PROCEEDINGS OF SCIENCE

Charmed hadron properties and spectroscopy at LHCb

Yixiong Zhou[a,*]
on behalf of the LHCb collaboration
[a] *University of Chinese Academy of Sciences, No.19(A) Yuquan Road, Beijing, China*
E-mail: zhouyixiong@mails.ucas.ac.cn

We report new measurements relative to charmed hadron spectroscopy and measurement of charm hadron properties by the LHCb collaboration. Two new Ξ_c^0 baryons are observed, and the lifetimes of the Λ_c^+, Ξ_c^0 and Ξ_c^+ baryons are measured with greatly improved precision compared to the current world average. The doubly Cabibbo-suppressed decays of $\Xi_c^+ \to p\phi$ and $\Xi_c^0 \to \Lambda_c^+\pi^-$ are observed for the first time. The most precise measurement of Ξ_{cc}^{++} mass and production ratio is performed. Finally, the Ξ_{cc}^+ baryon is searched for in the $\Lambda_c^+ K^- \pi^+$ final state.

40th International Conference on High Energy Physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

*Speaker

PoS(ICHEP2020)441

1. Introduction

The measurement of the properties of heavy-flavoured hadrons is essential to test various theoretical approaches, and therefore deepen our understanding of non-perturbative quantum chromodynamics (QCD). In this proceeding, seven new measurements from the LHCb collaboration are reported.

2. Observation of new Ξ_c^0 baryons decaying to $\Lambda_c^+ K^-$

Singly charmed baryons are composed of a charm quark and two light quarks. They provide an excellent laboratory to test various theoretical models, in which the three constituent quarks are effectively described in terms of a heavy quark plus a light diquark system [1]. In 2017, the LHCb collaboration reported the observation of five new narrow Ω_c^0 baryons decaying to the $\Xi_c^+ K^-$ final state [2]. It is currently not understood why the natural widths of these resonances are small. Investigating a different charmed mass spectrum could lead to a better understanding of this feature.

The $\Lambda_c^+(\rightarrow pK^-\pi^+)K^-$ mass spectrum is studied with LHCb data collected at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.6 fb^{-1}. Three narrow structures are observed in the $\Lambda_c^+ K^-$ candidate spectrum, hereafter named $\Xi_c(2923)^0$, $\Xi_c(2939)^0$ and $\Xi_c(2965)^0$ [3]. The measured masses and natural widths of $\Xi_c(2923)^0$, $\Xi_c(2939)^0$ and $\Xi_c(2965)^0$ are summarised in Table 1. The $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$ baryons are new states. The $\Xi_c(2965)^0$ state is in the vicinity of the known $\Xi_c(2970)^0$ baryon [4], however, their masses and natural widths differ significantly.

Table 1: Summary of the measured masses and the natural widths, where the first uncertainty is statistical and the second uncertainty is systematic.

Resonance	Mass [MeV/c^2]	Γ [MeV/c^2]
$\Xi_c(2923)^0$	$2923.04 \pm 0.25 \pm 0.24$	$7.1 \pm 0.8 \pm 1.8$
$\Xi_c(2939)^0$	$2938.55 \pm 0.21 \pm 0.22$	$10.2 \pm 0.8 \pm 1.1$
$\Xi_c(2965)^0$	$2964.88 \pm 0.26 \pm 0.20$	$14.1 \pm 0.9 \pm 1.3$

3. First branching fraction measurement of the suppressed decay $\Xi_c^0 \rightarrow \Lambda_c^+ \pi^-$

The $\Xi_c^0 \rightarrow \Lambda_c^+\pi^-$ decay proceeds through $s \rightarrow u(\bar{u}d)$ and $cs \rightarrow dc$ (weak scattering) processes. Studies of such decay will help us to understand the underlying dynamics of charmed baryon decays and distinguish between different theoretical models. The branching fraction of $\Xi_c^0 \rightarrow \Lambda_c^+\pi^-$ has not been previously measured.

The branching fraction $\mathcal{B}(\Xi_c^0 \rightarrow \Lambda_c^+\pi^-)$ is measured with LHCb data collected at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 3.8 fb^{-1}. To calculate the branching fraction for $\Xi_c^0 \rightarrow \Lambda_c^+\pi^-$, two normalisation methods are used. The first normalisation method uses the heavy-quark symmetry, where the production ratio of Ξ_c^0 to Λ_c^+ baryons $f_{\Xi_c^0}/f_{\Lambda_c^+}$ is estimated as $C \cdot f_{\Xi_b^-}/f_{\Lambda_b^0}$, where C is a correction factor for feed-downs of excited Ξ_b baryons that do not have equal rates to Ξ_b^- and Ξ_b^0 final states. The second method uses the branching fraction of $\Xi_c^+ \to pK^-\pi^+$ measured by Belle [5]. Taking the weighted average value of the two methods, the branching fraction of $\Xi_c^0 \to \Lambda_c^+\pi^-$ is determined to be $\mathcal{B}(\Xi_c^0 \to \Lambda_c^+\pi^-) = (0.55 \pm 0.02\,(\text{stat}) \pm 0.18\,(\text{syst}))\%$. The $\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)$ is determined to be $(1.135 \pm 0.002\,(\text{stat}) \pm 0.387\,(\text{syst}))\%$ using $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ as normalisation [6].

4. Observation of doubly Cabibbo-suppressed decay $\Xi_c^+ \to p\phi$

A systematic study of the relative contributions of doubly Cabibbo-suppressed (DCS) and Cabibbo-favoured process to decays of charm baryons could shed light onto the role of the non-spectator quark, and in particular Pauli interference [7]. Such studies would be helpful for a better understanding of the lifetime hierarchy of charm baryons. So far only one DCS charm-baryon decay, $\Lambda_c^+ \to pK^+\pi^-$, has been observed [8, 9].

In this work the ratio of branching fractions between the $\Xi_c^+ \to p\phi$ and $\Xi_c^+ \to pK^-\pi^+$ decay is measured with LHCb data collected at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 2 fb^{-1}. To determine the signal yield of $\Xi_c^+ \to p\phi$ decay, a two-dimensional unbinned extended maximum likelihood fit to the $m_{pK^+K^-}$ and $m_{K^+K^-}$ distributions is performed. The resulting relative branching fraction ratio with respect to the singly Cabibbo-suppressed $\Xi_c^+ \to pK^-\pi^+$ decay channel is measured to be $R_{p\phi} = (19.8 \pm 0.7\,(\text{stat}) \pm 0.9\,(\text{syst})) \times 10^{-3}$ [10]. The DCS $\Xi_c^+ \to p\phi$ decay is observed for the first time, and an evidence at the level of 3.5 σ is found for a non-ϕ contribution to the $\Xi_c^+ \to pK^+K^-$ decay.

5. Precision measurement of the Λ_c^+, Ξ_c^+ and Ξ_c^0 baryon lifetimes

Precision measurement of the baryons lifetime allows stringent test of their association theoretical predictions. Recently the LHCb collaboration reported a measurement of the Ω_c^0 lifetime that was nearly four times larger than, and inconsistent with, the world average value [11]. Given the overall relatively poor precision on the Λ_c^+, Ξ_c^+ and Ξ_c^0 lifetimes compared to those of the charm mesons, it is important to have additional precise measurements of the lifetimes of these baryons.

Using a similar approach as the Ω_c^0 lifetime measurement, the lifetimes are measured using samples of semileptonic $H_b \to H_c\mu\nu_\mu X$ decays, where H_b represents a Λ_b^0, Ξ_b^0 or Ξ_b^- baryon and H_c corresponds to a Λ_c^+, Ξ_c^+ or Ξ_c^0, respectively, X standing for any additional undetected particles. To reduce the systematic uncertainties, the ratio of the lifetime relative to that of the D^+ meson $r_{H_c} \equiv \frac{\tau_{H_c}}{\tau_{D^+}}$ is determined from a simultaneous fit to the H_c decay-time spectrum and to that of the D^+ meson. Multiplying these ratios by the D^+ lifetime leads to

$$\begin{aligned}
\tau_{\Lambda_c^+} &= 203.5 \pm 1.0 \pm 1.9\ \text{fs},\\
\tau_{\Xi_c^+} &= 456.8 \pm 3.5 \pm 4.2\ \text{fs},\\
\tau_{\Xi_c^0} &= 154.5 \pm 1.7 \pm 1.9\ \text{fs},
\end{aligned}$$

where the first uncertainty is statistical and the second is systematic [12]. The Λ_c^+ and Ξ_c^+ lifetimes are measured with about 1% precision and are consistent with the existing world averages. The Ξ_c^0 lifetime is measured with about 1.8% precision, and is 3.3σ larger than the world average value of

112^{+13}_{-10} fs. The uncertainties on these measurements are on average 3–4 times smaller than those of the existing world average, and have precision comparable to that achieved for charm mesons.

6. Precision measurement of the Ξ_{cc}^{++} mass

The doubly charmed baryon Ξ_{cc}^{++} (ccu) was first observed by the LHCb collaboration in 2017 via the $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decay channel, with Λ_c^+ decaying to the $pK^-\pi^+$ final state [13]. This observation was then confirmed in another decay channel, $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ with Ξ_c^+ decaying to $pK^-\pi^+$ final state [14]. The Ξ_{cc}^{++} mass was measured to be 3621.24 ± 0.65 (stat) ± 0.31 (syst) MeV/c^2. Theoretical calculations of the Ξ_{cc}^{++} mass after the LHCb observation fall into a ± 20 MeV/c^2 window around the experimental value measured by LHCb [15]. At present, experimental uncertainty on the Ξ_{cc}^{++} mass is still large compared to that of the singly charmed baryons.

In this work, the Ξ_{cc}^{++} mass was measured using the $\Xi_{cc}^{++} \to \Lambda_c^+(\to pK^-\pi^+)K^-\pi^+\pi^+$ and $\Xi_{cc}^{++} \to \Xi_c^+(\to pK^-\pi^+)\pi^+$ decay modes. The analysis uses a data sample corresponding to an integrated luminosity of 5.6 fb^{-1}, collected by the LHCb experiment at a centre-of-mass energy of 13 TeV. The resulting values of the Ξ_{cc}^{++} mass using the $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ decay modes are 3621.53 ± 0.24 (stat) ± 0.29 (syst) MeV/c^2, and 3621.95 ± 0.60 (stat) $\pm$ 0.49 (syst) MeV/c^2, respectively. By combining these two measurements the Ξ_{cc}^{++} mass is determined to be 3621.55 $\pm$ 0.23 (stat) $\pm$ 0.30 (syst) MeV/c^2 [16]. This is the most precise measurement of the Ξ_{cc}^{++} mass to date.

7. Measurement of Ξ_{cc}^{++} production in pp collisions at $\sqrt{s}$ = 13 TeV

Baryons containing two charm quarks and a light quark provide a unique system for testing the low-energy limit of QCD. The production cross-section of doubly charmed baryons in pp collisions at a centre-of-mass energy $\sqrt{s}$ = 13 TeV is predicted to be in 60-1800 nb range, which is between 10^{-4} and 10^{-3} times that of the total charm production [17].

The production of Ξ_{cc}^{++} in pp collisions at a centre-of-mass energy $\sqrt{s}$ = 13 TeV is measured by LHCb, with a dataset corresponding to an integrated luminosity of 1.7 fb^{-1}. The production cross-section, $\sigma(\Xi_{cc}^{+})$, times the branching fraction of the $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decay, is measured relative to the prompt Λ_c^+ production cross-section, $\sigma(\Lambda_c^+)$, in the transverse momentum range $4 < p_{\mathrm{T}} < 15$ GeV/c and the rapidity range $2.0 < y < 4.5$. The production ratio is defined as

$$R \equiv \frac{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)}.$$

The production ratio is measured to be $(2.22 \pm 0.27\,(\text{stat}) \pm 0.29\,(\text{syst})) \times 10^{-4}$ [18], assuming the central value of the Ξ_{cc}^{++} lifetime measured in Ref. [19]. This is the first measurement of the production of the doubly charmed baryons in pp collisions.

8. Search for the doubly charmed baryon Ξ_{cc}^{+}

The doubly charmed baryon Ξ_{cc}^{+} was first reported by the SELEX collaboration with its decays into $\Lambda_c^+ K^- \pi^+$ and pD^+K^- [20, 21]. Searches in different environments by the FOCUS [22], Barbar [23], LHCb [24] and Belle [25] experiments did not confirm the SELEX results.

In this work, we use full *pp* collision data recorded with the LHCb detector corresponding to a total integrated luminosity about 9 fb^{-1}. This data sample is about ten times larger than that of the previous Ξ_{cc}^{+} search by the LHCb collaboration using only 2011 data [24]. The largest local significance is about 3.1σ in region around 3620 MeV/c^2. Taking into account the look-elsewhere effect the global significance is about 1.7σ. Upper limits are set at 95% credibility level on the ratio of the Ξ_{cc}^{++} production cross-section times the branching fraction to that of the Λ_c^+ ($R(\Lambda_c^+)$) and Ξ_{cc}^{++} ($R(\Xi_{cc}^{++})$) baryons. The limits are determined as functions of the Ξ_{cc}^{+} mass for different lifetime hypotheses, in the rapidity range from 2.0 to 4.5 and the transverse momentum range from 4 to 15 GeV/c. The upper limit on the production ratio $R(\Lambda_c^+)(R(\Xi_{cc}^{++}))$ depends strongly on the considered mass and lifetime of the Ξ_{cc}^{+} baryon, varying from 0.45 $\times 10^{-3}$(2.0) for 40 fs to 0.12 $\times 10^{-3}$(0.5) for 160 fs [26]. The upper limits on $R(\Lambda_c^+)$ are improved by order of magnitude compared to the previous LHCb search and are significantly below the value reported by SELEX, albeit in a different production environment.

9. Summary

Seven new results on the charmed hadron properties and spectroscopy at LHCb are reported. The observation of two new Ξ_c^0 states [3], and the lifetime of Λ_c^+, Ξ_c^0 and Ξ_c^+ are measured with significantly improved precision [12], the first observation of suppressed decays of $\Xi_c^+ \to p\phi$ and $\Xi_c^0 \to \Lambda_c^+\pi^-$ [6, 10], and the most precise measurement of Ξ_{cc}^{++} mass and production ratio [16, 18], and last is the search of Ξ_{cc}^{+} [26]. More results of charm spectroscopy at LHCb are expected soon.

References

[1] A.G. Grozin. Introduction to the heavy quark effective theory. part 1. 12 1992.

[2] Roel Aaij et al. Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+K^-$. *Phys. Rev. Lett.*, 118(18):182001, 2017.

[3] Roel Aaij et al. Observation of new Ξ_c^0 baryons decaying to $\Lambda_c^+K^-$. *Phys. Rev. Lett.*, 124(22):222001, 2020.

[4] P.A. Zyla et al. Review of particle physics. *PTEP*, 2020(8):083C01, 2020.

[5] Y.B. Li et al. First measurements of absolute branching fractions of the Ξ_c^+ baryon at Belle. *Phys. Rev. D*, 100(3):031101, 2019.

[6] Roel Aaij et al. First branching fraction measurement of the suppressed decay $\Xi_c^0 \to \pi^-\Lambda_c^+$. *Phys. Rev. D*, 102(7):071101, 2020.

[7] S. Bianco, F.L. Fabbri, D. Benson, and I. Bigi. A Cicerone for the physics of charm. *Riv. Nuovo Cim.*, 26N7:1–200, 2003.

[8] S.B. Yang et al. First observation of doubly Cabibbo-Suppressed decay of a charmed baryon: $\Lambda_c^+ \to pK^+\pi^-$. *Phys. Rev. Lett.*, 117(1):011801, 2016.

PoS(ICHEP2020)441

[9] Roel Aaij et al. Measurements of the branching fractions of $\Lambda_c^+ \to p\pi^-\pi^+$, $\Lambda_c^+ \to pK^-K^+$, and $\Lambda_c^+ \to p\pi^-K^+$. *JHEP*, 03:043, 2018.

[10] Roel Aaij et al. Observation of the doubly Cabibbo-suppressed decay $\Xi_c^+ \to p\phi$. *JHEP*, 04:084, 2019.

[11] Roel Aaij et al. Measurement of the Ω_c^0 baryon lifetime. *Phys. Rev. Lett.*, 121(9):092003, 2018.

[12] Roel Aaij et al. Precision measurement of the Λ_c^+, Ξ_c^+ and Ξ_c^0 baryon lifetimes. *Phys. Rev. D*, 100(3):032001, 2019.

[13] Roel Aaij et al. Observation of the doubly charmed baryon Ξ_{cc}^{++}. *Phys. Rev. Lett.*, 119(11):112001, 2017.

[14] Roel Aaij et al. First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$. *Phys. Rev. Lett.*, 121(16):162002, 2018.

[15] Xin-Zhen Weng, Xiao-Lin Chen, and Wei-Zhen Deng. Masses of doubly heavy-quark baryons in an extended chromomagnetic model. *Phys. Rev. D*, 97(5):054008, 2018.

[16] Roel Aaij et al. Precision measurement of the Ξ_{cc}^{++} mass. *JHEP*, 02:049, 2020.

[17] V.V. Kiselev and A.K. Likhoded. Baryons with two heavy quarks. *Phys. Usp.*, 45:455–506, 2002.

[18] Roel Aaij et al. Measurement of $\mathit{\Xi}_{cc}^{++}$ production in pp collisions at $\sqrt{s} = 13$ TeV. *Chin. Phys. C*, 44(2):022001, 2020.

[19] Roel Aaij et al. Measurement of the lifetime of the doubly charmed baryon Ξ_{cc}^{++}. *Phys. Rev. Lett.*, 121(5):052002, 2018.

[20] M. Mattson et al. First observation of the doubly charmed baryon Ξ_{cc}^+. *Phys. Rev. Lett.*, 89:112001, 2002.

[21] A. Ocherashvili et al. Confirmation of the double charm baryon Ξ_{cc}^+ (3520) via its decay to pD^+K^-. *Phys. Lett. B*, 628:18–24, 2005.

[22] Sergio P. Ratti et al. New results on c-baryons and a search for cc-baryons in focus. *Nuclear Physics B - Proceedings Supplements*, 115:33 – 36, 2003. Hyperons, Charm and Beauty Hadrons.

[23] Bernard Aubert et al. Search for doubly charmed baryons Ξ_{cc}^+ and Ξ_{cc}^{++} in BABAR. *Phys. Rev. D*, 74:011103, 2006.

[24] R Aaij et al. Search for the doubly charmed baryon Ξ_{cc}^+. *JHEP*, 12:090, 2013.

[25] Y. Kato et al. Search for doubly charmed baryons and study of charmed strange baryons at Belle. *Phys. Rev. D*, 89(5):052003, 2014.

[26] Roel Aaij et al. Search for the doubly charmed baryon Ξ_{cc}^+. *Sci. China Phys. Mech. Astron.*, 63(2):221062, 2020.