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TWO-PARTICLE CORRELATIONS AT THE LHCb*

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Results from the LHCb experiment on two different types of correlations in proton–proton collisions at the centre-of-mass energies of 7 and 8 TeV are presented. Kinematic $b\bar{b}$ correlations are studied using inclusive $b \to J/\psi X$ decays and are observed to be in good agreement with theoretical predictions. Measurement of the Bose–Einstein correlations for same-sign charged pions is performed and dependence of the correlation parameters on the charged-particle multiplicity is investigated. The determined correlation radius is observed to increase with the charged-particle multiplicity, while the chaoticity parameter decreases.

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1. Introduction

The process of particle production is a very complex, yet a basic phenomenon in high-energy physics. Studying correlations between particles emerging from a collision region can provide information on various subprocesses of the particle production. This paper presents two recent results from the LHCb experiment [1, 2] on different kinds of correlations in high-energy proton–proton (pp) collisions. The LHCb detector is a single-arm spectrometer and has a unique acceptance ($2.0 < \eta < 5.0$) among other LHC experiments. Thus, the obtained results are first of their kind in the forward region and give additional input to understand the process of particle production.

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The first measurement concerns kinematic correlations between $b\bar{b}$ quarks. Heavy-flavor quarks are produced mostly in hard processes at the initial stage of the collision (due to their relatively high masses), which can be described by the perturbative quantum chromodynamics (QCD) [3]. Studying kinematic correlations between heavy-flavor quarks gives an opportunity to gain information on the contribution from specific subprocesses (*e.g.* gluon splitting, flavor-excitation) and higher-order QCD corrections to the heavy-flavor production. Measurements on the $b\bar{b}$ correlations have been performed at *e.g.* SPS [4], Tevatron [5] and LHC [6, 7]. LHCb provides the first result [8] in the forward region with a detector originally dedicated to heavy-flavor physics. The obtained correlations are compared to theoretical predictions from PYTHIA [9] and POWHEG [10] with leading-order (LO) and next-to-leading-order (NLO) calculations, respectively.

The second presented study is on the Bose–Einstein correlations (BEC) for same-sign charged pions in *pp* collisions. The BEC measurements allow to gain information on the evolution of the hadron emission volume. Parameters such as a correlation radius R (often interpreted as a size of a spherically symmetrical static source of particles) and a chaoticity parameter λ (related to the coherence of particle emission) are determined [11, 12]. Such studies have been done for multiple collision systems and particle species at *e.g.* ISR [13], LEP [14], RHIC [15] and LHC [16–18]. Many features of the BEC parameters have been observed, such as their dependence on the charged-particle multiplicity (N_{ch}). LHCb adds a unique measurement in the forward region [19], which can be used to investigate potential differences between the BEC effect in the forward and central regions.

2. Kinematic $b\bar{b}$ correlations

Kinematic $b\bar{b}$ correlations are studied with a data sample collected by the LHCb experiment in 7 and 8 TeV *pp* collisions [8]. The analysis is performed using inclusive $b \to J/\psi X$ decays, where J/ψ further decays to a $\mu^+\mu^-$ pair. Only events with two J/ψ candidates are selected and two-dimensional distributions of the $\mu^+\mu^-$ masses are constructed for four different requirements on the J/ψ transverse momentum ($p_{\mathrm{T}}^{J/\psi}$). From those distributions, a signal yield is determined by fitting a function with terms corresponding to the signal (two J/ψ mesons) and background contributions (at least one $\mu^+\mu^-$ pair not originating from a J/ψ decay). To study the kinematic correlations, normalized differential production cross sections are constructed

$$(1/\sigma)(\mathrm{d}\sigma/\mathrm{d}v) \equiv (1/N^{\mathrm{cor}})(\Delta N_i^{\mathrm{cor}}/\Delta v_i)\,, \tag{1}$$

where v is a generically denoted kinematic variable, N^{cor} is the total number of efficiency-corrected signal candidates and $\Delta N_i^{\mathrm{cor}}$ is the number of efficiency-corrected signal candidates in bin i of width Δv_i. The efficiency correction includes effects related to the acceptance of the LHCb detector, reconstruction and selection, muon identification and trigger. It is based on both simulation and data-driven techniques.

The correlations are studied for the following variables: difference in the azimuthal angle $|\Delta\phi^*|$ and pseudorapidity $|\Delta\eta^*|$ of the two beauty hadrons[1], mass $m^{J/\psi J/\psi}$, transverse momentum $p_{\mathrm{T}}^{J/\psi J/\psi}$ and rapidity $y^{J/\psi J/\psi}$ of the J/ψ pair and $A_{\mathrm{T}} \equiv |(p_{\mathrm{T}}^{J/\psi_1} - p_{\mathrm{T}}^{J/\psi_2})/(p_{\mathrm{T}}^{J/\psi_1} + p_{\mathrm{T}}^{J/\psi_2})|$, which is the p_{T} asymmetry of J/ψ mesons. The systematic uncertainties are negligible, since they are much smaller than the statistical ones (most of them cancel out in the definition of the normalized differential production cross section).

Results for a chosen $p_{\mathrm{T}}^{J/\psi}$ requirement ($p_{\mathrm{T}}^{J/\psi} > 5$ GeV/c) are shown in Fig. 1. Obtained distributions agree well with theoretical predictions from both PYTHIA and POWHEG, which suggests that the NLO effects in $b\bar{b}$ production are small compared to the experimental precision.

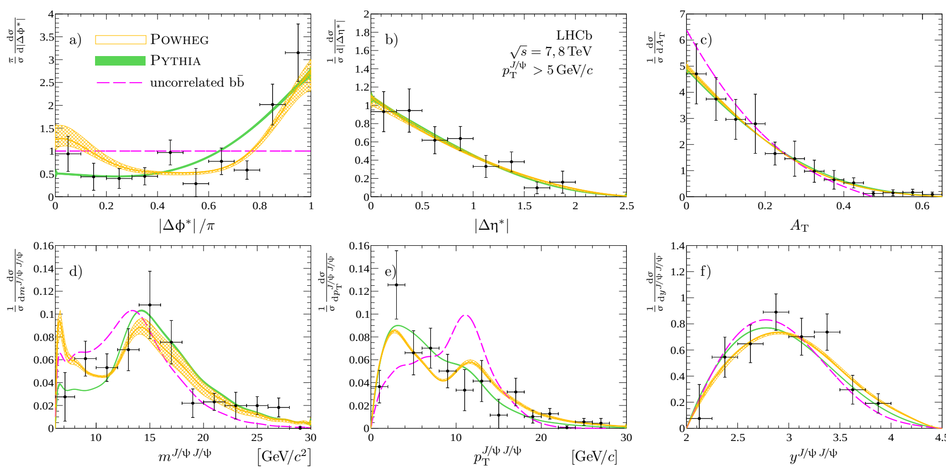

Fig. 1. (Colour on-line) Normalized differential production cross-sections (points with error bars) in $p_{\mathrm{T}}^{J/\psi} > 5$ GeV/c region for (a) $|\Delta\phi^*|\ /\pi$, (b) $|\Delta\eta^*|$, (c) A_{T}, (d) $m^{J/\psi J/\psi}$, (e) $p_{\mathrm{T}}^{J/\psi J/\psi}$, (f) $y^{J/\psi J/\psi}$. Expectations from POWHEG (grey/orange line), PYTHIA (black/green band) and model of uncorrelated $b\bar{b}$ production (dashed magenta line) are shown. Distributions for samples collected at both centre-of-mass energies of 7 and 8 TeV are very similar and they are treated together. The figures are taken from [8].

[1] Both variables are estimated on the basis of the direction of the vector from the primary vertex to the J/ψ decay vertex.

3. Bose–Einstein correlations

The Bose–Einstein correlations for same-sign charged pions are studied using a minimum bias data sample from 7 TeV pp collisions recorded by the LHCb experiment [19]. A corresponding sample from Monte Carlo simulation (MC) is obtained using PYTHIA 8 generator [9]. The data is split into three activity classes based on a distribution of the vertex locator (VELO) track multiplicity, which is a good measure of the charged-particle multiplicity. An unfolding procedure for the VELO track multiplicity is performed using the simulation, in order to obtain the corresponding N_{ch}.

The BEC effect can be studied using a correlation function

$$C_2(Q) = N(Q)^{\mathrm{LIKE}} \Big/ N(Q)^{\mathrm{REF}} , \tag{2}$$

where $Q = \sqrt{-(q_1 - q_2)^2}$ is determined from the difference of the particles four-momenta, $N(Q)^{\mathrm{LIKE}}$ is the Q distribution for pairs of signal particles (two same-sign charged pions from the same primary vertex) and $N(Q)^{\mathrm{REF}}$ is the Q distribution for a reference sample (sample not containing the BEC effect). An event-mixed reference sample is used in this study (pairs of particles from different events). In this method, also other types of correlations are not present, such as *e.g.* long-range ones. A double ratio $r_{\mathrm{d}}(Q)$ is introduced to account for such imperfections of the reference sample. It is a ratio of correlation functions for data and simulation (with the BEC effect switched off). Thus, effects which are properly simulated are removed in the $r_{\mathrm{d}}(Q)$. Coulomb interactions between final-state pions are among the phenomena that are not present in the simulation. This is accounted for by applying a Gamov penetration factor for the data [20]. The correlation function can be parametrized as [12]

$$C_2(Q) = N(1 + \lambda \exp(-RQ))\,(1 + \delta Q) , \tag{3}$$

where R is the correlation radius, λ is the chaoticity parameter, δ corresponds to long-range correlations and N is a normalization factor.

The BEC parameters obtained for each activity class are shown in Fig. 2. The systematic uncertainty (about 10% in each activity class) is dominated by MC generator tunings and pile-up effects. It is observed that R increases with charged-particle multiplicity, while λ decreases, which is consistent with other observations at LEP and LHC. Results from LHCb are compared to those from ATLAS [17] by relating the N_{ch} in those experiments' acceptances using the simulation. It is found that the BEC parameters in the forward direction are slightly lower than those at the central region.

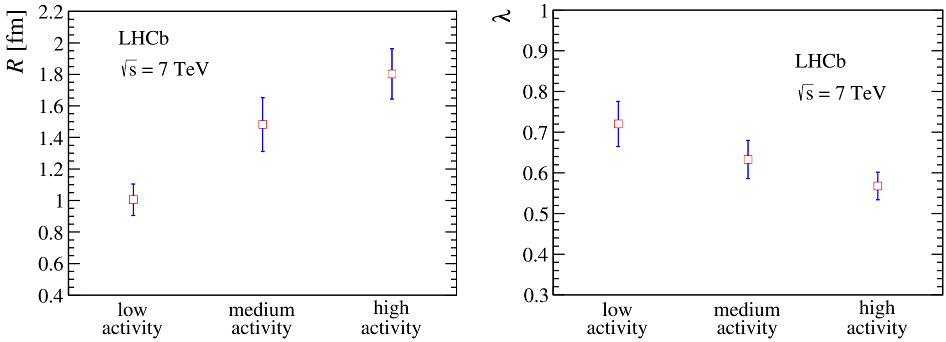

Fig. 2. (left) Correlation radius R and (right) chaoticity parameter λ as a function of activity. Error bars indicate the sum in quadrature of the statistical and systematic uncertainties. The points are placed at the centres of the activity bins. The figures are taken from [19].

4. Summary

Results from the LHCb experiment on two different kinds of correlations in high-energy pp collisions are presented. Both measurements are the first of their kind in the forward region and show the potential of LHCb.

Kinematic $b\bar{b}$ correlations are studied using data samples collected in 7 and 8 TeV pp collisions. The analysis is performed using inclusive $b \to J/\psi X$ decays. The observed correlations are in good agreement with predictions from both PYTHIA and POWHEG, suggesting that the effect of NLO corrections in $b\bar{b}$ production is small, at least compared to the experimental precision. Current data do not allow for discriminating between theory predictions, however, this should be possible in the future analyses with larger samples — especially in the region of large $p_{\mathrm{T}}^{J/\psi}$, where the differences between PYTHIA and POWHEG predictions are most prominent.

The BEC measurement is performed for same-sign charged pions from 7 TeV pp collisions. The BEC parameters are determined for three different charged-particle multiplicity bins. It is observed that the correlation radius increases with charged-particle multiplicity, while the chaoticity parameter decreases — similar behavior has been reported by other experiments at *e.g.* LEP and LHC. The BEC parameters measured in the forward region seem to be slightly lower than those observed by ATLAS for corresponding charged-particle multiplicities in the central region. A more detailed comparison is planned in the future analyses at the LHCb.

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