Net-Charge Fluctuations in Pb-Pb Collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

B. Abelev *et al.*[*]
(ALICE Collaboration)

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We report the first measurement of the net-charge fluctuations in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, measured with the ALICE detector at the CERN Large Hadron Collider. The dynamical fluctuations per unit entropy are observed to decrease when going from peripheral to central collisions. An additional reduction in the amount of fluctuations is seen in comparison to the results from lower energies. We examine the dependence of fluctuations on the pseudorapidity interval, which may account for the dilution of fluctuations during the evolution of the system. We find that the fluctuations at the LHC are smaller compared to the measurements at the BNL Relativistic Heavy Ion Collider, and as such, closer to what has been theoretically predicted for the formation of a quark-gluon plasma.

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The ALICE experiment [1] at the Large Hadron Collider (LHC) is a multipurpose detector designed to study the formation and evolution of nuclear matter at high temperatures and energy densities. One of the major goals of the experiment is to explore as many signals as possible toward characterizing the properties of the quark-gluon plasma (QGP), the deconfined state of quarks and gluons, produced in high energy heavy-ion collisions. The study of event-by-event fluctuations provides a powerful tool to characterize the thermodynamic properties of the system. The fluctuations of conserved quantities in a finite phase space window, like the net charge of the system, are predicted to be one of the most sensitive signals of the QGP formation and phase transition and may provide a complementary understanding of strong interactions [2–9].

In the QGP phase, the charge carriers are quarks with fractional charges, whereas the particles in a hadron gas (HG) carry unit charge. The fluctuations in the net charge depend on the squares of the charge states present in the system. Consequently, the net-charge fluctuations in the QGP phase are significantly smaller compared to that of a HG [2]. At the same time, if the initial QGP phase is strongly gluon dominated, the fluctuation per entropy may further be reduced as the hadronization of gluons increases the entropy [3]. Thus, the net-charge fluctuations are strongly dependent on which phase they originate from. However, the net-charge fluctuations may get affected by uncertainties arising from volume fluctuations, so one considers the fluctuations of the ratio $R = N_+/N_-$. Here, N_+ and N_- are the numbers of positive and negative particles, respectively, measured in a specific transverse momentum (p_T) and pseudorapidity (η) window. The parameter R is related to the fluctuations of the net charge via the D measure as per the following expression [2,4,5]:

$$D = \langle N_{\mathrm{ch}} \rangle \langle \delta R^2 \rangle \approx 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{\mathrm{ch}} \rangle}, \quad (1)$$

which provides a measure of the charge fluctuations per unit entropy. Here, the angled brackets denote an average of the quantity over an ensemble of events. The term $\langle \delta Q^2 \rangle$ is the variance of net charge $Q = N_+ - N_-$ and $N_{\mathrm{ch}} = N_+ + N_-$. The D measure has been estimated for several different theoretical considerations, including those of the lattice calculations. In a simple picture, by neglecting quark-quark interactions, D is found to be approximately 4 times smaller for a QGP compared to a HG [2]. Lattice calculations which include the quark-quark interactions give a quantitatively different estimate for a QGP phase, still significantly smaller than for a HG. It has been shown that $D = 4$ for an uncorrelated pion gas, and, after taking resonance yields into account, the value decreases to $D \simeq 3$. For a QGP, D is significantly lower and has been calculated to be $D \simeq 1.0$–1.5, where the uncertainty arises from the uncertainty of relating the entropy to the number of charged particles in the final state [5]. Thus, a measurement of D can be effectively used as a probe for distinguishing the two phases, the HG and the QGP. However, in reality, these fluctuations may get diluted in the rapidly expanding medium due to the diffusion of particles in rapidity space [8,9]. Several other effects, such as collision dynamics, radial flow, resonance decays, and final state interactions may also affect the amount of measured fluctuations [2,10–12].

In the experiment, the net-charge fluctuations are best studied [12–17] by calculating the quantity $\nu_{(+-,\mathrm{dyn})}$, defined as

$$\nu_{(+-,\mathrm{dyn})} = \frac{\langle N_+(N_+ - 1) \rangle}{\langle N_+ \rangle^2} + \frac{\langle N_-(N_- - 1) \rangle}{\langle N_- \rangle^2} - 2 \frac{\langle N_- N_+ \rangle}{\langle N_- \rangle \langle N_+ \rangle}, \quad (2)$$

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[*] Full author list given at the end of the article.

which is a measure of the relative correlation strength of particle pairs. A negative value of $\nu_{(+-,\mathrm{dyn})}$ signifies the dominant contribution from correlations between pairs of opposite charges. On the other hand, a positive value indicates the significance of the same charge pair correlations. The $\nu_{(+-,\mathrm{dyn})}$ has been found to be robust against random efficiency losses [17–19]. The D measure and $\nu_{(+-,\mathrm{dyn})}$ are related to each other by [5]

$$\langle N_{\mathrm{ch}}\rangle \nu_{(+-,\mathrm{dyn})} \approx D - 4. \tag{3}$$

The values of $\nu_{(+-,\mathrm{dyn})}$ need to be corrected for global charge conservation [17]. The predictions for the D measure are based on the assumption of vanishing net charge in the system. However, in a realistic situation, the system under consideration has a small but finite net charge. A correction due to the finite net-charge effect also needs to be applied [4].

In this Letter, we report the first measurements of net-charge fluctuations by calculating $\nu_{(+-,\mathrm{dyn})}$ and the D measure, as a function of collision centrality in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV at the LHC with the ALICE detector. We also make a comparison of the experimental results to the theoretical predictions.

Details of the ALICE experiment and its detectors can be found in [1]. For this analysis, we have used the time projection chamber (TPC) [20] to reconstruct charged particle tracks. The detector provides a uniform acceptance with an almost constant tracking efficiency of about 80% in the analyzed phase space ($|\eta| < 0.8$ and $0.2\ \mathrm{GeV}/c < p_T < 5\ \mathrm{GeV}/c$). The interaction vertex was measured using the silicon pixel detector (SPD), the innermost detector of the inner tracking system. In the analysis, we have considered events with a vertex $|v_z| < 10$ cm to ensure a uniform acceptance in the central pseudorapidity region. The minimum bias trigger consisted of a coincidence of at least one hit on each of the two VZERO scintillator detectors, positioned on both sides of the interaction point, while at the startup of the data taking period an additional requirement of having a coincidence with a signal from the SPD was also introduced. The background events coming from parasitic beam interactions are removed by a standard offline event selection procedure, which requires the VZERO timing information and hits in the SPD.

We present the results as a function of centrality that reflects the collision geometry. The collision centrality is determined by cuts on the VZERO multiplicity [21]. A study based on Glauber model fits [22–24] to the multiplicity distribution in the region corresponding to 90% of the most central collisions, where the vertex reconstruction is fully efficient, facilitates the determination of the cross section percentile and the number of participants. The resolution in centrality is found to be <0.5% rms for the most central (0%–5%) collisions, increasing toward 2% rms for peripheral (70%–80%) collisions [21].

We require tracks in the TPC to have at least 80 reconstructed space points with a χ^2 per TPC cluster of the momentum fit less than 4. We reject tracks with a distance of closest approach (DCA) to the vertex larger than 3 cm both in the transverse plane and in the longitudinal direction. We have performed an alternative analysis with tracks reconstructed using the combined tracking of the inner tracking system and the TPC. In this case, the DCA cuts were 0.3 cm in the transverse plane as well as in the longitudinal direction. The results obtained with both tracking approaches are in agreement.

The data analysis has been performed for Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and pp collisions at the same center-of-mass energy. An identical analysis procedure has been followed for both the data sets. We calculate the $\nu_{(+-,\mathrm{dyn})}$ from the experimental measurements of positive and negative charged particles counted in $\Delta\eta$ windows, defined around midrapidity (for example, $\Delta\eta = 1$ corresponds to $-0.5 \leq \eta \leq 0.5$), and in the p_T range from 0.2 to 5.0 GeV/c. Consistency checks had been performed for another p_T window, viz. $0.3\ \mathrm{GeV}/c < p_T < 1.5\ \mathrm{GeV}/c$. The differences in the fluctuation results are small and included in the systematic errors. In Fig. 1, we present the $\nu_{(+-,\mathrm{dyn})}$ as a function of centrality, expressed in terms of the number of participating nucleons. Moving from left to right along the x axis of the figure corresponds to moving from peripheral to central collisions. The results are presented for $\Delta\eta = 1$ and 1.6, for both Pb-Pb and pp collisions. In all cases, the magnitude of $\nu_{(+-,\mathrm{dyn})}$ is observed to be negative, indicating the dominance of the correlation term in Eq. (2). The absolute values of $\nu_{(+-,\mathrm{dyn})}$ for pp

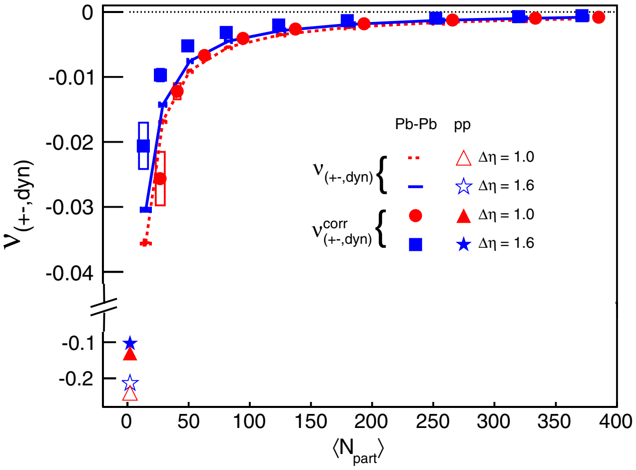

FIG. 1 (color online). Dynamical net-charge fluctuations $\nu_{(+-,\mathrm{dyn})}$ and their corrected values $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ for charged particles produced in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV as a function of centrality, expressed as the number of participating nucleons. The $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ points are shifted along the x axis for better representation. Superimposed are the results for pp collisions at $\sqrt{s} = 2.76$ TeV. The statistical (bar) and systematic (box) errors are plotted.

collisions are larger compared to those measured for Pb-Pb collisions. When going from peripheral to central events, the absolute values of $\nu_{(+-,\mathrm{dyn})}$ are seen to decrease monotonically.

The values of $\nu_{(+-,\mathrm{dyn})}$ have to be corrected for global charge conservation and finite acceptance [17]. If all charges were accepted, the global charge conservation would lead to vanishing fluctuations. This will yield the minimum value of $\nu_{(+-,\mathrm{dyn})}$ to be $-4/\langle N_{\mathrm{total}}\rangle$, where $\langle N_{\mathrm{total}}\rangle$ is the average total number of charged particles produced over a full phase space. The corrected $\nu_{(+-,\mathrm{dyn})}$ is

$$\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})} = \nu_{(+-,\mathrm{dyn})} + \frac{4}{\langle N_{\mathrm{total}}\rangle}. \tag{4}$$

The values of $\langle N_{\mathrm{total}}\rangle$ for Pb-Pb collisions have been estimated from the experimental data [25], whereas, for pp collisions, it is taken from the PYTHIA [26] event generator. As a reference, $\langle N_{\mathrm{ch}}\rangle$ for $\Delta\eta = 1$ and $\langle N_{\mathrm{total}}\rangle$ values are 1637 ± 61 and $17\,165 \pm 772$ for the most central (0%–5%) Pb-Pb collisions and 4.8 ± 0.2 and 36.0 for pp collisions. These are systematic errors; the statistical errors are negligible. The corrected values $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ are plotted in Fig. 1 as a function of the number of participating nucleons for Pb-Pb and pp collisions. The absolute values of $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ are smaller compared to $\nu_{(+-,\mathrm{dyn})}$ in all cases. The differences are more apparent for pp and peripheral Pb-Pb collisions than for central collisions.

Taking the above corrections into account, we obtain

$$D' = \langle N_{\mathrm{ch}}\rangle \nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})} + 4. \tag{5}$$

Alternatively, corrections to the D measure may also be obtained using [4]

$$D'' = (\langle N_{\mathrm{ch}}\rangle \nu_{(+-,\mathrm{dyn})} + 4)/(C_{\mu} C_{\eta}), \tag{6}$$

where C_{μ} $(= \frac{\langle N_+\rangle^2}{\langle N_-\rangle^2})$ corrects for the effects of the finite net charge and C_{η} $(= 1 - \frac{\langle N_{\mathrm{ch}}\rangle}{\langle N_{\mathrm{total}}\rangle})$ accounts for finite bin size in rapidity as well as global charge conservation. The differences in the two corrected values D' and D'' are within 4%–9%, depending on $\Delta\eta$. Subsequently, the mean values of D' and D'' are plotted in the figures as D, and the differences of those have been included as systematic errors.

The systematic uncertainties have additional contributions from the following sources: (a) uncertainty in the determination of the interaction vertex, (b) different magnetic field polarities, (c) contamination from secondary tracks (DCA cuts), (d) centrality definition using different detectors, (e) selection criteria at the track level, (f) different tracking scenarios, and (g) two different p_T windows. The total systematic error on $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ amounts to 6%–10% in going from peripheral to central collisions. The error on the product of the number of charged particles and $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ remains within 7%–13% at all centralities. The systematic and statistical uncertainties in all the figures are represented by boxes and error bars, respectively. The statistical errors are small and within the sizes of the symbols in most cases.

Figure 2 presents the values of $\langle N_{\mathrm{ch}}\rangle \nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ and D in the left and right axes, respectively, as a function of the number of participating nucleons. The $\langle N_{\mathrm{ch}}\rangle$ values have been measured for different centralities and $\Delta\eta$ windows and corrected for detector inefficiencies [21]. Both the results from the Pb-Pb and pp analyses are shown. The shaded bands in the figure indicate the predictions for a HG and a QGP. The results from the HIJING event generator [27] at $\Delta\eta = 1$ and 1.6 are observed to be close to the HG line and at the same time independent of centrality. The pp results agree well with the HG prediction. The experimental results for Pb-Pb for both the $\Delta\eta$ windows are observed to be below the HG predictions and above those of the QGP. The values of D for $\Delta\eta = 1.6$ are lower compared to those for $\Delta\eta = 1$ for all centralities.

A decreasing trend of D has been observed while going from peripheral to central collisions, as seen in Fig. 2. This centrality dependence may arise partly because of the presence of radial flow [10]. The radial flow velocity could lead to the kinetic focusing of the produced particles, causing a narrowing of the opening angles. This may affect the magnitude of the net-charge fluctuations. The effect of radial flow on $\nu_{(+-,\mathrm{dyn})}$ has been estimated by using an afterburner [28] on the HIJING events, where the particles get a boost in the transverse momenta because of the radial flow velocity. We observe no significant difference between the results from pure HIJING and HIJING with the afterburner. This indicates that the presence of radial flow

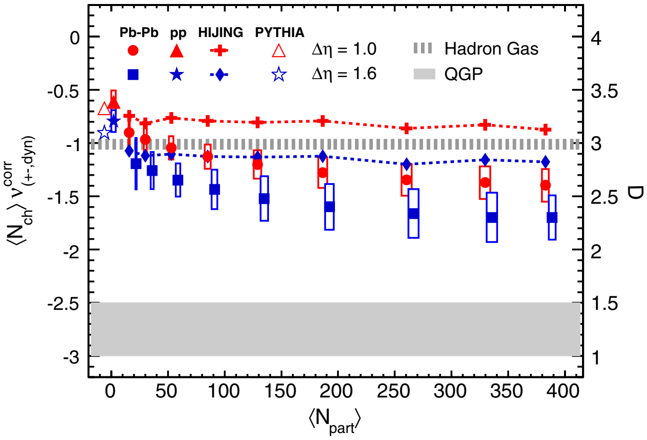

FIG. 2 (color online). $\langle N_{\mathrm{ch}}\rangle \nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ (left axis) and D (right axis) as a function of the number of participants for $\Delta\eta = 1$ and 1.6 in Pb-Pb at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and pp collisions at $\sqrt{s} = 2.76$ TeV. The corresponding results from the HIJING and PYTHIA event generators are also presented. The data points are shifted minimally along the x axis for a clear view. Both statistical (error bars) and systematic (boxes) errors are plotted.

may not be responsible for the centrality dependence of the D measure.

The measured fluctuations may get diluted during the evolution of the system from hadronization to kinetic freeze-out because of the diffusion of charged hadrons in rapidity. This has been addressed in Refs. [8,9], where a diffusion equation has been proposed to study the dependence of the net-charge fluctuations on the width of the rapidity window. Taking the dissipation into account, the asymptotic value of fluctuations may be close to the primordial fluctuations. This has been explored for the ALICE data points by plotting $\langle N_{\mathrm{ch}}\rangle \nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ and D as a function of $\Delta\eta$ for three centrality bins, as shown in Fig. 3. We observe that, for a given centrality bin, the D measure shows a strong decreasing trend with the increase of $\Delta\eta$. In fact, the curvature of D has a decreasing slope with a flattening tendency at large $\Delta\eta$ windows. Following the prescriptions of [8,9], we fit the data points with the functional form, $\mathrm{erf}(\Delta\eta/\sqrt{8}\sigma_f)$, which represents the diffusion in rapidity space. Here, σ_f characterizes the diffusion at freeze-out. The resulting values of σ_f are 0.41 ± 0.05, 0.44 ± 0.05, and 0.48 ± 0.07 for the 0%–5%, 20%–30%, and 40%–50% centralities, respectively. The fitted curves are shown as solid lines in Fig. 3. The dashed lines are extrapolations of the fitted curves to higher $\Delta\eta$, which yield the asymptotic values of D. For the top 5% centrality, the measured values of D are $2.6 \pm 0.02(\mathrm{stat}) \pm 0.15(\mathrm{syst})$ for $\Delta\eta = 1$ and $2.3 \pm 0.02(\mathrm{stat}) \pm 0.21(\mathrm{syst})$ for $\Delta\eta = 1.6$. The extrapolated value of D is $2.24 \pm 0.09(\mathrm{stat}) \pm 0.21(\mathrm{syst})$.

The evolution of the net-charge fluctuations with beam energy can be studied by combining the ALICE data with those of the STAR experiment [12] at RHIC. In Fig. 4, we present the values of $\langle N_{\mathrm{ch}}\rangle \nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ (left axis) and D (right axis) for the top central collisions from ALICE at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and, for STAR, Au-Au collisions at four different energies. The ALICE data points correspond to $\Delta\eta = 1$ and 1.6, whereas, for STAR, the values for $\Delta\eta = 1$ are shown. For the STAR data, $(dN_{\mathrm{ch}}/d\eta)\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ are plotted instead of $\langle N_{\mathrm{ch}}\rangle \nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$, as the $dN_{\mathrm{ch}}/d\eta$ values are approximately equal to $\langle N_{\mathrm{ch}}\rangle$ for $\Delta\eta = 1$ at central rapidity. The theoretical predictions for a HG and a QGP are indicated in the figure. In the absence of any dynamic model, these predictions do not have a dependence on the beam energy.

Figure 4 shows a monotonic decrease in the magnitude of the net-charge fluctuations with increasing beam energy. For the top RHIC energy of $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, the measured value of fluctuation is observed to be close to the HG prediction, whereas, at lower energy, the results are above the HG value. At $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, we observe significantly lower fluctuations compared to those of lower energies.

In summary, we have presented the first measurements of dynamic net-charge fluctuations at the LHC in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV in terms of $\nu_{(+-,\mathrm{dyn})}$ and their corrected values $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ (corrected for charge conservation and finite acceptance effects). The results for pp collisions at the same center-of-mass energy are found to be in agreement with hadron gas prediction. The values of $\nu_{(+-,\mathrm{dyn})}$ and $\nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ are seen to be negative in all cases, indicating the dominance of the correlation of positive and negative charges. A decrease in fluctuations is observed while going from peripheral to central collisions. The D

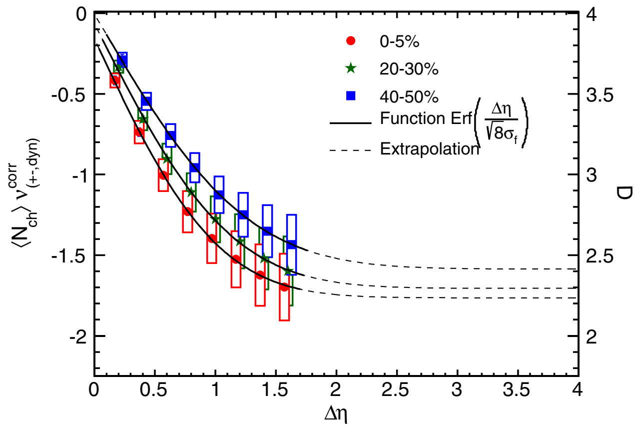

FIG. 3 (color online). $\langle N_{\mathrm{ch}}\rangle \nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ (left axis) and D (right axis) as a function of the $\Delta\eta$ window for three different centrality bins in the Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The data points are fitted with the functional form $\mathrm{erf}(\Delta\eta/\sqrt{8}\sigma_f)$. The dashed lines correspond to the extrapolation of the fitted curves. The points are shifted minimally along the x axis for a clear view. Both statistical (error bars) and systematic (boxes) errors are shown.

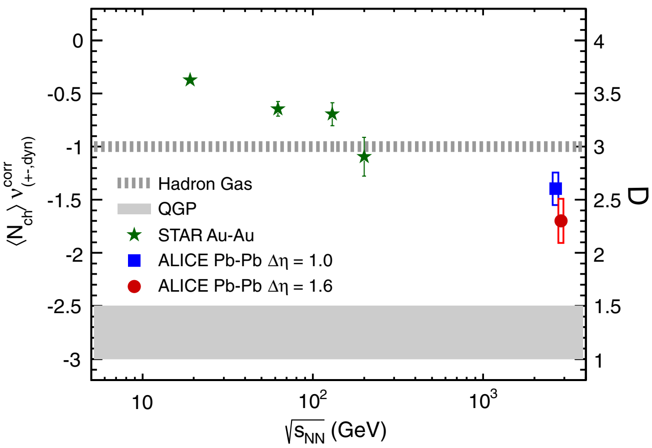

FIG. 4 (color online). Energy dependence of the net-charge fluctuations, measured in terms of $\langle N_{\mathrm{ch}}\rangle \nu^{\mathrm{corr}}_{(+-,\mathrm{dyn})}$ (left axis) and D (right axis) for the top central collisions. The results from the STAR [12] and ALICE experiments are presented for $\Delta\eta = 1$ after the correction for the charge conservation. The ALICE result for $\Delta\eta = 1.6$ is also shown. Both statistical (error bars) and systematic (boxes) errors are plotted.

measure, which gives the charge fluctuations per entropy, is calculated from $\nu^{\rm corr}_{(+-,{\rm dyn})}$ and from the measured average charged particle multiplicity. A decreasing trend of D is observed in going from peripheral to central collisions. Model studies indicate that the presence of radial flow may not be the cause of this decrease. The dissipation of signal during the evolution of the fireball from the hadronization to freeze-out has been estimated by fitting D as a function of the $\Delta\eta$ window. The extrapolation of the fit function yields the asymptotic value of D, which is not very different from the measurement at $\Delta\eta = 1.6$. The beam energy dependence of charge fluctuations has been studied by comparing the ALICE data with those from the STAR experiment at RHIC for Au-Au collisions at four energies. A monotonic decrease in the value of D, measured at $\Delta\eta = 1$, has been observed. The STAR data points at RHIC top energy are close to the prediction for a hadron gas. This may be due to the fact that the fluctuation may be not strong enough to be measured or because of the dilution of fluctuation during the evolution process. The fluctuations at $\sqrt{s_{\rm NN}} = 2.76$ TeV for $\Delta\eta = 1.0$ are below the measurements at RHIC. These data points show an additional decrease at $\Delta\eta = 1.6$, where D turns out to be $2.3 \pm 0.02({\rm stat}) \pm 0.21({\rm syst})$ for top central collisions. The fluctuations at the LHC energy might also have been diluted because of various effects, as discussed earlier. As these fluctuations are smaller than the theoretical expectations for a HG and show for the first time at the LHC energy a clear tendency toward expectations from a QGP, we may infer that they have their origin in the QGP phase. Dynamical model calculations are needed to better understand the results.

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B. Abelev,[1] J. Adam,[2] D. Adamová,[3] A. M. Adare,[4] M. M. Aggarwal,[5] G. Aglieri Rinella,[6] A. G. Agocs,[7]
A. Agostinelli,[8] S. Aguilar Salazar,[9] Z. Ahammed,[10] A. Ahmad Masoodi,[11] N. Ahmad,[11] S. A. Ahn,[12] S. U. Ahn,[13,14]
A. Akindinov,[15] D. Aleksandrov,[16] B. Alessandro,[17] R. Alfaro Molina,[9] A. Alici,[18,19] A. Alkin,[20]
E. Almaráz Aviña,[9] J. Alme,[21] T. Alt,[22] V. Altini,[23] S. Altinpinar,[24] I. Altsybeev,[25] C. Andrei,[26] A. Andronic,[27]
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A. Zarochentsev,[25] P. Závada,[112] N. Zaviyalov,[70] H. Zbroszczyk,[98] P. Zelnicek,[60] I. S. Zgura,[89] M. Zhalov,[52]
X. Zhang,[13,72] H. Zhang,[72] F. Zhou,[72] D. Zhou,[72] Y. Zhou,[58] J. Zhu,[72] J. Zhu,[72] X. Zhu,[72] A. Zichichi,[8,19]
A. Zimmermann,[28] G. Zinovjev,[20] Y. Zoccarato,[82] M. Zynovyev,[20] and M. Zyzak[34]

(ALICE Collaboration)

[1]*Lawrence Livermore National Laboratory, Livermore, California, USA*
[2]*Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic*
[3]*Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic*
[4]*Yale University, New Haven, Connecticut, USA*
[5]*Physics Department, Panjab University, Chandigarh, India*
[6]*European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[7]*KFKI Research Institute for Particle and Nuclear Physics, Hungarian Academy of Sciences, Budapest, Hungary*
[8]*Dipartimento di Fisica dell'Università and Sezione INFN, Bologna, Italy*
[9]*Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico*
[10]*Variable Energy Cyclotron Centre, Kolkata, India*
[11]*Department of Physics Aligarh Muslim University, Aligarh, India*
[12]*Korea Institute of Science and Technology Information, Daejeon, South Korea*
[13]*Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS–IN2P3, Clermont-Ferrand, France*
[14]*Gangneung-Wonju National University, Gangneung, South Korea*
[15]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[16]*Russian Research Centre Kurchatov Institute, Moscow, Russia*
[17]*Sezione INFN, Turin, Italy*
[18]*Sezione INFN, Bologna, Italy*
[19]*Centro Fermi-Centro Studi e Ricerche e Museo Storico della Fisica "Enrico Fermi," Rome, Italy*
[20]*Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine*
[21]*Faculty of Engineering, Bergen University College, Bergen, Norway*
[22]*Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany*
[23]*Dipartimento Interateneo di Fisica "M. Merlin" and Sezione INFN, Bari, Italy*
[24]*Department of Physics and Technology, University of Bergen, Bergen, Norway*
[25]*V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia*
[26]*National Institute for Physics and Nuclear Engineering, Bucharest, Romania*
[27]*Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany*
[28]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[29]*Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany*
[30]*Department of Physics, The Ohio State University, Columbus, Ohio, USA*
[31]*Rudjer Bošković Institute, Zagreb, Croatia*
[32]*Sezione INFN, Padova, Italy*
[33]*SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France*
[34]*Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany*
[35]*Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Joseph Fourier, CNRS-IN2P3, Institut Polytechnique de Grenoble, Grenoble, France*
[36]*Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain*
[37]*Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA*
[38]*Helsinki Institute of Physics (HIP) and University of Jyväskylä, Jyväskylä, Finland*
[39]*Sezione INFN, Catania, Italy*
[40]*Commissariat à l'Energie Atomique, IRFU, Saclay, France*
[41]*Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia*
[42]*Institute of Physics, Bhubaneswar, India*
[43]*Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy*
[44]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[45]*The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland*
[46]*Joint Institute for Nuclear Research (JINR), Dubna, Russia*
[47]*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
[48]*Indian Institute of Technology Bombay (IIT), Mumbai, India*
[49]*Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France*
[50]*University of Houston, Houston, Texas, USA*
[51]*Dipartimento di Fisica Sperimentale dell'Università and Sezione INFN, Turin, Italy*
[52]*Petersburg Nuclear Physics Institute, Gatchina, Russia*
[53]*Physics Department, University of Jammu, Jammu, India*
[54]*University of Tsukuba, Tsukuba, Japan*
[55]*Laboratori Nazionali di Frascati, INFN, Frascati, Italy*

[56]*Dipartimento di Fisica dell'Università and Sezione INFN, Padova, Italy*
[57]*Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands*
[58]*Nikhef, National Institute for Subatomic Physics and Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands*
[59]*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[60]*Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany*
[61]*Moscow Engineering Physics Institute, Moscow, Russia*
[62]*Institute for High Energy Physics, Protvino, Russia*
[63]*Faculty of Science, P.J. Šafárik University, Košice, Slovakia*
[64]*Wayne State University, Detroit, Michigan, USA*
[65]*Saha Institute of Nuclear Physics, Kolkata, India*
[66]*Institut de Physique Nucléaire d'Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France*
[67]*Lawrence Berkeley National Laboratory, Berkeley, California, USA*
[68]*Purdue University, West Lafayette, Indiana, USA*
[69]*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia*
[70]*Russian Federal Nuclear Center (VNIIEF), Sarov, Russia*
[71]*Physics Department, University of Cape Town, iThemba LABS, Cape Town, South Africa*
[72]*Hua-Zhong Normal University, Wuhan, China*
[73]*Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru*
[74]*Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy*
[75]*Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico*
[76]*Benemérita Universidad Autónoma de Puebla, Puebla, Mexico*
[77]*Universidade de São Paulo (USP), São Paulo, Brazil*
[78]*Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy*
[79]*Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba*
[80]*Yonsei University, Seoul, South Korea*
[81]*Physics Department, Creighton University, Omaha, Nebraska, USA*
[82]*Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, France*
[83]*Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil*
[84]*Division of Experimental High Energy Physics, University of Lund, Lund, Sweden*
[85]*Pusan National University, Pusan, South Korea*
[86]*Sezione INFN, Cagliari, Italy*
[87]*Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy*
[88]*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico*
[89]*Institute of Space Sciences (ISS), Bucharest, Romania*
[90]*Dipartimento di Fisica "E.R. Caianiello" dell'Università and Gruppo Collegato INFN, Salerno, Italy*
[91]*Sezione INFN, Bari, Italy*
[92]*Soltan Institute for Nuclear Studies, Warsaw, Poland*
[93]*Sezione INFN, Rome, Italy*
[94]*Department of Physics, University of Oslo, Oslo, Norway*
[95]*Institute for Nuclear Research, Academy of Sciences, Moscow, Russia*
[96]*Sezione INFN, Trieste, Italy*
[97]*Chicago State University, Chicago, USA*
[98]*Warsaw University of Technology, Warsaw, Poland*
[99]*Universidad Autónoma de Sinaloa, Culiacán, Mexico*
[100]*Physics Department, University of Rajasthan, Jaipur, India*
[101]*Technical University of Split FESB, Split, Croatia*
[102]*Yerevan Physics Institute, Yerevan, Armenia*
[103]*University of Tokyo, Tokyo, Japan*
[104]*Department of Physics, Sejong University, Seoul, South Korea*
[105]*Eberhard Karls Universität Tübingen, Tübingen, Germany*
[106]*Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany*
[107]*Yildiz Technical University, Istanbul, Turkey*
[108]*Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany*
[109]*California Polytechnic State University, San Luis Obispo, California, USA*
[110]*The University of Texas at Austin, Physics Department, Austin, Texas, USA*
[111]*Fachhochschule Köln, Köln, Germany*
[112]*Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[113]*University of Tennessee, Knoxville, Tennessee, USA*
[114]*Dipartimento di Fisica dell'Università "La Sapienza" and Sezione INFN, Rome, Italy*
[115]*Budker Institute for Nuclear Physics, Novosibirsk, Russia*

[116]*Institute of Theoretical Physics, University of Wroclaw, Wroclaw, Poland*
[117]*Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy*
[118]*Indian Institute of Technology Indore (IIT), Indore, India*
[119]*Hiroshima University, Hiroshima, Japan*
[120]*Physics Department, University of Athens, Athens, Greece*
[121]*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[122]*Centre de Calcul de l'IN2P3, Villeurbanne, France*

[a] Present address: M. V. Lomonosov Moscow State University, D. V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia.

[b] Present address: University of Belgrade, Faculty of Physics and "Vinča" Institute of Nuclear Sciences, Belgrade, Serbia.