Physics Letters B 807 (2020) 135564

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Global baryon number conservation encoded in net-proton fluctuations measured in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV

ALICE Collaboration *

ARTICLE INFO

Article history:
Received 6 May 2020
Received in revised form 8 June 2020
Accepted 13 June 2020
Available online 18 June 2020
Editor: L. Rolandi

ABSTRACT

Experimental results are presented on event-by-event net-proton fluctuation measurements in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, recorded by the ALICE detector at the CERN LHC. These measurements have as their ultimate goal an experimental test of Lattice QCD (LQCD) predictions on second and higher order cumulants of net-baryon distributions to search for critical behavior near the QCD phase boundary. Before confronting them with LQCD predictions, account has to be taken of correlations stemming from baryon number conservation as well as fluctuations of participating nucleons. Both effects influence the experimental measurements and are usually not considered in theoretical calculations. For the first time, it is shown that event-by-event baryon number conservation leads to subtle long-range correlations arising from very early interactions in the collisions.

Phase transitions in strongly interacting matter can be addressed by investigating the response of the system to external perturbations via measurements of fluctuations of conserved charges such as baryon number or electric charge [1,2]. At LHC energies there would be, for vanishing light quark masses (u and d quarks), a temperature-driven second order phase transition between a hadron gas and a quark–gluon plasma [3]. For realistic quark masses this transition becomes a smooth cross over [4,5]. However, because of the small masses of the current quarks, one can still probe critical phenomena at LHC energies (vanishing baryon chemical potential) as reported in [6]. Indeed, recent LQCD calculations [4,5] exhibit a rather strong signal for the existence of a pseudo-critical chiral temperature of about 156 MeV. Moreover, this pseudo-critical temperature is in agreement with the chemical freeze-out temperature as extracted by the analysis of hadron multiplicities [7,8] measured by the ALICE experiment. This implies that the strongly interacting matter created in central collisions of Pb nuclei at LHC energies freezes out very near the chiral phase transition line. Hence, the singularities arising from the second order phase transition can be captured by measuring fluctuations of conserved charges such as the net-baryon number. Evaluated within the framework of the Hadron Resonance Gas (HRG), net-baryon distributions coincide with the Skellam distribution, which is the probability distribution of the difference of two random variables, each generated from statistically independent Poisson distributions [9,10]. In fact, at the pseudo-critical temperature of 156 MeV, similar to the HRG framework, LQCD also predicts a Skellam behavior for the second cumulants of net-baryons, while the fourth cumulants of net-baryons from LQCD are significantly below the corresponding Skellam baseline [11,12].

Conserved quantities of course fluctuate only in sub-regions of the available total phase space of the reaction. In statistical mechanics they are, hence, analyzed within the Grand Canonical Ensemble (GCE) [13] formulation, where only the average number of net-baryons are conserved. In order to compare theoretical calculations within the GCE, such as the HRG [7] and LQCD [4,5], with experimental results, the data are analyzed in different acceptance windows by imposing selection criteria on rapidity and/or transverse momentum of the detected particles. Indeed, if the selected acceptance window is too small, possible dynamical correlations will be washed out and the measured fluctuations will approach the Poisson limit [14], implying that net-baryons will be distributed according to the Skellam distribution.

Recently the effects of limited acceptance were studied [15]. There, it was investigated under which conditions net-baryon fluctuations depend on the size of the acceptance. An obvious case is fluctuations caused by correlations due to baryon number conservation. To identify these and other long-range correlations it is interesting to perform the experimental analysis as a function of the acceptance size.

The analysis is set up by providing the necessary definitions. Given the number of baryons ($n_{\rm B}$) and antibaryons ($n_{\overline{\rm B}}$), the first and second cumulants of the net-baryon probability distribution $P(\Delta n_{\rm B})$, with $\Delta n_{\rm B} = n_{\rm B} - n_{\overline{\rm B}}$, are defined as

$$\kappa_1(\Delta n_{\rm B}) = \sum_{\Delta n_{\rm B}=-\infty}^{\infty} \Delta n_{\rm B} P(\Delta n_{\rm B}) = \langle \Delta n_{\rm B} \rangle \,, \tag{1}$$

---

* *E-mail address:* alice-publications@cern.ch.

https://doi.org/10.1016/j.physletb.2020.135564

$$\kappa_2(\Delta n_\mathrm{B}) = \sum_{\Delta n_\mathrm{B}=-\infty}^{\infty} (\Delta n_\mathrm{B} - \langle \Delta n_\mathrm{B} \rangle)^2 P(\Delta n_\mathrm{B}) = \left\langle (\Delta n_\mathrm{B} - \langle \Delta n_\mathrm{B} \rangle)^2 \right\rangle. \tag{2}$$

We note that, the first and second cumulants correspond to the expected value and the variance of net-baryon distribution, respectively. The second cumulant can be represented as a sum of the corresponding cumulants for single baryons and antibaryons plus the correlation term for the joint probability distributions of baryons and antibaryons $P(n_\mathrm{B}, n_{\bar{\mathrm{B}}})$

$$\kappa_2(\Delta n_\mathrm{B}) = \kappa_2(n_\mathrm{B}) + \kappa_2(n_{\bar{\mathrm{B}}}) - 2\left(\left\langle n_\mathrm{B} n_{\bar{\mathrm{B}}} \right\rangle - \langle n_\mathrm{B} \rangle \left\langle n_{\bar{\mathrm{B}}} \right\rangle\right), \tag{3}$$

where the mixed moment $\left\langle n_\mathrm{B} n_{\bar{\mathrm{B}}} \right\rangle$ is defined as

$$\left\langle n_\mathrm{B} n_{\bar{\mathrm{B}}} \right\rangle = \sum_{n_\mathrm{B}=0}^{\infty} \sum_{n_{\bar{\mathrm{B}}}=0}^{\infty} n_\mathrm{B} n_{\bar{\mathrm{B}}} P(n_\mathrm{B}, n_{\bar{\mathrm{B}}}). \tag{4}$$

Equation (3) shows that, for vanishing correlations between baryons and antibaryons ($\left\langle n_\mathrm{B} n_{\bar{\mathrm{B}}} \right\rangle = \langle n_\mathrm{B} \rangle \left\langle n_{\bar{\mathrm{B}}} \right\rangle$), the second cumulant of net-baryons is exactly equal to the sum of the corresponding second cumulants for baryons and antibaryons.

The data presented below were obtained by analyzing about 13×10^6 minimum-bias (cf. [16] for definition) Pb–Pb events at a center-of-mass energy per nucleon–nucleon pair of $\sqrt{s_\mathrm{NN}} = 2.76$ TeV recorded by the ALICE detector [17] in the year 2010. Two forward scintillator arrays (V0) are located on either side of the interaction point and cover the pseudorapidity intervals $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$ [18]. A minimum-bias trigger condition is defined by requiring a combination of hits in the two innermost layers of the ITS and coincidence in both V0 detectors. The event centrality is selected based on the signal amplitudes in the V0 detectors [18].

The detectors used for track reconstruction are the Time Projection Chamber (TPC) [19] and the Inner Tracking System (ITS) [20]. In order to keep the tracking efficiency as high as possible, only the TPC detector was used for particle identification, while precise vertex determination was performed with the ITS detector. The track selection criteria used are described in Section 3.1 of [21]. Charged particle tracks with at least 80 out of maximum of 159 specific energy loss ($\mathrm{d}E/\mathrm{d}x$) samples in the TPC were used in this analysis for the best particle identification. Moreover, in order to suppress contributions of secondary particles from weak decays, the distance-of-closest-approach (DCA) of the extrapolated track to the primary collision vertex was taken to be less than 2 cm along the beam direction. In the transverse plane, a more restrictive and transverse momentum (p_T) dependent DCA cut of less than (0.018 cm + $0.035 p_\mathrm{T}^{-1.01}$) with p_T in GeV/c, was imposed [22].

Since the energy loss of charged particles in the gas volume of the TPC depends explicitly on the particle momentum (p), the analysis was performed in momentum space. Correspondingly, the particle identification (PID) procedure consists of correlating particle momentum with the specific energy loss $\mathrm{d}E/\mathrm{d}x$. This allows the event-by-event fluctuation analysis to be performed with high overall reconstruction efficiency of about 80% for protons, almost independent of the collision centrality. The latter is important because small efficiencies induce Poisson fluctuations. To ensure the best possible $\mathrm{d}E/\mathrm{d}x$ resolution, the phase space coverage was restricted to $0.6 < p < 1.5$ GeV/c and $|\eta| < 0.8$ for the present analysis. The corresponding p_T range at $|\eta| = 0.8$ is about $0.45 < p_\mathrm{T} < 1.12$ GeV/c, which gradually approaches the used momentum range towards midrapidity. Moreover, a differential analysis is provided as function of $\Delta\eta$ in the range $\Delta\eta$ = 0.2 to 1.6.

The cumulants of net-protons were then reconstructed using the Identity Method (IM) [21,23–27]. This method is designed to deal efficiently with the overlapping $\mathrm{d}E/\mathrm{d}x$ distributions of protons, kaons, pions and electrons considered in the present analysis. Their specific probability distributions were obtained by unfolding the moments of the measured multiplicity distributions for each particle species. The IM counts proxies of particle multiplicities W_j event-by-event

$$W_j = \sum_{i=1}^{n} \frac{\rho_j(x_i)}{\rho(x_i)}, \quad \rho(x_i) = \sum_j \rho_j(x_i), \tag{5}$$

where j stands for a particle type, x_i denotes the measured values of $\mathrm{d}E/\mathrm{d}x$ for a given track i and $\rho_j(x)$ is the inclusive $\mathrm{d}E/\mathrm{d}x$ distribution of particle type j within a specified phase space bin. The summation in Eq. (5) runs over all selected n tracks in the given event. The pure and mixed moments of the W_j distributions were calculated by averaging over all events, leading to the moments of the true multiplicity distributions.

The IM is based on input of moments of W_j distributions and inclusive $\mathrm{d}E/\mathrm{d}x$ fits in bins of momentum and pseudorapidity. The $\mathrm{d}E/\mathrm{d}x$ distributions were fit with generalized Gaussian functions, taking into account non-Gaussian components of the experimental $\mathrm{d}E/\mathrm{d}x$ distributions. The fits of inclusive distributions of $\mathrm{d}E/\mathrm{d}x$ were performed separately for positively and negatively charged particles in 20 MeV/c momentum and 0.1 units of η bins.

In the upper panel of Fig. 1 the centrality dependence of the efficiency-corrected second cumulants of net-protons is compared with the sum of the mean multiplicities (first cumulants) of protons and antiprotons. Also included are the first and second cumulants of protons and antiprotons. The efficiency correction for the cumulants is performed by using proton and anti-proton efficiencies in analytic formulas derived in [28,29] assuming binomial efficiency losses. The characteristics of the ALICE detector response and applied analysis procedure ensures that this assumption is fulfilled. The accuracy of the correction procedure was estimated to be on the percent level and is included in the systematic uncertainties. We note that possible corrections for volume fluctuations such as discussed in [30,31] were not applied to the data since, at LHC energies, second cumulants of net protons, our main observable, are free from such effects [32].

The subsample approach was chosen to estimate the statistical uncertainties of the reconstructed cumulants [21,33]. In order to evaluate systematic uncertainties stemming from track selection criteria, the applied selection ranges were varied around their nominal values. Other sources of systematic uncertainties originate from the parameters of the $\rho_j(x_i)$ functions, entering Eq. (5). The latter was estimated by hypothesis testing using the Kolmogorov-Smirnov (K-S) statistics. For this purpose the parameters of the $\rho_j(x_i)$ functions were varied by testing the null hypothesis that measured $\mathrm{d}E/\mathrm{d}x$ distributions and fit functions are similar within a given significance level of 10% (cf. [21,33] for details). The final systematic uncertainties on cumulants were computed by adding in quadrature the maximum systematic variations from individual contributions.

By their definition, cumulants are extensive quantities, i.e., are proportional to the system volume. This also explains the centrality dependence of all cumulants, presented in the upper panel of Fig. 1. To remove the system size dependence, normalized cumulants R_1 and R_2 are introduced as

$$\mathrm{R}_1 = \kappa_2(n_\mathrm{p} - n_{\bar{\mathrm{p}}}) / < n_\mathrm{p} + n_{\bar{\mathrm{p}}} >, \quad \mathrm{R}_2 = \kappa_2(n_\mathrm{p}) / < n_\mathrm{p} > . \tag{6}$$

In the middle and bottom panels of Fig. 1, deviations from unity are visible for both R_1 and R_2. Moreover, the amount of deviation for R_2 is about twice as large compared to that of R_1.

In order to shed light on these observations, the results are compared with predictions from a model constructed recently [32],

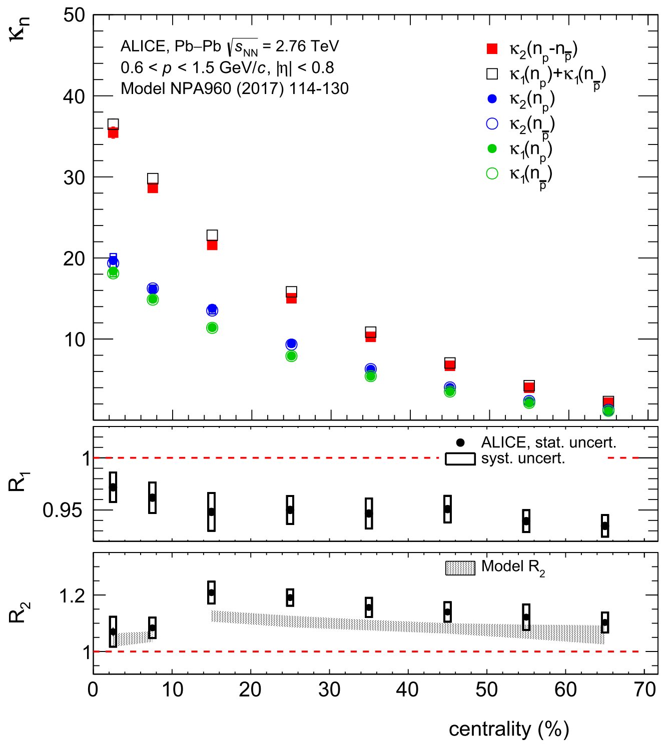

Fig. 1. Measured second cumulants of net-proton distributions (red solid boxes) compared with the sum of the mean multiplicities (open squares). The second cumulants of single proton and antiproton distributions are presented with the filled and open circles, respectively. The first cumulants of protons and antiprotons are hardly distinguishable because of the nearly equal mean numbers of protons and antiprotons at LHC energy. In the middle and bottom panels the normalized cumulants R_1 and R_2 are presented. The band visible in the bottom panel is the prediction for R_2 in the presence of volume fluctuations [32].

in which participant fluctuations are included following the analysis of the ALICE centrality selection [18]. Within uncertainties, the model predictions are fully consistent with the measured R_2 values, lending support to the interpretation that volume fluctuations are at the origin of the observed deviation. This is also supported by the observation of a small structure observed in the 10–20% centrality class, where, compared to the first two centrality classes, the centrality bin width is doubled.

On the other hand, by construction, for vanishing net-proton numbers, R_1 should not contain any contributions from volume fluctuations, i.e., the values of R_1 obtained from the model should be consistent with unity [32]. In fact at LHC energies R_1 becomes a strongly intensive quantity [34]. The origin for the deviation of the measured R_1 values from unity must therefore be beyond the volume fluctuations scenario. To further understand these differences, the acceptance dependence is studied.

The analysis is performed in eight different pseudorapidity intervals from $|\eta| < 0.1$ up to $|\eta| < 0.8$ in steps of 0.1. The obtained normalized second cumulants R_1 of net-protons are presented in Fig. 2. Again the data are below unity, with the deviation linearly increasing with increasing acceptance.

Such a behavior was predicted based on the assumption of global baryon number conservation [32,36,37], which induces correlations between protons and antiprotons leading to the following dependence on the acceptance factor α

$$\mathrm{R}_1 = 1 - \alpha, \tag{7}$$

where $\alpha = \langle n_{\mathrm{p}} \rangle / \langle N_{\mathrm{B}}^{4\pi} \rangle$ with $\langle n_{\mathrm{p}} \rangle$ and $\langle N_{\mathrm{B}}^{4\pi} \rangle$ referring to the mean number of protons inside the acceptance and the mean number of baryons in full phase space. It should be further noted that, for non-central collisions, baryon transport to mid-rapidity has to be taken into account, which is rather model dependent. In order to avoid the model dependence, the comparison is performed only for the central events and in the estimate of the alpha parameter only produced baryons are used. In doing so, the number of baryons are used in the pseudorapidity range of $|\eta| < 0.5$ as reported in [16,38–40]. Next, using HIJING and AMPT simulations, estimates were obtained for the total average number of baryons in full phase space. The average number of protons $\langle n_{\mathrm{p}} \rangle$ entering into the definition of α (cf. Eq. (7)) was taken from the current analysis for each pseudorapidity interval. Finally, using these values of α, the pink band in Fig. 2 is calculated with Eq. (7). The finite width of the band reflects the difference between predictions of the two event generators.

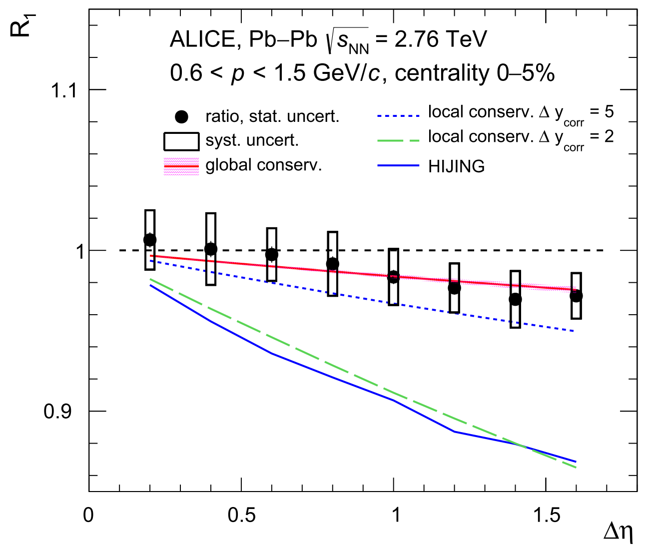

Fig. 2. Pseudorapidity dependence of the normalized second cumulants of net-protons R_1. Global baryon number conservation is depicted as the pink band. The dashed lines represent the predictions from the model with local baryon number conservation [35]. The blue solid line, represents the prediction using the HIJING generator.

Inspection of Fig. 2 shows that, for small pseudorapidity ranges of $|\eta| < 0.4$ corresponding to $\Delta\eta < 0.8$, the experimentally measured net-proton distributions closely follow a Skellam distribution. This agreement is expected because of the small acceptance window as discussed above. For $\Delta\eta > 0.8$, deviations from the Skellam distribution are observed. The amount of deviation is small but significant and in good agreement with the prediction assuming global baryon number conservation. The observed deviation is therefore consistent with the assumption of global baryon number conservation, i.e. conservation within the full phase space.

On the other hand, local baryon number conservation may induce additional correlations between protons and antiprotons, which would lead to a further reduction of the measured $\kappa_2(n_{\mathrm{p}} - n_{\bar{\mathrm{p}}})$ [35]. In Fig. 2 the data are compared to the predictions from an analysis of effects of local baryon number conservation for different values of correlation width Δy_{corr} between protons and antiprotons. Within the experimental uncertainties the data are best described with the assumption of global baryon number conservation, which corresponds to the correlation width $\Delta y_{\mathrm{corr}} = 2|y_{\mathrm{beam}}|$ but, within one standard deviation (1.56 for the last point at $\Delta\eta = 1.6$), the data are also consistent with a large correlation width of $\Delta y_{\mathrm{corr}} = 5$ [35]. We find that for $\Delta y_{\mathrm{corr}} = 4.5$, with a 5% significance level, the last point is not consistent with the experimental data. The results from the HIJING event generator (cf. blue solid line in Fig. 2), which can be described with $\Delta y_{\mathrm{corr}} = 2$, and from a recent study reported in [41] would imply much stronger correlations between protons and antiprotons, not consistent with the experimental data. We note here that correlations arising from baryon or charge conservation have also been analyzed in the framework of balance functions [42,43]. Such an analysis could also shed interesting light on global vs. local baryon conservation.

From the present results it is concluded that effects due to local baryon number conservation are not large, if present at all in second cumulants of net-protons. The large correlation length observed in the data implies that the normalized second cumulant R1 is determined by collisions in the very early phase of the Pb–Pb interaction [44]. We note that long range rapidity correlations were investigated in other contexts in [45,46]. The search for critical behavior, as predicted for higher cumulants of net-baryon distributions [12,47], will be the topic of future investigations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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; The 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'Énergie 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 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 Sciences, 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), 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 y Tecnología (CONACYT), 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 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 & 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] V. Koch, Hadronic fluctuations and correlations, in: R. Stock (Ed.), Relativistic Heavy Ion Physics, 2010, http://materials.springer.com/lb/docs/sm_lbs_978-3-642-01539-7_20.

[2] STAR Collaboration, L. Adamczyk, et al., Energy dependence of moments of net-proton multiplicity distributions at RHIC, Phys. Rev. Lett. 112 (2014) 032302, arXiv:1309.5681 [nucl-ex].

[3] M.A. Stephanov, QCD phase diagram and the critical point, Prog. Theor. Phys. Suppl. 153 (2004) 139–156, arXiv:hep-ph/0402115 [hep-ph], Int. J. Mod. Phys. A 20 (2005) 4387.

[4] A. Bazavov, et al., The chiral and deconfinement aspects of the QCD transition, Phys. Rev. D 85 (2012) 054503, arXiv:1111.1710 [hep-lat].

[5] S. Borsanyi, Z. Fodor, J.N. Guenther, S.K. Katz, K.K. Szabo, A. Pasztor, I. Portillo, C. Ratti, Higher order fluctuations and correlations of conserved charges from lattice QCD, J. High Energy Phys. 10 (2018) 205, arXiv:1805.04445 [hep-lat].

[6] B. Friman, F. Karsch, K. Redlich, V. Skokov, Fluctuations as probe of the QCD phase transition and freeze-out in heavy ion collisions at LHC and RHIC, Eur. Phys. J. C 71 (2011) 1694, arXiv:1103.3511 [hep-ph].

[7] A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Decoding the phase structure of QCD via particle production at high energy, Nature 561 (7723) (2018) 321–330, arXiv:1710.09425 [nucl-th].

[8] A. Andronic, P. Braun-Munzinger, B. Friman, P.M. Lo, K. Redlich, J. Stachel, The thermal proton yield anomaly in Pb-Pb collisions at the LHC and its resolution, Phys. Lett. B 792 (2019) 304–309, arXiv:1808.03102 [hep-ph].

[9] K. Redlich, Probing QCD chiral cross over transition in heavy ion collisions with fluctuations, Cent. Eur. J. Phys. 10 (2012) 1254–1257, arXiv:1207.2610 [hep-ph].

[10] J.G. Skellam, The frequency distribution of the difference between two Poisson variates belonging to different populations, J. R. Stat. Soc. A 109 (3) (1946) 296.

[11] HotQCD Collaboration, A. Bazavov, et al., Chiral crossover in QCD at zero and non-zero chemical potentials, Phys. Lett. B 795 (2019) 15–21, arXiv:1812.08235 [hep-lat].

[12] A. Bazavov, et al., The QCD equation of state to $\mathcal{O}(\mu_B^6)$ from Lattice QCD, Phys. Rev. D 95 (5) (2017) 054504, arXiv:1701.04325 [hep-lat].

[13] L.D. Landau, E.M. Lifshitz, Statistical Physics, Pergamon Press, 1980.

[14] A. Bzdak, V. Koch, Acceptance corrections to net baryon and net charge cumulants, Phys. Rev. C 86 (2012) 044904, arXiv:1206.4286 [nucl-th].

[15] P. Braun-Munzinger, A. Rustamov, J. Stachel, Experimental results on fluctuations of conserved charges confronted with predictions from canonical thermodynamics, Nucl. Phys. A 982 (2019) 307–310, arXiv:1807.08927 [nucl-th].

[16] ALICE Collaboration, B. Abelev, et al., Centrality dependence of π, K, p production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Rev. C 88 (2013) 044910, arXiv:1303.0737 [hep-ex].

[17] ALICE Collaboration, K. Aamodt, et al., The ALICE experiment at the CERN LHC, J. Instrum. 3 (2008) S08002.

[18] ALICE Collaboration, B. Abelev, et al., Centrality determination of Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with ALICE, Phys. Rev. C 88 (4) (2013) 044909, arXiv:1301.4361 [nucl-ex].

[19] J. Alme, et al., The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events, Nucl. Instrum. Methods A 622 (2010) 316–367, arXiv:1001.1950 [physics.ins-det].

[20] G. Dellacasa, et al., ALICE Collaboration, ALICE technical design report of the inner tracking system (ITS), CERN-LHCC-99-12, 1999.

[21] ALICE Collaboration, S. Acharya, et al., Relative particle yield fluctuations in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Eur. Phys. J. C 79 (3) (2019) 236, arXiv:1712.07929 [nucl-ex].

[22] ALICE Collaboration, K. Aamodt, et al., Suppression of charged particle production at large transverse momentum in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Lett. B 696 (2011) 30–39, arXiv:1012.1004 [nucl-ex].

[23] M. Gazdzicki, K. Grebieszkow, M. Mackowiak, S. Mrowczynski, Identity method to study chemical fluctuations in relativistic heavy-ion collisions, Phys. Rev. C 83 (2011) 054907, arXiv:1103.2887 [nucl-th].

[24] M.I. Gorenstein, Identity method for particle number fluctuations and correlations, Phys. Rev. C 84 (2011) 024902, arXiv:1106.4473 [nucl-th], Erratum: Phys. Rev. C 97 (2) (2018) 029903.

[25] A. Rustamov, M.I. Gorenstein, Identity method for moments of multiplicity distribution, Phys. Rev. C 86 (2012) 044906, arXiv:1204.6632 [nucl-th].

[26] T. Anticic, et al., Phase-space dependence of particle-ratio fluctuations in Pb + Pb collisions from 20 A to 158 A GeV beam energy, Phys. Rev. C 89 (5) (2014) 054902, arXiv:1310.3428 [nucl-ex].

[27] M. Arslandok, A. Rustamov, Tidentity module for the reconstruction of the moments of multiplicity distributions, Nucl. Instrum. Methods A 946 (2019) 162622, http://www.sciencedirect.com/science/article/pii/S0168900219311222.

[28] A. Bzdak, V. Koch, Acceptance corrections to net baryon and net charge cumulants, Phys. Rev. C 86 (2012) 044904, arXiv:1206.4286 [nucl-th].

[29] A. Bzdak, V. Koch, Local efficiency corrections to higher order cumulants, Phys. Rev. C 91 (2) (2015) 027901, arXiv:1312.4574 [nucl-th].

[30] T. Sugiura, T. Nonaka, S. Esumi, Volume fluctuation and multiplicity correlation on higher-order cumulants, Phys. Rev. C 100 (4) (2019) 044904, arXiv:1903.02314 [nucl-th].

[31] X. Luo, N. Xu, Search for the QCD critical point with fluctuations of conserved quantities in relativistic heavy-ion collisions at RHIC: an overview, Nucl. Sci. Tech. 28 (8) (2017) 112, arXiv:1701.02105 [nucl-ex].

[32] P. Braun-Munzinger, A. Rustamov, J. Stachel, Bridging the gap between event-by-event fluctuation measurements and theory predictions in relativistic nuclear collisions, Nucl. Phys. A 960 (2017) 114–130, arXiv:1612.00702 [nucl-th].

[33] T. Anticic, et al., Phase-space dependence of particle-ratio fluctuations in Pb + Pb collisions from 20 A to 158 A GeV beam energy, Phys. Rev. C 89 (5) (2014) 054902, arXiv:1310.3428 [nucl-ex].

[34] M.I. Gorenstein, M. Gazdzicki, Strongly intensive quantities, Phys. Rev. C 84 (2011) 014904, arXiv:1101.4865 [nucl-th].

[35] P. Braun-Munzinger, A. Rustamov, J. Stachel, The role of the local conservation laws in fluctuations of conserved charges, arXiv:1907.03032 [nucl-th].

[36] S. Mrowczynski, Measuring charge fluctuations in high-energy nuclear collisions, Phys. Rev. C 66 (2002) 024904, arXiv:nucl-th/0112007 [nucl-th].

[37] A. Bzdak, V. Koch, V. Skokov, Baryon number conservation and the cumulants of the net proton distribution, Phys. Rev. C 87 (1) (2013) 014901, arXiv:1203.4529 [hep-ph].

[38] ALICE Collaboration, B.B. Abelev, et al., K^0_S and Λ production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Rev. Lett. 111 (2013) 222301, arXiv:1307.5530 [nucl-ex].

[39] ALICE Collaboration, B.B. Abelev, et al., Multi-strange baryon production at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Lett. B 728 (2014) 216–227, arXiv:1307.5543 [nucl-ex], Erratum: Phys. Lett. B 734 (2014) 409.

[40] P. Braun-Munzinger, A. Kalweit, K. Redlich, J. Stachel, Confronting fluctuations of conserved charges in central nuclear collisions at the LHC with predictions from Lattice QCD, Phys. Lett. B 747 (2015) 292–298, arXiv:1412.8614 [hep-ph].

[41] C.A. Pruneau, Role of baryon number conservation in measurements of fluctuations, Phys. Rev. C 100 (3) (2019) 034905, arXiv:1903.04591 [nucl-th].

[42] S. Pratt, Correlations and fluctuations: a summary of Quark Matter 2002, Nucl. Phys. A 715 (2003) 389–398, arXiv:nucl-th/0308022 [nucl-th].

[43] ALICE Collaboration, B. Abelev, et al., Charge correlations using the balance function in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, Phys. Lett. B 723 (2013) 267–279, arXiv:1301.3756 [nucl-ex].

[44] A. Dumitru, F. Gelis, L. McLerran, R. Venugopalan, Glasma flux tubes and the near side ridge phenomenon at RHIC, Nucl. Phys. A 810 (2008) 91–108, arXiv:0804.3858 [hep-ph].

[45] A. Capella, A. Krzywicki, Unitarity corrections to short range order: long range rapidity correlations, Phys. Rev. D 18 (1978) 4120.

[46] V.V. Vechernin, Forward-backward correlations between multiplicities in windows separated in azimuth and rapidity, Nucl. Phys. A 939 (2015) 21–45, arXiv:1210.7588 [hep-ph].

[47] G.A. Almasi, B. Friman, K. Redlich, Baryon number fluctuations in chiral effective models and their phenomenological implications, Phys. Rev. D 96 (1) (2017) 014027, arXiv:1703.05947 [hep-ph].

ALICE Collaboration

S. Acharya[141], D. Adamová[94], A. Adler[74], J. Adolfsson[80], M.M. Aggarwal[99], G. Aglieri Rinella[33], M. Agnello[30], N. Agrawal[10,53], Z. Ahammed[141], S. Ahmad[16], S.U. Ahn[76], A. Akindinov[91], M. Al-Turany[106], S.N. Alam[141], D.S.D. Albuquerque[122], D. Aleksandrov[87], B. Alessandro[58], H.M. Alfanda[6], R. Alfaro Molina[71], B. Ali[16], Y. Ali[14], A. Alici[10,26,53], A. Alkin[2], J. Alme[21], T. Alt[68], L. Altenkamper[21], I. Altsybeev[112], M.N. Anaam[6], C. Andrei[47], D. Andreou[33], H.A. Andrews[110], A. Andronic[144], M. Angeletti[33], V. Anguelov[103], C. Anson[15], T. Antičić[107], F. Antinori[56], P. Antonioli[53], R. Anwar[125], N. Apadula[79], L. Aphecetche[114], H. Appelshäuser[68], S. Arcelli[26], R. Arnaldi[58], M. Arratia[79], I.C. Arsene[20], M. Arslandok[103], A. Augustinus[33], R. Averbeck[106], S. Aziz[61], M.D. Azmi[16], A. Badalà[55], Y.W. Baek[40], S. Bagnasco[58], X. Bai[106], R. Bailhache[68], R. Bala[100], A. Baldisseri[137], M. Ball[42], S. Balouza[104], R. Barbera[27], L. Barioglio[25], G.G. Barnaföldi[145], L.S. Barnby[93], V. Barret[134], P. Bartalini[6], K. Barth[33], E. Bartsch[68], F. Baruffaldi[28], N. Bastid[134], S. Basu[143], G. Batigne[114], B. Batyunya[75], D. Bauri[48], J.L. Bazo Alba[111], I.G. Bearden[88], C. Bedda[63], N.K. Behera[60], I. Belikov[136], A.D.C. Bell Hechavarria[144], F. Bellini[33], R. Bellwied[125], V. Belyaev[92], G. Bencedi[145], S. Beole[25], A. Bercuci[47], Y. Berdnikov[97], D. Berenyi[145], R.A. Bertens[130], D. Berzano[58], M.G. Besoiu[67], L. Betev[33], A. Bhasin[100], I.R. Bhat[100], M.A. Bhat[3], H. Bhatt[48], B. Bhattacharjee[41], A. Bianchi[25], L. Bianchi[25], N. Bianchi[51], J. Bielčík[36], J. Bielčíková[94], A. Bilandzic[104,117], G. Biro[145], R. Biswas[3], S. Biswas[3], J.T. Blair[119], D. Blau[87], C. Blume[68], G. Boca[139], F. Bock[33,95], A. Bogdanov[92], S. Boi[23], L. Boldizsár[145], A. Bolozdynya[92], M. Bombara[37], G. Bonomi[140], H. Borel[137], A. Borissov[92,144], H. Bossi[146], E. Botta[25], L. Bratrud[68], P. Braun-Munzinger[106], M. Bregant[121], M. Broz[36], E.J. Brucken[43], E. Bruna[58], G.E. Bruno[105], M.D. Buckland[127], D. Budnikov[108], H. Buesching[68], S. Bufalino[30], O. Bugnon[114], P. Buhler[113], P. Buncic[33], Z. Buthelezi[72,131], J.B. Butt[14], J.T. Buxton[96], S.A. Bysiak[118], D. Caffarri[89],

A. Caliva[106], E. Calvo Villar[111], R.S. Camacho[44], P. Camerini[24], A.A. Capon[113], F. Carnesecchi[10,26],
R. Caron[137], J. Castillo Castellanos[137], A.J. Castro[130], E.A.R. Casula[54], F. Catalano[30],
C. Ceballos Sanchez[52], P. Chakraborty[48], S. Chandra[141], W. Chang[6], S. Chapeland[33], M. Chartier[127],
S. Chattopadhyay[141], S. Chattopadhyay[109], A. Chauvin[23], C. Cheshkov[135], B. Cheynis[135],
V. Chibante Barroso[33], D.D. Chinellato[122], S. Cho[60], P. Chochula[33], T. Chowdhury[134], P. Christakoglou[89],
C.H. Christensen[88], P. Christiansen[80], T. Chujo[133], C. Cicalo[54], L. Cifarelli[10,26], F. Cindolo[53],
J. Cleymans[124], F. Colamaria[52], D. Colella[52], A. Collu[79], M. Colocci[26], M. Concas[58,ii],
G. Conesa Balbastre[78], Z. Conesa del Valle[61], G. Contin[24,127], J.G. Contreras[36], T.M. Cormier[95],
Y. Corrales Morales[25], P. Cortese[31], M.R. Cosentino[123], F. Costa[33], S. Costanza[139], P. Crochet[134],
E. Cuautle[69], P. Cui[6], L. Cunqueiro[95], D. Dabrowski[142], T. Dahms[104,117], A. Dainese[56],
F.P.A. Damas[114,137], M.C. Danisch[103], A. Danu[67], D. Das[109], I. Das[109], P. Das[85], P. Das[3], S. Das[3],
A. Dash[85], S. Dash[48], S. De[85], A. De Caro[29], G. de Cataldo[52], J. de Cuveland[38], A. De Falco[23],
D. De Gruttola[10], N. De Marco[58], S. De Pasquale[29], S. Deb[49], B. Debjani[3], H.F. Degenhardt[121],
K.R. Deja[142], A. Deloff[84], S. Delsanto[25,131], D. Devetak[106], P. Dhankher[48], D. Di Bari[32], A. Di Mauro[33],
R.A. Diaz[8], T. Dietel[124], P. Dillenseger[68], Y. Ding[6], R. Divià[33], D.U. Dixit[19], Ø. Djuvsland[21],
U. Dmitrieva[62], A. Dobrin[33,67], B. Dönigus[68], O. Dordic[20], A.K. Dubey[141], A. Dubla[106], S. Dudi[99],
M. Dukhishyam[85], P. Dupieux[134], R.J. Ehlers[146], V.N. Eikeland[21], D. Elia[52], H. Engel[74], E. Epple[146],
B. Erazmus[114], F. Erhardt[98], A. Erokhin[112], M.R. Ersdal[21], B. Espagnon[61], G. Eulisse[33], D. Evans[110],
S. Evdokimov[90], L. Fabbietti[104,117], M. Faggin[28], J. Faivre[78], F. Fan[6], A. Fantoni[51], M. Fasel[95],
P. Fecchio[30], A. Feliciello[58], G. Feofilov[112], A. Fernández Téllez[44], A. Ferrero[137], A. Ferretti[25],
A. Festanti[33], V.J.G. Feuillard[103], J. Figiel[118], S. Filchagin[108], D. Finogeev[62], F.M. Fionda[21], G. Fiorenza[52],
F. Flor[125], S. Foertsch[72], P. Foka[106], S. Fokin[87], E. Fragiacomo[59], U. Frankenfeld[106], U. Fuchs[33],
C. Furget[78], A. Furs[62], M. Fusco Girard[29], J.J. Gaardhøje[88], M. Gagliardi[25], A.M. Gago[111], A. Gal[136],
C.D. Galvan[120], P. Ganoti[83], C. Garabatos[106], E. Garcia-Solis[11], K. Garg[27], C. Gargiulo[33], A. Garibli[86],
K. Garner[144], P. Gasik[104,117], E.F. Gauger[119], M.B. Gay Ducati[70], M. Germain[114], J. Ghosh[109],
P. Ghosh[141], S.K. Ghosh[3], P. Gianotti[51], P. Giubellino[58,106], P. Giubilato[28], P. Glässel[103],
D.M. Goméz Coral[71], A. Gomez Ramirez[74], V. Gonzalez[106], P. González-Zamora[44], S. Gorbunov[38],
L. Görlich[118], S. Gotovac[34], V. Grabski[71], L.K. Graczykowski[142], K.L. Graham[110], L. Greiner[79], A. Grelli[63],
C. Grigoras[33], V. Grigoriev[92], A. Grigoryan[1], S. Grigoryan[75], O.S. Groettvik[21], F. Grosa[30],
J.F. Grosse-Oetringhaus[33], R. Grosso[106], R. Guernane[78], M. Guittiere[114], K. Gulbrandsen[88], T. Gunji[132],
A. Gupta[100], R. Gupta[100], I.B. Guzman[44], R. Haake[146], M.K. Habib[106], C. Hadjidakis[61], H. Hamagaki[81],
G. Hamar[145], M. Hamid[6], R. Hannigan[119], M.R. Haque[63,85], A. Harlenderova[106], J.W. Harris[146],
A. Harton[11], J.A. Hasenbichler[33], H. Hassan[95], D. Hatzifotiadou[10,53], P. Hauer[42], S. Hayashi[132],
S.T. Heckel[68,104], E. Hellbär[68], H. Helstrup[35], A. Herghelegiu[47], T. Herman[36], E.G. Hernandez[44],
G. Herrera Corral[9], F. Herrmann[144], K.F. Hetland[35], T.E. Hilden[43], H. Hillemanns[33], C. Hills[127],
B. Hippolyte[136], B. Hohlweger[104], D. Horak[36], A. Hornung[68], S. Hornung[106], R. Hosokawa[15,133],
P. Hristov[33], C. Huang[61], C. Hughes[130], P. Huhn[68], T.J. Humanic[96], H. Hushnud[109], L.A. Husova[144],
N. Hussain[41], S.A. Hussain[14], D. Hutter[38], J.P. Iddon[33,127], R. Ilkaev[108], M. Inaba[133], G.M. Innocenti[33],
M. Ippolitov[87], A. Isakov[94], M.S. Islam[109], M. Ivanov[106], V. Ivanov[97], V. Izucheev[90], B. Jacak[79],
N. Jacazio[53], P.M. Jacobs[79], S. Jadlovska[116], J. Jadlovsky[116], S. Jaelani[63], C. Jahnke[121],
M.J. Jakubowska[142], M.A. Janik[142], T. Janson[74], M. Jercic[98], O. Jevons[110], M. Jin[125], F. Jonas[95,144],
P.G. Jones[110], J. Jung[68], M. Jung[68], A. Jusko[110], P. Kalinak[64], A. Kalweit[33], V. Kaplin[92], S. Kar[6],
A. Karasu Uysal[77], O. Karavichev[62], T. Karavicheva[62], P. Karczmarczyk[33], E. Karpechev[62],
A. Kazantsev[87], U. Kebschull[74], R. Keidel[46], M. Keil[33], B. Ketzer[42], Z. Khabanova[89], A.M. Khan[6],
S. Khan[16], S.A. Khan[141], A. Khanzadeev[97], Y. Kharlov[90], A. Khatun[16], A. Khuntia[118], B. Kileng[35],
B. Kim[60], B. Kim[133], D. Kim[147], D.J. Kim[126], E.J. Kim[73], H. Kim[17,147], J. Kim[147], J.S. Kim[40], J. Kim[103],
J. Kim[147], J. Kim[73], M. Kim[103], S. Kim[18], T. Kim[147], T. Kim[147], S. Kirsch[38,68], I. Kisel[38], S. Kiselev[91],
A. Kisiel[142], J.L. Klay[5], C. Klein[68], J. Klein[58], S. Klein[79], C. Klein-Bösing[144], M. Kleiner[68], A. Kluge[33],
M.L. Knichel[33], A.G. Knospe[125], C. Kobdaj[115], M.K. Köhler[103], T. Kollegger[106], A. Kondratyev[75],
N. Kondratyeva[92], E. Kondratyuk[90], J. Konig[68], P.J. Konopka[33], L. Koska[116], O. Kovalenko[84],
V. Kovalenko[112], M. Kowalski[118], I. Králik[64], A. Kravčáková[37], L. Kreis[106], M. Krivda[64,110], F. Krizek[94],
K. Krizkova Gajdosova[36], M. Krüger[68], E. Kryshen[97], M. Krzewicki[38], A.M. Kubera[96], V. Kučera[60],
C. Kuhn[136], P.G. Kuijer[89], L. Kumar[99], S. Kumar[48], S. Kundu[85], P. Kurashvili[84], A. Kurepin[62],

A.B. Kurepin[62], A. Kuryakin[108], S. Kushpil[94], J. Kvapil[110], M.J. Kweon[60], J.Y. Kwon[60], Y. Kwon[147], S.L. La Pointe[38], P. La Rocca[27], Y.S. Lai[79], R. Langoy[129], K. Lapidus[33], A. Lardeux[20], P. Larionov[51], E. Laudi[33], R. Lavicka[36], T. Lazareva[112], R. Lea[24], L. Leardini[103], J. Lee[133], S. Lee[147], F. Lehas[89], S. Lehner[113], J. Lehrbach[38], R.C. Lemmon[93], I. León Monzón[120], E.D. Lesser[19], M. Lettrich[33], P. Lévai[145], X. Li[12], X.L. Li[6], J. Lien[129], R. Lietava[110], B. Lim[17], V. Lindenstruth[38], S.W. Lindsay[127], C. Lippmann[106], M.A. Lisa[96], V. Litichevskyi[43], A. Liu[19], S. Liu[96], W.J. Llope[143], I.M. Lofnes[21], V. Loginov[92], C. Loizides[95], P. Loncar[34], X. Lopez[134], E. López Torres[8], J.R. Luhder[144], M. Lunardon[28], G. Luparello[59], Y. Ma[39], A. Maevskaya[62], M. Mager[33], S.M. Mahmood[20], T. Mahmoud[42], A. Maire[136], R.D. Majka[146], M. Malaev[97], Q.W. Malik[20], L. Malinina[75,iii], D. Mal'Kevich[91], P. Malzacher[106], G. Mandaglio[55], V. Manko[87], F. Manso[134], V. Manzari[52], Y. Mao[6], M. Marchisone[135], J. Mareš[66], G.V. Margagliotti[24], A. Margotti[53], J. Margutti[63], A. Marín[106], C. Markert[119], M. Marquard[68], N.A. Martin[103], P. Martinengo[33], J.L. Martinez[125], M.I. Martínez[44], G. Martínez García[114], M. Martinez Pedreira[33], S. Masciocchi[106], M. Masera[25], A. Masoni[54], L. Massacrier[61], E. Masson[114], A. Mastroserio[52,138], A.M. Mathis[104,117], O. Matonoha[80], P.F.T. Matuoka[121], A. Matyja[118], C. Mayer[118], M. Mazzilli[52], M.A. Mazzoni[57], A.F. Mechler[68], F. Meddi[22], Y. Melikyan[62,92], A. Menchaca-Rocha[71], C. Mengke[6], E. Meninno[29,113], M. Meres[13], S. Mhlanga[124], Y. Miake[133], L. Micheletti[25], D.L. Mihaylov[104], K. Mikhaylov[75,91], A. Mischke[63,i], A.N. Mishra[69], D. Miśkowiec[106], A. Modak[3], N. Mohammadi[33], A.P. Mohanty[63], B. Mohanty[85], M. Mohisin Khan[16,iv], C. Mordasini[104], D.A. Moreira De Godoy[144], L.A.P. Moreno[44], I. Morozov[62], A. Morsch[33], T. Mrnjavac[33], V. Muccifora[51], E. Mudnic[34], D. Mühlheim[144], S. Muhuri[141], J.D. Mulligan[79], M.G. Munhoz[121], R.H. Munzer[68], H. Murakami[132], S. Murray[124], L. Musa[33], J. Musinsky[64], C.J. Myers[125], J.W. Myrcha[142], B. Naik[48], R. Nair[84], B.K. Nandi[48], R. Nania[10,53], E. Nappi[52], M.U. Naru[14], A.F. Nassirpour[80], C. Nattrass[130], R. Nayak[48], T.K. Nayak[85], S. Nazarenko[108], A. Neagu[20], R.A. Negrao De Oliveira[68], L. Nellen[69], S.V. Nesbo[35], G. Neskovic[38], D. Nesterov[112], L.T. Neumann[142], B.S. Nielsen[88], S. Nikolaev[87], S. Nikulin[87], V. Nikulin[97], F. Noferini[10,53], P. Nomokonov[75], J. Norman[78,127], N. Novitzky[133], P. Nowakowski[142], A. Nyanin[87], J. Nystrand[21], M. Ogino[81], A. Ohlson[80,103], J. Oleniacz[142], A.C. Oliveira Da Silva[121,130], M.H. Oliver[146], C. Oppedisano[58], R. Orava[43], A. Ortiz Velasquez[69], A. Oskarsson[80], J. Otwinowski[118], K. Oyama[81], Y. Pachmayer[103], V. Pacik[88], D. Pagano[140], G. Paić[69], J. Pan[143], A.K. Pandey[48], S. Panebianco[137], P. Pareek[49,141], J. Park[60], J.E. Parkkila[126], S. Parmar[99], S.P. Pathak[125], R.N. Patra[141], B. Paul[23,58], H. Pei[6], T. Peitzmann[63], X. Peng[6], L.G. Pereira[70], H. Pereira Da Costa[137], D. Peresunko[87], G.M. Perez[8], E. Perez Lezama[68], V. Peskov[68], Y. Pestov[4], V. Petráček[36], M. Petrovici[47], R.P. Pezzi[70], S. Piano[59], M. Pikna[13], P. Pillot[114], O. Pinazza[33,53], L. Pinsky[125], C. Pinto[27], S. Pisano[10,51], D. Pistone[55], M. Płoskoń[79], M. Planinic[98], F. Pliquett[68], J. Pluta[142], S. Pochybova[145,i], M.G. Poghosyan[95], B. Polichtchouk[90], N. Poljak[98], A. Pop[47], H. Poppenborg[144], S. Porteboeuf-Houssais[134], V. Pozdniakov[75], S.K. Prasad[3], R. Preghenella[53], F. Prino[58], C.A. Pruneau[143], I. Pshenichnov[62], M. Puccio[25,33], J. Putschke[143], R.E. Quishpe[125], S. Ragoni[110], S. Raha[3], S. Rajput[100], J. Rak[126], A. Rakotozafindrabe[137], L. Ramello[31], F. Rami[136], R. Raniwala[101], S. Raniwala[101], S.S. Räsänen[43], R. Rath[49], V. Ratza[42], I. Ravasenga[30,89], K.F. Read[95,130], A.R. Redelbach[38], K. Redlich[84,v], A. Rehman[21], P. Reichelt[68], F. Reidt[33], X. Ren[6], R. Renfordt[68], Z. Rescakova[37], J.-P. Revol[10], K. Reygers[103], V. Riabov[97], T. Richert[80,88], M. Richter[20], P. Riedler[33], W. Riegler[33], F. Riggi[27], C. Ristea[67], S.P. Rode[49], M. Rodríguez Cahuantzi[44], K. Røed[20], R. Rogalev[90], E. Rogochaya[75], D. Rohr[33], D. Röhrich[21], P.S. Rokita[142], F. Ronchetti[51], E.D. Rosas[69], K. Roslon[142], A. Rossi[28,56], A. Rotondi[139], A. Roy[49], P. Roy[109], O.V. Rueda[80], R. Rui[24], B. Rumyantsev[75], A. Rustamov[86], E. Ryabinkin[87], Y. Ryabov[97], A. Rybicki[118], H. Rytkonen[126], O.A.M. Saarimaki[43], S. Sadhu[141], S. Sadovsky[90], K. Šafařík[36], S.K. Saha[141], B. Sahoo[48], P. Sahoo[48,49], R. Sahoo[49], S. Sahoo[65], P.K. Sahu[65], J. Saini[141], S. Sakai[133], S. Sambyal[100], V. Samsonov[92,97], D. Sarkar[143], N. Sarkar[141], P. Sarma[41], V.M. Sarti[104], M.H.P. Sas[63], E. Scapparone[53], B. Schaefer[95], J. Schambach[119], H.S. Scheid[68], C. Schiaua[47], R. Schicker[103], A. Schmah[103], C. Schmidt[106], H.R. Schmidt[102], M.O. Schmidt[103], M. Schmidt[102], N.V. Schmidt[68,95], A.R. Schmier[130], J. Schukraft[88], Y. Schutz[33,136], K. Schwarz[106], K. Schweda[106], G. Scioli[26], E. Scomparin[58], M. Šefčík[37], J.E. Seger[15], Y. Sekiguchi[132], D. Sekihata[132], I. Selyuzhenkov[92,106], S. Senyukov[136], D. Serebryakov[62], E. Serradilla[71], A. Sevcenco[67], A. Shabanov[62], A. Shabetai[114], R. Shahoyan[33], W. Shaikh[109], A. Shangaraev[90], A. Sharma[99], A. Sharma[100], H. Sharma[118], M. Sharma[100], N. Sharma[99], A.I. Sheikh[141], K. Shigaki[45], M. Shimomura[82], S. Shirinkin[91], Q. Shou[39],

Y. Sibiriak[87], S. Siddhanta[54], T. Siemiarczuk[84], D. Silvermyr[80], G. Simatovic[89], G. Simonetti[33,104], R. Singh[85], R. Singh[100], R. Singh[49], V.K. Singh[141], V. Singhal[141], T. Sinha[109], B. Sitar[13], M. Sitta[31], T.B. Skaali[20], M. Slupecki[126], N. Smirnov[146], R.J.M. Snellings[63], T.W. Snellman[43,126], C. Soncco[111], J. Song[60,125], A. Songmoolnak[115], F. Soramel[28], S. Sorensen[130], I. Sputowska[118], J. Stachel[103], I. Stan[67], P. Stankus[95], P.J. Steffanic[130], E. Stenlund[80], D. Stocco[114], M.M. Storetvedt[35], L.D. Stritto[29], A.A.P. Suaide[121], T. Sugitate[45], C. Suire[61], M. Suleymanov[14], M. Suljic[33], R. Sultanov[91], M. Šumbera[94], S. Sumowidagdo[50], S. Swain[65], A. Szabo[13], I. Szarka[13], U. Tabassam[14], G. Taillepied[134], J. Takahashi[122], G.J. Tambave[21], S. Tang[6,134], M. Tarhini[114], M.G. Tarzila[47], A. Tauro[33], G. Tejeda Muñoz[44], A. Telesca[33], C. Terrevoli[125], D. Thakur[49], S. Thakur[141], D. Thomas[119], F. Thoresen[88], R. Tieulent[135], A. Tikhonov[62], A.R. Timmins[125], A. Toia[68], N. Topilskaya[62], M. Toppi[51], F. Torales-Acosta[19], S.R. Torres[9,120], A. Trifiro[55], S. Tripathy[49], T. Tripathy[48], S. Trogolo[28], G. Trombetta[32], L. Tropp[37], V. Trubnikov[2], W.H. Trzaska[126], T.P. Trzcinski[142], B.A. Trzeciak[63], T. Tsuji[132], A. Tumkin[108], R. Turrisi[56], T.S. Tveter[20], K. Ullaland[21], E.N. Umaka[125], A. Uras[135], G.L. Usai[23], A. Utrobicic[98], M. Vala[37], N. Valle[139], S. Vallero[58], N. van der Kolk[63], L.V.R. van Doremalen[63], M. van Leeuwen[63], P. Vande Vyvre[33], D. Varga[145], Z. Varga[145], M. Varga-Kofarago[145], A. Vargas[44], M. Vasileiou[83], A. Vasiliev[87], O. Vázquez Doce[104,117], V. Vechernin[112], A.M. Veen[63], E. Vercellin[25], S. Vergara Limón[44], L. Vermunt[63], R. Vernet[7], R. Vértesi[145], L. Vickovic[34], Z. Vilakazi[131], O. Villalobos Baillie[110], A. Villatoro Tello[44], G. Vino[52], A. Vinogradov[87], T. Virgili[29], V. Vislavicius[88], A. Vodopyanov[75], B. Volkel[33], M.A. Völkl[102], K. Voloshin[91], S.A. Voloshin[143], G. Volpe[32], B. von Haller[33], I. Vorobyev[104], D. Voscek[116], J. Vrláková[37], B. Wagner[21], M. Weber[113], S.G. Weber[144], A. Wegrzynek[33], D.F. Weiser[103], S.C. Wenzel[33], J.P. Wessels[144], J. Wiechula[68], J. Wikne[20], G. Wilk[84], J. Wilkinson[10,53], G.A. Willems[33], E. Willsher[110], B. Windelband[103], M. Winn[137], W.E. Witt[130], Y. Wu[128], R. Xu[6], S. Yalcin[77], K. Yamakawa[45], S. Yang[21], S. Yano[137], Z. Yin[6], H. Yokoyama[63], I.-K. Yoo[17], J.H. Yoon[60], S. Yuan[21], A. Yuncu[103], V. Yurchenko[2], V. Zaccolo[24], A. Zaman[14], C. Zampolli[33], H.J.C. Zanoli[63], N. Zardoshti[33], A. Zarochentsev[112], P. Závada[66], N. Zaviyalov[108], H. Zbroszczyk[142], M. Zhalov[97], S. Zhang[39], X. Zhang[6], Z. Zhang[6], V. Zherebchevskii[112], D. Zhou[6], Y. Zhou[88], Z. Zhou[21], J. Zhu[6,106], Y. Zhu[6], A. Zichichi[10,26], M.B. Zimmermann[33], G. Zinovjev[2], N. Zurlo[140]

[1] *A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia*
[2] *Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine*
[3] *Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India*
[4] *Budker Institute for Nuclear Physics, Novosibirsk, Russia*
[5] *California Polytechnic State University, San Luis Obispo, CA, United States*
[6] *Central China Normal University, Wuhan, China*
[7] *Centre de Calcul de l'IN2P3, Villeurbanne, Lyon, France*
[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] *Centro Fermi – Museo Storico della Fisica e Centro Studi e Ricerche 'Enrico Fermi', Rome, Italy*
[11] *Chicago State University, Chicago, IL, United States*
[12] *China Institute of Atomic Energy, Beijing, China*
[13] *Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovakia*
[14] *COMSATS University Islamabad, Islamabad, Pakistan*
[15] *Creighton University, Omaha, NE, 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, CA, 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.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy*
[30] *Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy*
[31] *Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy*
[32] *Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy*
[33] *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[34] *Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia*
[35] *Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway*
[36] *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic*
[37] *Faculty of Science, P.J. Šafárik University, Košice, Slovakia*
[38] *Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany*
[39] *Fudan University, Shanghai, China*

[40] Gangneung-Wonju National University, Gangneung, Republic of Korea
[41] Gauhati University, Department of Physics, Guwahati, India
[42] Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
[43] Helsinki Institute of Physics (HIP), Helsinki, Finland
[44] High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
[45] Hiroshima University, Hiroshima, Japan
[46] Hochschule Worms, Zentrum für Technologietransfer und Telekommunikation (ZTT), Worms, Germany
[47] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[48] Indian Institute of Technology Bombay (IIT), Mumbai, India
[49] Indian Institute of Technology Indore, Indore, India
[50] Indonesian Institute of Sciences, Jakarta, Indonesia
[51] INFN, Laboratori Nazionali di Frascati, Frascati, Italy
[52] INFN, Sezione di Bari, Bari, Italy
[53] INFN, Sezione di Bologna, Bologna, Italy
[54] INFN, Sezione di Cagliari, Cagliari, Italy
[55] INFN, Sezione di Catania, Catania, Italy
[56] INFN, Sezione di Padova, Padova, Italy
[57] INFN, Sezione di Roma, Rome, Italy
[58] INFN, Sezione di Torino, Turin, Italy
[59] INFN, Sezione di Trieste, Trieste, Italy
[60] Inha University, Incheon, Republic of Korea
[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, Orsay, France
[62] Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
[63] Institute for Subatomic Physics, Utrecht University/Nikhef, Utrecht, Netherlands
[64] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
[65] Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India
[66] Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[67] Institute of Space Science (ISS), Bucharest, Romania
[68] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[69] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
[70] Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
[71] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[72] iThemba LABS, National Research Foundation, Somerset West, South Africa
[73] Jeonbuk National University, Jeonju, Republic of Korea
[74] Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany
[75] Joint Institute for Nuclear Research (JINR), Dubna, Russia
[76] Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
[77] KTO Karatay University, Konya, Turkey
[78] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
[79] Lawrence Berkeley National Laboratory, Berkeley, CA, United States
[80] Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
[81] Nagasaki Institute of Applied Science, Nagasaki, Japan
[82] Nara Women's University (NWU), Nara, Japan
[83] National and Kapodistrian University of Athens, School of Science, Department of Physics, Athens, Greece
[84] National Centre for Nuclear Research, Warsaw, Poland
[85] National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India
[86] National Nuclear Research Center, Baku, Azerbaijan
[87] National Research Centre Kurchatov Institute, Moscow, Russia
[88] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[89] Nikhef, National institute for subatomic physics, Amsterdam, Netherlands
[90] NRC Kurchatov Institute IHEP, Protvino, Russia
[91] NRC «Kurchatov Institute» - ITEP, Moscow, Russia
[92] NRNU Moscow Engineering Physics Institute, Moscow, Russia
[93] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
[94] Nuclear Physics Institute of the Czech Academy of Sciences, Řež u Prahy, Czech Republic
[95] Oak Ridge National Laboratory, Oak Ridge, TN, United States
[96] Ohio State University, Columbus, OH, United States
[97] Petersburg Nuclear Physics Institute, Gatchina, Russia
[98] Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
[99] Physics Department, Panjab University, Chandigarh, India
[100] Physics Department, University of Jammu, Jammu, India
[101] Physics Department, University of Rajasthan, Jaipur, India
[102] Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
[103] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[104] Physik Department, Technische Universität München, Munich, Germany
[105] Politecnico di Bari, Bari, Italy
[106] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[107] Rudjer Bošković Institute, Zagreb, Croatia
[108] Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
[109] Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
[110] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[111] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[112] St. Petersburg State University, St. Petersburg, Russia
[113] Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
[114] SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France
[115] Suranaree University of Technology, Nakhon Ratchasima, Thailand
[116] Technical University of Košice, Košice, Slovakia
[117] Technische Universität München, Excellence Cluster 'Universe', Munich, Germany
[118] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland

[119] *The University of Texas at Austin, Austin, TX, United States*
[120] *Universidad Autónoma de Sinaloa, Culiacán, Mexico*
[121] *Universidade de São Paulo (USP), São Paulo, Brazil*
[122] *Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil*
[123] *Universidade Federal do ABC, Santo Andre, Brazil*
[124] *University of Cape Town, Cape Town, South Africa*
[125] *University of Houston, Houston, TX, United States*
[126] *University of Jyväskylä, Jyväskylä, Finland*
[127] *University of Liverpool, Liverpool, United Kingdom*
[128] *University of Science and Technology of China, Hefei, China*
[129] *University of South-Eastern Norway, Tonsberg, Norway*
[130] *University of Tennessee, Knoxville, TN, United States*
[131] *University of the Witwatersrand, Johannesburg, South Africa*
[132] *University of Tokyo, Tokyo, Japan*
[133] *University of Tsukuba, Tsukuba, Japan*
[134] *Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
[135] *Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, Lyon, France*
[136] *Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*
[137] *Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Départment de Physique Nucléaire (DPhN), Saclay, France*
[138] *Università degli Studi di Foggia, Foggia, Italy*
[139] *Università degli Studi di Pavia, Pavia, Italy*
[140] *Università di Brescia, Brescia, Italy*
[141] *Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India*
[142] *Warsaw University of Technology, Warsaw, Poland*
[143] *Wayne State University, Detroit, MI, United States*
[144] *Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany*
[145] *Wigner Research Centre for Physics, Budapest, Hungary*
[146] *Yale University, New Haven, CT, United States*
[147] *Yonsei University, Seoul, Republic of Korea*

[i] Deceased.
[ii] Dipartimento DET del Politecnico di Torino, Turin, Italy.
[iii] M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear, Physics, Moscow, Russia.
[iv] Department of Applied Physics, Aligarh Muslim University, Aligarh, India.
[v] Institute of Theoretical Physics, University of Wroclaw, Poland.