Event-by-event correlations and fluctuations with strongly intensive quantities in heavy-ion collisions with ALICE

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Abstract. The strongly intensive quantity Σ is a new observable, introduced recently to the domain of heavy-ion physics. In superposition models which assume independent particle production from statistically identical sources, Σ is insensitive to the number of sources and its fluctuations, contrary to the standard forward-backward correlation coefficient (b_{corr}). Therefore it provides direct information on the multiplicity correlations and fluctuations from a single source. This paper presents new results on forward-backward correlations studied with the quantity Σ, measured by ALICE at the LHC in Xe–Xe collisions at $\sqrt{s_{\text{NN}}}$ = 5.44 TeV and in Pb–Pb collisions at $\sqrt{s_{\text{NN}}}$ = 2.76 and 5.02 TeV. These results are compared with ALICE measurements in pp collisions at $\sqrt{s}$ = 13 TeV.

1 Introduction

Lattice QCD predicts that in ultrarelativistic heavy-ion collisions, sufficient energy is reached for the phase transition of hadron matter to quark–gluon plasma (QGP). As a result of the rapid expansion of this new partonic system, the free quarks and gluons become once again confined into baryons and mesons during the hadronization process. Therefore, the nature of the early stages of the collision in which the formation of QGP may occur and traits of the phase transition must be inferred based on the final state particles, namely hadrons, leptons, and photons measured in the detector.

One of the basic techniques for studying the properties of the system formed in a high-energy nucleus–nucleus interaction is the measurement of *correlations and fluctuations* in the number of particles produced in the collision. Their analysis in heavy-ion collisions has many facets, and this diversity in their measurement methods is widely used to study various phenomena manifesting in nuclear matter [1]. In particular, it provides a chance to understand the dynamic nature of multi-particle production.

Of the multiple ways of studying correlations, their so-called *forward-backward* (FB) analysis is one of the earliest applied in high-energy physics. The forward-backward multiplicity correlation determines the relation between particles produced in the forward and backward pseudorapidity (η) intervals, as illustrated in Fig. 1. So far, a widely used measure of the FB correlation strength was the correlation coefficient b^{n-n}_{corr}, defined by Eq. 1 as the ratio of the covariance between the number of particles measured in forward and backward η interval and the product of their standard deviations. The main limitation in using a b^{n-n}_{corr} coefficient as a measure of correlation strength was discussed in Refs. [2–4]. It has been

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demonstrated that the correlation coefficient is strongly contaminated by trivial effects such as event-by-event volume fluctuations and depends on how the geometry (centrality) of the collision is selected in the experiment.

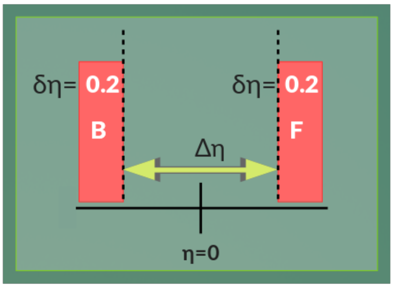

Figure 1: The illustration of the concept of measurement of forward-backward correlation for symmetrical (with respect to $\eta = 0$) forward-backward intervals in pseudorapidity of width $\delta\eta = 0.2$, and the separation gap $\Delta\eta$.

$$b_{corr}^{n-n} = \frac{Cov(n_B, n_F)}{\sqrt{Var(n_B)Var(n_F)}} \quad (1)$$

Many methods have already been proposed to overcome this problem; some involve studying b_{corr}^{n-n} in narrow centrality classes [4], thereby reducing the contribution from fluctuations in the system's volume, and others by measuring the partial correlation coefficient [5]. A relatively new technique with great potential, as shown in this work, is based on analyzing the forward-backward correlation with *strongly intensive quantities*.

The concept of strongly intensive quantities was originally brought to heavy-ion physics in Ref. [6]. They are observables that do not depend on the volume of the system and its fluctuations fluctuations. Their definition is derived under the independent source model assumption, implying that particles are produced independently from statistically identical sources. Two sets of strongly intensive observables are dedicated to correlation and fluctuation studies, namely Σ and Δ 'family'. The Σ group contains a correlation term and therefore is the subject of interest in this analysis. Regarding forward-backward multiplicity correlation analysis, Σ is expressed by the Eq. 2 as a combination of scaled variances $\omega_{F(B)}$, first moments $\langle n_{F(B)} \rangle$, and covariance of multiplicity distributions

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

It is noteworthy that the first-ever verification of the postulate that the Σ variable defined by the given formula has the properties of strongly intensive quantities was done in the ALICE [4]. One can easily deduce that for a symmetrical collision such as Pb–Pb, the Eq. 2 becomes

$$\Sigma = \omega(1 - b_{corr}^{n-n}). \quad (3)$$

In the context of the independent source model, a unique and important property of Σ emerges; namely, it provides direct information about the single source distribution characteristics.

This paper reviews the set of new results on forward-backward correlation analysis with strongly intensive quantity Σ obtained for different collision systems, including Xe–Xe at

$\sqrt{s_{\rm NN}}$ = 5.44 TeV, Pb–Pb at $\sqrt{s_{\rm NN}}$ = 2.76 and 5.02 TeV, and pp at $\sqrt{s}$ = 13 TeV. For the first time, such comprehensive studies of Σ measure are presented, where experimental results for heavy-ion collisions are compared with those for smaller systems such as Xe–Xe and elementary collisions and with available theoretical models.

2 Analysis details

The experimental data sample consists of minimum-bias Pb–Pb at $\sqrt{s_{\rm NN}}$ = 2.76 and 5.02 TeV, Xe–Xe collisions at $\sqrt{s_{\rm NN}}$ = 5.44 TeV, and pp collisions at $\sqrt{s}$ = 13 TeV recorded by the ALICE detector at the LHC during Run 1 and Run 2.

The main analysis is carried out for primary charged particles emitted within kinematic region $0.2 < p_{\rm T} < 5.0$ GeV/c and $-0.8 < \eta < 0.8$, in the full azimuthal range ($\varphi \in [0, 2\pi]$). For pp collisions, the cut on transverse momentum is slightly stricter, specifically $0.2 < p_{\rm T} < 2.0$ GeV/c.

The Σ observable is determined for particles registered in forward and backward pseudorapidity regions of width $\delta\eta = 0.2$ located symmetrically around midrapidity ($\eta = 0$). The separation gap between the forward and backward pseudorapidity intervals is defined as the distance between the lower edge of the forward and upper edge of the backward window ($\Delta\eta$ shown in Fig. 1). For pp, this distance is labeled as η_{gap} and it is a distance between centers of the forward and backward η intervals. The relation between these two definitions of the separation gap is as follows: $\eta_{gap} = \Delta\eta + 0.2$.

For heavy-ion collisions, classification regarding the event centrality was provided based on information from two independent ALICE centrality estimators, (a) V0 and (b) ZDCvsZEM, when available. At the same time, the pp events were categorized in terms of V0 multiplicity classes. The V0 detector provides centrality determination based on the energy deposition in its acceptance ($-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$). The ZDCvsZEM allows for centrality determination in the range of 0–40% of the total nuclear cross-section. The events are categorized according to the energy deposition of spectator nucleons in the ALICE Zero Degree Calorimeter (ZDC) correlated with two electromagnetic calorimeters (ZEM). More details about methods of centrality determination in ALICE can be found in Refs. [7, 8].

Experimental results for the Σ observable were compared with Monte Carlo predictions from HIJING [9], EPOS [10], or AMPT [11] models.

3 Results

3.1 Centrality dependence of the forward-backward strongly intensive quantity Σ

Figure 2 presents the overview of the results on forward-backward correlations with Σ quantity obtained for different collision systems as a function of centrality for fixed and large value of separation gap between forward and backward pseudorapidity windows, $\Delta\eta = 1.2$. Experimental data presented on the left panel are compared with predictions from HIJING, EPOS, and AMPT shown on the right panel.

In Fig. 2, four distinctive features manifesting in the behavior of the experimental data points can be observed:

1. From a comparison of the results obtained for Pb–Pb at $\sqrt{s_{\rm NN}}$ = 2.76 TeV for two different centrality estimators, V0 and ZEMvsZDC, it is immediately apparent that the values of the Σ do not depend on how centrality is selected in the experiment. It is a non-trivial finding as it is well known that many observables, such as b^{n-n}_{corr}, partial

correlation coefficient, or ω, depend on the way we determine collision geometry in the analysis. A more extensive discussion of the lack of dependence of Σ observable on the centrality estimator and the width of the centrality interval (volume fluctuation) was already addressed in great detail in Refs. [4, 12, 13].

2. Experimental results show an increase in Σ with energy, independent of system size. These findings corroborate the behavior observed for pp elementary collisions and the MC PYTHIA [14] results reported in Ref. [13]. A possible explanation for this might be, as already mentioned in Ref. [13], the change in the properties of particle emitting sources with the energy scale.

3. A characteristic trend in the evolution of sigma values as a function of centrality can be noted. Strongly intensive quantity Σ increases from central to peripheral Pb–Pb and Xe–Xe collisions.

4. One of the most striking results emerges from the comparison between experimental data and Monte Carlo simulations. None of the selected MC models, namely HIJING, EPOS, and AMPT, is able to describe the behavior of Σ quantity.

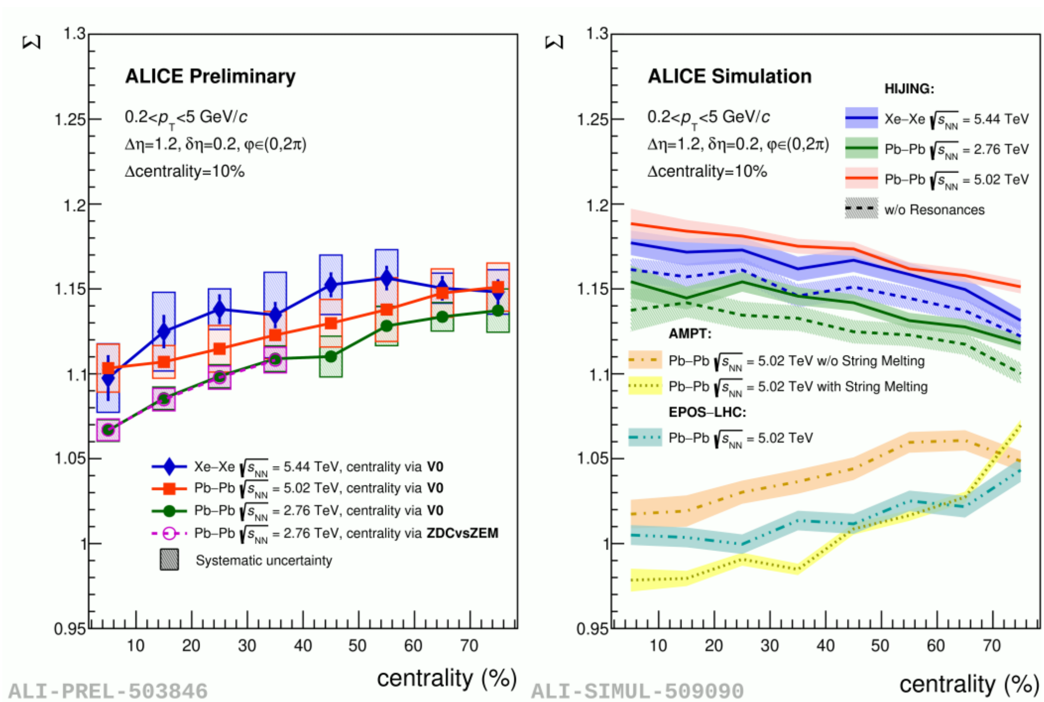

Figure 2: Centrality dependence of strongly intensive quantity Σ obtained for Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 and 5.02 TeV and Xe–Xe collisions at $\sqrt{s_{\rm NN}}$ = 5.44 TeV. Results are presented for a fixed value of the pseudorapidity gap $\Delta\eta = 1.2$. Experimental data presented on the left panel are compared with the results for MC HIJING, EPOS, and AMPT simulations (right panel).

Among the observations listed above, the evident discrepancy between the theoretical description and measured data is the most puzzling. A broader discussion regarding the conclusion that can be drawn from this comparison is required.

Closer inspection of the HIJING simulation outcome reveals that the model has similar values as the experimental data for Pb–Pb and Xe–Xe collisions; however, it fails on the level of their qualitative description. First, HIJING does not reproduce the Σ ordering with the energy of the collision system noted for the experimental data. Secondly, Σ values decrease from central to peripheral collisions; the opposite behavior characterizes measured results. Removing the contribution from resonance reduces the Σ values but does not change its ordering with centrality.

Surprisingly, AMPT and EPOS simulations were found to reproduce the ordering of Σ as a function of centrality as measured in the ALICE experiment. Nonetheless, both models break down on the quantitative description of the experimental data. The discrepancies are around 10%.

There is an important difference between the behavior of the data points observed for the two versions of the AMPT model. The main distinction between the two versions runs at the level of the hadronization mechanism. In default, AMPT scenario (labelled in Fig. 2 as AMPT w/o String Melting) adopted Lund string fragmentation while String Melting AMPT assumes quark coalescence. From the results for MC AMPT, it is evident that Σ is sensitive to the mechanism of particle production assumed in the model.

It should be emphasized that the observed discrepancies between the theoretical description and experimental data, as well as the strong dependence on the conditions assumed by the models (see the results for two versions of AMPT), were being noted only for the Σ variable. Other measures of correlation and fluctuation, such as b^{nn}_{corr} or $\nu_{\rm dyn}$ (see comparison of data with model calculations in Refs. [4, 13]), did not show similar behavior, even after eliminating the contributions coming from trivial fluctuations of volume. It may indicate the unusual and useful sensitivity of Σ to the processes of particle production occurring in the system created after the nuclear collision.

The presented results may cast a new light on the dynamical features of the system emitting particles implemented in popular Monte Carlo models used to describe heavy-ion collisions. The strongly intensive quantity Σ in terms of the independent source model provides information on the emission of particles from a single average source. Taking the latter into account, the observed discrepancies between the MC descriptions and measured values imply that the scenario of particle production mechanism in nuclear collisions still escapes full theoretical understanding. Strongly intensive quantities seem to be the right tool to verify those models.

3.2 Strongly intensive quantity Σ as a function of FB separation gap

The strongly intensive quantities were also studied in the ALICE as a function of the separation gap between forward and backward windows, as shown in Fig. 3. This figure compares the experimental results of Σ observable obtained in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV (left panel) with those measured from pp collisions at $\sqrt{s} = 13$ TeV (right panel).

A growth of the strongly intensive quantity with increasing $\Delta\eta$ is observed for Pb–Pb. Similar behavior is also noted for pp data. This trend is likely related to a decrease in the contribution from short-range correlations as the distance between the forward and backward pseudorapidity interval increases and directly follows Eq. 3.

Results presented in Fig. 3 were analyzed for different Pb–Pb centrality classes and selected multiplicity classes in pp collisions. Both classifications of events, in terms of centrality and multiplicity, were based on energy deposition in the V0 detector (V0 centrality

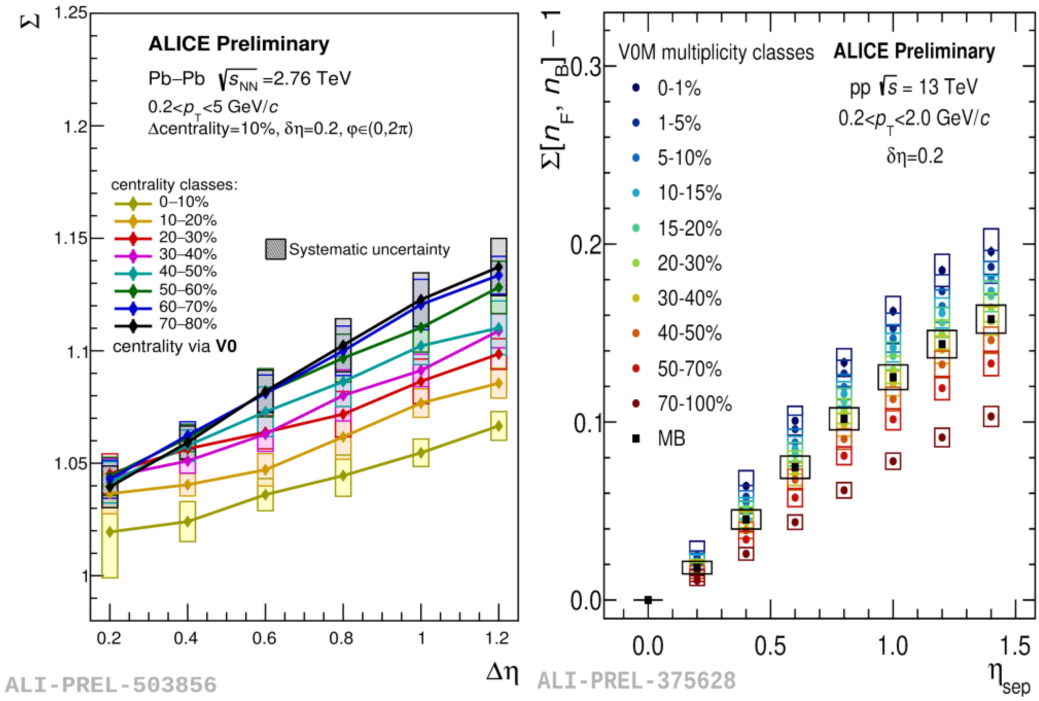

Figure 3: The strongly intensive quantity Σ obtained from Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV and pp collisions at $\sqrt{s}$ = 13 TeV. The left panel shows the values of Σ for Pb–Pb collisions as a function of $\Delta\eta$ obtained for different V0 centrality classes. The right panel presents the results of Σ − 1 as a function of $\eta_{gap} = \Delta\eta + 0.2$ for different V0 multiplicity classes in pp collisions.

estimator). The most interesting aspect of the findings presented in Fig. 3 comes directly from the comparison of the ordering of Σ values with respect to the multiplicity (centrality) class between pp and heavy-ion collisions. There is a clear trend of increasing Σ quantity with forward event multiplicity of pp collisions contrary to the behavior observed in Pb–Pb and Xe–Xe collisions (see left panels in Fig. 2 and Fig. 3). Interestingly, the centrality dependence of Σ predicted for Pb–Pb and Xe–Xe by the HIJING model (right panel in Fig. 2) coincides qualitatively with the one observed in pp collisions.

This discrepancy in Σ ordering concerning centrality reported between different collision systems indicates that, on average, the nature of particle-emitting sources and characteristics of its evolution with the system size created after a collision might differ in elementary pp interactions compared to ultrarelativistic heavy-ion collisions. Understanding the core of this change might be crucial for revealing the difference in properties of nuclear matter manifesting in small (pp) versus large (nucleus–nucleus) collision systems and requires future research.

4 Conclusions

This paper presents new results on forward-backward correlations with strongly intensive quantity Σ measured in various collision systems and energies by the ALICE Collaboration.

The research focuses on the comprehensive study of Σ observables in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 and 5.02 TeV, and Xe–Xe collisions at $\sqrt{s_{\rm NN}}$ = 5.44 TeV and their comparison with the elementary pp interactions.

This study has shown that Σ depends on the energy and centrality of the collision system. It increases with energy for experimental Pb–Pb, Xe–Xe, and pp collisions. It also grows with decreasing centrality for larger systems such as Pb–Pb and Xe–Xe; a contrary behavior is noted for pp collisions.

The analysis of strongly intensive quantity Σ exposed failure of the most commonly used heavy-ion MC models to describe this observable. Although MC HIJING reproduces quite well the values of Σ measured in the experiment, it cannot recreate its behavior qualitatively. The model is not able to replicate the energy dependence and shows the opposite trend of Σ with centrality than observed in Pb–Pb and Xe–Xe collisions. Removal of the resonance contribution does not change the ordering of Σ with centrality. On the other hand, AMPT and EPOS calculations reproduce the centrality dependence qualitatively but not quantitatively. From the results obtained for two versions of AMPT, it is evident that Σ is sensitive to the mechanism of particle production implemented in the model.

The comparison of centrality ordering in nucleus–nucleus collisions with theoretical models, and experimental pp data, may provide new insight into the underlying dynamics of a collision. Recognizing that in terms of the independent source model, the strongly intensive quantity Σ should provide direct information on the features of the average single source emitting particles presented in this paper's findings and the inability of existing theoretical models to describe them raise intriguing questions regarding the nature and extent of our understanding mechanism of particle production in high-energy nucleus–nucleus collisions.

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