Measurement of the Higher Order Azimuthal Anisotropy for Charged Hadrons at RHIC-PHENIX

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Abstract. Measuring the azimuthal anisotropy of particles produced in relativistic heavy ion collisions has been considered as a powerful probe for investigating the characteristics of the quark-gluon plasma (QGP), which is the phase in QCD matter of de-confined quarks and gluons. The event anisotropy \(v_2, v_3, v_4\) are measured in Au+Au collisions in various energies in PHENIX. The results of these higher-order event anisotropy constrain the initial geometrical eccentricity and viscosity that are used in hydrodynamical models. We present the latest results of \(v_2, v_3, v_4\) measurement and discuss the simultaneous description with the hydrodynamical calculations.

When two nuclei collide at relativistic energies, a hot dense QCD matter, or the quark-gluon plasma (QGP), is formed \[1\]. One of the methods to study the properties of QGP is to study the collective motion of the particles emitted from QGP \[2\]. At the early years of RHIC operations, this collective behavior is studied by measuring the particle azimuthal angular distributions respected to the reaction plane, \(\Psi\). The direction of the reaction plane is defined by the impact parameter of the colliding nuclei and the beam direction. Then the Fourier spectra of the particle angular distribution can be measured by the following equation:

\[
d\frac{N}{d\phi} \propto (1 + 2 \sum_{i=1}^{\infty} v_n \cos n(\phi - \Psi)),
\]

(1)

If both colliding nuclei has smooth density profile, because of the symmetrical shapes at the azimuthal direction, all \(v_{odd}\) terms in Eq. 1 will be zero. Therefore the second Fourier coefficient, \(v_2\) is the most important of these Fourier coefficients, which is also known as the elliptic flow strength. By studying \(v_2\), it was found that the QGP has strong collective motion of particles and has the \(\eta/s\) which is close to the quantum lower bound \[3\], which behaves as “nearly perfect fluid” \[4\].

But as pointed out by Alver and Roland \[5\], the nucleus density does not have a smooth profile. Instead, the nucleus has some density fluctuations. Because of these fluctuations, the symmetry of the interaction region at the azimuthal direction is broken. Therefore, \(v_{odd}\) may be substantial due to the fluctuation of the initial state geometry of colliding nuclei. Also because of the initial state geometry fluctuation, the maximum \(v_n\) does not necessary pointing along the direction of the reaction plane, \(\Psi\). Instead, it is pointing to the \(n\)-th event plane, \(\psi_n\). So the particle azimuthal angular distribution should be re-written as
The idea of \( v_3 \) is also useful in explaining other interesting phenomena found in QGP. When measuring two-particle \( \Delta \eta \Delta \phi \) correlations at intermediate transverse momentums, two interesting structures, “ridge” and “shoulder”, are found in central \( \text{Au+Au} \) collisions. The ridge is a structure sits at \( \Delta \phi \approx 0 \) and extend along \( \Delta \eta \) direction [6, 7]. The shoulder is a double-peaked structure at \( \Delta \phi \approx \pi \pm 1 \), which also extends along \( \Delta \eta \) direction [8]. When considering both “ridge” and “shoulder” together, we found that the peak position of these structure roughly correspond to th peak position of \( v_3 \)’s \( \cos(3\Delta \phi) \) structure, which makes \( v_3 \) even more interesting.

In Eq. 1, \( v_N \) is the Fourier coefficient measured relative to \( \psi_n \), or the n-th order event plane. PHENIX uses various detectors at forward directions (at \( 1 < |\eta| < 3.9 \), depending on detectors) to determine the event plane, \( \psi_n \). By using forward detectors with large \( \eta \) gap separated from the central arm spectrometer (\( |\eta| < 0.35 \)), the bias of the non-flow effects, such as jets, can be reduced significantly.

The \( v_n \) of inclusive charged hadrons, where \( n = 2, 3, 4 \), are measured by PHENIX as a function of \( p_T \) in various centralities, as shown in Fig. 1 [9]. All \( v_n \) shows an increasing trend as a function of \( p_T \). For \( v_2 \), there is a significant centrality dependence, where the \( v_2 \) increases when moving from most central (0-10%) to mid-central (50-60%) collisions. This is consistent with what we expect from the initial geometry of collisions because most central collisions are more circular in shape, therefore lower \( v_2 \) is expected.

The third harmonic, or \( v_3 \), which is believed that the main source is from the fluctuation, shows a interesting behavior. Unlike \( v_2 \), the \( v_3 \) as a function of \( p_T \) is rather independent from centrality, which means the source of \( v_3 \) is probably not strongly influenced by the geometry.

The new measurement of \( v_3 \) also provides extra constraints on theoretical models. In Fig. 2, The \( v_2 \) and \( v_3 \) in two different \( p_T \) are plotted as a function of number of participants. Several theory predictions of \( v_2 \) and \( v_3 \) with various initial state conditions and different \( \eta/s \) are plotted alongside with data. In Fig 2, all theories describe \( v_2 \) as a function of \( N_{\text{part}} \) fairly well, but not every theory can describe \( v_2 \) and \( v_3 \) simultaneously. From the selected calculations shown here, the data favor Glauber initial state conditions with \( \eta/s = 1/4\pi(0.08) \).

While \( v_3 \) of inclusive charged hadrons shows interesting properties of the QGP, \( v_2 \) of identified charged hadrons, such as pions, kaons and protons, also provide important insights. In previous PHENIX measurement on the \( v_2 \) of identified charged particles, these \( v_2 \) follows a "number of quark scaling" [10], or NQS, which is the \( v_2 \) is scaled by number of quarks of the particle, and plotted as a function of the transverse of kinetic energy, which is also scaled by number of quarks, all identified particle \( v_2 \) follow a universal trend.

In the 2007 run, with the two new detectors, Aerogel Cherenkov detector and Time of Flight west, PHENIX extends the PID \( v_2 \) measurement to higher \( p_T \) and finer centrality bins. In order to see if the NQS still holds, the \( v_2 \) of identified particles scaled by number of quarks are shown in Fig. 3 [11]. In the most central collisions (0-10%), after scaled by number of quarks, all \( v_2 \) curves of pion, kaon and proton are lined up in a universal curve. When move to mid-central collisions, the protons starts to show the deviation from the universal curves at \( KE_T \) at 1 GeV/c. The pions and kaons are still follow the same trend. When move to more peripheral collisions, the deviation of the proton \( v_2 \) is more and more significant. It is well known that the hydrodynamics can describe the \( v_2 \) behavior as a collective motion at \( p_T \) up to 2-3 GeV/c or roughly at 1GeV/c when considering the number of quark scaling. At high \( p_T \), the \( v_2 \) is generally be considered due to the path-length dependent parton energy loss. So this deviation from NQ scaling may provides some useful informations on the interplay of hydrodynamics and parton energy loss at this \( p_T \) region.

\[
\frac{dN}{d\phi} \propto (1 + 2 \sum_{i=1}^{\infty} v_n \cos n(\phi - \psi_n)),
\]
One of the unique strengths of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is the ability to collide the gold nuclei at different energies. From various experimental evidence, we already know that QGP has been created at the highest colliding energy ($\sqrt{s_{NN}} = 200$ GeV) at RHIC. By colliding gold nuclei at different energies, we are able to study the energy dependence of the various properties of QGP and hopefully to find the critical point for the phase transition between the hadron gas and QGP. In order to find the critical point, we need use some properties of the QGP to map out the energy dependence. Flow turns out to be a good one.

During the first energy scan in 2011, PHENIX collects Au+Au collision data at center of mass energy per nucleon pair at 62.4, 39 and 7 GeV. The $v_2$, $v_3$ and $v_4$ of the inclusive charged hadron at colliding energy at 200, 62 and 39 GeV are measured and shown in Fig. 4. Within errors, the $v_n$ as a function of $p_T$ are consistent throughout three colliding energies. This is a strong indication that the QGP has already been formed at 39 GeV, and it just thermalized as fast as the case in 200 GeV.
Figure 3. The $v_2$ of pions, kaons and protons scaled by number of quarks as a function of transverse kinetic energy scaled by number of quarks in various centralities [11].

In order to see if the energy dependence of NQ scaling still holds at 62.4 and 39 GeV, the $v_2$ of identified hadrons are also measured at 62.4 and 39 GeV. The measured $v_2$ which is scaled by number of quarks are shown in Fig. 5 and Fig. 6 [12]. As see in the figures, the NQ scaling holds down to 39 GeV, which means that at this energy, the flow already established at partonic level, which is another evidence of the de-confinement of the quarks in the QGP.

PHENIX also measured the $v_2$ of inclusive charged hadrons at 7.7 GeV. In order to see the energy dependence, $v_2$ of various energies (7.7, 39, 62.4, 200) are plotted in Fig. 7 [12]. It is easy to see that at energies above 39 GeV, the $v_2$ is independent from colliding energies. But the $v_2$ at 7.7 GeV is significantly lower than this trend. It seems like there should be a turnover somewhere between 7.7 GeV and 39 GeV, so the $v_2$ will start to be saturated. With data from more colliding energies, PHENIX should be able to have a clearer picture on this interesting trend.

Flow measurement has given us many important insight on the properties of the quark-gluon plasma. With a more realistic picture on initial collisional geometries, the odd harmonics such as $v_3$ are measured and provides extra constraint on theory modeling. With energy scan, we are able to study the energy dependence of the flow. Between 39-200 GeV, $v_n$ as a function of $p_T$ has no energy dependence. From studies of identified particles, the partonic flow already established at 39 GeV. But this number of quark scaling starts to deviate when the measurement extends to higher $p_T$. The protons begin to show some evidence of deviation from the universal trend. With more data at lower colliding energies, especially between $\sqrt{s_{NN}}$ at 7.7 and 39 GeV, we should have more insight on the phase transition process of quark-gluon plasma.

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Figure 4. The $v_2$, $v_3$ and $v_4$ of inclusive charged hadrons as a function of $p_T$ measured in different colliding energies [12].

Figure 5. $v_2$ of pions, kaons and protons scaled by number of quarks at $\sqrt{s_{NN}}$ at 62 GeV [12].

Figure 6. Same as Fig. 5, but at $\sqrt{s_{NN}} = 39$ GeV.

Figure 7. The $v_2$ as a function of $\sqrt{s_{NN}}$ [12].
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