Spectroscopy of Heavy Hadrons at LHCb

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Abstract. The spectroscopy of excited hadronic states in the beauty sector, double heavy hadrons and quarkonia provides a rich proofing ground for effective theories of the strong interaction. The decays of these states also provide a source of exotic hadrons, especially in the charmonium mass region. The unique data samples collected during Run I and II of the LHC open new possibilities for precision studies of these states. Recent results from LHCb on heavy hadron spectroscopy, including exotic mesons and baryons are presented.

1. Introduction
The LHCb experiment has a wide and productive spectroscopy programme, both on standard and exotic hadrons. These are extremely rich and relatively unexplored fields, which provide a perfect benchmark for tests of effective models of QCD. In the following, recent results obtained by the LHCb experiment in the heavy hadron spectroscopy sector are presented.

2. Recent results from standard heavy hadron spectroscopy
2.1. Observation of a new excited \( \Xi_b^-(5935) \) state
The LHCb experiment has reported the observation of two excited \( \Xi_b^- \) states, namely \( \Xi_b^-(5935)^- \) and \( \Xi_b^-(5955)^- \), both decaying in the \( \Xi_b^0 \pi^- \) final state [1]. They correspond to the two states where the light diquark has total spin \( J = 1 \). Furthermore, the CMS experiment has also observed a spin excitation of the \( \Xi_b^0 \) baryon in the decay \( \Xi_b^0(5945)^0 \rightarrow \Xi_b^- \pi^+ \) [2]; this observation has been confirmed by the LHCb experiment [3]. The higher excited states are expected to have a mass above the \( \Lambda_b^0 K^- \) mass threshold, allowing this second channel to be used to search for excited \( \Xi_b^- \) states. The LHCb experiment has performed [4] a search for structures in both the \( \Xi_b^0 \pi^- \) and \( \Lambda_b^0 K^- \) final states, using the full Run 1 dataset (1.0 fb\(^{-1}\) at 7 TeV, 2.0 fb\(^{-1}\) at 8 TeV) plus 1.5 fb\(^{-1}\) at 13 TeV. The \( \Xi_b^0 \) is reconstructed via an inclusive semileptonic mode, \( \Xi_b^0 \rightarrow \Xi_b^+ \mu^- X \), while the \( \Lambda_b^0 \) via an analogous inclusive semileptonic mode, \( \Lambda_b^0 \rightarrow \Lambda_b^+ \mu^- X \), and a fully hadronic mode, \( \Lambda_b^0 \rightarrow \Lambda_b^0 \pi^- \). Both \( \Xi_b^+ \) and \( \Lambda_b^0 \) are reconstructed in the \( pK^-\pi^+ \) final state. A peak over the combinatorial background is observed in all mass distributions with a statistical significance of 7.9\( \sigma \), 25\( \sigma \) and 9.2\( \sigma \), respectively in the \( \Lambda_b \) hadronic, \( \Lambda_b \) semileptonic and \( \Xi_b \) semileptonic channels, as shown in Figure 1. The mass of this new state is measured to be \( m(\Xi_b^-)(6227)^- = 6226.9 \pm 2.0 \pm 0.3 \pm 0.2 \text{ MeV}/c^2 \) from the \( \Lambda_b^0 \) hadronic channel (which is the one with best resolution, \( \simeq 2 \text{ MeV}/c^2 \)), where the first uncertainty is statistical, the second is systematic and the third comes from the uncertainty on the knowledge of the \( \Lambda_b \) mass. This state is consistent with predictions for either the \( \Xi_b(1P)^- \) or the \( \Xi_b(2S)^- \) states.
2.2. Observation of the doubly-charmed $\Xi_{cc}^{++}$ baryon

The SELEX experiment reported the observation of a peak in the $K^-\pi^+\Lambda^+_c$ mass spectrum [5] and of another peak, with mass compatible with the first, in the $pD^+K^-$ mass spectrum [6]. This peak can be identified with the $\Xi_{cc}^{++}$ state, although it has not been confirmed by BaBar, Belle nor by LHCb [7−9]. This should presumably be an isospin-1/2 state with quark content ccd, with its isospin partner being the $\Xi_{cc}^{++}$ baryon, with quark content ccu. The LHCb experiment has performed a search for the latter, reporting the observation of a peak in the $\Lambda_c^+K^-\pi^+\pi^+$ invariant mass spectrum, where the $\Lambda_c^+$ is reconstructed in the $pK^-\pi^+\pi^+$ final state [10]. The mass is measured to be $m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14 \text{ MeV}/c^2$, where the last uncertainty comes from the error on the $\Lambda_c^+$ BR. The mass difference between this state and the one observed by SELEX is $\Delta m = 103 \pm 2 \text{ MeV}/c^2$, which is too large to be the mass difference of an isospin splitting. A measurement of the lifetime of the $\Xi_{cc}^{++}$ has been done by LHCb [11], $\tau(\Xi_{cc}^{++}) = 0.256 \pm 0.024 \pm 0.014$ ps, and it is compatible with a weakly decaying $\Xi_{cc}^{++}$ baryon. Figure 2 shows the fit to the $\Xi_{cc}^{++}$ mass and the preliminary fit to its decay time.

Figure 1. (Colours online) Fits to the mass spectra for the different channels for different centre-of-mass energies.

Figure 2. Fit to the invariant mass of the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ candidates (left) and preliminary fit to the $\Xi_{cc}^{++}$ decay time (right).
2.3. Search for excited $B_c^+$ states

The ATLAS experiment has reported the observation of an excited state of the $B_c^+$ meson [12], with mass $6842\pm 4\pm 5$ MeV/c$^2$, analysing the decay chain $B_c^+(2S)^+ \rightarrow (B_c^+ \rightarrow B_c^+ \gamma)\pi^+\pi^-$. There might be a second contribution from a non-resolved peak from the decay $B_c(2S)^+ \rightarrow B_c^+\pi^+\pi^-$. The LHCb experiment has performed a search for the excited states $B_c(2S)^+$ and $B_c^+(2S)^+$ in the $B_c^+\pi^+\pi^-$ final state, using $2$ fb$^{-1}$ of data at 8 TeV of energy of centre of mass [13]. No signal is observed for either state, and upper limits at 90% CL are set on the $B_c^+$ production cross sections. The mass fits and the upper limits are shown in Figure 3.

3. Recent results from exotic heavy hadron spectroscopy

3.1. Search for weakly-decaying b-flavoured pentaquarks

The observation by the LHCb experiment of two resonances consistent with being pentaquark states [14] has opened a new window of searches for heavy flavour exotic states. According to the Skyrme model [15], the heavier the constituent quarks are, the more tightly bound the state is. The LHCb experiment has published a search for weakly-decaying, b-flavoured pentaquarks [16], analysing $3$ fb$^{-1}$ of data at a centre-of-mass energy of 7 and 8 TeV. Four states have been considered: $P_{B_{c0}p}^{++} \rightarrow J/\psi K^+p\pi^-$, $P_{A_{c0}}^{++} \rightarrow J/\psi K^+p\pi^+$, $P_{A_{c0}}^{--} \rightarrow J/\psi K^+p\pi^-$ and $P_{B_{c0}p}^{++} \rightarrow J/\psi \phi p$. The subscripts indicate the state into which the hypothetical pentaquarks would decay if they would decay via strong interactions. No signal is observed, and upper limits at 90% CL are set on the production cross sections times the BR, normalised using $\Lambda_b \rightarrow J/\psi K^-p$ decays. The mass windows are chosen to be below the strong decay threshold. Plots of the upper limits as a function of the invariant mass of the final states are shown in Figure 4.

3.2. Search for dibaryon states

A hypothetical dibaryon resonance $D^+_c$ could be produced from $\Lambda_b^0 \rightarrow \bar{p}(D^+_c \rightarrow \Lambda^+_c\pi^-p)$ decays [17]. The dibaryon decay would occur via an intermediate $\Sigma^+_c$ or $P^0_c$ decaying into the $\Lambda^+_c\pi^-$ final state, where $P^0_c$ is a hypothetical, not yet observed pentaquark state. The LHCb experiment has searched for this decay [18], analysing $3$ fb$^{-1}$ of data at a centre-of-mass energy of 7 and 8 TeV. In the paper, the first observation of the $\Lambda_b^0 \rightarrow \Lambda_c^0\bar{p}\pi^-\pi^-$ decay is reported, with a BR relative to $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ decays $\frac{B(\Lambda_b^0 \rightarrow \Lambda_c^0\bar{p}\pi^-\pi^-)}{B(\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-)} = 0.0540\pm 0.0023\pm 0.0032$. Figure 5 shows
the Λ⁺π⁻ mass distribution, where the Σ⁺⁰ and Σ⁺⁴⁰ peaks are clearly visible. No evidence for any new pentaquark state is observed, and no evidence for any dibaryon signal is observed in the Λ⁺π⁻ final state, as inferred from the absence of narrow peaks in the mass spectra.

3.3. Search for beautiful tetraquarks
A search for a bbbb bound state has been performed by the LHCb experiment using the whole Run 1 dataset (3.0 fb⁻¹) and 3.3 fb⁻¹, of Run 2 data. The article is in preparation [19].
strategy is to look for structures in the $\Upsilon(1S)\mu^+\mu^-$ mass spectrum, where the $\Upsilon(1S)$ decays into two muons. This choice is supported by several models which indicate that a hypothetical $bb\bar{b}\bar{b}$ should have a mass in the range $18.4 - 18.8$ GeV/$c^2$, which is less than the $\eta\eta_b$ mass threshold. No statistically significative signal is observed for mass hypotheses in the range $17.5 - 20.0$ GeV/$c^2$, and preliminary upper limits are set on the production cross section times the $\Upsilon(1S)\rightarrow\mu^+\mu^-$ decays. Figure 6 shows the fit to the 4-muons mass distribution, where no structures are present, and the limits at 95% CL for the whole search window.

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