Recent LHCb results on charm and charmonium spectroscopy

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Abstract. The recent results on charm and charmonium spectroscopy obtained by the LHCb collaboration are reviewed. In particular, observation of new charmonium state in the decay modes $X(3842) \rightarrow D^0 \bar{D}^0$ and $X(3842) \rightarrow D^+ D^-$, evidence for $\eta_c(1S)\pi^-$ resonance in $B^0 \rightarrow \eta_c(1S)K^+\pi^-$ decay and observation of three narrow P_c^+ pentaquark candidates decaying to $J/\psi p$ are obtained. Also, lifetimes of Ξ_c^+ , Λ_c^+ , Ξ_c^0 and Ω_c^0 baryons are measured with high precision.

1 Introduction

Charm and charmonium physics is of particular interest of the modern high energy physics. Many of the conventional charmonium states remain unobserved, parameters of some of the known charmed and charmonium hadrons states are poorly measured and on top of that there is a number of charmonium-like states which does not fit into the conventional charmonium spectrum.

The results described in this paper are based on the data samples collected by the LHCb experiment in proton-proton (pp) collision at centre-of-mass energies $\sqrt{s} = 7$ and 8 TeV corresponding to a total integrated luminosity of 3 fb⁻¹ (Run-I) and at centre-of-mass energy $\sqrt{s} = 13$ TeV corresponding to a total integrated luminosity of 6 fb⁻¹ (Run-II).

2 Precision measurement of charmed baryon lifetimes

Different theoretical approaches, e.g. heavy quark expansion (HQE) [1–8], are used to predict heavy-flavour hadrons parameters, such as lifetime. It has been shown that due to the contribution of high-order terms the hierarchy of charmed baryon lifetime should be $\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$ [9–14]. The previous measurements support this hierarchy [15]. Lifetimes of charmed baryons are measured with the uncertainty up to 17 %, whereas for charmed mesons the corresponding precision is of the order of 1 % [15]. Therefore, precise measurement of charmed baryon lifetimes would provide an important test of the theoretical approaches.

The lifetimes of Ω_c^0 , Ξ_c^0 , Λ_c^+ and Ξ_c^+ baryons are measured by the LHCb collaboration [16, 17]. The measurement is performed using pp collision data sample corresponding to an integrated luminosity of 3.0 fb⁻¹ of Run-I. The charmed baryons are reconstructed using $\Omega_c^0 \rightarrow pK^-K^-\pi^+$, $\Xi_c^0 \rightarrow pK^-K^-\pi^+$, $\Lambda_c^+ \rightarrow pK^-\pi^+$ and $\Xi_c^+ \rightarrow pK^-\pi^+$ decays originated from

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Figure 1. The (top left) Λ_c^+ , (top right) Ξ_c^+ , (bottom left) Ξ_c^0 and (bottom right) Ω_c^0 candidates decay time distribution. The fit results along with the uncertainties due to finite simulated sample sizes are superimposed as indicated in the legend.

the semileptonic decays of beauty baryon $\Omega_b^- \rightarrow \Omega_c^0 \mu^- \bar{\nu}_\mu X$, $\Xi_b^- \rightarrow \Xi_c^0 \mu^- \bar{\nu}_\mu X$, $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu X$ and $\Xi_b^0 \rightarrow \Xi_c^+ \mu^- \bar{\nu}_\mu X$, respectively¹. The X symbol is used here and throughout to refer to any additional undetected particles. The measurement of lifetime is done relatively to that of D^+ meson which is reconstructed using $\bar{B}^0 \rightarrow D^+ \mu^- \bar{\nu}_\mu X$ decay, with $D^+ \rightarrow K^- \pi^+ \pi^+$.

The background-subtracted decay time distributions are shown for Λ_c^+ , Ξ_c^+ , Ξ_c^0 and Ω_c^0 baryons in figure 1. Each charmed baryon lifetime is obtained from a simultaneous fit of its decay time distribution and that of the D^+ meson. The lifetimes are measured to be

$$\begin{aligned}\tau_{\Omega_c^0} &= 268 \pm 24 \pm 10 \pm 2 \text{ fs}, \\ \tau_{\Xi_c^0} &= 154.5 \pm 1.7 \pm 1.6 \pm 1.0 \text{ fs}, \\ \tau_{\Lambda_c^+} &= 203.5 \pm 1.0 \pm 1.3 \pm 1.4 \text{ fs} \\ \tau_{\Xi_c^+} &= 456.8 \pm 3.5 \pm 2.9 \pm 3.1 \text{ fs},\end{aligned}$$

where the first uncertainty is statistical, the second is systematic and the third is due to the uncertainty in the lifetime of D^+ meson. These are the most precise measurements to date. The lifetimes of Λ_c^+ and Ξ_c^+ baryons are consistent with the world averages [15]. The lifetime of Ξ_c^0 baryon is about 3.3σ larger than the world average, whereas the lifetime of Ω_c^0 baryon is approximately four times larger than the current world average. With these measurements the lifetime hierarchy of charmed baryons turns to be $\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$ [16, 17].

¹The inclusion of charge-conjugated processes is implied throughout this paper.

Figure 2. (left) The open red histogram represents $D^0\bar{D}^0$ combination mass spectra, the blue dashed histogram corresponds to D^+D^- combination mass spectra. (right) The (top) $D^0\bar{D}^0$ and (bottom) D^+D^- combination mass spectra in narrow region. Different components employed in the fit are indicated in the legend.

3 Near-threshold $D\bar{D}$ spectroscopy and observation of a new charmonium state

The discovery of the first $c\bar{c}$ -resonance, J/ψ meson, was made in 1974 [18, 19]. Since then, plenty of charmonium states have been observed experimentally and their spectrum is well described within the potential models [20]. But still many of the conventional states remain unobserved. Moreover, starting from the discovery of $\chi_{c1}(3872)$ meson [21] more than twenty exotic states which do not fit into the conventional charmonium spectrum are observed. Many theoretical interpretations of their structure are under discussion [22]. To distinguish between them it is necessary to account for all of the predicted hidden-charm states, to make the precise measurements of their parameters and to continue a search for new exotic states.

Making use of the full statistics collected in the LHC Run-I and Run-II by the LHCb experiment, corresponding to an integrated luminosity of 9 fb^{-1} , the $D^0\bar{D}^0$ and D^+D^- mass spectra are investigated [23]. The D^0 and D^+ candidates are reconstructed using $D^0 \rightarrow K^- \pi^+$ and $D^+ \rightarrow K^- \pi^+ \pi^+$ decay modes. The $D^0\bar{D}^0$ and D^+D^- combination mass spectra are shown in figure 2 (left). The four peaking structures are clearly seen in the spectra. Two of the peaks correspond to the known $\psi(3770)$ and $\chi_{c2}(3930)$ charmonium states. A narrow peak close to the threshold represents partially reconstructed $\chi_{c1}(3872) \rightarrow D^{*0}\bar{D}^0$ with subsequent $D^{*0} \rightarrow D^0 \gamma$ or $D^{*0} \rightarrow D^0 \pi^0$ decay with γ or π^0 meson missing, whose shape has been determined from simulations. The narrow peak with mass about $3840 \text{ MeV}/c^2$ is identified with a new charmonium state, referred to hereafter as $X(3842)$.

Simultaneous fits to the $D^0\bar{D}^0$ and D^+D^- combinations mass distributions are performed in three overlapping mass regions in order to better parametrise the background. Fit result is shown in figure 2 (right) for one of the mass regions containing $X(3842)$ state only. Measured parameters of the new $X(3842)$ state are

$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12 \text{ MeV}/c^2,$$

$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35 \text{ MeV},$$

where the first uncertainty is statistical and the second is systematic. The mass value and the small natural width of the new state suggest the interpretation as the $\psi_3(1^3D_3)$ charmonium state with quantum numbers $J^{PC} = 3^{--}$ [24].

In addition, prompt hadroproduction of the $\chi_{c2}(3930)$ and $\psi(3770)$ charmonium states is seen for the first time and their parameters are measured to be

$$\begin{aligned} m_{\chi_{c2}(3930)} &= 3921.9 \pm 0.6 \pm 0.2 \text{ MeV}/c^2, \\ \Gamma_{\chi_{c2}(3930)} &= 36.6 \pm 1.9 \pm 0.9 \text{ MeV}, \\ m_{\psi(3770)} &= 3778.1 \pm 0.7 \pm 0.6 \text{ MeV}/c^2, \end{aligned}$$

where the first uncertainty is statistical and the second is systematic. The measured parameters of $\chi_{c2}(3930)$ state are in 2σ tension with respect to the current world average [15].

4 Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$

In 2015 LHCb collaboration reported about observation of two pentaquark $P_c(4450)^+$ and $P_c(4380)^+$ candidates decaying to $J/\psi p$ system by means of full amplitude analysis of the $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay [25]. Also the exotic hadron character of the $J/\psi p$ structure around $4450 \text{ MeV}/c^2$ was confirmed in a model-independent way [26]. There are different theoretical interpretations suggested, including tightly bound duucc $\bar{c}$ state [27–33], loosely bound molecular baryon-meson state [34–39] or peaks due to triangle-diagram processes [40–43]. Therefore, it is interesting to study the same decay using full Run-I and Run-II data sample with significantly higher statistics.

Recently, the LHCb collaboration performed an update on the analysis of $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay [44]. The analysis makes use of full Run-I and Run-II data sample corresponding to a total integrated luminosity of 9 fb^{-1} . A ninefold increase of statistics is achieved due to improved selection criteria, larger data sample and increased $pp \rightarrow b\bar{b}$ cross-section at $\sqrt{s} = 13 \text{ TeV}$ in Run-II. For the candidates with mass consistent with nominal Λ_b^0 baryon mass the $J/\psi p$ and pK^- mass spectra are investigated. In the distribution of $J/\psi p$ mass the previously reported peaking structure around $4450 \text{ MeV}/c^2$ mass is confirmed and a new narrow peak with mass around $4312 \text{ MeV}/c^2$ is found. Also, the $\Lambda^* \rightarrow pK^-$ contributions are clearly seen in the Dalitz plot which is shown in figure 3 (right).

Since the newly observed peaks are narrow, the full amplitude analysis faces computational challenges, because resolution effects should be included in the formalism which complicates the fitting procedure. On the other side, narrow peaks can not be due to reflections from Λ^* states, motivating the validity of the one-dimensional fit approach to study the $J/\psi p$ invariant mass. Contribution from Λ^* resonances is suppressed in order to reduce the background level. The $J/\psi p$ mass distribution in the narrow region along with the fit results is shown in figure 3 (left). Previously reported peak around $4450 \text{ MeV}/c^2$ mass is now resolved into two-peak structure of $P_c(4440)^+$ and $P_c(4457)^+$ states. In total, three narrow pentaquark states are observed. The statistical significance of two-peak interpretation of previously stated $P_c(4450)^+$ is 5.4σ . The statistical significance of a new $P_c(4312)^+$ state is 7.3σ . Mass and width of the pentaquark candidates are measured. Taking into account the systematic uncertainties the widths are consistent with the mass resolution. Hence, upper limits on the natural widths at the 95 % confidence level (CL) are obtained. The fit results along with the upper limits on the widths are shown in table 1.

Figure 3. (left) Distribution of J/ψ p mass for the $\Lambda_b^0 \rightarrow J/\psi p K^-$ candidates, the fit results are superimposed and indicated in the legend. (right) Dalitz plot of the $\Lambda_b^0 \rightarrow J/\psi p K^-$ candidates.

Table 1. Measured parameters of the P_c^+ pentaquark candidates along with the upper limits on their natural widths. The first uncertainty is statistical and the second is systematic.

State	M [MeV/ <i>c</i> ²]	Γ [MeV]	95% CL [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

5 Evidence for $\eta_c(1S)\pi^-$ resonance in $B^0 \rightarrow \eta_c(1S)K^+\pi^-$

The exotic $Z_c(3900)^-$ state decaying into $J/\psi \pi^-$ system has been observed by BESIII collaboration [45] and confirmed by Belle [46] and CLEO [47] collaborations. There are different theoretical interpretations of this state, including those predicting an as-yet-unobserved charged charmonium-like states with quantum numbers allowing the decay to $\eta_c(1S)\pi^-$ system [48–52]. Therefore, observation of the charmonium-like resonance decaying to $\eta_c(1S)\pi^-$ would provide an important input to the understanding of the exotic hadrons structure.

Using a data sample collected at centre-of-mass energies of 7, 8 and 13 TeV, corresponding to an integrated luminosity of 4.7 fb⁻¹, the LHCb collaboration performed the Dalitz plot analysis of the $B^0 \rightarrow \eta_c(1S)K^+\pi^-$ decay [53]. The $\eta_c(1S)$ meson is reconstructed using the $\eta_c(1S) \rightarrow p\bar{p}$ decay mode. The background-subtracted $p\bar{p}$ mass distribution of $B^0 \rightarrow p\bar{p}K^+\pi^-$ candidates is shown in figure 4 (left). Two clear peaks are seen in the distribution, which correspond to $B^0 \rightarrow \eta_c(1S)K^+\pi^-$ and $B^0 \rightarrow J/\psi K^+\pi^-$ decays. The latter decay is used as a normalisation channel to measure branching fraction ratio which is found to be

$$\frac{\mathcal{B}(B^0 \rightarrow \eta_c(1S)K^+\pi^-)}{\mathcal{B}(B^0 \rightarrow J/\psi K^+\pi^-)} = 0.357 \pm 0.015 \pm 0.008,$$

where the first uncertainty is statistical and the second is systematic. For the further analysis the selected $B^0 \rightarrow \eta_c(1S)K^+\pi^-$ candidates are used to perform the Dalitz plot analysis. The fit function includes non-resonant and combinatorial background components, resonant $K^{*0} \rightarrow K^+\pi^-$ contributions and also the additional exotic $Z_c^- \rightarrow \eta_c(1S)\pi^-$ component is included. The background-subtracted Dalitz plot distribution is show in figure 4 (right). It is found that inclusion of only K^{*0} resonances in the fit model does not provide a good description of data. When including a charged charmonium-like resonance $Z_c^- \rightarrow \eta_c(1S)\pi^-$ the

Figure 4. (left) Background-subtracted $p\bar{p}$ mass distribution for $B^0 \rightarrow p\bar{p}K^+\pi^-$ candidates. The different components employed in the fit are indicated in the legend. (right) Dalitz plot of the background-subtracted $B^0 \rightarrow \eta_c(1S)K^+\pi^-$ candidates.

satisfactory description of the data is obtained. The measured parameters of the state are

$$\begin{aligned} m_{Z_c(4100)^-} &= 4096 \pm 20^{+18}_{-22} \text{ MeV}/c^2, \\ \Gamma_{Z_c(4100)^-} &= 152 \pm 58^{+60}_{-35} \text{ MeV}, \end{aligned}$$

where the first uncertainty is statistical and the second is systematic. The significance of the exotic $Z_c(4100)^-$ resonance is more than three standard deviations. Therefore, this is the first evidence for an exotic state decaying to two pseudoscalars. The preferred spin-parity assignments of the state are $J^P = 0^+$ and $J^P = 1^-$, which are not discriminated when taking into account systematic uncertainties [53].

6 Conclusion

Rich contribution to the knowledge of charm and charmonium spectroscopy is provided by the LHCb experiment. Recently, the lifetime of four charmed baryons are measured with high precision. New charmonium state $X(3842)$ is observed. The measured mass and width of this state favour the interpretation as the $\psi_3(1^3D_3)$ charmonium state with $J^{PC} = 3^{--}$. A new narrow pentaquark state $P_c(4312)^+$ is observed. Previously reported $P_c(4450)^+$ state is now resolved into two overlapping narrow peaks of $P_c(4440)^+$ and $P_c(4457)^+$ exotic baryons. Evidence for $\eta_c(1S)\pi^-$ resonance is obtained, which makes it the first evidence for an exotic state decaying to two pseudoscalars.

Three of the reviewed analyses are based only on Run-I data sample or in addition with part of Run-II. Many more spectroscopic measurements from LHCb are underway. In particular, the analyses of the full Run-I and Run-II data samples will provide an improvement of precision of current measurements and might also lead to a new unexpected results.

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