Beauty meson decays to charmonium-like states at LHCb

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Abstract

The decays $B_0^s \to J/\psi \pi^+ \pi^- K^+ K^-$ are studied using a data set corresponding to an integrated luminosity of 9 fb$^{-1}$, collected with the LHCb detector in proton-proton collisions at centre-of-mass energies of 7, 8 and 13 TeV. The decays $B_0^s \to J/\psi K^0\bar{K}^0$ and $B_0^s \to \chi_{c1}(3872) K^+ K^-$, where the $K^+ K^-$ pair does not originate from a $\phi$ meson, are observed for the first time. Precise measurements of the ratios of branching fractions between intermediate $\chi_{c1}(3872)\phi$, $J/\psi K^0\bar{K}^0$, $\psi(2S)\phi$ and $\chi_{c1}(3872) K^+ K^-$ states are reported. A structure, denoted as $X(4740)$, is observed in the $J/\psi \phi$ mass spectrum with a significance in excess of 5.3 standard deviation. In addition, the most precise single measurement of the mass of the $B_0^s$ meson is performed.

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1 Introduction

Decays of beauty hadrons to final states with charmonia provide a unique laboratory to study the properties of charmonia and charmonium-like states. A plethora of new charmonium-like states has been observed in the decays of beauty mesons, such as the $\chi_{c1}(3872)$ meson and numerous tetraquark candidates. The nature of many exotic charmonium-like candidates remains unclear. A comparison of production rates with respect to those of conventional charmonium states in decays of beauty hadrons can shed light on their production mechanisms.

The reported results are based on the data samples collected by the LHCb experiment in proton-proton (pp) collisions at centre-of-mass energies $\sqrt{s} = 7, 8$ and $13$ TeV between 2011 and 2018.

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

Candidate $B^+ \rightarrow J/\psi \pi^+\pi^- K^+$ decays are reconstructed using the $J/\psi \rightarrow \mu^+\mu^-$ decay mode. A loose pre-selection is applied, followed by a multivariate classifier based on a decision tree with gradient boosting [12].

![Figure 1: Distributions of the (left) $J/\psi \pi^+\pi^- K^+$ and (right) $J/\psi \pi^+\pi^-$ mass for the selected $B^+ \rightarrow \psi_2(3823)K^+$ candidates (points with error bars).](image)

The yields for the $B^+ \rightarrow J/\psi \pi^+\pi^- K^+$ decays via intermediate $\chi_{c1}(3872) \rightarrow J/\psi \pi^+\pi^-$, $\psi_2(3823) \rightarrow J/\psi \pi^+\pi^-$ and $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ chains are determined using a simultaneous unbinned extended maximum-likelihood fit to the $J/\psi \pi^+\pi^- K^+$ mass and the $J/\psi \pi^+\pi^-$ mass distributions. The fit is performed in the three non-overlapping regions around the $\psi_2(3823)$, $\chi_{c1}(3872)$ and $\psi(2S)$ masses. To improve the resolution on the $J/\psi \pi^+\pi^-$ mass and to eliminate a small correlation between $m_{J/\psi \pi^+\pi^- K^+}$ and $m_{J/\psi \pi^+\pi^-}$ variables, the $m_{J/\psi \pi^+\pi^-}$ variable is computed using a kinematic fit that constrains the mass of the $B^+$ candidate to its known value [14]. The signal yields are determined to be $137 \pm 26$ events for the $B^+ \rightarrow \psi_2(3823)K^+$ decay which correspond to statistical significance above $5.1\sigma$. The fit to the mass distribution for the signal channel are shown in figure [1]. Also the significant signal yield is observed for the $B^+ \rightarrow \chi_{c1}(3872)K^+$ decay $4230 \pm 70$ events which
allows the precise determination of the parameters of the $\chi_{c1}(3872)$ state, in particular for the first time the non-zero width for the $\chi_{c1}(3872)$ state is observed with significance more than 5 standard deviations

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

where the first uncertainty is statistical and the second is systematic. The value of the Breit–Wigner width agrees well with the value from the analysis of a large sample of $\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-$ decays from the inclusive decays of beauty hadrons [15].

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

$$\frac{B_{B^+ \rightarrow \psi(2S)K^+} \times B_{\psi(2S) \rightarrow J/\psi \pi^+ \pi^-}}{B_{B^+ \rightarrow \chi_{c1}(3872)K^+} \times B_{\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-}} = (3.56 \pm 0.67 \pm 0.11) \times 10^{-2},$$

$$\frac{B_{B^+ \rightarrow \psi(2S)K^+} \times B_{\psi(2S) \rightarrow J/\psi \pi^+ \pi^-}}{B_{B^+ \rightarrow \chi_{c1}(3872)K^+} \times B_{\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-}} = (1.31 \pm 0.25 \pm 0.04) \times 10^{-3},$$

$$\frac{B_{B^+ \rightarrow \psi(2S)K^+} \times B_{\psi(2S) \rightarrow J/\psi \pi^+ \pi^-}}{B_{B^+ \rightarrow \psi(2S)K^+} \times B_{\psi(2S) \rightarrow J/\psi \pi^+ \pi^-}} = (3.69 \pm 0.07 \pm 0.06) \times 10^{-2}.$$

### 3 Study of the $B_s^0 \rightarrow J/\psi \pi^+ \pi^- K^+ K^-$ decays

The $B_s^0 \rightarrow J/\psi \pi^+ \pi^- K^+ K^-$ decays are reconstructed using selection criteria based on kinematics, particle identification and topology [16]. The yields of $B_s^0 \rightarrow J/\psi \pi^+ \pi^- K^+ K^-$ decays via intermediate $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$ and $\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-$ chains are determined using a three-dimensional unbinned extended maximum-likelihood fit to the $J/\psi \pi^+ \pi^- K^+ K^-$, $J/\psi \pi^+ \pi^-$ and $K^+ K^-$ mass distributions. The fit is performed simultaneously in two separate regions corresponding to $B_s^0 \rightarrow \chi_{c1}(3872) \phi$ and $B_s^0 \rightarrow \psi(2S) \phi$ signals as described above.

The observed signal yield for the $B_s^0 \rightarrow \chi_{c1}(3872) \phi$ decays is found to be $154 \pm 15$ events which corresponds to the statistical significance more than 10$\sigma$ deviation. The fit to the mass distribution for the signal channel are shown in figure [2]. Using the obtained signal yields for $B_s^0 \rightarrow \chi_{c1}(3872) \phi$ and $B_s^0 \rightarrow \psi(2S) \phi$ channels and corresponding efficiency ratio the following branching fraction is calculated:

$$\frac{B_{B_s^0 \rightarrow \chi_{c1}(3872) \phi} \times B_{\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-}}{B_{B_s^0 \rightarrow \psi(2S) \phi} \times B_{\psi(2S) \rightarrow J/\psi \pi^+ \pi^-}} = (2.42 \pm 0.23 \pm 0.07) \times 10^{-2}. $$
The obtained value is found to be in a good agreement with the recent result by the CMS collaboration [17] but is more precise.

The decay $B_s^0 \rightarrow \chi_{c1}(3872)K^+K^-$ where the $K^+K^-$ pair does not originate from a $\phi$ meson, is studied using a sample of selected $B_s^0 \rightarrow J/\psi \pi^+\pi^- K^+K^-$ signal decays. A two-dimensional unbinned extended maximum-likelihood fit is performed to the $J/\psi \pi^+\pi^-$ and $J/\psi \pi^+\pi^- K^+K^-$ mass distributions. The yield of the $B_s^0 \rightarrow \chi_{c1}(3872)K^+K^-$ signal decays is $378 \pm 33$, that is significantly large than the yield of the $B_s^0 \rightarrow \phi K^+K^-$ decays, indicating a large $B_s^0 \rightarrow \chi_{c1}(3872)K^+K^-$ contribution. The background-subtracted and efficiency-corrected $K^+K^-$ mass distribution of the $B_s^0 \rightarrow \chi_{c1}(3872)K^+K^-$ candidates is shown in figure [3]. The $K^+K^-$ mass distribution for $m_{K^+K^-} > 1.1$ GeV/$c^2$ region cannot be described by phase-space shape, and possibly contains contributions from the $f_0(980)$, $f_2(1270)$, $f_0'(1520)$ and $f_2'(1520)$ resonances decaying to a pair of kaons, as has been observed in $B_s^0 \rightarrow J/\psi K^+K^-$ decays [18,19]. Therefore a component that accounts for non-resonant $B_s^0 \rightarrow \chi_{c1}(3872)K^+K^-$ decays and decays via broad high-mass $K^+K^-$ intermediate states, modelled by a product of a phase-space function for three-body $B_s^0 \rightarrow \chi_{c1}(3872)K^+K^-$ decays and a third-order polynomial function. An amplitude analysis of a larger data sample would be required to properly disentangle individual contributions. However, a narrow $\phi$ component can be separated from the non-$\phi$ components 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 $(38.9 \pm 4.9)\%$ and further propagated to the branching fraction ratio:

$$\frac{B_{B_s^0 \rightarrow \chi_{c1}(3872)(K^+K^-)_{non-\phi}}}{B_{B_s^0 \rightarrow \chi_{c1}(3872)\phi} \times B_{\phi \rightarrow K^+K^-}} = 1.57 \pm 0.32 \pm 0.12.$$

The yield of $B_s^0 \rightarrow J/\psi K^{*0}\overline{K}^{*0}$ decays is determined using a three-dimensional unbinned extended maximum-likelihood fit to the $J/\psi \pi^+\pi^- K^+K^-$, $K^- \pi^+$ and $K^+ \pi^-$ mass distributions. Using the obtained signal yields and the corresponding efficiency ratio the branching
The J/ψφ spectrum is studied using the $B^0_s \rightarrow J/ψ π^+ π^- φ$ decays. The $B^0_s \rightarrow J/ψ π^+ π^- φ$ candidates are determined with two-dimensional unbinned extended maximum-likelihood fit to the $J/ψ π^+ π^- K^+ K^-$ and $K^+ K^-$ mass distributions. The background-subtracted $J/ψ φ$ mass spectrum of selected $B^0_s \rightarrow J/ψ π^+ π^- φ$ decays shown in figure 4. It shows a prominent structure at a mass around 4.74 GeV/$c^2$. No such structure is seen if the $K^+ K^-$ mass is restricted to the region of $1.06 < m_{K^+ K^-} < 1.15$ GeV/$c^2$. This structure cannot be explained by $B^0_s \rightarrow χ_{c1}(3872) φ$ and $B^0_s \rightarrow ψ(2S) φ$ decays via a narrow intermediate $ψ(2S)$ and $χ_{c1}(3872)$ resonance since contributions from these decays are explicitly vetoed. No sizeable contributions from decays via other narrow charmonium states are observed in the background-subtracted $J/ψ π^+ π^-$ mass spectrum. The $φ π^+ π^-$ spectrum exhibits significant deviations from the phase-space distribution, indicating possible presence of excited $φ$ states, referred
to as $\phi^*$ states hereafter. The decays $B^0_s \to J/\psi \pi^+ \pi^- \phi$ via intermediate $\phi(1680)$, $\phi(1850)$ or $\phi(2170)$ states [14] are studied using simulated samples and no peaking structures are observed. Under the assumption that the observed structure, referred to as X(4740) hereafter, has a resonant nature, its mass and width are determined through an unbinned extended maximum-likelihood fit to the background-subtracted $J/\psi \phi$ mass distribution in the range $4.45 < m_{J/\psi \phi} < 4.90$ GeV/$c^2$. The fit result is superimposed in figure 4. The obtained signal yield is $175 \pm 39$ events and corresponds to a statistical significance above the $5.3 \sigma$. 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 $\chi_{c1}(4700)$ state observed by the LHCb collaboration in an amplitude analysis of $B^+ \to J/\psi \phi K^+$ decays [8,9]. The obtained mass also agrees with the one expected for the $2^{++}$ $c\bar{s}s$ tetraquark state [20].

The $B^0_s$ decays to the $J/\psi \pi^+ \pi^- K^+ K^-$ 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 $\psi(2S)K^+K^-$ mass distribution for a sample of $B^0_s \to J/\psi \pi^+ \pi^- K^+ K^-$ decays with $m_{K^+K^-} < 1.06$ GeV/$c^2$. 

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**Figure 4**: Background-subtracted $J/\psi \phi$ mass distribution for selected $B^0_s \to J/\psi \pi^+ \pi^- \phi$ candidates (points with error bars) [16]. The red filled area corresponds to the $B^0_s \to X(4740)\pi^+ \pi^-$ signal. The orange line is the total fit.
and with the J/ψπ+π− mass within a narrow region around the known mass of the ψ(2S) meson. 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/ψπ+π− system to a known mass of the ψ(2S) meson [14,21]. The measured value of the B_s^0 meson mass is found to be

\[ m_{B_s^0} = 5366.98 \pm 0.07 \pm 0.13 \text{ MeV}/c^2, \]

that is the most precise single measurement of this quantity. This result is combined with other precise measurements by the LHCb collaboration using B_s^0 → J/ψϕ [22], B_s^0 → J/ψϕ [23], B_s^0 → χ_{c2}K^+K^- [24] and B_s^0 → J/ψp\bar{p} [25] decays. The combined mass is calculated accounting for correlations of systematic uncertainties between the measurements. The LHCb average for the mass of the B_s^0 meson is found to be

\[ m_{B_s^{\text{LHCb}}} = 5366.94 \pm 0.08 \pm 0.09 \text{ MeV}/c^2. \]

The comparison with previous measurements is presented in figure 5.

4 Conclusions

A study of B-meson decays B^+ → J/ψπ+π−K^+ and B_s^0 → J/ψπ+π−K^+K^- is made using pp collision data corresponding to an integrated luminosity of 1, 2 and 6 fb^{-1}, collected with the LHCb detector at centre-of-mass energies of 7, 8 and 13 TeV, respectively [12,16]. The reported results include the first observation of the non-zero width of the χ_{c1}(3872) state; the most precise measurement of the masses of the χ_{c1}(3872) and ψ_2(3823) states; the first observation of the ψ_2(3823) → J/ψπ+π−, B^+ → ψ_2(3823)K^+, B_s^0 → χ_{c1}(3872) (K^+K^-)_{non-ϕ} and B_s^0 → J/ψK^0\bar{K}^0 decays; the most precise measurement of the ratios of branching fractions of the B^+ and B_s^0 mesons into the final states with χ_{c1}(3823) and ψ_2(3823) particles; the most precise single measurement of the B_s^0 meson mass and an observation of a new structure, denoted as a X(4740) state, in the J/ψφ mass spectrum.

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Figure 5: Compilation of the measurements of the $B^0_s$ meson mass. The inner error bars indicate the statistical uncertainty, and the outer error bars correspond to quadratic sum of statistic and systematic uncertainties. The band represents the value and the uncertainty on the average of LHCb measurements.

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