PROCEEDINGS OF SCIENCE

Spectroscopy at LHCb - conventional states

Matthew Needham[*†]
University of Edinburgh
E-mail: matthew.needham@cern.ch

During Run 1 and 2 of the LHC, the LHCb experiment collected the world's largest sample of heavy flavour decays. The precise tracking and particle identification capability of the experiment, together with the large dataset collected, allow to study the properties of heavy hadrons with unprecedented precision. In these proceeedings three recent results are discussed: the observation of two new excited Λ_b^0 baryons, the search for the Ξ_{cc}^{+} baryon and the observation of a candidate for the $^3D_3$ state of the charmonium system.

18th International Conference on B-Physics at Frontier Machines - Beauty2019 -
29 September / 4 October, 2019
Ljubljana, Slovenia

*Speaker.
†On behalf of the LHCb collaboration.

PoS(Beauty2019)012

1. Introduction

LHCb [1] is a dedicated heavy flavour physics experiment at the Large Hadron Collider (LHC). The production of beauty and charm particles 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. During Run 1 and Run 2 LHCb collected an integrated luminosity of 9fb^{-1} in pp collisions at centre-of-mass energies of 7, 8, and 13 TeV.

This is the largest dataset of heavy flavour decays collected by any experiment. The high precision tracking capability of the detector, combined with charged-hadron identification using two Ring-Imaging Cherenkov detectors and a dedicated high p_T hadron trigger allow measurements to be made with unprecedented precision. In this paper recent LHCb results related to the observation of excited Λ_b baryons, doubly charmed baryons and the missing $^3D_3$ state of the charmonium system are discussed. Studies of the Ξ_{cc}^{++} lifetime [2] and production [3], and results related to exotic states [4] are described elsewhere in these proceedings.

2. Observation of excited Λ_b baryons

The large samples of Λ_b baryons collected by LHCb provide a rich starting point to explore $b-$baryon spectroscopy. Already with Run-1 data two excited Λ_b baryons, the $\Lambda_b(5912)^0$ and the $\Lambda_b(5920)^0$, were observed decaying to the $\Lambda_b\pi^+\pi^-$ final state[5]. In addition, the properties of the $\Sigma_b^{(*)\pm}$ states, first observed by the CDF collaboration [6], were confirmed with improved precision [7].

The full LHCb dataset contains 893×10^3 fully reconstructed $\Lambda_b\to\Lambda_c\pi^-$ and 220×10^3 $\Lambda_b\to J/\psi pK^-$ candidates. This dataset allows the $\Lambda_b^0\pi^+\pi^-$ invariant mass distribution further from threshold to be explored [8]. The higher combinatorial background is suppressed using a multivariate technique. A new structure is observed around $6.15\,\text{GeV}/c^2$ which is above the $\Sigma_b^{(*)\mp}\pi^\pm$ threshold. To elucidate the nature of this structure, the data are split into three non-overlapping regions: candidates with a $\Lambda_b^0\pi^\pm$ mass within the natural width of the known $\Sigma_b^\pm$ mass; candidates with a $\Lambda_b^0\pi^\pm$ mass within the natural width of the known $\Sigma_b^{*\pm}$ mass and the remaining non-resonant region (Fig. 1). The new structure is consistent, at high significance, with the presence of two narrow peaks referred to as the $\Lambda_b(6146)^0$ and the $\Lambda_b(6152)^0$. The mass and width of these states are measured to be

$$\begin{aligned}
m_{\Lambda_b(6146)^0} &= 6146.17\pm0.33\pm0.22\pm0.16\,\text{MeV}/c^2\,,\\
m_{\Lambda_b(6152)^0} &= 6152.51\pm0.26\pm0.22\pm0.16\,\text{MeV}/c^2\,,\\
\Gamma_{\Lambda_b(6146)^0} &= 2.9\pm1.3\pm0.3\,\text{MeV}\,,\\
\Gamma_{\Lambda_b(6152)^0} &= 2.1\pm0.8\pm0.3\,\text{MeV}\,.
\end{aligned}$$

where the first uncertainty is statistical, the second systematic and for the mass measurements the third uncertainty derives from the knowledge of the mass of the Λ_b^0 baryon. The observed masses, widths and decay patterns are consistant with these states being a $\Lambda_b(1D)^0$ doublet with $J^P=\frac{3}{2}^+$ and $J^P=\frac{5}{2}^+$ [9, 10].

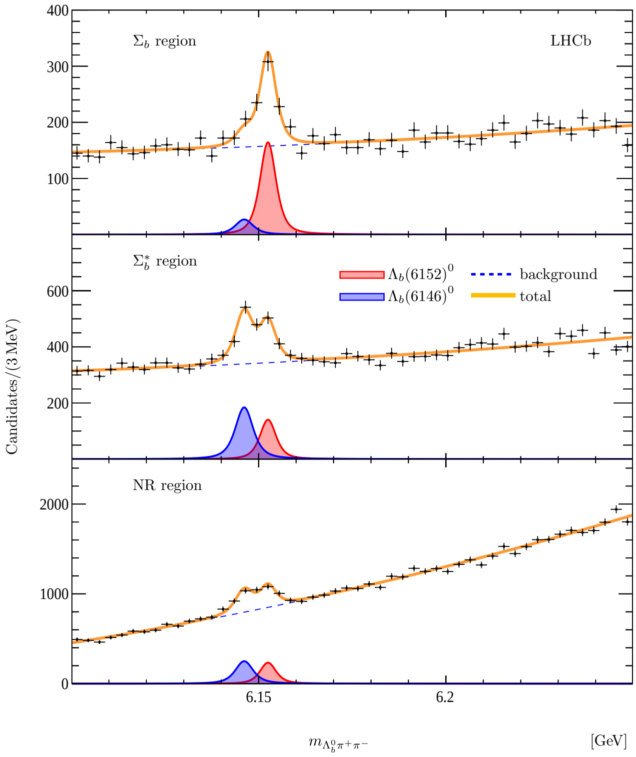

Figure 1: Mass distributions of selected $\Lambda_b^0\pi^+\pi^-$ candidates for the three regions in $\Lambda_b^0\pi^\pm$ mass: (top) $\Sigma_b^\pm$, (middle) $\Sigma_b^{*\pm}$ and (bottom) nonresonant (NR) region.

3. Doubly charmed baryons

The quark model predicts baryons containing two charm quarks. In 2017 the LHCb collaboration observed the Ξ_{cc}^{++} state (with quark content ccu) via the $\Lambda_c^+K^-\pi^+\pi^+$ decay mode [11]. Subsequently, this baryon has been observed to decay to the $\Xi_c^+\pi^+$ final state [12]. Combining both modes the mass of this state is determined to be $3621.24 \pm 0.65\,(\text{stat}) \pm 0.31(\text{syst})\,\text{MeV}/c^2$. Recently, LHCb has also searched for the $\Xi_{cc}^{++} \to D^+pK^-\pi^+$ decay mode [13]. No signal is observed and a limit set

$$\frac{\mathscr{B}(\Xi_{cc}^{++} \to D^+pK^-\pi^+)}{\mathscr{B}(\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+)} < 2.1 \times 10^{-2}$$

at 95% confidence-level.

Other doubly charmed baryons are expected to exist in particular the isospin partner of the Ξ_{cc}^{++}, the Ξ_{cc}^{+} with quark content ccd. It is predicted to have a similar mass to the Ξ_{cc}^{++} but a shorter lifetime. There is a longstanding but unconfirmed observation of the Ξ_{cc}^{+} state by the SELEX collaboration [14, 15]. SELEX report the mass to be $m(\Xi_{cc}^{+}) = 3518.7 \pm 1.7\text{MeV}/c^2$. This is around $100\text{MeV}/c^2$ lower than the measured mass of the Ξ_{cc}^{++}. The LHCb collaboration has searched for the Ξ_{cc}^{+} in the $\Lambda_c^+K^-\pi^+$ final state [16]. The expected shorter lifetime and less distinct experimental signature means this search is more challenging than the Ξ_{cc}^{++} case. No significant signal is seen in the invariant mass range $3400-3800\,\mathrm{MeV}/c^2$ (Fig. 2). The highest local statistical significance is 3.1σ around $3620\,\mathrm{MeV}/c^2$, close to the Ξ_{cc}^{++} mass. Allowing for the Look-Elsewhere-Effect the local significance corresponds to a global significance of 1.7σ. Consequently, limits are set on the production of this state, as a function of its unknown lifetime, relative to the production of the Λ_c^+ and Ξ_{cc}^{++} states are set. These limits improve by an order of magnitude on those obtained from Run 1 data by LHCb. They are significantly below what is expected based upon the SELEX results [14, 15], with the caveat that the production environment is different.

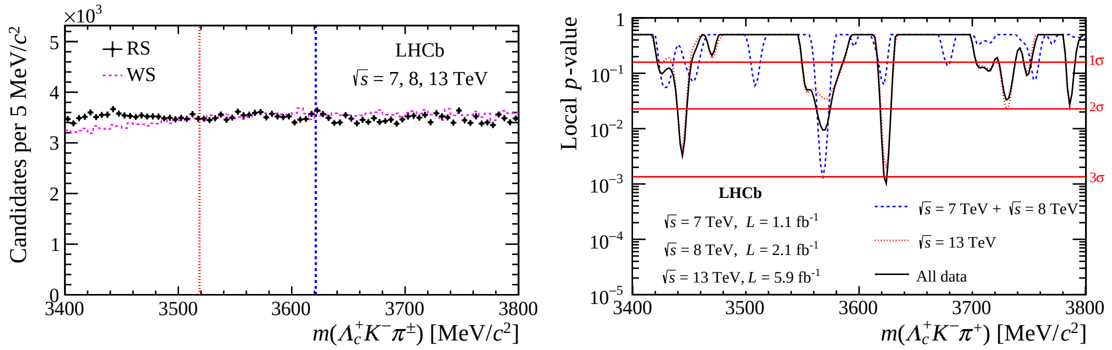

Figure 2: (left) Selected Ξ_{cc}^{+} candidates. The right-sign (RS) $m(\Lambda_c^+ K^- \pi^-)$ distribution is shown in the right plot along with the wrong-sign (WS) $m(\Lambda_c^+ K^- \pi^-)$ distribution normalised to the same area. The dotted red line at $3518.7\,\mathrm{MeV}/c^2$ indicates the mass of the Ξ_{cc}^{+} reported by SELEX [14, 15] and the dashed blue line at $3621.2\,\mathrm{MeV}/c^2$ indicates the mass of the isospin partner, the Ξ_{cc}^{++} baryon. (right) Local p-value (statistical only) at different Ξ_{cc}^{+} mass values evaluated with the likelihood-ratio test, for the data sets recorded at $\sqrt{s}=7$ TeV, $\sqrt{s}=8$ TeV and $\sqrt{s}=13$ TeV.

4. Missing hidden charm

Since the November revolution of 1974 [17, 18], the spectrum of hidden charm mesons has been mapped out with high precision. Of the lowest mass states at the start of 2019 only those with quantum numbers ${}^1D_2$ and ${}^3D_3$ [19, 20] remained to be discovered. The latter state is expected to be narrow even though it is above the open charm threshold due to the F-wave centrifugal barrier factor. However, it cannot be produced in gluon fusion or $\gamma\gamma$ since it has negative C-parity [21]. A suggested possible production mechanism is via radiative decays of the $\chi_{c2}(3930)$.

LHCb has exploited the large dataset collected in Run 1 and 2 to select events with two fully reconstructed charm mesons from the same proton-proton interaction [22]. Figure 3 show the invariant mass distribution for selected pairs of $D^0\overline{D}^0$ and D^+D^-. As well as a clear signals from the well-known $\psi(3770)$ (the ${}^3D_1$ state) and partially reconstructed $\chi_{c1}(3872)$ decays, a new narrow state, the $X(3842)$, is observed with high significance. The mass of this state is measured as $3842.71\pm0.16\,(\mathrm{stat})\pm0.12\,(\mathrm{syst})\,\mathrm{MeV}/c^2$ and the width to be $2.79\pm0.51\,(\mathrm{stat})\pm0.35\,(\mathrm{syst})\,\mathrm{MeV}/c^2$. The properties of this state are remarkably consistent with those expected for the ${}^3D_3$ state of the charmonium system.

The same analysis measures the mass of the $\psi(3770)$ state to be

$$m_{\psi(3770)} = 3778.1\,(\mathrm{stat})\pm0.7\pm0.6\,(\mathrm{syst})\,\mathrm{MeV}/c^2.$$

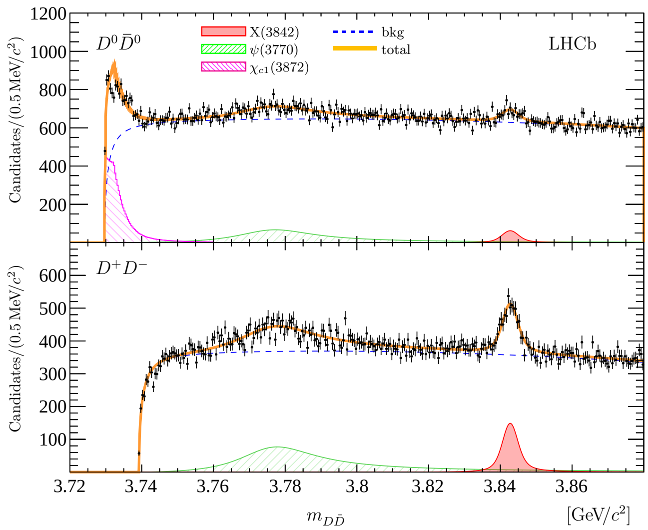

Figure 3: Mass spectra of (top) $D^0\overline{D}^0$ and (bottom) D^+D candidates in the near-threshold $m(D\overline{D}) <$ $3.88\mathrm{GeV}/c^2$ region. The result of a fit to the data is superimposed.

where the first uncertainty is statistical and the second systematic. The measurement agrees well with and has a better precision than the current PDG average [23] $m_{\psi(3770)} = 3778.1 \pm 1.2\mathrm{MeV}/c^2$. The PDG also quotes a value $m_{\psi(3770)} = 3773.13 \pm 0.35\mathrm{MeV}/c^2$, resulting from a fit that includes precision measurements of the mass difference between the $\psi(3770)$ and $\psi(2S)$ states made by the BES collaboration [24, 25, 26]. Both the measurement discussed here and the PDG average disagree with the PDG fit value.

In addition, prompt hadroproduction of the $\chi_{c2}(3930)$ discovered by the b-factories [27, 28] is observed. The resonance parameters of this state are measured to be

$$\begin{aligned} m_{\chi_{c2}(3930)} &= 3921.9 \pm 0.6\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst})\,\mathrm{MeV}/c^2\,, \\ \Gamma_{\chi_{c2}(3930)} &= 36.6 \pm 1.9\,(\mathrm{stat}) \pm 0.9\,(\mathrm{syst})\,\mathrm{MeV}\,. \end{aligned}$$

The measured mass is 2σ lower than the PDG average [23] while the measured width is 2σ higher. It should be noted that the measured value of the mass is roughly midway between the values quoted in Ref. [23] for this state and and for the $X(3915)$ meson, which is known to only decay to the $J/\psi\omega$ final state.

5. Summary

The LHCb experiment has profited from the large dataset collected during Run 1 and 2 of the LHC to make many measurements related to heavy flavour spectroscopy. In these proceedings recent results related to b-baryons, the search for the Ξ_c^{++} and the observation of the ${}^3D_3$ state of the charmonium system have been presented. Many further results exploiting this dataset are expected over the next years and we can look forward to further golden years for spectroscopy.

PoS(Beauty2019)012

References

[1] A. A. Alves, Jr. *et al.*, *The LHCb Detector at the LHC*, *JINST* **3** (2008) S08005.

[2] M. De Cian, *Measurements of lifetimes and other b properties at LHCb*, in proceedings of *Beauty2019*, PoS(Beauty2019)052

[3] M. Rotondo, *Heavy flavour production at LHCb*, in proceedings of *Beauty2019*, PoS(Beauty2019)025

[4] L. Zhang, *Spectroscopy at LHCb - exotic states*, in proceedings of *Beauty2019*, PoS(Beauty2019)026

[5] R. Aaij *et al.*, *Observation of excited Λ_b^0 baryons*, *Phys. Rev. Lett.* **109** (2012) 172003 [hep-ex/1205.3452]

[6] T. Aaltonen *et al.*, *First observation of heavy baryons Σ_b and Σ_b^**, *Phys. Rev. Lett.* **99** (2007) 202001 [hep-ex/0706.3868]

[7] R. Aaij *et al.*, *Observation of Two Resonances in the $\Lambda_b^0\pi^\pm$ Systems and Precise Measurement of $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ properties*,' *Phys. Rev. Lett.* **122** (2019) no.1, 012001 [hep-ex/1809.07752]

[8] R. Aaij *et al.*, *Observation of New Resonances in the $\Lambda_b^0\pi^+\pi^-$ System*, *Phys. Rev. Lett.* **123** (2019) no.15, 152001 [hep-ex/1907.13598]

[9] B. Chen, K. W. Wei and A. Zhang, *Assignments of Λ_Q and Ξ_Q baryons in the heavy quark-light diquark picture*, *Eur. Phys. J. A* **51** (2015) 82 [hep-ph/1406.6561]

[10] S. Capstick and N. Isgur, *Baryons in a relativized quark model with chromodynamics*, *Phys. Rev. D.* **34** (1986) 2809

[11] R. Aaij *et al.*, *Observation of the doubly charmed baryon Ξ_{cc}^{++}*,' *Phys. Rev. Lett.* **119** (2017) no.11, 112001 [hep-ex/1707.01621]]

[12] R. Aaij *et al.*, *First Observation of the Doubly Charmed Baryon Decay $\Xi_{cc}^{++} \to \Xi_{cc}^{++}\pi^+$*, *Phys. Rev. Lett.* **121** (2018) no.16, 162002 [hep-ex/1807.01919]

[13] R. Aaij *et al.*, *A search for $\Xi_{cc}^{++} \to D^+pK^-\pi^+$ decays*, *JHEP* **1910** (2019) 124 [hep-ex/1905.02421]

[14] M. Mattson *et al.*, *First Observation of the Doubly Charmed Baryon Ξ_{cc}^+*, *Phys. Rev. Lett.* **89** (2002) 112001 [hep-ex/0208014]

[15] A. Ocherashvili *et al. Confirmation of the double charm baryon $\Xi_{cc}^+(3520)$ via its decay to pD^+K^-*, *Phys. Lett. B* **628** (2005) 18 [hep-ex/0406033]

[16] R. Aaij *et al.*, *Search for the doubly charmed baryon Ξ_{cc}^+*, *Sci. China Phys. Mech. Astron.* **63** (2020) no.2, 221062 [hep-ex/1909.12273]

[17] J. J. Aubert *et al.*, *Experimental observation of a heavy particle*, *Phys. Rev. Lett.* **33** (1974) 1404

[18] J. .E. Augustin *et al.*, *Discovery of a narrow resonance in e^+e^- annihilation*, *Phys. Rev. Lett.* **33** (1974) 1406

[19] E. J. Eichten, K. Lane and C. Quigg, *B Meson Gateways to Missing Charmonium Levels*, *Phys. Rev. Lett.* **89** (2002) 162002 [hep-ph/0206018]

[20] E. J. Eichten, K. Lane and C. Quigg, *New states above charm threshold*, *Phys. Rev. D* **73** (2006) 014014 Erratum: [*Phys. Rev. D* **73** (2006) 079903] [hep-ph/0511179]

[21] T. Barnes, S. Godfrey and E. S. Swanson, *Higher charmonia*, *Phys. Rev. D* **72** (2005) 054026 [hep-ph/0505002]

[22] R. Aaij *et al.*, *Near-threshold $D\bar{D}$ spectroscopy and observation of a new charmonium state*, *JHEP* **1907** (2019) 035 [hep-ex/1903.12240]

[23] M. Tanabashi *et al.*, *Review of Particle Physics*, *Phys. Rev. D* **98**, (2018) 030001

[24] M. Ablikim *et al.*, *Determination of the $\psi(3770)$, $\psi(4040)$, $\psi(4160)$and$\psi(4415)$ resonance parameters*, *Phys. Lett. B* **660** (2008) 315 [hep-ex/0705.4500]

[25] M. Ablikim *et al.*, *Precison Measurements of the Mass, the Widths of $\psi(3770)$ Resonance and the Cross Section $\sigma[e^+e^- \to \psi(3770)]$ at $E_{cm} = 3.7724$ GeV*, *Phys. Lett. B* **652** (2007) 238 [hep-ex/0612056]

[26] M. Ablikim *et al.*, *Measurements of the branching fractions for $\psi(3770) \to D^0\overline{D}^0, D^+D^-, D\overline{D}$ and the resonance parameters of $\psi(3770)$ and $\psi(2S)$*, *Phys. Rev. Lett.* **97** (2006) 121801 [hep-ex/0605107]

[27] S. Uehara *et al.*, *Observation of a χ_{c2} candidate in $\gamma\gamma \to D\overline{D}$ production at BELLE*, *Phys. Rev. Lett.* **96** (2006) 082003 [hep-ex/0512035]

[28] B. Aubert *et al.*, *Observation of the $\chi_{c2}(2P)$ Meson in the Reaction $\gamma\gamma \to D\bar{D}$ at BaBar* , *Phys. Rev. D* **81** (2010) 092003 [hep-ex/1002.0281]