BOSE–EINSTEIN CORRELATIONS IN SMALL COLLISION SYSTEMS AT THE LHCb*

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The LHCb detector, recognized as a general-purpose detector in the forward rapidity region ($2 < \eta < 5$) is capable of exploring quantum interference effects at high rapidities and low transverse momenta. This summary presents measurements of Bose–Einstein correlations of the same-sign charged pions studied in proton–proton collisions at $\sqrt{s} = 7$ TeV and proton–lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV, marking the first such measurements in the forward region at LHC energies. Correlation parameters were analyzed across various charged-particle multiplicity ranges, showing consistency with central rapidity region observations from other LHC experiments. The correlation radii scale linearly with the cube root of charged-particle multiplicity, aligning with hydrodynamic model predictions, and there are also some indications of a dependence on pseudorapidity. The preliminary considerations of the studies on Bose–Einstein correlations for the triplets of the same-sign pions in proton–proton collisions, interpreted within the core-halo model, are also presented.

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1. Introduction

The LHCb detector [1] is a single-arm spectrometer with advanced tracking and particle identification systems, specifically designed for the forward rapidity region ($2 < \eta < 5$). Its capabilities in efficient track and vertex reconstruction allow for unique investigations of QCD effects. This document summarizes the first LHCb results on Bose–Einstein correlations of the same-sign charged pions from proton–proton [2] and proton–lead [3] collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV, respectively. The datasets, collected in 2011 and 2013, correspond to integrated luminosities of 1.0 fb^{-1}

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and 1.6 nb^{-1}. These small systems, with shorter lifetimes than heavy-ion systems, provide insights into early dynamics and initial system geometry [4]. The results contribute to understanding particle production at LHC energies, being an exclusive input to the development of the theoretical models. Moreover, it offers a valuable reference for comparing proton–proton and proton–lead collisions.

2. Bose–Einstein correlations for pion pairs in proton–proton collisions

The analysis of Bose–Einstein correlations (BEC) for pion pairs in proton–proton collisions at 7 TeV [2] focused on measuring the two-particle correlation function, $C_2(Q)$, commonly studied as a function of particles four-momenta difference Q, which is sensitive to the dynamic evolution of the hadron source. $C_2(Q)$ is defined as the ratio of the Q distribution for the same-sign pion pairs to a reference distribution, which lacks BEC effects. A data-driven event-mixed reference sample was used, where pions come from different events, ensuring no quantum interference in the pairs. The correlation function is commonly parameterized as the so-called symmetric Lévy-stable distribution [5] that reflects the radial distribution of the static source: $C_2(Q) = N\,(1 + \lambda\,\mathrm{e}^{-|RQ|^{\alpha_\mathrm{L}}})(1 + \delta\,Q)$. Here, R is the correlation radius, representing the size of the spherically symmetric emission source, N is the overall normalization, λ is the intercept parameter (indicating the source's coherence), and δ accounts for long-range correlations, such as those related to transverse momentum conservation. α_L is a parameter that can take values in the range of $0 < \alpha_\mathrm{L} < 2$ and is referred to as a Lévy index of stability. Frequently, to enable comparison of the correlation parameters between experiments and between different collision systems, α_L is fixed to unity, as it is assumed in the present analysis. To correct for imperfections in the reference distribution, a double ratio was employed in the analysis. This ratio compares the correlation function from the data (using the event-mixed reference sample) with the correlation function from the simulation (using an event-mixed sample built in the same way as the data, but without quantum interference effects). The correlation radius and intercept parameter dependence on event activity were examined in the forward acceptance region ($2 < \eta < 5$) for single pions with transverse momentum $p_\mathrm{T} > 0.1$ GeV/c. Activity bins were defined based on the charged-particle multiplicity in the vertex detector. The Coulomb-corrected double ratios for three activity bins were then fitted to the exponential parametrization defined above. An enhancement related to the BEC effect is observed in the double-ratio distribution for the same-sign charged pion pairs at low relative momentum. Figure 1 illustrates how the correlation parameters depend on event activity, showing that the correlation radius increases with activity, while the intercept parameter decreases. These trends align with previous measurements at LEP and other LHC experiments [6–10]. Additionally, the R and λ parameters measured in the forward region for the corresponding charged-particle multiplicity bins are slightly lower than those observed by ATLAS for similar proton–proton interaction multiplicities [9].

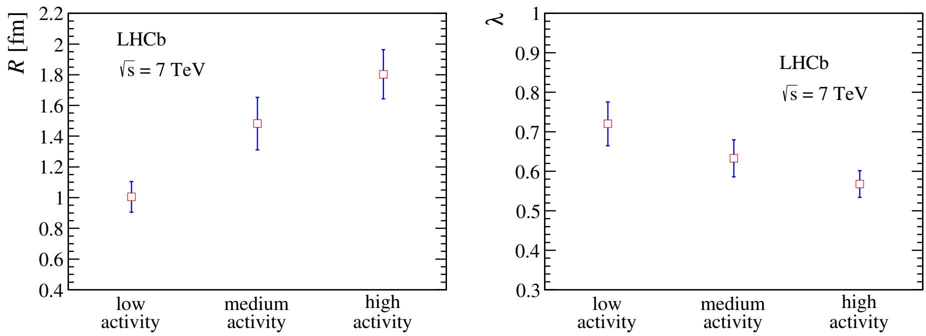

Fig. 1. Correlation radius R (left) and intercept parameter λ (right) as a function of activity. Error bars indicate the sum in quadrature of the statistical and systematic uncertainties. The points are placed at the centres of the activity bins. Figure taken from [2].

3. Bose–Einstein correlations for pion pairs in proton–lead collisions

The two-particle Bose–Einstein correlations for the same-sign charged pions were measured at the LHCb in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [3]. Data collected in 2013 included two beam modes: pPb, where the proton beam is aligned with the LHCb detector (towards positive z-axis values), and Pbp, with opposite beam directions. Due to the asymmetric nature of pPb collisions, there is a shift between pseudorapidities measured in the LHCb laboratory frame and in the nucleon–nucleon center-of-mass system. This shift allows for the examination of the pPb system in both the forward ($1.5 < \eta < 4.5$) and backward ($-5.5 < \eta < -2.5$) regions. The analysis uses a data-driven event-mixed reference sample and is performed in multiplicity bins of charged particles reconstructed in the vertex detector (N_{VELO}), enabling a direct comparison between the two beam configurations. Additionally, this approach provides an opportunity to investigate any potential dependence of the measured BEC parameters on rapidity. The results are interpreted within the framework of hydrodynamic models. In this analysis, the correlation function is parameterized using the Bowler–Sinyukov formalism [11, 12], which appropriately incorporates Coulomb interactions and the nonfemtoscopic background in the experimentally measured correlation function. The full parameterization of the correlation function is given by $C_2(Q) = N\left[1 - \lambda + \lambda K(Q) \times (1 + \mathrm{e}^{-|RQ|})\right] \times \Omega(Q)$, where N denotes a normalization factor, and $\Omega(Q)$ represents the general term for the nonfemtoscopic background. The general $K(Q)$ term is used to account for the Coulomb effect in extended sources [11]. Unlike point-like sources, where the Gamov factor corrects for Coulomb interactions, calculating $K(Q)$ for extended sources in its full form is computationally intensive and requires a numerical, iterative approach. Therefore, the present analysis employs a parameterization of the $K(Q)$ term developed by the CMS experiment, which is valid for Lévy sources with $\alpha_{\mathrm{L}} = 1$ [13]. The main contribution to the nonfemtoscopic background is the cluster contribution [14], which includes effects from minijet fragmentation and multibody resonance decays. These effects are most significant in the low-Q region and may overlap with the BEC signal. It has been shown that this background can be effectively parameterized using simple functions, such as a Gaussian [15]. These effects are studied using a cluster subtraction method developed by the CMS experiment [14], and are parameterized using correlation functions for the opposite-sign pairs. This approach is fully data-driven. Due to the presence of structures related to two-body decays of resonances in the correlation functions for the opposite-sign pairs, the affected regions are excluded from the fit to the correlation function. Since the bin contents in both the signal and reference Q distributions follow a Poisson distribution, a negative log-likelihood fitting method is employed [16]. Such a negative log-likelihood function is constructed for all of the N_{VELO} bins in the given dataset and minimized globally to obtain the best description of the data. The correlation parameters, as a function of the charged-particle multiplicity reconstructed in the vertex detector, are shown in Fig. 2 for both pPb and Pbp datasets. The dominant source of systematic uncertainty arises from the parameterization of the nonfemtoscopic background in the correlation function, which also includes the effects of removing structures induced by two-body resonance decays in the fits to the correlation functions for the opposite-sign pairs. These results are compared with correlation parameters from BEC studies in pp collisions [2]. It is observed that the measured correlation radii scale linearly with the cube root of the reconstructed charged-particle multiplicity. This scaling has also been reported by other LHC experiments for various collision systems [14–16], and is consistent with predictions from hydrodynamic models of system evolution [17–19]. The central R values in the Pbp sample are systematically higher compared to those in the pPb sample, although the results from both datasets are in good agreement within the systematic uncertainties. Since the proton–lead system is studied in both forward and backward directions, there are indications of potential sensitivity of the correlation parameters to rapidity.

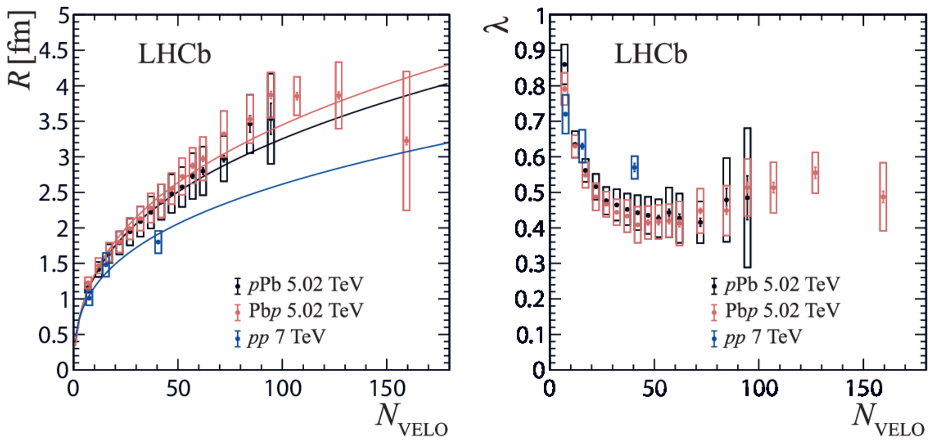

Fig. 2. Correlation radius (left) and intercept parameter (right) as a function of N_{VELO} measured in the *pp* [2] and *p*Pb (Pb*p*) [3] collision systems. Error bars denote the statistical uncertainties, while boxes illustrate the systematic ones. Data points are positioned at the centres of the multiplicity bins. Results of the fits to the correlation radii as a function of the reconstructed multiplicity as described in the text are indicated by the solid lines. Figure taken from [3].

It is also worth mentioning that preliminary consideration of Bose–Einstein correlations for triplets of the same-sign charged pions in proton–proton collisions performed in the forward region at the LHCb, interpreted within the core-halo model, provide an insight into the character of the hadron emission in terms of its coherency, indicating a possible coherent emission of pions.

4. Conclusions

The LHCb experiment provides complementary results on particle correlations in the forward kinematic region, distinct from those obtained by general-purpose LHC detectors. For the first time, Bose–Einstein correlations between two same-sign charged pions have been measured at the LHCb in both *pp* and *p*Pb collisions, at center-of-mass energies of $\sqrt{s} = 7$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV per nucleon, respectively. Both *pp* and *p*Pb analyses utilize the event-mixing method to construct the reference sample, with a Lévy-type parameterization of the correlation function, where the stability index is fixed to unity. Two different approaches are employed for modeling the nonfemtoscopic background: a double-ratio method for *pp* and a data-driven approach to parameterize the cluster contribution for *p*Pb. The measured correlation radii show a linear scaling with the cube root of the reconstructed charged-particle multiplicity, consistent with hydrodynamic model predictions for system evolution. The pPb system is studied in both the forward and backward directions, reflecting the asymmetric nature of the beams, with indications of potential sensitivity of the correlation radii to rapidity.

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