Transverse momentum dependent decorrelation in Pb-Pb collisions at LHC

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(Dated: April 8, 2020)

Based on a Multi-Phase Transport (AMPT) model simulations, the transverse momentum dependent decorrelation has been studied in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, respectively. It has found that the Factorization ratio $r_{m,n}$ value deviates significantly from unity in non-central collisions. Such effect becomes stronger with an increasing the $p_T$ difference $p_T^a - p_T^b$. These decorrelation is not only for the same order harmonic flow but also for the difference order harmonic flow. It has also found that the correlations involving higher powers of the flow vector yield stronger decorrelation, $r_{m,n;3} < r_{m,n;2} < r_{m,n;1}$ ($m = 2, 3$), except for the weighted factorization ratio $r_{3|4,k}$.

I. INTRODUCTION

The primary goal of ultra relativistic heavy-ion collisions is to understand the matter properties of Quark-Gluon Plasma (QGP), whose is produced in extreme conditions has been predicted by the Quantum Chromodynamics [1]. Anisotropic harmonics flow plays a major role in probing the properties of the QGP at the Relativistic Heavy Ion Collider (RHIC) at BNL [2] and Large Hadron Collider (LHC) at CERN [3]. The realization of higher order harmonics flow and its fluctuations [4], the correlation between the magnitude and phase of different order harmonics [5–7] and the transverse momentum and pseudorapidity dependence of event plane angles [8] has led to a good understanding of the initial fluctuating states and the properties of the strong QGP. Furthermore, the higher order harmonics ($n > 3$) can arise from initial fluctuating anisotropies in the same order harmonic (denoted linear response) or can be driven by lower order harmonics (denoted non-linear response) [9–12]. These mixed higher order harmonics $v_4\{\Psi_{22}\}, v_5\{\Psi_{23}\}, v_6\{\Psi_{222}\}, v_6\{\Psi_{33}\}$, and the non-linear response coefficients $\chi_{422}, \chi_{532}, \chi_{6222}, \chi_{633}$ are weakly sensitive to the initial-state conditions and transport properties of the QGP [13–16].

The experiment has been indicated that the flow vector fluctuations was observed by the decomposition of Fourier harmonics of the two-particles azimuthal correlations [17]. To test the flow vector fluctuations, a useful observable is the factorization ratio, $r_{n,n}$, which encodes the correlations of flow harmonics at different transverse momenta or pseudorapidities [8, 18–26]. These correlation revealed that the factorization ratio is sensitive to fluctuations in the initial states and not strongly dependent on the viscosity of the system [27].

Hypothetically, the factorization ratio can be broken down for different order harmonics correlations as a consequence of the initial fluctuations driven decorrelation between the higher order harmonics with its’ lower order harmonics and the same lower order harmonic. Following this idea, the main purpose of this paper is to illustrate a particular picture on the initial fluctuation driven mixed harmonics flows decorrelation (denoted mixed order factorization ratio breaking) in Pb-Pb collisions at LHC.

II. MATERIALS AND METHODS

Starting from the $V_n$ estimators studied in Ref. [9, 13, 15], the harmonic flow can be expressed as a sum of the linear and non-linear modes,

$$V_4 = V_{4L} + \chi_{422}V_2^2,$$

$$V_5 = V_{5L} + \chi_{532}V_2V_3.$$

where $V_{nL}$ denotes the linear part of $V_n$ ($n = 4, 5$) that is not induced by lower-order harmonics [11], and the $\chi$ are the nonlinear response coefficients, characterizing the non-linear flow mode induced by the lower order harmonics. More higher order $V_n$ ($n > 5$) are also shown in Ref. [15].

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The mixed higher-order harmonics in each $p_T$ range are extracted using the scalar-product method as shown in Ref. [14], which describe by a $Q$-vector, as

$$V_1 \{ \Psi_{22} \} (p_T) = \frac{\text{Re} \langle Q_4(p_T)Q_{2B}^*Q_{2B}^* \rangle}{\sqrt{\text{Re} \langle Q_{2A}Q_{2A}^*Q_{2B}^*Q_{2B}^* \rangle}};$$

$$V_5 \{ \Psi_{32} \} (p_T) = \frac{\text{Re} \langle Q_5(p_T)Q_{3B}^*Q_{3B}^* \rangle}{\sqrt{\text{Re} \langle Q_{3A}Q_{3A}^*Q_{3B}^*Q_{3B}^* \rangle}}.$$  \hspace{1cm} (2)

Here, $Q_{nA}$ and $Q_{nB}$ are vectors from two different parts of a single event with particles range in a positive or negative pseudorapidity region, $Q_n$ is the vector from charged particles in each $p_T$ range within a mid-pseudorapidity region, and angle brackets denote the average over all events within a given centrality range.

Similar to the mixed higher-order flow harmonics, the non-linear response coefficients in each $p_T$ range can be expressed as [14],

$$\chi_4 \{ \Psi_{22} \} (p_T) = \frac{\text{Re} \langle Q_4(p_T)Q_{2B}^*Q_{2B}^* \rangle}{\sqrt{\text{Re} \langle Q_{2Atrk}Q_{2Atrk}Q_{2B}^*Q_{2B}^* \rangle}};$$

$$\chi_5 \{ \Psi_{32} \} (p_T) = \frac{\text{Re} \langle Q_5(p_T)Q_{3B}^*Q_{3B}^* \rangle}{\sqrt{\text{Re} \langle Q_{3Atrk}Q_{3Atrk}Q_{3B}^*Q_{3B}^* \rangle}}.$$  \hspace{1cm} (3)

Where $Q_{nAtrk}$ is chosen the same pseudorapidity region with $Q_n$.

Correlations between $Q_n$ of different harmonics represent higher order correlations which can provide crucial information on the initial-state and its’ fluctuations of the medium. One observable to probe the $p_T$ dependent flow vector fluctuations is the factorization ratio, $r_{n,n}$ [18, 19, 24]. It can be calculated using the two-particle Fourier harmonic by the same order. To test the mixed harmonics flows decorrelation, a mix-order factorization ratio $r_{m,n}$, are expressed as

$$r_{m,n}(p_T^a, p_T^b) = \frac{V_{m,n}(p_T^a, p_T^b)}{\sqrt{V_{m,m}(p_T^a, p_T^b)V_{n,n}(p_T^b, p_T^b)}};$$

$$V_{m,n}(p_T^a, p_T^b) = \langle Q_m(p_T^a)Q_n^*(p_T^b) \rangle.$$  \hspace{1cm} (4)

Where $V_{m,n}$ is the $m^{th}$- and $n^{th}$-order Fourier harmonic of the two-particle azimuthal correlations of the triggered and associated particles from $p_T^a$ and $p_T^b$. To avoid self-correlation, the triggered particles (denoted $p_T^a$) are always selected from the positive pseudorapidity region and the associated particles (denoted $p_T^b$) are from the negative pseudorapidity region. A pseudorapidity gap is applied between $p_T^a$ and $p_T^b$ to suppress non-flow effects. In that case $r_{m,n}(p_T^a, p_T^b) \leq 1$ means that the harmonic flow at the transverse momenta $p_T^a$ and $p_T^b$ is partially decorrelated. This decorrelation can be due to the flow vector fluctuations both of flow magnitude and flow phase decorrelation [8] were generated by initial event-by-event geometry fluctuation.

Correlators of higher powers of the same order flow in two different $p_T$ bins has been calculated by Hydrodynamic [24]. Naturally, a mix-order factorization ratio weighted with different powers of $Q_n$ can be defined as

$$r_{m|n;k}(p_T^a, p_T^b) = \frac{V_{m|n;k}(p_T^a, p_T^b)}{\sqrt{V_{m|m;k}(p_T^a, p_T^a)V_{n|n;k}(p_T^b, p_T^b)}};$$

$$V_{m|n;k}(p_T^a, p_T^b) = \langle Q_m(p_T^a)^kQ_n^*(p_T^b)^k \rangle.$$  \hspace{1cm} (5)

For $k = 1$ one recovers the factorization ratio Eq. (4) $r_{m|1}(p_T^a, p_T^b) = r_{m,n}(p_T^b, p_T^b)$.

In this proceeding, the $p_T$-dependent factorization ratio is investigated in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV for the produced charged particles with the AMPT model [28], respectively. Base on AMPT event-by-event simulation [28], this paper present the factorization ratio by used the scalar-product method [14].

### III. RESULTS

Fig. 1 depicts the estimated magnitude of harmonic flow $v_n$ $(n = 4, 5)$ as a function of $p_T$ in 20-60% Pb-Pb collisions at 2.76 and 5.02 TeV from AMPT event-by-event simulations (colored band), respectively. Here, $Q_{nA}$ ($Q_{nB}$) are particles range in pseudorapidity region $2.9 < \eta < 5.2$ ($-5.2 < \eta < 2.9$), $Q_n$ is charged particles range in pseudorapidity region $|\eta| < 2.4$. It shows that the results of AMPT calculations on Pb-Pb systems are agree with the CMS [14] data with error bars. In Fig. 1,
FIG. 1: (Color online) The magnitude of harmonic flows $v_n$ ($n = 4, 5$) as a function of $p_T$ in 20-60% Pb-Pb collisions at 2.76 and 5.02 TeV from AMPT simulations (colored band), respectively. AMPT results are compared with the CMS [14] data (red points and black points).

FIG. 2: (Color online) Non-linear response coefficients $\chi_n$ ($n = 4, 5$) as a function of $p_T$ in 20-60% Pb-Pb collisions at 2.76 and 5.02 TeV from AMPT simulations (colored band), respectively. AMPT results are compared with the CMS [14] data (red points and black points).

The effect of $v_n$ ($n = 4, 5$) increases with transverse momentum increasing, is understood as a consequence of the degree of interaction in the proceeding of transport.

Fig. 2 shows that the non-linear response coefficients $\chi_n$ ($n = 4, 5$) as a function of $p_T$ in 20-60% Pb-Pb collisions at 2.76 and 5.02 TeV from AMPT event-by-event simulations (colored band), respectively. AMPT calculations on Pb-Pb systems are compatible with the CMS [14] data for the presented centrality class. In Fig. 2, the $\chi_n$ are increases with transverse momentum increasing. The $p_T$ dependent $\chi_n$ is quite different than the results of $p_T$ independent $\chi_n$ in Ref. [15] where are calculated by difference sub-events in the scalar-product method.

One study for $p_T$ dependent flow vector fluctuations can be via the observable of the factorization ratio, $r_{m,n}$. The results of $r_{m,n}$ are presented in Fig. 3 as a function of the $p_T$ difference $p_T^a - p_T^b$ with $|\Delta \eta| > 2$ in 40-50% Pb-Pb collisions at 2.76 and
FIG. 3: (Color online) Factorization ratio $r_{m,n}$ as a function of $p_T$ in 40-50% Pb-Pb collisions at 2.76 and 5.02 TeV from AMPT simulations (colored band), respectively. The simulate results are compared with the 2.76 TeV on CMS data (red points).
FIG. 4: (Color online) The weighted factorization ratio $r_{2|n,k}$ as a function of $p_T$ in 40-50% Pb-Pb collisions at 2.76 and 5.02 TeV, respectively. Up panels: 2.76 TeV for Pb-Pb collisions. Down panels: 5.02 TeV for Pb-Pb collisions.

FIG. 5: (Color online) Similar distributions as shown in Fig. 4, but for the weighted factorization ratio $r_{3|n,k}$.

5.02 TeV from AMPT event-by-event simulations (colored band), respectively. AMPT results are compared with the CMS [8] data (red points) at 2.76 TeV. In Fig. 3, the factorization ratio $r_{m,n}$ is significantly deviate from unity in non-central collisions. This effect has becomes stronger with an increasing the $p_T$ difference $p_T^a - p_T^b$. It is indicated that $p_T$ dependent flow vector are significant fluctuating in the presented $p_T$ range. From Fig. 3, it shows that the Factorization ratio broken effect is not only for the same order harmonic flow but also for the difference order harmonic flow. These decorrelation can be found in the difference order harmonic flow, e.g. $r_{2,4}$, $r_{2,5}$ and $r_{3,5}$. Note that the higher order harmonic flow are defined by the linear
same order harmonic and the non-linear lower order harmonics in Eq. (1), as a result, correlations of the higher order harmonic with its non-linear lower order harmonic and the same lower order harmonic can be decorrelate due to the initial fluctuations. Furthermore, the decorrelation is weakly dependent on the collision energy.

Fig. 4 and Fig. 5 shows that the weighted factorization ratio \( r_{m,n;k} \) as a function of \( p_T \) in 40-50% Pb-Pb collisions at 2.76 and 5.02 TeV from AMPT event-by-event simulations, respectively. In Fig. 4, the up panels are results of \( r_{2|n;k} \) for 2.76 TeV on Pb-Pb collisions and the down panels are results of \( r_{2|n;k} \) for 5.02 TeV on Pb-Pb collisions, respectively. The charged trigger particles are chosen region in \( 2.4 < p_T^b < 3.0 \) GeV/c. It has found that both ratios not agree with unity over the presented \( p_T^b \) range. The correlations involving higher powers of the flow vector yield stronger decorrelation, \( r_{2|n;3} < r_{2|n;2} < r_{2|n;1} \) where is shown in Fig. 4. Similar distributions for the weight factorization coefficient \( r_{3|n;k} \) is also shown in Fig. 5. From Fig. 5, the correlations involving higher powers of the flow vector yield also stronger decorrelation, \( r_{3|n;3} < r_{3|n;2} < r_{3|n;1} \), except for the weighted factorization ratio \( r_{3|4;k} \).

### IV. SUMMARY

Base on AMPT event-by-event calculations, this paper has carried out the \( p_T \) dependent \( v_n \) (\( n = 4, 5 \)) and \( r_{m,n} \) by AMPT simulations in non-central Pb-Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) and 5.02 TeV, respectively. The results of AMPT calculations on Pb-Pb systems are compatible with the CMS data within error bars. By AMPT simulations, it has found that the Factorization ratio \( r_{m,n} \) value deviates significantly from unity in non-central collisions. Such effect becomes stronger with an increasing the \( p_T \) difference \( p_T^b - p_T^f \). These Factorization ratio broken effect is not only for the same order harmonic flow, but also for the difference order harmonic flow, as a result of initial fluctuations driven decorrelation between the higher order harmonic with its non-linear lower order harmonic and the same lower order harmonic. It has also found that the correlations involving higher powers of the flow vector yield stronger decorrelation, \( r_{m|n;3} < r_{m|n;2} < r_{m|n;1} \) (\( m = 2, 3 \)), except for the weighted factorization ratio \( r_{3|4;k} \).

### Acknowledgements

This work was supported by the Youth Program of Natural Science Foundation of Guangxi (China), with Grant No. 2019GXNSFBA245080, the Special fund for talentes of Guangxi (China), with Grant No. GuiKeAD19245157, and also by the Doctor Startup Foundation of Guangxi University of Science and Technology, with Grant No. 19Z19.

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