

# Recent results on hadronic spectroscopy at LHCb

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**Abstract.** The LHCb experiment is optimized to make precision measurements in the flavour sector. The large datasets collected between 2010 and 2016 allow to study the properties of heavy hadrons with unprecedented precision. In these proceedings recent results related to three topics are discussed: studies of charmonium production and properties using inclusive  $b \rightarrow \phi\phi X$  decays, the observation of charmed pentaquarks and exotic mesons, and the observation of five new excited  $\Omega_c$  baryons.

## 1 Introduction

LHCb [1] is a dedicated heavy flavour physics experiment at the Large Hadron Collider (LHC). The production of  $b$ -quark pairs at the LHC is peaked in the forward region. Hence, the experiment is designed as a single arm spectrometer covering the polar angle of 15 - 300 mrad. The detector includes a high-precision tracking system and two ring imaging Cherenkov detectors for particle identification. Uniquely, amongst the LHC experiments LHCb has the capability to trigger on fully hadronic final states. During the first run of the LHC an integrated luminosity of  $1 \text{ fb}^{-1}$  was collected at a centre-of-mass energy of 7 TeV during 2011 and a further  $2 \text{ fb}^{-1}$  at 8 TeV during 2012. Run 2, at a centre-of-mass energy of 13 TeV, is ongoing and as of summer 2017 a further  $2 \text{ fb}^{-1}$  has already been collected. Apart from the observation of excited  $\Omega_c$  baryons the studies presented here use only the Run 1 data sample.

## 2 Inclusive $b \rightarrow \phi\phi X$ decays

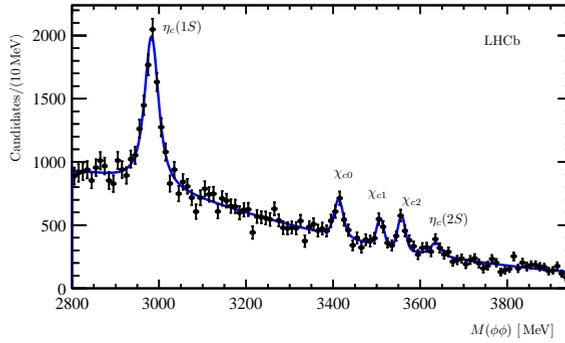
The unique particle identification and triggering capabilities of LHCb allow the study of charmonium production in  $b$ -hadron decays using the  $\phi\phi$  final state [2]. Figure 1 shows the invariant mass distribution for selected  $b \rightarrow \phi\phi X$  candidates. Clear signals for all conventional charmonium states with quantum numbers that permit the decay to the  $\phi\phi$  final state are seen. No exotic contributions are seen and limits are put on the decays of the  $X(3872)$ ,  $X(3915)$  and  $\chi_{c2}(2P)$  states to  $\phi\phi$ .

Among other measurements this dataset allows to determine the inclusive branching fractions of the  $b$ -quark to  $\chi_{cJ}(1P)$  mesons. The results are

$$\begin{aligned}\mathcal{B}(b \rightarrow \chi_{c0} X) &= ( 3.02 \pm 0.47 \text{ (stat)} \pm 0.23 \text{ (syst)} 0.94 \text{ (BF)} ) \times 10^{-3} \\ \mathcal{B}(b \rightarrow \chi_{c1} X) &= ( 2.76 \pm 0.59 \text{ (stat)} \pm 0.23 \text{ (syst)} 0.89 \text{ (BF)} ) \times 10^{-3} \\ \mathcal{B}(b \rightarrow \chi_{c2} X) &= ( 1.15 \pm 0.20 \text{ (stat)} \pm 0.07 \text{ (syst)} 0.36 \text{ (BF)} ) \times 10^{-3} .\end{aligned}$$

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**Figure 1.** Distribution of the  $\phi\phi$  invariant mass for selected  $b \rightarrow \phi\phi X$  candidates. The fitted function is superimposed in blue from Ref. [2].

The  $\chi_{c1,c2}$  branching fractions are consistent with similar ratios measured at LEP and the b-factories [3]. This is the first measurement of  $\mathcal{B}(b \rightarrow \chi_{c0}X)$ . The results are hard to reconcile with either the naive factorization hypothesis [4], which implies that the  $\chi_{c0,c2}$  decays are suppressed compared to the  $\chi_{c1}$ , or spin counting which would suppress the  $\chi_{c0}$  compared to the  $\chi_{c2}$ .

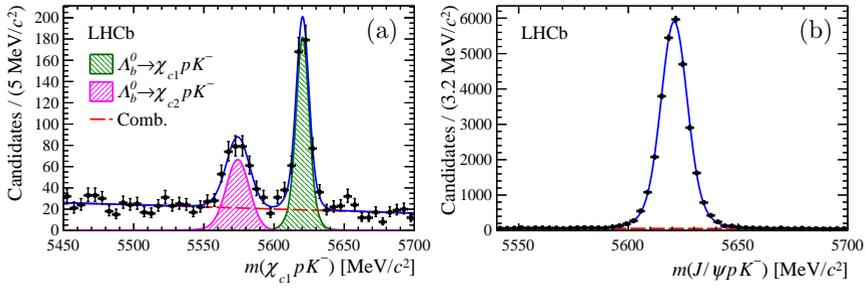
### 3 Exotic hadron spectroscopy

Even in the earliest days of the quark model it was recognised that bound states containing four or five quarks should exist [5]. Claims for such states have been made in the light quark sector but indisputable evidence for such states has not been found. For example, in the early 2000s many experiments found evidence for a strange pentaquark, the  $\theta^+$  which was later retracted. A review of this puzzling affair can be found in Ref. [6]. The discovery of the exotic charmonium state, the  $X(3872)$ , by Belle in 2003 [7] led to an explosion of interest in exotic spectroscopy in the heavy flavour sector. Subsequently, many new states have been found that do not fit into the conventional charmonium or bottomonium spectrum [8]. In 2015, the LHCb experiment observed two states consistent with having  $c\bar{c}uud$  quark content, the  $P_c(4380)$  and the  $P_c(4450)$ , through a full amplitude analysis of the  $\Lambda_b^0 \rightarrow J/\psi p K^-$  decay chain [9, 14]. Various models have been proposed to explain these states as pentaquarks [11], kinematic rescattering effects [12] or loosely bound molecular states [13]. It is important both to confirm these states and to search for other similar states.

To try to confirm these states the Cabibbo suppressed decay  $\Lambda_b^0 \rightarrow J/\psi p \pi^-$  [10] has also been studied. Several contributions to this decay chain are possible:  $N^*$  baryons decaying to  $p\pi^-$ , exotic four-quark states decaying to  $J/\psi p \pi^-$  and  $J/\psi p$  pentaquarks. The favoured model from an amplitude analysis of this decay supports contributions from the  $P_c(4380)$ ,  $P_c(4450)$  and the exotic tetraquark candidate the  $Z(4430)$ , with a significance of more than three standard deviations.

If the observed structures are pentaquarks other such states should exist. In Ref. [11] it is suggested to search for a  $c\bar{c}uds$  pentaquark in the decay  $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ . LHCb has around 300 candidates for this decay in the Run 1 data sample [15]. Using this sample the product of branching ratio times fragmentation fraction has been measured to be

$$\frac{f_{\Xi_b^-} \mathcal{B}(\Xi_b^- \rightarrow J/\psi \Lambda K^-)}{f_{\Lambda_b^0} \mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = (4.19 \pm 0.29(\text{stat}) \pm 0.15(\text{sys})) \times 10^{-2}.$$



**Figure 2.** Fits to the (a)  $\Lambda_b \rightarrow \chi_{c1} p K^-$  and (b)  $\Lambda_b^0 \rightarrow J/\psi p K^-$  invariant mass distributions. Data points are shown in black and the results of the fits are shown as solid blue lines. The components are the  $\Lambda_b \rightarrow \chi_{c1,c2} p K^-$  signal and combinatorial background (Comb.). The  $\Lambda_b \rightarrow \chi_{c1} p K^-$  component is shifted and broadened by the use of a  $\chi_{c1}$  mass constraint in the analysis. The figure is taken from Ref. [18]

The same data sample allows the  $\Xi_b^-$  mass difference with respect to the  $\Lambda_b^0$  baryon to be measured. The value found is

$$m(\Xi_b^-) - m(\Lambda_b^0) = 177.08 \pm 0.47 \pm 0.16 \text{ MeV}/c^2.$$

This is in good agreement with a previous LHCb result [16] using the  $\Xi_b^- \rightarrow \Xi_c^0 \pi^-$  decay mode. The measurement increases the tension between determinations of the  $\Xi_b^-$  mass by LHCb and CDF [17]. Including the Run 2 data sample will allow the first amplitude analysis of this mode to be made and to determine if exotic contributions are present.

The closeness of the  $P_c(4450)$  mass to the  $\chi_{c1} p$  threshold has led to the suggestion that it is a rescattering effect [12]. If this is the case the  $P_c(4450)$  would not be visible in the decay  $\Lambda_b \rightarrow \chi_{c1} p K^-$ . This mode together with the corresponding  $\chi_{c2}$  mode has recently been observed by LHCb. [18]. In Figure 2 the signals for these decays are shown. The branching fractions relative to the  $\Lambda_b^0 \rightarrow J/\psi p K^-$  mode are determined to be

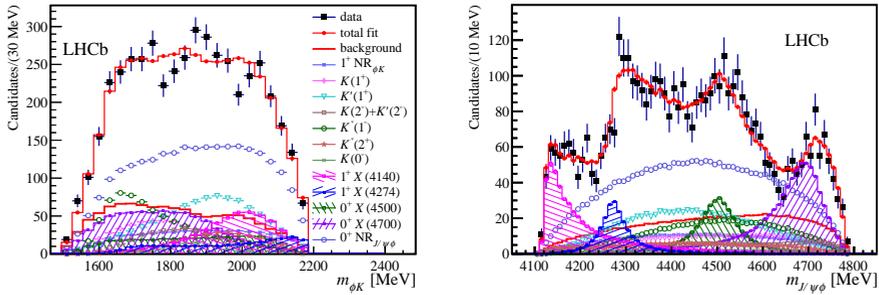
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

and

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)} = 0.248 \pm 0.02 \pm 0.014 \pm 0.009.$$

where the first uncertainty is statistical, the second systematic and the third due to the knowledge of the branching fraction of the radiative  $\chi_c$  decay. A full amplitude analysis is planned using the combined Run 1 and Run 2 data samples. It is interesting to note that the relative branching of the  $\chi_{c2}$  to the  $\chi_{c1}$  mode is close to unity in contrast to the naive factorization expectation.

Another important recent result from LHCb is the first full amplitude analysis of the decay  $B^+ \rightarrow J/\psi \phi K^+$  [19]. Previous studies of this mode by CDF [20], CMS [21] and LHCb [22] based upon 1-dimensional fits to the  $J/\psi \phi$  mass distribution gave somewhat contradictory results. Both CDF and CMS found evidence for a narrow structure close to threshold, the  $X(4140)$ , and a broader state at higher masses referred to as the  $X(4300)$ . However, the measured parameters of these structures were not in the best of agreement. In contrast, a first LHCb study [22], with a small fraction of the Run 1 data sample, found no evidence for a narrow state close to threshold.



**Figure 3.** Distributions of (left)  $\phi K^+$ , (right) and (right)  $J/\psi\phi$  invariant masses for  $B^+ \rightarrow J/\psi\phi K^+$  candidates (black data points) compared with the results of amplitude fit. The total fit is given by the red points with error bars. Individual fit components are also shown. The figure is taken from [19].

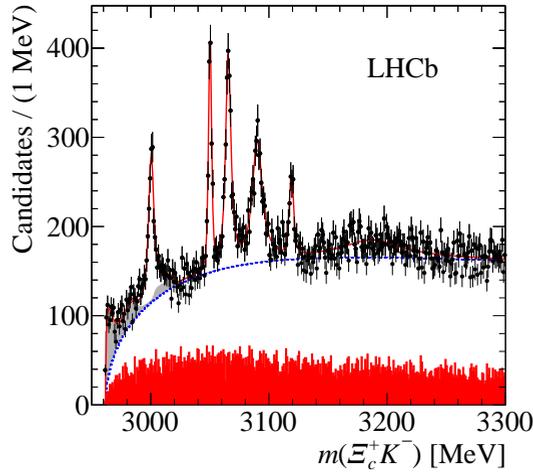
**Table 1.** Properties of the exotic resonances found in the amplitude analysis of the decay  $B^+ \rightarrow J/\psi\phi K^+$ .

State	$J^{PC}$	Mass [MeV/ $c^2$ ]	$\Gamma$ [MeV]
X(4140)	$1^{++}$	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$
X(4300)	$1^{++}$	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$
X(4500)	$0^{++}$	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$
X(4700)	$0^{++}$	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$

The new LHCb analysis clarifies the experimental situation somewhat. Figure 3 shows the fitted projections of the  $\phi K^+$  and  $J/\psi\phi$  mass respectively. As well as contributions from excited  $K^*$  states decaying to  $\phi K^+$  four exotic resonances are needed: the X(4140), X(4300), X(4500) and the X(4700). The properties of these states are summarized in Table 1. The preferred spin assignment is  $1^{++}$  for the first two states and  $0^{++}$  for the second two. All the states are found to be broad in tension with the CDF and CMS results. These states do not fit into the conventional charmonium spectrum and must be exotic in nature. Explanations put forward include tetraquarks, molecular state and rescattering effects (see Ref. [23] for a review). The preferred  $J^{PC}$  value for the X(4140) state rule out the  $0^{++}$  and  $2^{++}$  molecular models. The current data does not rule out the possibility that this state is a  $D_s^\pm D_s^{*\mp}$  cusp as suggested in Ref. [24]. Molecular bound-states or cusps cannot account for the preferred X(4274) quantum numbers.

## 4 Observation of excited $\Omega_c$ baryons

The large  $\Xi_c^+$  sample collected by LHCb during Run 1 and Run 2 has been exploited to search for excited  $\Omega_c^0$  baryons [25]. Combining selected  $\Xi_c^+$  candidates with well-identified kaons the invariant mass distribution shown in Fig. 4 is found. Five narrow structures are seen in the  $\Xi_c^+ K^-$  invariant mass distribution together with a broader structure in the 3188 MeV/ $c^2$  mass region. The properties of the five narrow states are summarized in Table 2. The narrow states are conventionally interpreted as being due to excited  $\Omega_c^0$  baryons [26] which are predicted to have masses in this range though it has been suggested some are pentaquark states [27]. Future measurements of the spin and parity of these states will help to clarify the picture.



**Figure 4.** Distribution of the reconstructed invariant mass  $m(\Xi_c^0 + K^-)$  for all candidates passing the likelihood ratio selection; the solid (red) curve shows the result of the fit, and the dashed (blue) line indicates the fitted background. The shaded (red) histogram shows the corresponding mass spectrum from the  $\Xi_c^+$  sidebands and the shaded (light gray) distributions indicate the feed-down from partially reconstructed  $\Omega_c(X)^0$  resonances. This figure is taken from Ref. [25].

**Table 2.** Properties of the excited  $\Omega_c^0$  states.

State	Mass [MeV/ $c^2$ ]	$\Gamma$ [MeV]
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
$\Omega(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$

## 5 Summary

The LHCb experiment has profited from its large collected dataset, precision tracking and excellent particle identification capabilities to make many measurements related to heavy-quark spectroscopy. In these proceedings several recent results have been presented. Run 2 will continue until 2019 and further discoveries can be expected with the increased dataset. During 2019-2020 the detector will be upgraded allowing a further factor of ten increase in the size of the data sample [28]. This will potentially allow to observe doubly heavy states such the  $\Xi_{bc}$  at LHCb [29].

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