New measures of longitudinal decorrelation of harmonic flow

Piotr Bożek
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, aleja Mickiewicza 30, 30-059 Krakow, Poland

Wojciech Broniowski
The H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, 31-342 Cracow, Poland
Institute of Physics, Jan Kochanowski University, 25-406 Kielce, Poland

Abstract
Harmonic flow in relativistic heavy-ion collisions is observed in a broad range of rapidities, and the flow at different rapidities is correlated. However, fluctuations lead to a small decorrelation of the harmonic flow magnitudes and flow angles at different rapidities. Using a hydrodynamic model with Glauber Monte Carlo initial conditions we show that the flow angle decorrelation strongly depends on the flow magnitude in the event. We propose observables to measure this effect in experiment.

Keywords: Heavy-ion collisions, collective flow, hydrodynamic model

1. Introduction
The expansion of the fireball created in relativistic heavy-ion collisions generates a collective flow of matter. Azimuthal asymmetry of the initial fireball generates harmonic components in the azimuthal distribution of emitted particles. The most important observables are the elliptic ($v_2$) and triangular ($v_3$) flow coefficients. Without fluctuations in the longitudinal direction, the initial shape of the fireball in the transverse plane is similar at different rapidities. This means that the pattern of azimuthally asymmetric collective flow repeats itself in a similar way at different rapidities as well.

Event by event fluctuations break this symmetry of the flow orientation [1]. This is expected, as event by event distributions of the forward- and backward-going participant nucleons are different. Such fluctuations in the initial state cause a torque on the initial fireball (Fig. 1 left panel). The torque angle in the orientation of the fireball asymmetry fluctuates from even to event. In each event the flow angle for a given harmonic changes slightly with rapidity. Obviously, this effect cannot be observed on event by event basis. On the
other hand, the average correlation between the flow vectors,

\[ q_n(\eta) = \frac{1}{m} \sum_{k=1}^{m} e^{i \omega n \eta_k} \equiv V_n(\eta)e^{i \omega n \Psi_n(\eta)}, \]

measured in two pseudorapidity intervals at \( \pm \eta \),

\[ r_n(\eta) = \frac{\langle q_n(\eta)q_n^*(\eta) \rangle}{\sqrt{\langle q_n(\eta)q_n^*(\eta) \rangle \langle q_n(\eta)q_n^*(\eta) \rangle}}, \]

can be measured.

The coefficient \( r_n(\eta) \) is smaller than 1 and decreases as \( \eta \) increases (Fig. 1, right panel). Unfortunately, this quantity is strongly influenced by non-flow correlations [1]. The CMS Collaboration proposed to use a correlator defined using 3 pseudorapidity bins,

\[ r_{n;1}(\eta) = \frac{\langle q_n(-\eta)q_n^*(\eta_{ref}) \rangle}{\langle q_n(\eta)q_n^*(\eta_{ref}) \rangle}, \]

which reduces non-flow contributions [2]. The decorrelation of flow (factorization breaking) in rapidity has been confirmed experimentally using the 3 bin correlator.

2. Magnitude and flow angle decorrelation

The correlator defined in Eq. (3) combines two types of harmonic flow decorrelation [3]. The first one is the decorrelation of the flow magnitude in separate pseudorapidity intervals. This effect means that in an ensemble of events a strong flow in one interval does not always come together with a strong flow in the other interval. The second effect measured by (4) is the cosine of the torque angle, i.e. of the the decorrelation of the flow angles in the two intervals, \( \Delta \Psi_n = \Psi_n(\eta) - \Psi_n(\eta_{ref}) \). The two effects can be estimated separately using additional correlators of harmonic flows in 3 or 4 pseudorapidity intervals [4].

The 4 bin correlator

\[ R_n(\eta) = \frac{\langle q_n(\eta)q_n^*(\eta_{ref})q_n(\eta)q_n^*(\eta_{ref}) \rangle}{\langle q_n(\eta)q_n^*(\eta)q_n(\eta)q_n^*(\eta) \rangle} \simeq 1 - 2F_{n,2}^{asy} \eta \]

measures the flow component, whereas the 3 bin correlator

\[ r_{n,2}(\eta) = \frac{\langle q_n(-\eta)^2 q_n^*(\eta_{ref})^2 \rangle}{\langle q_n(\eta)^2 q_n^*(\eta_{ref})^2 \rangle} \simeq 1 - 2F_{n,2}^{asy} - 2F_{n,2}^{tor} \eta \]

measures the torque angle and magnitude decorrelations combined. Measurements by the ATLAS Collaboration [5] have shown that the magnitude of the two components for the decorrelation is similar, \( F_{n,2}^{tor} \approx F_{n,2}^{asy} \).
3. Torque angle dependence on flow magnitude

The decorrelation of the harmonic flow magnitude and angle can be studied separately in the hydrodynamic model [6]. In the model, the angle and the magnitude of the collective flow can be estimated in each event. Besides the experimental observable $r_{n,1}(\eta)$ (Eq. [4]) one can calculate the torque angle decorrelation

$$\frac{\langle \cos(n(\Psi_n(-\eta) - \Psi_n(\eta_{ref}))) \rangle}{\langle \cos(n(\Psi_n(\eta) - \Psi_n(\eta_{ref}))) \rangle}$$

and the magnitude decorrelation

$$\frac{\langle v_n(-\eta) v_n(\eta_{ref}) \rangle}{\langle v_n(\eta) v_n(\eta_{ref}) \rangle}$$
directly. The results shown in Fig. 2 are quite surprising; one observes a sort of inverted hierarchy. The torque angle decorrelation is the largest, larger than the magnitude and torque angle correlation combined. Interestingly, a very similar result has been obtained recently in a hybrid model using hydrodynamics with the AMPT initial conditions [7].

This inverted hierarchy can be explained by the fact that the torque angle decorrelation (Eq. 6) is effectively weighted by a higher power of \( v_n \) than the correlator \( r_{n\eta}(\eta) \). It turns out that the magnitude of the flow coefficient \( V_n \) is strongly anticorrelated with the magnitude of the torque angle. In events with a large overall harmonic flow, the torque angle is smaller (\( \cos(\Delta \Psi_2) \)) close to 1 in Fig. 4). It turns out that the magnitude of the flow coefficient \( V_n \) is strongly anticorrelated with the magnitude of the torque angle. In events with a small magnitude of harmonic flow, the torque angle distribution is wider (\( \cos(\Delta \Psi_2) \)) than the correlator combined.

Experimentally, event by event correlation between the flow magnitude and the torque angle can be demonstrated using a series of correlators weighted with different powers of \( v_n \).

\[
t_{n\eta}^{2k}(\eta) = \frac{\langle n^{2k}(0) q^v_n(-\eta) q_p^v(\eta) \rangle}{\langle n^{2k}(0) q_p^v(\eta) q^v_n(\eta) \rangle}.
\]

(8)

for \( k = 0, 1, 2, \ldots \). The case \( k = 0 \) corresponds to the standard correlator \( t_{n\eta}(\eta) \). The model predicts a weaker decorrelation (correlator closer to 1) when weighting with higher powers of \( v_n \) (Fig. 4). It would be interesting to measure this correlation in experiment.

Acknowledgments

Research supported by the AGH UST statutory funds, by the National Science Centre grant 2015/17/B/ST2/00101 (PB) and grant 2015/19/B/ST2/00937 (WB).

References

[1] P. Bozek, W. Broniowski, J. Moreira, Phys. Rev. C83 (2011) 034911. doi:10.1103/PhysRevC.83.034911
[2] V. Khachatryan, et al., Phys. Rev. C92 (2015) 034911. doi:10.1103/PhysRevC.92.034911
[3] J. Jia, P. Huo, Phys. Rev. C90 (2014) 034905. doi:10.1103/PhysRevC.90.034905
[4] J. Jia, P. Huo, G. Ma, M. Nie, J. Phys. G44 (2017) 075106. doi:10.1088/1361-6471/aa74c3
[5] M. Aaboud, et al., Eur. Phys. J. C78 (2018) 142. doi:10.1140/epjc/s10052-018-5805-7
[6] P. Bozek, W. Broniowski, Phys. Rev. C97 (2018) 034913. doi:10.1103/PhysRevC.97.034913
[7] X.-Y. Wu, L.-G. Pang, G.-Y. Qin, X.-N. Wang. arXiv:1806.03702.