Femtoscopy in $\sqrt{s_{\text{NN}}} = 5.02$ TeV $p$-Pb collisions with ATLAS

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Abstract

Bose-Einstein correlations between identified charged pions are measured for $p$+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with the ATLAS detector using a total integrated luminosity of 28 nb$^{-1}$. Pions are identified using ionisation energy loss measured in the pixel detector. Two-particle correlation functions and the extracted source radii are presented as a function of collision centrality as well as average transverse pair momentum ($k_T$), rapidity ($y_{\pi\pi}^*$), and azimuthal angle with respect to the second-order event plane. Pairs are selected with a rapidity $-2 < y_{\pi\pi}^* < 1$ and with an average transverse momentum $0.1 < k_T < 0.8$ GeV. The effect on the two-particle correlation function from jet fragmentation is studied, and a new method for constraining its contributions to the measured correlations is described. The measured source sizes are substantially larger in more central collisions and are observed to decrease with increasing pair $k_T$. A correlation with the local single-particle multiplicity $dN_{\text{ch}}/dy^*$ is demonstrated. The cross term $K_{\text{ol}}$, which couples radial and longitudinal expansion, is measured as a function of rapidity, and a departure from zero is observed with 5.1σcombined significance for $y_{\pi\pi}^* > -1$ in the most central events. The azimuthal modulation of the radii in central events is observed to be consistent with that predicted by hydrodynamics and observed in A+A collisions.

Keywords: Femtoscopy, HBT, flow in small systems

1. Introduction

Multi-particle correlations in proton-lead ($p$+Pb) [1, 2, 3] and proton-proton ($p + p$) [4] collisions exhibit long-range azimuthal correlations similar to those observed in lead-lead (Pb+Pb) collisions, in which they are attributed to collective expansion of the quark-gluon plasma. Hydrodynamic models can describe the observed correlations in $p$+Pb [5, 6, 7], but the extent to which they are appropriate in “small” systems remains an open question.

Bose-Einstein correlations between charged pion pairs can be used to measure the spacetime extent of particle production with a technique called femtoscopy (see Reference [8] and references therein). The $k_T$ and $\phi_k$ dependence of the measured Hanbury Brown and Twiss (HBT) radii, which are interpreted as the size of the particle-emitting region at freezeout, can be used to address the questions raised by angular correlation results. While femtoscopic methods have already been applied to $p$+Pb systems at the LHC
[9, 10], the results presented here are obtained using a new data-driven technique to constrain the significant background contribution from jet fragmentation, and they provide the first measurements of the dependence of these source radii on the rapidity $y^\text{out}$ [11]. They also provide the first measurements in $p+Pb$ systems of the modulation of the source as a function of the azimuthal angle $\phi_k$ with respect to the second-order event plane $\Psi_2$ [12]. This modulation has been observed in A+A collisions [13, 14, 15], where the in-plane reduction and out-of-plane extension of the source is understood to be a consequence of hydrodynamic evolution.

2. Experimental Analysis

The data used in this analysis were collected by the ATLAS detector [16] during the 2013 $p+Pb$ run at the Large Hadron Collider (LHC) with a nucleon-nucleon centre-of-momentum energy of $\sqrt{s_{NN}} = 5.02$ TeV. Charged particles are reconstructed with the inner detector, which consists of a silicon pixel detector, a semiconductor tracker made of double-sided silicon microstrips, and a transition radiation tracker made of straw tubes. All three subdetectors are composed of a barrel and two symmetrically placed end-cap sections. Pions are identified using a measurement of the charge deposited in the pixel detector. The forward calorimeters, located in a pseudorapidity range of 3.1 < |$\eta$| < 4.9, are used to estimate the centrality of each collision [16].

The two-particle correlation functions are fit to functions of the form [11]

$$C_k(q) = [(1 - \lambda) + \Lambda K(q) C_{BE}(q)] \Omega(q),$$

where $K$ is a correction factor for final-state Coulomb interactions and $\Omega$ represents non-femtoscopic background, which arises due to jet fragmentation. The Bose-Einstein part of the three-dimensional correlation functions are taken to be of a quasi-exponential form

$$C_{BE}(q) = 1 + e^{-|qR|},$$

where $R$ is a symmetric matrix in the Bertsch-Pratt coordinate system:

$$R = \begin{pmatrix} R_{\text{out}} & R_{\text{os}} & R_{\text{ol}} \\ R_{\text{os}} & R_{\text{side}} & 0 \\ R_{\text{ol}} & 0 & R_{\text{long}} \end{pmatrix}.$$
The cross-term $R_{\text{os}}$ is allowed to be non-zero only in the azimuthally-dependent results, and $R_{\text{ol}}$ is allowed to be non-zero only in the rapidity-dependent results. In these coordinates, $q_{\text{out}}$ is the projection along $k_T$, $q_{\text{side}}$ is the projection along $\hat{z} \times k_T$ (with the $z$-axis along the beamline), and $q_{\text{long}}$ is the longitudinal component. The relative momentum of the pair is evaluated in the longitudinally comoving frame (LCMF), i.e., the frame boosted such that $k_z = 0$.

Reference [11] provides information on the determination of the jet background, $\Omega$, and Reference [12] provides details about the measurement of $\Psi_2$ and correction for the event plane resolution.

### 3. Results

Figure 1 shows the HBT radii as a function of $k_T$ and $y^{*}_{\pi\pi}$ in four centrality intervals. A decrease of the radii with rising $k_T$, interpreted as a signature of collective expansion, is observed in central events. This trend is diminished in peripheral events. Central collisions exhibit larger radii on the backward (Pb-going) side of the event, while peripheral events show no distinguishable variation of the radii with rapidity.

Source radii are observed to correlate strongly with the single-particle local multiplicity $dN_{ch}/dy^*$, as illustrated in Figure 2(a), which presents the transverse area $R_{\text{out}} R_{\text{side}}$ at $0.2 < k_T < 0.3$ GeV in several centrality and rapidity intervals as a function of $dN_{ch}/dy^*$. The linear behaviour with multiplicity indicates a constant areal density at low $k_T$.

The cross-term, $R_{\text{ol}}$, which couples to the lifetime of the source [17], is shown in Figure 2(b). In hydrodynamic models both longitudinal and transverse expansion are required to have a nonzero $R_{\text{ol}}$. A significant departure from zero is observed in this parameter in central events, but only for rapidities $y^{*}_{\pi\pi} > -1$. This indicates that the particle production at mid-rapidity and in the proton-going direction is sensitive to the local $z$-asymmetry of the system.

The radii as a function of azimuthal angle with respect to the second-order event plane are shown in Figure 3 along with their second-order Fourier components. The results are normalized by the zeroth-order Fourier components. The orientation of the modulation is consistent with hydrodynamic freeze-out of a short-lived expanding system.

The results presented here provide a detailed description of the freeze-out geometry of proton-lead collisions, in particular its rapidity and azimuthal dependence. Clear signatures of collective behaviour are observed in central collisions and are diminished in peripheral collisions. A link between elliptic geometry and the ellipticity of the final-state momentum is shown in central $p+$Pb collisions, which supports a hydrodynamic description of the evolution of the system.

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Figure 3. Three-dimensional HBT radii as a function of the average transverse momentum $k_T$ (top) and rapidity $y_{ch}$ (bottom) of pion pairs [12], normalized by the zeroth Fourier component. Five intervals of flow vector magnitude are shown.

References


