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First measurement of symmetric cumulants of hexagonal flow harmonics in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

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Abstract

Correlations between event-by-event fluctuations of anisotropic flow harmonics are measured in Pb–Pb collisions at a center-of-mass energy per nucleon pair of 5.02 TeV, as recorded by the ALICE detector at the LHC. This study presents correlations up to the hexagonal flow harmonic, v_6 , which was measured for the first time. The magnitudes of these higher-order correlations are found to vary as a function of collision centrality and harmonic order. These measurements are compared to viscous hydrodynamic model calculations with EKRT initial conditions and to the iEBE-VISHNU model with T_{RENTo} initial conditions. The observed discrepancies between the data and the model calculations vary depending on the harmonic combinations. Due to the sensitivity of model parameters estimated with Bayesian analyses to these higher-order observables, the results presented in this work provide new and independent constraints on the initial conditions and transport properties in theoretical models used to describe the system created in heavy-ion collisions.

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*See Appendix A for the list of collaboration members

1 Introduction

The study of ultrarelativistic heavy-ion collisions aims to investigate the properties of the strongly interacting matter characterized by high energy densities and temperatures, known as quark–gluon plasma (QGP) [1, 2]. These extreme conditions, needed for the production of QGP, can be achieved at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory and at the Large Hadron Collider (LHC) at CERN. Comparisons between experimental data and state-of-the-art model calculations have shown that the produced QGP is the most perfect fluid observed in nature so far, due to the small value of its shear viscosity over entropy density, η/s [3, 4]. In recent years, one of the main focuses in heavy-ion collision studies has been determining the properties of the QGP using Bayesian analyses, which are designed to constrain parameters of the theoretical models via a comparison with different measured quantities [5–12].

One important probe of the QGP properties is the collective anisotropic flow, which translates the initial-state anisotropies in coordinate space into final-state anisotropies in the momentum distributions of produced particles [13]. Anisotropic flow is quantified by the flow amplitudes v_n and the symmetry planes ψ_n using a Fourier decomposition of the azimuthal distribution $f(\varphi)$ of the final-state particles in the plane transverse to the beam direction [14],

$$f(\varphi) = \frac{1}{2\pi} \left[1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \psi_n)] \right]. \quad (1)$$

Previous measurements have demonstrated that anisotropic flow is particularly sensitive to η/s of the QGP [15]. While only the final-state particles can be measured experimentally, it is possible to relate the observed flow coefficients to the initial-state spatial eccentricities defined as [16, 17]

$$\varepsilon_n e^{in\Phi_n} = - \frac{\{r^n e^{in\varphi}\}}{\{r^n\}}, \quad n \geq 2. \quad (2)$$

In Eq. (2), the curly braces indicate an average defined by $\{\dots\} = \int r dr d\varphi \varepsilon(r, \varphi)$ with (r, φ) being the polar coordinates in the transverse plane, $\varepsilon(r, \varphi)$ the initial energy density, and Φ_n represents the participant plane angle (see Refs. [18, 19]). It has been shown [17, 20–25] that the second- and third-order flow harmonics, v_2 and v_3 , have linear contributions as well as non-linear dependencies from lower-order eccentricities [20, 26–28]. More details on the expressions of these higher-order flow harmonics can be found in Refs. [29, 30].

Experimental measurements [29–32] and theoretical calculations [11, 12] have demonstrated that observables related to the correlations between different flow harmonics are sensitive to the non-linear response, and in turn to the properties of the QGP [12]. Only for small eccentricities the harmonics v_n respond linearly to the eccentricities ε_n of the same order, $v_n \propto \varepsilon_n$ (linear response), while for large eccentricities the anisotropies in momentum and coordinate space are interrelated via a matrix equation, which couples a set of anisotropic flow harmonics $\{v_n\}$ on one side, with the set of eccentricities $\{\varepsilon_n\}$ on the other (non-linear response). Later studies quantified the linear and non-linear contributions to v_n and showed that the non-linear part becomes dominant in more peripheral collisions [29]. Recent Bayesian studies [11, 12] have measured the sensitivities to different observables used to constrain the model parameters, and concluded that the higher-order correlations are more sensitive to the medium properties than the ones used previously.

Correlations between different flow harmonics have been previously measured for harmonics n ranging from $n = 2$ to 5 [33–35]. This article extends the analysis of these correlations in Pb–Pb collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 5.02$ TeV up to the sixth order for the first time, building upon previous studies published in Refs. [31, 33, 35, 36]. The inclusion of the hexagonal flow

harmonic v_6 is particularly interesting because of the different scaling of its non-linear response with the eccentricities ε_2 and ε_3 in the initial state (cubic $v_6 \sim \varepsilon_2^3$ vs quadratic $v_6 \sim \varepsilon_3^2$, respectively) [28].

The article is organized as follows. Section 2 introduces the experimental observables. The data analysis and systematic uncertainty evaluation is described in Sec. 3 and the results are shown in Sec. 4. Finally, the main findings are summarized in Sec. 5.

2 Experimental observables

While individual flow amplitudes and their event-by-event fluctuations provide valuable insight into the initial conditions, exploring correlations between different flow amplitudes can yield further independent constraints. Previous studies on these correlated fluctuations have led to the development of new observables [20, 35, 37, 38]. For instance, the Symmetric Cumulants (SC) introduced by the ALICE Collaboration [33, 36, 37, 39, 40] are direct multivariate cumulants of flow amplitudes, and each higher-order SC observable provides information that the lower-order ones cannot access. These observables are not affected by the symmetry planes ψ_n and are robust against systematic biases resulting from nonflow correlations (i.e. correlations typically involving only a few particles, such as those induced by particle decays or jet fragmentation) [36]. As reported in Refs. [39, 41], SC observables satisfy all fundamental mathematical and statistical properties of cumulants for any number and choice of flow harmonics. Moreover, they are more sensitive to the temperature dependence of η/s than individual flow amplitudes which primarily reflect the average values $\langle \eta/s \rangle$ [19, 36]. In addition, it was demonstrated that these observables have the potential to disentangle contributions from initial conditions and medium properties, making it possible to directly constrain different stages in the evolution of heavy-ion collisions [19, 36]. A recent state-of-the-art Bayesian analysis [12] has quantified the sensitivity of the model parameters to all the observables included in the Bayesian estimation. This analysis is based on the TRenTo+IEBE-VISHNU model [42], which will be discussed in Sec. 4. The model is characterized by a total of 16 parameters, with key physics features embedded in the initial conditions, the temperature-dependent specific shear and bulk viscosity ($\eta/s(T)$ and $\zeta/s(T)$), free-streaming time (τ_{fs}), and switching temperature (T_{switch}). This study has also shown that the inclusion of the SC in the set of input observables has made it possible to reduce the uncertainties associated with the extracted medium properties.

Robust estimators for SC observables can be constructed experimentally using standard multiparticle azimuthal correlations [37, 39]. In the case of two-harmonic SC, their definition is given by [33, 36, 37]

$$\text{SC}(m, n) \equiv \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle = \langle \langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle \rangle - \langle \langle \cos[m(\varphi_1 - \varphi_2)] \rangle \rangle \langle \langle \cos[n(\varphi_1 - \varphi_2)] \rangle \rangle, \quad (3)$$

with the condition $m \neq n$ for two positive integers m and n . The double angular brackets indicate that the averaging is done in two separate steps. In the first step, all distinct particle quadruplets in each event are formed and used to obtain single-event averages $\langle \dots \rangle$. In the second step, these single-event averages are weighted with ‘number of combinations’ weight to obtain the final all-event averages $\langle \langle \dots \rangle \rangle$ (for further details, see Sec. IV C in Ref. [37]). It is crucial to define SC in terms of flow amplitudes v_n , to apply the cumulant expansion directly on v_n , and to use multiparticle azimuthal correlations only as estimators for each term in the resulting expression. This approach ensures the preservation of all the mathematical and statistical properties of the cumulants [39, 41]. The resulting SC can be normalized by the product $\langle v_m^2 \rangle \langle v_n^2 \rangle$ using the following definition [36, 43],

$$\text{NSC}(m, n) \equiv \frac{\text{SC}(m, n)}{\langle v_m^2 \rangle \langle v_n^2 \rangle}. \quad (4)$$

Normalized symmetric cumulants (NSC) allow for direct comparison of these observables in both momentum space (using v_n) and coordinate space (using ε_n). This is due to the fact that the constant of

proportionality which quantifies linear response in the relation $v_n \propto \varepsilon_n$ cancels exactly only in the NSC observables, and therefore a comparison of correlations in the initial coordinate and final momentum space can be performed at the same scale. An additional advantage of the NSC observables stems from the fact that any dependence of individual flow amplitudes on kinematic variables (e.g. transverse momentum p_T) is suppressed, and it can be probed directly how the non-trivial patterns of correlations of flow harmonics change as a function of kinematic variables [33].

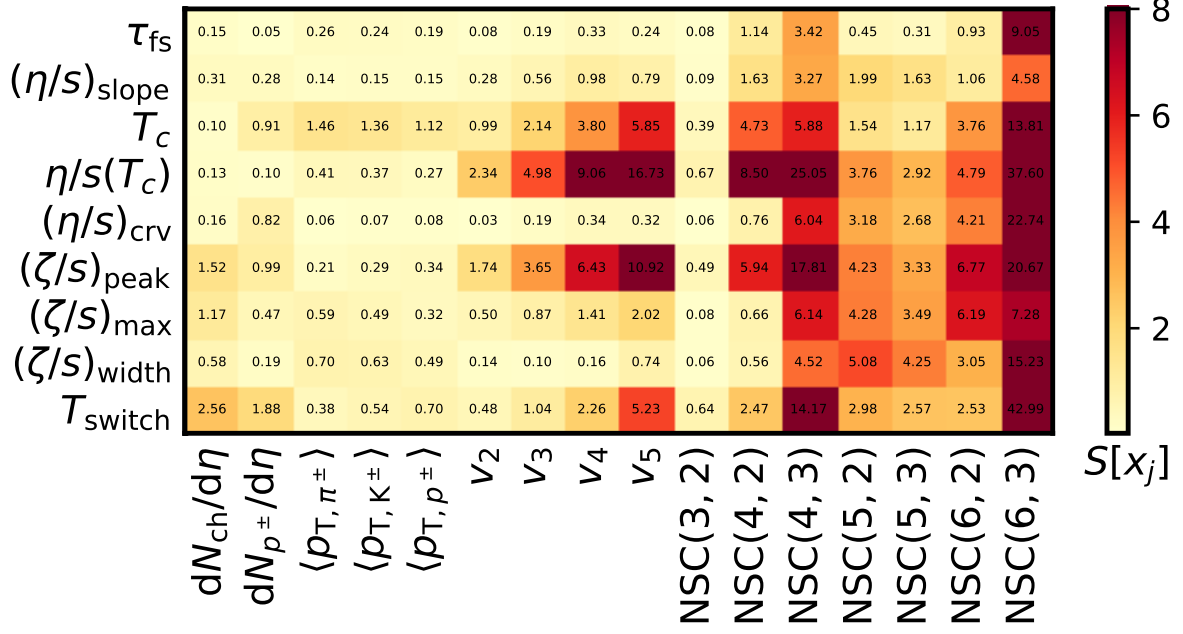


Figure 1: Sensitivity of the model parameters in Bayesian analysis to the flow observables, shown as a color map. Light yellow shades represent low or no sensitivity, whereas orange and red colors represent moderate or strong sensitivities to the corresponding model parameter variation, respectively. The sensitivity analysis is based on the TRENTo+iEBE-VISHNU model [42]. Several key parameters are displayed, including $\eta/s(T)$, $\zeta/s(T)$, τ_{fs} , and T_{switch} . More details can be found in Ref. [12].

The sensitivity of model parameters to higher-order harmonic NSC was quantified using the method from Ref. [12], with results presented in Fig. 1. The sensitivity $S[x_j]$ of an observable \hat{O} to parameter x_j is defined as $|\hat{O}(\vec{x}') - \hat{O}(\vec{x})|/\delta\hat{O}(\vec{x})$. This measures how much an observable changes when a parameter is slightly changed. Here, $\hat{O}(\vec{x})$ represents the observable value at parameter point $\vec{x} = (x_1, \dots, x_p)$, while \vec{x}' denotes a point with a small change δ in x_j . The results are averaged across the centrality range of 5–30%, where centrality is defined in terms of percentiles of the total hadronic cross section. This approach enables a quantitative assessment of which parameters most significantly impact the model’s predictions. The analysis reveals that the model’s transport properties are not highly sensitive to the number of charged particles or average transverse momentum $\langle p_T \rangle$. However, the temperature-dependent specific shear viscosity, $\eta/s(T)$, is sensitive to v_n values. Notably, NSC exhibit even greater sensitivity to a wider range of parameters. This enhanced sensitivity suggests that NSC could be valuable to better constrain the parameters related to the transport properties of the medium.

3 Data analysis

3.1 Event and track selection

This analysis utilizes data from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV recorded by the ALICE detector in 2015 and 2018. The ALICE detector includes several subdetectors immersed in a 0.5 T solenoidal

field. The Inner Tracking System (ITS) [44, 45] is used for track reconstruction. Positioned closest to the beam vacuum tube, the ITS consists of six silicon layers with three types of detector technologies. The two innermost layers, Silicon Pixel Detectors (SPD), provide high spatial granularity which is ideal for reconstructing primary and secondary vertices. Surrounding the ITS is the Time Projection Chamber (TPC) [46], a gas-filled cylindrical tracking detector that provides up to 159 reconstruction points for charged tracks traversing its full radial extent. It is used for reconstructing charged-particle tracks and for particle identification. The detailed descriptions of the various detectors and their performance are given in Refs. [47, 48].

Triggering and centrality determination is carried out using two scintillator arrays, V0A and V0C [47, 49]. The centrality determined using these V0 detectors is referred to as the V0 estimator. All three detectors (TPC, ITS, and the V0 arrays) cover the full azimuth. They have pseudorapidity ranges within $|\eta| < 0.9$ for the TPC and ITS, and $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$ for V0A and V0C, respectively.

Minimum bias (MB) events are triggered by a coincident signal in both the V0A and V0C. Only MB Pb–Pb events with a reconstructed primary vertex within ± 8.0 cm from the nominal interaction point along the beam direction are selected. To remove background events such as beam–gas collisions and pile-up, information from the V0 detector and the SPD is utilized as done in Ref. [50]. After applying all event selection criteria, 212 million events remain within the 0–60% centrality range.

This analysis involves tracks reconstructed using combined information from the ITS and TPC within a transverse momentum interval of $0.2 < p_T < 5.0$ GeV/ c and a pseudorapidity range of $|\eta| < 0.8$. To avoid contributions from secondary particles, only tracks with a specified distance of closest approach (DCA) to the primary vertex are accepted. Furthermore, the reconstructed tracks are required to have a minimum of 70 TPC space points and a minimum of 2 hits in the ITS. All kink topology tracks are rejected. The selection criteria employed in this analysis align closely with those outlined in Refs. [32, 51]. After these track selections, an extra criterion is enforced to discard any remaining events with fewer than 10 reconstructed tracks as this is the smallest number of tracks necessary for calculating all relevant $SC(m, n)$ observables, as done in Ref. [32].

Corrections for the non-uniform reconstruction efficiency (NUE) and the non-uniform acceptance (NUA) are applied as a function of transverse momentum and as a function of azimuthal angle, respectively, following previous studies [29, 37, 40]. The NUA correction is data-driven, while the NUE correction factor is calculated with a Monte Carlo simulation using the HIJING [52] event generator and GEANT3 [53] transport software, accounting for the track reconstruction efficiency and contamination from secondary particles.

In order to suppress the nonflow contribution resulting from the two-particle correlations in the denominator of the NSC in Eq. (4), a pseudorapidity gap of $|\Delta\eta| > 1.0$ is used. For the two two-particle correlations which appear in the definition of $SC(m, n)$ in Eq. (3), the pseudorapidity gap is not needed, since nonflow is suppressed by construction of this observable. This was demonstrated by HIJING model [52] simulations in Ref. [36].

3.2 Systematic uncertainties

The systematic uncertainties are estimated by varying the event and track selection criteria with respect to the default selections, previously summarized, taking into account the correlations between their statistical uncertainties as done in Ref. [32]. Each selection criterion variation is described below.

The effect of the centrality determination is estimated by changing the default V0 estimator to the SPD. The selection on the longitudinal position of the primary vertex is varied from ± 8 cm to ± 7 and ± 9 cm. About 20% of the data collected in 2015 and over 25% of the data collected in 2018 were affected by out-of-bunch pile-up collisions. The effects of pile-up collisions are studied using correlations between the number of tracks measured in the TPC and the number of tracks reconstructed with the ITS to reduce

contamination from events occurring in different bunch crossings [54]. The impact of the two configurations of the magnetic field polarity in the solenoid magnet of ALICE is investigated by performing the analysis on the data sets taken for each orientation separately. To test the track-quality selections, the minimum number of space points in the TPC required for the track reconstruction is changed from 70 to 80 and 65. The χ^2 value per space point from the track fit is reduced from 2.5 to 2.3. Finally, the DCA of the extrapolated track to the primary vertex position is tightened from 2 cm to 1 cm along the beam direction, while in the transverse plane a transverse-momentum dependent DCA selection was applied to account for the p_T dependence of the DCA resolution (using the expression $0.0208 + 0.04/p_T^{1.1}$ cm, with p_T expressed in units of GeV/c). It is important to note that the 2015 and 2018 datasets were collected under slightly different detector conditions [54], which particularly affected the 0–5% and 5–10% centrality percentiles, where track multiplicity is the highest. Therefore, the two data sets were analyzed separately, and the observed differences were assigned as an additional source of systematic uncertainty.

The significance of the difference for each variation is determined using the Barlow test [55]. A Barlow criterion of 2.0 is applied for all observables except NSC(6,2) and NSC(6,3). For NSC(6,2), a relaxed criterion of 1.0 is used to assign the systematic uncertainty. In the case of NSC(6,3), due to large statistical uncertainties, the Barlow test is not applied. Instead, all trials contribute to the systematic uncertainty, except for the variation in magnetic field polarity due to large statistical uncertainties of a given dataset with different polarity. The variations from each systematic source are added in quadrature to obtain the total systematic uncertainties.

4 Results

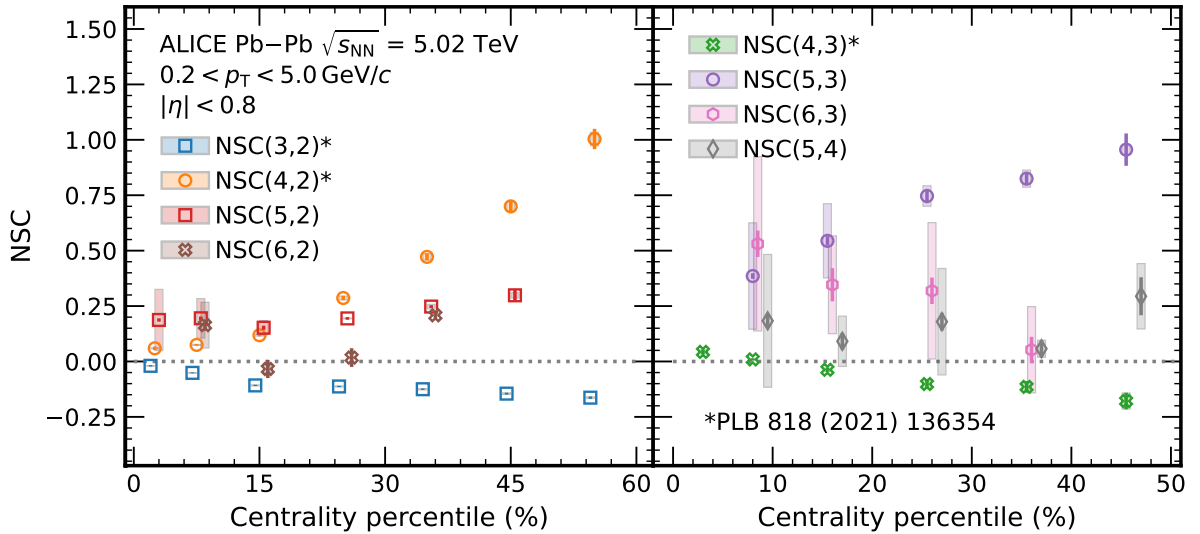


Figure 2: The centrality dependence of the NSC observables. The previously published lower-order harmonics [31] are marked with asterisk (*). The statistical and total systematic uncertainties are shown with vertical lines and boxes, respectively.

The results of the higher-order harmonic normalized symmetric cumulants are shown in Fig. 2 together with the lower-order NSC from Ref. [31] marked with an asterisk (*). The new measurements include the fifth and sixth harmonic amplitudes. All observables are positive except for NSC(3,2) and for NSC(4,3), in non-central collisions. In general, the sign of two-harmonic (N)SC observables has a non-trivial physics interpretation, and can be understood as follows. A positive (N)SC indicates that measuring v_m larger than $\langle v_m \rangle$ in an event will increase the probability of measuring v_n larger than $\langle v_n \rangle$ in that event, i.e. event-by-event fluctuations of v_m and v_n are correlated. On the other hand, a negative sign can be interpreted as anti-correlation between the event-by-event fluctuations of v_m and v_n amplitudes, meaning

that measuring v_m larger than $\langle v_m \rangle$ will decrease the probability of measuring v_n larger than $\langle v_n \rangle$ in the same event [36]. The physical interpretation of the sign of higher-order SC observables involving more than two harmonics is more challenging, and can be found in Ref. [40].

In Fig. 2, a strong centrality dependence is observed for NSC(5,3), along with a possible hint for a slightly decreasing trend for NSC(6,3) toward peripheral collisions, while no significant centrality dependence is seen for NSC(5,2), NSC(5,4) and NSC(6,2). The different trends of the different NSC observables from most central to semicentral collisions are expected due to the fact that the physical origin of the flow fluctuations is different in these two regimes. While the main driving force in the most central collisions are fluctuations of participating nucleons, in semicentral collisions fluctuations are of geometric origin due to the leading-order ellipsoidal shape. The centrality dependence of NSC(6,2) and NSC(6,3) is qualitatively different, despite large uncertainties for NSC(6,3). This difference is not surprising given the distinct scaling of the non-linear response contribution in these two cases ($v_6 \sim v_2^3$ and $v_6 \sim v_3^2$, respectively) [28]. Such different centrality dependence demonstrates that for different combinations of flow harmonics, NSC observables extract new and independent information about heavy-ion collisions.

A systematic comparison of the centrality dependence of the NSC(m,n) to initial- and final-state models has been performed and it is shown in Fig. 3. For the comparison to the EKRT and T_RENTo initial-state models, the observable is calculated using the initial state eccentricities. The data are also compared with the EKRT + viscous hydrodynamics model [19] and the T_RENTo+iEBE-VISHNU model [42].

In the event-by-event EKRT + viscous hydrodynamic calculations, the initial energy density profiles are calculated using a next-to-leading order perturbative quantum chromodynamics approach implemented with gluon saturation model [56, 57]. The subsequent space–time evolution is described by relativistic dissipative fluid dynamics with different parameterizations for the temperature dependence of the shear viscosity to entropy density ratio, $\eta/s(T)$. This model gives a good description of the charged hadron multiplicity and the low- p_T region of the charged hadron spectra at RHIC and the LHC (see Figs. 11–13 in Ref. [19]). Each $\eta/s(T)$ parameterization is tuned to reproduce the measured v_2 from central to semiperipheral collisions (see Fig. 10 in Ref. [58]), while keeping the average $\langle \eta/s(T) \rangle$ the same for all parameterizations.

The T_RENTo+iEBE-VISHNU model uses T_RENTo [42] to simulate the initial conditions, which are then connected with a free streaming phase transitioning into a 2+1 dimensional causal hydrodynamic model known as VISH2+1 [59]. The hydrodynamic evolution within VISH2+1 accounts for the expansion and cooling of the QGP, leading up to hadronization. After hadronization, the evolution continues using a hadronic cascade model (UrQMD) [60, 61], which simulates the interactions and decays of the produced hadrons, ensuring a realistic description of the final-state particles. The model calculation uses the best-fit parameterization for transport coefficients selected based on maximum a posteriori (MAP) for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The MAP values are based on Ref. [12] and labeled MAP(2022) in Fig. 3.

Figure 3 presents all the measured NSC’s, where panels (a) to (c) show the data from Ref. [31]. A good agreement between the final-state models, the EKRT + viscous hydrodynamics model [58] and T_RENTo+iEBE-VISHNU, and data can be seen for NSC(3,2), NSC(4,3), NSC(5,2), and NSC(5,4). The comparison between initial and final states in the models reveals that, with the exceptions of NSC(3,2) and NSC(5,4), all other observables demonstrate a pronounced non-linear hydrodynamic response. This response significantly outweighs the influence of initial-state eccentricities. Most observables show an increasing correlation in peripheral collisions, with two exceptions: NSC(6,3) and NSC(5,4). NSC(5,4) demonstrates minimal centrality dependence within the uncertainties. NSC(6,3), however, exhibits a distinct centrality dependence. This suggests a negative contribution from NSC(3,2) coupled with an increasing correlation towards peripheral collisions, which results in a decreasing trend in peripheral collisions. In summary, the discrepancies between experimental data and model calculations vary across

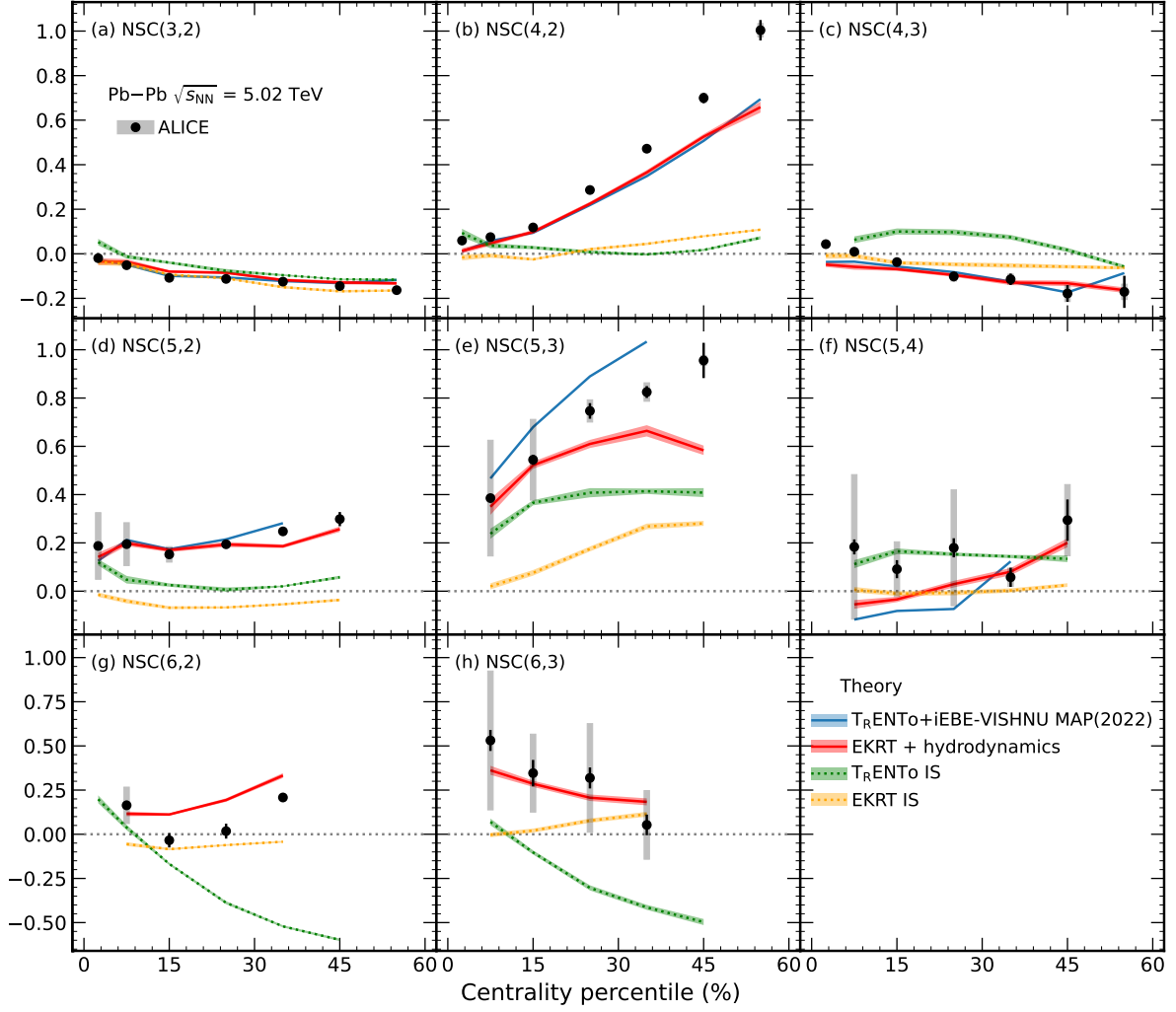


Figure 3: The centrality dependence of $\text{NSC}(m,n)$ in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Results for each observable are compared with the final-state predictions from the event-by-event EKRT + viscous hydrodynamic calculations [19] and $\text{T}_{\text{RENTo}}+\text{iEBE-VISHNU MAP}(2022)$, as well as with the initial-state calculations from EKRT and T_{RENTo} . Panels (a) to (c) present data from Ref. [31]. The statistical and total systematic uncertainties of the data are shown with vertical lines and boxes, respectively. The model results are shown as colored bands with the width of the band denoting the statistical uncertainties.

different harmonic combinations. The two models for the initial state, EKRT and T_{RENTo} , show distinct initial-state correlations for most observables. Additionally, the hydrodynamic response to these initial states differs between the models, leading to distinct predictions for the final-state observables. These variations offer valuable opportunities to constrain both initial conditions and final-state effects in heavy-ion collision models.

5 Summary

In conclusion, the first measurements of higher-order harmonic $\text{NSC}(6,2)$ and $\text{NSC}(6,3)$ in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are reported. These observables are crucial for further constraining theoretical models, as they provide new and independent information on the evolution of a heavy-ion collision. It was also demonstrated that the model parameterization in Bayesian analysis is sensitive to higher-order harmonic $\text{NSC}(m,n)$ and can therefore be used to decrease the uncertainty on the transport properties of the QGP. These newly measured observables and the lower-order harmonic $\text{NSC}(m,n)$ are compared

with hydrodynamic calculations, where, generally, the agreement with data is worse for higher-order NSC(m, n). It is also observed that both NSC(6,2) and NSC(6,3) are positive, and that NSC(6,3) is the only observable with hint of a decreasing correlation with increasing centrality. Discrepancies between data and model calculations vary across harmonic combinations. The EKRT and iEBE-VISHNU with T_RENTo models show distinct initial state correlations and hydrodynamic responses. These variations help constrain initial conditions and final-state effects in heavy-ion collision models. Moreover, the sensitivity of Bayesian model parameterization to these higher-order observables offers new constraints on initial conditions and transport properties in theoretical models of heavy-ion collisions.

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