence quarks n_q of the hadron, the flowing medium reflects quark degrees of freedom, otherwise hadronic stage is responsible for elliptic flow development [2].

The study of φ-meson production in heavy ion collisions, such as Cu+Au and U+U collisions, indicate additional mechanisms involved in its production in these collision systems

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[7, 8]. Additionally, anisotropic flow is strongly coupled to the medium density, initial geometric shape, therefore v_2 for φ-mesons was studied in asymmetric Cu+Au collisions and collisions of deformed uranium nucleus U+U.

To investigate the underlying processes behind v_2 evolution, the comparison of experimental elliptic flow v_2 for φ-mesons to theoretical predictions is needed. The iEBE-VISHNU model [9] performs event-by-event simulations for relativistic heavy-ion collisions using (2+1)D viscous hydrodynamic and hadronic cascade model. This model has proved itself valid for recent PHENIX results on elliptic and triangular flow for charged hadrons, published in the Nature Physics [10].

In this paper elliptic flow for φ-mesons in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and in U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV is studied as a function of centrality and kinetic properties, i.e. transverse momentum p_T and transverse kinetic energy KE_T. The obtained results are compared to iEBE-VISHNU hydrodynamic model predictions.

2 Results and discussion

The procedure for calculating reaction plane azimuthal angle in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and in U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV, φ meson v_2, and systematic uncertainties can be found elsewhere [11–13].

The left and right panels of Figure 1 compare the unscaled and scaled (respectively) φ-meson v_2 (p_T) in 0-20%, 20-40%, 40-60%, and 20-60% Cu+Au, 0-50% U+U collisions, previous 20-60% Au+Au PHENIX results, 0-30% and 30-80% Au+Au STAR results [11]. The scaling of φ-meson elliptic flow suggests that the v_2 values follow common empirical scaling with $\varepsilon_2 N_{part}^{1/3}$. The same scaling was observed in previous PHENIX results on charged hadrons v_2 in Cu+Au, Au+Au, and Cu + Cu collisions at $\sqrt{s_{NN}}$ = 200 GeV [13]. The average number of participating nucleons $N_{\rm part}$ and participant eccentricity of second order ε_2 were estimated using Glauber model Monte-Carlo simulation of the each collision system. Scaling with participant eccentricity of second order ε_2 represents dependence of v_2 on collision geometry. While N_{part} is proportional to the volume of the QGP, $N_{part}^{1/3}$ is proportional to the radius of the QGP.

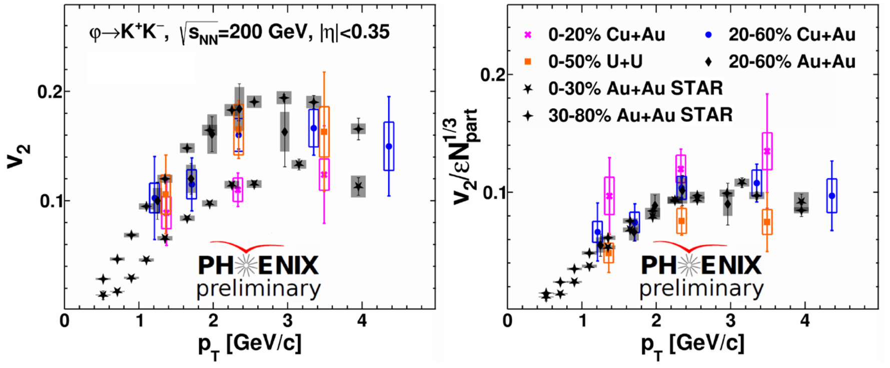

Figure 1. The elliptic flow v_2 (left) and $v_2/(\varepsilon_2 N_{part}^{1/3})$ (right) vs. p_T for φ-mesons in 0-20%, 20-40%, 40-60%, and 20-60% Cu+Au collisions, 0-50% U+U collisions, previous 20-60% Au+Au PHENIX results, 0-30% and 30-80% Au+Au STAR results. Here and below error bars and open boxes around points correspond to statistical and systematic uncertainties.

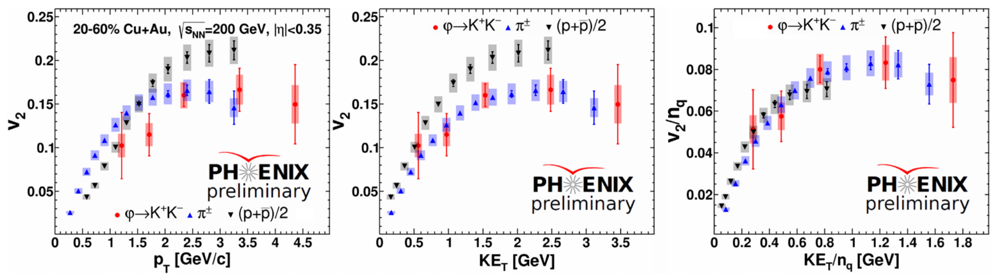

Figure 2. The comparison of elliptic flow v_2 and v_2/n_q for φ-mesons in 20-60% Cu+Au collisions to those for $\pi^{\pm}$ and $(p + \bar{p})/2$ [14] as a function of p_T (left), KE_T (middle) and KE_T/n_q (right).

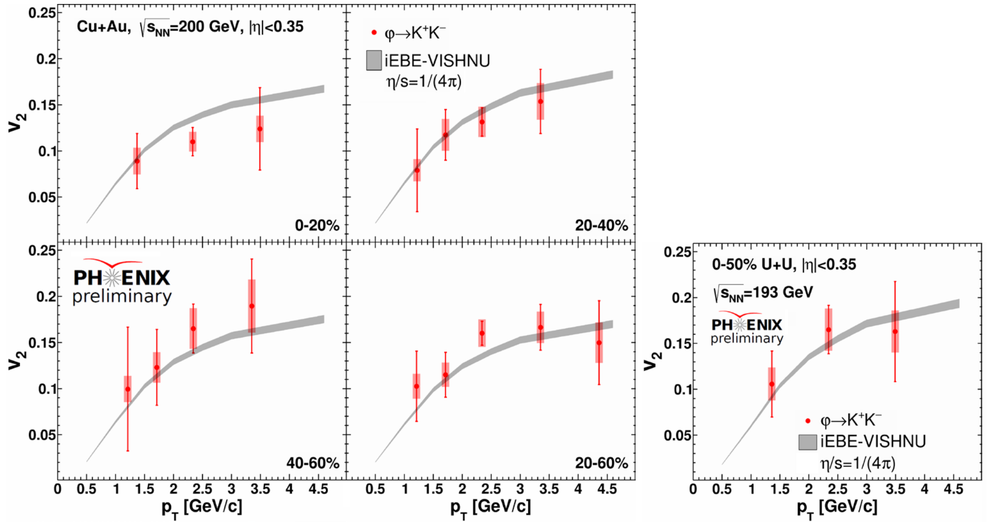

Figure 3. The comparison of measured elliptic flow v_2 (p_T) for φ-mesons in 0-20%, 20-40%, 40-60%, and 20-60% Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and in 0-50% U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV to iEBE-VISHNU hydrodynamic model prediction with specific viscosity $\eta/s = 1/(4\pi)$.

The example of the comparison of elliptic flow obtained for φ-mesons in 20-60% Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV to those for $\pi^{\pm}$ and $(p + \bar{p})/2$ [14] is shown in Figure 2. The scaling of elliptic flow for light hadrons with the number of valence quarks n_q of the hadron and transverse kinetic energy per one quark KE_T/n_q is observed (Figure 2 right panel). This result along with a smaller rescattering cross section for φ-mesons than for $\pi^{\pm}$ may indicate that elliptic flow development occurs before hadronization in the QGP phase of heavy-ion collision.

In order to better understand the physics behind v_2 development, the comparisons of measured elliptic flow for φ-mesons in 0-20%, 20-40%, 40-60%, and 20-60% Cu+Au collisions and in 0-50% U+U collisions to iEBE-VISHNU model predictions are shown in Figure 3. The iEBE-VISHNU model is based on (2+1)D viscous hydrodynamic and includes the QGP formation. The results are well described with v_2 obtained with iEBE-VISHNU calculations. A specific viscosity value of $\eta/s = 1/(4\pi)$ was used in the calculations.

3 Conclusion

Elliptic flows for φ-mesons were measured in Cu+Au collisions at $\sqrt{s_{_{NN}}}$ = 200 GeV and in U+U collisions at $\sqrt{s_{_{NN}}}$ = 193 GeV as a function of p_T, KE_T, and KE_T/n_q and compared with previous measurements in Au+Au collisions, v_2 for $\pi^{\pm}$ and $(p+\bar{p})/2$, and hydrodynamic model iEBE-VISHNU calculations.

The scaling of obtained φ-meson v_2 with second order participant eccentricity, and cube root of the number of participant nucleons is observed and confirms the previous PHENIX results. Additionally, data suggest dependence of light hadron elliptic flow on the number of valence quarks n_q of the hadron. Therefore, system size and geometry influence can be considered by normalizing factor $\varepsilon_2 N_{part}^{1/3}$, whereas hadron type dependence - by scaling with n_q. Due to all above, elliptic flow development probably occurs before hadronization in the QGP phase of heavy-ion collision.

The agreement of experimental data with iEBE-VISHNU calculations suggests that QGP behaviour can be described with (2+1)D viscous hydrodynamic with specific viscosity $\eta/s = 1/(4\pi)$.

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