Vol. 12 (2019) *Acta Physica Polonica B Proceedings Supplement* No 2

BARYONIC AND MESONIC RESONANCES AT THE LHCb*

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(Received January 24, 2019)

The LHCb experiment is designed to study properties and decays of heavy-flavoured hadrons produced from pp collisions at the LHC. LHCb has recorded the world's largest data sample of beauty and charm hadrons, enabling precise spectroscopy studies of such particles. The valuable results obtained by LHCb include observation of doubly charmed baryons Ξ_{cc} and five new narrow Ω_c states.

DOI:10.5506/APhysPolBSupp.12.375

1. Introduction

The resonances can be regarded as extremely short-lived particles with lifetime around 10^{-23} seconds or less. In a more technical way, resonances are poles in the unphysical sheets of the S-matrix, which manifest themselves as structures in experimental observables. In practice isolated, relatively narrow resonance can be described by the Breit–Wigner parametrization. In more complicated cases such as several overlapping resonances, a K-matrix formalism can be applied [1].

Resonances carry quantum numbers, which can be determined experimentally from the study of the angular distributions and correlations. For this, one of the several spin formalisms should be chosen [2]: non-relativistic tensor formalism, spin-projection formalisms (helicity, canonical or transversality formalism depending on quanization axis) or relativistic tensor formalism. In practice, quantum number of resonances are determined by the following procedure: after observation of the new bump in experimental observables, the experimentalist has to make sure that the observed structure

* Presented at the XIII Workshop on Particle Correlations and Femtoscopy, Kraków, Poland, May 22–26, 2018.

is a real signal and not *e.g.* kinematic reflection; possible quantum number assignments should be identified; amplitude and a fit model corresponding to each possible resonance quantum number should be prepared; and, finally, fit the models and perform hypothesis tests to identify which is the model preferred by data.

The LHCb experiment at CERN applied the described procedure successfully to study resonances with charm and beauty quarks and identify their quantum numbers and, therefore, their nature for a range of exotic (such as tetraquarks and pentaquarks) and conventional (mesons and baryons) hadrons. The LHCb detector [3, 4] is a single-arm forward spectrometer covering the pseudorapidity range of $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector elements that are particularly relevant to study beauty and charm hadrons are: a silicon-strip vertex detector surrounding the pp-interaction region that allows c and b hadrons to be identified from their characteristically long flight distance; a tracking system that provides a measurement of momentum, p, of charged particles; and two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons. LHCb focuses its experimental efforts in hadron spectroscopy on beyond ground-state hadrons, *e.g.* spin, angular momentum, and radial excitations of charm mesons (D^+, D^0, D_s^+), charm baryons (Λ_c^+, Ξ_c^+, Ξ_c^0, Ω_c^0), beauty mesons (B^+, B^0, B_s^0, B_c^+), and beauty baryons (Λ_b^0, Ξ_b^0, Ξ_b^-, Ω_b^-).

2. Mesconic resonances

2.1. Study of D_s family

Studies of heavy-meson spectroscopy provide an important probe of quantum chromodynamics and spectrum of charmed mesons is well-predicted theoretically [5]. After initial discovery of two S-wave states (D_s, D_s^*), the interest returned after observation of $D_{s0}^*(2317)^-$ and $D_{s1}(2460)^-$ as their masses were found to be below the DK and D^*K thresholds, respectively, in contrast to prior predictions. Later, the observed family of P-wave states has been extended by $D_{s1}(2536)^-$ and $D_{s2}^*(2573)^-$. Several other states have been observed at the B-factories in DK and D^*K modes ($D_{s1}(2700)^+$, $D_{sJ}(2860)^+$ and $D_{sJ}(3040)^+$) with quantum number assignments not known.

The LHCb performed two studies of D_s spectra: in production analysing D^+K_s and D^0K^+ final state [6] and in Dalitz plot analysis of $B_s^0 \to D_0K^-\pi^+$ [7] (Fig. 1). In the first measurement, $D_{s1}(2700)^+$ and $D_{sJ}(2860)^+$ have been observed for the first time in hadronic interactions, and their mass and width have been measured. In the latter analysis, the full amplitude analysis has been performed (angular distributions are given in the

Zemach tensor). It shows with more than 10σ significance that the structure at $m(D^0K^-) \approx 2.86\,\mathrm{MeV}/c^2$ contains both spin-1 and spin-3 components. Mass and width for both spin-1 and spin-3 components have been measured.

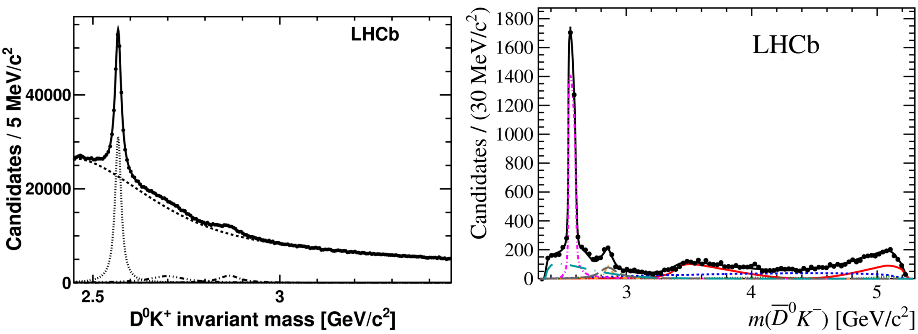

Fig. 1. Invariant mass distribution for D_0K^+ (left) [6] and results of the $m(D^0K^-)$ projection of Dalitz plot (right) [7].

2.2. Search for $B_c(2S)$

The B_c meson family is unique in the Standard Model, as its states contain two different heavy flavour valence quarks. Due to its flavour quantum numbers $B = -C = \pm 1$, the B_c^+ cannot decay strongly, but only weakly, either via $\bar{b} \to \bar{c}W^+, c \to sW^+$, or the so-called weak-annihilation process $\bar{b}c \to W+$. The ground state of the B_c meson family, the B_c^+ meson, was first observed by the CDF experiment in 1998. Recently, the ATLAS Collaboration reported observation of an excited B_c state with a mass of $6842 \pm 4(\mathrm{stat.}) \pm 5(\mathrm{syst.})\,\mathrm{MeV}/c^2$ [8]. The most probable interpretation of the observed peak is either a signal for $B_c(2^3S_1)^+ \to B_c^{*+}\pi^+\pi^-$, followed by $B_c^{*+} \to B_c^+\gamma$ with a missing low-energy photon, or an unresolved pair of peaks from the decays $B_c(2^1S_0)^+ \to B_c^+\pi^+\pi^-$ and $B_c(2^3S_1)^+ \to B_c^{*+}\pi^+\pi^-$. The $B_c(2^1S_0)^+$ and $B_c(2^3S_1)^+$ states are denoted as $B_c(2S)^+$ and $B_c^{*+}(2S)$ hereafter, and $B_c^{(*)}(2S)^+$ denotes either state.

The LHCb experiment searched for $B_c(2S)$ and $B_c^*(2S)$ mesons in the data sample collected at $\sqrt{s} = 8\,\mathrm{TeV}$ corresponding to an integrated luminosity of 2 fb^{-1}. The $B_c(2S)$ and $B_c^*(2S)$ mesons are reconstructed via decays $B_c(2S)^+ \to B_c^+\pi^+\pi^-$ and $B_c(2S)^{*+} \to B_c{}^*{+}\pi^+\pi^-$, $B_c^+ \to J/\Psi\pi^+$, $J/\Psi \to \mu^+\mu^-$.

The analysed data set contained 3325 ± 73 of reconstructed B_c^+. No evidence of the $B_c^{(*)}(2S)^+$ signal is observed and the upper limit on the ratio $R = N(B_c^{(*)}(2S)^+)/N(B_c^+)$ has been determined.

2.3. Muonic decays of χ_{c1} and χ_{c2}

Most studies of χ_{c1} and χ_{c2} mesons at hadron colliders have exploited the radiative decays $\chi_{c1,c2} \to J/\Psi\gamma$ with the subsequent decay $J/\Psi \to \mu^+\mu^-$. The analysis of the LHCb data set collected in pp collisions up to the end of 2016 reported the first observation of the $\chi_{c1} \to J/\Psi\mu^+\mu^-$ and $\chi_{c2} \to J/\Psi\mu^+\mu^-$ decay modes using $J/\Psi \to \mu^+\mu^-$ [10] (Fig. 2). These decays are used to measure the χ_{c1} and χ_{c2} masses together with the χ_{c2} natural width. The very low Q-value of the decay and the absence of Bremssrahlung of the soft muons allow extraordinary resolution. The results for the mass measurements are: $m(\chi_{c1}) = 3510.71 \pm 0.04 \pm 0.09\,\mathrm{MeV}/c^2$ and $m(\chi_{c2}) = 3556.10 \pm 0.06 \pm 0.11\,\mathrm{MeV}/c^2$ and are in good agreement with previous results. They are considerably more precise than the best measurement based on the final-state reconstruction and have comparable precision to the best previous results obtained at B-factories.

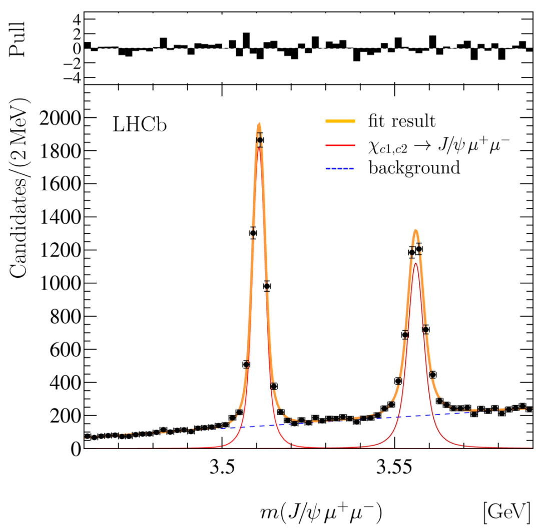

Fig. 2. Mass distribution for selected $J/\Psi\mu^+\mu^-$ candidates [10].

3. Baryonic resonances

3.1. Doubly charmed baryons Ξ_{cc}^{++}

The quark model predicts existence of three weakly decaying states with $C = 2$ and $J^P = 1/2^+$: one isospin doublet ($\Xi_{cc}^{++} = ccu$ and $\Xi_{cc}^{+} = ccd$) and one isospin singlet ($\Omega_{cc}^{+} = ccs$). Their properties have been calculated within several theoretical models predicting mass of Ξ_{cc}^{++} in the range from 3 500 to 3 700 MeV$/c^2$. Approximate isospin symmetry implies that mass of Ξ_{cc}^{+} differs by only a few MeV/c^2. There is a large ambiguity of lifetime prediction for Ξ_{cc}^{+} (from 50 to 250 fs) and Ξ_{cc}^{++} (from 200 to 700 fs) with consistent prediction that lifetime of the latter is 3–4 times larger. Before the LHCb measurement, experimental evidence for Ξ_{cc}^{++} and Ξ_{cc}^{+} existence has been somehow controversial. In 2002, the SELEX experiment claimed observation of $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-}\pi^{+}$ with 6.3σ significance and later confirmed observation in $\Xi_{cc}^{+} \to D^{+}pK^{-}$ with 4.8σ significance. The lifetime was estimated to be surprisingly short (below 33 fs at 90% confidence level). However searches by BaBar, FOCUS and Belle experiments did not find evidence for a state with the properties reported by SELEX, and neither did a search at the LHCb with data collected in 2011 corresponding to an integrated luminosity of 0.65 fb^{-1}.

The LHCb experiment observed Ξ_{cc}^{++} in the final state $\Lambda_c^{+}(\to pK^{-}\pi^{+})$ $K^{-}\pi^{+}\pi^{-}$ with 12 sigma significance from the 13 TeV data taken in 2016, corresponding to an integrated luminosity of 1.7 fb^{-1} [11]. The measured mass is $m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.17(\Lambda_c^{+})\,\text{MeV}/c^2$ and the mass difference with the SELEX measurement ($\Delta m = 103\,\text{MeV}/c^2$) is too large for two particles to be an isospin partners. Studies are ongoing on lifetime, production rate, other decay modes, and the isospin partner.

3.2. Study of Ω_c^{**} family

In the $\Omega_c(css)$ system, the large difference in mass between the charm quark and the light quarks provides a natural way to understand the spectrum by using the symmetries provided by the Heavy Quark Effective Theories (HQET). In many models, the heavy quark is essentially a spectator and it interacts with the diquark which is treated as a single object. Precise measurements of the excited heavy meson properties are a sensitive test of the validity of HQET. All the ground states of the SU(3) multiplet containing charmed baryons have been observed. Excited states of Λ_c^{+}, Ξ_c, Σ_c have been reported but no excited Ω_c states have been observed before the LHCb measurements.

The search for new Ω_c^{0} resonances decaying to $\Xi_c^{+}K^{-}$ final states with Ξ_c^{+} reconstructed via $\Xi_c^{+} \to pK^{-}\pi^{+}$ have been performed by LHCb with 3.3 fb^{-1} of integrated luminosity. Five new narrow structures have been observed assigned as $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, $\Omega_c(3119)^0$. The $\Omega_c(3050)^0$ and $\Omega_c(3119)^0$ resonances have very narrow width below 1 MeV/c^2. There is no theory consensus on their interpretation and quantum number assignment. Particularly, the narrow width of $\Omega_c(3050)^0$ and $\Omega_c(3119)^0$ could lead to their interpretation in Chiral QCD framework as pentaquark states with experimentally verifiable signature such as existence of isospin partners [13].

4. Summary

The LHCb experiment has a rich program in spectroscopy of b and c hadrons. Several recent results have been summarised covering both meson and baryon states. The analysed data set includes 3 fb^{-1} of integrated luminosity collected in years 2011–2012 and a part of data set at higher energy which is expected by the end of 2018 to be around 6 fb^{-1}. Measurements of the lifetime, production rate and quantum number assignment for observed states is in progress and among the high priority analysis, there are searches of Ξ_{cc}^{+} and Ω_{cc}^{+} with measurements of their properties.

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