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Recent femtoscopy results from ALICE

Adam Kisiel[1,a] for the ALICE Collaboration

[1] *Faculty of Physics, Warsaw University of Technology, ul. Koszykowa 75, 00-662 Warsaw, Poland*

Abstract. ALICE, an experiment dedicated to the analysis of heavy-ion collisions is ideally suited for femtoscopic studies, with its excellent particle identification capabilities at low and intermediate momenta. It measures correlations of pions which provide crucial information on the size and the dynamics of the system. Recent results for femtoscopic radii from p+p, p–Pb and Pb–Pb collisions will be discussed with emphasis on similarities and differences between small and large systems. In particular the multiplicity and transverse momentum dependence of the radii will be discussed.

1 Introduction

Femtoscopy is a technique, which relies on the measurement of the two-particle correlations as a function of the relative momentum of the pair. In heavy-ion collisions it is most commonly performed for pairs of identical charged pions, which are the most commonly produced particles. At the Large Hadron Collider (LHC), the ALICE experiment is especially well suited for such measurement, beacause of its excellent particle identification (PID) at low relative momenta of registered particles [1]. This work discussed measurements of such correlations for p+p, p–Pb, and Pb–Pb collisions performed by ALICE.

The aim of the femtoscopic analysis is to extract the information on the size of the emitting system from the measured two-particle correlations. For pairs of identical charged pions the correlation effect arises mostly from the enhanced pair production due to the Bose-Einstein statistics. In the correlation function constructed versus the relative momentum $\vec{q} = \vec{p_1} - \vec{p_2}$ it manifests as an increased correlation at low $\vec{q}$ which has roughly a Gaussian shape (with an additional dip at lowest values of $\vec{q}$ caused by the Coulomb repulsion) [4, 5]. Its width is inversely proportional to the size of the emission region, usually called "radius". The analysis can be performed separately for each of the three independent components of $\vec{q}$, yielding three independent radii. The three directions are usually chosen according to the Bertsch-Pratt convention: "long" along the beam axis, "out" along the pair transverse momentum, and "side" perpendicular to the other two. The measured correlation function is analyzed via the Bowler-Sinyukov fitting formula:

$$C(\vec{q}) = (1 - \lambda) + K(q)\left[1 + \lambda \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2)\right], \quad (1)$$

where λ characterized the strength of the correlation, R parameters are the radii, while the K function accounts for the Coulomb interaction.

[a] e-mail: kisiel@if.pw.edu.pl, Supported by the Polish National Science Centre Grant No. UMO-2014/13/B/ST2/04054

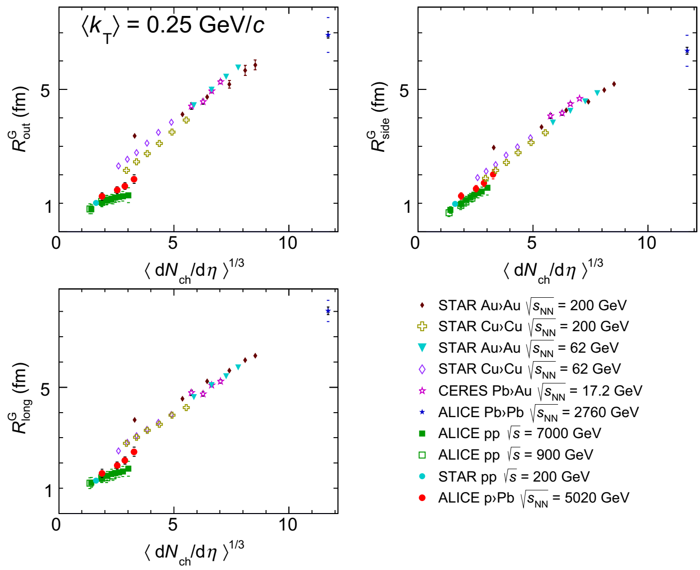

Figure 1. Comparison of femtoscopic radii (Gaussian), as a function of the measured charged-particle multiplicity, for various collision systems and energies. Figure from [5]

The value of the measured size is interesting in itself, but its dependence on event multiplicity as well as pair transverse momentum k_T is of additional significance. Firstly all experimental data collected so far have shown a linear dependence of the total femtoscopic volume of the system (obtained as a product of the radii in three dimensions) on event multiplicity. We extend this measurement to the new energy regime, and perform it, in a consistent way, in small (p+p and p–Pb) and large (Pb–Pb) systems. Such increase is universally reproduced in models of heavy-ion collisions, while its interpretation in small systems is less clear. In this work we compare these dependencies and speculate on the origin of similarities and differences between them.

The dependence of radii on k_T is interpreted in the hydrodynamic framework, which appears to work well for heavy-ion collisions in the LHC energy regime [2, 3]. In particular strong collective movement of matter (flow), which appears naturally in such models, leads to the decrease of the apparent size of the system with increasing pair momentum. Model predictions for this effect have become precise enough to speculate on the relative strenght of this decrease in different directions. In this work we compare the data in heavy-ion collisions and its model description to the effects observed in small systems and speculate on the role of collective flow there.

2 Multiplicity dependence

A comprehensive set of femtoscopic results as a function of particle multplicity is shown in Fig. 1. It presents the results for heavy-ion collision for a wide set of collision energies, for the largest possible collision system sizes (Pb and Au nuclei). These data show a linear scaling with $\langle dN_{\rm ch}/d\eta\rangle^{(1/3)}$ in the "long" direction. In the "side" direction the scaling is also apparent, altough less precise. The scaling in the "out" direction is only approximate. In this direction the size of the system is coupled to the emission duration as well as the shape of the emission hypersurface. In particular in hydrodynamic models, it may show additional dependence on the collision energy, which would break the trivial scaling. This effect is discussed in more detail in the following section.

The heavy-ion data is also, for the first time in such detail, compared to p+p and p–Pb collisions. The p+p data is also very precisely following a liner scaling with multiplicity in all directions, but with significantly different slopes than the ones given by the heavy-ion trend. The difference may be due simply to the quite different initial stage. In particular in the region where p+p and AA data produce similar multiplicities, the initial stages are expected to be quite different - a single violent nucleon-nucleon collision in p+p versus a collection of less violent collisions in peripheral AA collisions. This interpretation however presents an interesting open question. In AA collision a growth of the system size with multiplicity is naturally explained in the Glauber model, as being simply the reflection of the growth of the nuclei overlap region, coupled to the system evolution duration growing with collision energy. However in p+p collisions the "initial stage" has identical size, regardless of final state multiplicity. Therefore, the reason why the system radius grows with multiplicity is not yet known, especially since the space-time evolution is not yet properly modelled in popular Monte-Carlo codes such as Pythia or Phojet.

An equally interesing question arises from the analysis of the p–Pb data. At low multiplicity they tend to be similar to p+p data. But the radii grow much faster with multiplicity and appear to approach the AA scaling line. This presents and intriguing possibility that the p–Pb system is a "transitional" one, and as we analyze the evolution of various observables with the increase of the final state multiplicity, we may observe a change from the "elementray" to the "complex" system.

3 Transverse momentum dependence

The dependence of radii on k_T for heavy-ion collisions in ALICE is shown in Fig. 2. A clear decrease of the radii with k_T is seen, which is roughly power-law in shape. The decrease is more steep in the "long" direction when compared to the "transvere" directions. These results are compared to the predictions of two hydrodynamics codes. Both models, even though they differ significantly on their implementation, reproduce the data very well, both qualitatively and quantitatively. Therefore, the current interpretation of data is based on hydrodynamics. The decrease is a direct consequence of collective flows. Through the mechanism known as "lengths of homogeneity" [2, 3] such flows cause the apparent size of the system to fall with k_T. Such dependence can then be proposed as a well calibrated and sensitive probe for collectivity in the system.

The system size in the "out" direction is comparable or smaller than in the "side" direction. This is particularly interesting, when compared to data at lower energies, where the "out" radius was usually larger. The decrease of the ratio of the two radii is a non-trivial consequence of radial flow and the change of the initial conditions for the hydrodynamic system with the increase of collision energy [2]. The modelling shows that at lower energies the system freezes out in the "outside-in" configuration. But at the LHC energies a significant change occurs. Much higher initial energy density results in the larger final system (indeed data at LHC show a size up to 30% larger than at RHIC), which also freezes out in the "inside-out" configuration. The "out" radius is sensitive to this scenario and is predicted to be smaller than "side" if such freeze-out occurs. This is precisely what is observed in ALICE data, giving additional confidence in the validity of hydrodynamic modelling of the heavy-ion collisions.

This calibrated probe can then be applied to p–Pb collisions. We show the k_T dependence of radii for this dataset in Fig. 3. The results are also compared to the dependence observed in p+p collisions at the highest multiplicity. The data show a clear increase of radius with final state multiplicity, as was already discussed above. The decrease of the radii with k_T is observed, however it is not universal. Firstly in the "long" direction the decrease is significant, quite similar in all multiplicities,

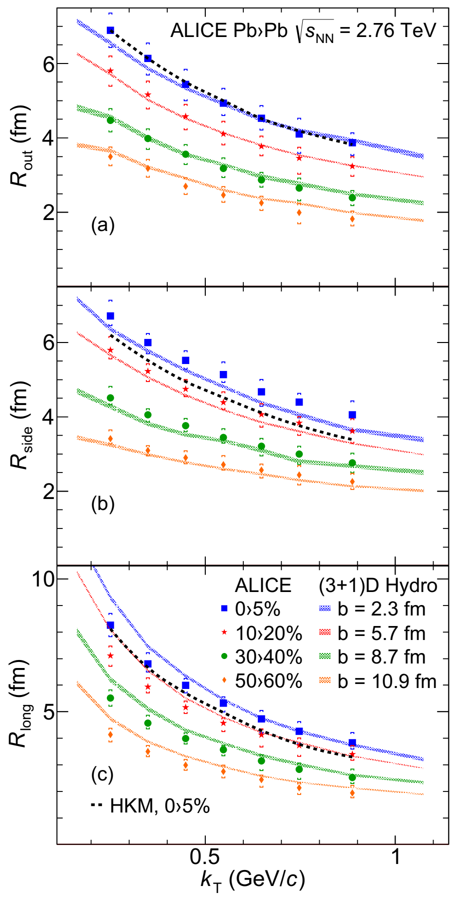

Figure 2. Comparison of femtoscopic radii, as a function of pair transverse momentum, with the calculation from the Therminator and 3+1D hydro model [2], for four centralities and with the HKM model [3] for the central data. Closed symbols are experimental data, bands and dashed lines are the model calculations. Figure from [4]

and also comparable to the one observed in p+p collisions. This resembles the situation in the AA collisions, where in this direction the dependence seemed to be universal. The "side" radius has a more complicated dependence. At small multiplicities it does not change with momentum. The slope of the dependence grows with multiplicity and is significant in the highest range. A similar evolution is also observed in p+p collisions. In the "out" direction the slope is significant at all multiplicities. The absolute values of the radii are smaller than in "side", sometimes significantly more so than in heavy-ion collisions.

Even though the decrease of radii with k_T is observed in p-Pb collisions, it is not as universal as in AA collisions. Especially the evolution of the "side" radius dependence prevents us from drawing a strong conclusion about the existence of flow in p–Pb collisions. Similar conclusions can be drawn from the comparison of the data to the hydrodynamic calculations, shown in the same Figure. The "long" radius dependence is reasonably reproduced, as is the "side" direction. Both radii show a strong preference for calculations starting with low initial size. They are however unable to fully

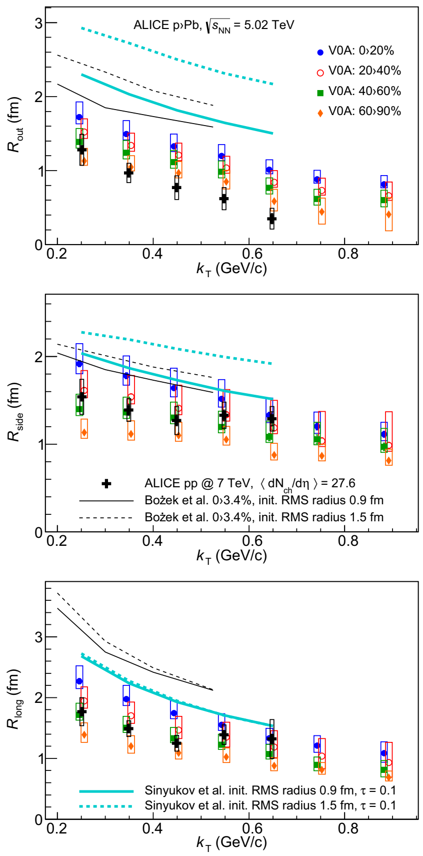

Figure 3. Comparison of femtoscopic radii (Gaussian) in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, as a function of the measured charged-particle multiplicity, for various collision systems and energies. Figure from [5]

predict the "out" radii, showing values larger by at least 20%. The comparison is consistent with the speculation mentioned above in the discussion of muliplicity dependence. It seems that in the p–Pb collisions a transition is observed from a system at low multiplicity, which probably does not exhibit hydrodynamic collectivity, to the system at large multiplicity, which starts to resemble the collective system. Nevertheless the k_T dependence of the radii proves to be a sensitive and non-trivial observable crucial in the correct intrepretation of the physics of the elementrary and heavy-ion collisions.

4 Conclusions

We have shown a comprehensive collection of femtoscopic results from the ALICE experiment, covering the p+p, p–Pb, and Pb–Pb collisions. The measured volume increases linearly with final-state event multiplicity in all measured systems. In addition all of the three-dimensional radii separately increase linearly with cube root of the multiplicity. This dependence is natutally explained in hydrodynamic models of AA collisions. The slope of the dependence in p+p collisions is significanlty different. It suggests that other mechanisms may be responsible for this increase in the elementary collisions. The p–Pb collisions exhibit a behavior which suggests that a transition from “elementary” to “compund” system is observed as the multiplicity of the collision is increased. The pair transverse momentum dependence of the radius is Pb–Pb collisions is very well reproduced by hydrodynamic models. It is a well calibrated and sensitive probe of the collectivity of the system. In addition the results show a transition to the “outside-in” freeze-out configuration at the LHC. In the p–Pb collisions the decrease of the radii is changing with event multiplicity. It is significant at the largest multiplicity, but the hydrodynamic codes are not able to reproduce it fully. This signature again suggests that the p–Pb is a system in which a transition from “elementary” to the “collective” regime occurs as the event multiplicity is increased.

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