Investigations of Anisotropic Flow Using Multiparticle Azimuthal Correlations in pp, p-Pb, Xe-Xe, and Pb-Pb Collisions at the LHC

Alice Collaboration

Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.123.142301

Publication date:
2019

Document version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
https://doi.org/10.1103/PhysRevLett.123.142301
Investigations of Anisotropic Flow Using Multiparticle Azimuthal Correlations in \( pp, p\text{-}Pb, \text{Xe}-\text{Xe}, \text{and} \ Pb\text{-}Pb \) Collisions at the LHC

S. Acharya et al.*

(A Large Ion Collider Experiment Collaboration)

(Received 11 March 2019; published 2 October 2019)

Measurements of anisotropic flow coefficients \( (v_n) \) and their cross-correlations using two- and multiparticle cumulant methods are reported in collisions of \( pp \) at \( \sqrt{s} = 13 \) TeV, \( p\text{-}Pb \) at a center-of-mass energy per nucleon pair \( \sqrt{s_{NN}} = 5.02 \) TeV, \( \text{Xe}\text{-Xe} \) at \( \sqrt{s_{NN}} = 5.44 \) TeV, and \( \text{Pb}\text{-Pb} \) at \( \sqrt{s_{NN}} = 5.02 \) TeV recorded with the ALICE detector. The multiplicity dependence of \( v_n \) is studied in a very wide range from 20 to 3000 particles produced in the midrapidity region \( |\eta| < 0.8 \) for the transverse momentum range \( 0.2 < p_T < 3.0 \) GeV/c. An ordering of the coefficients \( v_2 > v_3 > v_4 \) is found in \( pp \) and \( p\text{-}Pb \) collisions, similar to that seen in large collision systems, while a weak \( v_2 \) multiplicity dependence is observed relative to nucleus-nucleus collisions in the same multiplicity range. Using a novel subevent method, \( v_2 \) measured with four-particle cumulants is found to be compatible with that from six-particle cumulants in \( pp \) and \( p\text{-}Pb \) collisions. The magnitude of the correlation between \( v_2^2 \) and \( v_4^2 \), quantified by symmetric cumulants \( SC(m, n) \), evaluated with the symmetric cumulants \( SC(m, n) \) is observed to be positive at all multiplicities for \( v_2 \) and \( v_4 \), while for \( v_2 \) and \( v_3 \) it is negative and changes sign for multiplicities below 100, which may indicate a different \( v_n \) fluctuation pattern in this multiplicity range. The observed long-range multiparticle azimuthal correlations in high multiplicity \( pp \) and \( p\text{-}Pb \) collisions can neither be described by \textsc{pythia} 8 nor by impact-parameter-Glauber, \textsc{music}, and ultrarelativistic quantum molecular dynamics model calculations, and hence, provide new insights into the understanding of collective effects in small collision systems.

DOI: 10.1103/PhysRevLett.123.142301

Experiments investigating ultrarelativistic collisions of heavy ions intend to explore a deconfined state of quarks and gluons, the quark-gluon plasma (QGP). Azimuthal correlations of final state particles over a wide range in pseudorapidity relative to the collision symmetry plane \( \Psi_n \) (\( n \geq 1 \)), whose magnitudes are quantified by flow coefficients \( v_n \), provide important information into the matter created in these collisions [1–3]. Extensive measurements of \( v_n \) for inclusive [4–9] and identified hadrons [10] were performed for \( \text{Xe}\text{-Xe} \) and \( \text{Pb}\text{-Pb} \) collisions at the Large Hadron Collider (LHC). These studies, together with quantitative descriptions by hydrodynamic calculations, have enabled an extraction of the properties of the QGP [11], revealing that it behaves as a nearly perfect fluid with a shear viscosity over entropy density ratio \( \eta/s \) close to the universal lower limit \( 1/(4\pi) \) from AdS/CFT [12]. Recently, significant progress has also been achieved by measuring correlations between different flow coefficients and symmetry planes [6,7,13–18]. In particular, the correlation strength between different flow coefficients \( v_n^2 \) and \( v_m^2 \), quantified by symmetric cumulants \( SC(m, n) \) [19], was found to be sensitive to the temperature dependence of \( \eta/s \) and the initial conditions [14]. The experimental measurements of \( SC(m, n) \), together with \( v_n \), thus, provide tighter constraints on theoretical models than the individual flow coefficients alone [14,17].

Striking similarities between numerous observables, thought to indicate the emergence of a QGP, were observed across different collision systems at both RHIC and LHC energies, when compared at similar multiplicity of produced particles within a specific phase space [20–22]. The “ridge” structure measured using two-particle correlations as a function of the pseudorapidity difference \( \Delta\eta \) and the azimuthal angle difference \( \Delta\phi \), which in heavy-ion collisions results from anisotropic flow, was also observed in high multiplicity \( p\text{-}A \) and \( pp \) collisions [23]. In addition, measurements of azimuthal correlations using multiparticle cumulants revealed signatures’ collective effects in small systems, such as a negative four-particle cumulant \( c_2 \) [4] [24–28].

Whether the observed similarities between small (\( pp \) and \( p\text{-}A \)) and large (\( A\text{-}A \)) collision systems arise from the same physics mechanism is under intense debate. Besides hydrodynamic descriptions [29–33], calculations

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.
from transport models [34–36], hadronic rescattering [37,38], a string rope and shoving mechanism [39], as well as initial stage effects [40–42] have been investigated.

We report measurements of $v_n$ and SC($m,n$) as a function of produced particle multiplicity across small and large collision systems. These measurements provide information on the collective effects observed in all systems, which can be studied via long-range multiparticle correlations. A significant extension of recent studies [28,43,44] is achieved by adding new results of $v_2$ and SC($m,n$) for all available collision systems at the LHC, together with a comprehensive comparison to the available models ranging from nonflow dominated (PYTHIA 8) to the state of the art hydrodynamic model calculations. They rely on a new technique of performing multiparticle long range correlations named the subevent method [45,46], which is achieved by adding new results of subevents to the collective effects observed in all collision systems. A pronounced multiplicity dependence of the integrated $v_2$ is observed in the flow dominated collision systems (Pb-Pb and Xe-Xe) as a result of the medium response to the eccentricity of the initial overlap region of the colliding nuclei. The Pb-Pb data exhibit larger $v_2$ values and to reduce the contribution from jets, respectively. A criterion on the maximum distance of closest approach (DCA) of the track to the collision point of less than 2 cm in longitudinal direction and a $p_T$-dependent selection in the transverse direction, ranging from 0.2 cm at $p_T = 0.2$ GeV/$c$ down to 0.02 cm at $p_T = 3.0$ GeV/$c$, was applied leading to a residual contamination from secondaries between 1% and 3%.

The results were calculated from two- and multiparticle azimuthal correlations using the generic framework [19], recently extended to include the subevent method [46]. The ranges of the subevents were chosen to be ($-0.8,0.0$) and (0.0,0.8) for the two-subevent, and ($-0.8,-0.4$), ($-0.4,0.4$), and (0.4,0.8) for three-subevent measurements.

A correction dependent on $\eta$ and $Z_{\text{vtx}}$ was applied to account for azimuthal nonuniformity. The correction for tracking inefficiencies was obtained from Monte Carlo simulations as a function of $p_T$, $\eta$, and $Z_{\text{vtx}}$ from generated particles and from tracks reconstructed from a GEANT3 simulation [52]. The systematic uncertainties were estimated as follows. The contribution from the event selection was examined by narrowing the selection on $Z_{\text{vtx}}$ to $\pm 5$ cm. The track reconstruction biases were evaluated by tightening the selection criteria on the DCA in both the longitudinal and transverse directions, by increasing the required minimum number of TPC clusters in the track reconstruction, and by comparing the results to those obtained with tracks having different requirements regarding the role of the ITS. The uncertainty from the Monte Carlo simulation was estimated by comparing calculations at the event generator level with the simulation output after the full reconstruction. The individual contributions were summed in quadrature to form the systematic uncertainties, ranging between 1%–6% for the two-particle cumulant, and 10%–17% for the multi-particle cumulant results. The results are reported as a function of the number of produced charged particles $N_C(\eta < 0.8,0.2 < p_T < 3.0$ GeV/$c$).

Figure 1 presents the measurements of anisotropic flow coefficients $v_n(k)$ of order $n$, obtained from $k$-particle correlations, in $pp$, $p$-Pb, Xe-Xe, and Pb-Pb collisions. The collision energies are similar except for $pp$ collisions, where no collision energy dependence of the integrated $v_n$ is expected [27].

Figures 1(a)–1(c) show $v_2$, $v_3$, and $v_4$ measured using two-particle ($k=2$) cumulants with a pseudorapidity separation $|\Delta \eta| > 1.4, 1.0$, and 1.0, respectively, chosen to suppress nonflow contributions. Because of the limited statistics of the $pp$ data sample, the $|\Delta \eta|$ separation in the cases of $v_3$ and $v_4$ was reduced to 1.0, consistently across all collision systems. A pronounced multiplicity dependence of $v_2$ is observed in the flow dominated collision systems (Pb-Pb and Xe-Xe) as a result of the medium response to the eccentricity of the initial overlap region of the colliding nuclei. The Pb-Pb data exhibit larger $v_2$ values...
than the Xe-Xe data, but they are compatible for \(N_{ch} < 200\). An ordering of \(v_2 > v_3 > v_4\) is observed in large systems except for the very high multiplicities, where \(v_2 \approx v_3\). At low multiplicity, the magnitudes of \(v_n\) are similar to those measured in \(pp\) and \(p-Pb\) collisions. The measurements from large systems are compared with calculations using impact-parameter Glasma (IP-Glasma) initial conditions, MUSIC hydrodynamic model, and the ultrarelativistic quantum molecular dynamics (UrQMD) model for hadronic rescatterings [31,54]. The calculations qualitatively describe all the \(v_n\) measurements except for \(N_{ch} < 200\) where they overestimate the \(v_2\).

In small collision systems, all the \(v_n\) coefficients exhibit a weak dependence on multiplicity. The trend and magnitudes, particularly for \(v_2\), cannot be explained solely by model calculations without collective effects. This can be demonstrated by the comparison with predictions from PYTHIA 8 [53], computed with a similar multiplicity definition as the experimental results from \(pp\) collisions. The ordering of \(v_n\) in \(pp\) collisions for all multiplicities is the same as in large collision systems (\(v_2 > v_3 > v_4\)) and is not described by PYTHIA 8 where \(v_2 > v_4 > v_3\) for \(N_{ch} > 30\). These observations suggest the presence of effects other than just nonflow correlations at multiplicities larger than about 2–3 times the minimum bias value of \(\langle N_{ch} \rangle \approx 10\) in \(pp\) and \(\langle N_{ch} \rangle \approx 24\) in \(p-Pb\) collisions. In \(p-Pb\) collisions, these conclusions are further supported by the qualitative agreement with the IP-Glasma+MUSIC +UrQMD calculations. Nevertheless, the hydrodynamic model reveals a strong decrease of \(v_2\) with multiplicity in \(pp\) collisions, which is in stark contrast with the data. A further nonflow suppression with a larger \(|\Delta \eta|\) separation in the experimental results of \(p-Pb\) collisions, or improvements in the phenomenological description, might help to reach a quantitative agreement.

Figure 1(d) shows measurements of \(v_2(k)\) using cumulants with a number \(k = 4, 6\) and 8 particles. Measurements of \(v_2\{4\}\) with the three-subevent method, and of \(v_2\{6\}\) and \(v_2\{8\}\) in \(p-Pb\) collisions with the two-subevent method, are also presented. Compared to \(v_2\{2\}\), multiparticle cumulants are less influenced by nonflow effects, since the latter usually involve only a few particles. No further nonflow suppression was observed by increasing the \(|\Delta \eta|\) separation in the subevents in the multiparticle cumulant measurements. In Xe-Xe and Pb-Pb collisions, characteristic patterns of long-range multiparticle correlations, such as consistent results from the standard and subevent methods (\(v_2\{4\} \approx v_2\{4\}_3\)-sub, \(v_2\{6\} \approx v_2\{6\}_2\)-sub), and compatible measurements of \(v_2\) with multiparticle cumulants (\(v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}\)) are found, signaling a negligible contribution from nonflow correlations and the dominance of collective effects. Moreover, a good agreement of \(v_2\{4\}\) between data and calculations from the IP-Glasma+MUSIC+UrQMD [31,54] model is found for \(p-Pb\) collisions down to \(N_{ch} \approx 200\). The same model prediction, which does not include any tuning of its parameters to other collision systems, underestimates the \(v_2\{4\}\) from Xe-Xe collisions by about 15%–20%.

In \(p-Pb\) collisions, a further nonflow suppression with the three-subevent method leads to a decrease of the cumulant \(c_2\{4\}_3\)-sub, which, due to the relation \(v_2\{4\} = \sqrt{-c_2\{4\}}\), corresponds up to a 2\(\sigma\) increase \(v_2\{4\} < v_2\{4\}_3\)-sub. The three-subevent method allows for a measurement of a real-valued \(v_2\{4\}_3\)-sub at a lower \(N_{ch}\) than the standard \(v_2\{4\}\) measurement, making it possible to study collectivity at even lower multiplicities.
Genuine multiparticle correlations in \( p-Pb \) collisions are indicated by consistent results of \( v_2 \{4\} \) and \( v_2 \{6\} \). In \( pp \) collisions, significant nonflow contributions to the four-particle cumulant \( \langle v_2 \{4\} \rangle > 0 \) prevent the extraction of a real-valued \( v_2 \{4\} \). However, a measurement of the real-valued \( v_2 \{4\} \) \( _{3-sub} \) is possible with the three-subevent method. Similarly, for \( v_2 \{2,|\Delta \eta| > 1.4\} \), the \( v_2 \{4\} \) \( _{3-sub} \) exhibits only a weak dependence on multiplicity. These results confirm the existence of long-range multiparticle correlations in \( pp \) and \( p-Pb \) collisions at multiplicities \( N_{ch} \geq 30 \). PYTHIA 8 calculations, which do not contain genuine long-range multiparticle correlations, do not give a real valued \( v_2 \{4\} \) even with the subevent method \[45\]. The superSONIC \[32\] and iEBE-VISHNU \[33\] hydrodynamic models, which can quantitatively describe all available two-particle correlation measurements in \( pp \), \( p-Pb \), and \( Pb-Pb \) collisions, cannot reproduce the four-particle cumulants with the currently used initial state model, not even on a qualitative level. Another model with initial-state calculations predicts the multiparticle cumulants with correct signs and a weak dependence on the saturation scale \( Q_s^2 \), but the predictions are 10 times larger than what is observed in the data, and there is no direct connection of the \( v_2 \) to the experimentally measured number of produced charged particles \[41\]. Therefore, with \( v_{n} \) measurements alone, it is not completely clear whether the origin of the apparent collectivity observed in small collision systems is the same as in large collision systems.

Further information about the origin of the observed collectivity can be obtained from symmetric cumulants \( SC(m, n) \), which quantify the correlation between \( v_m^n \) and \( v_2^n \). Figures 2(a) and 2(c) present the multiplicity dependence of \( SC(m, n) \) measured with the three-subevent method. In Fig. 2(a), a positive \( SC(4, 2) \) \( _{3-sub} \) is observed in large systems over the entire multiplicity range, similar to what was measured previously in \( Pb-Pb \) collisions at 2.76 TeV \[14,17\] without the subevent method. The trend is reproduced by the IP-Glasma+MUSIC+UrQMD \[31,54\] calculations. A similar positive \( SC(4, 2) \) \( _{3-sub} \) is observed both in \( pp \) and \( p-Pb \) collisions, as was also found in \[44\]. The measurements in \( pp \) collisions are compared with PYTHIA 8 \[53\], which shows a decrease of \( SC(4, 2) \) \( _{3-sub} \) with decreasing multiplicity, different from what is seen in data. Calculations \[41,55\] with initial state correlations or parton-escape mechanism can qualitatively or even semi-quantitatively describe the \( p-Pb \) data. We note that the results from the initial state model \[41\] were calculated as a function of variables that cannot be directly computed from experimental data.

An anticorrelation between \( v_2^2 \) and \( v_2^3 \) is implied by the negative \( SC(3, 2) \) \( _{3-sub} \) observed in \( Xe-Xe \) and \( Pb-Pb \) collisions for \( N_{ch} > 100 \) in Fig. 2(c), similar to that in \[14,17\]. There is a hint of a change to a positive sign of \( SC(3, 2) \) \( _{3-sub} \) in \( Pb-Pb \) collisions below multiplicities of \( N_{ch} \approx 100 \). This tendency is observed at even lower multiplicities in small collision systems, suggesting a common positive correlation between \( v_2^2 \) and \( v_2^3 \) among collision systems of different sizes. Such a behavior is not observed for small collision systems with a larger \( \eta \) acceptance \[44\], where \( SC(3, 2) \) \( _{3-sub} \) remains negative in the whole multiplicity range. One possible explanation is the different contributions from nonflow effects. The IP-Glasma+MUSIC+UrQMD \[31,54\] calculations for \( Xe-Xe \) and \( Pb-Pb \) collisions reproduce the negative correlation at large multiplicities. This negative sign persists in simulations down to the lowest multiplicities. PYTHIA 8 \[53\] fails to quantitatively describe the results from \( pp \) collisions, but it does qualitatively reproduce the trend of the data.
No hydrodynamic calculations of SC($m,n$) in small systems are currently available. Nevertheless, calculations based on initial state correlations in [40,41] reflect the crossing from negative to positive SC(3,2) in p-Pb collisions, whereas a positive correlation is predicted in pp collisions [40].

While SC($m,n$) encodes information on both the magnitude of and correlation between the flow coefficients, in the absence of nonflow, the latter can be accessed directly by dividing SC($m,n$)$_{3\text{-sub}}$ by the corresponding flow coefficients ($v^m_n/v^n_n$). The normalized ratios, shown in Figs. 2(b) and 2(d), indicate that the correlation between flow coefficients is possibly the same between different collision systems at the same $N_{ch}$, and reveals a large increase in magnitude in the correlation strength for collisions with $N_{ch}<100$ compared to higher multiplicities. While this may be indicative of a different fluctuation pattern at low multiplicity, nonflow effects likely persist in this region based on the observed finite values of PYTHIA 8 calculations. Such effects make the interpretation of an increase of the normalized ratio significantly less straightforward and requires further study.

In summary, we have presented the measurements of flow coefficients $v_n(k)$ and symmetric cumulants SC($m,n$) as a function of the produced particle multiplicity in small (pp, p-Pb) and large (Xe-Xe, Pb-Pb) collision systems. In pp and p-Pb collisions, an ordering $v_2>v_3>v_4$ and a weak dependence of $v_n$ on the multiplicity, is observed. The values of $v_n$ from pp and p-Pb collisions are compatible with heavy-ion collisions at low multiplicities. These first ALICE measurements of $v_2$ using multiparticle cumulants in small collision systems are found to be compatible with each other after a suppression of nonflow contributions with the subevent method. Positive values of SC(4,2)$_{3\text{-sub}}$ are seen in all four collision systems (pp, p-Pb, Xe-Xe, and Pb-Pb). The observed anticorrelation between $v_2$ and $v_3$ measured with SC(3,2)$_{3\text{-sub}}$ in large collision systems seems to evolve into a positive correlation at low multiplicity. A similar sign change is also indicated in pp and p-Pb collisions. Thus, the different systems exhibit a similar SC($m,n$) at the same $N_{ch}$, and below $N_{ch}<100$, reveal a large variation of the correlation strength and/or an increasing contribution of nonflow. The measurements in pp collisions can not be reproduced by the PYTHIA 8 model. The hydrodynamic description with the IP-Glasma+MUSIC+UrQMD calculations shows rather good agreement with data in Pb-Pb, Xe-Xe, and p-Pb collisions, but fails to describe the measurements in pp collisions, where applicable. The presented data provide new information about the origin of the observed collectivity and provides key constraints to the various approaches for modeling collectivity in small systems.

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); [Grant No. 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), Universidade Federal do Rio Grande do Sul (UFRGS), Financiadora de Estudos e Projetos (Finep) and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Brazil; Ministry of Science & Technology of China (MSTC), National Natural Science Foundation of China (NSFC) and Ministry of Education of China (MOEC), China; Croatian Science Foundation and Ministry of Science and Education, 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 Carlsberg Foundation and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l’Energie Atomique (CEA), Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS) and Région des Pays de la Loire, France; Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (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; Centro Fermi—Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi and Istituto Nazionale di Fisica Nucleare (INFN), Italy; Institute for Innovative Science and Technology, Nagasaki Institute of Applied Science (IIST), Japan Society for the Promotion of Science (JSPS) KAKENHI and Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through
PHYSICAL REVIEW LETTERS 123, 142301 (2019)

Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Académico (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 and National Science Centre, 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 and Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; National Science and Technology Development Agency (NSTDA), Suranaree University of Technology (SUT) 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.

B. Abelev et al. (ALICE Collaboration), Multiparticle azimuthal correlations in $p$-$Pb$ and $Pb$-$Pb$ collisions at the CERN Large Hadron Collider, Phys. Rev. C 90, 054901 (2014).


H. Mäntysaari, B. Schenke, C. Shen, and P. Trzibedy, Imprints of fluctuating proton shapes on flow in proton-lead collisions at the LHC, Phys. Lett. B 772, 681 (2017); The results from $pp$ collisions are private communications based on this work.


R. Brun, F. Carminati, and S. Giani, GEANT Detector Description and Simulation Tool, CERN Program Library Long Write-up, W5013 (1994).


13 Chonbuk National University
14 Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics
15 COMSATS University Islamabad
16 Creighton University
17 Department of Physics, Aligarh Muslim University
18 Department of Physics, Pusan National University
19 Department of Physics, Sejong University
20 Department of Physics, University of California
21 Department of Physics, University of Oslo
22 Department of Physics and Technology, University of Bergen
23a Dipartimento di Fisica dell'Università ‘La Sapienza’
23b Sezione INFN
24a Dipartimento di Fisica dell’Università
24b Sezione INFN
25a Dipartimento di Fisica dell’Università
25b Sezione INFN
26a Dipartimento di Fisica dell’Università
26b Sezione INFN
27a Dipartimento di Fisica e Astronomia dell’Università
27b Sezione INFN
28a Dipartimento di Fisica e Astronomia dell’Università
28b Sezione INFN
29a Dipartimento di Fisica e Astronomia dell’Università
29b Sezione INFN
30a Dipartimento di Fisica ‘E.R. Caianiello’ dell’Università
30b Gruppo Collegato INFN
31 Dipartimento DISAT del Politecnico and Sezione INFN
32 Dipartimento di Scienze e Innovazione Tecnologica dell’Università del Piemonte Orientale and INFN Sezione di Torino
33a Dipartimento Interateneo di Fisica ‘M. Merlin’
33b Sezione INFN
34 European Organization for Nuclear Research (CERN)
35 Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split
36 Faculty of Engineering and Science, Western Norway University of Applied Sciences
37 Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague
38 Faculty of Science, P.J. Šafářik University
39 Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt
40 Gangneung-Wonju National University
41 Gauhati University, Department of Physics
42 Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn
43 Helsinki Institute of Physics (HIP)
44 High Energy Physics Group, Universidad Autónoma de Puebla
45 Hiroshima University
46 Hochschule Worms, Zentrum für Technologietransfer und Telekommunikation (ZTT)
47 Horia Hulubei National Institute of Physics and Nuclear Engineering
48 Indian Institute of Technology Bombay (IIT)
49 Indian Institute of Technology Indore
50 Indonesian Institute of Sciences
51 INFN, Laboratori Nazionali di Frascati
52 INFN, Sezione di Bari
53 INFN, Sezione di Bologna
54 INFN, Sezione di Cagliari
55 INFN, Sezione di Catania
56 INFN, Sezione di Padova
57 INFN, Sezione di Roma
58 INFN, Sezione di Torino
59 INFN, Sezione di Trieste
60 Inha University
61 Institut de Physique Nucléaire d’Orsay (IPNO), Institut National de Physique Nucléaire et de Physique des Particules (IN2P3/CNRS), Université de Paris-Sud, Université Paris-Saclay
62 Institute for Nuclear Research, Academy of Sciences
Institute for Subatomic Physics, Utrecht University/Nikhef
Institute for Theoretical and Experimental Physics
Institute of Experimental Physics, Slovak Academy of Sciences
Institute of Physics, Homi Bhabha National Institute
Institute of Physics of the Czech Academy of Sciences
Institute of Space Science (ISS)
Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México
Instituto de Física, Federal University of Rio Grande do Sul (UFRGS)
Instituto de Física, Universidad Nacional Autónoma de México
Thembisa LABS, National Research Foundation
Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik
Joint Institute for Nuclear Research (JINR)
Korea Institute of Science and Technology Information
KTO Karatay University
Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3
Lawrence Berkeley National Laboratory
Lund University Department of Physics, Division of Particle Physics
Nagasaki Institute of Applied Science
Nara Women’s University (NWU)
National and Kapodistrian University of Athens, School of Science, Department of Physics
National Centre for Nuclear Research
National Institute of Science Education and Research, Homi Bhabha National Institute
National Nuclear Research Center
National Research Centre Kurchatov Institute
Nagoya Institute of Applied Science
NRC Kurchatov Institute IEPE
NRNU Moscow Engineering Physics Institute
Nuclear Physics Group, STFC Daresbury Laboratory
Nuclear Physics Institute of the Czech Academy of Sciences
Oak Ridge National Laboratory
Ohio State University
Petersburg Nuclear Physics Institute
Physics department, Faculty of science, University of Zagreb
Physics Department, Panjab University
Physics Department, University of Jammu
Physics Department, University of Rajasthan
Physikalisches Institut, Eberhard-Karls-Universität Tübingen
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg
Physik Department, Technische Universität München
Politecnico di Bari
Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH
Rudjer Bošković Institute
Russian Federal Nuclear Center (VNIIEF)
Saha Institute of Nuclear Physics, Homi Bhabha National Institute
School of Physics and Astronomy, University of Birmingham
Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú
Shanghai Institute of Applied Physics
St. Petersburg State University
Stefan Meyer Institut für Subatomare Physik (SMI)
SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3
Suranaree University of Technology
Technical University of Košice
Technische Universität München, Excellence Cluster ‘Universe’
The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences
The University of Texas at Austin
Universidad Autónoma de Sinaloa
Universidade de Sao Paulo (USP)
Universidade Estadual de Campinas (UNICAMP)
Universidade Federal do ABC
University College of Southeast Norway
University of Cape Town
University of Houston
University of Jyväskylä
University of Liverpool
University of Science and Technology of China
University of Tennessee
University of the Witwatersrand
University of Tokyo
University of Tsukuba
Université Clermont Auvergne, CNRS/IN2P3, LPC
Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne
Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
Université Paris-Saclay Centre d’Études de Saclay (CEA), IRFU, Département de Physique Nucléaire (DPhN)
Università degli Studi di Foggia
Università degli Studi di Pavia
Università di Brescia
Variable Energy Cyclotron Centre, Homi Bhabha National Institute
Warsaw University of Technology
Wayne State University
Westfälische Wilhelms-Universität Münster, Institut für Kernphysik
Wigner Research Centre for Physics, Hungarian Academy of Sciences
Yale University
Yonsei University

"Deceased.
"Also at Dipartimento DET del Politecnico di Torino, Turin, Italy.
"Also at M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear, Physics, Moscow, Russia.
"Also at Department of Applied Physics, Aligarh Muslim University, Aligarh, India.
"Also at Institute of Theoretical Physics, University of Wroclaw, Poland.