Spectroscopy in beauty decays at the LHCb experiment

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Abstract

The beauty hadron decays is unique laboratory to study charmonium and charmonium-like states, such as the $\chi_{c1}(3872)$ meson, other exotic states and the tensor $D$-wave $\psi_2(3823)$ states. However the nature of many exotic charmonium-like candidates are still unknown. The most recent LHCb results related to $b$-hadron decays to charmonium states and obtained using large data samples collected during the Run 1 and Run 2 periods are presented. This includes the most precise determination of the mass and width of the $\chi_{c1}(3872)$ state using the $B^+ \rightarrow J/\psi \pi^+ \pi^- K^+$ decays, observation of a resonant structure denoted as $X(4740)$ in the $J/\psi \phi$ mass spectrum from $B^0 \rightarrow J/\psi \pi^+ \pi^- K^+ K^-$ decays and the precise measurement of the $B^0_s$ meson mass.

Presented at XXVII Cracow EPIPHANY Conference on future of particle physics

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1 Introduction

In the last two decades a plethora of new results in the charmonium spectra have been obtained in the beauty decays studies. A lot of the conventional and exotic charmonium resonances are observed such as $\chi_{c1}(3872)$, $\chi_{c1}(4700)$ and $P_{c}(4312)^+$ and conventional $\psi_{2}(3823)$ state. The LHCb experiment has collected high statistics during Run 1 and Run 2 periods that allows us to perform many precise measurements of the branching fractions of $B$- and $B_{s}^{0}$-meson decays and searches for new decays and states. The results described below are based on the data samples collected by the LHCb experiment in proton-proton (pp) collisions at the Large Hadron Collider from 2011 to 2018 with centre-of-mass energies of $\sqrt{s} = 7, 8$ and 13 TeV.

2 Study of the $B^{+} \rightarrow J/\psi \pi^{+}\pi^{-}K^{+}K^{-}$ decays

Candidates of the $B_{s}^{0} \rightarrow J/\psi \pi^{+}\pi^{-}K^{+}K^{-}$ decays are reconstructed via $J/\psi \rightarrow \mu^{-}\mu^{+}$ and selected using based on kinematics, particle identification and topology [1]. The yields of $B_{s}^{0} \rightarrow J/\psi \pi^{+}\pi^{-}K^{+}K^{-}$ decays via the $B_{s}^{0} \rightarrow \psi(2S)\phi$ and $B_{s}^{0} \rightarrow \chi_{c1}(3872)\phi$ and $B_{s}^{0} \rightarrow J/\psi K^{*0}K^{0}$ chains are determined using three-dimensional unbinned extended maximum-likelihood fits. The observed signal yield for the $B_{s}^{0} \rightarrow \chi_{c1}(3872)\phi$ decays is $154 \pm 15$ which corresponds to a statistical significance more than 10 standard deviations. The fit to the mass distribution for the signal channel is shown in figure [1].

![Figure 1: Distributions of the (left) $J/\psi \pi^{+}\pi^{-}K^{+}K^{-}$ and (right) $J/\psi \pi^{+}\pi^{-}$ mass for selected $B_{s}^{0} \rightarrow \chi_{c1}(3872)\phi$ candidates (points with error bars) [1]. The red filled area corresponds to the $B_{s}^{0} \rightarrow \chi_{c1}(3872)\phi$ signal. The orange line is the total fit.](image)

In addition, the decays $B_{s}^{0} \rightarrow \chi_{c1}(3872)K^{+}K^{-}$ where the $K^{+}K^{-}$ pair does not originate from a $\phi$ meson, is studied using a two-dimensional unbinned extended maximum-likelihood fit which is performed to corresponding mass distributions. The observed yield of signal decays is $378 \pm 33$, that is significantly larger than the yield of the $B_{s}^{0} \rightarrow \chi_{c1}(3872)\phi$ decays, indicating a significant $B_{s}^{0} \rightarrow \chi_{c1}(3872)K^{+}K^{-}$ contribution. A narrow $\phi$ component can be separated from the non-$\phi$ channels using an unbinned maximum-likelihood fit to the background-subtracted and efficiency-corrected $K^{+}K^{-}$ mass distribution. The fraction of the $B_{s}^{0} \rightarrow \chi_{c1}(3872)K^{+}K^{-}$ signal component is found to be $(38.9 \pm 4.9)\%$. Using the obtained signal yields and fractions for described channels and corresponding efficiency
Yields/(15 MeV/c²) vs. $m_{K^+K^-}$

Figure 2: Background-subtracted $K^+K^-$ mass distribution for selected $B^0_s \rightarrow \chi_{c1}(3872)K^+K^-$ candidates (points with error bars) \[1\]. The orange line is the total fit.

ratios the following branching fractions are calculated:

\[
\frac{B_{B^0_s \rightarrow \chi_{c1}(3872)\phi} \times B_{\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-} }{B_{B^0_s \rightarrow \psi(2S)\phi} \times B_{\psi(2S) \rightarrow J/\psi\pi^+\pi^-}} = (2.42 \pm 0.23 \pm 0.07) \times 10^{-2},
\]

\[
\frac{B_{B^0_s \rightarrow J/\psi K^0\pi^0} \times B_{K^0 \rightarrow K^+K^-} }{B_{B^0_s \rightarrow \psi(2S)\phi} \times B_{\psi(2S) \rightarrow J/\psi\pi^+\pi^-}} = 1.22 \pm 0.03 \pm 0.04,
\]

\[
\frac{B_{B^0_s \rightarrow \chi_{c1}(3872)(K^+K^-)_{non-\phi}} }{B_{B^0_s \rightarrow \chi_{c1}(3872)\phi} \times B_{\phi \rightarrow K^+K^-}} = 1.57 \pm 0.32 \pm 0.12,
\]

where the first uncertainty is statistical and the second is systematic. The result for $B^0_s \rightarrow \chi_{c1}(3872)\phi$ decay is found to be in a good agreement with the result by the CMS collaboration \[2\] but is more precise.

Four tetraquark candidates have been observed by the LHCb collaboration using an amplitude analysis of the $B^+ \rightarrow J/\psi\phi K^+$ decays \[3,4\]. A search of the exotic states in the $J/\psi\phi$ spectrum is performed using the $B^0_s \rightarrow J/\psi\pi^+\pi^-\phi$ decays. The $B^0_s \rightarrow J/\psi\pi^+\pi^-\phi$ candidates are determined with two-dimensional unbinned extended maximum-likelihood fit to the $J/\psi\pi^+\pi^-K^+K^-$ and $K^+K^-$ mass distributions.

The background-subtracted $J/\psi\phi$ mass spectrum of $B^0_s \rightarrow J/\psi\pi^+\pi^-\phi$ candidates are shown in figure \[3\]. It shows a prominent structure at a mass around 4.74 GeV/c². Since the regions of $\psi(2S)$ and $\chi_{c1}(3872)$ resonance masses are vetoed and no sizeable contributions from decays via other narrow charmonium states are observed in the background-subtracted $J/\psi\pi^+\pi^-$ mass spectrum, this structure cannot be explained by cross-feed from the $J/\psi\pi^+\pi^-$ mass spectrum. Moreover no such structure is seen in non-$\phi$ region of the $K^+K^-$ mass. However the $\phi\pi^+\pi^-$ spectrum exhibits significant deviations from the phase-space distribution, indicating possible presence of excited $\phi$ states, referred to as $\phi^*$ states hereafter. The decays $B^0 \rightarrow J/\psi\phi^*$ via intermediate $\phi(1680)$, $\phi(1850)$ or $\phi(2170)$ states \[3\] are studied using simulated samples and no peaking structures are observed. Under the assumption that the observed structure, referred to as $X(4740)$
Figure 3: Background-subtracted J/ψφ mass distribution for the selected B^0_s → J/ψ π^+ π^- φ signal candidates (points with error bars). The red filled area corresponds to the B^0_s → X(4740) π^+ π^- signal. The orange line is the total fit.

hereafter, has a resonant nature, its mass and width are determined through an unbinned extended maximum-likelihood fit. The fit result is superimposed in figure 3. The obtained signal yield is 175 ± 39 and corresponds to a statistical significance above 5.3 standard deviations. The mass and width for the X(4740) state are found to be

$$m_{X(4740)} = 4741 \pm 6 \pm 6 \text{ GeV}/c^2,$$

$$\Gamma_{X(4740)} = 53 \pm 15 \pm 11 \text{ MeV}.$$ 

The observed parameters qualitatively agree with those of the χc1(4700) state observed by the LHCb collaboration in references [3,4]. The obtained mass also agrees with the one expected for the 2^{++} csc barρ tetraquark state [6].

The B^0_s decays to the ψ(2S)K^+ K^- final states characterize the relatively small energy release allowing precise measurement of the B^0_s meson mass. The mass of the B^0_s meson is determined from an unbinned extended maximum-likelihood fit to the ψ(2S)K^+ K^- mass distribution. The improvement in the B^0_s mass resolution and significant decrease of the systematic uncertainties is achieved by imposing a constraint on the reconstructed mass of the J/ψ π^+ π^- system to the known ψ(2S) meson mass [5]. The measured value of the B^0_s meson mass is found to be

$$m_{B^0_s} = 5366.98 \pm 0.07 \pm 0.13 \text{ MeV}/c^2,$$

that is the most precise single measurement of this quantity.

3 Study of the B^+ → J/ψ π^+ π^- K^+ decays

The search of the spin-2 component of the D-wave charmonium triplet, the ψ_2(3823) state, is performed with B^+ → J/ψ π^+ π^- K^+ decays [7,8]. To extract the B^+ candidates, a
A study of the Breit–Wigner mass of the $\chi_\psi J$ structure, denoted as the $X(4740)$ state, in the $J/\psi\pi\pi$ mass spectrum.

The results include the observation of the non-zero width of the $\chi_\psi J$ state. The most precise single measurement of the $B^+ \rightarrow \chi_\psi J K^+$ signal, 4230 ± 70, allows for the precise measurement of the mass and width of the $X_{c1}(3872)$ state. For the first time the non-zero Breit–Wigner width is observed for the $X_{c1}(3872)$ state with significance more than 5 standard deviations. Large signal yield for the $B^+ \rightarrow \psi(2S)K^+$ signal is determined to be $137 \pm 26$ which correspond to statistical significance above 5.1 standard deviations. Large signal yield for the $B^+ \rightarrow \psi(2S)K^+$ signal, 4230 ± 70, allows for the precise measurement of the mass and width of the $X_{c1}(3872)$ state. For the first time the non-zero Breit–Wigner width is observed for the $X_{c1}(3872)$ state with significance more than 5 standard deviations and its measured value is:

$$\Gamma_{X_{c1}(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21 \text{MeV}. $$

The upper limit for the Breit–Wigner width of $\psi_2(3823)$ is improved and its value is set to be $\Gamma_{\psi_2(3823)} < 5.2 \ (6.6) \text{MeV}$, for 90 (95)% C.L. The mass splitting between the states are found to be

$$\delta m_{X_{c1}(3872)} = 47.50 \pm 0.53 \pm 0.13 \text{MeV}/c^2, $$
$$\delta m_{\psi_2(3823)} = 137.98 \pm 0.53 \pm 0.14 \text{MeV}/c^2, $$
$$\delta m_{\psi(2S)} = 185.49 \pm 0.06 \pm 0.03 \text{MeV}/c^2. $$

The results Breit–Wigner mass of the $X_{c1}(3872)$ state are in good agreement with an independent analysis of inclusive $b \rightarrow X_{c1}(3872)\chi$ decays [9]. The binding energy of the $X_{c1}(3872)$ state is derived from the mass splitting and its value is found to be $\delta E = 0.12 \pm 0.13 \text{MeV}$. It is consistent with zero within uncertainties, that are currently dominated by the uncertainty for the neutral and charged kaon mass measurements [10][11].

The measured yields of the $B^+ \rightarrow X_{c1}(3872)K^+$, $B^+ \rightarrow \psi_2(3823)K^+$ and $B^+ \rightarrow \psi(2S)K^+$ signal decays allow for a precise determination of the ratios of the branching fractions:

$$\frac{B_{B^+ \rightarrow X_{c1}(3872)K^+} \times B_{\psi_2(3823) \rightarrow J/\psi \pi^+ \pi^-}}{B_{B^+ \rightarrow \psi_2(3823)K^+} \times B_{X_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-}} = (3.56 \pm 0.67 \pm 0.11) \times 10^{-2}, $$
$$\frac{B_{B^+ \rightarrow \psi_2(3823)K^+} \times B_{\psi_2(3823) \rightarrow J/\psi \pi^+ \pi^-}}{B_{B^+ \rightarrow \psi(2S)K^+} \times B_{\psi(2S) \rightarrow J/\psi \pi^+ \pi^-}} = (1.31 \pm 0.25 \pm 0.04) \times 10^{-3}, $$
$$\frac{B_{B^+ \rightarrow \psi(2S)K^+} \times B_{\psi(2S) \rightarrow J/\psi \pi^+ \pi^-}}{B_{B^+ \rightarrow X_{c1}(3872)K^+} \times B_{X_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-}} = (3.69 \pm 0.07 \pm 0.06) \times 10^{-2}. $$

## 4 Conclusion

A study of $b$-meson decays $B^+ \rightarrow J/\psi \pi^+ \pi^- K^+$ and $B_s^0 \rightarrow J/\psi \pi^+ \pi^- K^+ K^-$ is made using the Run 1 and Run 2 data, collected with the LHCb detector [1][7]. The reported results include the observation of the non-zero width of the $X_{c1}(3872)$ state; the most precise measurement of the masses of the $X_{c1}(3872)$ and $\psi_2(3823)$ states; the most precise measurement of several ratios of branching fractions of the $B^+$ and $B_s^0$ mesons decays; the most precise single measurement of the $B_s^0$ meson mass and the observation of a new structure, denoted as the $X(4740)$ state, in the $J/\psi \phi$ mass spectrum.
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