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Exotic hadrons: Recent LHCb discoveries

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Summary. — Recent results on exotic hadrons at the LHCb experiment are reported. These include the observation of $X(4740)$ in the $J\psi\phi$ mass spectrum from $B_s \to J/\psi\pi^+\pi^-K^+K^-$ decays, evidence of a $J/\psi\Lambda$ resonance in $\Xi_b^- \to J/\psi\Lambda K^-$, and observation of four new resonances decaying to $J/\psi K^+$ or $J/\psi\phi$ from $B^+ \to J/\psi\phi K^+$ decays.

1. – Introduction

Multiquark states were first predicted in 1964 within the quark model by Gell-Mann [1] and Zweig [2]. The first tetraquark candidate was observed by the Belle experiment in 2003 [3], and the first observation of a pentaquark candidate was reported by the LHCb experiment in 2015 [4]. Study of heavy-flavour exotic hadrons provides a unique opportunity to shed light on the nature of QCD binding rules, giving us a deeper understanding of the underlying structure of the exotic hadrons. Over the past ten years 59 new hadrons were discovered at the LHC, and the majority of them were found by the LHCb collaboration. These observations demonstrate that LHCb is a good experiment to search for exotic hadrons and study their properties. These proceedings report the recent discoveries in the field of exotic spectroscopy at the LHCb experiment.

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

Decays of beauty hadrons to final states with charmonia provide a unique laboratory to study the properties of charmonia and charmonium-like states. A comparison of production rates with respect to those of conventional charmonium states in decays of beauty hadrons can shed light on exotic charmonium-like candidates' production mechanisms. In $B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$ decays, the decay chain $B_s^0 \to (\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)(\phi \to K^+K^-)$ is experimentally easiest to study in (quasi) two-body decays of a B_s^0 meson with a $\chi_{c1}(3872)$ particle in the final state. Moreover, the mass spectrum of the $J\psi\phi$ system can be studied as well.

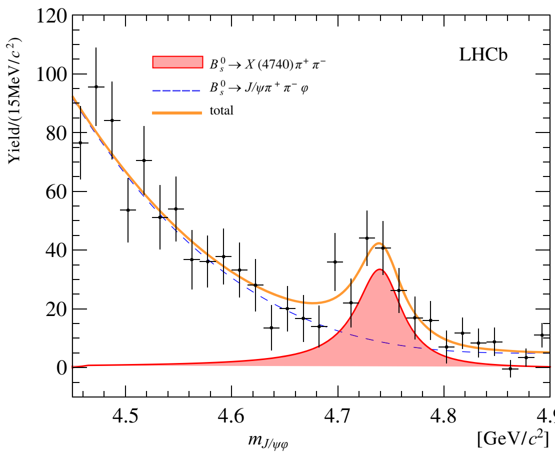

Fig. 1. – Background-subtracted $J/\psi\phi$ mass distribution from $B_s^0 \to J/\psi\pi^+\pi^-\phi$ decays. A fit is overlaid.

Using the 9 fb^{-1} data sample collected by the LHCb detector, the decays $B_s^0 \to J/\psi K^{*0}\bar{K}^{*0}$ and $B_s^0 \to \chi_{c1}(3872)K^+K^-$, where the K^+K^- pair does not originate from a ϕ meson, are observed for the first time [5]. In addition, the most precise single measurement of the mass of the B_s^0 meson is performed and is found to be

$$m(B_s^0) = 5366.98 \pm 0.07 \pm 0.13\,\mathrm{MeV}/c^2.$$

A structure, denoted as $X(4740)$, is observed in the $J/\psi\phi$ mass spectrum in this decay. The background-subtracted $J/\psi\phi$ mass spectrum with superimposed results of the fit is shown in fig. 1, where this resonance is parameterised by the product of the squared absolute value of a relativistic S-wave Breit-Wigner amplitude and a two-body phase-space distribution. Its mass and width are determined to be

$$m(X(4740)) = 4741 \pm 6 \pm 6\,\mathrm{MeV}/c^2,$$
$$\Gamma(X(4740)) = 53 \pm 15 \pm 11\,\mathrm{MeV}$$

where the first uncertainty is statistical and the second is systematic. A structure, denoted as $X(4700)$, is also seen in the mass spectrum of $B \to J/\psi\phi K^+$ decays in previous LHCb analysis [6,7]. The masses of $X(4740)$ and $X(4740)$ are similar to each other. A dedicated analysis using a larger data set is needed to resolve if this state is different from the $X(4740)$ state.

3. – Evidence of a $J/\psi\Lambda$ resonance and observation of excited Ξ^{*-} states in $\Xi_b^- \to J/\psi\Lambda K^-$

The first pentaquark candidates, P_c^+, were observed in $\Lambda_b^0 \to J/\psi p K^-$ decays [4]. The minimal quark content of these pentaquark states is $[uudc\bar{c}]$. Their strange counterparts, namely P_{cs}^0, with $[udsc\bar{c}]$ valence quark content, can be searched in $\Xi_b^- \to J/\psi\Lambda K^-$ decays.

The LHCb collaboration first observed the decay $\Xi_b^- \to J/\psi\Lambda K^-$ using 3 fb^{-1} of integrated luminosity and measured the Ξ_b^- production rate with $\Xi_b^- \to J/\psi\Lambda K^-$ decays

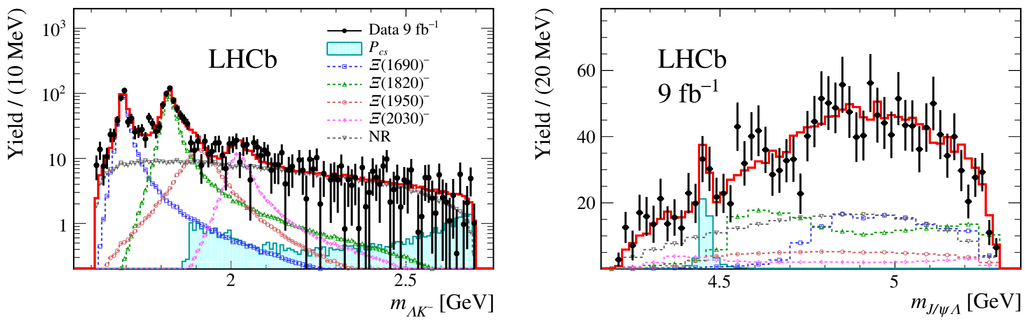

Fig. 2. – The $m_{\Lambda K^-}$ (left) and $m_{J/\psi\Lambda}$ (right) distributions of selected candidates overlaid with the projections of the amplitude fit, including the P_{cs}^0 state.

relative to $\Lambda_b^0 \to J/\psi p K^-$ decays [8]. Using the full Run 1 and Run 2 data sample corresponding to a total integrated luminosity of 9 fb^{-1}, around 1750 $\Xi_b^- \to J/\psi \Lambda K^-$ signal candidates are reconstructed in total [9]. An amplitude analysis is performed to examine possible contributions from any P_{cs}^0 pentaquark states decaying into $J/\psi\Lambda$ and to measure the properties of the $\Xi(1690)^-$ and $\Xi(1820)^-$ resonances. The amplitude analysis follows a similar strategy to that of $\Lambda_b^0 \to J/\psi p K^-$ decays in Ref. [4], with the Λ_b^0 baryon and proton replaced by the Ξ_b^- and Λ baryons, respectively. The P_{cs}^+ structure is modeled by Breit-Wigner function in the nominal fit. Figure 2 shows the projections of the full amplitude fit onto the ΛK^- and $J/\psi\Lambda$ invariant mass distributions. With systematic uncertainties and the look-elsewhere effect included, the significance of the $P_{cs}^0 \to J/\psi\Lambda$ states is measured to be $3.1\,\sigma$, providing the first evidence for a charmonium pentaquark candidate with strangeness. In addition, the narrow excited Ξ^- states, $\Xi(1690)^-$ and $\Xi(1820)^-$, are observed for the first time in Ξ_b^- decays, and their masses and widths are measured with improved precision. The measured mass, width and fit fraction of P_{cs}^0 and the two Ξ^{*-} are listed in table I.

The measured $P_{cs}(4459)^0$ mass is about 19 MeV below the $\Xi_c^0 \bar{D}^{*0}$ threshold: this property is similar to the two $P_c(4440)^+$ and $P_c(4457)^+$ pentaquark states, which is just below the $\Sigma_c^+ \bar{D}^{*0}$ threshold.

4. – Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$

The electrically-charged tetraquark candidates that contain at least one $c\bar{c}$ pair are a clear evidence of states with a minimal content of four valence quarks. Previously, only

TABLE I. – *Mass (M_0), width (Γ_0) and fit fraction (FF) of the P_{cs}^0 and new observed two Ξ^{*-} components involved in the default fit. The quoted uncertainties are statistical and systematic.*

State	M_0 [MeV]	Γ_0 [MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$	$22.1\,^{+6.2}_{-2.6}\,^{+6.7}_{-8.9}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$	$32.9\,^{+3.2}_{-6.2}\,^{+6.9}_{-4.1}$

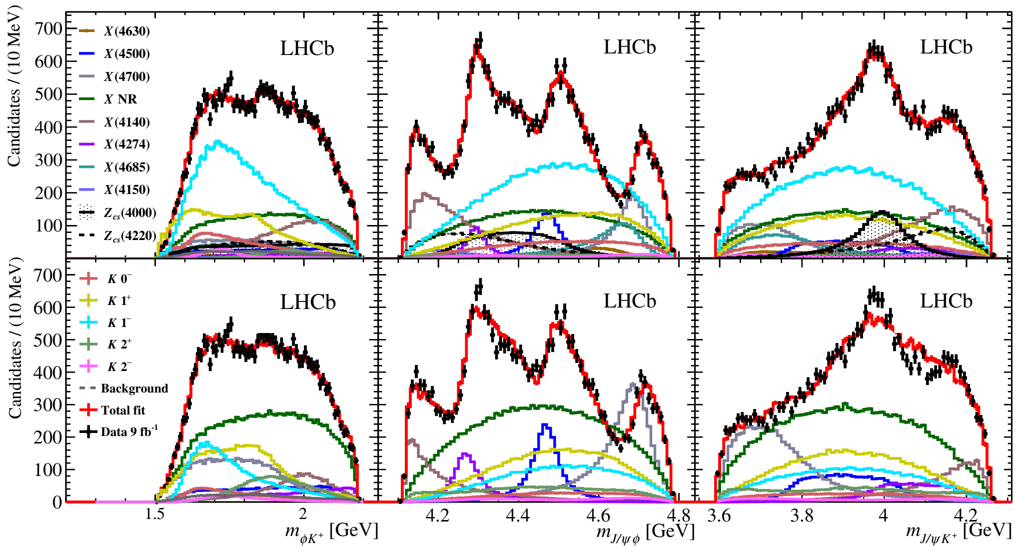

Fig. 3. – Distributions ϕK^+, $J/\psi\phi$ and $J/\psi K^+$ invariant mass for signal candidates with the fit result shown by the red solid lines. The improved model is the top row and the Run 1 model is the bottom row.

the u or d quarks were observed to constitute the light quark content of such charged exotic states. However, a hypothetical Z_{cs}^+ ($[c\bar{c}u\bar{s}]$) can be searched in $B^+ \to J/\psi\phi K^+$ decays as strangeness-flavour partner of the Z_c^+ ($[c\bar{c}u\bar{u}]$)

This decay mode has been studied previously using the Run 1 data set where four $J/\psi\phi$ structures were found with a significance of over 5σ, and some properties of kaon excitations decaying to ϕK^+ were also studied [6,7]. The quantum numbers of the structures were determined by constructing the decay amplitude using the helicity formalism in six dimensions. Notably, the $X(4140)$ width was substantially larger than previously determined [7]. With the Run 2 data sample included, the exotic hadron candidates decaying to $J/\psi K^+$ and more candidates decaying $J/\psi\phi$ can be searched.

A data sample corresponding to an integrated luminosity of 9 fb^{-1} is used in this study [10]. Compared to the previous Run 1 analysis, the total signal yield is around 6 times larger, due to a larger dataset and a 15% signal efficiency improvement, thanks to the inclusion of particle identification information in the Gradient Boosted Decision Tree classifier. The resultant fit to the B^+ mass spectrum yields $N(J/\psi\phi K^+) = 24220 \pm 17$ signal candidates.

To investigate the resonant structures, a full amplitude fit is performed using an unbinned maximum-likelihood method. Resonance lineshapes are parametrised using the Breit-Wigner approximation, while simplified Flatté and K-Matrix models are also explored for systematic uncertainties, for a detailed description see Ref. [7]. The signal decay is described in the helicity formalism by three decay chains: $K^* \to \phi K^+$, $X \to J/\psi\phi$ and $Z_{cs} \to J/\psi K^+$. Each chain is described by one mass and five angular observables. Initially, the model used in the Run 1 analysis is tested; however, it is found not to describe data well. Therefore, the previous fit model is improved with some new added components listed below. The Run 1 model and its improved version, taken as new baseline, are shown in fig. 3.

TABLE II. – *Fit results relative to the exotic components from the improved amplitude model. The significances are evaluated accounting for total (statistical) uncertainties.*

J^P	Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
2^-	$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
1^-	$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
	$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+10}_{-8}$	$5.6 \pm 0.7\,^{+2.4}_{-0.6}$
0^+	$X(4700)$	17 (18)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
	$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
	$X(4140)$	13 (16)	$4118 \pm 11\,^{+19}_{-36}$	$162 \pm 21\,^{+24}_{-49}$	$17 \pm 3\,^{+19}_{-6}$
1^+	$X(4274)$	18 (18)	$4294 \pm 4\,^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+0.8}_{-0.4}$
	$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$
1^+	$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
	$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$

Multiple contributions are required in the improved model, most notably is the inclusion of two new Z_{cs}^+ and two new X components, all with a statistical significance of over 5σ. The spin and parity of each state are probed by testing different spin-parity (J^P) hypotheses. For the $X(4685)$ state a $J^P = 1^+$ is preferred. The J^P of $X(4630)$ is more likely to be 1^- than 2^- with a significance of 3σ. The preferred J^P for $X(4150)$ is 2^- with more than 4σ significance. The $Z_{cs}(4000)^+$ state is found to be 1^+ with a high significance. The $Z_{cs}(4220)^+$ state could be 1^+ or 1^-. The fit results relative to the exotic components are listed in table II.

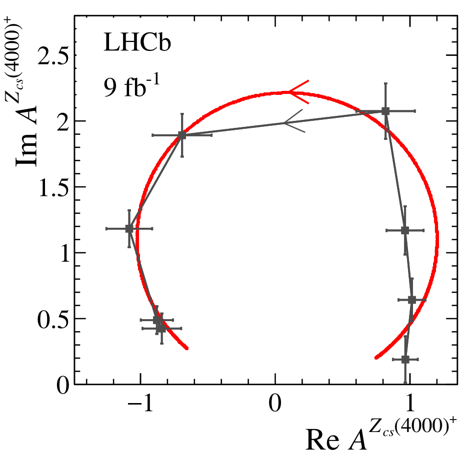

Fig. 4. – Fitted values of the $Z_{cs}(4000)^+$ amplitude in eight $m_{J/\psi K^+}$ intervals, shown on an Argand diagram (black points). The red curve represents the expected Breit-Wigner behaviour between $-1.4\Gamma_0$ to $1.4\Gamma_0$ around the $Z_{cs}(4000)^+$ mass.

Further evidence for the resonant character of $Z_{cs}(4000)^+$ is observed in fig. 4, showing the evolution of the complex amplitude on the Argand diagram, obtained with the same method as previously reported for the $Z_c(4430)^-$ state [11]. The magnitude and phase have approximately circular evolution with $m_{J/\psi K^+}$ in the counter-clockwise direction, indicating a rapid shift in the amplitude phase across the peak, as it is expected for a resonance.

The BESIII experiment reported observation of the $Z_{cs}(3985)^-$ resonance [12]. Its mass $3982.5^{+1.8}_{-2.6} \pm 2.1$ MeV is consistent with the 1^+ $Z_{cs}(4000)^+$ state observed in this analysis, but with significantly narrower width $12.8^{+5.3}_{-4.4} \pm 3.0$ MeV. When fixing the mass and width of this state to the nominal BESIII result in the amplitude fit to our data, the fit becomes much worse. The narrower width is also not supported by an alternative Flatté model with parameters obtained from our data. Therefore, there is no evidence that the $Z_{cs}(4000)^+$ state observed here is the same as the $Z_{cs}(3985)^-$ state observed by BESIII.

5. – Summary

In conclusion, recent results on searches for exotic hadrons at LHCb are presented. The state $X(4740)$ was observed the $B_s \to J/\psi\pi^+\pi^-K^+K^-$ decays, in the $J\psi\phi$ mass spectrum. It is still uncertain if this is the same state as the $X(4740)$ observed in $B^+ \to J/\psi\phi K^+$ channel. The first P^0_{cs} evidence was found in $\Xi^-_b \to J/\psi\Lambda K^-$ decays. We hope to confirm this state with larger data sample in future. In the decay $B^+ \to J/\psi\phi K^+$, four new tetraquark candidates, 1^+ $X(4685)$, $X(4630)$, 1^+ $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$ are observed. Besides, the existences of previous observed 1^+ $X(4140)$, 1^+ $X(4274)$, 0^+ $X(4500)$ and 0^+ $X(4700)$ are also confirmed.

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