

# Azimuthal anisotropy of the identified charged hadrons in Au+Au collisions at $\sqrt{s_{NN}} = 39 - 200$ GeV at RHIC

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**Abstract.** A new form of nuclear matter, where quarks and gluons are deconfined and interact strongly with each other, is produced in heavy ion collisions at the relativistic heavy ion collider (RHIC). Azimuthal anisotropies of particle distributions relative to the symmetry plane in high energy heavy ion collisions are used to characterize the collision dynamics. The results of measurements of the azimuthal anisotropy parameters  $v_n$  ( $n=2,3$ ) of identified charged hadrons (pions, kaons and protons) in Au+Au collisions at  $\sqrt{s_{NN}} = 39, 62.4$  and 200 GeV are presented and discussed. The energy dependence of the difference between the flow of the particles and their anti-particles are discussed as well.

## 1. Introduction

Quantum Chromodynamics (QCD) predicts that at sufficiently high temperatures  $T$  and/or baryonic chemical potentials  $\mu_B$ , normal nuclear matter turns into a state of deconfined quarks and gluons, called the Quark-Gluon Plasma (QGP) [1]. To produce this new state of matter and study its properties – these are main goals of the heavy ion collision program at the Relativistic Heavy Ion Collider (RHIC) facility. An experimental way to understand the formation of the QGP is by varying collision energies and studying observables as a function of collision centrality, transverse momentum,  $p_T$ , and rapidity,  $y$ . With these goals, the Beam Energy Scan (BES) program [2] was started in the 2010 at RHIC where Au+Au collisions were recorded at wide range of energies:  $\sqrt{s_{NN}} = 7.7 - 200$  GeV.

The azimuthal anisotropy of produced particles is one of the most widely studied observables. In non-central heavy ion collisions, the overlap region of the colliding nuclei has the almond-like shape and perpendicular to the plane defined by the impact parameter vector and the beam axis - reaction plane. Due to finite number fluctuations of participating nucleons in reactions with the same centrality, the geometric symmetry plane in each event is not necessarily the same as the reaction plane, and is often called the participant plane [3]. The initial spatial anisotropy and subsequent interactions among the constituents result in pressure gradients that are larger in the direction of the participant plane compared to out of this plane. This results in an azimuthal anisotropy of the momenta of the produced particles [4]. To numerically evaluate the anisotropy, the Fourier expansion of the distribution of the azimuthal angles of the particles with respect to the reaction plane is used. The coefficients of such distribution are called flow harmonics. The second harmonic is denoted as an elliptic flow  $v_2$ , the third is a triangular one  $v_3$ .

At low transverse momenta ( $p_T < 2$  GeV/c), a mass ordering in  $v_2(p_T)$  between the different particle species was observed [5, 6]. This behaviour can be described by non-viscous hydrodynamic calculations [7]. The relative mass ordering can be suppressed by using the reduced transverse kinetic



energy  $KE_T = (m_T - m_0)$  instead of  $p_T$ , where  $m_T = \sqrt{(p_T^2 + m_0^2)}$  and  $m_0$  is the mass of the particle. At large  $KE_T$  a splitting in  $v_2(KE_T)$  between baryons and mesons was observed which cannot be described by hydrodynamic calculations. The splitting can be explained by assuming that the particle production occurs via coalescence of constituent quarks [8].

At intermediate  $p_T$  values ( $2 < p_T < 6$  GeV/c) a Number-of-Constituent Quark (NCQ) scaling of  $v_2$  for the identified hadrons was observed. This observation, coupled with the comparable values of the elliptic flow measured for multi-strange hadrons and light quark hadrons, was used to conclude that the relevant degrees of freedom in the systems formed at the top RHIC energy are quarks and gluons [9].

It is generally expected that the system will spend less time in the partonic phase as the beam energy is lowered, and that at the lowest BES energies the system might not reach the QGP regime. In such a scenario, it is expected that NCQ scaling of  $v_2$  of produced particles would be broken [10]. Furthermore, with decreasing beam energy, the baryon chemical potential of the system at chemical freeze-out increases. These aspects could lead to new trends in the identified hadron  $v_n$  in the BES program at RHIC.

The main results of  $v_2$  and  $v_3$  measurements of PHENIX and STAR collaborations at RHIC will be presented and discussed.

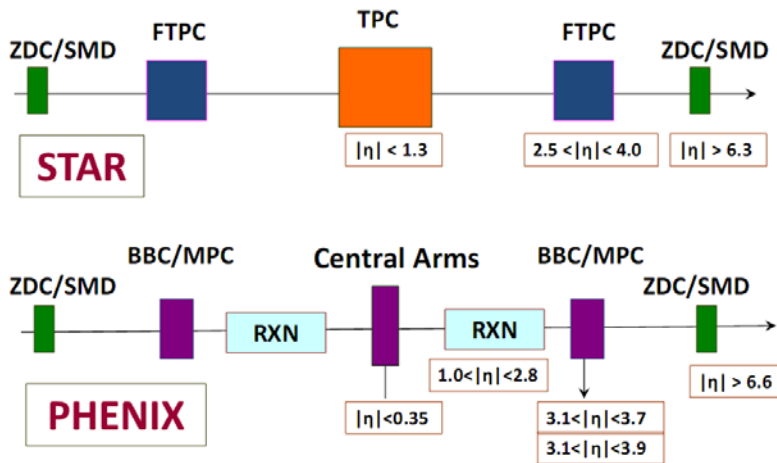
## 2. Experimental setup

The used results were obtained from two detector systems STAR and PHENIX. This section describes main features, advantages and differences between the detectors.

The Solenoidal Tracker At RHIC (STAR) is a multipurpose experiment at the RHIC facility at Brookhaven National Laboratory. It consists of a solenoidal magnet and an array of detectors for triggering, particle identification, and event categorization. A detailed description can be found in Ref. [11].

The PHENIX detector consists of two central spectrometer arms at midrapidity that are designated East and West for their location relative to the interaction region, and two muon spectrometers at forward rapidity, similarly called North and South. A detailed description of the PHENIX detector can be found in Ref. [12].

Figure 1 shows the comparative pseudorapidity coverage of the STAR and PHENIX detector subsystems. One could see that PHENIX has variety of detectors with big enough  $\eta$ -gap to the central arms. That could be used for determination of the reaction plane and wide  $\eta$ -gap helps to suppress non-flow effects such as jets, resonances decays etc. The advantage of the STAR detector is a good acceptance. It has full azimuthal coverage of  $2\pi$  while PHENIX has two arms of  $\pi/2$ .



**Figure 1.** The pseudo-rapidity  $\eta$  acceptance of the PHENIX and STAR detectors used for event-plane reconstruction, along with the mid-rapidity detectors used for charged hadron measurements.

### 3. Event Plane (EP) method

To calculate values of the flow harmonics the decomposition of the azimuthal angles of the particles with respect to the reaction plane is used:

$$\frac{dN}{d(\varphi - \Psi_m)} \propto 1 + 2 \sum_{n \geq 1} v_n \cos [n(\varphi - \Psi_m)], \quad (1)$$

where  $\varphi$  is the azimuthal angle of the particle,  $\Psi_m$  is the event plane [13].

In the standard event plane method, the particles were first identified, then their yields were determined as a function of the relative angle  $\varphi - \Psi_m$ . The event plane (EP) is obtained from the angles of the reconstructed particles and the beam. It is an estimate of the participant plane which is defined by the participant nucleons in the collision. To avoid self-correlations and reduce non-flow effects, between particles of interest and particles used for EP reconstruction should be gap in pseudorapidity.

For measurements STAR normally uses TPC (Time Projection Chamber). PHENIX uses central arm spectrometer for tracking and RNX (Reaction Plane Detector) or BBC (Beam-Beam Counters) for event plane evaluation.

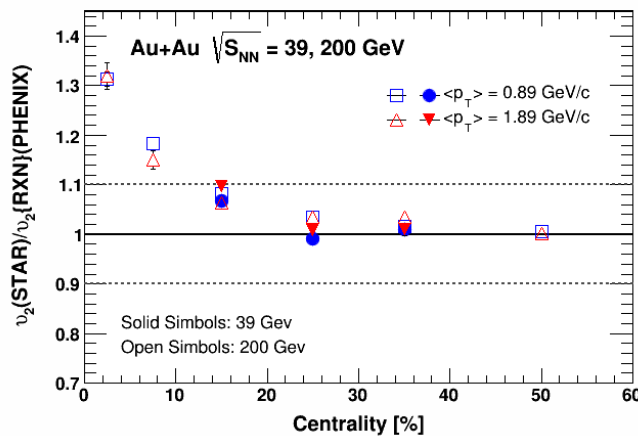
### 4. Comparison of the STAR and PHENIX flow results

The comparison between results of two experiments requires careful attention to the details of each measurement.

In order to make the proper comparison for EP method we should use the event plane detectors with the same  $\eta$  coverage. This is the case for STAR FTPC and PHENIX BBC. Unfortunately, we have only one colliding system and one beam energy for the proper comparison of the published elliptic flow ( $v_2$ ) results between STAR and PHENIX: the  $v_2$  values of charged hadrons from Cu+Cu collisions at  $\sqrt{s_{NN}} = 200$  GeV obtained using the EP from STAR FTPC and PHENIX BBC. The difference between two data sets is less than 5-10% within a typical systematic uncertainty of the measurements of 5% [14].

For other systems and sets of detectors the comparison of the results doesn't show the high consistency. Figure 2 shows the centrality dependence of the ratio of STAR  $v_2(p_T)$  values to the  $v_2$  values obtained from PHENIX for charged hadrons at  $\sqrt{s_{NN}} = 200$  and 39 GeV. While the two data sets overlap excellently for centralities  $> 20\%$ , they increasingly diverge at small centralities up to a 30% difference between STAR and PHENIX in the 0-5% centrality bin.

The results for  $v_3$  also show divergence even within STAR measurements with different detectors [14].



**Figure 2.** Centrality dependence of the ratio of STAR  $v_2(p_T)$  values obtained using EP from STAR TPC to the  $v_2$  values obtained using EP from PHENIX RXN. The data are for charged hadrons from Au+Au collisions at  $\sqrt{s_{NN}} = 39$  and 200 GeV [14].

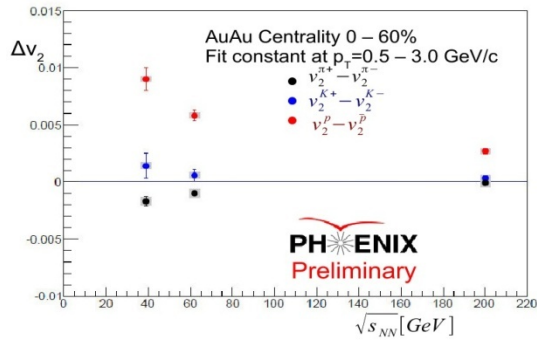
### 5. Flow measurements at different energies

The important step in the investigations of the phase diagram of the nuclear matter is to study the changes which undergo with varying of the energy. The measurements of the elliptic  $v_2$  and triangular  $v_3$  flow for energies of  $\sqrt{s_{NN}} = 200$  GeV and lower are presented and discussed below.

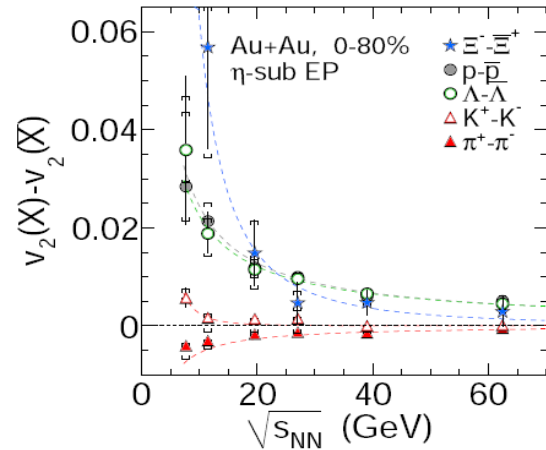
The splitting in  $v_n(m_T - m_0)$  between the mesons and baryons at transverse mass values above  $1 \text{ GeV}/c^2$  implies a dependence of the  $v_n$  values on the number of constituent quarks,  $n_q$ . The NCQ scaling was originally predicted for  $v_2(p_T)$  at intermediate transverse momenta [15]. This is interpreted as a possible signature for partonic degrees of freedom (quarks and gluons) in the initial stage of the system, where most of the flow of the particles develops. This scaling should vanish in a hadron gas system at lower energies. Thus, the breakdown of NCQ scaling would be a necessary signature for a QCD phase transition from partonic to hadronic matter.

### 5.1. Elliptic flow $v_2$ measurements

The measurements of  $v_2$  in Au+Au collisions at energy range  $\sqrt{s_{NN}} = 39 - 200 \text{ GeV}$  for inclusive charged hadrons are consistent within the uncertainties [16]. But if compare the elliptic flow of the identified particles one can see the increasing divergence between particles and antiparticles with decreasing of the energy both for PHENIX [17] and STAR [18] (figures 3 and 4). This observed difference in flow values for the particles with the same mass and number of quarks leads to the breaking of the NQC scaling at lower energies. But the scaling still holds if consider particles and antiparticles separately [18].



**Figure 3.** The difference in the  $v_2$  values between a particle X and its corresponding anti-particle ( $\bar{X}$ ) (see legend) as a function of  $\sqrt{s_{NN}}$  for 0–60% central Au+Au collisions [17].

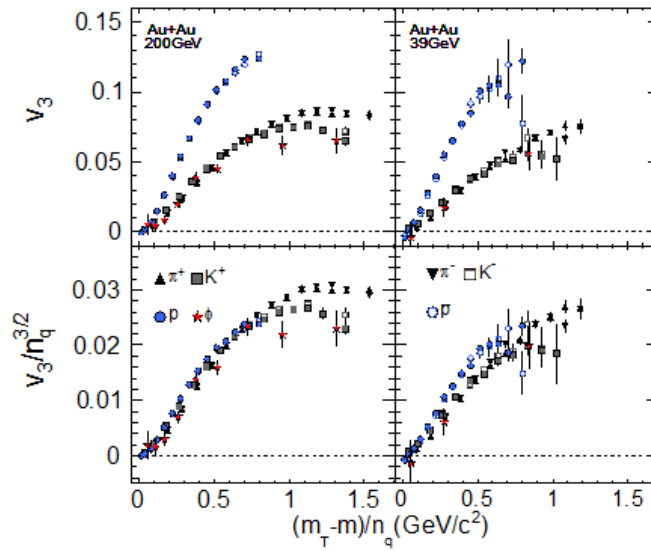


**Figure 4.** The difference in the  $v_2$  values between a particle X and its corresponding anti-particle ( $\bar{X}$ ) (see legend) as a function of  $\sqrt{s_{NN}}$  for 0–80% central Au+Au collisions [18].

### 5.2. Triangular flow $v_3$ measurements

The triangular flow  $v_3$  exhibits the same pattern. The results for  $\sqrt{s_{NN}} = 39 - 200 \text{ GeV}$  are consistent within statistical and systematic errors for inclusive charged hadrons [16]. And due to the difference in particles and corresponding antiparticles flow the NQC scaling noticeably breaks at  $\sqrt{s_{NN}} = 39 \text{ GeV}$ .

Figure 5 shows the  $KE_T = (m_T - m_0)$  divided by number of constituent quarks  $n_q$  dependence of  $v_3$  (top panels) and  $v_3/n_q^{3/2}$  (bottom panels) for two energies of 200 and 39 GeV. One could clearly see the violation of the NQC scaling at  $\sqrt{s_{NN}} = 39 \text{ GeV}$  while it holds up to  $KE_T/n_q = 1 \text{ GeV}$  for  $\sqrt{s_{NN}} = 200 \text{ GeV}$  [19].



**Figure 5.** NCQ scaling for identified particles ( $\pi^+$ ,  $K^+$ ,  $p$ ,  $\bar{p}$  and  $\phi$ )  $v_3$  for 0%–80% central Au+Au collisions at  $\sqrt{s_{NN}} = 200$  and 39 GeV. Upper panel:  $v_3$  as a function of  $(m_T - m_0)/n_q$ . Lower panel:  $v_3/n_q^{3/2}$  as a function of  $(m_T - m_0)/n_q$ . []

## 6. Summary

The detailed comparison of RHIC experimental data for anisotropic flow harmonics has been presented and discussed. The  $KE_T$  number of constituent quarks scaling of  $v_2$  and  $v_3$  is observed at 200 GeV and broken at lower energies. The difference of elliptic flow between particles and antiparticles is increasing with decreasing of the energy of the collision. One should note that different experiments (such as STAR and PHENIX) have slightly divergent results, so it is important to keep track of the differences and carefully interpret the obtained measurements.

## Acknowledgments

This work was performed within the framework of the Center of nanostructured electronics supported by MEPhI Academic Excellence Project (contract № 02.a03.21.0005, 27.08.2013)

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