

LHCb RESULTS ON EXOTIC SPECTROSCOPY*

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The latest years have observed a resurrection of interest in searches for exotic states motivated by precision spectroscopy studies of beauty and charm hadrons providing the observation of many new exotic states. The recent results on spectroscopy of exotic hadrons obtained by the LHCb Collaboration are reviewed. This is, in particular, an observation of $P_c(4312)^+$ and two-peak structure of $P_c(4450)^+$, observation of $B_{(s)}^0 \rightarrow J/\psi p \bar{p}$ decays and an evidence of exotic $Z_c(4100)^-$ state.

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1. Introduction

The spectroscopy of exotic hadrons is of particular interest of the modern high-energy physics. Up to now, many new exotic states have been observed at b -factories, Tevatron and LHC experiments with masses lying on the limits of the quarkonia spectrum. They may coincide with other SU(3) colour-neutral combinations of quarks and gluons such as gg glueballs, $q\bar{q}g$ hybrids, $q\bar{q}q\bar{q}$ tetraquarks, $\bar{q}qqq$ pentaquarks *etc.*, predicted in the quark model [1]. The world's largest data sample of beauty and charm hadrons collected by LHCb during LHC Run 1 and Run 2 provides great opportunities for studying the production and properties of heavy hadrons. The LHCb experiment [2] has already collected an impressive set of results on exotic heavy-flavour states, and the present document describes some of the recent ones. The results described in this paper are based on the data samples collected by the LHCb experiment in proton–proton collision at the centre-of-mass energies of $\sqrt{s} = 7$ and 8 TeV corresponding to a total integrated luminosity of 3 fb^{-1} (Run 1) and at the centre-of-mass energy of $\sqrt{s} = 13$ TeV corresponding to a total integrated luminosity of 6 fb^{-1} (Run 2).

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2. Observation of $P_c(4312)^+$ and two-peak structure of $P_c(4450)^+$

In 2015, the LHCb Collaboration observed exotic contributions in $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay, $P_c(4380)^+$ and $P_c(4450)^+$, with a large significance [3]. A full amplitude analysis was performed, and the exotic character of the $J/\psi p$ structure around 4450 MeV was also confirmed by the model-independent approach [4]. An update on this analysis has been recently performed by the LHCb Collaboration with a significantly higher statistics of the full Run 1 and Run 2 data sample, corresponding to a total integrated luminosity of 9 fb^{-1} [5]. Improved selection criteria employing multivariate analysis for particle identification, together with a higher $pp \rightarrow b\bar{b}$ cross section at $\sqrt{s} = 13 \text{ TeV}$ in Run 2, allowed for increasing the statistics by a factor nine. The previously reported peaking structure at 4450 MeV is now resolved into two narrower structures of $P_c(4440)^+$ and $P_c(4457)^+$ states. An additional narrow peak with the mass around 4312 MeV has also been observed. A Dalitz plot in Fig. 1 (left) shows a strong $\Lambda(1520)$ resonance and two clear P_c bands. The newly observed structures are narrow, allowing to use a one-dimensional mass fit with the Breit–Wigner amplitudes. The $J/\psi p$ mass distribution in the narrow region along with the fit results is shown in Fig. 1 (right). The statistical significance of two-peak interpretation of the previously observed structure around 4450 MeV is 6.2σ , while the statistical significance of a new $P_c(4312)^+$ state is 8.2σ . Measured masses and widths of the observed three narrow pentaquark candidates are summarized in Table I. Taking into account the systematic uncertainties, the widths are consistent with the mass resolution. Therefore, upper limits on the natural widths at the 95% confidence level (C.L.) are quoted. Narrow widths and

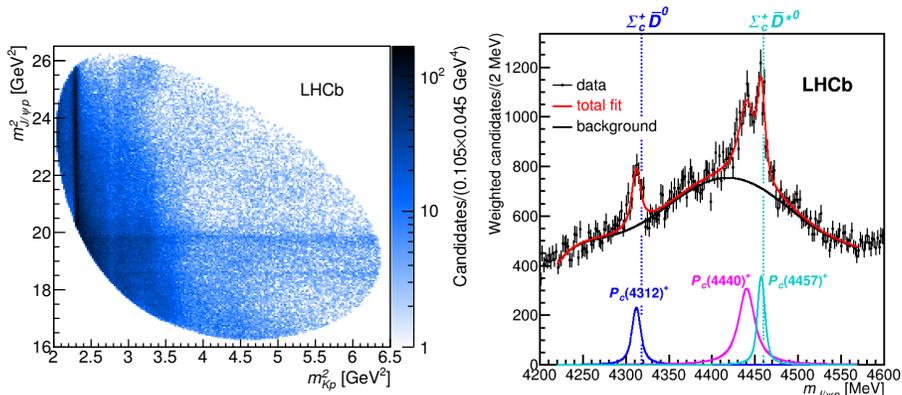


Fig. 1. Left: Dalitz plot of the $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay. Right: Fit to the $m_{J/\psi p}$ distribution with three Breit–Wigner amplitudes and a sixth-order polynomial background. Figure adopted from [5].

the proximity to the $\Sigma_c^+ \bar{D}^{*0}$ threshold suggest baryon–meson molecules [6]. $P_c(4457)^+$ state can be generated by the triangle diagram processes [7], but this is unlikely for $P_c(4312)^+$ and $P_c(4440)^+$ states.

TABLE I

Measured masses and widths of the observed pentaquark candidates with the upper limits on their natural widths. The first uncertainty is statistical and the second one systematic.

State	Mass [MeV]	Γ [MeV]	(95% C.L.) [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(< 20)

3. Observation of $B_{(s)}^0 \rightarrow J/\psi p \bar{p}$ decays

As the $B_{(s)}^0 \rightarrow J/\psi p \bar{p}$ decays are sensitive to the pentaquark searches in the $J/\psi p$ and $J/\psi \bar{p}$ components as well as to the glueball states in the $p \bar{p}$ system [8], the LHCb Collaboration searched for such decays using a data sample corresponding to 5.2 fb^{-1} of proton–proton collisions collected by the LHCb experiment at center-of-mass energies of 7 and 8 TeV (3 fb^{-1}) and 13 TeV (2.2 fb^{-1}), during the Run 1 (2011 and 2012) and Run 2 (2015 and 2016) data taking periods, respectively [9]. These decays are suppressed due to limited available phase space, as well as due to Okubo–Zweig–Iizuka or Cabibbo suppression. Such a suppression can be lifted by the pentaquark in the $J/\psi \bar{p}$ system or by the glueball in the $p \bar{p}$ system. The theoretical expectation for the branching fraction $\text{BF}(B_s^0 \rightarrow J/\psi p \bar{p})$ is at the level of 10^{-9} [10]. However, the presence of an intermediate pentaquark or glueball state can enhance the decay rate. The signal and background yields for both B^0 and B_s^0 modes were extracted from an extended maximum likelihood fit to the $J/\psi p \bar{p}$ invariant mass distribution, where signal shapes were modelled as the sum of two Crystal Ball functions, while the background by a first-order polynomial with parameters determined from the fit to data. The fit to the signal mode candidates is shown in Fig. 2. The measured branching fractions are $\text{BF}(B^0 \rightarrow J/\psi p \bar{p}) = [4.51 \pm 0.40(\text{stat.}) \pm 0.44(\text{syst.})] \times 10^{-7}$, $\text{BF}(B_s^0 \rightarrow J/\psi p \bar{p}) = [3.58 \pm 0.19(\text{stat.}) \pm 0.39(\text{syst.})] \times 10^{-6}$. The measured branching fraction for the $B^0 \rightarrow J/\psi p \bar{p}$ is consistent with theoretical predictions, while for the B_s^0 meson, the branching fraction is enhanced by two orders of magnitude with respect to the predictions without resonant contributions [10]. Nevertheless, more data are needed to perform a full Dalitz plot analysis to search for exotic states. The small available phase

space in the $B_{(s)}^0 \rightarrow J/\psi p\bar{p}$ decays allows for precise measurement of both B^0 and B_s^0 masses, *i.e.* $m_{B^0} = 5279.74 \pm 0.30(\text{stat.}) \pm 0.10(\text{syst.})$ MeV and $m_{B_s^0} = 5366.85 \pm 0.19(\text{stat.}) \pm 0.13(\text{syst.})$ MeV, being the world's best single measurements of m_{B^0} and $m_{B_s^0}$.

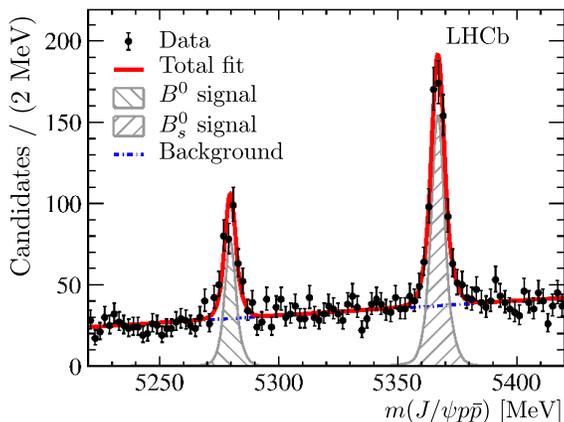


Fig. 2. Fit to the $J/\psi p\bar{p}$ invariant mass distribution of the $B_{(s)}^0$ signal modes. Figure adopted from [9].

4. Evidence of $\eta_c(1S)\pi^-$ resonance in $B^0 \rightarrow \eta_c(1S)K^+\pi^-$

The $Z_c(3900)^-$ state was first reported by the BESIII Collaboration as a charged resonance structure in the $J/\psi\pi^-$ invariant mass distribution of the $B^0 \rightarrow J/\psi K^+\pi^-$ decay [11]. It was then confirmed by Belle [12] and CLEO [13] collaborations. Some of theoretical interpretations of this state predict an as-yet-unobserved charged charmonium-like states whose dominant decay mode is to the $\eta_c(1S)\pi^-$ system [14]. Thus, searching for $\eta_c(1S)\pi^-$ resonances is important to understand the structure of exotic hadrons. A Dalitz plot analysis of $B^0 \rightarrow \eta_c(1S)K^+\pi^-$ decays was performed in LHCb using the data sample corresponding to an integrated luminosity of 4.7 fb^{-1} of proton–proton collisions collected with the LHCb detector at the centre-of-mass energies of $\sqrt{s} = 7, 8$ and 13 TeV in 2011, 2012 and 2016, respectively [15]. $\eta_c(1S)$ meson was reconstructed from the $\eta_c(1S) \rightarrow p\bar{p}$ decay mode. Around 2000 signal events were selected after the two-dimensional fit to the $m_{K^+\pi^-}$ and $m_{p\bar{p}}$ in the $\eta_c(1S)$ mass region. The background-subtracted $p\bar{p}$ mass distribution of $B^0 \rightarrow p\bar{p}K^+\pi^-$ candidates is shown in Fig. 3 (left), where two clear peaks correspond to $B^0 \rightarrow \eta_c(1S)K^+\pi^-$ and $B^0 \rightarrow J/\psi K^+\pi^-$. In the Dalitz plot analysis, the fit function included non-resonant and combinatorial background compo-

nents, resonant $K^{*0} \rightarrow K^+\pi^-$ contributions and also the additional exotic $Z_c^- \rightarrow \eta_c(1S)\pi^-$ component. The background-subtracted Dalitz plot distribution is shown in Fig. 3 (right). Only by including a charged charmonium-like resonance $Z_c^- \rightarrow \eta_c(1S)\pi^-$, a good description of data can be obtained. The significance of the exotic $Z_c(4100)^-$ resonance is more than 3σ , with the measured mass and width $m_{Z_c(4100)^-} = 4096 \pm 20(\text{stat.})_{-22}^{+18}(\text{syst.})$ MeV and $\Gamma_{Z_c(4100)^-} = 152 \pm 58(\text{stat.})_{-35}^{+60}(\text{syst.})$ MeV, respectively. This is the first evidence for an exotic state decaying into two pseudoscalars. The preferred spin-parity assignments of the state are $J^P = 0^+$ and $J^P = 1^-$, being not discriminated when taking into account systematic uncertainties.

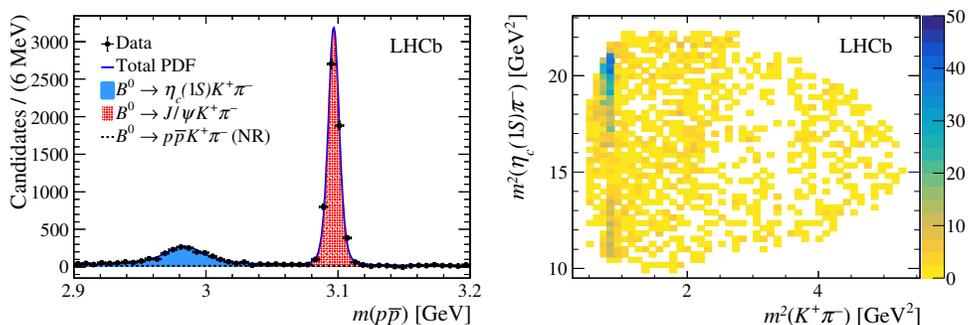


Fig. 3. Left: Background-subtracted $p\bar{p}$ mass distribution of $B^0 \rightarrow p\bar{p}K^+\pi^-$ candidates. Right: Dalitz plot of the background-subtracted $B^0 \rightarrow \eta_c(1S)K^+\pi^-$ candidates. Figure adopted from [15].

5. Summary

Many new exotic states have been discovered since the first observation of the $X(3872)$. Detailed exotic spectroscopy measurements were performed in the LHCb experiment using data samples collected during the Run 1 and Run 2 phases of the LHC running. LHCb has recently provided valuable contributions to the heavy flavour spectroscopy, such as an observation of new narrow pentaquark state $P_c(4312)^+$. Previously reported $P_c(4450)^+$ state is now resolved into two overlapping narrow peaks of $P_c(4440)^+$ and $P_c(4457)^+$. An observation of $Z_c(4100)^-$ is the first evidence for an exotic state decaying into two pseudoscalars, and the measured branching fraction for $B_s^0 \rightarrow J/\psi p\bar{p}$ is enhanced by two orders of magnitude with respect to the predictions without resonant contributions.

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