IL NUOVO CIMENTO **48 C** (2025) 11
DOI 10.1393/ncc/i2025-25011-8

Colloquia: WPCF-Resonance 2023

Probing particle production and transport in small collision systems with ALICE

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received 23 July 2024

Summary. — Many recent measurements in small collision systems such as pp and p–Pb collisions show signs of collective behavior of produced particles. The two-particle number and transverse momentum (differential) correlators and charged-particle balance function measurements in Pb–Pb collisions provided valuable information about the particle production mechanisms and their time evolution as well as about the transport properties of the created medium, such as the ratio of shear viscosity to entropy density. Thus, these correlation functions have a great potential to help by disentangling the particle production mechanisms and the origin of the collective-like behavior in small collision systems. The two-particle correlation functions and the charged-particle balance function are presented in pp and p–Pb collisions at different energies. Their widths are compared with those from Pb–Pb collisions showing the evolution of the correlation functions with the charged-particle multiplicity. The results are compared with different Monte Carlo models, such as PYTHIA, DPMJET, and HIJING. Moreover, the first measurement of these correlation functions in pp collisions at $\sqrt{s}$=13.6 TeV, collected during Run 3, are presented. The large data set enables for a significant reduction of statistical uncertainties.

1. – Introduction

The presence of the quark–gluon plasma (QGP), a deconfined state of quarks and gluons, in heavy-ion collisions at the LHC and RHIC was already confirmed by many measurements [1, 2]. Some of the features connected with the QGP formation, were observed also in smaller collision systems like pp or p–A collisions. One of these is the near-side long-range ridge structure in two-particle correlation function, which is significant in all the pp, p–Pb, and Pb–Pb collision sytems [3, 4]. Moreover, a continuous increase of production of strange particles over pions as a function of charged-particle multiplicity suggests a smooth transition from small to large collision systems rather than a presence of a threshold system size for the QGP creation. Throughout all the measurements, the origin of the collective-like features in small collision systems remains unclear.

Different types of two-particle correlation measurements in heavy–ion collisions proved to be a good tool to study the presence and properties of the QGP. The evolution of the width of the near-side peak of the transverse momentum correlation function G_2 with multiplicity was successfully used to estimate the shear viscosity over entropy density of the QGP to be close to the KSS limit [5,6]. The same approach was used also in pp and p–Pb collisions at $\sqrt{s}$ =7 TeV and $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, respectively, but the evolution is not smooth through the multiplicities of all collision systems leaving two possible explanations: there is no QGP created in small collision systems or the system lives not long enough to create a significant viscous broadening [7]. In order to shed more light into the problem, new results on two-particle correlations in pp collisions at $\sqrt{s}$ =13 TeV and $\sqrt{s}$ =13.6 TeV are presented.

2. – Normalised two-particle cumulant

The strength of a correlation between two particles, α and β, can be evaluated with the normalised two-particle cumulant defined as

$$R_2^{\alpha\beta} = \frac{\rho_2^{\alpha\beta}}{\rho_1^{\alpha}\rho_1^{\beta}} - 1, \tag{1}$$

where the ρ_1 and ρ_2 are the single- and two-particle densities. These can be written as

$$\rho_1 = \frac{\mathrm{d}^2 N}{\mathrm{d}\varphi \mathrm{d}\eta},\ \rho_2^{\alpha\beta} = \frac{\mathrm{d}^4 N_{\mathrm{pair}}}{\mathrm{d}\varphi^{\alpha}\mathrm{d}\eta^{\alpha}\mathrm{d}\varphi^{\beta}\mathrm{d}\eta^{\beta}}. \tag{2}$$

The cumulants are calculated separately for the like sign $(++,--)$ and unlike sign $(+-)$ particle pairs. These are afterwards merged to the charge independent correlator (R_2^{CI}) and the charge dependent correlator (R_2^{CD}) as

$$R_2^{\mathrm{CI}} = \frac{1}{2}(R_2^{\mathrm{US}} + R_2^{\mathrm{LS}}),\ R_2^{CD} = \frac{1}{2}(R_2^{\mathrm{US}} - R_2^{\mathrm{LS}}). \tag{3}$$

The charge dependent correlator is mostly influenced by the charge conservation, while the charge independent R_2 is sensitive to the collective behaviour. Both correlators have a prominent shape with a near-side peak centered at $(\Delta\varphi, \Delta\eta)$ = (0,0) and an away-side structure. The width of the near-side peak is studied as a function of the event charged particle multiplicity. All presented results are measured for soft particles with $0.2 < p_{\mathrm{T}} < 2$ GeV/c.

In fig. 1, the multiplicity evolution of the longitudinal width of the near-side peak of the normalised two-particle cumulant is shown with the blue markers. For the CI cumulant, different evolution can be observed for p–Pb and Pb–Pb systems, an increase in Pb–Pb and a constant in p–Pb, suggesting the diffusion processes being more significant in the longer-lived system [8]. The point from pp collisions agrees with the width in p–Pb collisions at the same multiplicity hinting a smooth transition between the systems. In the right panel of the same figure, a continuous narrowing of the near-side peak of R_2^{CD} in both, p–Pb and Pb–Pb collisions, is pointing to a presence of a strong radial flow and two-stage particle emission in both systems [8]. In this case, the pp point is lower than the p–Pb one at the same multiplicity. One of the possible explanations is that

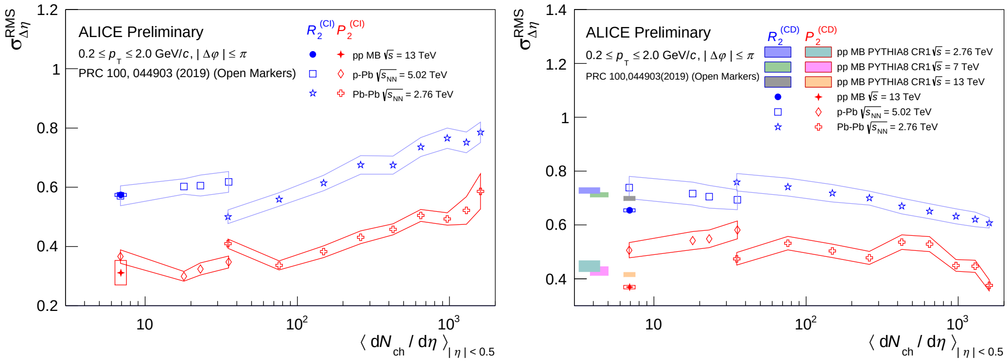

Fig. 1. – Width of the charge independent (left) and charge dependent (right) two-particle normalised cumulant in the longitudinal direction as a function of charged particle multiplicity in pp, p–Pb, and Pb–Pb collisions. The results are compared with the width of transverse momentum correlator (P_2), which is not discussed in this paper.

the peak is getting narrower as the collision energy increases, as shown with the PYTHIA calculations.

The narrowing with multiplicity of the $R_2^{\rm CD}$ in both, longitudinal and azimuthal, directions can be observed also in the newest data from Run 3 at the LHC of pp collisions at $\sqrt{s}$ =13.6 TeV as shown in fig. 2. This observation is consistent with other measurements suggesting the presence of the radial flow also in pp collisions [9, 10]. The broadening of the $R_2^{\rm CI}$ near-side peak with multiplicity, as visible in the left panel of fig. 3, could be possibly explained by diffusion processes in the QGP, similarly as in Pb–Pb collisions. Nevertheless, this explanation is in contrast with the flat distribution of the width in the azimuthal direction within uncertainties, pointing out that more complex processes could be at play.

3. – Balance function

The probability that a charged particle produced in a collision will be accompanied by another particle of opposite charge somewhere in the phase space can be measured with

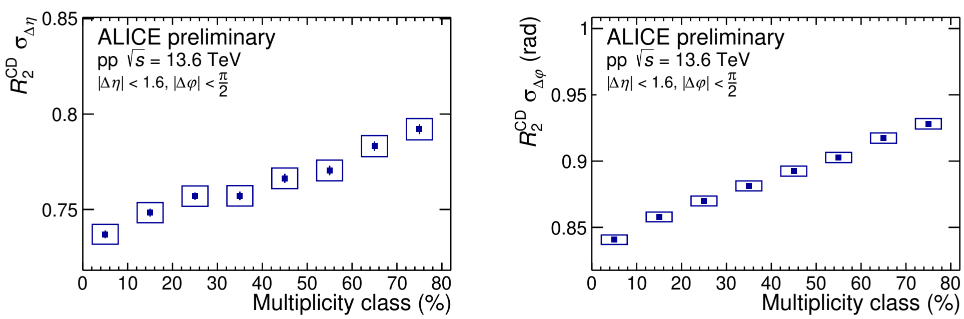

Fig. 2. – Width of the charge dependent two-particle normalised cumulant in the longitudinal (left) and azimuthal (right) directions in pp collisions at $\sqrt{s}$ =13.6 TeV.

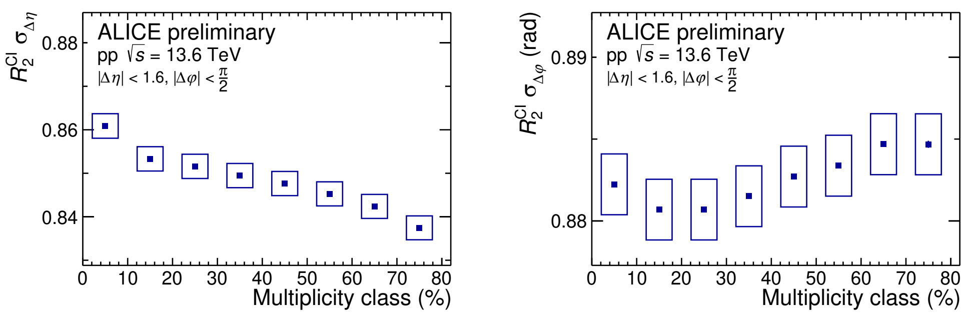

Fig. 3. – Width of the charge independent two-particle normalised cumulant in the longitudinal (left) and azimuthal (right) directions in pp collisions at $\sqrt{s}$ =13.6 TeV.

the balance function (BF). Besides being a measure of balancing charges, BF can give insight on charged-particle production and transport mechanisms, because it is sensitive to the delayed hadronisation, two-states quark production, diffusivity of light quarks, and charge susceptibility of the QGP [11, 12]. The BF can be defined with the help of the R_2 correlator

$$B^{\alpha\beta} = \frac{1}{2}\Big\{\rho_1^{\beta^-}\left[R_2^{\alpha^+\beta^-} - R_2^{\alpha^-\beta^-}\right] + \rho_1^{\beta^+}\left[R_2^{\alpha^-\beta^+} - R_2^{\alpha^+\beta^+}\right]\Big\}. \tag{4}$$

In fig. 4, the longitudinal and azimuthal projections of BF in pp collisions at $\sqrt{s}$ = 13.6 TeV are shown for three multiplicity classes. The amplitude of the correlation in the BF increases with the multiplicity. This follows from eq. (4), as the BF does not depend on the average number of particles. Thus, the amplitude is fully driven by the balancing charges. The BF narrows at high multiplicity in pp collisions as shown in the left panel of fig. 5. This observation is consistent with the narrowing of the R_2^{CD}. Similar narrowing was observed in Pb–Pb collisions and interpreted as a consequence of presence of a strong radial flow and late particle production due to the presence of the QGP phase [11]. The right panel of fig. 5 presents predictions from two PYTHIA8

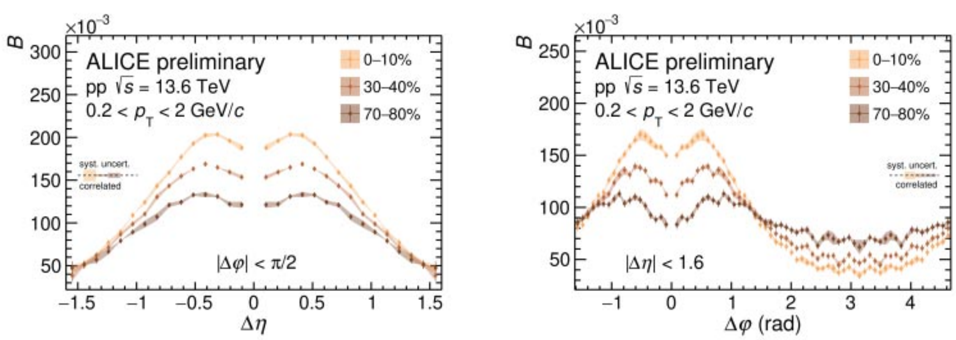

Fig. 4. – Longitudinal and azimuthal projections of the balance function for different multiplicity classes in pp collisions at $\sqrt{s}$ =13.6 TeV.

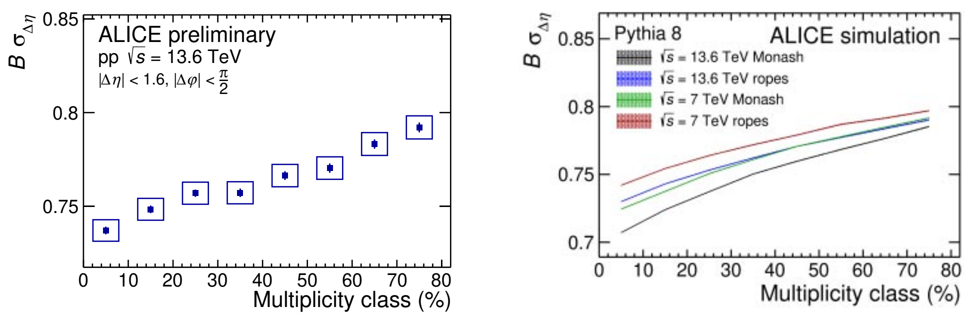

Fig. 5. – Multiplicity dependence of the longitudinal width of the BF in pp collisions at $\sqrt{s}$ =13.6 TeV (left) compared with PYTHIA predictions (right).

modes, Monash [13] and ropes [14], for two collision energies. It can be seen that the BF narrowing with increasing multiplicity is predicted by both PYTHIA modes, suggesting that the narrowing can not be simply explained by the presence of the QGP.

4. – Conclusion

Different types of correlation function continuously prove to be a powerful tool bringing insights into the understanding of particle production in different collision systems. The new measurements of the two-particle normalised cumulant in pp collisions at $\sqrt{s}$ =13 TeV and $\sqrt{s}$ =13.6 TeV increase the range of covered multiplicities and reveal some similar features in the multiplicity evolution of its width as observed in Pb–Pb collisions. These observations can serve as another evidence of collectivity in small collision systems. Nevertheless, the observed narrowing of the BF in pp collisions, similar to the observation in Pb–Pb collisions, is reproduced by PYTHIA calculations without any collective effects.

REFERENCES

[1] The ALICE Collaboration, CERN-EP-2022-227, arXiv:2211.04384.
[2] The STAR Collaboration, *Phys. Rev. Lett.*, **90** (2003) 082302.
[3] The CMS Collaboration, *Phys. Lett. B*, **724** (2013) 213.
[4] The CMS Collaboration, *JHEP*, **09** (2010) 091.
[5] The ALICE Collaboration, *Phys. Lett. B*, **804** (2020) 135375.
[6] Kovtun P. K., Son D. T. and Starinets A. O., *Phys. Rev. Lett.*, **94** (2005) 111601.
[7] The ALICE Collaboration, *Phys. Rev. C*, **107** (2023) 054617.
[8] The ALICE Collaboration, *Phys. Rev. C*, **100** (2019) 044903.
[9] The ALICE Collaboration, *Phys. Lett. B*, **845** (2023) 138110.
[10] The CMS Collaboration, *Eur. Phys. J. C*, **72** (2012) 2164.
[11] The ALICE Collaboration, *Phys. Lett. B*, **723** (2013) 267.
[12] The ALICE Collaboration, *Phys. Lett. B*, **833** (2022) 137338.
[13] Skands P., Carrazza S. and Rojo J., *Eur. Phys. J. C*, **74** (2014) 3024.
[14] Bierlich C. *et al.*, *JHEP*, **03** (2015) 148.