TWO-PARTICLE CORRELATIONS AT THE LHCb*

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Due to its unique pseudorapidity coverage ($2 < \eta < 5$) and excellent performance, the LHCb detector allows the study of various aspects of particle correlations at large rapidities and low transverse momenta. Selected results are summarized, such as the first measurement of the Bose–Einstein correlations of the same-sign pions and kinematic correlations for pairs of beauty hadrons performed using large samples of proton–proton collision data accumulated with the LHCb detector at $\sqrt{s} = 7$ and 8 TeV, together with the long-range correlations on the near side measured in proton–lead and lead–proton collisions at a nucleon–nucleon centre-of-mass energy of $\sqrt{s} = 5$ TeV. The results provide a unique insight into particle production in the forward region at the LHC.

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1. Introduction

The unique construction of the LHCb detector [1] in a form of single-arm spectrometer fully instrumented in the forward direction provides an efficient track reconstruction and excellent particle identification at small angles with respect to the beam direction, corresponding to pseudorapidity coverage $2 < \eta < 5$. It proved to be a universal tool to study a broad spectrum of physics phenomena in the forward region. It has a potential to investigate particle correlations at small angles, and to obtain high precision results at the highest available collision energy. The forward acceptance and particle identification abilities of the LHCb detector allows the study of proton–ion collisions in a unique way, being complementary to other LHC experiments. The present document focuses on the first LHCb results on the Bose–Einstein correlations of the same-sign pions in proton–proton collisions at $\sqrt{s} = 7$ TeV, and the first measurement of the long-range correlations on

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the near side in high multiplicity proton–nucleus collisions in the forward region, measured in proton–lead and lead–proton collisions at a nucleon–nucleon centre-of-mass energy of $\sqrt{s} = 5$ TeV. It also reports recent results on kinematic correlations for pairs of beauty hadrons, produced in proton–proton collisions at centre-of-mass energies of 7 and 8 TeV.

2. Bose–Einstein correlations for pion pairs in proton–proton collisions at 7 TeV

The analysis of the correlations between indistinguishable pions with a small four-momenta difference, emitted by a finite-size source, allows determination of the space-time properties of the hadron emission volume. The correlations originate from the effects of quantum statistics as well as the strong and Coulomb final-state interactions. The nature of multi-particle production within the process of hadronization has been investigated for nearly five decades, but it is still not well-understood. In the case of identical bosons, the HBT (Hanbury Brown–Twiss) interference effect [2] results in Bose–Einstein Correlations (BEC), and in the case of fermions, in Fermi–Dirac Correlations (FDC). Both types of correlations are examined by measuring a two-particle correlation function, commonly studied as a function of four-momenta difference Q, which is sensitive to the dynamic processes related to the evolution of the hadron source. The correlation function $C_2(Q)$ is commonly parameterised as an exponential function corresponding to the radial distribution of the static source [3], $C_2(Q) = N \times (1 + \lambda\, e^{-RQ}) \times (1 + \delta\, Q)$, where the parameter R, the correlation radius, can be interpreted as the radius of the spherically symmetric source of the emission volume, N accounts for the overall normalisation and λ is the chaoticity parameter, which accounts for the partial incoherence of the source. The chaoticity parameter can vary from zero, in the case of a completely coherent source, to unity for an entirely chaotic source. The δ parameter accounts for long-range correlations, *e.g.* related to the transverse momentum conservation. By construction of the correlation function, the effects due to single-particle efficiency, detector occupancy, acceptance and material budget are accounted for by dividing the Q distribution for the same-sign pion pairs by a reference distribution. There are a number of different methods to obtain the reference sample. In the analysis presented, a data-driven event-mixed reference sample is used. This approach is based on the choice of two identical pions, each originating from different events, which naturally do not contain quantum interference effects. The main drawback of the event-mixing method lies in the fact that not only the BEC or FDC effect is removed from the data sample but other correlations, such as correlations due to Coulomb interactions or long-range effects, are also eliminated in this way. To account for imperfections in the reference distribution derived from the data, a double ratio is commonly used in femtoscopic studies, defined as a ratio of the correlation function in the data constructed using the event-mixed reference sample and the correlation function in the simulation without the quantum interference effects, using an event-mixed sample built with simulated events in the same way as for data. Using a data sample collected by the LHCb experiment in proton–proton collisions at a centre-of-mass energy of 7 TeV, the dependence of the correlation radius and chaoticity parameter on event activity has been investigated in the analysis presented [4] in the forward acceptance region of $2 < \eta < 5$ for single pions with transverse momentum $p_{\mathrm{T}} > 0.1$ GeV/c, by fitting the Coulomb corrected double ratio with the exponential parametrization mentioned above. An enhancement related to the BEC effect on the double ratio distribution for pairs of the same-sign charged pions with small relative momentum is observed in Fig. 1, which shows the dependence of the correlation parameters on event activity, defined as a fractions of the vertex detector charged-particle multiplicity. It may be observed that the correlation radius increases with event activity, while the chaoticity parameter is decreasing. Such trends are in agreement with the dependences previously observed at LEP and in the other LHC experiments. The R and λ parameters measured in the forward region in corresponding charged-particle multiplicity bins are slightly lower with respect to those measured by ATLAS for corresponding pp interaction multiplicities [5].

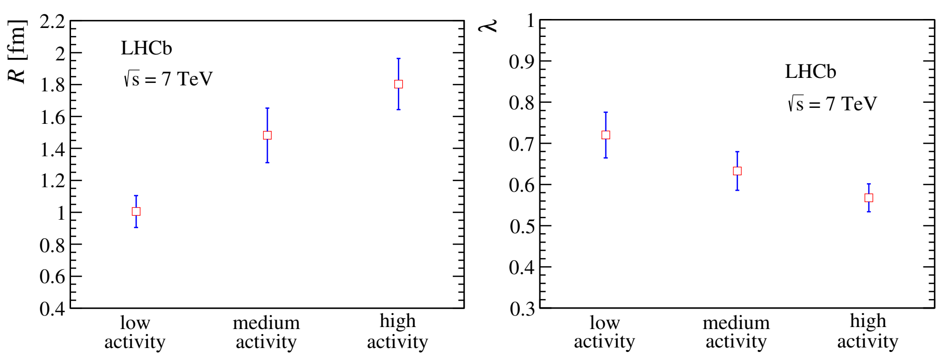

Fig. 1. Correlation radius (left) and chaoticity parameter (right) as a function of event activity. Error bars indicate the sum in quadrature of the statistical and systematic uncertainties. The points are placed at the centres of the activity bins. Figure adopted from [4].

3. Long-range correlations on the near side

Two-particle angular correlations of prompt charged particles have been studied in LHCb for both pPb and Pbp collisions [6]. This study has been motivated by the long-range correlation on the near side, $\Delta\phi \approx 0$ ('ridge effect'), observed in pp and pPb (and PbPb) collisions at central rapidities ($\eta < 2.5$). LHCb can confirm such effects at large rapidities ($2.0 < \eta < 4.9$). The correlations have been measured as a function of relative pseudorapidity, $\Delta\eta$, and relative azimuthal angle, $\Delta\phi$, for events with one primary vertex in different classes of event activity and for different bins of particle $p_{\rm T}$. Five event-activity classes, from low (50–100%) to very high (0–3%) multiplicity classes have been defined as fractions of the hit-multiplicity distributions of the minimum-bias samples. The correlation function has been constructed as a ratio of the signal, *i.e.* particle pairs for all combinations of two particles within the same event, and the background, which are the particle pairs from different events. Figure 2 shows that in the Pbp configuration, the near-side ridge effect is clearly visible in the high event activity class, while for low activity, it is minor. To study the evolution of the long-range correlations on the near and away sides in more detail, the correlation function has been projected onto $\Delta\phi$. In the next step, the two-dimensional yield has been averaged in the η range (2.0–2.9) to exclude short-range correlations. Furthermore, the zero yield at minimum has been subtracted. It has been observed that the correlation yield increases with event activity and the away-side ridge decreases towards higher $p_{\rm T}$. The near-side effect is more pronounced in the Pbp than pPb configuration due to the larger event activity in the backward configuration. For common absolute activity ranges, the near-side correlation yield is compatible for the forward and backward samples. This is the first observation of long-range correlations on the near side in the forward region.

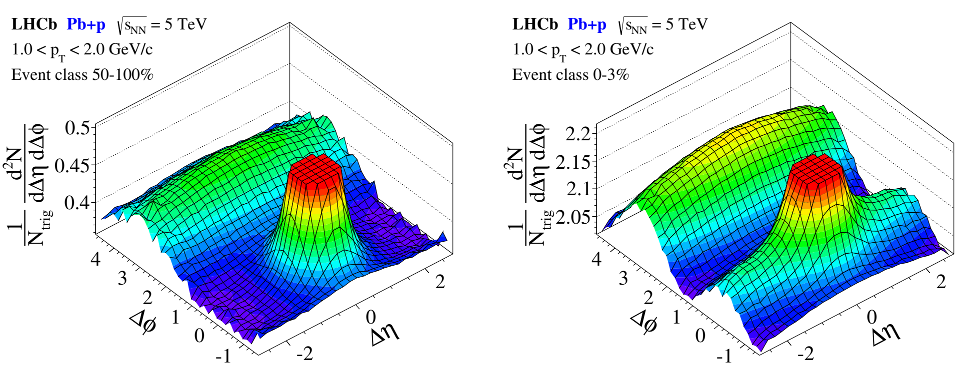

Fig. 2. Two-particle correlation functions for events recorded in the Pbp configuration showing the (left) low and (right) high event-activity classes. The analysed pairs of prompt charged particles are selected in a $p_{\rm T}$ range of 1–2 GeV/c. Figure adopted from [6].

4. Kinematic correlations for pairs of beauty hadrons

The production of heavy-flavour hadrons can provide important tests for the predictions of QCD. They enable a better understanding of the production mechanism, such as contributions from gluon splitting, flavour creation or flavour excitation, and also the role of higher-order corrections. Such correlations have been already studied for beauty hadrons at the SPS, Tevatron and LHC. As the LHCb experiment has a unique acceptance coverage and a detector designed to study B physics, it may provide valuable results complementary to the central rapidity detectors. The analysis of the kinematic correlations for pairs of beauty hadrons, produced at 7 and 8 TeV in proton–proton collisions, is based on inclusive decays of beauty hadrons into J/ψ mesons ($J/\psi \to \mu^+\mu^-$) [7]. The muon candidates have to be positively identified as muons with a good reconstruction quality, with $p_{\rm T} > 500$ MeV/c and $2 < \eta < 5$. Both reconstructed J/ψ candidates are required to have a good-quality vertex, a reconstructed mass in the range of $3.00 < m^{\mu^+\mu^-} < 3.18$ GeV/c^2, $2 < p_{\rm T}^{J/\psi} < 25$ GeV/c and $2 < y^{J/\psi} < 4.5$. Such criteria ensure a good reconstruction and trigger efficiency. The signal yield is determined from the fit to the two-dimensional mass distribution of muon pairs. Normalized differential cross sections, $(1/\sigma)\,({\rm d}\sigma/{\rm d}v) \equiv (1/N^{\rm corr})\,(\Delta N_i^{\rm corr}/\Delta v_i)$, where $N^{\rm corr}$ is a total number of efficiency-corrected signal candidates and $\Delta N^{\rm corr}$ is the number of efficiency-corrected signal candidates in a given Δv_i bin, are determined for a set of the following kinematic variables: *(i)* difference in azimuthal angle of two beauty hadrons $|\Delta\phi^*|$; *(ii)* difference in pseudorapidity of two beauty hadrons $|\Delta\eta^*|$, where both ϕ^* and η^* are determined from the direction of the vector from the primary vertex to the decay vertex of the J/ψ meson; *(iii)* $p_{\rm T}$ asymmetry of two J/ψ mesons $A_{\rm T} \equiv |(p_{\rm T}^{J/\psi_1} - p_{\rm T}^{J/\psi_2})/(p_{\rm T}^{J/\psi_1} + p_{\rm T}^{J/\psi_2})|$, *(iv)* mass of the J/ψ pair $m^{J/\psi J/\psi}$; *(v)* transverse momentum of the J/ψ pair $p_{\rm T}^{J/\psi J/\psi}$; *(vi)* rapidity of the J/ψ pair $y^{J/\psi J/\psi}$. The systematic uncertainty mostly cancels out by the construction of the cross section, but it is anyway much smaller than the corresponding statistical error. The normalized differential production cross sections for $p_{\rm T}^{J/\psi} > 2$ GeV/c, shown in Fig. 3, are compared with the PYTHIA [8] and POWHEG [9] generator predictions, which describe the data reasonably well. In particular, contrary to $c\bar{c}$ production, there is only a small contribution from gluon splitting at low $|\Delta\phi^*|$, as it is suppressed due to the large mass of the beauty quark. The NLO and LO predictions are similar when compared to the experimental sensitivity, so more data is needed to discriminate them and probe the production mechanisms.

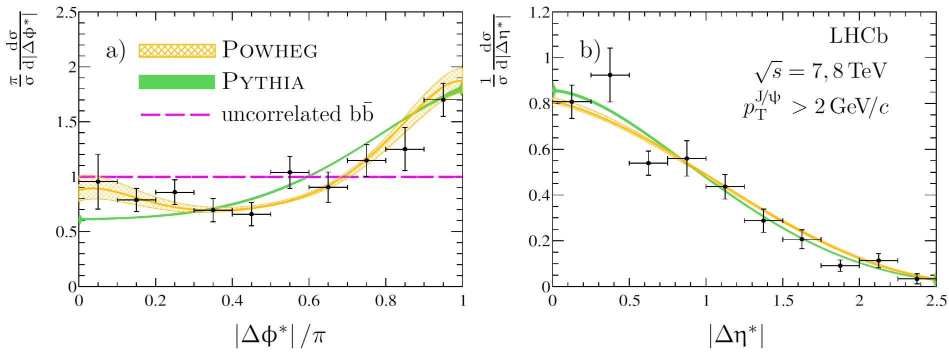

Fig. 3. (Colour on-line) Normalized differential production cross sections (points with error bars) for (a) $|\Delta\phi^*|/\pi$ and (b) $|\Delta\eta^*|$. Dashed grey/magenta line on the left plot denotes the expectations for artificial data-driven model of uncorrelated $b\bar{b}$ production, light gray/orange and dark gray/green areas denote the uncertainties of the POWHEG and PYTHIA predictions, respectively. Figure adopted from [7].

5. Summary

LHCb provides complementary results on various aspects of the particle correlations to the general purpose LHC detectors in the forward kinematic region. The Bose–Einstein correlations between two indistinguishable pions as well as the near-side ridge effect have been observed for the first time in the forward region. New LHCb results on kinematic $b\bar{b}$ correlations in proton–proton collisions are expected to be updated with larger statistics allowing the production mechanisms to be probed at higher sensitivity. The results reported in the present document show the LHCb potential in the related fields and may provide important constraints for the tuning of models describing multi particle production in high-energy hadronic interactions.

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