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News on collectivity in Pb-Pb collisions from the ALICE experiment

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Abstract. The collective expansion of the color-deconfined fireball created in ultra-relativistic heavy-ion collisions maps the initial state of the quark-gluon plasma (QGP) to the final-state particle spectrum. The ALICE experiment has been leading important roles for completing the individual flow harmonic measurements at the highest energies to date as well as improving flow harmonic correlation techniques to understand the properties of the QGP and the full evolution of the heavy-ion collisions. In this article, a brief summary of the individual flow harmonic measurements, the details of the new observables developed in recent years from ALICE collaboration and their implications to future studies are discussed.

1 Introduction

The main emphasis of the ultra-relativistic heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) is to study deconfined phase of the strongly interacting nuclear matter, the Quark-Gluon Plasma (QGP). This matter exhibits strong collective and anisotropic flow in the plane transverse to the beam direction, which is driven by the anisotropic pressure gradients, resulting in more particles emitted in the direction of the largest gradients. The large elliptic flow discovered at RHIC energies [1] continues to increase also at LHC energies [2, 3]. This has been predicted by calculations utilizing viscous hydrodynamics [4–9]. These calculations also demonstrated that the shear viscosity to the entropy density ratio (η/s) of QGP is close to a universal lower bound $1/4\pi$ [10] in heavy-ion collisions at RHIC and LHC energies.

The temperature dependence of the η/s has some generic features that most of the known fluids obey. For instance, one such general behavior is that the ratio typically reaches its minimum value close to the phase transition region [11]. It was shown, using kinetic theory and quantum mechanical considerations [12], that $\eta/s \sim 0.1$ would be the correct order of magnitude for the lowest possible shear viscosity to entropy ratio value found in nature. Later it was demonstrated that an exact lower bound $(\eta/s)_{\rm min} = 1/4\pi \approx 0.08$ can be calculated using the AdS/CFT correspondence [10]. Hydrodynamical simulations support as well the view that the QGP matter is close to that limit [8]. This in turn may have important implications for other fundamental physics goals. It is argued that such a low value might imply that thermodynamic trajectories for the expanding matter would lie close to the quantum chromodynamics (QCD) critical end point, which is another subject of intensive experimental quest [11].

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Anisotropic flow [13] is traditionally quantified with harmonics v_n and corresponding symmetry plane angles Ψ_n in the Fourier series decomposition of the azimuthal particle distribution in the plane transverse to the beam direction [14]:

$$E\frac{\mathrm{d}^3N}{\mathrm{d}p^3} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\mathrm{T}\mathrm{d}p_\mathrm{T}\mathrm{d}\eta}\Big\{1 + 2\sum_{n=1}^{\infty} v_n(p_\mathrm{T},\eta)\cos[n(\varphi-\Psi_n)]\Big\}, \tag{1}$$

where E, N, p, p_T, φ and η are the energy, particle yield, total momentum, transverse momentum, azimuthal angle and pseudorapidity of particles, respectively, and Ψ_n is the azimuthal angle of the symmetry plane of the n^th-order harmonic. The n^th-order flow coefficients are denoted as v_n and can be calculated as $v_n = \langle\cos[n(\varphi-\Psi_n)]\rangle$, where the brackets denote an average over all particles in all events. The anisotropic flow in heavy-ion collisions is understood as the hydrodynamic response of produced matter to spatial deformations of the initial energy density profile [15]. This profile fluctuates event-by-event due to fluctuations of the positions of the constituents inside the colliding nuclei, which in turn implies that the flow also fluctuates [16, 17]. The recognition of the importance of flow fluctuations has led to measurements of triangular flow and higher flow harmonics [18, 19] as well as the correlations between different Fourier harmonics [20, 21]. The higher order harmonics are expected to be particularly sensitive to fluctuations in the initial conditions and to the η/s [22, 23], while correlations have the potential to discriminate the two respective contributions to anisotropic flow development [20].

However, difficulties on extracting η/s in heavy-ion collisions can be attributed mostly to the fact that it strongly depends on the specific choice of the initial conditions [4, 23, 24]. The viscous effects reduce the magnitude of the elliptic flow. Furthermore, the magnitude of η/s used in hydrodynamic model calculations should be considered as an average over the temperature history of the expanding fireball as it is known that η/s of other fluids depends on temperature. In addition, part of the elliptic flow can also originate from the hadronic phase [25–27]. Therefore, knowledge of both the temperature dependence and the relative contributions from the partonic and hadronic phases should be understood better to quantify η/s of the partonic fluid.

The ALICE experiment has been leading important roles for completing the individual flow harmonic measurements at the highest energies to date as well as improving flow harmonic correlation techniques to understand the properties of the QGP and the full evolution of the heavy-ion collisions. In this article, few selected results from recently published papers from the ALICE experiment are discussed in the following sections on the emphasis of extracting η/s.

2 Results

Firstly, we show the multiparticle observables, the Symmetric 2-harmonic 4-particle Cumulants (SC), which quantify the relationship between event-by-event fluctuations of two different flow harmonics [28]. These observables are particularly robust against few-particle non-flow correlations and they provide orthogonal information to recently analyzed symmetry plane correlators. It was demonstrated that they are sensitive to the temperature dependence of η/s of the expanding medium and therefore simultaneous descriptions of different order harmonic correlations would constrain both the initial conditions and the medium properties [28, 29]. These results are discussed in Sec. 2.1. Second, pseudorapidity dependent charge particle v_2, v_3 and v_4 are measured in wide range of pseudorapidity and shown in Sec. 2.2. These results can provide access to a range of varying medium properties, even at a fixed collision energy. Thirdly, the first results of the charged hadron v_n with the highest LHC beam energy are presented in Sec. 2.3.

2.1 Event-by-event fluctuations of two different flow harmonics

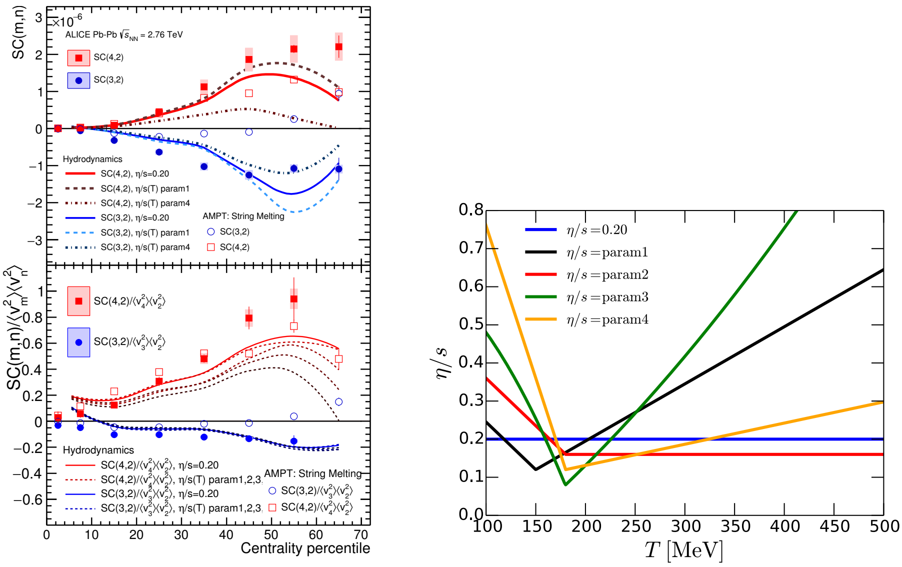

Figure 1. (Top Left) Comparison of observables SC(4,2) (red filled squares) and SC(3,2) (blue filled circles) to theoretical model from [30]. (Left Bottom) The results from top left panel have been rescaled with $\langle v_m^2\rangle\langle v_n^2\rangle$. (Right) The $\eta/s(T)$ parameterizations used in theoretical model [30].

The SC observables are defined as:

$$\begin{aligned}\langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle_c &= \langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle \\ &\quad -\langle\langle\cos[m(\varphi_1-\varphi_2)]\rangle\rangle\langle\langle\cos[n(\varphi_1-\varphi_2)]\rangle\rangle \\ &= \left\langle v_m^2v_n^2\right\rangle-\left\langle v_m^2\right\rangle\left\langle v_n^2\right\rangle, \qquad (2)\end{aligned}$$

with the condition $m \neq n$ for two positive integers m and n. The complete discussion can be found in Section IV C of Ref. [31]. SC(m,n) can be normalized with the product $\langle v_m^2\rangle\langle v_n^2\rangle$ to obtain *normalized* symmetric cumulants [28, 32]. Normalized symmetric cumulants reflect only the degree of the correlation which is expected to be insensitive to the magnitudes of v_m and v_n, while SC(m,n) contains both the degree of the correlations between two different flow harmonics and individual v_n harmonics. That products in the denominator are obtained with two-particle correlations and using a pseudorapidity gap of $|\Delta\eta| > 1.0$ to suppress biases from few-particle nonflow correlations. On the other hand, in the two two-particle correlations which appear in the definition of SC(m,n) in Eq. 2 the pseudorapidity gap is not needed, since nonflow is suppressed by construction in SC observable, as the study based on HIJING model has clearly demonstrated in Ref. [28].

The measurements of SC observables have revealed that fluctuations of v_2 and v_3 are anti-correlated, while fluctuations of v_2 and v_4 are correlated in all centralities as shown in Figure. 1 (Top Left). The comparison between experimental data and the theoretical calculations [30], which incorporate both the initial conditions and system evolution, is shown in Figure. 1 (Top Left). The model captures qualitatively the centrality dependence, but not quantitatively. Most notably, there is

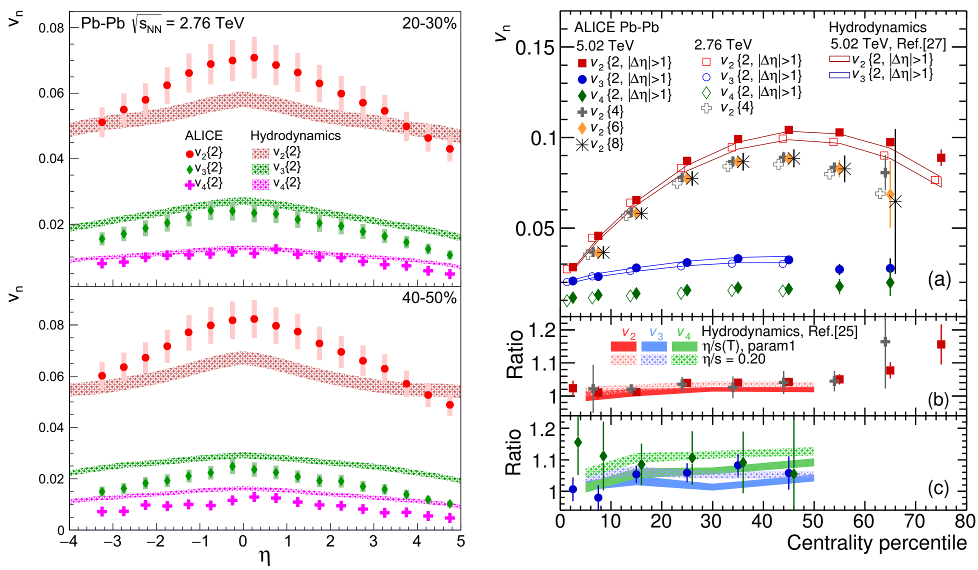

Figure 2. (Left) Comparisons to hydrodynamics predictions [33], where input parameters (temperature dependence of η/s) have been tuned to RHIC data for the Pb-Pb 20-30% (top) and 40-50% (Bottom) centralities. (Right) The first anisotropic flow measurements of charged particles in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.

no single centrality for which a given $\eta/s(T)$ parameterization describes simultaneously both SC(4, 2) and SC(3, 2). On the other hand, the same theoretical model captures quantitatively the centrality dependence of individual v_2, v_3 and v_4 harmonics with a precision better than 10% in central and mid-central collisions [30]. We therefore conclude that individual flow harmonics v_n and new SC(m, n) observables together provide a better handle on the initial conditions and $\eta/s(T)$ than each of them alone. This is further emphasized in Figure 1 (Bottom), where SC(3, 2) and SC(4, 2) observables were divided with the products $\left\langle v_3^2\right\rangle\left\langle v_2^2\right\rangle$ and $\left\langle v_4^2\right\rangle\left\langle v_2^2\right\rangle$, respectively. We have found that the normalized SC(4, 2) observable exhibits stronger sensitivity to different $\eta/s(T)$ parameterizations than the normalized SC(3, 2) observable, see Figure 1 (Bottom), and than the individual flow harmonics [30]. These findings indicate that the normalized SC(3, 2) observable is sensitive mainly to the initial conditions, while the normalized SC(4, 2) observable is sensitive to both the initial conditions and the system properties like η/s, which is consistent with the prediction from [20].

2.2 Moving forward to constrain the shear viscosity of QCD matter

ALICE recently published peudorapidity dependence of flow harmonics up to 4$^{\text{th}}$ order harmonics [34]. At forward rapidities, the system will spend less time in the QGP phase. This implies that the viscosity from the hadronic phase would play a greater role in affecting the flow harmonics [33, 35]. Therefore, the relative decrease of the flow harmonics in different η ranges may help to disentangle the viscous effects from the hadronic phase with those from the QGP phase. The results are shown on the left panel in Fig. 2, the shape of $v_n(\eta)$ is largely independent of centrality for all order harmonic coefficients measured (v_2, v_3 and v_4). The results are compared to hydrodynamic calculations tuned to RHIC data [33]. The tuning involves finding a parameterization of the temperature dependence of η/s, so that the hydrodynamical calculations describe PHOBOS measurements of $v_2(\eta)$ [36, 37]. It is clear that the same parameterization does not describe the LHC data. For both centralities shown on the left in Figure 2, the elliptic flow coefficient v_2 is generally underestimated, while the higher order coefficients v_3 and v_4 are overestimated. These results could provide better independent constraints for the initial state fluctuations in three-dimensional space and $\eta/s(T)$ even at a fixed collision energy.

2.3 Anisotropic flow of charged particles at $\sqrt{s_{NN}}$=5.02 TeV

We have presented the first anisotropic flow measurements of charged particles in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 from the data taken in November 2015 in Run 2 at the LHC in Figure 2 [3]. Only one low luminosity run (with trigger rate of 27 Hz) was used, being least affected by pile-up and distortions from space charge in the main tracking detector, the Time Projection Chamber (TPC). In the right panel of Figure 2 (a), the centrality dependence of v_2, v_3 and v_4 is presented from two- and multi-particle cumulants, integrated over the $p_{\rm T}$ range $0.2 < p_{\rm T} < 5.0$ GeV/c, for 2.76 and 5.02 TeV Pb–Pb collisions. To elucidate the energy evolution of v_2, v_3 and v_4, the ratios of anisotropic flow measured at 5.02 TeV to 2.76 TeV are presented in Figure 2 right panel (b) and (c). The predictions of anisotropic flow coefficients v_n from the hydrodynamic model [38] are compared to the measurements in Figure 2. (a). The predictions are compatible with the measured anisotropic flow v_n coefficients. At the same time, a different hydrodynamic calculation [39], which employs both constant $\eta/s = 0.20$ and temperature dependent η/s, can also describe the increase in anisotropic flow measurements of v_2. The increase of v_2 and v_3 from the two energies is rather moderate, while for v_4 it is more pronounced. An increase of (3.0±0.6)%, (4.3±1.4)% and (10.2±3.8)%, is obtained for elliptic, triangular and quadrangular flow, respectively, over the centrality range 0–50% in Pb–Pb collisions when going from 2.76 TeV to 5.02 TeV.

3 Summary

The ALICE experiment continues to play a critical role for completing the individual flow harmonic measurements at the highest energies to date. We are improving flow harmonic correlation techniques to understand the properties of the QGP and the full evolution of the heavy-ion collisions i.e different order flow harmonic correlations and peudorapidity dependence of flow harmonics. The different order flow harmonic correlation measurements provide strong constraints on the temperature dependence of the shear viscosity to the entropy density ratio in hydrodynamics in combination with the individual flow harmonics. Pseudorapidity dependence of $v_{2,3,4}$ results can provide access to a range of varying medium properties, even at a fixed collision energy. The individual flow harmonics with the highest LHC energy were measured and show a quantitative agreement with various models. Many analyses with Run2 Pb-Pb data with the full statistics are underway and the statistical and systematic errors will be reduced in the future to give valuable inputs to model calculations with discriminating powers on initial conditions and the transport properties of nuclear matter in heavy-ion collisions.

References

[1] K.H. Ackermann et al. (STAR), Phys. Rev. Lett. **86**, 402 (2001), nucl-ex/0009011
[2] K. Aamodt et al. (ALICE), Phys. Rev. Lett. **105**, 252302 (2010), 1011.3914
[3] J. Adam et al. (ALICE), Phys. Rev. Lett. **116**, 132302 (2016), 1602.01119
[4] P. Romatschke, U. Romatschke, Phys. Rev. Lett. **99**, 172301 (2007), 0706.1522
[5] C. Shen, U. Heinz, P. Huovinen, H. Song, Phys. Rev. **C84**, 044903 (2011), 1105.3226
[6] B. Schenke, S. Jeon, C. Gale, J. Phys. **G38**, 124169 (2011)

[7] P. Bozek, I. Wyskiel-Piekarska, Phys. Rev. **C85**, 064915 (2012), 1203.6513
[8] Phys. Rev. Lett. **110**, 012302 (2013), 1209.6330
[9] T. Hirano, P. Huovinen, Y. Nara, Phys. Rev. **C84**, 011901 (2011), 1012.3955
[10] P. Kovtun, D.T. Son, A.O. Starinets, Phys. Rev. Lett. **94**, 111601 (2005), hep-th/0405231
[11] R.A. Lacey, N.N. Ajitanand, J.M. Alexander, P. Chung, W.G. Holzmann, M. Issah, A. Taranenko, P. Danielewicz, H. Stoecker, Phys. Rev. Lett. **98**, 092301 (2007), nucl-ex/0609025
[12] P. Danielewicz, M. Gyulassy, Phys. Rev. D **31**, 53 (1985)
[13] J.Y. Ollitrault, Phys. Rev. **D46**, 229 (1992)
[14] S. Voloshin, Y. Zhang, Z. Phys. **C70**, 665 (1996), hep-ph/9407282
[15] S. Floerchinger, U.A. Wiedemann, A. Beraudo, L. Del Zanna, G. Inghirami, V. Rolando, Phys. Lett. **B735**, 305 (2014), 1312.5482
[16] M. Miller, R. Snellings (2003), nucl-ex/0312008
[17] B. Alver et al. (PHOBOS), Phys. Rev. Lett. **98**, 242302 (2007), nucl-ex/0610037
[18] B. Alver, G. Roland, Phys. Rev. **C81**, 054905 (2010), [Erratum: Phys. Rev.C82,039903(2010)], 1003.0194
[19] K. Aamodt et al. (ALICE), Phys. Rev. Lett. **107**, 032301 (2011), 1105.3865
[20] H. Niemi, G.S. Denicol, H. Holopainen, P. Huovinen, Phys. Rev. **C87**, 054901 (2013), 1212.1008
[21] G. Aad et al. (ATLAS), Phys. Rev. **C90**, 024905 (2014), 1403.0489
[22] B.H. Alver, C. Gombeaud, M. Luzum, J.Y. Ollitrault, Phys. Rev. **C82**, 034913 (2010), 1007.5469
[23] M. Luzum, J.Y. Ollitrault, Nucl. Phys. **A904-905**, 377c (2013), 1210.6010
[24] C. Shen, S.A. Bass, T. Hirano, P. Huovinen, Z. Qiu, H. Song, U. Heinz, J. Phys. **G38**, 124045 (2011), 1106.6350
[25] P. Bozek, Phys. Rev. **C85**, 034901 (2012), 1110.6742
[26] J.B. Rose, J.F. Paquet, G.S. Denicol, M. Luzum, B. Schenke, S. Jeon, C. Gale, Nucl. Phys. **A931**, 926 (2014), 1408.0024
[27] S. Ryu, J.F. Paquet, C. Shen, G.S. Denicol, B. Schenke, S. Jeon, C. Gale, Phys. Rev. Lett. **115**, 132301 (2015), 1502.01675
[28] J. Adam et al. (ALICE), Phys. Rev. Lett. **117**, 182301 (2016), 1604.07663
[29] X. Zhu, Y. Zhou, H. Xu, H. Song (2016), 1608.05305
[30] H. Niemi, K.J. Eskola, R. Paatelainen, Phys. Rev. **C93**, 024907 (2016), 1505.02677
[31] A. Bilandzic, C.H. Christensen, K. Gulbrandsen, A. Hansen, Y. Zhou, Phys. Rev. **C89**, 064904 (2014), 1312.3572
[32] G. Giacalone, L. Yan, J. Noronha-Hostler, J.Y. Ollitrault, Phys. Rev. **C94**, 014906 (2016), 1605.08303
[33] G. Denicol, A. Monnai, B. Schenke, Phys. Rev. Lett. **116**, 212301 (2016), 1512.01538
[34] J. Adam et al. (ALICE), Phys. Lett. **B762**, 376 (2016), 1605.02035
[35] E. Molnar, H. Holopainen, P. Huovinen, H. Niemi, Phys. Rev. **C90**, 044904 (2014), 1407.8152
[36] B.B. Back et al. (PHOBOS), Phys. Rev. **C72**, 051901 (2005), nucl-ex/0407012
[37] B.B. Back et al. (PHOBOS), Phys. Rev. Lett. **94**, 122303 (2005), nucl-ex/0406021
[38] J. Noronha-Hostler, M. Luzum, J.Y. Ollitrault, Phys. Rev. **C93**, 034912 (2016), 1511.06289
[39] H. Niemi, K.J. Eskola, R. Paatelainen, K. Tuominen, Phys. Rev. **C93**, 014912 (2016), 1511.04296