PARTICLE CORRELATIONS AT LHCb*

Miłosz Zdybał

on behalf of the LHCb Collaboration

Institute of Nuclear Physics Polish Academy of Sciences, 31-342 Kraków, Poland

(Received May 6, 2020)

Studies of particle correlations provide an insight into hadronization, the process that after many years of research is still not fully described. Past and ongoing analyses at the LHCb investigate this phenomenon in the unique forward kinematic region of the detector ($2 < \eta < 5$), expanding the knowledge gathered by other experiments. Studies of the Bose–Einstein Correlations for pairs and triplets of identical pions unveil temporal and spatial properties of the hadronic source as well as characteristics of the particle emission.

DOI:10.5506/APhysPolB.51.1593

1. Introduction

The LHCb detector [1] is characterized by the unique pseudorapidity coverage ($2 < \eta < 5$) related to its single-arm construction. Originally designed for heavy-flavor physics, it has proven to be a universal tool to study a wide range of physics phenomena in the forward region. Full instrumentation in this region allows for efficient track reconstruction and excellent particle identification over a wide momentum range. Both of those features play an important role in the analysis of the particle correlations. It makes results from the LHCb valuable and complementary to results from other LHC experiments. Studies on particle correlations has started in the 1950s and continue until this day trying to get an insight into the hadronization process. The presented document focuses on the two- and three-body Bose–Einstein Correlations of the same sign pions in proton–proton collisions at $\sqrt{s} = 7$ TeV observed for small angles of the beam direction.

* Presented at XXVI Cracow Epiphany Conference on LHC Physics: Standard Model and Beyond, Kraków, Poland, January 7–10, 2020.

2. Bose–Einstein Correlations for pion pairs

The first observation of quantum correlations between pions was done by Goldhaber, Goldhaber, Lee and Pais [2]. They noticed the unexpected correlations comparing four-momenta differences of the same-sign and unlike-sign pion pair created in proton–antiproton annihilation. They attributed the enhancement in identical bosons with small momentum difference to the Bose–Einstein statistics.

Correlations between indistinguishable pions coming from the same finite-size source are the effect of quantum statistics, strong and final-state interactions. The analysis of those correlations can provide information about the space-time properties of hadronization region. The Bose–Einstein Correlations (BEC) between identical bosons are caused by the Hanbury Brown–Twiss interference effect [3]. The analogous phenomenon for fermions is known as Fermi–Dirac Correlations (FDC). A parametrized form of correlation function is commonly expressed as a function of four-momenta difference Q with Lévy parametrization. In the two-pion case, it takes the form of $C_2(Q) = N \times (1 + \lambda \mathrm{e}^{-RQ}) \times (1 + \delta Q)$, where N is normalization parameter, λ is chaoticity parameter, R is radius of the spherically symmetric source and δ is a parameter related to long-range correlations. The experimental form of correlation function is expressed using a ratio of the distribution of the like-sign pairs to the reference sample. It is very important that the reference sample is constructed in a way that ensures it does not include the Bose–Einstein Correlations. There are three main ways to achieve it: Monte Carlo samples, unlike-signed pions and event-mix. In the presented analysis, the latter was used. Identical pions from the two different events with the same multiplicity are not correlated with each other. The effect of electrostatic repulsion of the same-signed pions is corrected using the Gamow factor. Correlation function can be improved with introduction of the double ratio (DR). In this method, correlation function is divided by the correlation function calculated for the Monte Carlo sample that has the Bose–Einstein Correlations switched off. Other effects, like long-range correlations are included in the simulation, so building a double ratio cancels those effects providing cleaner correlation function.

Analyzed dataset contained events from the proton–proton collisions at 7 TeV taken by the LHCb in 2011. The correlations were measured in three bins of activity related to the charged particle multiplicity of the primary vertex [4].

Calculated values of the correlation radius and the chaoticity parameter show dependence on the charged particle multiplicity, as presented in Fig. 1. Values of both parameters for forward region are slightly lower than the measurements done in central rapidities by ATLAS [5].

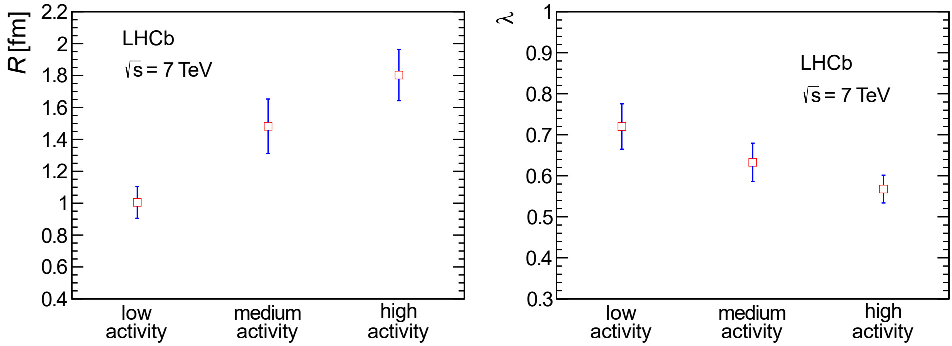

Fig. 1. Correlation radius (left) and chaoticity parameter (right) presented as a function of event activity. Error bars indicate sum of the statistical and systematic uncertainties in quadrature. Figure adopted from [4].

3. Three-pion Bose–Einstein Correlations

3.1. Correlation function

The analysis of Bose–Einstein Correlations for the pion triplets is based on the analysis for the pion pairs. Definition of the correlation function is analogous — it is the ratio of probability density distribution of triplet of particles with four-momenta q_1, q_2 and q_3 to the product of probability density distributions of single particles with respective momenta. To calculate differences in four-momenta, pions inside each triplet are combined into all possible pairs, marked by indices in equations (1) and (2). Results from the previous analysis are the input parameters — correlation radius R is used in the correlation function, value of λ_2 in the further calculations. Equation (1) includes normalization parameter N and long-range contributions from each of the pion pairs

$$C_3(Q_{12},Q_{13},Q_{23}) = N(1+\delta Q_{12})(1+\delta Q_{13})(1+\delta Q_{23})G_3C_3^{(0)}(Q_{12},Q_{13},Q_{23})\,. \tag{1}$$

Parameter G_3 corresponds to the Coulomb correction. According to the Riverside method [6], total correction can be approximated using factorization of the corrections calculated for each of the pion pairs

$$\begin{aligned} C_3^{(0)}(Q_{12},Q_{13},Q_{23}) &= 1+\ell_3\mathrm{e}^{-0.5(|Q_{12}R|^\alpha+|Q_{13}R|^\alpha|Q_{23}R|^\alpha)} \\ &\quad +\ell_2\left(\mathrm{e}^{-|Q_{12}R|^\alpha}+\mathrm{e}^{-|Q_{13}R|^\alpha}+\mathrm{e}^{-|Q_{23}R|^\alpha}\right)\,. \end{aligned} \tag{2}$$

The Lévy-type correlation function $C_3^{(0)}$ (equation (2)) includes parameters ℓ_3 and ℓ_2 which describe correlation strength coming from three- and two-pion correlations, respectively. Parameter α is set to 1, as in previous analysis.

3.2. Core–halo model

The new way to look at the results it is the interpretation in the framework of core–halo model [7, 8]. This method was used for heavy ions in PHENIX experiment [9] but was not performed before for the proton–proton collisions. In this model, hadronic source is divided into two parts. Pions in the central core are directly produced from the excited strings or in the mechanism of hydrodynamic evolution. The core is surrounded by the halo of pions that are emitted from the decay of long-lived hadronic resonances, such as ω, η, η' and k_0. There are three main parameters describing core–halo properties of the source. First of them is the fraction of the core, f_c. It shows ratio of the pions that originated in the core to all pions emitted from the source. The partial coherence parameter, p_c, is defined as the ratio of particles coherently emitted from the core to all particles produced in the core. The core–halo-independent parameter κ_3 gives insight into the core characteristics and can be used to determine if there are additional effects in the core, *i.e.* partial coherence or not fully thermalized core. To calculate values of those parameters, results from two- and three-pion correlations are needed. All parameters can be expressed using correlation strengths λ_2 and λ_3. The value of λ_2 is taken from the two-pion analysis, λ_3 can be calculated using equation (3), where ℓ_3 and ℓ_2 are parameters of the fit

$$\lambda_3 = C_3(Q_{12} = Q_{13} = Q_{23} \to 0) - 1 = \ell_3 + 3\ell_2 \,. \tag{3}$$

3.3. Further possibilities

The scope of the presented analysis can be extended to gain further insight on this phenomenon, for instance, by studying the correlations as a function of transverse momentum. Additionally, datasets collected by the LHCb experiment at different energies and collision types could be used to broaden the range of the analysis.

4. Summary

Analysis of the particle correlations is a very useful tool for studying the process of hadronization in collider experiments. Results of two-body correlations provide information about the spatial and temporal characteristics of the hadronization region. With three-pion correlations, detailed properties of the particle emission can be obtained. At the LHCb, the Bose–Einstein correlations of identical bosons have been explored in one published measurement, and are the focus on ongoing studies covering a wide variety of cases. Those were the first observations of this phenomenon in the forward kinematic region, providing results complementary to other experiments.

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