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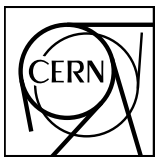

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Correlated event-by-event fluctuations of flow harmonics in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV

ALICE Collaboration*

Abstract

We report the measurements of correlations between event-by-event fluctuations of amplitudes of anisotropic flow harmonics in nucleus–nucleus collisions, obtained for the first time using a new analysis method based on multiparticle cumulants in mixed harmonics. This novel method is robust against systematic biases originating from non-flow effects and by construction any dependence on symmetry planes is eliminated. We demonstrate that correlations of flow harmonics exhibit a better sensitivity to medium properties than the individual flow harmonics. The new measurements are performed in Pb–Pb collisions at the centre-of-mass energy per nucleon pair of $\sqrt{s_{\rm NN}} = 2.76$ TeV by the ALICE experiment at the Large Hadron Collider (LHC). The centrality dependence of correlation between event-by-event fluctuations of the elliptic, v_2, and quadrangular, v_4, flow harmonics, as well as of anti-correlation between v_2 and triangular, v_3, flow harmonics are presented. The results cover two different regimes of the initial state configurations: geometry-dominated (in mid-central collisions) and fluctuation-dominated (in the most central collisions). Comparisons are made to predictions from MC-Glauber, viscous hydrodynamics, AMPT and HIJING models. Together with the existing measurements of individual flow harmonics the presented results provide further constraints on initial conditions and the transport properties of the system produced in heavy-ion collisions.

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*See Appendix A for the list of collaboration members

The properties of an extreme state of matter, the Quark-Gluon Plasma (QGP), are studied by colliding heavy ions at BNL's Relativistic Heavy Ion Collider (RHIC) and at CERN's Large Hadron Collider (LHC). One of the most widely utilized physical phenomena in the exploration of QGP properties is collective anisotropic flow [1, 2]. The large elliptic flow discovered at RHIC energies [3], which at the LHC energy of 2.76 TeV is 30% larger [4] and recently reported in [5] to increase even further at 5.02 TeV, demonstrated that the QGP behaves like a strongly coupled liquid with a very small ratio of the shear viscosity to entropy density (η/s), which is close to a universal lower bound of $1/4\pi$ [6].

Anisotropic flow is traditionally quantified with harmonics v_n and corresponding symmetry plane angles ψ_n in the Fourier series decomposition of particle azimuthal distribution (parameterized with azimuthal angle φ) in the plane transverse to the beam direction [7]:

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \psi_n)]\,. \tag{1}$$

The shape of the intersecting zone of two identical heavy ions in non-central collisions is approximately ellipsoidal. This initial anisotropy is transferred via interactions among constituents and the pressure gradients developed in the QGP medium to an observable final-state anisotropic emission of particles with respect to the symmetry plane(s) of the intersecting zone. The resulting anisotropic flow for such an idealized ellipsoidal geometry is determined solely by even Fourier harmonics v_{2n}, and only one symmetry plane (the reaction plane spanned by the impact parameter vector and the beam axis) exists. Recently the importance of flow fluctuations and related additional observables have been identified. This has led to new concepts such as: non-vanishing odd harmonics v_{2n-1} at midrapidity [8], non-identical symmetry plane angles ψ_n and their inter-correlations [9–14], stochastic nature of harmonic v_n and its probability density function $P(v_n)$ [15–20], and, finally, the importance of higher order flow moments $\langle v_n^k \rangle$ (where the angular brackets denote an average over all events, and $k \geq 2$) [21]. Two distinct regimes for anisotropic flow development are nowadays scrutinized separately: geometry-dominated (in mid-central collisions) and fluctuation-dominated (in the most central collisions) [11].

Anisotropic flow is generated by the initial anisotropic geometry and its fluctuations coupled with an expansion of the produced medium. The initial coordinate space anisotropy can be quantified in terms of eccentricity coefficients ε_n and corresponding symmetry plane angles Φ_n [8, 15, 22]. A great deal of effort is being invested to understand the relations between momentum space Fourier harmonics v_n and symmetry planes ψ_n on one side, and their spatial counterparts, ε_n and Φ_n, on the other side. These relations describe the response of the produced system to the initial coordinate space anisotropies, and therefore provide a rich repository of constraints for the system properties. In the early studies it was regularly assumed that, for small eccentricities, the harmonics v_n respond linearly to the eccentricities ε_n of the same order, $v_n \propto \varepsilon_n$, and that $\psi_n \simeq \Phi_n$ [8, 10, 23]. However, for sizable eccentricities recent studies argue that the anisotropies in momentum and coordinate space are related instead with the matrix equation connecting a set of anisotropic flow harmonics $\{v_n\}$ and a set of eccentricity coefficients $\{\varepsilon_n\}$; it was demonstrated that the response matrix between two sets is both non-diagonal and non-linear, and that in general $\psi_n \neq \Phi_n$ [9, 11, 24, 25]. The first realization led to the conclusion that a relationship between event-by-event fluctuations of amplitudes of two different flow harmonics v_m and v_n can exist. This is hardly surprising for even flow harmonics in non-central collisions because the ellipsoidal shape generates non-vanishing values for all even harmonics v_{2n} [26], not only for elliptic flow. However, this simple geometrical argument cannot explain the possible relation between even and odd flow harmonics in non-central collisions, and the argument is not applicable in the central collisions, where all initial shapes are equally probable since they originate solely from fluctuations. Recently a linear correlation coefficient $c(a,b)$ was defined in this context, which becomes 1 (-1) if observables a and b are fully linearly (antilinearly) correlated and zero in the absence of correlation [24]. Model calculations of this new observable showed that neither v_2 and v_3 nor v_3 and v_4 are linearly correlated in non-central collisions. Most importantly, it was demonstrated that $c(v_2, v_4)$ depends strongly both on the η/s of the QGP and on

the value of $c(\varepsilon_2,\varepsilon_4)$, which quantifies the relationship between corresponding eccentricities in the initial state [24]. Therefore it was concluded that new observables $c(v_n,v_m)$, depending on the choice of flow harmonics v_n and v_m, are sensitive both to the fluctuations of the initial conditions and to the transport properties of the QGP, with the potential to discriminate between the two respective contributions when combined with a measurement of individual flow harmonics [24].

In this Letter we study the relationship between event-by-event fluctuations of magnitudes of two different flow harmonics of order n and m by using a recently proposed 4-particle observable [27]

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

with the condition $m\neq n$ for two positive integers m and n. We refer to these new observables as *Symmetric 2-harmonic 4-particle Cumulant*, and use notation $\mathrm{SC}(m,n)$, or just SC. The double angular brackets indicate that the averaging procedure has been performed in two steps — first over all distinct particle quadruplets in an event, and then in the second step the single-event averages were weighted with 'number of combinations'. The latter for single-event average 4-particle correlations is mathematically equivalent to a unit weight for each individual quadruplet when the multiplicity differs event-by-event [28]. In both 2-particle correlators above all distinct particle pairs are considered in each case. The four-particle cumulant in Eq. (2) is less sensitive to non-flow correlations than any 2- or 4-particle correlator on the right-hand side taken individually [29]. It is zero in the absence of flow fluctuations, or if the magnitudes of harmonics v_m and v_n are uncorrelated [27]. It is also unaffected by relationship between symmetry plane angles ψ_m and ψ_n. The four-particle cumulant in Eq. (2) is proportional to the linear correlation coefficient $c(a,b)$ introduced in [24] and discussed above, with $a=v_m^2$ and $b=v_n^2$. Experimentally it is more reliable to measure the higher order moments of flow harmonics v_n^k $(k\geq 2)$ with 2- and multiparticle correlation techniques [29–31], than to measure the first moments v_n with the event plane method, due to systematic uncertainties involved in the event-by-event estimation of symmetry planes [32, 33]. Therefore, we have used the new multiparticle observable in Eq. (2) as meant to be the least biased measure of the correlation between event-by-event fluctuations of magnitudes of two different harmonics v_m and v_n [27].

The 2- and 4-particle correlations in Eq. (2) were evaluated in terms of Q-vectors [30]. The Q-vector (or flow vector) in harmonic n for a set of M particles, where throughout this paper M is multiplicity of an event, is defined as $Q_n\equiv\sum_{k=1}^{M}e^{in\varphi_k}$ [7, 34]. We have used for a single-event average 2-particle correlation, $\langle\cos(n(\varphi_1-\varphi_2))\rangle$, the following definition and analytic result in terms of Q-vectors:

$$\frac{1}{\binom{M}{2}2!}\sum_{\substack{i,j=1\\(i\neq j)}}^{M} e^{in(\varphi_i-\varphi_j)} = \frac{1}{\binom{M}{2}2!}\left[|Q_n|^2-M\right]. \tag{3}$$

For 4-particle correlation, $\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle$, we used:

$$\begin{aligned}&\frac{1}{\binom{M}{4}4!}\sum_{\substack{i,j,k,l=1\\(i\neq j\neq k\neq l)}}^{M} e^{i(m\varphi_i+n\varphi_j-m\varphi_k-n\varphi_l)} = \\ &\frac{1}{\binom{M}{4}4!}\left[|Q_m|^2|Q_n|^2-2\mathfrak{Re}\left[Q_{m+n}Q_m^*Q_n^*\right]-2\mathfrak{Re}\left[Q_mQ_{m-n}^*Q_n^*\right]\right. \\ &\left.+|Q_{m+n}|^2+|Q_{m-n}|^2-(M-4)(|Q_m|^2+|Q_n|^2)+M(M-6)\right]. \end{aligned} \tag{4}$$

In order to obtain the all-event average correlations, denoted by $\langle\langle\cdots\rangle\rangle$ in Eq. (2), we have weighted single-event expressions in Eqs. (3) and (4) with weights $M(M-1)$ and $M(M-1)(M-2)(M-3)$, respectively [28].

The dataset used in this analysis was obtained with the ALICE detector [35, 36]. It consists of minimum-bias Pb–Pb collisions recorded during 2010 LHC Pb–Pb run at $\sqrt{s_{\rm NN}} = 2.76$ TeV. With the default event and track selection criteria described below, we have obtained in total about 1.8×10^5 events per 1% centrality bin width.

The centrality was determined with the V0 detector [37, 38]. The resolution of centrality determination with the V0 is about 0.5% centrality bin width in the most central collisions, and is still better than 2% centrality bin width for peripheral collisions [39]. As a part of systematic checks centrality was determined independently with the Time Projection Chamber (TPC) [40] and the Silicon Pixel Detector (SPD) [41, 42], which have slightly worse resolution [39]. A systematic difference of up to 3% was observed in $\mathrm{SC}(m,n)$ results when using different centrality estimations. Charged particles were reconstructed with the TPC and the Inner Tracking System (ITS) [41, 42] immersed in a 0.5 T solenoidal field. The TPC is capable of detecting charged particles in the transverse momentum range $0.1 < p_{\rm T} < 100$ GeV/c, with a $p_{\rm T}$ resolution of less than 6% for tracks below 20 GeV/c. Due to TPC dead zones between neighboring sectors, the track finding efficiency saturates at about 85% for $p_{\rm T} > 1$ GeV/c in Pb–Pb collisions. The TPC covers full azimuth and has a pseudorapidity coverage of $|\eta| < 0.9$. The ITS improves the transverse momentum and angular resolution of particles reconstructed by the TPC. Tracks reconstructed using the TPC and ITS are referred to as *global*, while tracks reconstructed only with the TPC are referred to as *TPC-only*.

For online triggering, the V0 and SPD detectors were used [36]. The reconstructed primary vertex is required to lie within $\pm$ 10 cm of the nominal interaction point in the longitudinal direction along the beam axis. The cut on the position of the primary vertex along the beam axis was varied from $\pm$12 cm to $\pm$6 cm, the resulting SC measurements are consistent with those obtained with the default cut.

The main analysis was performed with global tracks selected in the transverse momentum interval $0.2 < p_{\rm T} < 5.0$ GeV/c and pseudorapidity region $|\eta| < 0.8$. With this choice of low $p_{\rm T}$ cut-off we are reducing event-by-event biases from smaller reconstruction efficiency at lower $p_{\rm T}$, while the high $p_{\rm T}$ cut-off was introduced to reduce the contribution to the anisotropies from jets. Reconstructed tracks were required to have at least 70 TPC space points (out of a maximum of 159). Only tracks with a transverse distance of closest approach (DCA) to the primary vertex less than 3 mm, both in longitudinal and transverse direction, are accepted to reduce the contamination from secondary tracks (for instance the charged particles produced in the detector material, particles from weak decays, etc.). Tracks with kinks (the tracks that appear to change direction due to multiple scattering, $K^{\pm}$ decays) were rejected.

An independent analysis was performed with TPC-only and hybrid tracks (see below). In the analysis with TPC-only tracks, the DCA cut was relaxed to 3 cm both in the longitudinal and transverse directions, providing different sensitivity to contamination from secondary tracks. Both the azimuthal acceptance and the reconstruction efficiency as a function of transverse momentum differ between TPC-only and global tracks. The resulting difference between independent analyses with global and TPC-only tracks was found to be 1–5% in all the centrality ranges studied, both for $\mathrm{SC}(3,2)$ and $\mathrm{SC}(4,2)$. In another independent analysis with hybrid tracks, three different types of tracks were combined, in order to overcome the non-uniform azimuthal acceptance due to dead zones in SPD, and to achieve the best transverse momentum resolution [36]. In this analysis the DCA cut was set to 3.2 cm in the longitudinal and to 2.4 cm in the transverse direction. The results between global and hybrid tracks differ by 3 to 5%, depending on the observable considered.

One of the largest contributions to the systematic uncertainty originates from the non-uniform reconstruction efficiency as a function of transverse momentum. For the observables $\mathrm{SC}(3,2)$ and $\mathrm{SC}(4,2)$ the uncertainty is 7% and 8%, respectively. In order to correct the measurements of these azimuthal correlators for various detector inefficiencies, we have constructed particle weights as a function of azimuthal angle φ and transverse momentum $p_{\rm T}$, and used the prescription outlined in [27]. In particular,

p_{T}-weights were constructed as a ratio of transverse momentum distribution obtained from Monte Carlo generated tracks and from tracks reconstructed after they have passed through the detector simulated with GEANT3 [43].

We have used four Monte Carlo models in this paper. The HIJING model [44, 45] was utilized to obtain the p_{T}-weights [27] which were used to estimate systematic bias due to non-uniform reconstruction efficiency. Secondly, the HIJING model was used to estimate the strength of non-flow correlations (typically few-particle correlations insensitive to the collision geometry). We have evaluated the observables of interest in coordinate space by modeling the initial conditions with a MC-Glauber model [46]. We have compared the centrality dependence of our observables with theoretical model from [47], where the initial energy density profiles are calculated using a next-to-leading order perturbative-QCD+saturation model [48, 49]. The subsequent spacetime evolution is described by relativistic dissipative fluid dynamics with different parametrizations for the temperature dependence of the shear viscosity to entropy density ratio $\eta/s(T)$. Each of the $\eta/s(T)$ parametrizations is adjusted to reproduce the measured v_n from central to mid-peripheral collisions. Finally, we provide an independent estimate of the centrality dependence of our observables by utilizing the AMPT model [50].

The centrality dependence of $\mathrm{SC}(4,2)$ (red squares) and $\mathrm{SC}(3,2)$ (blue circles) are presented in Fig. 1. Positive values of $\mathrm{SC}(4,2)$ are observed for all centralities. This suggests a correlation between the event-by-event fluctuations of v_2 and v_4, which indicates that finding v_2 larger than $\langle v_2 \rangle$ in an event enhances the probability of finding v_4 larger than $\langle v_4 \rangle$ in that event. On the other hand, the negative results of $\mathrm{SC}(3,2)$ show the anti-correlation between v_2 and v_3 magnitudes, which further imply that finding v_2 larger than $\langle v_2 \rangle$ enhances the probability of finding v_3 smaller than $\langle v_3 \rangle$. We have calculated the SC

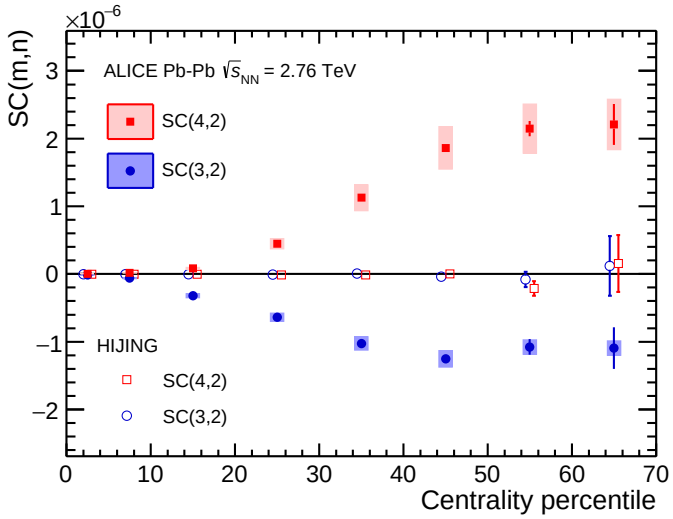

Fig. 1: Centrality dependence of observables $\mathrm{SC}(4,2)$ (red filled squares) and $\mathrm{SC}(3,2)$ (blue filled circles) in Pb–Pb collisions at 2.76 TeV. Systematical errors are represented with boxes. Results for HIJING model are shown with hollow markers.

observables using HIJING which does not include anisotropic collectivity but e.g. azimuthal correlations due to jet production [44, 45]. It is found that in HIJING both $\langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle$ and $\langle\langle\cos[m(\varphi_1-\varphi_2)]\rangle\rangle\langle\langle\cos[n(\varphi_1-\varphi_2)]\rangle\rangle$ are non-zero. However, the calculation of SC observables from HIJING are compatible with zero for all centralities, which suggests that the SC measurements are nearly insensitive to non-flow correlations. We have also performed a study using the like-sign technique, which is another powerful approach to estimate the non-flow effects [4]. It was found that the difference between correlations for like-sign and all charged combinations are within 10%. This further illustrates

the fact that non-zero values of SC measurements cannot be explained by non-flow effects.

A study based on the AMPT model showed that the observed (anti-)correlations are also sensitive to the transport properties, e.g. the partonic and hadronic interactions [20, 27]. Fig. 2 shows the comparison of $\mathrm{SC}(3,2)$ and $\mathrm{SC}(4,2)$ to the AMPT calculations which generally predict the correct sign but underestimate their magnitude. The comparison between experimental data and the theoretical calculations [47], which incorporate both the initial conditions and system evolution, is shown in Fig. 2 (top). The model captures qualitatively the centrality dependence, but not quantitatively. Most notably, there is no single centrality for which a given $\eta/s(T)$ parameterization describes simultaneously both $\mathrm{SC}(4,2)$ and $\mathrm{SC}(3,2)$. 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 [47]. We therefore conclude that individual flow harmonics v_n and new $\mathrm{SC}(m,n)$ observables together provide a better handle on the initial conditions and $\eta/s(T)$ than each of them alone. This is further emphasized in Fig. 2 (middle), where $\mathrm{SC}(3,2)$ and $\mathrm{SC}(4,2)$ observables were divided with the products $\langle v_3^2\rangle\langle v_2^2\rangle$ and $\langle v_4^2\rangle\langle v_2^2\rangle$, respectively, in order to obtain the normalized SC observables (the result for 60–70% is omitted due to large statistical uncertainty). These products were obtained with 2-particle correlations and using a pseudorapidity gap of $|\Delta\eta| > 1.0$ to suppress biases from few-particle non-flow correlations. We have found that the normalized $\mathrm{SC}(4,2)$ observable exhibits much better sensitivity to different $\eta/s(T)$ parameterizations than the normalized $\mathrm{SC}(3,2)$ observable, see Fig. 2 (middle), and than the individual flow harmonics [47]. These findings indicate that the normalized $\mathrm{SC}(3,2)$ observable is sensitive mainly to the initial conditions, while the normalized $\mathrm{SC}(4,2)$ observable is sensitive to both the initial conditions and the system properties, which is consistent with the prediction from [24].

It can be seen in Fig. 1 that $\mathrm{SC}(4,2)$ and $\mathrm{SC}(3,2)$ increase non-linearly up to centrality 60%. In Fig. 2 (bottom) we therefore investigate to what extent this non-trivial trend can be captured solely by correlations of the corresponding eccentricities in the initial state. Assuming only linear response $v_n \propto \varepsilon_n$, we expect that the normalized $\mathrm{SC}(m,n)$ evaluated in coordinate space can capture the measurement of centrality dependence of normalized $\mathrm{SC}(m,n)$ in the momentum space. The correlations between the nth and mth order harmonics were estimated with calculations of $(\langle\varepsilon_n^2\varepsilon_m^2\rangle - \langle\varepsilon_n^2\rangle\langle\varepsilon_m^2\rangle)/\langle\varepsilon_n^2\rangle\langle\varepsilon_m^2\rangle$, i.e. a normalized SC observable in the coordinate space, which we denote $\mathrm{SC}(m,n)_\varepsilon/\langle\varepsilon_n^2\rangle\langle\varepsilon_m^2\rangle$. Here the ε_n (or ε_m) is the nth (or mth) order coordinate space anisotropy, following the definition in [8]. Different scenarios of the MC-Glauber model, named wounded nucleon (WN) and binary collisions (BC) weights, have been used. An increasing trend from central to peripheral collisions with different sign has been observed in Fig. 2 (bottom) for $\mathrm{SC}(4,2)$ and $\mathrm{SC}(3,2)$. A dramatic deviation of $\mathrm{SC}(4,2)$ between data and model calculation is observed for non-central collisions. This deviation increases from mid-central to peripheral, which could be understood as the contribution of the non-linear response (ε_2 contributes to v_4) increasing as a function of centrality, which is consistent with that reported in [51]. Since the normalized $\mathrm{SC}(3,2)$ appears to be sensitive only to initial conditions and not to $\eta/s(T)$, see Fig. 2 (middle), MC-Glauber model consistently captures better its centrality dependence than for normalized $\mathrm{SC}(4,2)$ observable, see Fig. 2 (bottom).

The relationship between the flow harmonics v_2, v_3, v_4 have also been investigated by the ATLAS Collaboration using the ESE technique [51–53]. Within a centrality bin, events are subdivided with respect to the magnitude of their v_2. For events with a larger v_2, the ATLAS Collaboration showed these have a smaller than average v_3, and a larger than average v_4. For events with a smaller v_2, the opposite trend occurred. These observations are consistent with the patterns observed via the SC measurements presented in this Letter. The SC observables, however, provide a compact quantitative measure of these correlations, without fitting correlations between v_n and v_m. This simplify the quantitative comparison of the SC observables with hydrodynamical calculations as shown in Fig. 2.

In the most central collisions the anisotropies originate mainly from fluctuations, i.e. the initial ellipsoidal geometry characteristic for mid-central collisions plays little role in this regime. Therefore we have per-

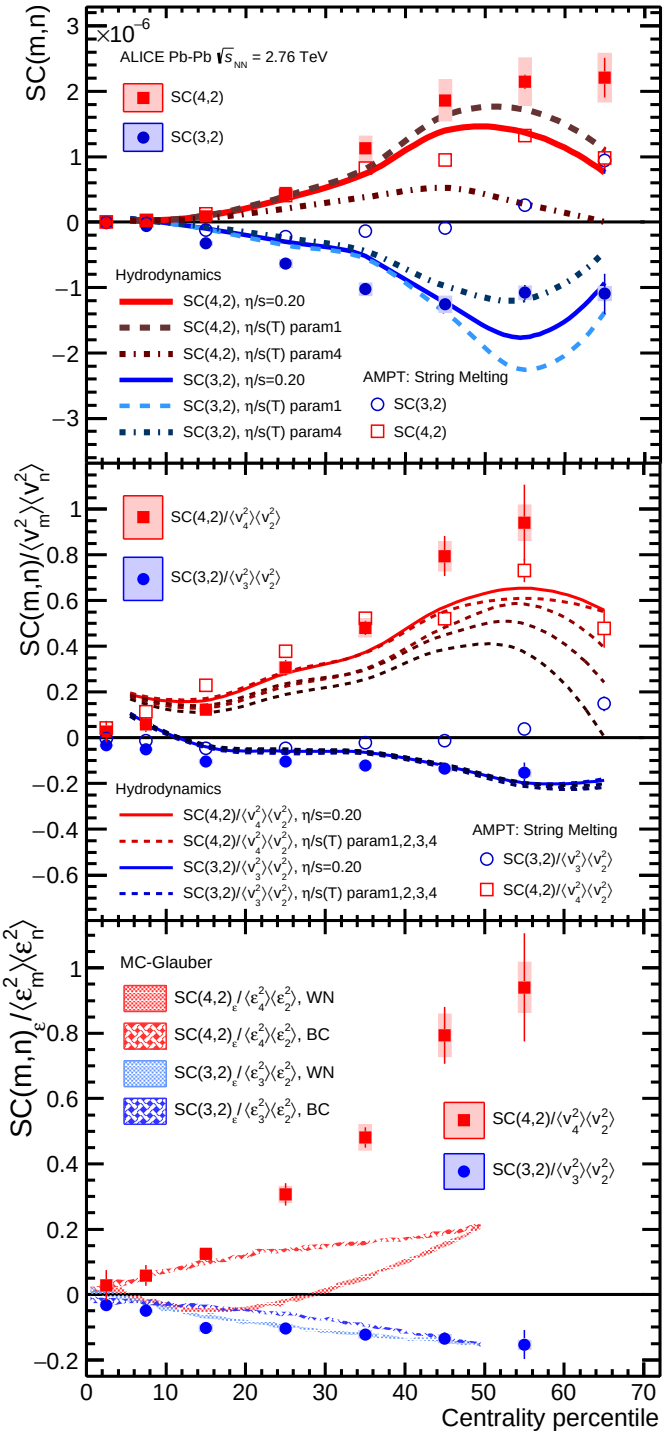

Fig. 2: AMPT model predictions are shown as hollow symbols in the (top) and (middle) panels. (top) Comparison of observables SC(4,2) (red filled squares) and SC(3,2) (blue filled circles) to theoretical model from [47]. Solid lines indicate the predictions with constant η/s, while the dashed lines indicate predictions for different parameterizations of η/s temperature dependence (labeled in the same way as in Fig. 1 in [47]). (middle) The results from top panel have been rescaled with $\langle v_m^2 \rangle \langle v_n^2 \rangle$. (bottom) Comparison to MC-Glauber using wounded nucleon (WN) and binary collisions (BC) weights.

formed a separate analysis for centrality range 0–10% in centrality bins of 1%. The results are presented in Fig. 3. We observe that event-by-event fluctuations of v_2 and v_4 remain correlated, and of v_2 and v_3

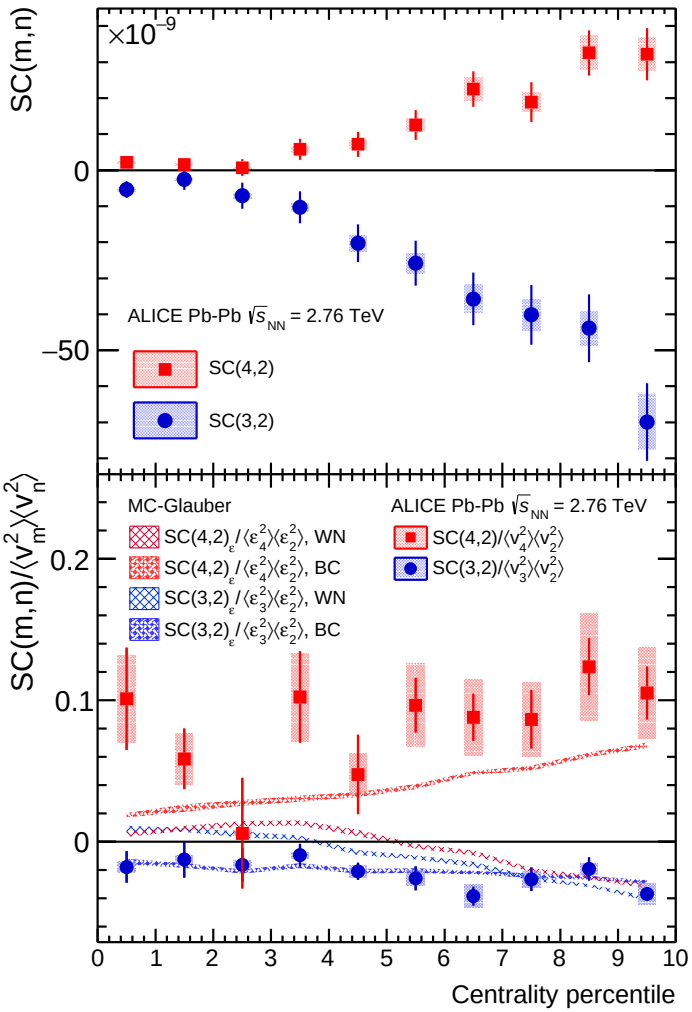

Fig. 3: Correlated and anti-correlated event-by-event fluctuations in coordinate (MC-Glauber) and momentum space (data). On the bottom panel we present the normalized SC observables, where pseudorapidity gap $|\Delta\eta| > 1.0$ was applied in both two-particle correlations in denominator used to estimate individual flow harmonics.

anti-correlated, also in this regime. However, the strength of the (anti)-correlations exhibits a different centrality dependence than for the wider centrality range shown in Fig. 1. As seen in Fig. 3 (top) the centrality dependence cannot be linearly extrapolated from the 0–10% region to the full centrality range. Comparison with two different parameterizations of the MC-Glauber initial conditions for normalized SC observables presented in Fig. 3 (bottom) suggests that the BC parameterization (binary collisions weights) is favored by the data in most central collisions. This agreement may suggest the scaling with the number of quark participants [54–58] in central collisions at the LHC energies.

In summary, we have measured for the first time the new multiparticle observables, the Symmetric 2-harmonic 4-particle Cumulants (SC), which quantify the relationship between event-by-event fluctuations of two different flow harmonics. The new observables are particularly robust against few-particle non-flow correlations and they provide orthogonal information to recently analysed symmetry plane correlators. We have found that fluctuations of v_2 and v_3 are anti-correlated in all centralities, however the

details of the centrality dependence differ in the fluctutation-dominated (most central) and the geometry-dominated (mid-central) regimes. Fluctuations of v_2 and v_4 are correlated for all centralities. Measurements of flow coefficients v_n and new SC(n,m) observables combined together provide a better handle on the initial conditions and $\eta/s(T)$ than their individual measurements. This feature was explored to discriminate between the state-of-the-art hydro model calculations with different parameterizations of the temperature dependence of η/s, for all of which the centrality dependence of elliptic, triangular and quadrangular flow has weaker sensitivity at the LHC. In particular, the centrality dependence of SC$(4,2)$ cannot be captured with the constant η/s. We have also used our results to discriminate between two different parameterizations of initial conditions and have demonstrated that in the fluctuation-dominated regime (in central collisions) MC-Glauber initial conditions with binary collisions weights are favored over wounded nucleon weights. The results presented in this Letter can be used to further optimize model parameters and put better constraints on the initial conditions in ultra-relativistic heavy-ion collisions.

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