INTERFEROMETRY IN CENTRAL p+Pb COLLISIONS*

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We present the results of HBT radii calculations performed for the pion emission source created in central p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Space-time expansion of the dense matter is simulated using hydrodynamic model with the Glauber Monte Carlo initial conditions. We present momentum and rapidity dependence of all interferometry parameters and their comparison to the experimental data reported by the ATLAS Collaboration. Overall, a fairly good agreement between the model and the data is achieved. The parameterization of the correlation function includes a cross term coupling the *out* and *long* directions, which is found to be nonzero. It is a first quantitative comparison of the model prediction of the cross term values with the experimental measurements and they appear to be well reproduced.

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1. Introduction

Collisions of high-energy nuclei form a region of dense matter, properties of which, in general, depend strongly on the size of collided nuclei. Experimental studies of multi-particle correlations show resemblance between high

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multiplicity p+Pb or pp collisions and Pb+Pb collisions, in which collective effects are present [1]. Such phenomena in smaller systems like p+Pb can be explained either by strong correlations in the initial state [2] or, similarly to large systems, by a collective flow caused by final-state interactions during expansion [3]. The latter can be modelled using hydrodynamic simulations and, in this paper, we present results obtained with this approach applied to 1% most central p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

One of the observables measured frequently in all collision systems is the size of the particle-emitting region at the moment of thermal freeze-out. It can be estimated by analysing the correlations between two identical particles, which in the case of mesons are enhanced by bosonic quantum properties [4]. Then size of particles source is related to the inverse of width of the correlation function $C(\boldsymbol{q})$. The values of parameters obtained in the fitting procedure are called Hanbury Brown–Twiss (HBT) radii.

In symmetric systems, HBT radii along three directions are usually used [5, 6]: *out* — along the pair transverse momentum, *long* — parallel to the beam axis and *side* — perpendicular to both. Measurements of these three parameters show good agreement between experimental data and the results of hydrodynamic simulations in a wide range of system sizes [7, 8].

For non-central rapidities, a new parameter, $R_{\rm ol}$, coupling *out* and *long* directions was proposed [9]. The same term can appear in central rapidities when asymmetric systems, like p+Pb, are measured. It is a consequence of asymmetry in time evolution of the source, which results in y distribution, which is not boost-invariant (Figs. 3 and 4 in [7]).

Thanks to novel ATLAS measurements [10], we are now able to perform quantitative comparison of the hydrodynamic model predictions to the experimental data for a wide range of rapidities, also without neglecting the cross term coupling *out* and *long* directions.

2. Hydrodynamic model and the correlation function

We perform modelling of the time evolution of the system using a viscous hydrodynamic model. The initial conditions come from the Glauber Monte Carlo model. Such calculations proved to correctly reproduce basic physical quantities like azimuthal flow coefficients and spectra. A more extensive description of the model that was used can be found in [8] and [11].

HBT radii are extracted from the fit to the correlation function with the following formula:

$$C(\boldsymbol{q}) = 1 + \lambda e^{-||R\boldsymbol{q}||}\,,$$

where

$$
\begin{aligned}
||R\boldsymbol{q}|| &= \left[\left(R^E_{\rm out}q_{\rm out}+R^E_{\rm mix}q_{\rm long}\right)^2 + {R^E_{\rm side}}^2 q^2_{\rm side} + \left(R^E_{\rm long}q_{\rm long}+R^E_{\rm mix}q_{\rm out}\right)^2\right]^{1/2} \\
&= \left[\left({R^E_{\rm out}}^2 + {R^E_{\rm mix}}^2\right) q^2_{\rm out} + {R^E_{\rm side}}^2 q^2_{\rm side} + \left({R^E_{\rm long}}^2 + {R^E_{\rm mix}}^2\right) q^2_{\rm long}\right. \\
&\quad \left. +2\left(R^E_{\rm out} + R^E_{\rm long}\right) R^E_{\rm mix}\, q_{\rm out}q_{\rm long}\right]^{1/2}
\end{aligned}
$$

which was used by the ATLAS Collaboration, arguing that it better describes the shape of $C(\boldsymbol{q})$ (compare Fig. 3 in [8] and Fig. 1 in [11]).

We note that it differs from the standard Gaussian formula (used *e.g.* in [7]) in several aspects other than the function shape ($e^{-||R\boldsymbol{q}||}$ instead of $e^{-||R\boldsymbol{q}||^2}$). First of all, $R^E_{\rm out,side,long}$ parameters can no longer be interpreted directly as the extent of the effective emission source in respective directions, although they still grow monotonically with the size of the source. Secondly, the scale in specific directions is no longer determined solely by a single parameter: $q^2_{\rm out}$ ($q^2_{\rm long}$) is multiplied by term ${R^E_{\rm out}}^2 + {R^E_{\rm mix}}^2$ (${R^E_{\rm long}}^2 + {R^E_{\rm mix}}^2$) not just ${R^E_{\rm out}}^2$ (${R^E_{\rm long}}^2$). As shown later, the $R^E_{\rm mix}$ values are at least 20 times smaller and introduce only a negligible change for *out* and *long* directions. It is no longer true for the off-diagonal term, where $q_{\rm out}\, q_{\rm long}$ is multiplied by $2(R^E_{\rm out} + R^E_{\rm long})R^E_{\rm mix}$, which is much larger than ${R^E_{\rm mix}}^2$. To sum up, parameterization used by ATLAS fits better to the correlation function, but one should be cautious when comparing obtained results with studies utilizing other forms of fitted functions. In order to be able to collate our result, we followed the ATLAS convention.

3. Results

The interferometry radii as a function of average pair transverse momentum $k_{\rm T}$ are shown in Fig. 1 and their dependencies on average pair rapidity $y_{\pi\pi}$ are shown in Fig. 2.

The correlation function was fitted to the relative momentum of pions $|\boldsymbol{q}|$, with the upper limit of the fit equal 0.3 GeV, while the lower limit was varied from 0.02 to 0.03 GeV, giving us an estimation of the uncertainty in the fitted parameters values. Those uncertainties are shown as the vertical size of the light grey/blue boxes in Figs. 1 and 2, whereas heights of the dark grey/red boxes correspond to the experimental uncertainties of ATLAS measurements.

The size of the effective emission region decreases with average pair transverse momentum $k_{\rm T}$. All four interferometry parameters follow a similar trend, which is common for both the experimental data and the model calculations. Obtained experimentally values of $R^E_{\rm out}$ and $R^E_{\rm long}$ are fairly well reproduced by the model, while its predictions for $R^E_{\rm side}$ are a bit underesti-

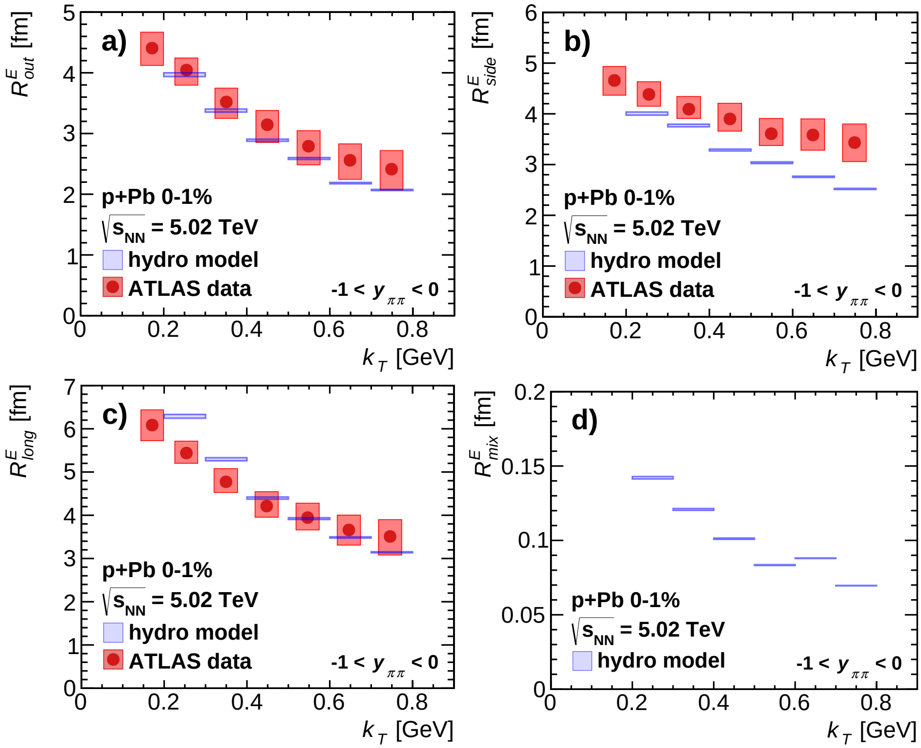

Fig. 1. (Colour on-line) Interferometry radii ($R^E_{\rm out}$, $R^E_{\rm side}$, $R^E_{\rm long}$ and $R^E_{\rm mix}$ on consecutive panels) in central p+Pb collisions as a function of average pair momentum $k_{\rm T}$. Results of 3-dimensional hydrodynamic calculations are compared to data from the ATLAS Collaboration [10].

mated. The relation between HBT radii and $k_{\rm T}$ could be explained by the collective flow, which accelerates more strongly the particles emitted from a smaller source region. Nonzero values of the mixing parameter $R^E_{\rm mix}$ can be related to the lack of forward–backward asymmetry in p+Pb collisions.

The rapidity dependence of the HBT radii shown in Fig. 2 is weaker for the hydrodynamic model compared to the experimental data, however, the complex dependence of $R^E_{\rm mix}$ is reproduced rather well. The effective emission source is larger on the Pb going side (negative rapidity), where a number of participants and, therefore, a number of produced particles is greater. Also $R^E_{\rm mix}$ behaviour appears to be closely related to the shape of the rapidity distribution of pions — namely its slope. (Sec. 4 in [11] and Fig. 4 therein.)

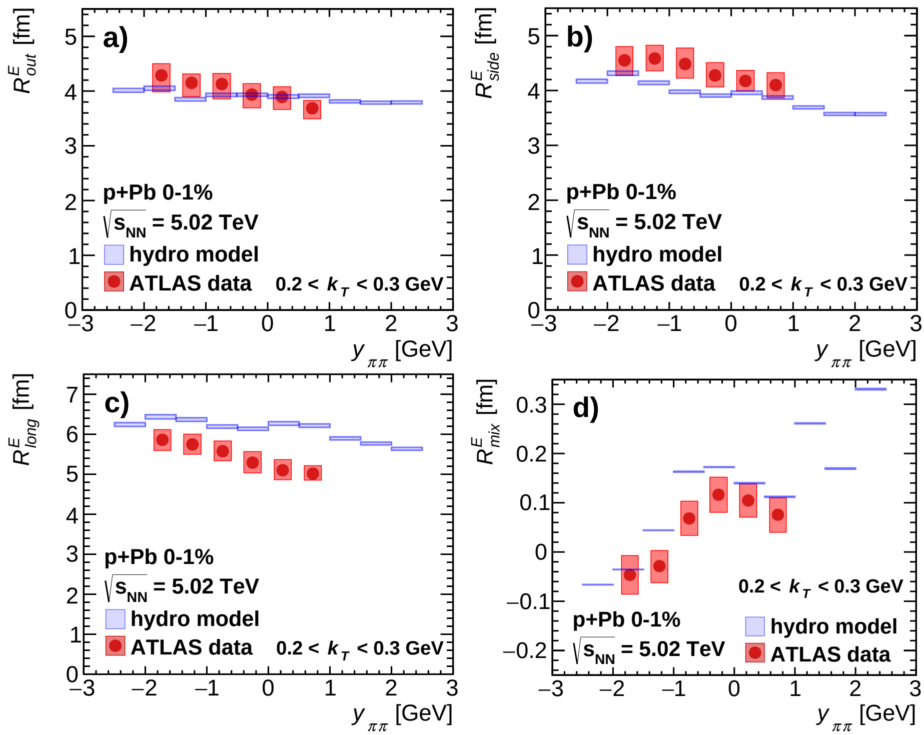

Fig. 2. (Colour on-line) Interferometry radii ($R^E_{\rm out}$, $R^E_{\rm side}$, $R^E_{\rm long}$ and $R^E_{\rm mix}$ on consecutive panels) in central p+Pb collisions as a function of average pair rapidity $y_{\pi\pi}$. Results of 3-dimensional hydrodynamic calculations are compared to data from the ATLAS Collaboration [10].

4. Summary

We have calculated the size of the effective source from which pions produced in central p+Pb collisions are emitted. We have compared predictions of the viscous hydrodynamic model with the Glauber Monte Carlo initial conditions to the measurements performed by the ATLAS Collaboration. Like-sign pions were used to construct the correlation function which has been fitted using an exponential formula taking into account coupling of *out* and *long* directions.

The HBT radii have been presented as a function of average transverse momentum $k_{\rm T}$ and rapidity $y_{\pi\pi}$ of the pair. Obtained values of $R^E_{\rm out}$, $R^E_{\rm side}$ and $R^E_{\rm long}$ were smaller for larger $k_{\rm T}$ and on the proton going side. Non-negligible values of cross term $R^E_{\rm mix}$ show similar dependence on $k_{\rm T}$ as the other parameters, while its relation to $y_{\pi\pi}$ is determined by the rapidity distribution of pions.

Hydrodynamic models can qualitatively describe the space-time evolution of matter created in central p+Pb collisions also with parametrization other than Gaussian and after taking into consideration *out–long* cross term.

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