Global and Collective Dynamics at PHENIX

Takafumi Niida for the PHENIX Collaboration
University of Tsukuba, 1-1-1 Tennoudai, Tsukuba, Ibaraki 305-8571, Japan
E-mail: niida@rcf.rhic.bnl.gov

Abstract. In order to study the properties of the hot and dense matter created by heavy ion collisions, various physics observables have been measured in RHIC and the LHC, such as spectra, collective flow, two particle correlations and HBT. The higher harmonic flow \( v_n \) have been recently measured, which is primarily coming from the spatial fluctuation of the initial participant density. Measurements related to the \( v_n \) and event planes will give us new insight into the properties of the hot and dense matter and space-time evolution in the heavy ion collisions. We present the latest results of higher harmonic flow \( v_n \) for identified particles and azimuthal hadron correlations with the subtraction of backgrounds from higher harmonic flow \( v_n \). Besides, we present \( m_T \) dependence of final eccentricity obtained by azimuthal HBT measurement.

1. Introduction

The initial geometry of the overlap region in heavy ion collisions have been treated as the collisions of nuclei with smooth density profile so far. In recent study, it is considered that the spatial position of the participating nucleons fluctuates geometrically and it leads to higher harmonic deformation. This spatial fluctuation is converted to momentum space by the collective expansion and then higher harmonic flow \( v_n \) is created.

Azimuthal distribution of emitted particles is written as the following:

\[
\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{2} 2v_n \cos(n(\phi - \Phi_n)) \tag{1}
\]

\[
v_n = \langle \cos(n(\phi - \Phi_n)) \rangle \tag{2}
\]

where \( n \) indicates the harmonic order, \( \phi \) and \( \Phi_n \) denote the azimuthal angle of emitted particles and event plane for each harmonic orders. The flow strength \( v_n \) is represented as the Fourier coefficient. The event planes are determined by the Reaction Plane Detector which covers \( 1.0 < |\eta| < 2.8 \) and charged particles are measured by the PHENIX central detectors with \( |\eta| < 0.35 \) in this analysis. Charged hadron \( v_n \) have been measured at PHENIX [1], where \( v_2 \) increases from central to peripheral collisions, while \( v_3 \) doesn’t seems to have centrality
dependence. It indicates that $v_3$ mainly comes from the initial fluctuation. Though some theoretical models with different initial conditions can explain $v_2$ well, some of them fail to explain $v_3$. So $v_3$ provides the new constraints on the theoretical models. It is expected that $v_n$ for identified particles will provide more constraints on the theoretical models.

2. Higher harmonic flow

Figure 1 shows higher harmonic flow of $\pi^\pm$, $K^\pm$ and $p(\bar{p})$ as a function of $p_T$ in 0-50% in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions. The measured $v_4(\Phi_2)$ with respect to 2\textsuperscript{nd} ord event plane is also shown. Green bands indicate $p_T$ correlated systematic uncertainties. The shown $v_3(\Phi_3)$, $v_4(\Phi_4)$ and $v_4(\Phi_2)$ are multiplied by factor, 1.5, 1.5 and 5.0 respectively when plotted in Fig.1. Each $v_n$ for different species shows same trends. Particle mass dependence at low $p_T$ and baryon/meson difference at mid $p_T$ can be seen in $v_3, v_4$ as well as $v_2$. It is considered that higher harmonic flow shows the behavior like the hydrodynamics at low $p_T$ region, and described by the quark recombination model at mid $p_T$ region as well as $v_2$.

![Figure 1](image_url)

Figure 1. (Color online)$v_2(\Phi_2), v_3(\Phi_3), v_4(\Phi_4)$ and $v_4(\Phi_2)$ of $\pi^\pm, K^\pm$ and $p(\bar{p})$ as a function of $p_T$ in 0-50%. Green bands indicate $p_T$ correlated systematic uncertainties. $v_3$ and $v_4$ are plotted after being multiplied by scale factors.

Figure 2 shows the modified $n_q$ scaling of higher harmonic flow as a function of $KE_T/n_q$, where $n_q$ is the number of constituent quark, $KE_T = (p_T^2 + m_0^2)^{1/2} - m_0$, $m_0$ is the particle mass, and $v_n$ is scaled by $n_q^{1/2}$ using higher harmonic order n. The modified $n_q$ scaling succeeds to scale $v_n$. It indicates that higher harmonic flow $v_n$ also arises at partonic level.

In the PHENIX experiment, charged pions and protons can be identified up to $p_T = 6$ GeV/c and kaons up to $p_T = 4$ GeV/c by combining Time-Of-Flight detector and Aerogel Cherenkov Counter. Figure 3 shows PID $v_2$ as functions of $p_T$, $KE_T/n_q$ and $p_T/n_q$ for two different centrality bins. $KE_T/n_q$ scaling works better than $p_T/n_q$ scaling in central collisions. However, it breaks for protons at $KE_T/n_q \approx 1.0$ GeV in non-central collisions. It is considered that particle production at $p_T > 4$ GeV/c is not dominated by quark recombination, but by jet energy loss. So this result may give us any information on the interplay between the recombination and jet energy loss at high $p_T$ region.
3. Two particle correlations

Two particle azimuthal correlations have been measured in heavy ion collisions to study the interaction between hard-scattered partons and the hot and dense matter. In recent studies, it is considered that higher harmonic flow will be a possible source of "ridge" and "march cone" [2], which are the long range $\Delta \eta$ correlations at near side and double hump structure at away side. Figure 4 shows the recent result of the two particle correlations for charged hadrons with $p_T^{\text{TRIG}}=2-4$ GeV/$c$ and $p_T^{\text{ASSOC}}=1-2$ GeV/$c$ for $|\Delta \eta| < 0.7$ in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions, where $v_2$, $v_3$, $v_4$ backgrounds are subtracted by ZYAM method [3]. In most central collisions, away side yield is suppressed, while the yield and double hump structure still remain in moving to mid central collisions. It is difficult to explain the structure only by higher harmonic flow $v_n$.

Figure 2. (Color online) $v_2(\Phi_2)$, $v_3(\Phi_3)$, $v_4(\Phi_4)$ and $v_4(\Phi_2)$ divided by $n_q^{n/2}$ of $\pi^{\pm}, K^{\pm}$ and $p(\bar{p})$ as a function of $KE_T/n_q$ in 0-50%, where n and $n_q$ denote harmonic order and the number of constituent quarks of hadrons. Green bands indicate $p_T$ correlated systematic uncertainties.

Figure 3. (Color online) $v_2$ of $\pi^{\pm}, K^{\pm}$ and $p(\bar{p})$ with and without $n_q$ scaling

Figure 4. Two particle correlations for charged hadrons with $p_T^{\text{TRIG}}=2-4$ GeV/$c$ and $p_T^{\text{ASSOC}}=1-2$ GeV/$c$ for $|\Delta \eta| < 0.7$ in Au+Au 200 GeV collisions, where $v_2$, $v_3$, $v_4(\Phi_4)$ background are subtracted by ZYAM method [3].
4. Azimuthal HBT measurement

HBT measurement is a powerful tool to study the space-time evolution of particle emitting source. Azimuthal HBT radii with respect to 2nd-order event plane have been measured for charged pions and kaons to investigate the source shape at freeze-out at PHENIX [4]. The result shows that final eccentricity of kaons defined as \( \varepsilon_{\text{final}} = 2R_{s,2}/R_{s,0}^2 \) [5] is larger than that of pions and almost the same as the initial eccentricity. However, since HBT radii show a transverse mass (\( m_T \)) dependence and average \( m_T \) of pions and kaons are different, the \( m_T \) dependence needs to be considered in the comparison of the final eccentricities. Figure 5 shows the relative amplitude of azimuthal HBT radii of charged pions and kaons as a function of average \( m_T \) for two centrality bins in \( \sqrt{s_{NN}} = 200 \) GeV Au+Au collisions. Left top panel shows final eccentricity, and there is still difference between pions and kaons in non-central collisions even at the same \( \langle m_T \rangle \). The difference may indicate faster freeze-out of kaons due to the lower cross section. The relative amplitude of \( R_o \) and \( R_{os} \) at low \( m_T \) in most central collisions have finite value though final eccentricity is close to zero. This result may indicate a temporal variation of emission duration of particles because \( R_o \) and \( R_{os} \) have temporal information in addition to geometrical information.

![Figure 5.](image)

Figure 5. (Color online) Relative amplitude of azimuthal HBT radii of charged pions and kaons as a function of average \( m_T \) for 2 centrality bins. Left top panel corresponds to final eccentricity.

5. Summary

Recent results on higher harmonic flow for identified particles, two particle correlations with the background subtraction from higher harmonic flow and \( m_T \) dependence of azimuthal HBT measurement are presented. There are still some open questions about each of the topics discussed and further study in experiment and theory will be needed to understand them.

References
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