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Overview of the femtoscopy studies in Pb–Pb and pp collisions at the LHC by the ALICE experiment

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We report on the results of femtoscopic analysis of pairs of identical pions measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and pp collisions at $\sqrt{s} = 0.9$, 2.76 and 7 TeV. The data from Pb–Pb collisions indicateth existence of a flowing medium and provide constraints on existing dynamical models. The analysis of the data from pp collisions, and especially in high multiplicity collisions, show some similarities with the observations made in heavy-ion data. Comparison to low-energy pre-LHC pp data is also shown. In the high-multiplicity pp data of our measurements the multiplicity range is extended so taht it reaches pseudorapidity densities in peripheral Cu-Cu and Au-Au collisions from RHIC. This allows for the first time to compare freeze-out sizes for systems with very different initial states and to directly test the scaling reported earlier.

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1. Introduction

We report on preliminary results of analysis of femtoscopy of identical (like-sign) pion pairs in Pb–Pb collisions produced by the CERN Large Hadron Collider at $\sqrt{s_{NN}}$=2.76 AGeV and measured with the ALICE detector. The first results of the analysis, limited to 0-5% central events, were reported by ALICE in [1]. In this work we present results as a function of collision centrality, for the centrality range 0-60%.

2. Data taking and track reconstruction

The proton-proton collisions have been recorded by ALICE collaboration experiment [2] in 2010 and at the beginning of 2011 for the collision energy of $\sqrt{s} = 2.76$ TeV. The details of the detectors used as well as the analysis are given in [3].

The Pb–Pb collisions were produced by the LHC in November and December of 2010. ALICE experiment registered approximately 12 million minimum-bias events; used for this analysis. The particle trajectories were analyzed using two ALICE subdetectors: the ALICE Time Projection Chamber (TPC) and the Inner Tracker System (ITS). In addition, the VZERO detector was used for triggering and centrality determination. The primary vertex for the events was required to be within 8 cm of the center of the TPC. The centrality of the event was determined based on the response of the VZERO detectors, for details see [4]. The events were grouped into seven classes, corresponding to 0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, and 50-60% of the total hadronic cross section.

We selected primary tracks based on the distance of the track to the primary vertex. The pseudorapidity range was limited to $|\eta| < 0.8$, corresponding to the region where the ALICE TPC has uniform acceptance. The transverse momenta of the particles were between 0.14 and 2.0 GeV/c. Pions were selected according to the specific ionization response of the TPC. In addition, tracks were reconstructed from at least 80 points in the TPC (out of the maximum of 159), the χ^2 per degree of freedom of the fit was required to be at most 1.

3. Correlation function analysis

Pions were combined into like-sign pairs. Specific selection criteria, designed to suppress the effects of track merging and splitting, were applied (for details see [1]). Analysis was performed for seven ranges in average pair transverse momentum $k_{\rm T} = |\vec{k_{T,1}} + \vec{k_{T,2}}|/2$: 0.2-0.3, 0.3-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7, 0.7-0.8, and 0.8-1.0 GeV/c.

Femtoscopic correlation functions are constructed as a ratio of signal distributions $A(\vec{q})$, formed from pairs of particles coming from the same event, and the background distribution $B(\vec{q})$, formed from pairs where each particle comes from a different event. $\vec{q}$ is the relative momentum of the pair, calculated in the Longitudinally Co-Moving System (LCMS) [5], where longitudinal pair momentum vanishes[1]. We analyzed this 3-dimensional object in the Spherical Harmonics representation [6, 7, 8].

[1]More generally for non-collider experiments or asymmetric collision systems it is a system obtained by a Lorentz boost along the event axis to the frame where the pair momentum is perpendicular to that axis

In order to extract the femtoscopic information, the correlation function is fitted with:

$$C(\vec{q}) = (1-\lambda) + \lambda K_C(q_{inv}) \left[1 + \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2)\right] \quad (3.1)$$

where $long, out, side$ subscripts correspond to three directions: $long$ along the beam, out along the pair transverse momentum, and $side$ perpendicular to the other two, while q_{inv} is the magnitude of the invariant pair relative momentum. R's are femtoscopic sizes in each of the directions. The K_C factor accounts for the Coulomb interaction between two charged pions.

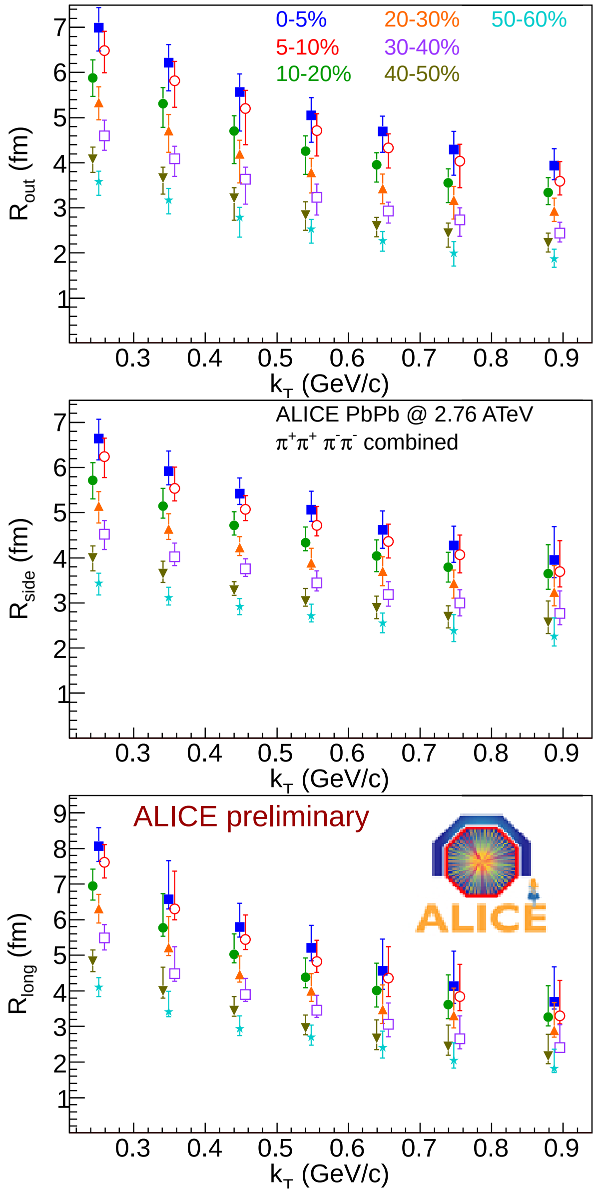

Figure 1: Femtoscopic radii for Pb–Pb collisions, for seven centrality ranges [4] and seven ranges in pair momentum. The top, middle, and bottom panels show R_{out}, R_{side}, and R_{long} respectively, see text. The error bars correspond to the combined statistical+systematic uncertainty.

The correlation functions for all centrality classes and pair momentum ranges have been fitted with Eq. 3.1. No additional correlation structures, which are not accounted for in this formula, have been found. The resulting femtoscopic radii are shown in Fig. 1. We shortly discuss the trends visible in this plot. Firstly all three radii, at all pair momentum ranges grow with event multiplicity (decreasing event centrality). This is consistent with the expectation that the system with larger initial size, which later produces more final state particles also has larger size at freeze-out, to which the femtoscopic radii correspond. The exact nature of this scaling is illustrated in Fig. 2. The radii from Pb–Pb collisions scale linearly with cube root of the final-state charged-particle multiplicity, this scaling holds for all pair momentum ranges. Secondly all three radii, for all centrality ranges, show a power-law decrease with pair momentum. This is qualitatively consistent with the "lengths of homogeneity" mechanism arising in hydrodynamic modeling of heavy-ion collisions [9]. In addition, the scaling of the femtoscopic radii factorize into a linear dependence on cube root of multiplicity and power-law behavior on transverse momentum [10].

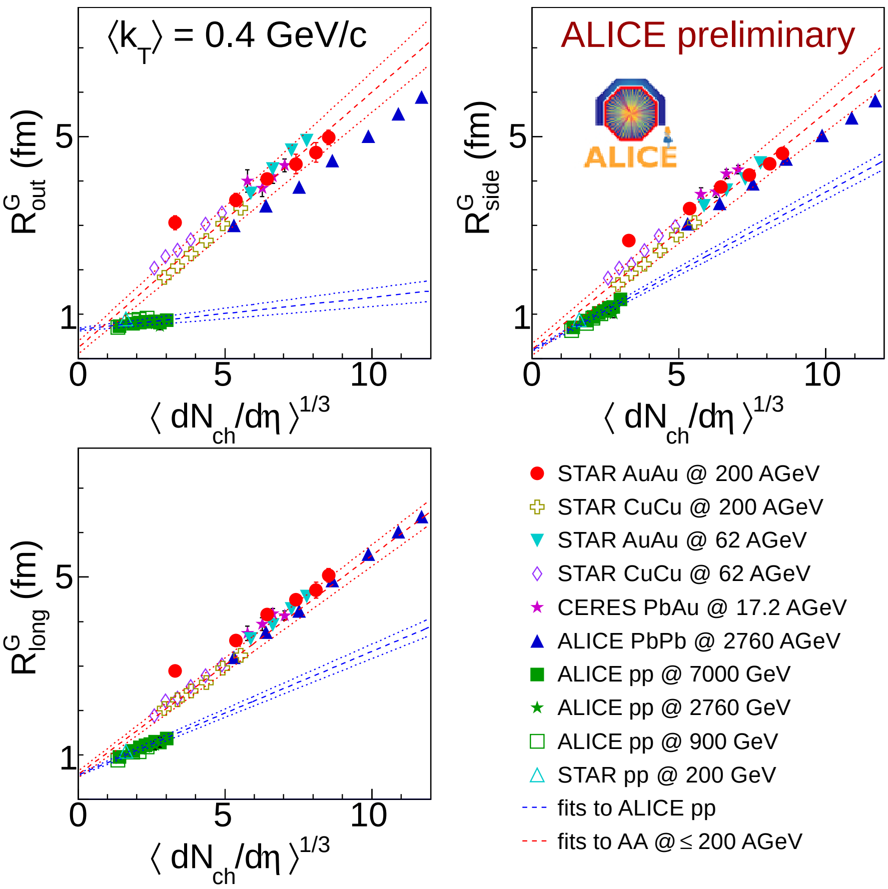

Figure 2: Comparison of femtoscopic radii, as a function of measured charged particle multiplicity, for many collision systems and collision energies. Lines show linear fits done separately to heavy-ion data and proton-proton data.

The dependence of the radii on pair momentum and centrality is consistent with the hypothesis that a heavy-ion collision can be viewed as one collective system which undergoes a rapid expansion. This evolution can be qualitatively described with hydrodynamic equations. However, the specific equation of state to be used, as well as the details of initial conditions and freeze-out criteria need to be determined via a careful quantitative comparison of experimental data to model calculations.

In Fig. 2 the heavy-ion data from Pb–Pb collisions at the LHC are compared to various results obtained at lower collision energies, as well as to results from proton-proton collisions. It has been argued [10] that 3-dimensional femtoscopic radii scale with cube root of measured charged particle multiplicity. The dashed lines in the figure are linear fits to heavy-ion data available before the startup of the LHC. The linear scaling is good for *long* and *side* directions and only approximate in *out*. Concerning the ALICE data the scaling in *long* direction is preserved. The data for the *side* direction go below the scaling trend, although within a large statistical uncertainty. A clear departure from the linear scaling is seen in the *out* direction; data from the LHC lie below the trend. Such behavior was predicted by hydrodynamic calculations [11] and was the result of the modification of the freeze-out shape. Larger initial deposited energy produces larger temperature gradients and longer evolution time at LHC. This results in a change from outside-in to inside-out freeze-out and this modification of the space-time correlation drives the R_{out}/R_{side} ratio to values lower than at RHIC. Therefore already for heavy-ion data in the transverse direction the simple linear scaling is broken.

Another feature shown in Fig. 2 is the comparison of heavy-ion and proton-proton collision data. The multiplicities and the available event statistics for proton-proton collisions at the LHC allowed for the first time to perform the analysis in several ranges of multiplicity. Moreover, the largest multiplicities are comparable to those obtained in peripheral heavy-ion collisions. This allows for direct comparisons of systems with similar final state (at least in terms of multiplicity) and very different initial states. Firstly we note that proton-proton radii scale linearly with cube root of charged particle density. This scaling seems to be good in all three directions. The dash-dotted lines in the figure show the scaling together with the statistical uncertainty. However, the scaling parameters are significantly different than the ones for heavy-ion data. Also, in regions of overlapping multiplicities, the proton-proton sizes are smaller than the ones from heavy-ion data. Therefore the system with smaller initial size produces smaller final freeze-out shapes. This is consistent with what the intuition would suggest; however one has to stress that there is no model, which could quantitatively predict the size, shape and multiplicity evolution of the emitting region in proton-proton collisions. Nevertheless, it seems that naïve scaling arguments do not hold for proton-proton collisions and thus the initial state needs to be taken into account when calculating the femtoscopic radii.

4. Conclusions

We reported on the centrality dependence of the pion femtoscopic radii in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Both the centrality (multiplicity) and pair transverse momentum dependence were studied. It was found that the femtoscopic radii scaling factorizes into a linear dependence on cube root of charged particle density (for each one of the 3-dimensional radii) and a power-law dependence on pair transverse momentum. The scaling was also compared to the ones observed in heavy-ion collisions at lower energies and to proton-proton collisions. It was found that the radii at LHC follow the scaling in the *long* direction, but deviations are observed in the transverse directions. These were in qualitative agreement with predictions from hydrodynamic models. The multiplicity scaling was also observed for proton-proton collisions at $\sqrt{s} = 0.9$, 2.76, and 7 TeV.

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However, the scaling parameters were different for those from heavy-ion collisions, pointing that simple scaling arguments seem not valid for the two types of collisions and the initial state needs to be taken into account.

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