

Elliptic flow for φ -mesons in Cu+Au and U+U collisions

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Abstract. An important goal of current ultra-relativistic heavy ion research is the investigation of the quark-gluon plasma (QGP). Measurements of elliptic flow lend insight on reaction dynamics and are important for defining parameters of viscous hydrodynamic, which can describe QGP behavior. 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 kinetic properties and centrality. The obtained results are compared to hydrodynamic model predictions. New FVTX detector and combinations of different approaches of flow measurements provide a possibility to measure the elliptic flow for the φ -mesons for the first time as a function of centrality at PHENIX. The elliptic flow for φ -mesons in Cu+Au and U+U collisions as function of transverse kinetic energy per one quark follows the trend for other hadrons with respect to the number of quarks in hadrons, regardless of centrality. This result along with agreement of obtained data to hydrodynamic model iEBE-VISHNU predictions suggests that QGP can be described with viscous hydrodynamic with specific viscosity $\eta/s = 1/(4\pi)$.

1. Introduction

An important goal of current ultra-relativistic heavy ion research is the investigation of the quark gluon plasma (QGP) [1]. Study of elliptic flow has played a pivotal role in the discovery of the QGP at the Relativistic Heavy Ion Collider [2]. Elliptic flow is commonly quantified by the second Fourier moment $v_2 \equiv \langle \cos 2(\phi - \Psi_R) \rangle$ 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-Izuka (OZI) rule φ -mesons have a relatively large mean free path, compared to the transverse size of the emitting system and those of (anti)protons and π^\pm -meson [5, 6]. Also, the φ -mesons mostly decay after the QGP phase [5, 1], therefore φ kinematic properties are not affected by hadronic stage and bring information of the QGP properties. Due to φ -meson's mass is comparable to the (anti)protons $(p + \bar{p})/2$ mass, the comparisons of φ -meson, π^\pm -meson and $(p + \bar{p})/2$ provide an investigation of v_2 dependence on quark content and hadron mass. The proportionality of v_2 to number of quarks indicate that the flowing medium reflects quark degrees of freedom, otherwise hadronic stage is responsible for elliptic flow development [1].



The study of φ -meson production in U+U and Cu+Au collisions suggests additional mechanisms involved in its production in these collision systems [7]. 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 [8] 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 [9].

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. Analysis Method

2.1. Elliptic flow terminology

The description of azimuthal particle emission by a Fourier series was first proposed by Voloshin in 1994 [3]. The angular distribution of single particles can be represented by:

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_n))$$

where ϕ is the azimuthal angle of some particle and Ψ_n is the symmetry plane of the n^{th} harmonic. The symmetry plane represents plane formed by the beam axis oz and impact parameter \vec{b} [3]. The dependence of experimental observable - centrality on impact parameter \vec{b} can be found in the details elsewhere [7]. The harmonic coefficients v_n are, by construction,

$$v_n = \langle \cos(n(\phi - \Psi_n)) \rangle$$

One can estimate the symmetry plane of any harmonic by using the Q -vector components [10, 11], where $Q_n = Q_{n,x} + iQ_{n,y}$:

$$n\Psi_n = \arctan \frac{Q_{n,x}}{Q_{n,y}}$$

$$Q_{n,x} = \sum_i^N \cos n\phi_i$$

$$Q_{n,y} = \sum_i^N \sin n\phi_i$$

The N is the number of particles in the collision. When calculating v_n for a particle in an event, it is necessary to ensure that the particle is excluded from the set of particles used to determine the event plane to prevent any autocorrelations.

In an analysis of real data, the symmetry plane Ψ_n is estimated using a finite number of particles, meaning there is an inherent statistical smearing away from the true value. The resultant quantity is called the event plane to distinguish it from the true symmetry plane. This smearing is quantified through the "event plane resolution" [10], which is defined as

$$Res(\Psi_n^{observed}) = \langle \cos(n(\Psi_n^{observed} - \Psi_n^{true})) \rangle$$

Since Ψ_n^{true} is not known *a priori*, it cannot be used to determine the resolution of the observed event plane. Instead, one needs to rely on the correlations between event planes in different subevents to estimate the event plane resolution [11]:

$$Res(\Psi_n^A) = \sqrt{\frac{\langle \cos(n(\Psi_n^A - \Psi_n^B)) \rangle \langle \cos(n(\Psi_n^A - \Psi_n^C)) \rangle}{\langle \cos(n(\Psi_n^B - \Psi_n^C)) \rangle}}$$

In the analysis FVTX [12], BBC [13], and MPC [14] detectors were used for event plane determination. Due to high efficiency and large pseudorapidity acceptance ($1 < |\eta| < 3$) of new FVTX detector, event plane resolution has high values providing measurements of φ -meson v_2 as a function of centrality.

The resolution corrected v_n are calculated as:

$$v_n = \langle \cos(n(\phi - \Psi_n)) \rangle / Res(\Psi_n)$$

In this paper the elliptic flow v_2 is studied, so $n \equiv 2$.

2.2. Experimental methods for elliptic flow study of resonance particles

Following method can be used to study the elliptic flow of a resonance particles, such as $\varphi \rightarrow K^+ + K^-$. Since one cannot distinguish K^\pm -mesons from φ -meson decays from other K^\pm -mesons, there is no way to identify φ -mesons directly in the analysis. In spite of this, φ -meson raw yields can be measured by handling invariant mass distribution of opposite charged K^\pm -mesons pairs [15]. Therefore, the elliptic flow is calculated from the distribution of φ -mesons raw yields as a function of azimuthal angle ϕ relative to the azimuth Ψ_2 of the reaction plane. The φ -meson raw yields calculation procedure based on three different approaches of K^\pm -mesons identification is the same as for φ -meson R_{AB} measurements [16]. For a given bin in reaction centrality and transverse momentum of φ -mesons, the decomposition between the combinatorial background and the φ -meson peak is performed independently for six bins in $\phi_{pair} - \Psi_2$.

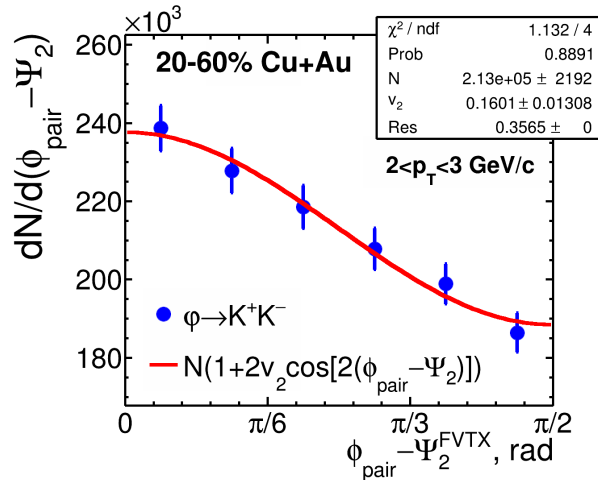


Figure 1. The φ -meson yields $dN/d(\phi_{pair} - \Psi_2)$ vs. azimuthal angle relative to the azimuth of the reaction plane ($\phi_{pair} - \Psi_2$) and $N(1 + 2v_2 \cos[2(\phi_{pair} - \Psi_2)])$ fit.

The raw yield $dN/d(\phi_{pair} - \Psi_2)$ for each bin in $\phi_{pair} - \Psi_2$ is extracted by integrating the background-subtracted invariant mass distributions in a range of two φ -meson width $\pm 2\Gamma$ around the φ -meson PDG mass [5]. The elliptic flow v_2 can then be extracted from a fit (Figure 1) to the distribution $dN/d(\phi_{pair} - \Psi_2)$ using the function $dN/d(\phi_{pair} - \Psi_2) = N(1 + 2v_2 \cos[2(\phi_{pair} - \Psi_2)])$ [10], where N is a normalization constant. The v_2 extractions were performed for three approaches and the results with the smallest statistical uncertainties were used in the following analysis.

3. Results and discussion

The comparison of elliptic flow v_2 obtained for φ -mesons in 20-60% Cu+Au collisions to those for π^\pm and $(p + \bar{p})/2$ [10] is shown in the Figure 2. The scaling of light hadron v_2/n_q with the number of quarks in hadron n_q and transverse kinetic energy per one quark kE_T/n_q is observed (Figure 2 right panel). This result along with smaller rescattering cross section for φ -mesons than for π^\pm and $(p + \bar{p})/2$ may indicate that elliptic flow development occurs before hadronization in the QGP phase of heavy-ion collision.

Figure 3 compares measurements of φ -meson $v_2(p_T)$ in Cu+Au different centrality bins, 0-50% U+U collisions, and previous 20-60% Au+Au results and suggests that the v_2 values follow common empirical scaling with $\varepsilon_2 N_{part}^{1/3}$. The average number of participating nucleons N_{part} and participant eccentricity of second order ε_2 were estimated using Glauber model Monte-Carlo simulation of the each collision systems. Scaling with participant eccentricity of second order ε_2 represents dependence of v_2 on collision geometry. The motivation for introducing the $N_{part}^{1/3}$ factor is under the assumption that N_{part} is proportional to the volume of the QGP, while $N_{part}^{1/3}$ is proportional to the radii of the QGP. This means that influence of collisions size and geometry on v_2 and thereby on QGP properties might be considered by scaling factor $\varepsilon_2 N_{part}^{1/3}$.

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

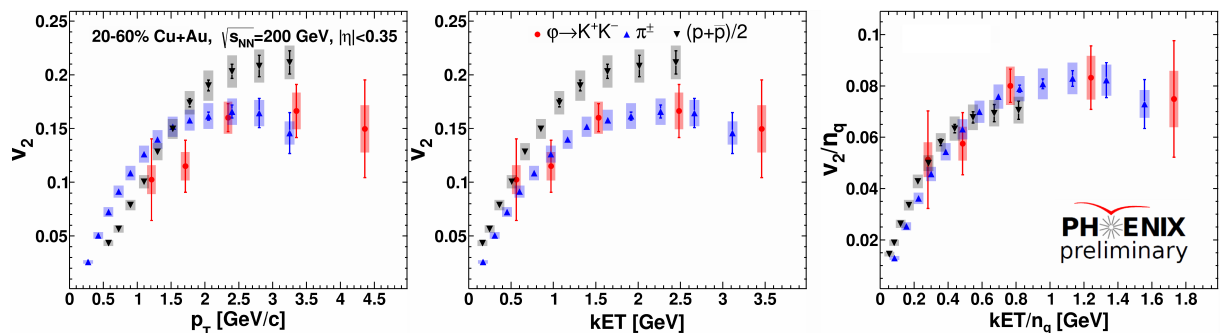


Figure 2. The comparison of elliptic flow v_2 and v_2/n_q for φ -mesons in 20-60% Cu+Au collisions to those for π^\pm and $(p + \bar{p})/2$ [10] as a function of p_T , kE_T and kE_T/n_q . Here and below error bars and open boxes around points correspond to statistical and systematic uncertainties.

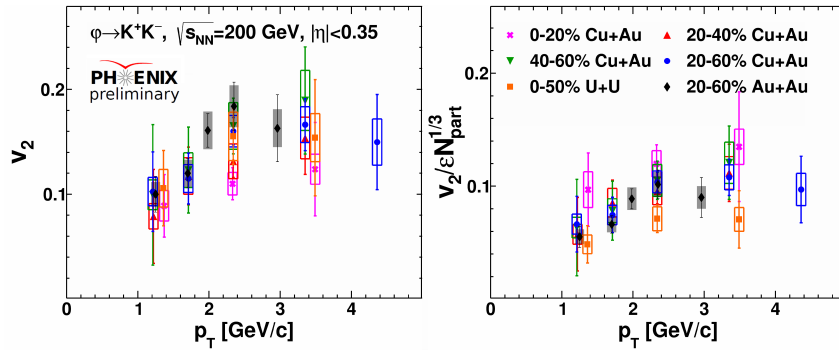


Figure 3. The elliptic flow v_2 and $v_2/(\epsilon_2 N_{part}^{1/3})$ vs. p_T for φ -mesons in 0-20%, 20-40%, 40-60%, and 20-60% Cu+Au collisions, 0-50% U+U collisions, and 20-60% Au+Au collisions.

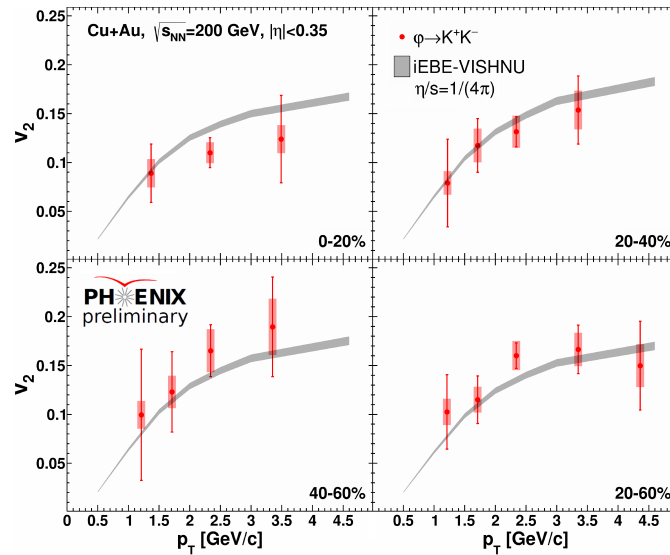


Figure 4. The comparison of measured elliptic flow $v_2(p_T)$ for φ -mesons in 0-20%, 20-40%, 40-60%, and 20-60% Cu+Au collisions to iEBE-VISHNU hydrodynamic model prediction with specific viscosity $\eta/s = 1/(4\pi)$.

4. Conclusion

The elliptic flow for φ -mesons was measured in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and in U+U collisions at $\sqrt{s_{NN}} = 192$ GeV and compared with each other, charged hadron v_2 , previous measurements in Au+Au collisions, and hydrodynamic model calculations.

The scaling of obtained φ -meson v_2 with the number of quark in hadron, second order participant eccentricity, and quibick root of the number of participant is observed. These results indicate that elliptic flow development probably occurs in QGP phase. System size and geometry influence can be considered by scaling factor $\epsilon_2 N_{part}^{1/3}$, whereas hadron type dependence - by scaling with the number of quarks in hadron.

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

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