EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP-2021-005
6 January 2021

# Event-by-event multi-harmonic correlations of different flow amplitudes in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV

ALICE Collaboration*

**Abstract**

The genuine event-by-event correlations between three flow amplitudes are measured for the first time in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV by the ALICE Collaboration at the Large Hadron Collider. The results are obtained with recently developed observables, the higher order Symmetric Cumulants (SC), in the midrapidity region $|\eta| < 0.8$ and the transverse momentum range $0.2 < p_{\rm T} < 5.0$ GeV/$c$. These higher order observables show the same robustness against systematic biases arising from nonflow effects as the two-harmonic SC. The new results cannot be interpreted in terms of lower order flow measurements, since they are dominated by different patterns of event-by-event flow fluctuations. The results are compared with expectations from initial state models such as T$_{\rm R}$ENTo and next-to-leading order perturbative-QCD+saturation model of initial conditions, followed by iEBE-VISHNU and EKRT viscous hydrodynamic calculations. Model comparisons provide an indication of the development of genuine correlations between the elliptic $v_2$, the triangular $v_3$ and the quadrangular $v_4$ flow amplitudes during the collective evolution of the medium. The comparison with the predictions for the correlations between $v_2$, $v_3$ and the pentagonal flow magnitude $v_5$ illustrate the need for further tuning of model parameterizations. Therefore, these results can provide new and independent constraints for the initial conditions and system properties of nuclear matter created in heavy-ion collisions, complementary to previous flow measurements.



*See Appendix A for the list of collaboration members

Under extreme values of temperature and/or baryon density, the fundamental theory of the strong nuclear force, quantum chromodynamics (QCD), predicts the existence of a quark–gluon plasma (QGP). In the QGP state, quarks are deconfined from ordinary hadrons, but contrary to the initial theoretical expectations, they remain strongly coupled with the other liberated quarks and form a liquid state [1]. Results extracted from heavy-ion collision data are consistent with the scenario in which the QGP undergoes collective expansion, during which the dominant feature is its hydrodynamic response to the anisotropies in the initial state geometry. This phenomenon is known as anisotropic flow [2]. The collective dynamics of the QGP is sensitive to $\eta/s$ and $\zeta/s$, where $\eta$ and $\zeta$ are shear and bulk viscosities, and $s$ the entropy density. The overall success of hydrodynamic models to describe the heavy-ion data was pivotal in determining that the value of $\eta/s$ of the QGP is lower than that of any other liquid found in nature [3]. This conclusion established the perfect liquid paradigm, which is one of the most striking recent discoveries in high-energy physics [4–6].

In models that describe heavy-ion collisions the produced matter evolves collectively, with particles being emitted independently along the azimuthal direction with a distribution $f(\varphi)$. The Fourier series of this distribution is given by

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

where the flow amplitude $v_n$ and the symmetry plane angle $\Psi_n$ are two independent degrees of freedom to quantify anisotropic flow [7]. Experimental challenges of measuring these anisotropic flow observables are overcome with the development of multiparticle azimuthal correlations [8–12]. A great deal of additional information can be extracted from correlations between different flow amplitudes or different symmetry planes, or from observables which are sensitive to their intercorrelations [13–17].

The multiparticle observables which quantify the correlations between event-by-event fluctuations of two different flow amplitudes, the *Symmetric Cumulants* (SC), were studied in Refs. [12, 18]. That initial analysis focused only on the centrality dependence of correlations between lower order amplitudes using $\mathrm{SC}(k,l) \equiv \langle v_k^2 v_l^2\rangle - \langle v_k^2\rangle\langle v_l^2\rangle$, where the angular brackets denote an average over all events. It was later extended to higher orders (up to $5^{\text{th}}$ order) as well as to the transverse momentum ($p_{\mathrm{T}}$) dependence of correlations for the lower order amplitudes in Ref. [19]. These results revealed that correlations among different flow magnitudes depend on harmonic orders as well as the collision centrality, while showing moderate $p_{\mathrm{T}}$ dependence in semicentral collisions. It was found that the different $\mathrm{SC}(k,l)$ observables have different sensitivities to the initial conditions of a heavy-ion collision and the properties of the created system, while providing discriminating power in separating the effects of $\eta/s$ from the initial conditions in the final state particle anisotropies. In addition, the SC observables exhibit a better sensitivity to the temperature dependence $\eta/s(T)$ than the individual flow amplitudes, which are sensitive only to the average values $\langle\eta/s\rangle$ [18, 20].

In this paper, a new set of observables, dubbed *higher order SC*, are analyzed [21]. These higher order observables extract the genuine correlation among multiple flow amplitudes, and provide new and independent constraints for both the initial conditions and the QGP properties. The genuine correlation (or cumulant) of three flow amplitudes can be obtained with the following expression [21, 22]:

$$\mathrm{SC}(k,l,m) \equiv \left\langle v_k^2 v_l^2 v_m^2\right\rangle - \left\langle v_k^2 v_l^2\right\rangle\left\langle v_m^2\right\rangle - \left\langle v_k^2 v_m^2\right\rangle\left\langle v_l^2\right\rangle - \left\langle v_l^2 v_m^2\right\rangle\left\langle v_k^2\right\rangle + 2\left\langle v_k^2\right\rangle\left\langle v_l^2\right\rangle\left\langle v_m^2\right\rangle . \tag{2}$$

The observable $\mathrm{SC}(k,l,m)$ is, by definition, the 3rd order cumulant of three flow amplitudes $v_k^2$, $v_l^2$ and $v_m^2$. If the previously used low order flow observables, like $v_n\{2\}$, $v_n\{4\}$ [10] or $\mathrm{SC}(k,l)$ [12], would be able to characterize all collective correlations and anisotropic flow in the system, $\mathrm{SC}(k,l,m)$ would be identically zero. On the contrary, the non-vanishing results for $\mathrm{SC}(k,l,m)$ provide access to the information to which these traditionally used flow observables are insensitive. A further refinement can be achieved with the normalized versions of these observables defined as

$$\mathrm{NSC}(k,l,m) \equiv \frac{\mathrm{SC}(k,l,m)}{\langle v_k^2\rangle\langle v_l^2\rangle\langle v_m^2\rangle}\,, \tag{3}$$

which makes it easier to identify the origin of the correlations, either from the initial stage or from the collective expansion [21].

Another important aspect is the sign of the $\mathrm{SC}(k,l,m)$ observables which is not trivial and can be understood if the definition in Eq. (2) is rewritten as:

$$\mathrm{SC}(k,l,m) = \left\langle \left(v_k^2 - \langle v_k^2\rangle\right)\left(v_l^2 - \langle v_l^2\rangle\right)\left(v_m^2 - \langle v_m^2\rangle\right)\right\rangle\,. \tag{4}$$

For $\mathrm{SC}(k,l,m) > 0$ there are the following two distinct possibilities: a) if in an event it was found that $v_k^2 > \langle v_k^2\rangle$ and $v_l^2 > \langle v_l^2\rangle$, then the probability to find $v_m^2 > \langle v_m^2\rangle$ in that event is enhanced (this case is marked as $(+,+,+)$ pattern in the event-by-event flow fluctuations); b) if $v_k^2 > \langle v_k^2\rangle$ and $v_l^2 < \langle v_l^2\rangle$ in an event, that enhances the probability to find $v_m^2 < \langle v_m^2\rangle$ in that event and this is marked as $(+,-,-)$ pattern. By using the same reasoning, it can be concluded that $\mathrm{SC}(k,l,m) < 0$ permits only the $(+,+,-)$ and $(-,-,-)$ patterns. These persistent patterns of event-by-event flow fluctuations are invariant with respect to permutations of amplitudes of flow harmonics in the definition of $\mathrm{SC}(k,l,m)$, and they are a direct imprint of genuine three-harmonic correlations.

Since the flow amplitudes cannot be measured directly in an experiment, Eq. (2) can be used only in theoretical studies.

It was demonstrated in Ref. [21] that $\mathrm{SC}(k,l,m)$, as defined in Eq. (2), can be estimated reliably in an experiment with the following combination of azimuthal correlators:

$$\begin{aligned}
\mathrm{SC}(k,l,m) \;=\;& \langle\langle\cos[k\varphi_1+l\varphi_2+m\varphi_3-k\varphi_4-l\varphi_5-m\varphi_6]\rangle\rangle \\
-\;& \langle\langle\cos[k\varphi_1+l\varphi_2-k\varphi_3-l\varphi_4]\rangle\rangle\,\langle\langle\cos[m(\varphi_5-\varphi_6)]\rangle\rangle \\
-\;& \langle\langle\cos[k\varphi_1+m\varphi_2-k\varphi_5-m\varphi_6]\rangle\rangle\,\langle\langle\cos[l(\varphi_3-\varphi_4)]\rangle\rangle \\
-\;& \langle\langle\cos[l\varphi_3+m\varphi_4-l\varphi_5-m\varphi_6]\rangle\rangle\,\langle\langle\cos[k(\varphi_1-\varphi_2)]\rangle\rangle \\
+\;& 2\,\langle\langle\cos[k(\varphi_1-\varphi_2)]\rangle\rangle\,\langle\langle\cos[l(\varphi_3-\varphi_4)]\rangle\rangle\,\langle\langle\cos[m(\varphi_5-\varphi_6)]\rangle\rangle\,.
\end{aligned} \tag{5}$$

The double average notation indicates that in the first step averaging is performed over all distinct combinations of 2, 4, or 6 particles within the same event, and then these results are averaged over all events. Each azimuthal correlator in the above estimator can be measured efficiently and exactly with the Generic Framework published in Ref. [12]. By definition, this estimator ensures that large systematic biases from self-correlations and symmetry planes $\Psi_n$ are eliminated. In the absence of nonflow (correlations between a few particles unrelated to collective phenomena and anisotropic flow), it reduces analytically to Eq. (2), even for the case of large event-by-event flow fluctuations [21].

The results presented in this paper are obtained with the data sample from Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} =$ 2.76 TeV collected with the ALICE detector in 2010. After the event and track selection criteria are applied, the data sample corresponds to about $8.2 \times 10^6$ minimum bias events for the 0–50% centrality range.

A detailed description of the ALICE detector and its performance can be found in Refs. [23–26]. The time projection chamber (TPC) was used to reconstruct charged particles and measure their momenta with full azimuthal coverage in the pseudorapidity range $|\eta| < 0.8$ [27]. The inner tracking system (ITS) was also used in the reconstruction to improve the vertex determination and the momentum resolution, while its innermost part, the silicon pixel detector (SPD) [28, 29], provided the default centrality estimator in this analysis. Two scintillator arrays (V0A and V0C), which cover the pseudorapidity ranges

$2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively, were used for triggering and for an alternative determination of centrality [30–32]. The trigger conditions are identical to those described in Refs. [30, 33].

The event and track selection criteria are based on the previous lower order SC analyses [18, 19]. A requirement that the reconstructed primary vertex (PV) is within $\pm 10$ cm from the nominal interaction point along the beam axis is applied. The main analysis is performed using tracks reconstructed only with the TPC (referred to as TPC-only further in the text) in the kinematic range $0.2 < p_{\mathrm{T}} < 5.0$ GeV/$c$ and $|\eta| < 0.8$. The low $p_{\mathrm{T}}$ cutoff decreases the biases from the smaller reconstruction efficiency, while the high $p_{\mathrm{T}}$ cutoff reduces the anisotropic contaminations in the azimuthal distributions emerging from the jets. The selected tracks are reconstructed with a minimum of 70 space points out of the maximum of 159 in TPC and the $\chi^2/NDF$ of their momentum fit is required to be $0.1 < \chi^2/NDF < 4.0$. Furthermore, only tracks with a maximum distance of closest approach (DCA) to the primary vertex of 2.4 cm in the transverse plane and 3.2 cm along the beam axis are kept for the analysis. This choice of selection for the DCA reduces the contributions from secondary tracks. These criteria have already been used in Ref. [18] with hybrid tracks, for which the tracking information is combined from both the TPC and the ITS detectors to achieve the best transverse momentum resolution and to correct for the non-uniform azimuthal acceptance due to dead zones in the SPD [26, 34]. The tracks that appear to change abruptly the direction, e.g. due to multiple scattering or $K^{\pm}$ decays, are rejected. Using the previous selection criteria, the contamination from secondaries in TPC-only tracks varies from about 16% at 0.2 GeV/$c$ to about 7% at 5 GeV/$c$. The track reconstruction efficiency is almost constant at about 80–88% as a function of transverse momentum.

Corrections both for non-uniform reconstruction efficiency (NUE) as a function of transverse momentum and non-uniform acceptance (NUA) as a function of azimuthal angle are computed in form of particle weights to each individual azimuthal correlator in Eq. (5), by following the prescription outlined in Ref. [12]. Particle weights for NUE were obtained with the Monte Carlo generator HIJING (Heavy-Ion Jet INteraction Generator) [35], by comparing the $p_{\mathrm{T}}$ yields at reconstructed and generated level. On the other hand, particle weights for NUA are data driven, since due to random event-by-event fluctuations of the impact parameter vector (which is defined as a vector connecting two centers of colliding heavy-ions), the azimuthal distribution of produced particles averaged over all events must be flat for a detector with uniform azimuthal acceptance. Only corrections for NUE as a function of $p_{\mathrm{T}}$ are applied to all the tracks selected for the main analysis using the default selection criteria. Effects of NUA in the distribution of azimuthal angles of TPC-only tracks were also checked, but found to be negligible.

The estimator in Eq. (5) can be systematically biased due to nonflow correlations, which can be estimated with HIJING. This is a widely used Monte Carlo model to study particle production and jets in nuclear collisions that implements all relevant sources of nonflow correlations (jet production and fragmentation, particle decays, etc.), but has no collective effects like anisotropic flow. Therefore, it is an ideal realistic model to estimate the nonflow contribution in the $\mathrm{SC}(k,l,m)$ observables. The overall nonflow contribution to $\mathrm{SC}(k,l,m)$ exhibits the generic scaling as a function of multiplicity $M$, which can be parameterized as $\delta_3^{\mathrm{SC}} = \frac{\alpha}{M^5} + \frac{\beta}{M^4} + \frac{\gamma}{M^3}$, where $\alpha, \beta$ and $\gamma$ are three constants [21]. In heavy-ion collisions, characterized by large values of multiplicity, such contribution is well suppressed. For all $\mathrm{SC}(k,l,m)$ observables reported in this paper, HIJING results are compatible with zero for the centrality range 0–50% (for instance, predictions for SC(2,3,4) and SC(2,3,5) can be found in Fig. 7 of Ref. [21]).

The remaining systematic uncertainties are estimated by varying each criterion of the event and track selection independently. The values of $\mathrm{SC}(k,l,m)$ obtained after the variation are compared in each centrality interval with the ones from the default selection. The variation contributes to the systematic uncertainty if the difference between the two results lie more than one $\sigma$ away from zero. In the previous, $\sigma$ is the uncertainty of the difference, calculated considering the correlation between the two results. The total systematic uncertainty is obtained as the quadratic sum of all sources. The importance of each trial depends on the observable under consideration. The data sample was collected with two configurations of the magnetic field polarity in the solenoid magnet in which the ALICE central barrel detectors are embedded, giving two samples with similar numbers of events. As the main analysis uses both samples, the systematic effect is estimated individually for each orientation of the field polarity. No significant impact is seen in this case. In the next paragraph, the ranges of relative variations observed in semicentral collisions for each trial are reported. It has to be noted that the variations observed in collisions with a centrality up to 20%, and for $\mathrm{SC}(2,4,6)$ and $\mathrm{SC}(3,4,5)$ in the range 20–30%, can be larger than the ones indicated due to the small size of the signal and are therefore not reported. The systematic uncertainties are represented by the shaded boxes around each data point in all figures. On the other hand, there are variations which impact some, if not all, of the analysed combinations of $\mathrm{SC}(k,l,m)$. For example, the distance of the PV to the nominal interaction point along the beam direction when changed to $\pm6$ cm and to $\pm12$ cm does not impact half of the combinations, i.e. $\mathrm{SC}(2,3,5)$, $\mathrm{NSC}(2,3,5)$ and $\mathrm{SC}(3,4,5)$, but results to an uncertainty of about 3.2% for $\mathrm{SC}(2,3,4)$ and $\mathrm{NSC}(2,3,4)$. For the tightening the DCA criterion in the plane transverse to the beam direction from 2.4 cm to 1 cm and 2 cm, only $\mathrm{SC}(2,4,6)$ is not affected, while there is an effect of about 12% for $\mathrm{NSC}(2,3,4)$ to about 36% for $\mathrm{SC}(2,3,5)$. The default analysis uses the centrality estimated from the particle multiplicity in the SPD, while the systematic check is based on the determination of the centrality with the V0 detector. This change impacts the final results for all combinations with the exception of $\mathrm{SC}(3,4,5)$, with values ranging from about 15% for $\mathrm{SC}(2,3,4)$ and its normalised version to 21% for $\mathrm{SC}(2,3,5)$. The variation of the number of space points in the TPC, from at least 70 points to 50 and then to 100, leads to systematic bias in the final results in $\mathrm{SC}(2,3,4)$, $\mathrm{SC}(2,3,5)$ and $\mathrm{NSC}(2,3,5)$ ranging from 5% for $\mathrm{SC}(2,3,4)$ to 14% for $\mathrm{SC}(2,3,5)$. This is also the case for the quality of fit $\chi^2/NDF$, when the default range of $0.1 < \chi^2/NDF < 4.0$ is changed into $0.3 < \chi^2/NDF < 4.0$ and $0.1 < \chi^2/NDF < 3.5$. This leads to significant differences for $\mathrm{SC}(2,4,6)$, $\mathrm{SC}(3,4,5)$ and $\mathrm{NSC}(2,3,5)$ (about 12% for $\mathrm{NSC}(2,3,5)$), and for the tightening of the DCA criterion along the beam axis from 3.2 cm to 2.1 cm with $\mathrm{SC}(2,3,5)$ and its normalised version (about 8–10%). Finally, non-negligible systematic effects can be seen using hybrid tracks, which also contain smaller contamination from secondaries, leading to an estimation of their systematic effects in the default selection. For this last systematic check, all combinations see significant changes (between 4% and 19% for $\mathrm{SC}(2,3,4)$ and $\mathrm{NSC}(2,3,5)$, respectively).

The centrality dependence of $\mathrm{SC}(k,l,m)$ and $\mathrm{NSC}(k,l,m)$ for the different combinations of flow amplitudes is shown in Fig. 1 (a) and Fig. 1 (b), respectively. When moving from central to semicentral collisions, the deviation from zero of both $\mathrm{SC}(2,3,4)$ and $\mathrm{SC}(2,3,5)$ becomes stronger, albeit with opposite sign. These non-zero values for semicentral collisions are the first experimental indications of genuine correlations between three flow amplitudes. The results for $\mathrm{SC}(2,3,5)$ provide new and independent constraints on the non-linear response contribution in $v_5$ from $v_2$ and $v_3$, which for the first time do not require any assumption in the derivation on the nature of two-harmonic correlations [36]. For the higher order flow amplitudes, the measurements for $\mathrm{SC}(2,4,6)$ and $\mathrm{SC}(3,4,5)$ are compatible with zero for all centralities. The negative increasing trend observed for $\mathrm{SC}(2,3,4)$ is also present for $\mathrm{NSC}(2,3,4)$ (Fig. 1(b)). However, this is not the case for the pair $\mathrm{SC}(2,3,5)$ and $\mathrm{NSC}(2,3,5)$. The increase seen in the former cannot be found in the latter, which shows a decrease for semicentral events. This different behavior originates from the fact that the non-linear response introduces a genuine correlation among all three amplitudes in SC(2,3,5), while such contribution is not present in SC(2,3,4). The signatures of all observables hold for the whole centrality range within uncertainties.

The results for the higher order SC observables are compared with the event-by-event Eskola-Kajantie-Ruuskanen-Tuominen (EKRT)+viscous [20] and T$_\mathrm{R}$ENTo + iEBE-VISHNU hydrodynamic models [37]. In the EKRT model, the initial energy density profiles are calculated using a next-to-leading order perturbative-QCD+saturation model [38, 39]. The subsequent space–time evolution is described by relativistic dissipative fluid dynamics with different temperature parameterizations $\eta/s(T)$. This state-of-the-art model gives a good description of the charged hadron multiplicity and the low-$p_\mathrm{T}$ region of the charged hadron spectra at BNL's Relativistic Heavy Ion Collider and at CERN's Large Hadron Collider

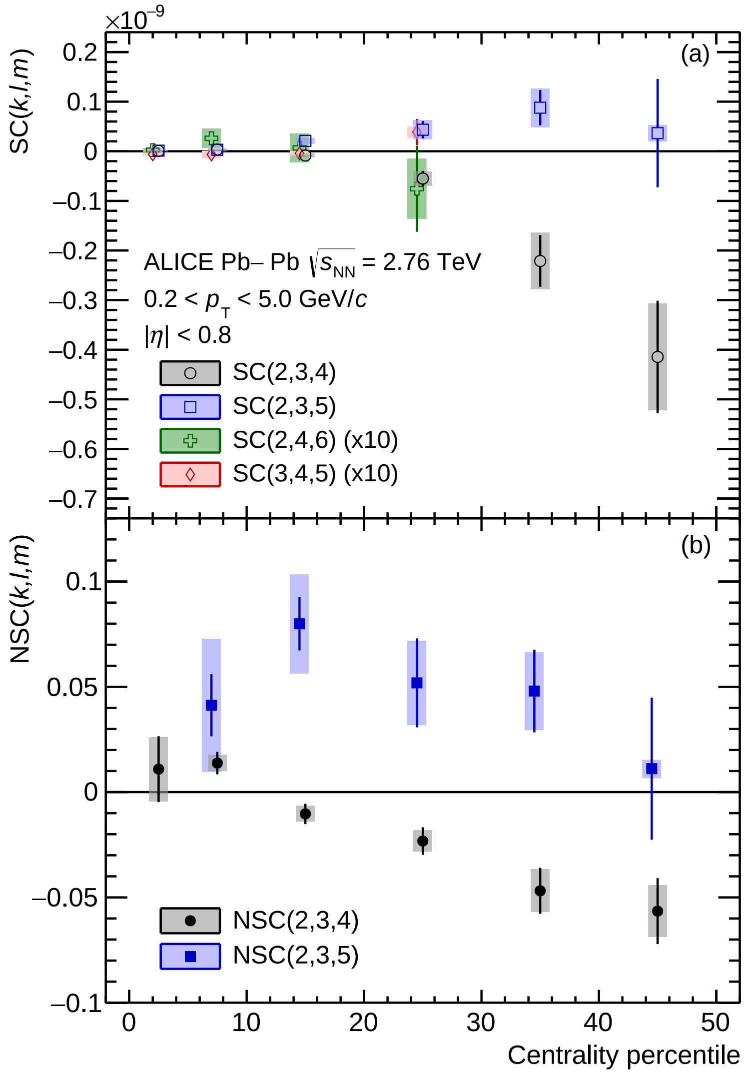


**Figure 1:** Centrality dependence of SC(2,3,4), SC(2,3,5), SC(2,4,6) and SC(3,4,5) (a) and of NSC(2,3,4) and NSC(2,3,5) (b) in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV. The statistical (systematic) uncertainties are shown with the lines (boxes).

(see Figs. 11–13 in Ref. [20]). Each of the $\eta/s(T)$ parameterizations is adjusted to reproduce the measured $v_n$ from central to semiperipheral collisions (see Fig. 15 in Ref. [20] and Fig. A.2 in Ref. [19]). For the "param1" parameterization of $\eta/s(T)$, the phase transition from the hadronic to the QGP phase occurs at the lowest temperature, around 150 MeV [20]. This parameterization is also characterized by a moderate slope in $\eta/s(T)$ which decreases (increases) in the hadronic (QGP) phase. The model calculations in which the temperature of the phase transition is larger than for "param1" parameterization are ruled out by the previous measurements [18, 19]. In the study presented in this paper, the EKRT prediction for the centrality dependence of SC$(k,l,m)$ was obtained from a sample consisting of 40k events in the 0–100% centrality range.

The calculations for the $\eta/s(T) =$ "param1" parametrisation, which gives a good description of the lower order SC results, are thus compared to our new results for higher order SC in Fig. 2. They can describe the overall trends of all combinations in the centrality dependence. However, SC$(2,4,6)$ is found to be strictly positive in models.

The hybrid hydrodynamic model T$_{\rm R}$ENTo+iEBE-VISHNU has successfully described the previous AL-

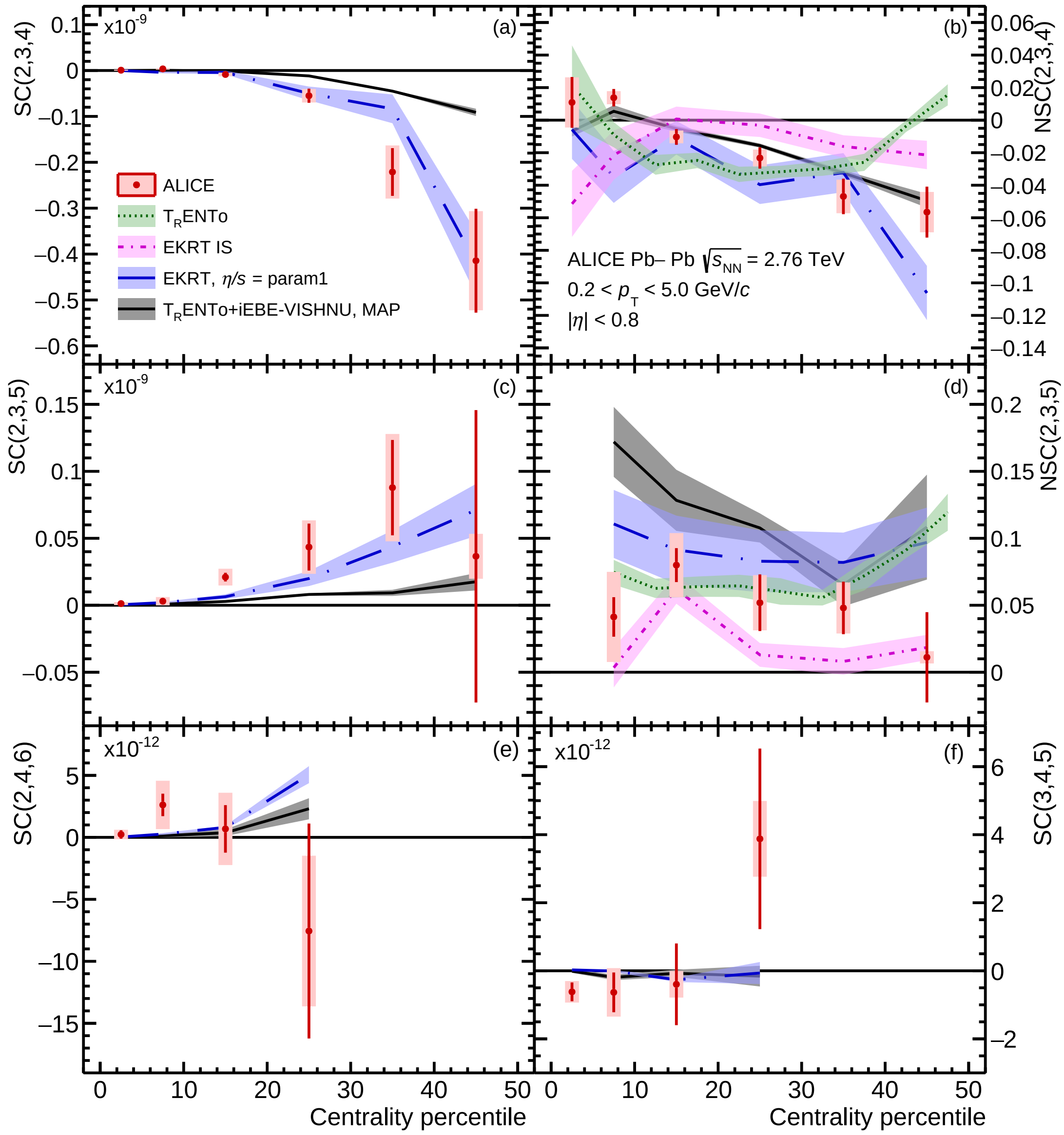


**Figure 2:** Predictions from the hydrodynamical models for the centrality dependence for the SC$(k,l,m)$ [panels (a), (c), (e) and (f)] and NSC$(k,l,m)$ [panels (b) and (d)] in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The statistical uncertainties are shown with coloured bands. The predictions are compared with the ALICE results from Fig. 1 shown with red markers.

ICE measurements [37]. It consists of the T$_{\rm R}$ENTo model [40] for the initial condition, which is connected with a free streaming to a 2+1 dimensional causal hydrodynamic model VISH2+1 [41, 42]. The evolution is continued after particlization via the UrQMD model [43, 44]. The initial conditions, $\eta/s(T)$, $\zeta/s(T)$ and other free parameters of the hybrid model are extracted by the global Bayesian analysis. We perform a model calculation with the best-fit parameter points chosen by maximum a posteriori (MAP) for Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV as they are reported in Ref. [37]. All the kinematic cuts such as transverse momentum and pseudorapidity intervals are matched with the data reported in this article.

In heavy-ion collisions, the main source of anisotropy in the azimuthal distribution in the final state originates from anisotropies in the initial state geometry. The initial state geometry can be described by quantities called eccentricities $\varepsilon_n$ which are the moments of the initial energy (or entropy) density. For instance, the values of $\varepsilon_2$ and $\varepsilon_3$ indicate to what extent the initial geometry is elliptical and triangular, respectively. For small values of eccentricities, one can approximate the response of the collective evolution to the initial state as a linear relation $v_n = k_n \varepsilon_n$ [45, 46]. For $n = 2,3$, this linear approximation is more accurate than for higher harmonics where non-linear terms play a non-negligible role [13]. If the higher order eccentricity cumulants are normalized by their averages (analogous to Eq. (3)), the response coefficients $k_n$ can cancel between numerator and denominator. Therefore, any difference in the NSC values calculated from the eccentricities in the initial state to those obtained from the measured flow amplitudes in the final state is an indication of a hydrodynamic non-linear response.

The comparison to the T$_{\rm R}$ENTo+iEBE-VISHNU calculation is shown in Fig. 2. The overall trends in the centrality dependence are captured by this model. Both SC(2,3,4) and SC(2,3,5) are clearly underestimated, while NSC(2,3,4) and NSC(2,3,5) are in a better agreement with the data. In the case of NSC($k$,$l$,$m$), predictions from T$_{\rm R}$ENTo for the initial state are also shown in Fig. 2. As iEBE-VISHNU uses T$_{\rm R}$ENTo as input, the comparisons between the two sets of predictions can give insights about the development of correlations in the system. The relative change in NSC(2,3,4) for iEBE-VISHNU calculations from the ones from T$_{\rm R}$ENTo for 10–30% centralities indicates that the correlations have developed during the hydrodynamic evolution of the medium. The same phenomenon is hinted within uncertainties in NSC(2,3,5). In this latter case, this can be explained by the non-linear response contribution to $v_5$ induced by the low order $v_2$ and $v_3$ found in Refs. [47, 48]. For SC(2,4,6) and SC(3,4,5), iEBE-VISHNU is in agreement with the predictions from EKRT within uncertainties.

Recent Bayesian analyses [37, 49] show that the T$_{\rm R}$ENTo model reproduces certain features of EKRT models with the energy deposition parameter, p $\approx$ 0.0. However, as it is shown in Fig. 2 (b) and Fig. 2 (d), the T$_{\rm R}$ENTo model shows stronger correlations than the EKRT model in semicentral collisions and the resulting SC($k$,$l$,$m$) show differences as well. Since the EKRT-hydro model does not include effects from bulk viscosity yet and the extracted bulk viscosities from two different Bayesian analyses give sizeable differences, more theoretical studies will be necessary to get any firm conclusions. In summary, we have presented the first measurements of event-by-event correlations between three flow amplitudes, obtained with higher order SC observables in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The non-zero values of $\mathrm{SC}(k,l,m)$ for semicentral collisions are the first experimental indication of genuine correlations between three flow amplitudes. The relative changes between T$_{\rm R}$ENTo and iEBE-VISHNU for NSC(2,3,4) and NSC(2,3,5) are consistent with the development of correlations during the collective evolution of the medium. A similar indication can be extracted from the EKRT model. These results provide new constraints on the non-linear response contribution in $v_5$ from $v_2$ and $v_3$. The new results for $\mathrm{SC}(k,l,m)$ provide independent constraints for the initial conditions, system properties, non-linear response and possible patterns of event-by-event flow fluctuations.

## Acknowledgements

The ALICE Collaboration would like to thank Harri Niemi for providing the latest predictions from the state-of-the-art hydrodynamic model.

The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF): [M 2467-N36] and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High

Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (Finep), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Universidade Federal do Rio Grande do Sul (UFRGS), Brazil; Ministry of Education of China (MOEC) , Ministry of Science & Technology of China (MSTC) and National Natural Science Foundation of China (NSFC), China; Ministry of Science and Education and Croatian Science Foundation, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research | Natural Sciences, the VILLUM FONDEN and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l'Energie Atomique (CEA) and Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS), France; Bundesministerium für Bildung und Forschung (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial Research (CSIR), India; Indonesian Institute of Science, Indonesia; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Institute for Innovative Science and Technology , Nagasaki Institute of Applied Science (IIST), Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Society for the Promotion of Science (JSPS) KAKENHI, Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Academico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Commission on Science and Technology for Sustainable Development in the South (COMSATS), Pakistan; Pontificia Universidad Católica del Perú, Peru; Ministry of Science and Higher Education, National Science Centre and WUT ID-UB, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics and Ministry of Research and Innovation and Institute of Atomic Physics, Romania; Joint Institute for Nuclear Research (JINR), Ministry of Education and Science of the Russian Federation, National Research Centre Kurchatov Institute, Russian Science Foundation and Russian Foundation for Basic Research, Russia; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; Suranaree University of Technology (SUT), National Science and Technology Development Agency (NSDTA) and Office of the Higher Education Commission under NRU project of Thailand, Thailand; Turkish Atomic Energy Agency (TAEK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and United States Department of Energy, Office of Nuclear Physics (DOE NP), United States of America.

## References

[1] B. Jacak and P. Steinberg, "Creating the perfect liquid in heavy-ion collisions", *Phys. Today* **63N5** (2010) 39–43.

[2] J.-Y. Ollitrault, "Anisotropy as a signature of transverse collective flow", *Phys. Rev.* **D46** (1992) 229–245.

[3] P. Kovtun, D. T. Son, and A. O. Starinets, "Viscosity in strongly interacting quantum field theories

from black hole physics”, *Phys. Rev. Lett.* **94** (2005) 111601, arXiv:hep-th/0405231 [hep-th].

[4] U. Heinz and R. Snellings, “Collective flow and viscosity in relativistic heavy-ion collisions”, *Ann. Rev. Nucl. Part. Sci.* **63** (2013) 123–151, arXiv:1301.2826 [nucl-th].

[5] P. Braun-Munzinger, V. Koch, T. Schäfer, and J. Stachel, “Properties of hot and dense matter from relativistic heavy ion collisions”, *Phys. Rept.* **621** (2016) 76–126, arXiv:1510.00442 [nucl-th].

[6] W. Busza, K. Rajagopal, and W. van der Schee, “Heavy Ion Collisions: The Big Picture, and the Big Questions”, *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 339–376, arXiv:1802.04801 [hep-ph].

[7] S. Voloshin and Y. Zhang, “Flow study in relativistic nuclear collisions by Fourier expansion of Azimuthal particle distributions”, *Z. Phys.* **C70** (1996) 665–672, arXiv:hep-ph/9407282 [hep-ph].

[8] S. Wang, Y. Z. Jiang, Y. M. Liu, D. Keane, D. Beavis, S. Y. Chu, S. Y. Fung, M. Vient, C. Hartnack, and H. Stoecker, “Measurement of collective flow in heavy ion collisions using particle pair correlations”, *Phys. Rev.* **C44** (1991) 1091–1095.

[9] J. Jiang *et al.*, “High order collective flow correlations in heavy ion collisions”, *Phys. Rev. Lett.* **68** (1992) 2739–2742.

[10] N. Borghini, P. M. Dinh, and J.-Y. Ollitrault, “Flow analysis from multiparticle azimuthal correlations”, *Phys. Rev.* **C64** (2001) 054901, arXiv:nucl-th/0105040 [nucl-th].

[11] A. Bilandzic, R. Snellings, and S. Voloshin, “Flow analysis with cumulants: Direct calculations”, *Phys. Rev.* **C83** (2011) 044913, arXiv:1010.0233 [nucl-ex].

[12] A. Bilandzic, C. H. Christensen, K. Gulbrandsen, A. Hansen, and Y. Zhou, “Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations”, *Phys. Rev.* **C89** no. 6, (2014) 064904, arXiv:1312.3572 [nucl-ex].

[13] H. Niemi, G. Denicol, H. Holopainen, and P. Huovinen, “Event-by-event distributions of azimuthal asymmetries in ultrarelativistic heavy-ion collisions”, *Phys. Rev. C* **87** no. 5, (2013) 054901, arXiv:1212.1008 [nucl-th].

[14] **ATLAS** Collaboration, G. Aad *et al.*, “Measurement of event-plane correlations in $\sqrt{s_{NN}} = 2.76$ TeV lead-lead collisions with the ATLAS detector”, *Phys. Rev. C* **90** no. 2, (2014) 024905, arXiv:1403.0489 [hep-ex].

[15] J. Jia, “Event-shape fluctuations and flow correlations in ultra-relativistic heavy-ion collisions”, *J. Phys. G* **41** no. 12, (2014) 124003, arXiv:1407.6057 [nucl-ex].

[16] **ATLAS** Collaboration, G. Aad *et al.*, “Measurement of the correlation between flow harmonics of different order in lead-lead collisions at $\sqrt{s_{NN}}$=2.76 TeV with the ATLAS detector”, *Phys. Rev. C* **92** no. 3, (2015) 034903, arXiv:1504.01289 [hep-ex].

[17] J. Qian and U. Heinz, “Hydrodynamic flow amplitude correlations in event-by-event fluctuating heavy-ion collisions”, *Phys. Rev. C* **94** no. 2, (2016) 024910, arXiv:1607.01732 [nucl-th].

[18] **ALICE** Collaboration, J. Adam *et al.*, “Correlated event-by-event fluctuations of flow harmonics in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV”, *Phys. Rev. Lett.* **117** (2016) 182301, arXiv:1604.07663 [nucl-ex].

[19] **ALICE** Collaboration, S. Acharya *et al.*, “Systematic studies of correlations between different order flow harmonics in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV”, *Phys. Rev.* **C97** no. 2, (2018) 024906, `arXiv:1709.01127 [nucl-ex]`.

[20] H. Niemi, K. Eskola, and R. Paatelainen, “Event-by-event fluctuations in a perturbative QCD + saturation + hydrodynamics model: Determining QCD matter shear viscosity in ultrarelativistic heavy-ion collisions”, *Phys. Rev. C* **93** no. 2, (2016) 024907, `arXiv:1505.02677 [hep-ph]`.

[21] C. Mordasini, A. Bilandzic, D. Karakoç, and S. F. Taghavi, “Higher order Symmetric Cumulants”, *Phys. Rev. C* **102** no. 2, (2020) 024907, `arXiv:1901.06968 [nucl-ex]`.

[22] R. Kubo, “Generalized Cumulant Expansion Method”, *Journal of the Physical Society of Japan* **17** (1962) 1100–1120.

[23] **ALICE** Collaboration, K. Aamodt *et al.*, “The ALICE experiment at the CERN LHC”, *JINST* **3** (2008) S08002.

[24] **ALICE** Collaboration, P. Cortese *et al.*, “ALICE: Physics performance report, volume I”, *J. Phys.* **G30** (2004) 1517–1763.

[25] **ALICE** Collaboration, P. Cortese *et al.*, “ALICE: Physics performance report, volume II”, *J. Phys.* **G32** (2006) 1295–2040.

[26] **ALICE** Collaboration, B. B. Abelev *et al.*, “Performance of the ALICE Experiment at the CERN LHC”, *Int. J. Mod. Phys.* **A29** (2014) 1430044, `arXiv:1402.4476 [nucl-ex]`.

[27] J. Alme *et al.*, “The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events”, *Nucl. Instrum. Meth.* **A622** (2010) 316–367, `arXiv:1001.1950 [physics.ins-det]`.

[28] **ALICE** Collaboration, G. Dellacasa *et al.*, “ALICE technical design report of the inner tracking system (ITS), CERN-LHCC-99-12”,.

[29] **ALICE** Collaboration, K. Aamodt *et al.*, “Alignment of the ALICE Inner Tracking System with cosmic-ray tracks”, *JINST* **5** (2010) P03003, `arXiv:1001.0502 [physics.ins-det]`.

[30] **ALICE** Collaboration, K. Aamodt *et al.*, “Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, *Phys. Rev. Lett.* **106** (2011) 032301, `arXiv:1012.1657 [nucl-ex]`.

[31] **ALICE** Collaboration, E. Abbas *et al.*, “Performance of the ALICE VZERO system”, *JINST* **8** (2013) P10016, `arXiv:1306.3130 [nucl-ex]`.

[32] **ALICE** Collaboration, J. Adam *et al.*, “Centrality dependence of the charged-particle multiplicity density at midrapidity in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV”, *Phys. Rev. Lett.* **116** no. 22, (2016) 222302, `arXiv:1512.06104 [nucl-ex]`.

[33] **ALICE** Collaboration, K. Aamodt *et al.*, “Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV”, *Phys. Rev. Lett.* **105** (2010) 252302, `arXiv:1011.3914 [nucl-ex]`.

[34] **ALICE** Collaboration, S. Acharya *et al.*, “Constraining the Chiral Magnetic Effect with charge-dependent azimuthal correlations in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 and 5.02 TeV”, *JHEP* **09** (2020) 160, `arXiv:2005.14640 [nucl-ex]`.

[35] M. Gyulassy and X.-N. Wang, “HIJING 1.0: A Monte Carlo program for parton and particle production in high-energy hadronic and nuclear collisions”, *Comput. Phys. Commun.* **83** (1994) 307, `arXiv:nucl-th/9502021 [nucl-th]`.

[36] L. Yan and J.-Y. Ollitrault, "$v_4, v_5, v_6, v_7$: nonlinear hydrodynamic response versus LHC data", *Phys. Lett. B* **744** (2015) 82–87, arXiv:1502.02502 [nucl-th].

[37] J. E. Bernhard, J. S. Moreland, and S. A. Bass, "Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma", *Nature Phys.* **15** no. 11, (2019) 1113–1117.

[38] R. Paatelainen, K. J. Eskola, H. Holopainen, and K. Tuominen, "Multiplicities and $p_T$ spectra in ultrarelativistic heavy ion collisions from a next-to-leading order improved perturbative QCD + saturation + hydrodynamics model", *Phys. Rev.* **C87** no. 4, (2013) 044904, arXiv:1211.0461 [hep-ph].

[39] R. Paatelainen, K. J. Eskola, H. Niemi, and K. Tuominen, "Fluid dynamics with saturated minijet initial conditions in ultrarelativistic heavy-ion collisions", *Phys. Lett.* **B731** (2014) 126–130, arXiv:1310.3105 [hep-ph].

[40] J. S. Moreland, J. E. Bernhard, and S. A. Bass, "Alternative ansatz to wounded nucleon and binary collision scaling in high-energy nuclear collisions", *Phys. Rev. C* **92** no. 1, (2015) 011901, arXiv:1412.4708 [nucl-th].

[41] C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass, and U. Heinz, "The iEBE-VISHNU code package for relativistic heavy-ion collisions", *Comput. Phys. Commun.* **199** (2016) 61–85, arXiv:1409.8164 [nucl-th].

[42] H. Song and U. W. Heinz, "Causal viscous hydrodynamics in 2+1 dimensions for relativistic heavy-ion collisions", *Phys. Rev. C* **77** (2008) 064901, arXiv:0712.3715 [nucl-th].

[43] S. Bass *et al.*, "Microscopic models for ultrarelativistic heavy ion collisions", *Prog. Part. Nucl. Phys.* **41** (1998) 255–369, arXiv:nucl-th/9803035.

[44] M. Bleicher *et al.*, "Relativistic hadron hadron collisions in the ultrarelativistic quantum molecular dynamics model", *J. Phys. G* **25** (1999) 1859–1896, arXiv:hep-ph/9909407.

[45] D. Teaney and L. Yan, "Triangularity and Dipole Asymmetry in Heavy Ion Collisions", *Phys. Rev.* **C83** (2011) 064904, arXiv:1010.1876 [nucl-th].

[46] F. G. Gardim, F. Grassi, M. Luzum, and J.-Y. Ollitrault, "Mapping the hydrodynamic response to the initial geometry in heavy-ion collisions", *Phys. Rev. C* **85** (2012) 024908, arXiv:1111.6538 [nucl-th].

[47] **ALICE** Collaboration, S. Acharya *et al.*, "Linear and non-linear flow modes in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV", *Phys. Lett. B* **773** (2017) 68–80, arXiv:1705.04377 [nucl-ex].

[48] **ALICE** Collaboration, S. Acharya *et al.*, "Higher harmonic non-linear flow modes of charged hadrons in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV", *JHEP* **05** (2020) 085, arXiv:2002.00633 [nucl-ex].

[49] J. E. Bernhard, J. S. Moreland, S. A. Bass, J. Liu, and U. Heinz, "Applying Bayesian parameter estimation to relativistic heavy-ion collisions: simultaneous characterization of the initial state and quark-gluon plasma medium", *Phys. Rev. C* **94** no. 2, 024907, arXiv:1605.03954 [nucl-th].

## A The ALICE Collaboration

S. Acharya[142], D. Adamová[97], A. Adler[75], J. Adolfsson[82], G. Aglieri Rinella[35], M. Agnello[31], N. Agrawal[55], Z. Ahammed[142], S. Ahmad[16], S.U. Ahn[77], Z. Akbar[52], A. Akindinov[94], M. Al-Turany[109], D.S.D. Albuquerque[124], D. Aleksandrov[90], B. Alessandro[60], H.M. Alfanda[7], R. Alfaro Molina[72], B. Ali[16], Y. Ali[14], A. Alici[26], N. Alizadehvandchali[127], A. Alkin[35], J. Alme[21], T. Alt[69], L. Altenkamper[21], I. Altsybeev[115], M.N. Anaam[7], C. Andrei[49], D. Andreou[92], A. Andronic[145], V. Anguelov[106], T. Antičić[110], F. Antinori[58], P. Antonioli[55], C. Anuj[16], N. Apadula[81], L. Aphecetche[117], H. Appelshäuser[69], S. Arcelli[26], R. Arnaldi[60], M. Arratia[81], I.C. Arsene[20], M. Arslandok[147,106], A. Augustinus[35], R. Averbeck[109], S. Aziz[79], M.D. Azmi[16], A. Badalà[57], Y.W. Baek[42], X. Bai[109], R. Bailhache[69], R. Bala[103], A. Balbino[31], A. Baldisseri[139], M. Ball[44], D. Banerjee[4], R. Barbera[27], L. Barioglio[25], M. Barlou[86], G.G. Barnaföldi[146], L.S. Barnby[96], V. Barret[136], C. Bartels[129], K. Barth[35], E. Bartsch[69], F. Baruffaldi[28], N. Bastid[136], S. Basu[82,144], G. Batigne[117], B. Batyunya[76], D. Bauri[50], J.L. Bazo Alba[114], I.G. Bearden[91], C. Beattie[147], I. Belikov[138], A.D.C. Bell Hechavarria[145], F. Bellini[35], R. Bellwied[127], S. Belokurova[115], V. Belyaev[95], G. Bencedi[70,146], S. Beole[25], A. Bercuci[49], Y. Berdnikov[100], A. Berdnikova[106], D. Berenyi[146], L. Bergmann[106], M.G. Besoiu[68], L. Betev[35], P.P. Bhaduri[142], A. Bhasin[103], I.R. Bhat[103], M.A. Bhat[4], B. Bhattacharjee[43], P. Bhattacharya[23], A. Bianchi[25], L. Bianchi[25], N. Bianchi[53], J. Bielčík[38], J. Bielčíková[97], A. Bilandzic[107], G. Biro[146], S. Biswas[4], J.T. Blair[121], D. Blau[90], M.B. Blidaru[109], C. Blume[69], G. Boca[29], F. Bock[98], A. Bogdanov[95], S. Boi[23], J. Bok[62], L. Boldizsár[146], A. Bolozdynya[95], M. Bombara[39], P.M. Bond[35], G. Bonomi[141], H. Borel[139], A. Borissov[83,95], H. Bossi[147], E. Botta[25], L. Bratrud[69], P. Braun-Munzinger[109], M. Bregant[123], M. Broz[38], G.E. Bruno[108,34], M.D. Buckland[129], D. Budnikov[111], H. Buesching[69], S. Bufalino[31], O. Bugnon[117], P. Buhler[116], P. Buncic[35], Z. Buthelezi[73,133], J.B. Butt[14], S.A. Bysiak[120], D. Caffarri[92], A. Caliva[109], E. Calvo Villar[114], J.M.M. Camacho[122], R.S. Camacho[46], P. Camerini[24], F.D.M. Canedo[123], A.A. Capon[116], F. Carnesecchi[26], R. Caron[139], J. Castillo Castellanos[139], E.A.R. Casula[23], F. Catalano[31], C. Ceballos Sanchez[76], P. Chakraborty[50], S. Chandra[142], W. Chang[7], S. Chapeland[35], M. Chartier[129], S. Chattopadhyay[142], S. Chattopadhyay[112], A. Chauvin[23], T.G. Chavez[46], C. Cheshkov[137], B. Cheynis[137], V. Chibante Barroso[35], D.D. Chinellato[124], S. Cho[62], P. Chochula[35], P. Christakoglou[92], C.H. Christensen[91], P. Christiansen[82], T. Chujo[135], C. Cicalo[56], L. Cifarelli[26], F. Cindolo[55], M.R. Ciupek[109], G. Clai[II,55], J. Cleymans[126], F. Colamaria[54], J.S. Colburn[113], D. Colella[54,146], A. Collu[81], M. Colocci[35,26], M. Concas[III,60], G. Conesa Balbastre[80], Z. Conesa del Valle[79], G. Contin[24], J.G. Contreras[38], T.M. Cormier[98], P. Cortese[32], M.R. Cosentino[125], F. Costa[35], S. Costanza[29], P. Crochet[136], E. Cuautle[70], P. Cui[7], L. Cunqueiro[98], A. Dainese[58], F.P.A. Damas[117,139], M.C. Danisch[106], A. Danu[68], I. Das[112], P. Das[88], P. Das[4], S. Das[4], S. Dash[50], S. De[88], A. De Caro[30], G. de Cataldo[54], L. De Cilladi[25], J. de Cuveland[40], A. De Falco[23], D. De Gruttola[30], N. De Marco[60], C. De Martin[24], S. De Pasquale[30], S. Deb[51], H.F. Degenhardt[123], K.R. Deja[143], L. Dello Stritto[30], S. Delsanto[25], W. Deng[7], P. Dhankher[19], D. Di Bari[34], A. Di Mauro[35], R.A. Diaz[8], T. Dietel[126], Y. Ding[7], R. Divià[35], D.U. Dixit[19], Ø. Djuvsland[21], U. Dmitrieva[64], J. Do[62], A. Dobrin[68], B. Dönigus[69], O. Dordic[20], A.K. Dubey[142], A. Dubla[109,92], S. Dudi[102], M. Dukhishyam[88], P. Dupieux[136], T.M. Eder[145], R.J. Ehlers[98], V.N. Eikeland[21], D. Elia[54], B. Erazmus[117], F. Ercolessi[26], F. Erhardt[101], A. Erokhin[115], M.R. Ersdal[21], B. Espagnon[79], G. Eulisse[35], D. Evans[113], S. Evdokimov[93], L. Fabbietti[107], M. Faggin[28], J. Faivre[80], F. Fan[7], A. Fantoni[53], M. Fasel[98], P. Fecchio[31], A. Feliciello[60], G. Feofilov[115], A. Fernández Téllez[46], A. Ferrero[139], A. Ferretti[25], A. Festanti[35], V.J.G. Feuillard[106], J. Figiel[120], S. Filchagin[111], D. Finogeev[64], F.M. Fionda[21], G. Fiorenza[54], F. Flor[127], A.N. Flores[121], S. Foertsch[73], P. Foka[109], S. Fokin[90], E. Fragiacomo[61], U. Fuchs[35], N. Funicello[30], C. Furget[80], A. Furs[64], M. Fusco Girard[30], J.J. Gaardhøje[91], M. Gagliardi[25], A.M. Gago[114], A. Gal[138], C.D. Galvan[122], P. Ganoti[86], C. Garabatos[109], J.R.A. Garcia[46], E. Garcia-Solis[10], K. Garg[117], C. Gargiulo[35], A. Garibli[89], K. Garner[145], P. Gasik[107], E.F. Gauger[121], M.B. Gay Ducati[71], M. Germain[117], J. Ghosh[112], P. Ghosh[142], S.K. Ghosh[4], M. Giacalone[26], P. Gianotti[53],

P. Giubellino[109,60], P. Giubilato[28], A.M.C. Glaenzer[139], P. Glässel[106], V. Gonzalez[144], L.H. González-Trueba[72], S. Gorbunov[40], L. Görlich[120], S. Gotovac[36], V. Grabski[72], L.K. Graczykowski[143], K.L. Graham[113], L. Greiner[81], A. Grelli[63], C. Grigoras[35], V. Grigoriev[95], A. Grigoryan[I,1], S. Grigoryan[76,1], O.S. Groettvik[21], F. Grosa[60], J.F. Grosse-Oetringhaus[35], R. Grosso[109], R. Guernane[80], M. Guilbaud[117], M. Guittiere[117], K. Gulbrandsen[91], T. Gunji[134], A. Gupta[103], R. Gupta[103], I.B. Guzman[46], R. Haake[147], M.K. Habib[109], C. Hadjidakis[79], H. Hamagaki[84], G. Hamar[146], M. Hamid[7], R. Hannigan[121], M.R. Haque[143,88], A. Harlenderova[109], J.W. Harris[147], A. Harton[10], J.A. Hasenbichler[35], H. Hassan[98], D. Hatzifotiadou[55], P. Hauer[44], L.B. Havener[147], S. Hayashi[134], S.T. Heckel[107], E. Hellbär[69], H. Helstrup[37], T. Herman[38], E.G. Hernandez[46], G. Herrera Corral[9], F. Herrmann[145], K.F. Hetland[37], H. Hillemanns[35], C. Hills[129], B. Hippolyte[138], B. Hohlweger[107], J. Honermann[145], G.H. Hong[148], D. Horak[38], S. Hornung[109], R. Hosokawa[15], P. Hristov[35], C. Huang[79], C. Hughes[132], P. Huhn[69], T.J. Humanic[99], H. Hushnud[112], L.A. Husova[145], N. Hussain[43], D. Hutter[40], J.P. Iddon[35,129], R. Ilkaev[111], H. Ilyas[14], M. Inaba[135], G.M. Innocenti[35], M. Ippolitov[90], A. Isakov[38,97], M.S. Islam[112], M. Ivanov[109], V. Ivanov[100], V. Izucheev[93], B. Jacak[81], N. Jacazio[35,55], P.M. Jacobs[81], S. Jadlovska[119], J. Jadlovsky[119], S. Jaelani[63], C. Jahnke[123], M.J. Jakubowska[143], M.A. Janik[143], T. Janson[75], M. Jercic[101], O. Jevons[113], M. Jin[127], F. Jonas[98,145], P.G. Jones[113], J. Jung[69], M. Jung[69], A. Junique[35], A. Jusko[113], P. Kalinak[65], A. Kalweit[35], V. Kaplin[95], S. Kar[7], A. Karasu Uysal[78], D. Karatovic[101], O. Karavichev[64], T. Karavicheva[64], P. Karczmarczyk[143], E. Karpechev[64], A. Kazantsev[90], U. Kebschull[75], R. Keidel[48], M. Keil[35], B. Ketzer[44], Z. Khabanova[92], A.M. Khan[7], S. Khan[16], A. Khanzadeev[100], Y. Kharlov[93], A. Khatun[16], A. Khuntia[120], B. Kileng[37], B. Kim[62], D. Kim[148], D.J. Kim[128], E.J. Kim[74], H. Kim[17], J. Kim[148], J.S. Kim[42], J. Kim[106], J. Kim[148], J. Kim[74], M. Kim[106], S. Kim[18], T. Kim[148], S. Kirsch[69], I. Kisel[40], S. Kiselev[94], A. Kisiel[143], J.L. Klay[6], J. Klein[35,60], S. Klein[81], C. Klein-Bösing[145], M. Kleiner[69], T. Klemenz[107], A. Kluge[35], A.G. Knospe[127], C. Kobdaj[118], M.K. Köhler[106], T. Kollegger[109], A. Kondratyev[76], N. Kondratyeva[95], E. Kondratyuk[93], J. Konig[69], S.A. Konigstorfer[107], P.J. Konopka[2,35], G. Kornakov[143], S.D. Koryciak[2], L. Koska[119], O. Kovalenko[87], V. Kovalenko[115], M. Kowalski[120], I. Králik[65], A. Kravčáková[39], L. Kreis[109], M. Krivda[113,65], F. Krizek[97], K. Krizkova Gajdosova[38], M. Kroesen[106], M. Krüger[69], E. Kryshen[100], M. Krzewicki[40], V. Kučera[35], C. Kuhn[138], P.G. Kuijer[92], T. Kumaoka[135], L. Kumar[102], S. Kundu[88], P. Kurashvili[87], A. Kurepin[64], A.B. Kurepin[64], A. Kuryakin[111], S. Kushpil[97], J. Kvapil[113], M.J. Kweon[62], J.Y. Kwon[62], Y. Kwon[148], S.L. La Pointe[40], P. La Rocca[27], Y.S. Lai[81], A. Lakrathok[118], M. Lamanna[35], R. Langoy[131], K. Lapidus[35], P. Larionov[53], E. Laudi[35], L. Lautner[35], R. Lavicka[38], T. Lazareva[115], R. Lea[24], J. Lee[135], J. Lehrbach[40], R.C. Lemmon[96], I. León Monzón[122], E.D. Lesser[19], M. Lettrich[35], P. Lévai[146], X. Li[11], X.L. Li[7], J. Lien[131], R. Lietava[113], B. Lim[17], S.H. Lim[17], V. Lindenstruth[40], A. Lindner[49], C. Lippmann[109], A. Liu[19], J. Liu[129], I.M. Lofnes[21], V. Loginov[95], C. Loizides[98], P. Loncar[36], J.A. Lopez[106], X. Lopez[136], E. López Torres[8], J.R. Luhder[145], M. Lunardon[28], G. Luparello[61], Y.G. Ma[41], A. Maevskaya[64], M. Mager[35], S.M. Mahmood[20], T. Mahmoud[44], A. Maire[138], R.D. Majka[I,147], M. Malaev[100], Q.W. Malik[20], L. Malinina[IV,76], D. Mal'Kevich[94], N. Mallick[51], P. Malzacher[109], G. Mandaglio[33,57], V. Manko[90], F. Manso[136], V. Manzari[54], Y. Mao[7], J. Mareš[67], G.V. Margagliotti[24], A. Margotti[55], A. Marín[109], C. Markert[121], M. Marquard[69], N.A. Martin[106], P. Martinengo[35], J.L. Martinez[127], M.I. Martínez[46], G. Martínez García[117], S. Masciocchi[109], M. Masera[25], A. Masoni[56], L. Massacrier[79], A. Mastroserio[140,54], A.M. Mathis[107], O. Matonoha[82], P.F.T. Matuoka[123], A. Matyja[120], C. Mayer[120], A.L. Mazuecos[35], F. Mazzaschi[25], M. Mazzilli[35,54], M.A. Mazzoni[59], A.F. Mechler[69], F. Meddi[22], Y. Melikyan[64], A. Menchaca-Rocha[72], C. Mengke[28,7], E. Meninno[116,30], A.S. Menon[127], M. Meres[13], S. Mhlanga[126], Y. Miake[135], L. Micheletti[25], L.C. Migliorin[137], D.L. Mihaylov[107], K. Mikhaylov[76,94], A.N. Mishra[146,70], D. Miśkowiec[109], A. Modak[4], N. Mohammadi[35], A.P. Mohanty[63], B. Mohanty[88], M. Mohisin Khan[16], Z. Moravcova[91], C. Mordasini[107], D.A. Moreira De Godoy[145], L.A.P. Moreno[46], I. Morozov[64], A. Morsch[35], T. Mrnjavac[35], V. Muccifora[53], E. Mudnic[36], D. Mühlheim[145], S. Muhuri[142], J.D. Mulligan[81], A. Mulliri[23], M.G. Munhoz[123], R.H. Munzer[69], H. Murakami[134], S. Murray[126], L. Musa[35],

J. Musinsky[65], C.J. Myers[127], J.W. Myrcha[143], B. Naik[50], R. Nair[87], B.K. Nandi[50], R. Nania[55], E. Nappi[54], M.U. Naru[14], A.F. Nassirpour[82], C. Nattrass[132], S. Nazarenko[111], A. Neagu[20], L. Nellen[70], S.V. Nesbo[37], G. Neskovic[40], D. Nesterov[115], B.S. Nielsen[91], S. Nikolaev[90], S. Nikulin[90], V. Nikulin[100], F. Noferini[55], S. Noh[12], P. Nomokonov[76], J. Norman[129], N. Novitzky[135], P. Nowakowski[143], A. Nyanin[90], J. Nystrand[21], M. Ogino[84], A. Ohlson[82], J. Oleniacz[143], A.C. Oliveira Da Silva[132], M.H. Oliver[147], A. Onnerstad[128], C. Oppedisano[60], A. Ortiz Velasquez[70], T. Osako[47], A. Oskarsson[82], J. Otwinowski[120], K. Oyama[84], Y. Pachmayer[106], S. Padhan[50], D. Pagano[141], G. Paić[70], A. Palasciano[54], J. Pan[144], S. Panebianco[139], P. Pareek[142], J. Park[62], J.E. Parkkila[128], S. Parmar[102], S.P. Pathak[127], B. Paul[23], J. Pazzini[141], H. Pei[7], T. Peitzmann[63], X. Peng[7], L.G. Pereira[71], H. Pereira Da Costa[139], D. Peresunko[90], G.M. Perez[8], S. Perrin[139], Y. Pestov[5], V. Petráček[38], M. Petrovici[49], R.P. Pezzi[71], S. Piano[61], M. Pikna[13], P. Pillot[117], O. Pinazza[55,35], L. Pinsky[127], C. Pinto[27], S. Pisano[53], M. Płoskoń[81], M. Planinic[101], F. Pliquett[69], M.G. Poghosyan[98], B. Polichtchouk[93], N. Poljak[101], A. Pop[49], S. Porteboeuf-Houssais[136], J. Porter[81], V. Pozdniakov[76], S.K. Prasad[4], R. Preghenella[55], F. Prino[60], C.A. Pruneau[144], I. Pshenichnov[64], M. Puccio[35], S. Qiu[92], L. Quaglia[25], R.E. Quishpe[127], S. Ragoni[113], A. Rakotozafindrabe[139], L. Ramello[32], F. Rami[138], S.A.R. Ramirez[46], A.G.T. Ramos[34], R. Raniwala[104], S. Raniwala[104], S.S. Räsänen[45], R. Rath[51], I. Ravasenga[92], K.F. Read[98,132], A.R. Redelbach[40], K. Redlich[V,87], A. Rehman[21], P. Reichelt[69], F. Reidt[35], R. Renfordt[69], Z. Rescakova[39], K. Reygers[106], A. Riabov[100], V. Riabov[100], T. Richert[82,91], M. Richter[20], P. Riedler[35], W. Riegler[35], F. Riggi[27], C. Ristea[68], S.P. Rode[51], M. Rodríguez Cahuantzi[46], K. Røed[20], R. Rogalev[93], E. Rogochaya[76], T.S. Rogoschinski[69], D. Rohr[35], D. Röhrich[21], P.F. Rojas[46], P.S. Rokita[143], F. Ronchetti[53], A. Rosano[33,57], E.D. Rosas[70], A. Rossi[58], A. Rotondi[29], A. Roy[51], P. Roy[112], N. Rubini[26], O.V. Rueda[82], R. Rui[24], B. Rumyantsev[76], A. Rustamov[89], E. Ryabinkin[90], Y. Ryabov[100], A. Rybicki[120], H. Rytkonen[128], W. Rzesa[143], O.A.M. Saarimaki[45], R. Sadek[117], S. Sadovsky[93], J. Saetre[21], K. Šafařík[38], S.K. Saha[142], S. Saha[88], B. Sahoo[50], P. Sahoo[50], R. Sahoo[51], S. Sahoo[66], D. Sahu[51], P.K. Sahu[66], J. Saini[142], S. Sakai[135], S. Sambyal[103], V. Samsonov[I,100,95], D. Sarkar[144], N. Sarkar[142], P. Sarma[43], V.M. Sarti[107], M.H.P. Sas[147,63], J. Schambach[98,121], H.S. Scheid[69], C. Schiaua[49], R. Schicker[106], A. Schmah[106], C. Schmidt[109], H.R. Schmidt[105], M.O. Schmidt[106], M. Schmidt[105], N.V. Schmidt[98,69], A.R. Schmier[132], R. Schotter[138], J. Schukraft[35], Y. Schutz[138], K. Schwarz[109], K. Schweda[109], G. Scioli[26], E. Scomparin[60], J.E. Seger[15], Y. Sekiguchi[134], D. Sekihata[134], I. Selyuzhenkov[109,95], S. Senyukov[138], J.J. Seo[62], D. Serebryakov[64], L. Šerkšnytė[107], A. Sevcenco[68], A. Shabanov[64], A. Shabetai[117], R. Shahoyan[35], W. Shaikh[112], A. Shangaraev[93], A. Sharma[102], H. Sharma[120], M. Sharma[103], N. Sharma[102], S. Sharma[103], O. Sheibani[127], A.I. Sheikh[142], K. Shigaki[47], M. Shimomura[85], S. Shirinkin[94], Q. Shou[41], Y. Sibiriak[90], S. Siddhanta[56], T. Siemiarczuk[87], T.F.D. Silva[123], D. Silvermyr[82], G. Simatovic[92], G. Simonetti[35], B. Singh[107], R. Singh[88], R. Singh[103], R. Singh[51], V.K. Singh[142], V. Singhal[142], T. Sinha[112], B. Sitar[13], M. Sitta[32], T.B. Skaali[20], G. Skorodumovs[106], M. Slupecki[45], N. Smirnov[147], R.J.M. Snellings[63], C. Soncco[114], J. Song[127], A. Songmoolnak[118], F. Soramel[28], S. Sorensen[132], I. Sputowska[120], J. Stachel[106], I. Stan[68], P.J. Steffanic[132], S.F. Stiefelmaier[106], D. Stocco[117], M.M. Storetvedt[37], C.P. Stylianidis[92], A.A.P. Suaide[123], T. Sugitate[47], C. Suire[79], M. Suljic[35], R. Sultanov[94], M. Šumbera[97], V. Sumberia[103], S. Sumowidagdo[52], S. Swain[66], A. Szabo[13], I. Szarka[13], U. Tabassam[14], S.F. Taghavi[107], G. Taillepied[136], J. Takahashi[124], G.J. Tambave[21], S. Tang[136,7], Z. Tang[130], M. Tarhini[117], M.G. Tarzila[49], A. Tauro[35], G. Tejeda Muñoz[46], A. Telesca[35], L. Terlizzi[25], C. Terrevoli[127], G. Tersimonov[3], S. Thakur[142], D. Thomas[121], R. Tieulent[137], A. Tikhonov[64], A.R. Timmins[127], M. Tkacik[119], A. Toia[69], N. Topilskaya[64], M. Toppi[53], F. Torales-Acosta[19], S.R. Torres[38], A. Trifiró[33,57], S. Tripathy[70], T. Tripathy[50], S. Trogolo[28], G. Trombetta[34], V. Trubnikov[3], W.H. Trzaska[128], T.P. Trzcinski[143], B.A. Trzeciak[38], A. Tumkin[111], R. Turrisi[58], T.S. Tveter[20], K. Ullaland[21], E.N. Umaka[127], A. Uras[137], M. Urioni[141], G.L. Usai[23], M. Vala[39], N. Valle[29], S. Vallero[60], N. van der Kolk[63], L.V.R. van Doremalen[63], M. van Leeuwen[92], P. Vande Vyvre[35], D. Varga[146], Z. Varga[146], M. Varga-Kofarago[146], A. Vargas[46], M. Vasileiou[86], A. Vasiliev[90], O. Vázquez Doce[107], V. Vechernin[115], E. Vercellin[25], S. Vergara Limón[46], L. Vermunt[63], R. Vértesi[146],

M. Verweij[63], L. Vickovic[36], Z. Vilakazi[133], O. Villalobos Baillie[113], G. Vino[54], A. Vinogradov[90], T. Virgili[30], V. Vislavicius[91], A. Vodopyanov[76], B. Volkel[35], M.A. Völkl[105], K. Voloshin[94], S.A. Voloshin[144], G. Volpe[34], B. von Haller[35], I. Vorobyev[107], D. Voscek[119], J. Vrláková[39], B. Wagner[21], M. Weber[116], A. Wegrzynek[35], S.C. Wenzel[35], J.P. Wessels[145], J. Wiechula[69], J. Wikne[20], G. Wilk[87], J. Wilkinson[109], G.A. Willems[145], E. Willsher[113], B. Windelband[106], M. Winn[139], W.E. Witt[132], J.R. Wright[121], Y. Wu[130], R. Xu[7], S. Yalcin[78], Y. Yamaguchi[47], K. Yamakawa[47], S. Yang[21], S. Yano[47,139], Z. Yin[7], H. Yokoyama[63], I.-K. Yoo[17], J.H. Yoon[62], S. Yuan[21], A. Yuncu[106], V. Yurchenko[3], V. Zaccolo[24], A. Zaman[14], C. Zampolli[35], H.J.C. Zanoli[63], N. Zardoshti[35], A. Zarochentsev[115], P. Závada[67], N. Zaviyalov[111], H. Zbroszczyk[143], M. Zhalov[100], S. Zhang[41], X. Zhang[7], Y. Zhang[130], V. Zherebchevskii[115], Y. Zhi[11], D. Zhou[7], Y. Zhou[91], J. Zhu[7,109], Y. Zhu[7], A. Zichichi[26], G. Zinovjev[3], N. Zurlo[141]

## Affiliation Notes

[I] Deceased
[II] Also at: Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy
[III] Also at: Dipartimento DET del Politecnico di Torino, Turin, Italy
[IV] Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear, Physics, Moscow, Russia
[V] Also at: Institute of Theoretical Physics, University of Wroclaw, Poland

## Collaboration Institutes

[1] A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
[2] AGH University of Science and Technology, Cracow, Poland
[3] Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine
[4] Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
[5] Budker Institute for Nuclear Physics, Novosibirsk, Russia
[6] California Polytechnic State University, San Luis Obispo, California, United States
[7] Central China Normal University, Wuhan, China
[8] Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
[9] Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
[10] Chicago State University, Chicago, Illinois, United States
[11] China Institute of Atomic Energy, Beijing, China
[12] Chungbuk National University, Cheongju, Republic of Korea
[13] Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovakia
[14] COMSATS University Islamabad, Islamabad, Pakistan
[15] Creighton University, Omaha, Nebraska, United States
[16] Department of Physics, Aligarh Muslim University, Aligarh, India
[17] Department of Physics, Pusan National University, Pusan, Republic of Korea
[18] Department of Physics, Sejong University, Seoul, Republic of Korea
[19] Department of Physics, University of California, Berkeley, California, United States
[20] Department of Physics, University of Oslo, Oslo, Norway

[21] Department of Physics and Technology, University of Bergen, Bergen, Norway
[22] Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, Italy
[23] Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
[24] Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
[25] Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
[26] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
[27] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
[28] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
[29] Dipartimento di Fisica e Nucleare e Teorica, Università di Pavia and Sezione INFN, Pavia, Italy
[30] Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
[31] Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
[32] Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy
[33] Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy
[34] Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
[35] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[36] Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
[37] Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway
[38] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[39] Faculty of Science, P.J. Šafárik University, Košice, Slovakia
[40] Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[41] Fudan University, Shanghai, China
[42] Gangneung-Wonju National University, Gangneung, Republic of Korea
[43] Gauhati University, Department of Physics, Guwahati, India
[44] Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
[45] Helsinki Institute of Physics (HIP), Helsinki, Finland
[46] High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
[47] Hiroshima University, Hiroshima, Japan
[48] Hochschule Worms, Zentrum für Technologietransfer und Telekommunikation (ZTT), Worms, Germany
[49] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[50] Indian Institute of Technology Bombay (IIT), Mumbai, India
[51] Indian Institute of Technology Indore, Indore, India
[52] Indonesian Institute of Sciences, Jakarta, Indonesia
[53] INFN, Laboratori Nazionali di Frascati, Frascati, Italy
[54] INFN, Sezione di Bari, Bari, Italy
[55] INFN, Sezione di Bologna, Bologna, Italy
[56] INFN, Sezione di Cagliari, Cagliari, Italy
[57] INFN, Sezione di Catania, Catania, Italy
[58] INFN, Sezione di Padova, Padova, Italy
[59] INFN, Sezione di Roma, Rome, Italy
[60] INFN, Sezione di Torino, Turin, Italy
[61] INFN, Sezione di Trieste, Trieste, Italy
[62] Inha University, Incheon, Republic of Korea
[63] Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef, Utrecht,

Netherlands
[64] Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
[65] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
[66] Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India
[67] Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[68] Institute of Space Science (ISS), Bucharest, Romania
[69] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[70] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
[71] Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
[72] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[73] iThemba LABS, National Research Foundation, Somerset West, South Africa
[74] Jeonbuk National University, Jeonju, Republic of Korea
[75] Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany
[76] Joint Institute for Nuclear Research (JINR), Dubna, Russia
[77] Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
[78] KTO Karatay University, Konya, Turkey
[79] Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie, Orsay, France
[80] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
[81] Lawrence Berkeley National Laboratory, Berkeley, California, United States
[82] Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
[83] Moscow Institute for Physics and Technology, Moscow, Russia
[84] Nagasaki Institute of Applied Science, Nagasaki, Japan
[85] Nara Women's University (NWU), Nara, Japan
[86] National and Kapodistrian University of Athens, School of Science, Department of Physics , Athens, Greece
[87] National Centre for Nuclear Research, Warsaw, Poland
[88] National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India
[89] National Nuclear Research Center, Baku, Azerbaijan
[90] National Research Centre Kurchatov Institute, Moscow, Russia
[91] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[92] Nikhef, National institute for subatomic physics, Amsterdam, Netherlands
[93] NRC Kurchatov Institute IHEP, Protvino, Russia
[94] NRC «Kurchatov»Institute - ITEP, Moscow, Russia
[95] NRNU Moscow Engineering Physics Institute, Moscow, Russia
[96] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
[97] Nuclear Physics Institute of the Czech Academy of Sciences, Řež u Prahy, Czech Republic
[98] Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
[99] Ohio State University, Columbus, Ohio, United States
[100] Petersburg Nuclear Physics Institute, Gatchina, Russia
[101] Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
[102] Physics Department, Panjab University, Chandigarh, India
[103] Physics Department, University of Jammu, Jammu, India
[104] Physics Department, University of Rajasthan, Jaipur, India
[105] Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
[106] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[107] Physik Department, Technische Universität München, Munich, Germany
[108] Politecnico di Bari and Sezione INFN, Bari, Italy
[109] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für

Schwerionenforschung GmbH, Darmstadt, Germany
[110] Rudjer Bošković Institute, Zagreb, Croatia
[111] Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
[112] Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
[113] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[114] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[115] St. Petersburg State University, St. Petersburg, Russia
[116] Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
[117] SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France
[118] Suranaree University of Technology, Nakhon Ratchasima, Thailand
[119] Technical University of Košice, Košice, Slovakia
[120] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[121] The University of Texas at Austin, Austin, Texas, United States
[122] Universidad Autónoma de Sinaloa, Culiacán, Mexico
[123] Universidade de São Paulo (USP), São Paulo, Brazil
[124] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
[125] Universidade Federal do ABC, Santo Andre, Brazil
[126] University of Cape Town, Cape Town, South Africa
[127] University of Houston, Houston, Texas, United States
[128] University of Jyväskylä, Jyväskylä, Finland
[129] University of Liverpool, Liverpool, United Kingdom
[130] University of Science and Technology of China, Hefei, China
[131] University of South-Eastern Norway, Tonsberg, Norway
[132] University of Tennessee, Knoxville, Tennessee, United States
[133] University of the Witwatersrand, Johannesburg, South Africa
[134] University of Tokyo, Tokyo, Japan
[135] University of Tsukuba, Tsukuba, Japan
[136] Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
[137] Université de Lyon, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon , Lyon, France
[138] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France
[139] Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Départment de Physique Nucléaire (DPhN), Saclay, France
[140] Università degli Studi di Foggia, Foggia, Italy
[141] Università di Brescia and Sezione INFN, Brescia, Italy
[142] Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India
[143] Warsaw University of Technology, Warsaw, Poland
[144] Wayne State University, Detroit, Michigan, United States
[145] Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany
[146] Wigner Research Centre for Physics, Budapest, Hungary
[147] Yale University, New Haven, Connecticut, United States
[148] Yonsei University, Seoul, Republic of Korea