

Method for the analysis of forward-backward multiplicity correlations in heavy-ion collisions

Sudipan De,¹ T. Tarnowsky,² T. K. Nayak,¹ R. P. Scharenberg,³ and B. K. Srivastava³

¹Variable Energy Cyclotron Center, Kolkata, India

²National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA

³Department of Physics, Purdue University, West Lafayette, Indiana 47907, USA

(Received 5 August 2013; published 9 October 2013)

In heavy-ion (A - A) collisions, the correlations among the particles produced across a wide range in rapidity probe the early stages of the reaction. The analyses of forward-backward multiplicity correlations in these collisions are complicated by several effects, which are absent or minimized in hadron-hadron collisions. This includes effects, such as the centrality selection in the A - A collisions, that interfere with the measurement of the dynamical correlations. A method that takes into account the fluctuations in centrality selection has been utilized to determine the forward-backward correlation strength b_{corr} in A - A collisions. This method has been validated by using the HIJING event generator in the case of Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. It is shown that the effect of impact parameter fluctuations is to be considered properly in order to obtain meaningful results.

DOI: 10.1103/PhysRevC.88.044903

PACS number(s): 25.75.Gz, 25.75.Nq, 12.38.Mh

I. INTRODUCTION

The major goals of colliding heavy ions at relativistic energies are to create a new form of matter, called quark-gluon plasma (QGP), and to study its properties. The QGP matter is formed very early in the reaction and it is a major challenge to experimentally probe this initial stage as the majority of the detected particles are emitted at freeze-out. Correlations that are produced across a wide range of rapidity are thought to reflect the earliest stages of the heavy-ion collisions, free from final-state effects [1]. The study of correlations among particles produced in different rapidity regions may provide an understanding of the elementary (partonic) interactions which lead to hadronization. Several experiments involving collisions of electrons, muons, and protons show strong short-range correlations (SRCs) over a region of about ± 1 unit in rapidity [2–4]. In high-energy nucleon-nucleon collisions ($\sqrt{s} \gg 100$ GeV) the non-single diffractive inelastic cross section increases significantly with energy, as does the magnitude of the long-range forward-backward multiplicity correlations. The component involving the long-range correlations in these collisions has been shown to increase with the energy [4]. These effects can be understood in terms of multiparton interactions [5]. For heavy-ion collisions, it has been predicted that multiple parton interactions would produce long-range forward-backward multiplicity correlations that extend beyond one unit in rapidity, compared to hadron-hadron scattering at the same energy. The model based on multipomeron exchanges (the dual parton model) predicts the existence of long range correlations [6,7]. In the color glass condensate (CGC) framework, the correlations of the particles created at early stages of the collision can spread over large rapidity intervals, unlike the particles produced at the later stage [1]. Thus the measurement of the long-range rapidity correlations of the produced particle could give information about the space-time dynamics of the early stages of the collisions.

The measurement of forward-backward (FB) multiplicity correlations in nucleus-nucleus collisions has been studied

by the STAR experiment at the BNL Relativistic Heavy Ion Collider (RHIC) [8–12]. These results have generated a great deal of theoretical interest [13–23].

Forward-backward correlations have been characterized by the correlation strength b_{corr} , the slope extracted from a linear relationship between the average multiplicity measured in the backward rapidity hemisphere $\langle N_b \rangle$ and the multiplicity in the forward rapidity hemisphere N_f . This relationship can be expressed as [2]

$$\langle N_b(N_f) \rangle = a + b_{\text{corr}} N_f. \quad (1)$$

In this definition, b_{corr} can be positive or negative with a range of $|b_{\text{corr}}| < 1$. This maximum (minimum) represents total correlation (anticorrelation) of the produced particles separated in rapidity. $b_{\text{corr}} = 0$ is the limiting case of entirely uncorrelated particle production. Experimentally, the slope of b_{corr} in hadron-hadron experiments is found to be positive [2]. In Eq. (1), the intercept a is related to the number of uncorrelated particles.

The correlation strength can also be expressed in terms of the ratio of the covariance of the forward-backward multiplicity and the variance of the forward multiplicity. This is done by performing a linear regression of Eq. (1) and minimizing χ^2 . Thus, Eq. (1) can be expressed in terms of the following calculable average quantities:

$$b_{\text{corr}} = \frac{\langle N_f N_b \rangle - \langle N_f \rangle \langle N_b \rangle}{\langle N_f^2 \rangle - \langle N_f \rangle^2} = \frac{D_{\text{bf}}^2}{D_{\text{ff}}^2}, \quad (2)$$

where D_{ff}^2 and D_{bf}^2 are the forward-forward and backward-forward dispersions.

The correlations obtained from above expressions can be a combination of both short and long ranges. The short-range correlations (SRCs) normally extend over a small range of pseudorapidity ($|\eta| < 1.0$) and are due to various short-range order effects [2]. These correlations can arise from various effects, such as particles produced from cluster decay, resonance decay, or jet correlations. The particles produced in

a single inelastic collision are known to only exhibit SRC [3]. Long-range correlations (LRCs) are correlations that extend over a wide range in pseudorapidity, beyond $|\eta| > 1.0$. The presence of a LRC is a violation of short-range order. Short-range order is expected to hold as long as unitarity constraints are neglected [2]. In the approximation of short-range order, only single scattering can be considered. Therefore, quantum mechanical probability is not conserved, since it is possible to have multiple scattering terms.

Recently, FB correlations have been studied extensively with different model simulations, particularly the color glass condensate (CGC) [20] model and the color string percolation model (CSPM) [24]. The CGC model provides a QCD-based description and predicts the growth of LRCs with collision centrality. It is argued that long-range rapidity correlations are due to the fluctuations of the number of gluons and can only be created in early times shortly after the collision [13,20]. In the CGC model, the long-range component has the form

$$b_{\text{corr}} = \frac{1}{1 + c\alpha_s^2}, \quad (3)$$

where α_s^2 is coupling constant and is related to the saturation momentum Q_s^2 and c is a constant. From the above expression, it is observed that as the centrality increases the FB correlation also increases because α_s^2 decreases [24]. A similar behavior is also obtained in the CSPM approach, where b_{corr} is expressed in terms of the string density ξ , which is related to the number of strings formed in the collision:

$$b_{\text{corr}} = \frac{1}{1 + \frac{d}{(1 - e^{-\xi})^{3/2}}}, \quad (4)$$

which vanishes at low string density and at high density grows to become $1/(1 + d)$, where d is a constant, independent of the density and energy [24]. The experimental data for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [8] show similar trends as predicted by the CGC and CSPM models.

FB correlation strength has also been studied in the framework of the wounded nucleon model [16,25]. The results are compared to the STAR data [8] in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. It has been concluded that FB correlation strengths for central collisions are due to the fluctuations of wounded nucleons at a given centrality bin. Thus it is essential to control the centrality of the collisions while reporting the experimental results on correlations.

In the data analysis adopted for the STAR experiment [8], the centrality was defined using the charged particle multiplicity in the midrapidity region. To avoid a self-correlation of the results with the window used for centrality definition, a profile method was used. In this paper we investigate the profile method to extract the LRC strength in heavy-ion collisions and demonstrate its applicability in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the HIJING event generator [26].

II. ANALYSIS METHOD

In a center-of-mass coordinate system, the forward and backward hemispheres are conventionally defined to be opposite to each other, as shown in the schematic diagram of Fig. 1.

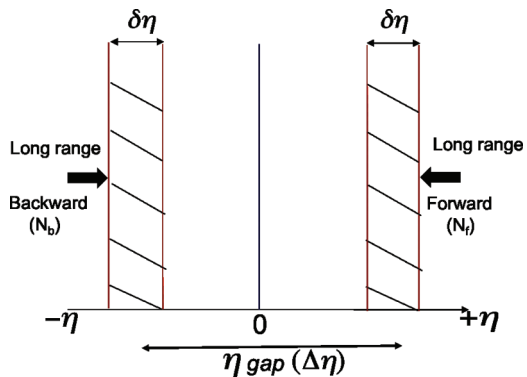


FIG. 1. (Color online) Schematic diagram of the measurement of a forward-backward correlation.

N_f and N_b are the charged particle multiplicities within the forward and backward measurement intervals within a width of $\delta\eta$. In our analysis, a value of $\delta\eta = 0.2$ has been chosen. The FB correlations are measured symmetrically around $\eta = 0$ with varying rapidity gaps, designated as $\Delta\eta$, measured from the center of each bin. Thus depending on the available η window, the values of $\Delta\eta = 0.2, 0.4, 0.6, 0.8, 1.0, \dots$ are possible.

In this analysis, data from the HIJING event generator have been used, in which the particles are produced based on perturbative QCD processes [26]. Nearly one million minimum bias Au-Au events at $\sqrt{s_{NN}} = 200$ GeV and Pb-Pb events at $\sqrt{s_{NN}} = 2.76$ TeV have been generated and used for the analysis. The centrality of the collision is normally designated in terms of the impact parameter of the collision. In the experiments, it is not possible to determine the impact parameter directly, hence one uses charged particle multiplicity within a range of η , which is not overlapping with the η range where the analysis is performed. This is called the reference multiplicity N_{ref} . The use of nonoverlapping pseudorapidity regions—one for the centrality determination and others for FB analysis—avoids bias on the correlation measurements. In the experiments, it is ideal to obtain reference multiplicity from very forward measurements of charged particles. But if this is not available, then the centrality can be defined from the central windows as well. For example, in the present study, for determining FB correlations in $\Delta\eta = 0.2, 0.4$, and 0.6 , reference multiplicity has been obtained within $0.5 < |\eta| < 1.0$, while for $\Delta\eta = 0.8$ and 1.0 the sum of the multiplicities from $|\eta| < 0.3$ and $0.8 < |\eta| < 1.0$ are used for centrality determination. For $\Delta\eta = 1.2, 1.4, 1.6, 1.8, \dots$ the centrality is taken from $|\eta| < 0.5$. In the correlation analysis, the centrality windows are normally selected over a range of cross section, which correspond to a range in reference multiplicity. Within a given centrality window, the FB multiplicity correlations can be affected by the fluctuations in impact parameter and number of participants. To extract true correlations, it is desirable to control the centrality and minimize the effect of centrality fluctuations.

To calculate the correlation strength as a function of the η gap and as a function of centrality, two different methods have been discussed. In the first method, quantities such as $\langle N_f \rangle$, $\langle N_b \rangle$, $\langle N_f^2 \rangle$, and $\langle N_f N_b \rangle$ have been obtained by averaging

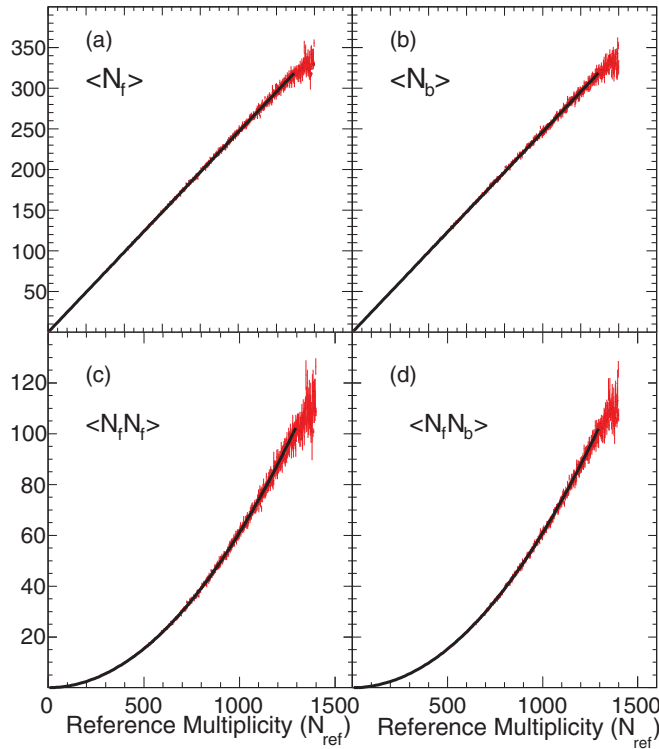


FIG. 2. (Color online) Average multiplicities and their products for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of reference multiplicity N_{ref} . The upper panels show (a) mean forward charged particle multiplicity $\langle N_f \rangle$ and (b) mean backward charged particle multiplicity $\langle N_b \rangle$, both fitted with linear polynomial functions. The lower panels show (c) $\langle N_f N_b \rangle$ and (d) $\langle N_f N_b \rangle$, both fitted with second-order polynomials.

over the events within a centrality bin, and thereby calculating the dispersions D_{ff}^2 and D_{bf}^2 . This method of event averaging does not take into account the fluctuation within a centrality window. This method is called the $FB_{average}$ method.

To eliminate or reduce the effect of the centrality window on the correlation analysis, a second method, called the profile method ($FB_{profile}$) has been introduced. In this method, the distributions of $\langle N_f \rangle$, $\langle N_b \rangle$, $\langle N_f^2 \rangle$, and $\langle N_f N_b \rangle$ have been plotted as a function of the reference multiplicities. Linear fits to $\langle N_f \rangle$ and $\langle N_b \rangle$ and second-order polynomial fits to $\langle N_f^2 \rangle$ and $\langle N_f N_b \rangle$ have been made. These distributions, along with the fits, are shown in Fig. 2. These fit parameters are used to extract the D_{ff}^2 and D_{bf}^2 , binned by centrality, and normalized by the total number of events in each bin. This is shown in Fig. 3. This method removes the dependence of the FB correlation strength on the width of the centrality bin. In the next section, results from both the average and profile methods will be presented and compared.

III. RESULTS AND DISCUSSION

The FB correlations have been studied for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the HIJING event generator. The forward-forward and backward-forward dispersions are calculated as functions of centrality, within a pseudorapidity

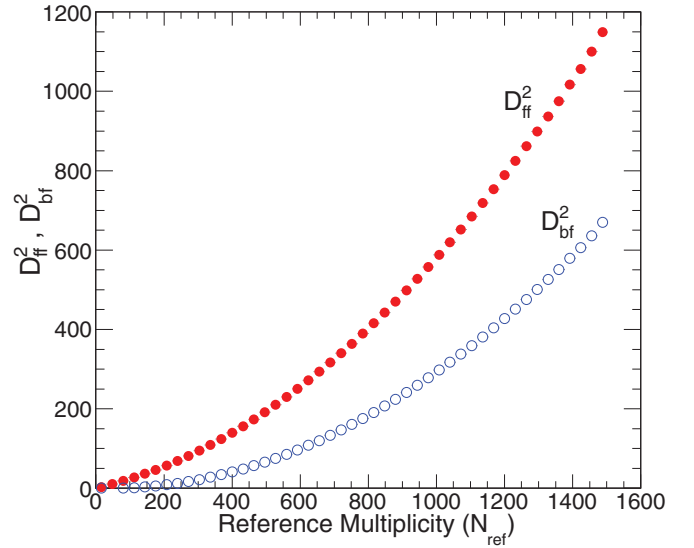


FIG. 3. (Color online) Variance D_{ff}^2 and covariance D_{bf}^2 as a function of reference multiplicity for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

gap extending up to 2.2 units, using both average and profile methods. Figure 4 shows D_{ff}^2 and D_{bf}^2 as a function of $\Delta\eta$ for two overlapping centralities, 0–5% and 0–10% of total cross sections. The dispersions remain approximately constant over the rapidity ranges covered. It is observed that $FB_{average}$ yields

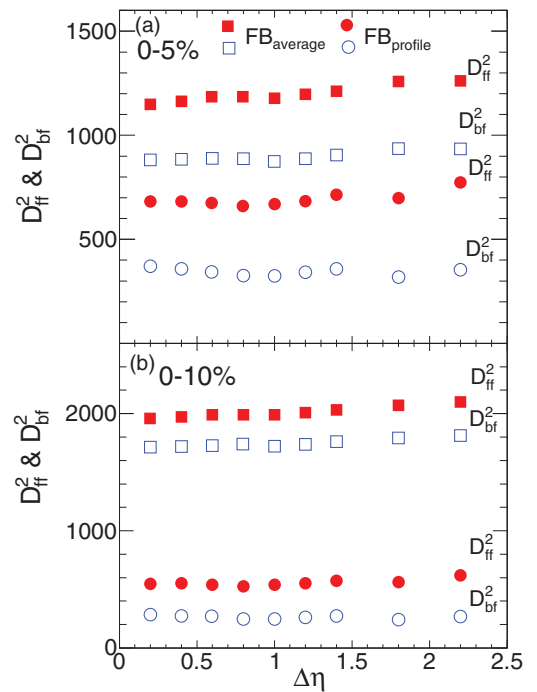


FIG. 4. (Color online) Comparison of D_{ff}^2 and D_{bf}^2 using $FB_{average}$ and $FB_{profile}$ methods. The results are shown for 0–5% and 0–10% centralities for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The centrality is selected using charged particle multiplicity within a particular pseudorapidity window.

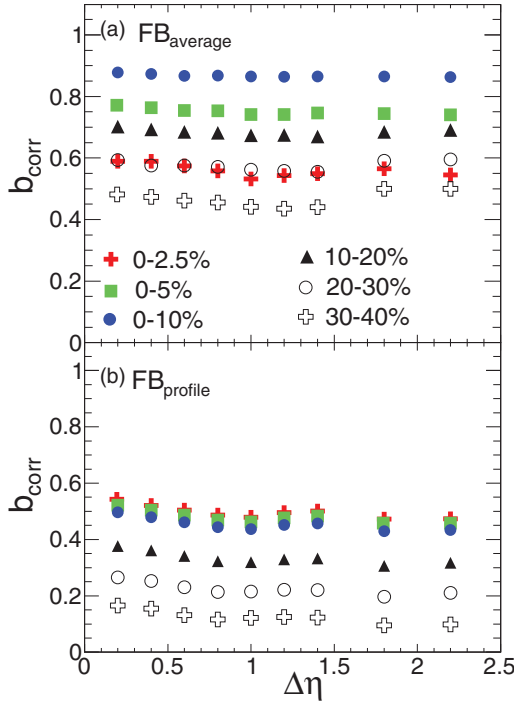


FIG. 5. (Color online) Correlation strength b_{corr} as a function of η gap for 6 centrality bins using results from (a) $\text{FB}_{\text{average}}$ and (b) $\text{FB}_{\text{profile}}$ for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

higher values of both D_{ff}^2 and D_{bf}^2 compared to $\text{FB}_{\text{profile}}$. This is true for both centrality windows.

It is expected that the correlation strength increases with the increase of the centrality of the collision. The correlation strengths b_{corr} are calculated from the ratios of the dispersions for six different centrality windows, 0–2.5%, 0–5%, 0–10%, 10–20%, 20–30%, and 30–40% of the cross section. These centralities are determined from the reference multiplicities as discussed above. Results from both methods are presented in Fig. 5, where the upper panel shows the values of b_{corr} using the $\text{FB}_{\text{average}}$ method and the lower panel gives the results for the $\text{FB}_{\text{profile}}$ method. We observe that b_{corr} for the $\text{FB}_{\text{average}}$ method does not follow any regular pattern in terms of centrality selection. For example, the b_{corr} is seen to be higher for the 0–10% centrality bin compared to 0–2.5% and 0–5% centrality bins, which is counterintuitive to our expectation. This shows that the impact parameter fluctuations are not completely removed when the $\text{FB}_{\text{average}}$ method is used. On the other hand, it can be seen that using the $\text{FB}_{\text{profile}}$ method, the values of b_{corr} have an increasing trend with the increase of centrality of the collisions. The correlation strength is highest for 0–2.5% centrality, as expected.

To confirm the above observation, a study using the impact parameter window for centrality selection, rather than the reference multiplicity, has been made. Results for b_{corr} for various impact parameter selections are shown in Figs. 6(a) and 6(b) for the average and profile methods, respectively. The average method arrives at improper results. In this example, the larger centrality window yields the highest correlation strength, which should not be the case. On the other hand, the $\text{FB}_{\text{profile}}$ method gives similar results whether centrality

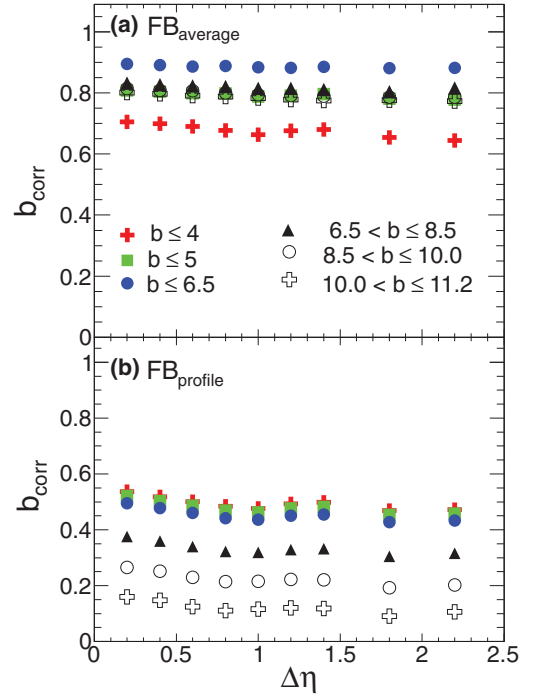


FIG. 6. (Color online) Correlation strength b_{corr} as a function of η gap for various impact parameters using (a) $\text{FB}_{\text{average}}$ and (b) $\text{FB}_{\text{profile}}$ methods for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

selection is made using the impact parameter or the reference multiplicity.

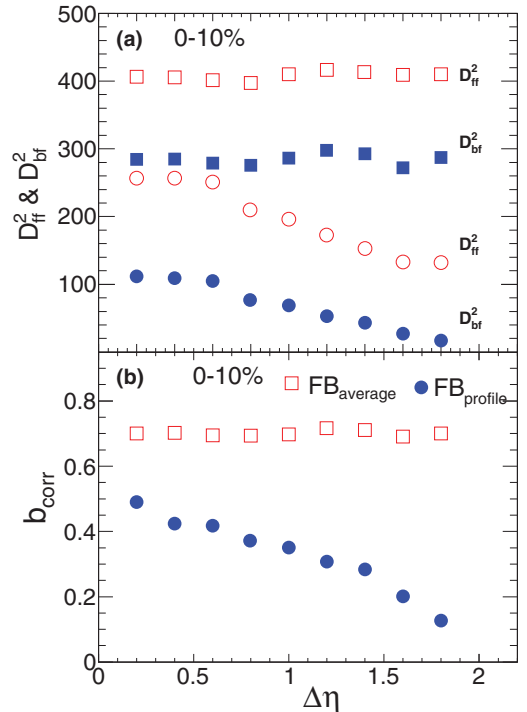


FIG. 7. (Color online) (a) D_{ff}^2 and D_{bf}^2 and (b). Correlation strength b_{corr} as a function of η gap for 0–10% centrality from $\text{FB}_{\text{profile}}$ and (b) method $\text{FB}_{\text{average}}$ for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

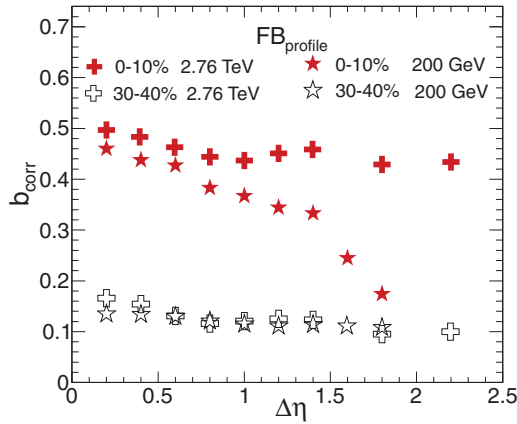


FIG. 8. (Color online) Correlation length as a function of rapidity gap for 0–10% and 30–40% centralities in the case of Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. For central collisions, a clear difference in the correlation length has been observed.

A similar study has been made for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV using the HIJING event generator for the top 10% in central collisions. The upper panel of Fig. 7 shows D_{ff}^2 and D_{bf}^2 and the lower panel shows b_{corr} for both the average and profile methods. The $FB_{average}$ results yield higher values for b_{corr} compared to $FB_{profile}$. The profile results are similar to what had been reported by the STAR Collaboration at RHIC [8,10].

Finally, a comparison of the correlation strengths has been made for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the results from the HIJING event generator and following the $FB_{profile}$ method. The results of the study for two centrality windows (0–10% and 30–40%) are shown in Fig. 8. It is observed that for the noncentral collisions of 30–40% cross section, the correlation strengths are very similar. For central collisions, a decreasing trend is observed for Au-Au collision at $\sqrt{s_{NN}} = 200$ GeV, whereas for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, a flatter distribution is observed. This implies a much stronger correlation over a broad range in pseudorapidity at energies available at the CERN Large Hadron Collider (LHC) compared to those at RHIC.

IV. SUMMARY

Study of forward-backward multiplicity correlation strengths in hadron-hadron and heavy-ion collisions provide

crucial information toward understanding particle production mechanisms and represent useful tools for differentiating different types of reactions and their energy dependence. It has been observed that the correlations show strong short-range correlations and also extend to much wider separation in rapidity. In heavy-ion collisions, the correlation strengths are expected to increase with increase of the beam energy as well as centrality of the collision. Within a given centrality window, the fluctuations in the impact parameter or the number of participants lead to multiplicity fluctuations which affect the accurate determination of correlation strength. Therefore, control of the centrality of the collisions is needed while performing the correlation analysis.

In this paper, two different methods—the average method and the profile method—have been presented to study the forward-backward multiplicity correlations in heavy-ion collisions as a function centrality. It is observed that in the $FB_{average}$ method, the correlation strength does not follow any pattern as a function of centrality window. This reflects the impact parameter fluctuation due to a finite centrality bin width. The second method, $FB_{profile}$, has been introduced, which properly takes care of the effects due to finite centrality bin width. Appropriate centrality dependence has been observed in going from peripheral to central collisions. A comparison of the correlation strengths has been made for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the data from the HIJING event generator. It has been observed that the correlation strengths are higher for higher energy collision. The correlation strengths decrease as a function of the rapidity gap. This decrease is much slower at LHC energy than at RHIC energies. The $FB_{profile}$ method can be used to study the FB correlation strength as a function of centrality in Pb-Pb collisions at LHC. As is shown in this work, along with the correlation strength b_{corr} , it is essential to show the behavior of both the forward-forward (D_{ff}^2) and backward-forward (D_{bf}^2) dispersions as a function of pseudorapidity gap $\Delta\eta$ for different centrality classes. This will allow one to make a direct comparison of experimental data with theoretical models such as CGC and CSPM.

ACKNOWLEDGMENTS

This research was supported by the Office of Nuclear Physics within the U.S. Department of Energy Office of Science under Grant No. DE-FG02-88ER40412. S.D. and T.N were supported by the Department of Atomic Energy, Government of India.

[1] Y. V. Kovchegov, E. Levin, and L. McLerran, *Phys. Rev. C* **63**, 024903 (2001).
 [2] G. J. Alner *et al.*, *Phys. Rep.* **154**, 247 (1987).
 [3] A. Capella and J. Tran Thanh Van, *Z. Phys. C* **18**, 85 (1983).
 [4] T. Alexopoulos *et al.*, *Phys. Lett. B* **353**, 155 (1995).
 [5] W. D. Walker, *Phys. Rev. D* **69**, 034007 (2004).
 [6] A. Capella and A. Krzywicki, *Phys. Rev. D* **18**, 4120 (1978).
 [7] A. Capella *et al.*, *Phys. Rep.* **236**, 225 (1994).

[8] B. I. Abelev *et al.* (STAR Collaboration), *Phys. Rev. Lett.* **103**, 172301 (2009).
 [9] T. Tarnowsky (STAR Collaboration), *Int. J. Mod. Phys. E* **16**, 3363 (2007).
 [10] T. Tarnowsky (STAR Collaboration), in *4th International Workshop on Critical Point and Onset of Deconfinement* (PoS, SISSA, Trieste, Italy, 2007), PoS(CPOD2007)019.
 [11] B. K. Srivastava (STAR Collaboration), *Int. J. Mod. Phys. E* **16**, 3371 (2007).

- [12] B. K. Srivastava (STAR Collaboration), *Eur. Phys. J. A* **31**, 862 (2007).
- [13] N. Armesto, L. McLerran, and C. Pajares, *Nucl. Phys. A* **781**, 201 (2007).
- [14] V. P. Konchakovski, M. Hauer, G. Torrieri, M. I. Gorenstein, and E. L. Bratkovskaya, *Phys. Rev. C* **79**, 034910 (2009).
- [15] P. Brogueira, J. Dias de Deus, and C. Pajares, *Phys. Lett. B* **675**, 308 (2009).
- [16] A. Bzdak, *Phys. Rev. C* **80**, 024906 (2009).
- [17] Y.-L. Yan, D.-M. Zhou, B.-G. Dong, X.-M. Li, H.-L. Ma, and B.-H. Sa, *Phys. Rev. C* **79**, 054902 (2009).
- [18] F. Gellis, T. Lappi, and L. McLerran, *Nucl. Phys. A* **828**, 149 (2009).
- [19] Y.-L. Yan, D.-M. Zhou, B.-G. Dong, X.-M. Li, H.-L. Ma, and B.-H. Sa, *Phys. Rev. C* **81**, 044914 (2010).
- [20] T. Lappi and L. McLerran, *Nucl. Phys. A* **832**, 330 (2010).
- [21] A. Bialas and K. Zalewski, *Phys. Lett. B* **698**, 416 (2011).
- [22] K. Fialkowski and R. Wit, arXiv:1203.3671.
- [23] A. Olszewski and W. Broniowski, arXiv:1303.5280.
- [24] C. Pajares, *Nucl. Phys. B* **854**, 125 (2011).
- [25] A. Bialas, M. Bleszynski, and W. Czyz, *Nucl. Phys. B* **111**, 461 (1976).
- [26] X.-N. Wang and M. Gyulassy, *Phys. Rev. D* **44**, 3501 (1991).