# Measurements of identified particle anisotropic flow in Cu+Au and U+U collisions by PHENIX experiment

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## Abstract

In this paper, new measurements of anisotropic flow  $(v_1, v_2)$  for identified particles such as pions and protons in Cu+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV and U+U collisions at  $\sqrt{s_{NN}} = 193$  GeV are reported. The anisotropic flow is studied as a function of  $p_T$  and centrality in these two collision systems. In ultra-central U+U collisions (0-2% centrality),  $v_2$  of protons shows a weak  $p_T$  dependence for  $p_T < 1.0$  GeV/c. A positive  $v_1$  for charged pions is observed for  $p_T > 1$ GeV/c with respect to the first-order event plane, the angle of which is determined by the Augoing spectators. The scaling of identified particle  $v_2$  with the number of valence quarks  $(n_a)$  has been observed in these two collision systems, with the transverse kinetic energy.

#### 1. Introduction

Measurements of the anisotropic flow with different order harmonic coefficients ( $v_n, n =$ 1, 2, 3, 4) have played a pivotal role in the discovery of quark-gluon plasma (OGP) at RHIC and the LHC [1]. They are also important for the study of viscous hydrodynamics and the extraction of the shear viscosity over entropy density  $(\eta/s)$  [2]. Anisotropic flow is strongly coupled to the medium density, initial geometry shape, and corresponding event-by-event fluctuations, which are crucial for further accurate measurements of elliptic flow and understanding the QGP properties [3].

The flexibility of RHIC can provide different kinds of heavy ion collisions in addition to Au+Au and Cu+Cu collisions, which include the colliding of two deformed nuclei, such as U+U at 193 GeV, and species-asymmetric collisions, such as Cu+Au at 200 GeV. In central U+U collisions, the initial geometry and eccentricity will be quite different for tip-tip and bodybody collisions [4]. Additionally, Cu+Au collisions can provide an asymmetric geometry and density both in the transverse plane and longitudinally [5]. Measurements of these systems will open new windows to investigate the influence of different initial geometry and densities.

In this paper, I will present new measurements of identified particle  $v_2$  in U+U collisions at 193 GeV and identified particle  $v_1$ ,  $v_2$  in Cu+Au collisions at 200 GeV. The number of valence quark  $(n_a)$  scaling is also tested for  $v_2$  in the Cu+Au and U+U collisions.

## 2. Analysis Methods

In 2012, PHENIX recorded 3.0 B and 4.6 B minimum-bias events in U+U at 193 GeV and Cu+Au collisions at 200 GeV, respectively. For the results shown in this paper, 70 M and 600 M events are used for U+U collisions and Cu+Au collisions respectively. Preprint submitted to Nuclear Physics A November 8, 2018

The  $v_n$  measurement is performed by correlating the particle azimuthal angle  $\varphi$  with the corresponding harmonic event-plane angle  $\Psi_n$ , and correcting the observed signal for the event-plane resolution as follows:

$$v_n = \frac{\langle \cos(n(\varphi - \Psi_n)) \rangle}{Res(\Psi_n)} \tag{1}$$

Here the brackets  $\langle \rangle$  indicate an average over all particles in all events for a certain centrality bin and  $Res(\Psi_n)$  indicates the correction factor for the event-plane resolution.

The SMDs (Shower Maximum Detectors) [6], with a rapidity coverage of  $|\eta| \ge 6.5$ , are used to measure the angle of  $\Psi_1$ . The BBCs [7] ( $3.1 \le |\eta| \le 3.9$ ) and MPCs [8] ( $3.1 \le |\eta| \le 3.9$ ) are used to measure the angle of  $\Psi_2$  in Cu+Au and U+U collisions respectively. Two TOF (Timeof-Flight) detectors [7, 9] which sit in the west and east arms of PHENIX were used to identify the particles. The pions, kaons and protons can be separated up to  $p_T \sim 3$  GeV/c by TOF with a timing resolution of 89 ps (TOFw) and 120 ps (TOFe), respectively.

## 3. Results and discussions

3.1.  $v_2$  of pions and protons in U+U collisions at 193 GeV







Figure 2:  $v_2$  of pions and protons as a function of  $p_T$  for the finer centrality bins of 0–2%, 2–4%, 4–6% and 6–10% in U+U collisions at 193 GeV.

The results for  $v_2$  of pions and protons in U+U collisions at 193 GeV are presented in Fig.1; As Fig.1 shows, the protons show a weaker  $p_T$  dependence in 0–10% centrality bin below  $p_T < 1$  GeV/c, compared with that of Au+Au collisions [9]. However, the  $p_T$  dependence of  $v_2$  of pions, and for both particles in non-central collisions are quite similar between Au+Au and U+U collisions.

To further investigate this behavior, the  $v_2$  of pions and protons are studied in finer centrality bins such as 0–2%, 2–4%, 4–6% and 6–10% in U+U collision, with centrality being defined by the total charge signal from the BBCs. As Fig.2 shows, the weak  $p_T$  dependence for  $v_2$  of protons below  $p_T < 1$  GeV/c grows more pronounced in the more central U+U collisions such as 0-2%. In the future, we will try to separate the collision geometry into tip-tip and body-body collisions, so that we can further understand what cause this behavior. Possible explanations are stronger radial flow due to a high medium density or the complicated initial geometry in central U+U collisions.

## 3.2. $v_1$ of charged pions in Cu+Au collisions at 200 GeV



Figure 3:  $v_1$  of pions as a function of  $p_T$  for centrality bins of 30–40%, 40–50%, 50–60% and 30–60% in Cu+Au collisions at 200 GeV. The angle of  $\Psi_1$  is determined by the Au-going spectators which are measured by SMD.

In asymmetric collisions such as Cu+Au, the asymmetric initial density profile may generate an asymmetric pressure gradient with respect to the reaction plane, which will lead to an asymmetric momentum space distribution with respect to the reaction plane. The partons generated by hard scattering will lose different amounts of energy, due to the fact that they are emitted from different medium surfaces, either on the Au-going side or the Cu-going side, which will also generate an asymmetric momentum space distribution at high  $p_T$ . Therefore, the measurements of first order harmonic coefficients ( $v_1$ ) in a broad  $p_T$  region in Cu+Au will supply more information about this asymmetric medium. The  $v_1$  of charged pions as a function of  $p_T$  and centrality is shown in Fig.3. A positive  $v_1$  is observed for  $p_T \ge 1$  GeV/c. The angle of  $\Psi_1$  is determined by the Au-going spectators, so a positive  $v_1$  measured by Equ. 1 indicates that there are more particles emitted from the Au-going side at  $p_T \ge 1$  GeV/c.

#### 3.3. $n_q$ scaling in Cu+Au and U+U collisions

The observation of  $n_q$  scaling has been the basis of the claim that a partonic matter with quark-like degrees of freedom and significant collectivity has been generated in heavy ion collisions [10]. In U+U collisions, the  $n_q$  scaling may be affected by the stronger radial flow, higher medium density, and complicated initial geometry. In Cu+Au collisions, it is also interesting to determine whether there are cold nuclear matter effects, which may give extra contributions to the particle production. We measured the  $n_q$  scaling in U+U and Cu+Au collisions in different centrality bins, which are shown in Fig.4. Due to statistical limitations, the measurement is limited to the region of  $KE_T/n_q \leq 0.8$  GeV, where the  $n_q$  scaling is still observed to hold.



Figure 4:  $v_2/n_q$  of pions and protons as a function of  $KE_T/n_q$  for centrality bins 0–10%, 10–20%, 20–40% and 40–60% in U+U collisions at 193 GeV (left panel) and Cu+Au collisions at 200 GeV (right panel). The error bars (shaded boxes) represent the statistical (systematic) uncertainties.

## 4. Summary

The  $v_1$  and  $v_2$  of pions and protons are measured in U+U collisions at 193 GeV and Cu+Au collisions at 200 GeV. The  $v_2$  of proton shows a weak  $p_T$  dependence for  $p_T < 1$  GeV/c in 0–2% ultra-central U+U collisions. Additionally, a positive  $v_1$  of charged pions is observed for  $p_T \ge 1$  GeV/c. These new measurements will give us further information to understand the initial geometry, medium density, and their corresponding fluctuations in heavy ion collisions.

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