PROCEEDINGS OF SCIENCE

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

Iwona Sputowska
for the ALICE Collaboration

Institute of Nuclear Physics, Polish Academy of Sciences,
ul. Radzikowskiego 152, Kraków, Poland

E-mail: iwona.sputowska@cern.ch

This paper presents a short overview of event-by-event correlations and fluctuations analysis with strongly intensive quantities measured by ALICE at LHC in pp, p–Pb, Xe–Xe, and Pb–Pb collisions in the overall energy regime ranging from $\sqrt{s_{\mathrm{NN}}} = 0.9$ up to 13 TeV. The evolution of the forward-backward strongly intensive quantity Σ is analyzed as a function of the distance between forward and backward pseudorapidity intervals (η gap), the centrality of the collision, and the width of the centrality bin. The observable is studied by means of different centrality estimators. The net-charge fluctuations with $\nu_{\mathrm{dyn}}[+,-]$, are examined as a function of charged-particle density ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$). Our study demonstrates that Σ indeed exhibits the properties of a strongly intensive quantity in terms of the independent source models, providing information on the early collision dynamics which is far more direct than that obtained from b_{corr}^{n-n}. The measured negative values of $\nu_{\mathrm{dyn}}[+,-]$ indicate the dominance of the correlation between oppositely charged particles. A smooth evolution of net-charge fluctuations is observed from small to large collision systems.

The International conference on Critical Point and Onset of Deconfinement - CPOD2021
15 – 19 March 2021
Online - zoom

https://pos.sissa.it/

PoS(CPOD2021)027

1. Introduction

There are indications that a new state of matter, called the quark-gluon plasma (QGP) is formed in an early phase of the ultrarelativistic heavy-ion collision. This system built with quarks and gluons rapidly expands, making partons quickly freeze out into hadrons which we measure as final particles in our detectors. One of the field's greatest challenges is finding observables sensitive to the system characteristics *before* its freezeout.

There is enough theoretical evidence suggesting that studies on event-by-event correlations and fluctuations of final state particles can provide information on the properties of hot QCD matter. In this context, this paper discusses recent results on forward-backward (FB) multiplicity correlations and net-charge fluctuations measured at LHC energies.

The forward-backward (FB) multiplicity correlations refer to the dependence between the number of particles emitted in the backward and forward pseudorapidity (η) interval and thus, can give us access to potentially relevant information on the initial dynamics of heavy-ion collisions. In recent times, however, questions have been raised about the use of the standard measure of FB correlation strength, which is Pearson's correlation coefficient b_{corr}^{n-n} (see definition in Ref. [1]). Theoretical studies from Refs. [2, 3] revealed that this observable is strongly affected by spurious effects from geometrical (volume) fluctuations, which overshadow the physical information it could provide on the early dynamics of heavy-ion collisions.

One of the solutions to this problem is the analysis of FB fluctuations using *strongly intensive quantities*. These are event-by-event observables constructed in such a way that they do not depend on system volume, nor system volume variations. Strongly intensive quantities are defined in the framework of a class of superposition models that assume independent particle production from statistically identical sources, the number of which fluctuates from event to event. As such, these quantities are insensitive to the number of sources and its fluctuations but instead, provide direct information about the characteristics of a single source distribution.

Two groups of such observables constructed as a combination of second moments were introduced in heavy-ion physics in Ref. [4]. The strongly intensive quantities that include the correlation term are called the 'Σ family'. For forward-backward multiplicity analysis, the Σ quantity is described with eq. (1), which relates the combination of forward and backward first moments $\langle n_{B(F)} \rangle$ with scaled variances $\omega_{B(F)} = Var(n_{B(F)})/\langle n_{B(F)} \rangle$ and the covariance of forward and backward multiplicity distributions:

$$\Sigma = \frac{(\omega_B \langle n_F \rangle + \omega_F \langle n_B \rangle - 2Cov(n_B, n_F))}{\langle n_B \rangle + \langle n_F \rangle}. \tag{1}$$

An observable related to the strongly intensive quantity Σ often used to quantify the dynamic net-charge fluctuations is the ν_{dyn} variable, see Refs. [4, 5]. Fluctuations of globally conserved quantities such as net-charge, in a limited phase space window, are sensitive to the composition of hot and dense matter in the early stages of the collision. Consequently, they provide insight into microscopic features of the QGP medium. This sensitivity arises from a difference between the unit of charge characterizing the confined and de-confined phase of nuclear matter, 1 and 1/3 respectively. The fluctuations in net charge depend on the the square of the charges; thus, their measurement can provide information about the system's degrees of freedom. A decrease in net-charge fluctuations is an expected signal for the QGP (Ref. [6]).

In the context of net-charge fluctuation analysis, $\nu_{\rm dyn}$ measures the relative correlation strength of particle pairs, and it is defined by eq. (2). In the formula N_+ and N_- are the numbers of positive and negative particles, respectively.

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

As it is the case for the Σ, $\nu_{\rm dyn}$ does not depend on the fluctuation of sources, but it is not a strongly intensive quantity because it scales inversely with the system size. The main advantage of the $\nu_{\rm dyn}$ variable is its robustness against random efficiency losses.

This paper reports a large set of new measurements on the strongly-intensive quantity Σ and the $\nu_{\rm dyn}$ variable, obtained by the ALICE experiment at the LHC in pp, p–Pb, Xe–Xe, and Pb–Pb reactions in the overall energy regime ranging from $\sqrt{s_{\rm NN}} = 0.9$ up to 13 TeV. Both observables have been obtained in the pseudorapidity range $-0.8 < \eta < 0.8$. For Σ measurements, two independent centrality estimators have been used in order to investigate experimentally their strongly-intensive character: one estimator ("V0") relies on the number of charged particles emitted outside of the η range under consideration; the other estimator ("ZDCvsZEM") is based on the energy deposit in the forward (zero-degree) calorimeters of the ALICE detector.

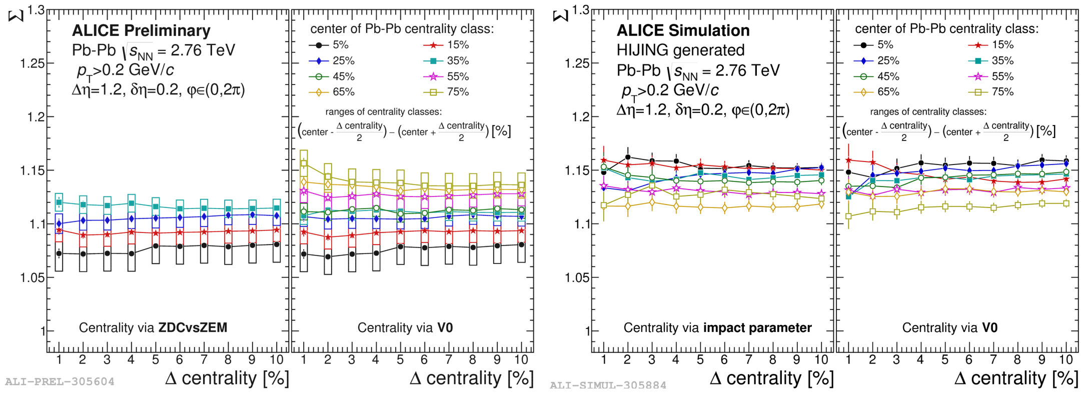
2. Forward-backward multiplicity fluctuations with strongly intensive quantity Σ

2.1 Results for Pb–Pb colisions

Figure 1 (a) shows the first experimental results obtained by ALICE on the forward-backward strongly intensive quantity Σ in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. We studied the Σ observable as a function of the centrality class width (Δ centrality) for a fixed value of η gap ($\Delta\eta = 1.2$) between forward and backward pseudorapidity intervals, in chosen centrality classes of Pb–Pb collisions varying from central to peripheral. Forward and backward windows have width $\delta\eta = 0.2$. Results were measured for two different centrality selection methods provided by ALICE, namely V0 and 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) [7]. The Σ observable was determined for charged tracks in the kinematic region $p_{\rm T} > 0.2$ GeV/c and $-0.8 < \eta < 0.8$, in the full azimuthal range ($\varphi \in [0, 2\pi]$).

From the behavior of the data points in Fig. 1 (a), it is immediately apparent that the Σ quantity exhibits no dependence on the size of the centrality class. Moreover, the direct comparison between left and right panels of the figure reveals that the Σ observable is not sensitive to the way centrality was selected in the experiment.

The result of associated Monte Carlo (MC) HIJING simulations of Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV presented in Fig. 1 (b) are in line with the outcome of experimental data regarding the robustness of the results to the centrality class size and the centrality estimator. These observations support the idea that the Σ is indifferent to volume fluctuations and exhibits the properties of a strongly intensive quantity.



(a) (b)

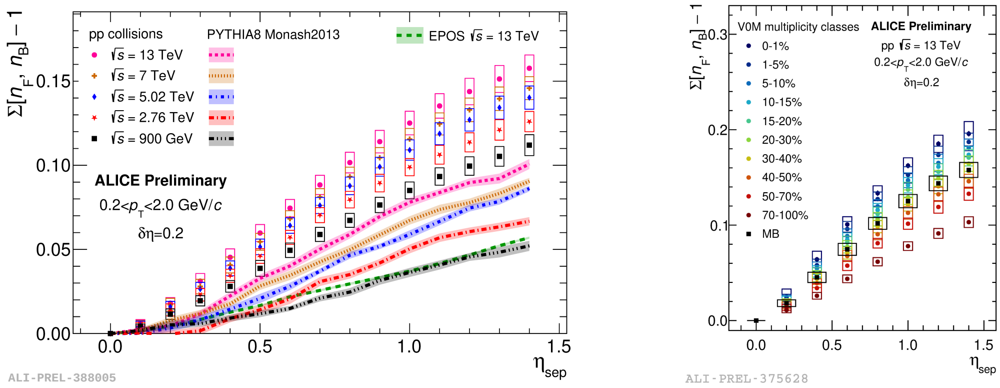
Figure 1: The Σ observable obtained for (a) experimental data and (b) HIJING generated Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, drawn as a function of centrality class size (Δ centrality), for a fixed value of the pseudorapidity gap $\Delta\eta = 1.2$. The $\Delta\eta$ parameter refers to the distance between the lower edge of the forward pseudorapidity interval and the upper edge of the backward pseudorapidity window. 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 striking observation to emerge from the data comparison in Fig. 1 is the opposite ordering of centrality classes of Pb–Pb collisions observed between the experimental data and in MC HIJING simulations. Taking into consideration that the strongly intensive quantity Σ should be only dependent on fluctuations arising from a single source emitting particles, the reported discrepancy between the ordering of the values of Σ with the centrality of Pb–Pb collision for the MC simulation and the experimental data implies that physical mechanism of particle production might be different from the one predicted by models.

This finding demonstrates the potential hidden in the analysis of FB correlations using strongly intensive quantities. In particular, it demonstrates that studying the dependence of the Σ quantity on the centrality of Pb–Pb collisions makes an excellent tool for the verification of phenomenological models of particle production, which is able to provide new information on the early dynamics of ultra-relativistic heavy-ion collisions.

2.2 Results for pp collisions

Recently ALICE measured forward-backward charged particle correlations using the strongly intensive quantity Σ in pp collisions. Results were obtained in a wide energy range varying from $\sqrt{s}$ = 0.9 TeV to 13 TeV in the kinematic region $0.2 < p_T < 2$ GeV/c and $-0.8 < \eta < 0.8$. The strongly intensive quantity Σ was studied as a function of collision energy (Fig. 2 (a)), as well as multiplicity class in the pp collision (Fig. 2 (b)) for the energy of the pp collision equal to $\sqrt{s}$ = 13 TeV. The classification of pp events it terms of multiplicity was based on charged-particle multiplicity measurement in the V0 detector.



(a) (b)

Figure 2: The value of $(\Sigma - 1)$ obtained for pp collisions in the energy range from $\sqrt{s} = 0.9$ TeV up to 13 TeV, plotted as a function of pseudorapidity gap η_{sep}. The gap η_{sep} was defined as the distance between centers of the forward and backward pseudorapidity interval. The panel (a) shows the energy dependence of $\Sigma - 1$. The different colors of the data points correspond to different energies of the pp collision. In panel (a), the experimental results were compared to MC PYTHIA and EPOS simulations. Panel (b) shows the values of $\Sigma - 1$ for different V0 multiplicity classes in pp collisions at $\sqrt{s} = 13$ TeV.

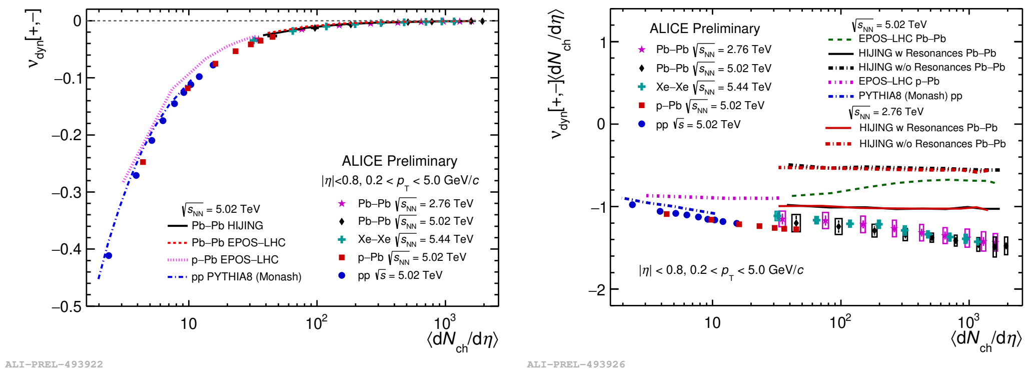
From the data in Fig. 2 (a), it is evident that the values of the Σ quantity grow with the pp collision energy. A possible explanation for these results may be the evolution of properties of particle emitting sources with the energy scale. The comparison between experimental data and corresponding MC simulations shows that the event generators PYTHIA8 (Monash tune) from Ref. [8] and EPOS from Ref. [9] describe the experimental results qualitatively, but are not able to reproduce their behavior quantitatively.

As can be seen from Fig. 2 (b), results on the strongly intensive quantity Σ for elementary collisions exhibit an increase as a function of forward event multiplicity. This is contrary to the behavior observed in Pb-Pb interactions. Whether this is a hint of a difference in the mechanism of particle production occurring in pp and Pb–Pb collisions requires further investigation.

3. Net-charge fluctuations with $\nu_{\rm dyn}$

The results of the ALICE event-by-event net-charge fluctuation analysis with the $\nu_{\rm dyn}[+,-]$ values are reported in Fig. 3 (a) as a function of the system size. These results were obtained for various collision systems such as pp, p–Pb and Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV and Xe-Xe collisions at $\sqrt{s_{\rm NN}} = 5.44$ TeV, within the phase space $0.2 < p_{\rm T} < 5$ GeV/c and $-0.8 < \eta < 0.8$, for selected centrality classes of heavy-ion collisions.

The measurements show negative values of $\nu_{\rm dyn}[+,-]$ for all the collision systems. This finding implies the dominance of the correlation between oppositely charged particles. In Fig. 3 (a), a smooth evolution of net-charge fluctuations is observed from small to large collision systems. This behavior is quite well reproduced by dedicated MC simulations such as HIJING, EPOS, and PYTHIA8 (Monash tune).



(a) (b)

Figure 3: Panel (a) shows the value of the dynamical net-charge fluctuations $\nu_{\text{dyn}}[+,-]$ as a function of system size, expressed in terms of charged particle density. Panel (b) presents the results of $\nu_{\text{dyn}}[+,-]$, scaled by charged-particle density at mid-rapidity $\langle dN_{\text{ch}}/d\eta\rangle$. In both figures (a) and (b), the experimental results were compared to MC HIJING, PYTHIA8 and EPOS simulations.

In Fig. 3 (a), a clear trend of decreasing magnitude of net-charge fluctuations with increasing system size is possibly driven by the inversely proportional dependence of the $\nu_{\text{dyn}}[+,-]$ observable on system size. In order to eliminate this trivial intrinsic sensitivity to multiplicity, the values of $\nu_{\text{dyn}}[+,-]$ quantity were scaled by charged-particle density at mid-rapidity $\langle dN_{\text{ch}}/d\eta\rangle$. The outcome of such scaling is plotted in Fig. 3 (b).

From this data, we can see that the amplitude of net-charge fluctuations increases with the centrality of the system. This trend is not reproduced by MC HJING and EPOS. Only for pp collisions, the PYTHIA8 (Monash tune) agrees with the experimental data. The key observation to emerge from model predictions is the significant contribution from the resonance decays to the measured values of the $\nu_{\text{dyn}}[+,-]$ quatity. The presence of resonances reduces the magnitude of net-charge fluctuations.

4. Summary

Recently ALICE has measured new data on net-charge fluctuations $\nu_{\text{dyn}}[+,-]$ and first experimental data on forward-backward correlations with strongly intensive quantity Σ in pp, p–Pb, Xe–Xe, and Pb–Pb reactions in the energy regime ranging from $\sqrt{s_{\text{NN}}} = 0.9$ up to 13 TeV.

In summary, the findings discussed above show that the Σ observable in Pb-Pb collisions, in contrast to the FB correlation coefficient b_{corr}^{n-n}, is not affected by the volume fluctuations and does not depend on the size of the centrality class and centrality estimator. It exhibits the properties of a strongly intensive quantity and, as such, provides direct information about the characteristics of the single source. This demonstrates its potential as a direct probe for phenomenological models. In pp collisions, the values of Σ increase with collision energy and forward multiplicity.

Net-charge fluctuations $\nu_{\text{dyn}}[+,-]$ have been studied in pp, p-Pb, Pb-Pb, and Xe-Xe collisions and show a smooth evolution from smaller to larger collision systems. A large contribution to measured values of the $\nu_{\text{dyn}}[+,-]$ comes from resonance decays.

References

[1] I. Sputowska [ALICE Collaboration], *Forward-Backward Correlations and Multiplicity Fluctuations in Pb–Pb Collisions at $\sqrt{s_{NN}}$ = 2.76 TeV from ALICE at the LHC*, *MDPI Proc.* **10**, no. 1, 14 (2019).

[2] V. P. Konchakovski, M. Hauer, G. Torrieri, M. I. Gorenstein and E. L. Bratkovskaya, *Forward-backward correlations in nucleus-nucleus collisions: baseline contributions from geometrical fluctuations*, *Phys. Rev. C* **79**, 034910 (2009)

[3] A. Bzdak, *Forward-backward multiplicity correlations in the wounded nucleon model*, *Phys. Rev. C* **80**, 024906 (2009)

[4] M. I. Gorenstein and M. Gazdzicki, *Strongly Intensive Quantities*, *Phys. Rev. C* **84**, 014904 (2011)

[5] C. Pruneau, S. Gavin and S. Voloshin, Phys. Rev. C **66** (2002), 044904 doi:10.1103/PhysRevC.66.044904 [arXiv:nucl-ex/0204011 [nucl-ex]].

[6] S. Jeon and V. Koch, Phys. Rev. Lett. **85** (2000), 2076-2079 doi:10.1103/PhysRevLett.85.2076 [arXiv:hep-ph/0003168 [hep-ph]].

[7] B. Abelev *et al.* [ALICE Collaboration], *Centrality determination of Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ =2.76 TeV with ALICE*, *Phys. Rev. C* **88**, no. 4, 044909 (2013)

[8] P. Skands, S. Carrazza and J. Rojo, Eur. Phys. J. C **74** (2014) no.8, 3024 doi:10.1140/epjc/s10052-014-3024-y [arXiv:1404.5630 [hep-ph]].

[9] T. Pierog, I. Karpenko, J. M. Katzy, E. Yatsenko and K. Werner, Phys. Rev. C **92** (2015) no.3, 034906 doi:10.1103/PhysRevC.92.034906 [arXiv:1306.0121 [hep-ph]].

PoS(CPOD2021)027