Interferometry correlations in central p+Pb collisions

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Abstract We present results on interferometry correlations for pions emitted in central p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in a 3+1 dimensional viscous hydrodynamic model with initial conditions from the Glauber Monte Carlo model. The correlation function is calculated as a function of the pion pair rapidity. The extracted interferometry radii show a weak rapidity dependence, reflecting the lack of boost invariance of the pion distribution. A cross-term between the out and long directions is found to be nonzero. The results obtained in the hydrodynamic model are in fair agreement with recent data of the ATLAS Collaboration.

Keywords relativistic heavy-ion collisions · femtoscopy · hydrodynamic model

1 Introduction

In relativistic p+Pb collisions at the CERN Large Hadron Collider (LHC) a small region of large density matter is formed, which makes possible the generation of a collective flow in the expansion [1]. A number of signatures of collectivity due to final state interactions have been observed experimentally in small collision systems at relativistic energies (see e.g. [2]). We use the viscous hydrodynamic model to describe the dynamics in p+Pb interactions. We note that initial state effect can also explain the observed two-particle correlations [3].

Quantum interferometry correlations for identical particles can serve as a measure of space-time correlations in the source [4,5]. These interferometry (also named Hanbury Brown-Twiss (HBT)) correlations have been studied in both elementary and nuclear collisions. An estimate of the size of the emission region, in the form of the HBT radii, can be extracted from a fit to the interferometry correlations. HBT radii have been measured in p+Pb collisions [6,7] and can be reproduced fairly well in hydrodynamic models with Glauber model or color glass condensate initial conditions [8,9,10].

In collisions of symmetric systems the correlation function in relative momentum of the pair is usually parametrized using three HBT radii [11,12]. For a source without forward-backward symmetry, e.g. for pairs at forward/backward rapidity, an additional cross-term can appear in the correlations function [13]. Such a term is predicted to be significant in the case of asymmetric collisions d+Au or p+Pb [14].

Recently the ATLAS Collaboration has presented results on the interferometry correlations in p+Pb collisions for different rapidities of the pion pair [15]. The HBT radii show a rapidity dependence. The size of the emission region is larger on the Pb going side. The cross-term is also found to be nonzero, reflecting the rapidity dependence of the charged particle density. In this paper we present results for the interferometry radii in central p+Pb collisions. We use the same exponential form of the correlation function and the same kinematic cuts as those used by the ATLAS Collaboration. We show that the hydrodynamic model with Glauber model initial conditions can semi-quantitatively reproduce the experimental observations.

2 Hydrodynamic model and HBT correlations

We describe the evolution of the matter created in p+Pb collisions using the viscous hydrodynamic model, with initial entropy density given by the nucleon Glauber
Monte Carlo model. The details and the parameters of the model can be found in [8]. The model describes well the spectra and the azimuthal flow coefficients. At the end of the hydrodynamic evolution pions are emitted from the freeze-out hypersurface. In the paper we use the rapidity in the nucleon-nucleon center of mass frame, which is shifted by 0.465 rapidity units from the laboratory frame at the LHC.

Pairs of same-charged pions emitted at positions $x_1$ and $x_2$, with momenta $p_1$ and $p_2$, are counted. The three dimensional correlation function is constructed by binning in relative ($q = p_1 - p_2$) and average transverse ($k_T = |p_1 + p_2|/2$) momentum of the pair, in the longitudinal comoving system [16]. To increase the statistics for the pion pairs, for each hydrodynamic freeze-out hypersurface 500 realistic events are generated (using a statistical emission procedure [16]) and combined together.

We use a symmetrized plane wave two-pion wave function in the definition of the correlation function. Therefore, no corrections are made for Coulomb interaction in simulated correlation function. The fitted form of the correlation function is

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

(1)

where

$$||R|| = \left[ (R_{\text{out}}q_{\text{out}} + R_{\text{side}}q_{\text{side}})^2 + R_{\text{side}}^2q_{\text{side}}^2 + (R_{\text{long}}q_{\text{long}} + R_{\text{out}}q_{\text{out}})^2 \right]^{1/2},$$

(2)

with the three components of the relative momentum $q_{\text{out}}$, $q_{\text{side}}$, and $q_{\text{long}}$ [11][12]. The exponential ansatz (1) is the same as the one used by the ATLAS Collaboration [15], the fitted HBT radii $R_{\text{out}}$, $R_{\text{side}}$, and $R_{\text{long}}$ and the cross-term $R_{\text{out}}$ are different than for the Gaussian ansatz used in ref. [14].

Three cross sections of the interferometry correlation function are shown in Fig. 1, obtained in the hydrodynamic model for the pair transverse momentum $0.2 \text{ GeV} < k_T < 0.3 \text{ GeV}$ and rapidity $-1 < y_{\pi\pi} < 0$. Note that in the general case there is no reflection symmetry $q_{\text{out}} \leftrightarrow -q_{\text{out}}$ or $q_{\text{long}} \leftrightarrow -q_{\text{long}}$. Both negative and positive values for the $q$ components are taken into account for the fits. The correlation function is calculated for several bins in the average transverse momentum and rapidity of the pair $y_{\pi\pi}$.

### 3 Transverse momentum dependent interferometry correlations

In Fig. 2 are shown the three HBT radii and the cross-term $R_{\text{out}}$ as functions of the average transverse momentum $k_T$, for $-1 < y_{\pi\pi} < 0$. The values of the fitted
Fig. 2 Interferometry radii in central p+Pb collisions as a function of average pair momentum $k_T$. Results of 3-dimensional hydrodynamic calculations are compared to data from the ATLAS Collaboration [15]. $R_{\text{out}}$, $R_{\text{side}}$, $R_{\text{long}}$, and $R_{\text{ol}}$ are shown in panels a) through d).

The size of the effective emission region decreases with $k_T$. This indicates the existence of strong correlations between the momentum and the emission point for the emitted particles. Due to the collective flow pion pairs of high transverse momentum are effectively emitted from a smaller region of the source [17]. The model describes well the experimental data for $R_{\text{out}}$, while $R_{\text{side}}$ is slightly underestimated. The pion distribution in rapidity is not flat, which makes the correlations asymmetric in the forward backward direction. We find a nonzero cross-term $R_{\text{ol}}$, the magnitude of this term decrease with $k_T$ in a similar way as $R_{\text{out}}$ and $R_{\text{long}}$. The asymmetry of the interferometry correlation function can be related to the forward-backward asymmetry of the average emission times of pions from the source (Fig. 4 in [14]). Pions are emitted earlier on the proton going side and the correlation coefficient between the longitudinal position and time becomes nonzero.

4 Rapidity dependent interferometry correlations

In Fig. 3 presents the rapidity dependence of the HBT parameters and the $R_{\text{ol}}$ cross-term for pion pairs with $0.2 \text{ GeV} < k_T < 0.3 \text{ GeV}$. Both the experimental data and the simulation results show some dependence on the pion pair rapidity $y_{\pi\pi}$. However, the experimentally observed rapidity dependence is slightly stronger. We notice that the model correctly describes the experimental data for the cross-term $R_{\text{ol}}$ (panel d) in Fig. 3). Both the magnitude and the sign of the cross-term are fairly well reproduced.

The rapidity distribution of pions emitted in central p+Pb collisions is far from boost invariant (Fig. 4). The
Fig. 3 Interferometry radii 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 [15]. $R_{\text{out}}$, $R_{\text{side}}$, $R_{\text{long}}$, and $R_{\text{ol}}$ are shown in panels a) through d).

asymmetry results from the large difference in the number of participants between the two projectiles, one for the proton and 19 on average for the Pb nucleus. The change in the number of emitted pions with rapidity determines the change in the effective size of the emission region as measured through the HBT radii. The sign of the cross-term $R_{\text{ol}}$ follows approximately the reverse sign of the slope of the rapidity distribution of pions.

5 Summary

We analyze the interferometry correlations for pions emitted in central p+Pb collisions at the LHC. The correlations functions are calculated in the viscous hydrodynamic model with Glauber Monte Carlo initial conditions. The correlation function is constructed from same-charged pion pairs. Three interferometry radii are extracted from an exponential fit to the correlation function. The lack of forward-backward symmetry in the emission region leads to an additional cross-term coupling the $q_{\text{out}}$ and $q_{\text{long}}$ directions. The corresponding cross-term parameter $R_{\text{ol}}$ is found to be nonzero.

Fig. 4 Rapidity distribution of $\pi^+$ in central (0-1%) p+Pb collisions with $0.2 < p_T < 0.3$ GeV, calculated in the viscous hydrodynamic model with Glauber Monte Carlo model initial conditions.
The interferometry radii $R_{\text{out}}$, $R_{\text{side}}$, $R_{\text{long}}$, and the cross-term $R_{\text{ol}}$ are calculated as functions of the average transverse momentum $k_T$ and rapidity $y_{\pi\pi}$ of the pion pair. The model reproduces the recent ATLAS Collaboration data to 10% accuracy for the $k_T$ dependence of the HBT parameters. We find that the HBT radii as functions of the pair rapidity $y_{\pi\pi}$ are smaller on proton going side. The rapidity dependence of the cross-term follows the slope of the rapidity distribution of emitted pions and is in good agreement with experimental data. The calculation confirms that the hydrodynamic model can reproduce qualitatively the space-time features of the emission source produced in high energy p+Pb collisions.

Acknowledgements Supported in part by Polish Ministry of Science and Higher Education (MNiSW), by National Science Centre, grant 2015/17/B/ST2/00101, and by PL-Grid Infrastructure.

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