

Forward-backward correlations and multiplicity fluctuations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from ALICE at the LHC

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Forward-backward (FB) multiplicity correlations carry important information on the early dynamics of ultra-relativistic heavy-ion collisions. This paper presents recent data on forward-backward multiplicity correlations and fluctuations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV obtained in the ALICE experiment. The analysis focuses on two observables: the forward-backward correlation coefficient b_{corr}^{n-n} and the strongly intensive quantity Σ . The objective of this study is to investigate the dependence of these measured quantities on the centrality estimator and the influence of event-by-event volume fluctuations in the Pb–Pb collisions.

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1. Introduction

From the point of view of a complementary interplay between theory and experiment in heavy-ion physics, it is crucial to find reliable observables that can give insight into the features of nuclear matter created at the early stage of high-energy nucleus–nucleus reactions. Theoretical studies indicate that such relevant information on the early dynamics of heavy-ion collisions can be obtained from the analysis of event-by-event correlations and fluctuations in particular the measurement of *the forward-backward (FB) multiplicity correlations*, which refer to the analysis of the (linear) dependence between the number of particles n_B and n_F emitted in the backward and forward pseudorapidity (η) interval. The strength of FB correlations is usually defined in terms of the Pearson's correlation coefficient b_{corr}^{n-n} as the covariance between the multiplicity distributions measured in forward and backward pseudorapidity intervals, divided by the product of their standard deviations:

$$b_{corr}^{n-n} = \frac{Cov(n_B, n_F)}{\sqrt{Var(n_B)Var(n_F)}}. \quad (1.1)$$

The recent theoretical developments have revealed a major difficulty in the direct interpretation of measurement results for this observable (see Ref. [1, 2]). The important information on the early dynamics of the heavy-ion collision provided by the FB correlation coefficient b_{corr}^{n-n} is heavily obscured by the contribution coming from geometrical (volume) fluctuations, i.e., event-by-event fluctuations of the number of participant nucleons.

One way to overcome this problem is to define quantities which are sensitive to fluctuations and correlations in a physical system but do not depend on system volume nor system volume fluctuations themselves. Two families Δ and Σ of such observables, called *strongly intensive quantities*, were introduced in heavy-ion physics in Ref. [3]. The group of strongly intensive quantities which includes the correlation term forms the Σ family¹. In the context of forward-backward multiplicity studies, the Σ quantity is defined with eq. 1.2, which relates the combination of forward and backward first moments $\langle n_{B(F)} \rangle$ with forward and backward scaled variances $\omega_{B(F)}$ and the covariance of forward and backward multiplicity distributions:

$$\Sigma = \frac{(\omega_B \langle n_F \rangle + \omega_F \langle n_B \rangle - 2Cov(n_B, n_F))}{\langle n_B \rangle + \langle n_F \rangle}. \quad (1.2)$$

The Σ quantity is constructed in such a way that in the framework of independent source models of multi-particle production², it does not depend on the number of sources or their event-by-event fluctuations. Therefore, it carries direct information on the characteristics of the single source distribution.

The aim of this paper is to present a comparative study of the FB correlation coefficient b_{corr}^{n-n} and the strongly intensive quantity Σ , mainly focused on the dependence of these observables on centrality of Pb–Pb collisions. The work also puts together experimental results and Monte Carlo HIJING simulations of the Σ variable. Both experimental data and simulations have been obtained in the framework of the ALICE experiment for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

¹Strongly intensive quantities which include only variances are called the Δ family.

²Simple superposition models which assume independent particle production from statistically identical sources, the number of which fluctuates from event to event. A good example of an independent source model is the Wounded Nucleon Model [4].

2. Analysis Details

The experimental data sample consists of minimum-bias Pb–Pb events measured during Run I (2010) at $\sqrt{s_{\text{NN}}} = 2.76$ TeV with the ALICE apparatus at the LHC. The total number of events after a selection on the vertex position along the beam axis $|Z_{\text{vtx}}| < 10$ cm is around 16 M. This analysis was confined to primary charged particles emitted into forward and backward pseudorapidity intervals of width $\delta\eta = 0.2$, located symmetrically around mid-rapidity ($\eta = 0$). The observables b_{corr}^{n-n} and Σ were studied as a function of the centrality class width (Δ centrality) and as a function of the η gap ($\Delta\eta$) between forward and backward pseudorapidity intervals. The $\Delta\eta$ parameter was defined as the distance between the lower edge of the forward pseudorapidity interval and the upper edge of the backward pseudorapidity window. In this analysis, the width of the centrality class was varied from 10%, where the largest contribution from volume fluctuations was expected, down to 1% centrality class width. Results on the forward-backward correlation coefficient b_{corr}^{n-n} and the strongly intensive quantity Σ were determined for chosen centrality classes of Pb–Pb collisions varying from central to peripheral. All observables were studied for charged tracks in the kinematic region $p_T < 0.2$ GeV/c and $-0.8 < \eta < 0.8$, in the full azimuthal range ($\phi \in [0, 2\pi]$).

Results for the forward-backward correlations b_{corr}^{n-n} and Σ observable were studied for two different centrality selection methods. The classification of the experimental data sample with regards to the Pb–Pb event centrality was based on information provided with two independent ALICE centrality estimators (a) V0M and (b) ZDCvsZEM. The V0M centrality estimator provides centrality determination in the range 0–80% of the total nuclear cross section based on charged particle multiplicity measurement in the V0 detector acceptance ($-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$). The ZDCvsZEM allows for centrality determination in the range 0–40% of the total nuclear cross section based on the energy deposit of spectator nucleons in the ALICE Zero Degree Calorimeter (ZDC) correlated with two electromagnetic calorimeters (ZEM) [5].

Experimental results for the Σ observable were compared to MC HIJING simulations of Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$. For MC HIJING simulations, the centrality of the Pb–Pb collision in the first method was determined using the V0 estimator. Since the present version of the ALICE simulation framework does not provide event generator based calorimetric centrality selection which would coincide with the ALICE ZDCvsZEM, the second method was a direct selection of the impact parameter of the collision.

3. Results

3.1 Centrality dependence of the forward-backward correlation coefficient b_{corr}^{n-n} and the strongly intensive quantity Σ

Figure 1 shows the experimental results obtained on the forward-backward correlation coefficient b_{corr}^{n-n} (Fig. 1 (a)) and strongly intensive quantity Σ (Fig. 1 (b)) measured in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. The direct comparison of the behavior of the data points between the b_{corr}^{n-n} coefficient and the Σ quantity shows the following with regards to their dependence on centrality class size and selected centrality selection method:

1. From Fig. 1 (a) it is immediately apparent that values obtained for the FB correlation coefficient b_{corr}^{n-n} strongly depend on the size of the centrality class and are highly sensitive to

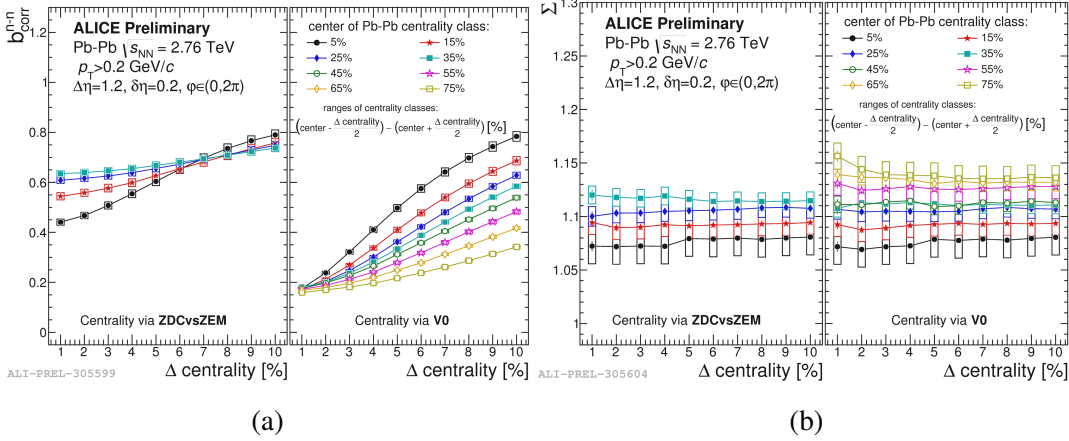


Figure 1: (a) the forward-backward correlation coefficient b_{corr}^{n-n} and (b) the Σ observable obtained for experimental data in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, drawn as a function of centrality class size (Δ centrality), for a fixed value of the pseudorapidity gap $\Delta\eta = 1.2$. The results are obtained for different centrality selection methods: via ZDCvsZEM and via V0. The width of the centrality class changes from 1% to 10%. The different colors of the data points correspond to different centralities of the Pb–Pb collision. Systematic uncertainties are shown as rectangles, statistical uncertainties are smaller than marker sizes.

the centrality selection method. The significant decrease of the correlation strength with decreasing size of the centrality class interval (from 10% to 1%), visible in Fig. 1 (a), regardless of the chosen centrality selection method, supports the claim of the dominant role of geometry (volume) fluctuations in the FB correlation coefficient b_{corr}^{n-n} measurements (see also Ref. [1, 2]). Qualitatively, the trends in Fig. 1 (a) are consistent with the theoretical expression given in Ref. [2] for the behavior of the FB correlation coefficient as a function of the fluctuations of the wounded nucleons (participants):

$$b_{corr}^{n-n} = 1 - \left[1 + \frac{\hat{n}}{4} \left(\frac{2}{k} + \frac{\langle w^2 \rangle - \langle w \rangle^2}{\langle w \rangle} \right) \right]^{-1}. \quad (3.1)$$

Equation 3.1 on b_{corr}^{n-n} coefficient was derived under the assumption of the Wounded Nucleon Model (WNM) [4], with particle emission from a single nucleon implemented according to the negative binomial multiplicity distribution (NBD) characterized with parameters: \hat{n} , namely average multiplicity, and k which determines the shape of the distribution.

2. Compared to the results on the FB correlation coefficient the values of the Σ quantity, presented in Fig. 1 (b), do not exhibit a visible dependence on the size of the centrality class. Moreover, from the direct comparison between left and right panels of Fig. 1 (b) it emerges that, contrary to the b_{corr}^{n-n} coefficient, the behavior of the Σ observable shows no sensitivity to the way centrality was selected in the experiment. These findings support the notion that the Σ observable is not influenced by volume fluctuations and, as such, it displays the properties of a strongly intensive quantity.

3.2 Comparison of experimental data and MC HIJING simulations for the strongly intensive quantity Σ

Figure 2 shows the direct juxtaposition of the Σ observable results measured in experimental data (Fig. 2 (a)) and obtained in the Monte Carlo HIJING (Fig. 2 (b)) simulations of Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV. The outcome of MC HIJING simulations displays similar trends depending on the centrality as observed in the experimental data, namely the lack of sensitivity to the centrality class size and the centrality estimator.

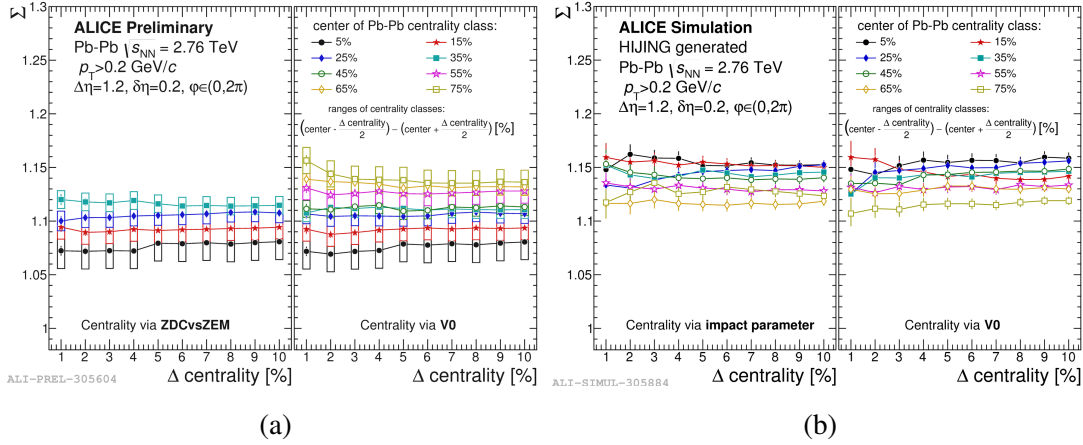


Figure 2: The Σ observable obtained for (a) experimental data and (b) HIJING generated Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, drawn as a function of centrality class size (Δ centrality), for a fixed value of the pseudorapidity gap $\Delta\eta = 1.2$. The results are obtained for different centrality selection methods: via ZDCvsZEM, via V0 and via impact parameter selection. The width of the centrality class changes from 1% to 10%. The different colors of the data points correspond to different centralities of the Pb–Pb collision. Systematic uncertainties are shown as rectangles, statistical uncertainties are labeled with vertical lines.

The most surprising finding of the comparison presented in Fig. 2 is the different ordering of centrality classes of Pb–Pb collisions observed in the experimental data and in MC HIJING simulations. This is a rather interesting outcome keeping in mind that, in terms of independent source models, the strongly intensive quantities such as Σ should be only dependent on fluctuations arising from a single source emitting particles. The discrepancy observed between the ordering of the values of Σ with the centrality of Pb–Pb collision for the MC simulation and the experimental data supports the hypothesis that the mechanism of particle production from the sources present in the experiment may not be reproduced by MC HIJING simulations.

This finding demonstrates the importance of further analysis focused on the dependence of the values of Σ quantity on the centrality of Pb–Pb collisions to provide new information on the early dynamics of ultra-relativistic heavy-ion collisions. More research in this domain is also strongly motivated by the fact that some phenomenological models predict a specific ordering of observables like e.g. the long-range correlation with centrality.

4. Conclusions

Recently new data on forward-backward multiplicity correlations and fluctuations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV have been measured in the ALICE experiment. This paper focuses on a detailed discussion of the results obtained on the values of the forward-backward correlation coefficient b_{corr}^{n-n} and the strongly intensive quantity Σ .

The observed dependence on centrality class width and centrality selection method for the b_{corr}^{n-n} coefficient supports the evidence from previous studies which imply that the potential information on the early dynamics of the heavy-ion collisions carried by this observable is strongly overshadowed by the contribution coming from event-by-event volume fluctuations. Therefore, any interpretation of the b_{corr}^{n-n} observable in the context of new information from the early stage of collision should be approached with caution.

The first measurement of the Σ quantity at LHC energies presented in this paper verifies that this observable fulfills the properties of a strongly intensive quantity in experimental data and in MC HIJING simulations. It means that, in contrast to the FB correlation coefficient b_{corr}^{n-n} , it was observed that the Σ quantity is not affected by the volume fluctuations, namely it does not depend on the centrality class width and is not sensitive to the way centrality is selected.

A direct comparison between experimental data and MC HIJING simulations exposes the discrepancy between the ordering of the values of the Σ variable with the centrality of the Pb–Pb collision. The importance of this observation rises from the fact that the Σ observable as a strongly intensive quantity (sensitive to the correlation term), when interpreted in the context of independent source models, should carry information related only to characteristics of single average sources producing particles. Therefore further analysis of this finding may reveal possible new information on the early dynamics of the ultra-relativistic heavy-ion collision.

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