

Three-pion Bose-Einstein correlations measured in proton-proton collisions



The LHCb collaboration

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ABSTRACT: A study on the Bose-Einstein correlations for triplets of same-sign pions is presented. The analysis is performed using proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV, recorded by the LHCb experiment, corresponding to an integrated luminosity of 1.0 fb^{-1} . For the first time, the results are interpreted in the core-halo model. The parameters of the model are determined in regions of charged-particle multiplicity. This measurement provides insight into the nature of hadronisation in terms of coherence, being consistent with the presence of coherent emission of pions.

KEYWORDS: Hadron-Hadron Scattering, Particle Correlations and Fluctuations, Multi-Parton Interactions, QCD

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1 Introduction

In particle and nuclear physics, intensity interferometry offers a direct experimental approach to determine the size, shape, and lifetime of particle-emitting sources [1–3]. Specifically, boson interferometry is a valuable tool for studying the space-time structure of particle production processes. This is because Bose-Einstein correlations (BEC) [2] between two or three identical bosons reveal both the geometric and dynamic characteristics of the particle-emitting source. The correlations result from quantum statistics and the final-state interactions of strong and electromagnetic origins. When identical pions are produced close together in phase space, their quantum wavefunctions interfere constructively [1], enhancing the probability of detecting pion pairs with small relative momenta. The space-time properties of the hadron-emission volume can be studied through the parameters of the density function in the region of small four-momenta difference using the quantum interference effect between indistinguishable particles emitted by a finite-size source. Such measurements are also often referred to as femtoscopy [4]. The so-called small systems, i.e. proton-proton (pp) and proton-ion collisions, are characterised by significantly shorter lifetimes than their ion-ion counterparts [5], giving a better experimental insight into the early system dynamics and the initial geometry [5, 6]. The

available accuracy and data-sample sizes in various high-energy physics experiments make it possible to study three-particle correlations, which may reveal the nature of the hadronisation stage and support the validation of theoretical models [7–9]. The main interest in three-particle correlations is the study of hadron creation mechanisms beyond chaotic emission as opposed to two-particle correlations, sensitive to thermalisation. Study of two- and three-particle correlations can be used to experimentally measure thermalisation and coherence in the source.

Previous results on three-particle correlations have already been reported by the ALICE experiment in PbPb collisions at the LHC [10]. However, with a limited interpretation of the results within the core-halo model [9]. Recently, measurements of three-particle correlations in AuAu collisions were interpreted within the core-halo model (see section 2.4) at the PHENIX experiment [11, 12]. This model provides a set of parameters describing the expansion of the system after a collision and describes hadronic source properties not available in two-particle correlation analyses.

This paper reports for the first time the measurements of the three-particle correlations in small collision systems, performed in different regions of charged-particle multiplicity, employing pp collisions at $\sqrt{s} = 7$ TeV recorded by the LHCb experiment, corresponding to an integrated luminosity of 1 fb^{-1} . A convolution of the information from the two-particle correlation function, determined in a previous LHCb analysis [13], with the three-particle BEC, may probe the parameters of the core-halo model [9], disentangling the partial coherence and the halo contribution. In particular, the parameters can be studied in relation to a thermalised core. To achieve this, a new parameter is introduced, κ_3 [11], being a function of both two- and three-particle correlation strengths, λ_2 and λ_3 [11, 14]. This new parameter is different from unity when additional effects are present within the core, such as an imperfectly thermalised core or partial coherence. The analysis investigates whether κ_3 reflects such additional effects. The values of the partial coherence parameter p_c and the fraction of the particles that originate from the core f_c are also measured as a function of the charged-particle multiplicity. A key question is whether coherent emission can also be observed in small collision systems like pp , which would manifest in the multiplicity-dependence of p_c and κ_3 parameters.

The paper is organised as follows. In section 2 an overview of the theory regarding the two- and three-particle correlations is given, followed by an introduction of the core-halo model used in the present analysis. The LHCb detector and data samples used are described in section 3, while the event selection and the fits to the three-pion correlation functions are reported in section 4 and 5, respectively. The systematic uncertainties and final results are presented in sections 6 and 7. A summary of the studies performed is given in section 8.

2 Theoretical framework

The BEC effect arises from quantum statistics, resulting from the symmetrisation of the wavefunction describing a system of bosons. The present study is based on the assumption of a static, spherically symmetric source that can be characterised by univariate distributions. To measure the three-particle correlation strength λ_3 as well as the parameters of the core-halo model, the three-particle correlation function is measured, which is a convolution of two-particle correlation functions for each particle pair within a given triplet. In the present analysis the correlation radius R and the two-particle correlation strength λ_2 are obtained from the

two-particle correlation studies [13]. For consistency with the published two-pion BEC analysis, the same event data set is used, collected in 2011 at a centre-of-mass energy of $\sqrt{s} = 7$ TeV.

2.1 Two-particle correlation function

The correlation function is commonly studied using the Lorentz-invariant variable Q [15], which is related to the difference in the four-momenta k_1 and k_2 of two indistinguishable particles of rest mass m by

$$Q \equiv \sqrt{-(k_1 - k_2)^2} = \sqrt{M^2 - 4m^2} . \tag{2.1}$$

This provides a measure of the phase-space separation within the two-particle system of invariant mass M . The two-particle correlation function C_2 is formulated as the ratio of the Q distributions for signal and reference pairs,

$$C_2(Q) \equiv \frac{\rho_2(Q)^{\text{sig}}}{\rho_2(Q)^{\text{ref}}} = \left(\frac{N^{\text{ref}}}{N^{\text{sig}}} \right) \left(\frac{dN^{\text{sig}}(Q)/dQ}{dN^{\text{ref}}(Q)/dQ} \right) , \tag{2.2}$$

where $\rho_2(Q)^{\text{sig}}$ represents the Q distribution of the same-charge (same-sign) particle pairs, while $\rho_2(Q)^{\text{ref}}$ represents the reference sample without the BEC effect. Here N^{sig} and N^{ref} correspond to the number of signal and reference pairs, respectively, obtained from an integral of the relevant Q distributions. In this study, the reference sample without the BEC effect is created by pairing particles from different events in data using the event-mixing method [16]. Reference pairs are selected similarly to signal pairs to ensure that the kinematic distributions agree. Specifically, the particles in the reference pairs must come from primary vertices with a comparable number of tracks reconstructed in the vertex detector (see section 3).

In the case of static, univariate sources, the two-particle correlation function is commonly parametrised with the Lévy-type function [17]

$$C_2(Q) = N(1 + \lambda_2 e^{-(RQ)^{\alpha_L}})(1 + \delta Q). \tag{2.3}$$

The value of R can be interpreted as the radius of the spherically symmetric source of the pion-emission volume, and N is the overall normalisation factor. The intercept parameter λ_2 corresponds to the extrapolated value of the correlation function at $Q = 0$ GeV [14].¹ This parameter is also referred to as the correlation strength. The parameter δ corresponds to the long-range momentum correlations. The value of the Lévy index of stability α_L depends on the assumed density distribution [17] and it can take values in the range $(0, 2]$.

The effects related, among others, to the imperfections of the construction of the reference sample, can be mitigated using the so-called *double ratio*, a technique commonly used in BEC studies [18]. The ratio of the correlation functions for data and simulation, used in the final fit, is expressed as

$$r_d(Q) \equiv \frac{C_2^{\text{data}}(Q)}{C_2^{\text{sim}}(Q)}. \tag{2.4}$$

The correlation function is constructed for the simulated sample with the BEC effect turned off. The double ratio is used to suppress some nonfemtoscopic effects. It applies only to well-simulated phenomena, such as long-range correlations, and it is important to maintain the same set of selection parameters for both samples.

¹If not indicated otherwise, natural units are used throughout the paper.

2.2 Three-particle correlation function

The three-particle correlation function is defined as the ratio of the three-particle four-momentum distribution to the product of one-particle distributions

$$C_3(k_1, k_2, k_3) \equiv \frac{N_3(k_1, k_2, k_3)}{N(k_1)N(k_2)N(k_3)}, \quad (2.5)$$

where the single-particle four-momentum distribution is defined as $N(k) = \int d^4x S(x, k)$ and $S(x, k)$ is the source distribution, which describes the probability density of particle creation at the spacetime point x with four-momentum k . The three-particle distribution is defined as

$$N_3(k_1, k_2, k_3) \equiv \int d^4x_1 d^4x_2 d^4x_3 S(x_1, k_1) S(x_2, k_2) S(x_3, k_3) |\Psi_{k_1, k_2, k_3}(x_1, x_2, x_3)|^2, \quad (2.6)$$

with Ψ_{k_1, k_2, k_3} being the three-particle wavefunction.

Assuming properly symmetrised plane-waves for the wavefunctions and the Lévy distribution as the source function, the three-particle correlation function can be expressed as a convolution of two-particle correlation functions for each pair of particles from the triplet [11, 17]

$$\begin{aligned} C_3^{(0)}(Q_{12}, Q_{13}, Q_{23}) &= C_2^{(0)}(Q_{12}) C_2^{(0)}(Q_{13}) C_2^{(0)}(Q_{23}) \\ &= 1 + \ell_3 e^{-0.5[(Q_{12}R)^{\alpha_L} + (Q_{13}R)^{\alpha_L} + (Q_{23}R)^{\alpha_L}]} + \ell_2 [e^{-(Q_{12}R)^{\alpha_L}} + e^{-(Q_{13}R)^{\alpha_L}} + e^{-(Q_{23}R)^{\alpha_L}}], \end{aligned} \quad (2.7)$$

where $Q_{mn} = \sqrt{-(k_m - k_n)^2}$ is the four-momentum difference, and the subscript labels the particle in the triplet. The upper script (0) describes correlation functions with the pure BEC effect. The Lévy index of stability α_L is set to 1 to be compatible with the two-particle correlation analysis results [13] from which the R and λ_2 parameters are taken. The three-particle correlation strength is defined as $\lambda_3 \equiv \ell_3 + 3\ell_2$ [11]. The fitted three-pion double ratio is defined as $r_{d_3}(Q) \equiv C_3^{\text{data}}(Q)/C_3^{\text{sim}}(Q)$.

2.3 Final-state interactions and nonfemtoscopic background

Additional effects, known as final-state interactions, can affect the correlation function. These effects are associated with strong and electromagnetic forces. The effect of the strong interactions in the case of pions is relatively small [19, 20] and is usually neglected in BEC studies. The more significant is Coulomb repulsion related to the same-sign electric charge of particles being investigated, affecting the correlations, especially in the low- Q region. For point-like sources, the Coulomb interaction is equivalent to the so-called Gamov penetration factor [21–23],

$$G_2(Q) = \frac{2\pi\zeta}{e^{2\pi\zeta} - 1}, \quad \zeta = \pm \frac{\alpha m}{Q}, \quad (2.8)$$

where α is the fine-structure constant and the sign of ζ is positive for the same-sign particles, and negative otherwise.

Long-range correlations, being one of the nonfemtoscopic effects [24] related mainly to energy-momentum conservation, are largely reduced by using the double-ratio method and are

accounted for through the introduction of the δ parameter with N serving as the normalisation

$$C_3(Q_{12}, Q_{13}, Q_{23}) = N(1 + \delta_{12}Q_{12})(1 + \delta_{13}Q_{13})(1 + \delta_{23}Q_{23})G_3(Q_{12}, Q_{13}, Q_{23})C_3^{(0)}(Q_{12}, Q_{13}, Q_{23}), \quad (2.9)$$

where G_3 represents the correction of the Coulomb effect. According to the generalised Riverside method [22, 25], the Coulomb correction for the particle triplet can be approximated by a factorization of the corrections calculated for each of the pairs in the triplet $G_3(Q_{12}, Q_{13}, Q_{23}) \approx G_2(Q_{12})G_2(Q_{13})G_2(Q_{23})$. It is important to note that the Coulomb effect is not present in the simulated data, hence, the correction is applied only to the data.

The effect referred to as the cluster contribution [24] is another prominent issue and is related to minijet fragmentations and multibody resonance decays. It is more challenging to correct than long-range correlations as it appears in the range of $Q < 1.0$ GeV that overlaps with the BEC signal. However, this contribution is not expected to be prominent in proton-proton collisions, as the double-ratio distributions for opposite-sign pion pairs are almost uniform and close to unity [13]. This indicates that the nonfemtoscopic background is properly modelled in simulation and corrected for when the double ratio is used. Potential discrepancies related to the event generator used to simulate the same-sign and opposite-sign pairs are addressed in the systematic uncertainty studies.

2.4 Core-halo model

The region of pion emission after a proton-proton collision can be described as a system with a large halo [9]. Depending on the characteristics of the hadron emission, the volume can be divided into two distinguishable parts — the core and the halo. In the central part, the *core*, particles are created in direct processes of the hydrodynamic evolution or particle production from excited strings and following rescattering. The *halo* around the core consists of pions originating from decays of long-lived hadronic resonances, e.g. η , η' , ω and K^0 , where long-lived means a decay length over 20 fm [9]. In the case of a relatively small core, the dimensions of the core can be determined using Bose-Einstein correlations. As the model accounts also for the partial coherence in the core, both the partial coherence and the halo contribution constrain the value of the two-particle Bose-Einstein correlation function to below 2 at $Q = 0$ GeV. Therefore, in order to disentangle the partial coherence and the halo contribution, two separate measurements are necessary, the two- and three-particle Bose-Einstein correlation. The parameters of the core-halo system can be used to describe the properties of the hadron emission.

The fraction of the core, f_c , which quantifies the portion of particles that originated from the core, together with the partial coherence parameter, p_c , which represents the fraction of particles emitted coherently, can be used to express the correlation strengths [14]

$$f_c^2[(1 - p_c)^2 + 2p_c(1 - p_c)] = \lambda_2, \quad (2.10)$$

$$2f_c^3[(1 - p_c)^3 + 3p_c(1 - p_c)^2] + 3f_c^2[(1 - p_c)^2 + 2p_c(1 - p_c)] = \lambda_3, \quad (2.11)$$

where λ_2 is taken from the published two-pion BEC analysis [13], while λ_3 is determined based on fitted parameters (see section 2.2).

Experimentally, to be able to investigate the partial coherence within the limits of the core-halo model, eqs. (2.10) and (2.11) should be solved for f_c and p_c using the measured values of the λ_2 and λ_3 parameters as input.

The measurement of λ_2 , in conjunction with λ_3 , has the potential to challenge the boundaries of the core-halo model [9] with a thermalised core. Consequently, a novel observable, κ_3 , is introduced [11], being a function of λ_3 and λ_2 ,

$$\kappa_3 = 0.5(\lambda_3 - 3\lambda_2)/\lambda_2^{3/2}. \quad (2.12)$$

This parameter is independent of the fraction of particles originating from the core, and can be used to determine additional effects in the core, such as partial coherence or a not fully thermalised core. Its value is unity if the particle emission has no coherent component [12, 17].

2.5 Parameterisation of the three-particle correlation function

The experimentally measurable three-particle correlation function, corrected for the Coulomb effect and including long-range correlations, is modelled by

$$C_3(Q_{12}, Q_{13}, Q_{23}) = N(1 + \delta_{12}Q_{12})(1 + \delta_{13}Q_{13})(1 + \delta_{23}Q_{23}) \\ (1 + \ell_3 e^{-0.5R(Q_{12}+Q_{13}+Q_{23})} + \ell_2(e^{-Q_{12}R} + e^{-Q_{13}R} + e^{-Q_{23}R})), \quad (2.13)$$

where the Lévy index of stability α_L is fixed to 1, and where ℓ_2 and ℓ_3 are parameters related to the two-particle correlation strength λ_2 and three-particle correlation strength λ_3 [11], giving information about the hadron creation mechanism.

Events are selected with the four-momenta differences satisfying $Q_{12} \approx Q_{13} \approx Q_{23}$ to determine λ_3 and the values of the parameters of the core-halo model at a specific value of Q . Both parameters are related to the correlation strengths in the way described in eqs. (2.10) and (2.11). The third parameter of this model, κ_3 , can also be expressed using correlation strengths, as demonstrated in eq. (2.12). The correlation radius R as well as the λ_2 parameters are obtained from the previous two-particle correlation analysis [13].

3 Detector and dataset

The LHCb detector [26, 27] is a single-arm forward spectrometer designed to study particles containing b or c quarks. It features a high-precision tracking system, which includes a silicon-strip vertex detector (VELO) [28] surrounding the pp interaction region, covering the pseudorapidity range $2 < \eta < 5$.² Upstream of a dipole magnet with a bending power of about 4 T m, a large-area silicon-strip detector is located, along with three stations of silicon-strip detectors and straw drift tubes [29] downstream of the magnet. The tracking system measures the momentum, p , with a relative uncertainty ranging from 0.5% at low momentum to 1% at 200 GeV. The impact parameter, or the minimum distance of a track to

²Pseudorapidity is the variable that corresponds to the polar angle θ of the track with respect to the beam axis, $\eta = -\ln(\tan(\theta/2))$. References to pseudorapidity in the present study correspond to the values in the LHCb laboratory frame. The LHCb coordinate system is right-handed, with the z -axis pointing along the beam axis, y -axis in the vertical direction, and x -axis in the horizontal direction. The (x, z) -plane is the bending plane of the dipole magnet.

a primary vertex (PV), is measured with a resolution of $(15 + 29/p_T) \mu\text{m}$, where p_T is the transverse component of p in GeV. Charged hadrons are identified using information from two ring-imaging Cherenkov detectors [30]. Photons, electrons and hadrons are identified by a calorimeter system. Muons are detected by a system of alternating layers of iron and multiwire proportional chambers [31]. The trigger [32] consists of a hardware stage based on information from the calorimeter and muon systems, followed by a software stage that performs full event reconstruction.

In this analysis, a pp collision dataset of no-bias and minimum-bias triggered events is used, collected in 2011 at a centre-of-mass energy of $\sqrt{s} = 7 \text{ TeV}$, corresponding to an integrated luminosity of 1.0 fb^{-1} . The data sample available in the present study corresponds to $\sim 4 \times 10^7$ events. The no-bias trigger selects events randomly, while the minimum-bias trigger requires at least one reconstructed VELO track.³ The data were collected with an average number of visible interactions per bunch crossing (pile-up) of 1.4 [33]. To avoid biases related to trigger requirements, a sample of uncorrelated pp interactions is constructed as described in section 3.

In the simulation, pp collisions are generated using PYTHIA 8 [34] with a specific LHCb configuration [35], excluding the BEC effect. The decays of hadronic particles are simulated using EvtGen [36], with final-state radiation generated by PHOTOS [37]. The interaction of the generated particles with the detector and its response are modelled using the GEANT4 toolkit [38, 39], as described in [40].⁴ The simulated dataset contains $\sim 2 \times 10^7$ minimum bias events. For the study of systematic effects, an additional sample of $\sim 10^7$ minimum bias events is simulated using PYTHIA 6.4 [41] with the Perugia0 tune [42].

In order to be compatible with the two-pion correlation analysis results [13], the same data and simulation samples, together with the same packages versions, are used.

4 Event selection

The analysis utilizes a sample of events that may include multiple pp collisions. Without trigger requirements, each pp interaction within an event can be analysed independently. Consequently, when an event is selected by the no-bias trigger, all primary vertices are included. For events with multiple pp collisions selected by the minimum-bias trigger, any related biases are mitigated by randomly removing one of the PVs associated with the track(s) that triggered the event.

As the correlation parameters are expected to be dependent upon the particle multiplicity, the BEC effect is studied across different bins of reconstructed charged-particle multiplicity. Three *activity classes* are introduced to reflect the total multiplicity in the full solid angle. These classes are defined based on the VELO track multiplicity ($N_{\text{ch}}^{\text{VELO}}$) of the reconstructed primary vertices, which is a reliable analogue of the total multiplicity. The low-activity class consists of PVs with $N_{\text{ch}}^{\text{VELO}} \in [5, 10]$ (48% of all reconstructed PVs), the medium activity with $N_{\text{ch}}^{\text{VELO}} \in [11, 20]$ (37%) and the high activity with $N_{\text{ch}}^{\text{VELO}} \in [21, 60]$ (15%).

The following single-particle selection criteria are applied. All pion candidates must have reconstructed track segments in the VELO, with $2 < \eta < 5$, and in tracking stations

³A VELO track is reconstructed only with hits registered in the VELO detector.

⁴The version numbers of key simulation tools: PYTHIA 8.1, EvtGen 2.2, PHOTOS 2.0, Geant4 v70r0p1.

downstream of the magnet. Each track is required to have a good-quality fit [43], a transverse momentum $p_T > 0.1$ GeV, and no associated signal in the muon stations. Both pion candidates must be assigned to the same PV. Particles are assigned to the PV that minimises the χ^2 value of the impact parameter, defined as the difference in the vertex-fit χ^2 values of a given PV reconstructed with and without the track in question. A loose requirement on the track impact parameter (< 0.4 mm) is applied to retain the majority of the particles originating from the selected PV. To reduce contamination from fake and clone tracks,⁵ only the track with the best χ^2 is retained when multiple tracks share the same hits in the VELO subdetector. Additionally, fake tracks are removed by applying requirements on the track χ^2 and using the output of a dedicated neural network [30].

To mitigate the effect from clone tracks, the slopes of the tracks are studied, as clone tracks typically share very similar trajectories, resulting in small differences in the relevant slopes, defined as ratios of appropriate momentum components ($\Delta t_x = p_{x1}/p_{z1} - p_{x2}/p_{z2}$ and $\Delta t_y = p_{y1}/p_{z1} - p_{y2}/p_{z2}$). If both $|\Delta t_x|$ and $|\Delta t_y|$ are less than 0.3×10^{-3} , the pair is discarded. After applying such requirements, the effect of clone particles is found to be negligible in the region $Q > 0.05$ GeV.

Particle identification (PID) is performed using a neural network that incorporates subdetector information to calculate the probability for a particle to be identified as a specific type [30]. The simulated PID quantities are corrected using calibration samples from the data [44]. Corrections of PID variables among particles are also taken into account. It is crucial to maintain a sample with high purity; however, applying a strict requirement on the probability for a particle to be identified as a pion, $\mathcal{P}(\pi)$, could suppress low-momentum pions that contribute to the BEC effect and significantly impact the signal region of the correlation function. To ensure consistency with previous two-pion analyses of pp collisions [13], the requirement of $\mathcal{P}(\pi) > 0.65$ is applied. With this relatively loose selection criterion, the single-track pion identification purity is approximately 98%. This leads to a pion pair purity of 96%. The contamination from mixed pairs containing only one true pion is about 4%. This level of contamination has been verified to have no impact on the correlation function, as the Bose-Einstein correlation effect does not occur in such cases. The total contribution from same-type particle pairs not containing pions is below 10^{-4} . Varying $\mathcal{P}(\pi)$ threshold from 0.5 to 0.8 does not result in significant changes in the measured correlation function.

5 Fitting the correlation function

Correlation functions are constructed for Q values in the range 0.05–2.00 GeV with a bin width of 0.005 GeV for consistency with the two-pion BEC analysis [13]. In order to collect unique triplets of the same-sign charged pions coming from the same PV, three same-sign pions are randomly selected from the initial set of such particles. Used pions are then removed from the set. The reference sample is prepared using the event-mixing method. To ensure that the correlations are absent in reference triplets, each particle is chosen from a different event, from a PV with the same charged particle multiplicity. The reference triplets

⁵Fake tracks are those which do not correspond to any particle trajectory, but are reconstructed from a number of unrelated hits. Clone tracks are multiple tracks reconstructed from hits which were deposited by a single charged particle.

are processed in the same way as the signal ones, to ensure that the signal distribution is reproduced as closely as possible.

As the final results for the three-particle correlation measurement depend on the λ_2 and R parameters as measured with two-particle correlations, the parameters for the pairs from particle triplets were checked to be compatible with the previous LHCb results for two-particle BEC [13].

The calculation of the three-pion correlation function is based on the convolution of the two-pion correlation functions, where the pion pairs must originate from the triplet of the same-sign pions assigned to the same PV. First, the double ratios of the two-particle correlation functions (as outlined in eq. (2.4)) are fitted separately for the three Coulomb-corrected two-particle double ratios for Q_{12} , Q_{23} and Q_{13} using the formula for the two-particle correlations (eq. (2.3)) with $\alpha_L = 1$,

$$C_2(Q) = N(1 + \lambda_2 e^{-RQ})(1 + \delta Q). \quad (5.1)$$

The obtained results for the R and λ_2 parameters from these fits are then compared to the values published in ref. [13] in order to verify their compatibility. The values of R and λ_2 are found to be consistent in all bins of VELO track multiplicity.

Finally, the distributions of the double ratio of correlation functions for same-sign pion triplets, r_{d3} , using the event-mixed reference sample (as described in section 2.1), are fitted. The fit is performed in three different regions (bins) of VELO track multiplicity per pp collision using the parameterisation in eq. (2.13) with four-momenta differences Q_{12} , Q_{13} , Q_{23} selected to fall into the same Q -bin. A binned maximum-likelihood fit is used. The fitted parameters are N , δ , ℓ_2 and ℓ_3 , while the values of R and λ_2 are taken from the published two-pion BEC analysis [13], whose values are, depending of $N_{\text{ch}}^{\text{VELO}}$ bin, in the range 1.01–1.80 fm and 0.57–0.72, respectively. The results of the fits to the three-particle double ratios are presented in figure 1, while the related χ^2/ndf can be found in appendix A. The Bose-Einstein correlation effect is evident as a signal enhancement for low values of Q . It is worth noting that the fit quality in BEC studies is not expected to be perfect. Due to the lack of theoretical description of nonfemtoscopic background contributions as well as the compromise between the fit quality and interpretability of the measured correlation parameters, the obtained values of χ^2 per degree of freedom are often larger than unity.

6 Systematic uncertainties

Several sources of systematic uncertainties are considered. The values for each source are summarised in table 1, where the correlation functions are refitted using different requirements, and the difference with respect to the baseline result is assigned as a systematic uncertainty, excluding those found to be negligible. The total systematic uncertainty is obtained as the sum in quadrature of the individual components.

The primary source of systematic uncertainty arises from differences in the event generators used to determine the correlation function in the simulation. To assess this effect, a sample of minimum-bias events generated with the PYTHIA 6.4 generator and the Perugia0 tune is used to construct the double ratio. The contribution to the systematic uncertainty

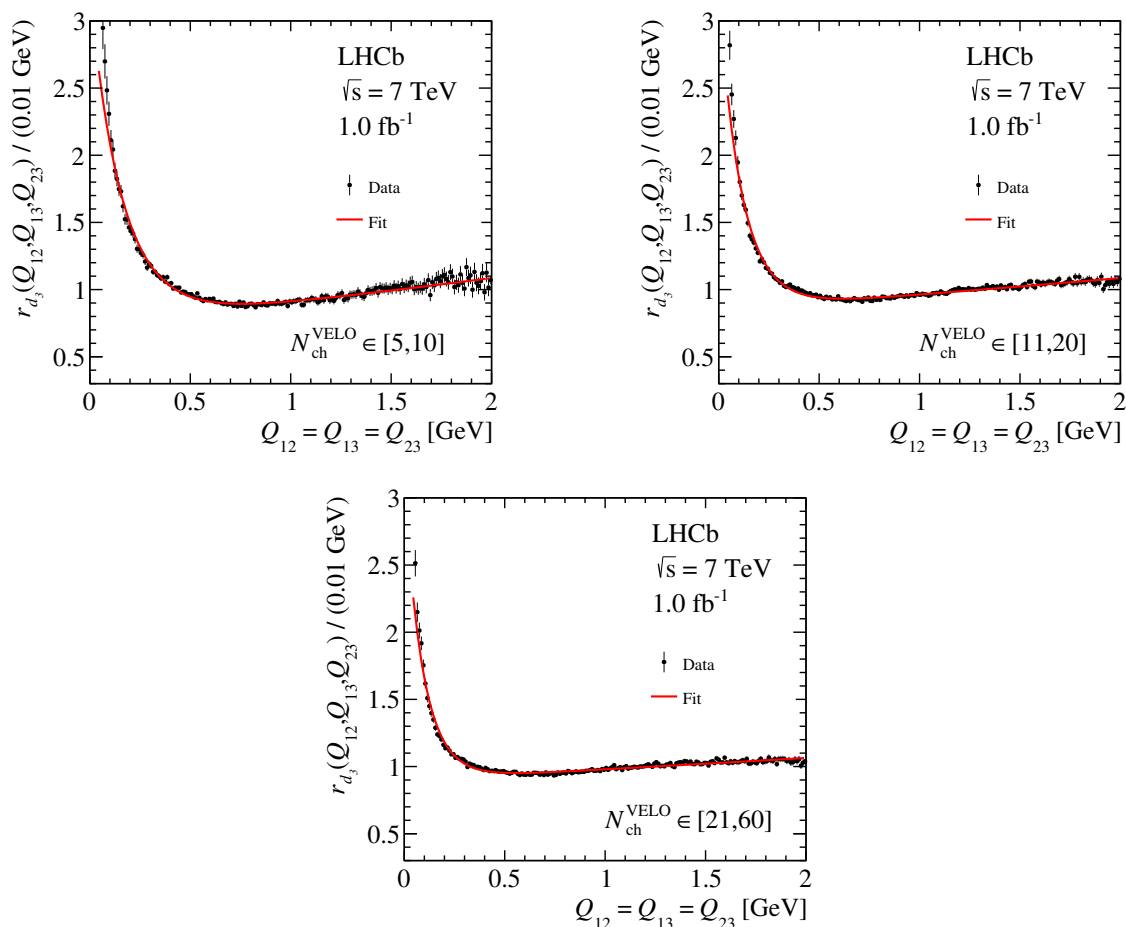


Figure 1. Results of the fit to the three-particle double ratio (r_{d_3}) for same-sign pion triplets, are presented in three bins of the VELO track multiplicity: (top left) $[5,10]$, (top right) $[11,20]$, (bottom) $[21,60]$. The red line illustrates the fit performed using the parameterisation outlined in eq. (2.13), selecting the triplets of same-sign pions with Q values within the same bin.

is determined by comparing the central values of the results derived from the PYTHIA 8 and PYTHIA 6.4 datasets.

In the case of multiple primary vertices in a single event, the correlation function could be affected by the way the reference sample is formed. Residual correlations between primary vertices of a single event could be preserved and included in the correlation function. This contribution to the systematic uncertainty is calculated as a difference between the central values of the most differing fit results obtained using two extreme cases: a single PV, two PVs, and three or four PVs in the event. For each subsample, a fit is performed, and the maximum difference observed for each measured parameter is taken as the systematic uncertainty.

The systematic uncertainty due to the primary-vertex reconstruction efficiency is also considered. To account for the effects of pile-up and inefficiencies in PV reconstruction, a systematic uncertainty is estimated by comparing the baseline fit results with those obtained from a fit to the data where the PV reconstruction is repeated after randomly removing a subset of tracks from the event.

$N_{\text{ch}}^{\text{VELO}} \in [5,10]$				
Source	σ_{λ_3} [%]	σ_{f_c} [%]	σ_{p_c} [%]	σ_{κ_3} [%]
Event generator	8.7	10.4	9.7	10.4
PV multiplicity	5.9	8.6	8.3	4.7
PV reconstruction	< 0.1	0.1	0.1	< 0.1
Fit binning	0.7	0.1	0.4	1.2
Fit low- Q range	0.3	0.6	1.0	0.3
Fit high- Q range	0.4	0.5	0.5	0.3
Fake tracks	2.1	2.4	2.4	1.8
$\mathcal{P}(\pi)$	2.1	2.7	1.8	3.3
Total	11.0	14.0	13.2	12.1

$N_{\text{ch}}^{\text{VELO}} \in [11,20]$				
Source	σ_{λ_3} [%]	σ_{f_c} [%]	σ_{p_c} [%]	σ_{κ_3} [%]
Event generator	3.6	5.1	5.0	3.2
PV multiplicity	2.1	5.0	5.0	2.1
PV reconstruction	1.1	1.6	1.6	1.1
Fit binning	1.1	1.1	1.1	1.1
Fit low- Q range	1.4	1.5	1.8	2.5
Fit high- Q range	1.8	1.9	1.8	2.1
Fake tracks	1.8	4.3	4.3	1.8
$\mathcal{P}(\pi)$	2.1	1.7	1.4	3.9
Total	5.7	9.0	9.0	6.8

$N_{\text{ch}}^{\text{VELO}} \in [21,60]$				
Source	σ_{λ_3} [%]	σ_{f_c} [%]	σ_{p_c} [%]	σ_{κ_3} [%]
Event generator	2.4	2.8	2.8	0.4
PV multiplicity	3.3	5.3	5.4	3.7
PV reconstruction	2.4	2.5	2.4	2.8
Fit binning	1.0	0.4	0.7	2.0
Fit low- Q range	1.8	2.4	3.0	3.7
Fit high- Q range	3.0	3.4	3.4	3.3
Fake tracks	2.0	2.1	2.2	2.4
$\mathcal{P}(\pi)$	4.1	3.9	3.7	5.7
Total	7.5	8.9	9.1	9.4

Table 1. Systematic uncertainties split by sources and bins of VELO track multiplicity. Sources that proved to be negligible, not listed in the table, are mentioned in section 6.

Most fake tracks are already removed through the requirements on the track χ^2 and the probability of being a fake track, as well as by applying a requirement on shared VELO hits, but there may be a discrepancy in fake-track ratios between the data and simulation. To determine the systematic uncertainty related to the fake tracks, the double ratio is refitted

with a looser requirement on the probability of being a fake track < 0.50 , the loosest possible value after preselection. The fraction of fake tracks after the final selection for three different bins of VELO track multiplicity and for different requirements on the probability of being a fake track < 0.25 and < 0.50 is less than 1%. The fraction of same-sign pion pairs containing a clone track after the selection is found to be below 1%. The systematic uncertainty arising from cloned tracks is estimated by fitting the double ratio after applying a strict requirement on the Kullback-Leibler distance [45], ensuring that the clone contribution is completely removed in the simulation. The effect is determined to be negligible for all activity classes.

A requirement on $\mathcal{P}(\pi)$ reduces the contamination of misidentified pions. The systematic impact of this selection on the measured parameters is assessed using a looser requirement that increases the fraction of misidentified pions by 50%. The systematic uncertainty due to the calibration of PID in the simulation is estimated by comparing different variants of the calibration procedure, using acceptances evaluated across various binning schemes for particle momentum, pseudorapidity, and track multiplicity. The largest difference observed after refitting the double ratios is taken as the systematic uncertainty.

The systematic uncertainty arising from the fit range in the low- Q (high- Q) region is determined by adjusting the lower (upper) boundary of the Q value by ± 0.01 GeV (± 0.20 GeV). Fits to the double ratios are performed for the three activity classes using two different lower (upper) Q limits, and the largest difference observed is taken as a systematic uncertainty.

Other effects related to the Coulomb correction, fit binning, resolution of the Q variable, different magnet polarities, beam-gas interactions and residual acceptance effects related to possible differences between data and simulation in the low- Q region below 0.2 GeV, are also investigated, and are found to be negligible.

7 Results

Fitted BEC parameters are used to calculate the values of the parameters in the core-halo model. The final results are presented in table 2, categorised into three bins based on VELO charged-particle multiplicity, along with their statistical and systematic uncertainties. As there is a correlation between the parameters ℓ_2 and ℓ_3 , the uncertainty on λ_3 is determined taking into account this correlation, having however a negligible impact on the statistical uncertainty. Appendix A includes fit parameters together with their correlation matrix.

The dependence of the core-halo parameters on the VELO track multiplicity is shown in figure 2. The fraction of the core f_c decreases only slightly for classes of higher activity, indicating that the fraction of particles that originated from the core of the emission volume does not depend strongly on the number of charged particles produced in the event. Conversely, the partial coherence p_c increases significantly with higher multiplicities, showing the presence of partially coherent emission of pions. The central values of the parameter κ_3 , which are systematically lower than unity for higher-multiplicity bins, also suggest a partially coherent emission. However, since they remain consistent with unity within statistical and systematic uncertainties, no definitive conclusion can be drawn. The parameter λ_3 , related to the three-particle correlation strength is decreasing with charged-particle multiplicity, as expected. The systematic uncertainties are comparable to the statistical ones.

$N_{\text{ch}}^{\text{VELO}} \in [5,10]$
$\lambda_3 = 3.37 \pm 0.24 \pm 0.37$
$f_c = 0.85 \pm 0.06 \pm 0.12$
$p_c = 0.08 \pm 0.01 \pm 0.01$
$\kappa_3 = 0.99 \pm 0.09 \pm 0.12$
$N_{\text{ch}}^{\text{VELO}} \in [11,20]$
$\lambda_3 = 2.80 \pm 0.17 \pm 0.16$
$f_c = 0.83 \pm 0.05 \pm 0.07$
$p_c = 0.29 \pm 0.02 \pm 0.03$
$\kappa_3 = 0.91 \pm 0.09 \pm 0.06$
$N_{\text{ch}}^{\text{VELO}} \in [21,60]$
$\lambda_3 = 2.46 \pm 0.20 \pm 0.18$
$f_c = 0.81 \pm 0.07 \pm 0.07$
$p_c = 0.35 \pm 0.03 \pm 0.03$
$\kappa_3 = 0.87 \pm 0.12 \pm 0.08$

Table 2. Measured values of core-halo parameters with statistical and systematic uncertainties, for different activity classes.

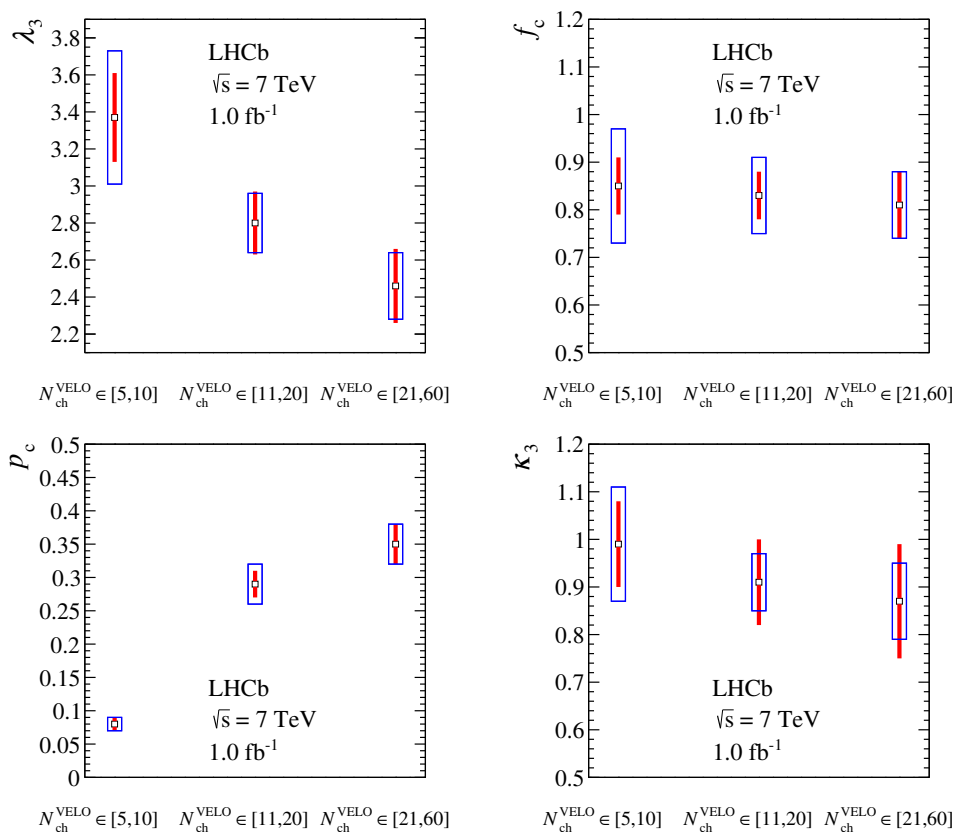


Figure 2. Values of correlation strength λ_3 and the parameters of the core-halo model determined for three bins of VELO track multiplicity. Statistical and systematic uncertainties are marked with red and blue bars, respectively.

The analysis most closely aligned in scope with the present study was performed by the PHENIX experiment at RHIC [11, 12]. It uses the core-halo model to interpret BEC for triplets of pions in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV in bins of transverse mass,⁶ measuring κ_3 and correlation strength λ_3 . Despite the differences in the experimental setups, the central values of κ_3 display a similar tendency to the results of the present study, which could indicate a partially coherent emission. However, these central values are consistent with unity within statistical and systematic uncertainties, preventing definitive conclusions. The reported values of three-particle correlation strengths are higher than those measured for pp collisions in the present analysis. The PHENIX analysis does not present the dependence on particle multiplicity, therefore, a direct comparison of the results for pp and Au-Au is not possible.

8 Conclusions

The correlations among three indistinguishable pions are studied using data collected by the LHCb experiment in 2011 at a centre-of-mass energy of 7 TeV in proton-proton collisions. The double-ratio technique is employed to correct for nonfemtoscopic background, together with the Gamov penetration factor utilised to account for electromagnetic final-state interactions that can be factorised using the generalised Riverside method. The fits applied to the three-pion double ratios of the correlation function provide parameters used to interpret the results within the frame of the core-halo model. The values of the core-halo parameters are studied in three activity classes related to the charged-particle multiplicity. The measured dependencies of the core-halo parameters on the charged-particle multiplicity suggest a partially coherent emission of pions. In particular, the partial coherence parameter p_c increases with multiplicity, indicating coherent emission of pions. At the same time, the κ_3 parameter, which is systematically below unity for higher-multiplicity bins, further suggests a partially coherent emission. However, due to the large uncertainties, it is also consistent with unity, preventing any firm conclusions from being drawn in this case. The behaviour of f_c indicates that the fraction of particles that originated from the core of the emission volume does not depend strongly on the number of charged particles produced in the event.

A Fit parameters and correlation matrices

Parameters of the fit to the three-particle double ratio are summarised in table 3, while the correlation matrices of fitted parameters can be found in tables 4–6.

	$N_{\text{ch}}^{\text{VELO}} \in [5,10]$	$N_{\text{ch}}^{\text{VELO}} \in [11,20]$	$N_{\text{ch}}^{\text{VELO}} \in [21,60]$
χ^2/ndf	170/191	285/191	262/191
N	0.74 ± 0.01	0.85 ± 0.01	0.90 ± 0.01
ℓ_2	0.47 ± 0.05	0.52 ± 0.03	0.46 ± 0.05
ℓ_3	1.93 ± 0.19	1.25 ± 0.15	1.08 ± 0.18
δ	0.07 ± 0.01	0.04 ± 0.01	0.03 ± 0.01

Table 3. The parameters of the fit to the three-particle double ratio.

⁶Transverse mass $m_T = \sqrt{m^2 + k_T^2}$, where k_T is the average pair transverse momentum.

	N	δ	ℓ_3	ℓ_2
N	1	-0.97	0.66	-0.85
δ	-0.97	1	-0.58	0.77
ℓ_3	0.66	-0.58	1	-0.94
ℓ_2	-0.85	0.77	-0.94	1

Table 4. Correlation matrix between fit parameters for $N_{\text{ch}}^{\text{VELO}} \in [5,10]$.

	N	δ	ℓ_3	ℓ_2
N	1	-0.95	0.57	-0.73
δ	-0.95	1	-0.49	0.64
ℓ_3	0.57	-0.49	1	-0.95
ℓ_2	-0.73	0.64	-0.95	1

Table 5. Correlation matrix between fit parameters for $N_{\text{ch}}^{\text{VELO}} \in [11,20]$.

	N	δ	ℓ_3	ℓ_2
N	1	-0.94	0.50	-0.64
δ	-0.94	1	-0.43	0.56
ℓ_3	0.50	-0.43	1	-0.95
ℓ_2	-0.64	0.56	-0.95	1

Table 6. Correlation matrix between fit parameters for $N_{\text{ch}}^{\text{VELO}} \in [21,60]$.

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