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SPECTROSCOPY IN BEAUTY DECAYS AT THE LHCb EXPERIMENT*

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The beauty hadron decays provide a 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 is 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 $B^+ \to J/\psi\pi^+\pi^-K^+$ decays, observation of a resonant structure denoted as $X(4740)$ in the $J/\psi\phi$ mass spectrum from $B^0_s \to J/\psi\pi^+\pi^-K^+K^-$ decays and the precise measurement of the B^0_s meson mass.

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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 $\mathrm{P}_c(4312)^+$, and the 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^0_s-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 the centre-of-mass energies of $\sqrt{s} = 7, 8$ and 13 TeV.

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2. Study of the $B^+ \to J/\psi\pi^+\pi^-K^+K^-$ decays

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

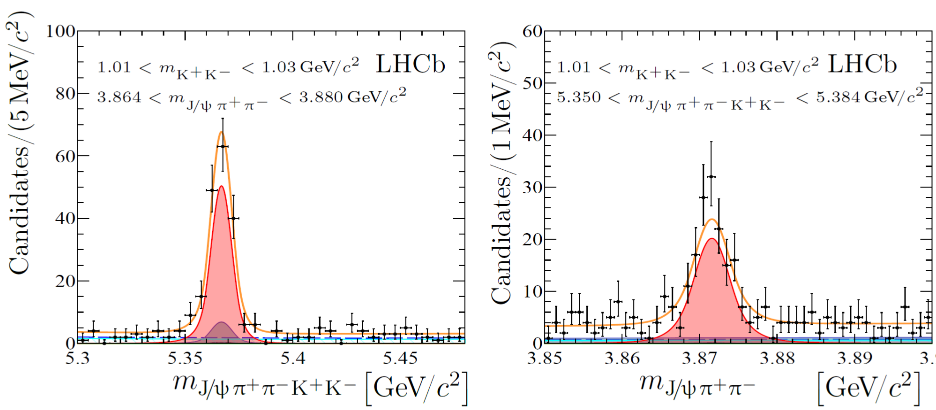

Fig. 1. (Colour on-line) Distributions of the (left) $J/\psi\pi^+\pi^-K^+K^-$ and (right) $J/\psi\pi^+\pi^-$ mass for selected $B_s^0 \to \chi_{c1}(3872)\phi$ candidates (points with error bars) [1]. The light grey/red filled area corresponds to the $B_s^0 \to \chi_{c1}(3872)\phi$ signal. The grey/orange line is the total fit.

In addition, the $B_s^0 \to \chi_{c1}(3872)K^+K^-$ decays where the K^+K^- pair does not originate from a ϕ 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 ± 33, that is significantly larger than the yield of the $B_s^0 \to \chi_{c1}(3872)\phi$ decays, indicating a significant $B_s^0 \to \chi_{c1}(3872)K^+K^-$ contribution. A narrow ϕ component can be separated from the non-ϕ components using an unbinned maximum-likelihood fit to the background-subtracted and efficiency-corrected K^+K^- mass distribution. The fit result is shown in figure 2. The fraction of the $B_s^0 \to \chi_{c1}(3872)K^+K^-$ signal component is found to be $(38.9 \pm 4.9)\%$. Using the obtained signal yields and fractions for described channels and corresponding efficiency ratios, the following branching fractions are calculated:

$$\frac{\mathcal{B}_{B_s^0\to\chi_{c1}(3872)\phi}\times\mathcal{B}_{\chi_{c1}(3872)\to J/\psi\pi^+\pi^-}}{\mathcal{B}_{B_s^0\to\psi(2S)\phi}\times\mathcal{B}_{\psi(2S)\to J/\psi\pi^+\pi^-}} = (2.42\pm0.23\pm0.07)\times10^{-2}\,,$$

$$\frac{\mathcal{B}_{B_s^0\to J/\psi K^{*0}\bar{K}^{*0}}\times\mathcal{B}^2_{K^{*0}\to K^+\pi^-}}{\mathcal{B}_{B_s^0\to\psi(2S)\phi}\times\mathcal{B}_{\psi(2S)\to J/\psi\pi^+\pi^-}\times\mathcal{B}_{\phi\to K^+K^-}} = 1.22\pm0.03\pm0.04\,,$$

$$\frac{\mathcal{B}_{B_s^0\to\chi_{c1}(3872)(K^+K^-)_{\text{non-}\phi}}}{\mathcal{B}_{B_s^0\to\chi_{c1}(3872)\phi}\times\mathcal{B}_{\phi\to K^+K^-}} = 1.57\pm0.32\pm0.12\,,$$

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

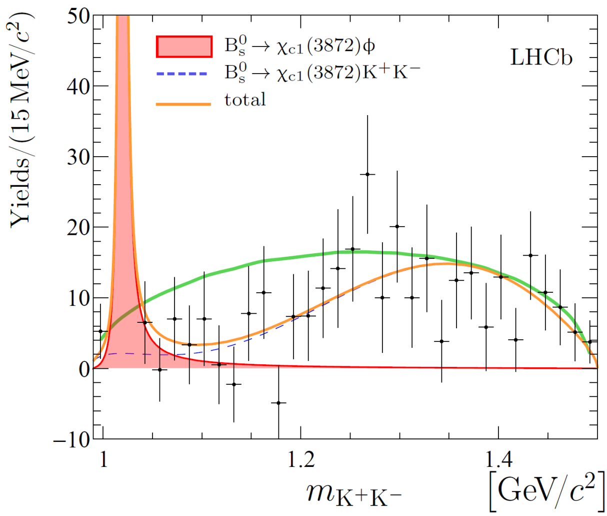

Fig. 2. (Colour on-line) Background-subtracted K^+K^- mass distribution for selected $B_s^0\to\chi_{c1}(3872)K^+K^-$ candidates (points with error bars) [1]. The grey/orange line is the total fit.

Four tetraquark candidates have been observed by the LHCb Collaboration using an amplitude analysis of the $B^+\to J/\psi\phi K^+$ decays [3, 4]. A search of the exotic states in the $J/\psi\phi$ spectrum is performed using the $B_s^0\to J/\psi\pi^+\pi^-\phi$ decays. The $B_s^0\to J/\psi\pi^+\pi^-\phi$ 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 $B_s^0\to J/\psi\pi^+\pi^-\phi$ candidates are shown in figure 3. It shows a prominent structure at a mass around 4.74 GeV/c^2. Since the regions of $\psi(2S)$ and $\chi_{c1}(3872)$ resonance masses are vetoed and no sizeable contributions from decays via other narrow

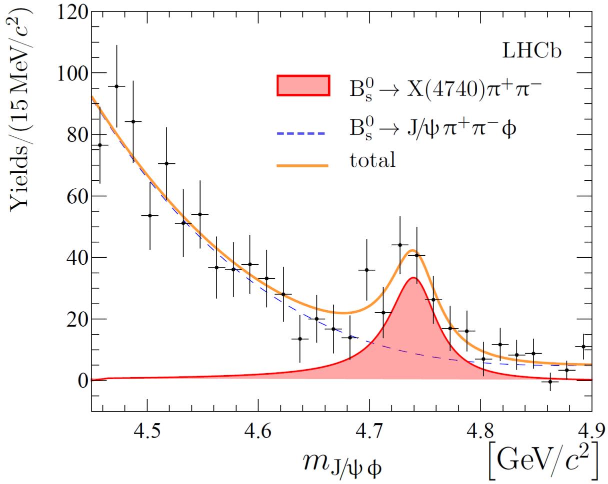

Fig. 3. (Colour on-line) Background-subtracted $J/\psi\phi$ mass distribution for the selected $B_s^0 \to J/\psi\pi^+\pi^-\phi$ signal candidates (points with error bars) [1]. The grey/red filled area corresponds to the $B_s^0 \to X(4740)\pi^+\pi^-$ signal. The grey/orange line is the total fit.

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-ϕ 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 ϕ states, referred to as ϕ^* states hereafter. The $B_s^0 \to J/\psi\phi^*$ decays via intermediate $\phi(1680)$, $\phi(1850)$ or $\phi(2170)$ states [5] are studied using simulated samples and no peaking structures are observed. Under the assumption that the observed structure, hereafter referred to as $X(4740)$, 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

$$\begin{aligned} m_{X(4740)} &= 4741 \pm 6 \pm 6 \text{ GeV}/c^2\,, \\ \mathit{\Gamma}_{X(4740)} &= 53 \pm 15 \pm 11 \text{ MeV}\,. \end{aligned}$$

The observed parameters qualitatively agree with those of the $\chi_{c1}(4700)$ state observed by the LHCb Collaboration in references [3, 4]. The obtained mass also agrees with the one expected for the 2^{++} $cs\bar{c}\bar{s}$ tetraquark state [6].

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

$$m_{B_s^0} = 5366.98 \pm 0.07 \pm 0.13 \text{ MeV}/c^2 \,, \tag{1}$$

that is the most precise single measurement of this quantity.

3. Study of the $B^+ \to J/\psi\pi^+\pi^-K^+$ decays

The search of the spin-2 component of the D-wave charmonium triplet, the $\psi_2(3823)$ state, is performed with $B^+ \to J/\psi\pi^+\pi^-K^+$ decays [7, 8]. To extract the B^+ candidates, a multivariate classifier algorithm based on a decision tree with gradient boosting is applied. For signal yield determinations of the $B^+ \to (\psi(2S) \to J/\psi\pi^+\pi^-)K^+$, $B^+ \to (\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)K^+$ and $B^+ \to (\psi_2(3823) \to J/\psi\pi^+\pi^-)K^+$, a simultaneous unbinned extended maximum-likelihood fit to the $m_{J/\psi\pi^+\pi^-K^+}$ and $m_{J/\psi\pi^+\pi^-}$ variables is performed. The signal yield for the $B^+ \to \psi_2(3823)K^+$ decays is determined to be 137 ± 26 which corresponds to statistical significance above 5.1 standard deviations. Large signal yield for the $B^+ \to \psi(2S)K^+$ signal, 4230 ± 70, allows for the precise measurement of the mass and width of the $\chi_{c1}(3872)$ state. For the first time, the non-zero Breit–Wigner width is observed for the $\chi_{c1}(3872)$ state with significance of more than 5 standard deviations and its measured value is

$$\mathit{\Gamma}_{\chi_{c1}(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21 \text{ MeV} \,. \tag{2}$$

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

$$\begin{aligned}
\delta m^{\chi_{c1}(3872)}_{\psi_2(3823)} &= 47.50 \pm 0.53 \pm 0.13 \text{ MeV}/c^2 \,, \\
\delta m^{\psi_2(3823)}_{\psi(2S)} &= 137.98 \pm 0.53 \pm 0.14 \text{ MeV}/c^2 \,, \\
\delta m^{\chi_{c1}(3872)}_{\psi(2S)} &= 185.49 \pm 0.06 \pm 0.03 \text{ MeV}/c^2 \,.
\end{aligned}$$

The results for Breit–Wigner mass of the $\chi_{c1}(3872)$ state are in good agreement with an independent analysis of inclusive $b \to \chi_{c1}(3872)X$ decays [9]. The binding energy of the $\chi_{c1}(3872)$ state is derived from the mass splitting and its value is found to be $\delta E = 0.12 \pm 0.13$ 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 $B^+ \to \chi_{c1}(3872)K^+$, $B^+ \to \psi_2(3823)K^+$ and $B^+ \to \psi(2S)K^+$ signal decays allow for a precise determination of the ratios of the branching fractions

$$\frac{\mathcal{B}_{B^+\to\psi_2(3823)K^+} \times \mathcal{B}_{\psi_2(3823)\to J/\psi\pi^+\pi^-}}{\mathcal{B}_{B^+\to\chi_{c1}(3872)K^+} \times \mathcal{B}_{\chi_{c1}(3872)\to J/\psi\pi^+\pi^-}} = (3.56 \pm 0.67 \pm 0.11) \times 10^{-2}\,,$$

$$\frac{\mathcal{B}_{B^+\to\psi_2(3823)K^+} \times \mathcal{B}_{\psi_2(3823)\to J/\psi\pi^+\pi^-}}{\mathcal{B}_{B^+\to\psi(2S)K^+} \times \mathcal{B}_{\psi(2S)\to J/\psi\pi^+\pi^-}} = (1.31 \pm 0.25 \pm 0.04) \times 10^{-3}\,,$$

$$\frac{\mathcal{B}_{B^+\to\chi_{c1}(3872)K^+} \times \mathcal{B}_{\chi_{c1}(3872)\to J/\psi\pi^+\pi^-}}{\mathcal{B}_{B^+\to\psi(2S)K^+} \times \mathcal{B}_{\psi(2S)\to J/\psi\pi^+\pi^-}} = (3.69 \pm 0.07 \pm 0.06) \times 10^{-2}\,.$$

4. Conclusion

A study of b-meson $B^+ \to J/\psi\pi^+\pi^-K^+$ and $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays 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 $\chi_{c1}(3872)$ state; the most precise measurement of the masses of the $\chi_{c1}(3872)$ 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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