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LHCb results in charm baryons *

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Abstract

The LHCb experiment collected the world's largest sample of charmed hadrons during LHC Run 1 and Run 2. With this data set, LHCb is currently providing the world's most precise measurements of properties and production of known charmed baryons, as well as discovering many previously unobserved states. The latest results from the LHCb Collaboration on charmed baryons are presented.

Keywords: LHCb experiment, Excited charm baryons, Doubly charmed baryons, Charmed baryon lifetimes.

1. Introduction

Updated to the beginning of 2021, there are 59 new hadrons discovered at the LHC, while 52 of them are contributed by the LHCb experiment [1].

As the LHCb detector has excellent ability for the vertex reconstruction and very good performance for tracking and particle identification, it is a good platform to study heavy flavour decays. The world's largest sample of reconstructed charmed hadrons are collected by LHCb during the Run1 (2010-2012) and Run2 (2015-2018) data-taking periods, which provide the world's most precise measurements of properties and production of known charmed baryons. In this proceeding, we present 5 recent results from LHCb on charmed baryons.

2. Observation of excited Ω_c^0 baryons in Ω_b^- decays

In 2017, LHCb collaboration found 5 excited Ω_c^0 baryons in $\Xi_c^+ K^-$ final states, which are $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$ and $\Omega_c(3119)^0$ [2]. Since theses excited Ω_c^0 are observed by the prompt production modes, their quantum numbers are not determined. Recently, the excited Ω_c^0 are confirmed by an exclusive $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decay as the structures in $\Xi_c^+ K^-$ resonance. The LHCb Run1 and Run2 data are used in this search, corresponding to an integrated luminousity of 9 fb^{-1}. $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$ are seen with the significance of over 5σ [3].

The invariant mass spectrum of the $m(\Xi_c^+ K^- \pi^-)$ is shown in Fig 1. The mass difference between the $\Xi_c^+ K^-$ and the Ξ_c^+ and K^- is shown in Fig 2.

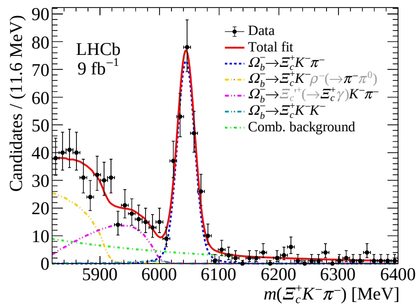

Figure 1: Distribution of the reconstructed invariant mass $m(\Xi_c^+ K^- \pi^-)$ with $\Xi_c^+ \to pK^- \pi^+$. The missing particles in partially reconstructed decays are indicated in grey in the legends. The figure is cited from Ref [3].

Since the spin of the mother particle Ω_b^- is 1/2, the

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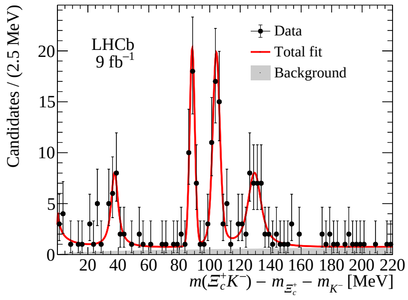

Figure 2: Distribution of the reconstructed mass difference m(Ξ_c^+K$^-$) - $m_{\Xi_c^+}$-m_{K^-}. The four peaking structures are consistent with being the previously observed $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$, with corresponding significance 6.2σ, 9.9σ, 11.9σ and 7.8σ respectively. There is also an additional peak included in the fit at the threshold with significance 4.3σ. The total fit is overlaid in red. The figure is cited from Ref [3].

spin of the confirmed excited Ω_c^0 could be test. The helicity angle θ is defined as the angle between the $\vec{p_{K^-}}$ and -$\vec{p_{\pi^-}}$ in the Ξ_c^+K$^-$ rest frame, where $\vec{p}$ is momenta. The spin of a state is determined by comparing the distribution of cos$\theta$from data with the expected distributions under the spin hypotheses J = 1/2, 3/2 and 5/2. In Fig 3, the rejection of J = 1/2 hypothesis for $\Omega_c(3050)^0$ and $\Omega_c(3065)^0$ are 2.2σ and 3.6σ. One possible assignment is given, J = 1/2, 3/2, 3/2 and 5/2 for $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$ respectively (lowered by systematic uncertainty).

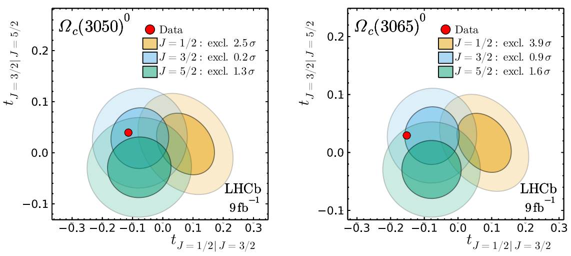

Figure 3: Values of the spin-hypothesis estimators $t_{J=1/2|J=3/2}$ and $t_{J=3/2|J=5/2}$. The red point shows th value measured in the default fit to the data. The rejection significance of every spin-J hypothesis are shown in the legend for the default fit. The figure is cited from Ref [3].

3. Observation of new Ξ_c^0 baryons decaying to Λ_c^+K$^-$ decays

As a natural extension to the Ξ_c^+K$^-$, search for the structures in Λ_c^+K$^-$ resonance were processing since many years ago. In 2007, Babar collaboration published 2 papers for the search of excited Ξ_c^0, one observed a structure peaking in 2.93 GeV from the Λ_c^+K$^-$ mass spectrum in B$^-$ → K$^-\Lambda_c^+$Lam$\bar{\text{b}}$da$_c^-$ decays [4], the other has scanned the mass spectrum of Λ_c^+K$^-$ but found no resonance for Ξ_c^+K$^-$ [5]. In 2018, Bell collaboration reported observed a compatible result, $\Xi_c(2930)^0$ was found in Λ_c^+K$^-$ resonance within B$^-$ → K$^-\Lambda_c^+\bar{\Lambda}_c^-$ decay [6]. In 2020, LHCb collaboration reported to find 3 new excited $\Xi_c(2930)^0$ with local significance over 20σ for each state using the LHCb data collected from Run2 at centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.6 fb^{-1} [7]. The distribution of the reconstructed mass difference is shown in Fig 4.

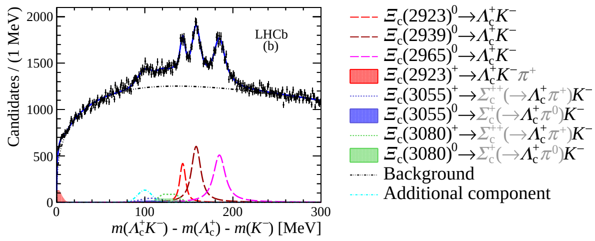

Figure 4: Distributions of the reconstructed mass different m(Λ_c^+K$^-$)-m(Λ_c^+)-m(K$^-$). The result of a fit, described in the text, is overlaid (solid blue line). The missing child particles in the reconstruction are indicated in grey in the legend. The figure is cited from Ref [7].

The masses and natural widths are measured to be

$$m(\Xi_c(2923)^0) = 2923.04 \pm 0.25 \pm 0.20 \pm 0.14 \text{ MeV},$$
$$\Gamma(\Xi_c(2923)^0) = 7.1 \pm 0.8 \pm 1.8 \text{ MeV},$$
$$m(\Xi_c(2939)^0) = 2938.55 \pm 0.21 \pm 0.17 \pm 0.14 \text{ MeV},$$
$$\Gamma(\Xi_c(2939)^0) = 10.2 \pm 0.8 \pm 1.1 \text{ MeV},$$
$$m(\Xi_c(2965)^0) = 2964.88 \pm 0.26 \pm 0.14 \pm 0.14 \text{ MeV},$$
$$\Gamma(\Xi_c(2965)^0) = 14.1 \pm 0.9 \pm 1.3 \text{ MeV}$$

where the uncertainties are statistical, systematic, and due to the limited knowledge of the Λ_c^+ mass. There is not any $\Xi_c(2930)^0$ signal observed in this work, which possibly indicates that the it might be overlap of $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$. The $\Xi_c(2965)^0$ is very close to the known $\Xi_c(2970)^0$ but with significantly different natural width and mass. The mass and natural width of $\Xi_c(2970)^0$ are m($\Xi_c(2923)^0$) = 2967 $^{+24}_{-22}$ MeV and Gamma($\Xi_c(2970)^0$) = 28.1 $^{+3.4}_{-4.0}$ MeV. The equal spacing rule [8, 9] is applicative for these new excited Ξ_c^0 states:

$$\begin{aligned} m(\Omega_c(3050)^0) - m(\Xi_c(2923)^0) &\simeq m(\Xi_c(2923)^0) - m(\Sigma_c(2800)^0) \\ &\simeq m(\Omega_c(3065)^0) - m(\Xi_c(2939)^0) \\ &\simeq m(\Omega_c(3090)^0) - m(\Xi_c(2965)^0) \\ &\simeq 125 \text{ MeV} \end{aligned}$$

4. Search for the doubly charmed baryon Ξ_{cc}^{+} in the $\Xi_{c}^{+}\pi^{-}\pi^{-}$ final state

In 2017, LHCb collaboration has observed the first doubly charmed baryon Ξ_{cc}^{++}, containing double heavy charm quarks and a light up quark through its decaying to $\Lambda_{c}^{+}K^{-}\pi^{+}\pi^{+}$ [10]. Then LHCb confirm this observation by $\Xi_{c}^{+}\pi^{+}$ final state [11]. As an isospin partner, Ξ_{cc}^{+} is containing double charm quarks as well as a down quark and predicted to have a similar mass as Ξ_{cc}^{++}. The Ξ_{cc}^{+} was first search by $\Xi_{cc}^{+} \to \Lambda_{c}^{+}K^{-}\pi^{+}$ decay mode, using 9 fb^{-1} LHCb data collected in Run1 and Run2 [12]. There isn't significant signal observed, so the upper limits are set on the production ratio. In this search, another decay mode $\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{-}\pi^{+}$ is used with 5.4 fb^{-1} LHCb data collected in Run2 [13]. $\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{+}$ is set as the normalisation mode. The final results are combined with the $\Xi_{cc}^{+} \to \Lambda_{c}^{+}K^{-}\pi^{+}$ mode first to see the significant signals. If the significance is not enough, upper limits would be set. The invariant mass spectrums of the $m(\Xi_{c}^{+}\pi^{+}\pi^{-})$ and $m(\Lambda_{c}^{+}K^{-}\pi^{+})$ are shown in Fig 5 with simultaneous fits.

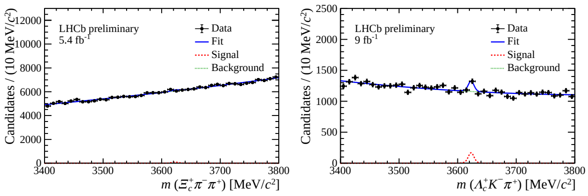

Figure 5: The invariant mass spectra of (left) $\Xi_{c}^{+}\pi^{-}\pi^{+}$ cited from Ref [13] and (right) $\Lambda_{c}^{+}K^{-}\pi^{+}$ cited from Ref [12]. The blue solid curve represents the result of a simultaneous fit to the two spectra, with the red dashed (green dotted) curve showing the signal (background) component.

The p-value scanned is done by fitting the mass spectrum with the peak position varied in steps and combining contributions from two decay modes, while 4σ is obtained for local significance, as shown in Fig 6 but only 2.9σ for global significance.

Hence the upper limits are set on the relative production ratio , define as:

$$R \equiv \frac{\varepsilon(\Xi_{cc}^{++})}{\varepsilon(\Xi_{cc}^{+})} \times \frac{N(\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{-}\pi^{+})}{N(\Xi_{cc}^{++} \to \Xi_{c}^{+}\pi^{+})} \quad (1)$$

Where ε is the efficiency evaluated from the simulation sample and N is the signal yields gained from data sample. The upper limits results are scanned as a function of mass at different lifetime hypotheses at 95% CL as shown in the Fig 7

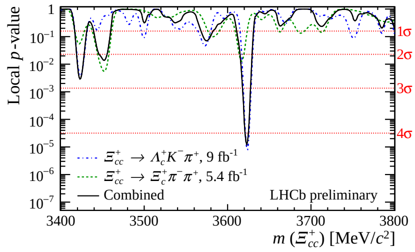

Figure 6: The p-value as a function of the Ξ_{cc}^{+} invariant mass, for Ξ_{cc}^{+} candidate decays reconstructed in the $\Lambda_{c}^{+}K^{-}\pi^{+}$ (blue dash-dotted curve) and $\Xi_{c}^{+}\pi^{-}\pi^{+}$ (green dashed curve) modes, or combining both modes (black solid curve). The figure is cited from Ref [13].

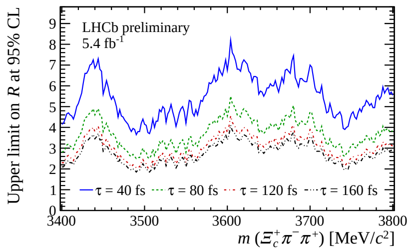

Figure 7: Upper limits on R as a function of the assumed Ξ_{cc}^{+} mass for four different lifetime hypotheses at 95% CL. The figure is cited from Ref [13].

5. Search for the doubly charmed baryon Ω_{cc}^{+}

Besides the Ξ_{cc} doublet, the quark model predict that there is another doubly charmed weakly decaying states: Ω_{cc}^{+} singlet, containing double charm quarks and a light strange quark. As the doubly charmed baryon with strangeness, it is predicted that its mass should be a little bit higher that the Ξ_{cc} baryons, within 3.6-3.9 GeV, due to the mass difference between u quark and s quark [14]. In this search, $\Omega_{cc}^{+} \to \Xi_{c}^{+}K^{-}\pi^{+}$ mode is used, which is predicted to have a relatively large branching fraction. $\Xi_{cc}^{++} \to \Lambda_{c}^{+}K^{-}\pi^{+}\pi^{+}$ mode is set as normalisation mode. The data samples are collected in LHCb Run2, corresponding to an integrated luminousity of 5.4 fb^{-1} [15].

Two different selection criteria are developed in this search. The selection A is optimised to maximise the hypothetical signal sensitivity, which is used for the observation of Ω_{cc}^{+} signal. The selection B is optimised for the efficiency evaluation, which is used for the production ratio measurement. The invariant mass spectrums of the $m(\Xi_{c}^{+}K^{-}\pi^{+})$ is shown in Fig 8.

The p-value scanned is done by fitting the mass spectrum with the peak position varied in steps, while 3.2σ is obtained for local significance, as shown in Fig 9 but only 1.8σ for global significance.

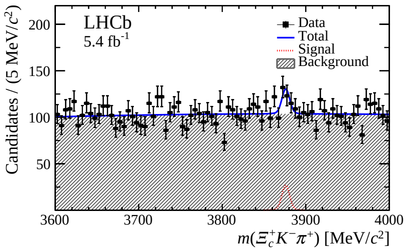

Figure 8: The $\Xi_c^+ K^- \pi^+$ invariant mass spectrum from (black points) selection A, with (blue solid line) the fit with the largest local significance at the mass of 3876 MeV superimposed.

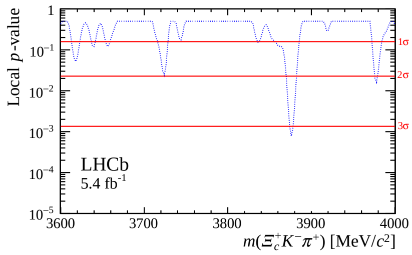

Figure 9: The p-value as a function of the Ω_{cc}^+ invariant mass, Lines indicating one, two and three standard deviations (σ) of local significance are also shown. The figure is cited from Ref [15].

As there is no significant signal observed, the upper limits are set on the relative production ratio , define as:

$$R \equiv \frac{\varepsilon(\Xi_{cc}^{++})}{\varepsilon(\Omega_{cc}^{+})} \times \frac{\mathrm{N}(\Omega_{cc}^{+} \to \Xi_c^+ \mathrm{K}^- \pi^+)}{\mathrm{N}(\Xi_{cc}^{++} \to \Lambda_c^+ \mathrm{K}^- \pi^+ \pi^+)} \quad (2)$$

Where ε is the efficiency evaluated from the simulation sample and N is the signal yields gained from data sample. The upper limits results are scanned as a function of mass at different lifetime hypotheses at 95% CL as shown in the Fig 10.

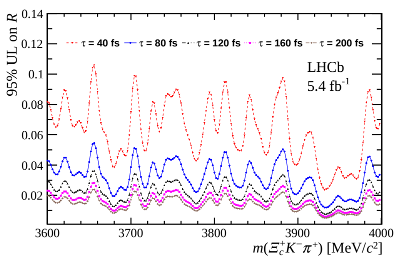

Figure 10: Upper limits on R as a function of the assumed Ω_{cc}^+ mass for four different lifetime hypotheses at 95% CL. The figure is cited from Ref [15].

6. Measurement of the lifetimes of Ω_c^0 and Ξ_c^0 baryons with prompt production

The effective theory of Heavy Quark Expansion (HQE) [16, 17] is the common approch for lifetime calculations of heavy flavour hadrons through an expansion in inverse powers of the mass of the heavy quark $\mathrm{m_Q}$. As the charm quark is lighter than the beauty quark, the higher-order of the HQE would effect the calculation for charmed-hadrons more so that the predictions are very sensitive to the higher-order corrections. More knowledge is needed to understand the natural behind the charmed-hadrons decays, hence the experimental measurements are highly required.

In 2018 and 2019, LHCb has measured the Ω_c^0 and Ξ_c^0 lifetimes using Run1 data and semileptonic b-hadron decays [18, 19], where the measured Ω_c^0 lifetime is nearly four times larger than the previous world average, inconsistent at a level of 7 standard deviations, and the measured Ξ_c^0 also has a tension with the previous world average beyond 3 standard deviations. This measurement perform an independent measurements with prompt production modes, $\Omega_c^0 \to \mathrm{pK^-K^-\pi^+}$ and $\Xi_c^0 \to \mathrm{pK^-K^-\pi^+}$, using LHCb Run2 data corresponding to an integrated luminousity of 5.4 $\mathrm{fb^{-1}}$ [20]. The normalisation mode is $\mathrm{D^0 \to K^+K^-\pi^+\pi^-}$.

The decay-time distributions for Ω_c^0 and Ξ_c^0 are extracted by χ^2 fit, as shown in Fig 11.

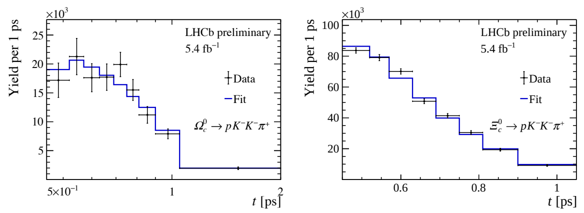

Figure 11: The decay-time distributions in data for (left) Ω_c^0 and (right) Ξ_c^0 modes with the χ^2 fit superposed. The figure is cited from Ref [20].

The measured lifetimes are:

$$\tau(\Omega_c^0) = 276.5 \pm 13.4(\mathrm{stat}) \pm 4.4(\mathrm{syst}) \pm 0.7(\mathrm{from\ D^0})\ \mathrm{fs},$$
$$\tau(\Xi_c^0) = 148.0 \pm 2.3(\mathrm{stat}) \pm 2.2(\mathrm{syst}) \pm 0.2(\mathrm{from\ D^0})\ \mathrm{fs},$$

which is consistent with the previous LHCb semileptonic results.

The weighted average of LHCb measurements is

$$\tau(\Omega_c^0) = 274.5 \pm 12.4\ \mathrm{fs},$$
$$\tau(\Xi_c^0) = 152.0 \pm 2.0\ \mathrm{fs},$$

as shown in Fig 12.

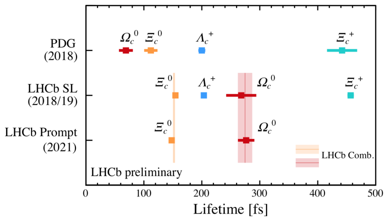

Figure 12: An illustration of the LHCb measurements of Ω_c^0 and Ξ_c^0 lifetimes and the previous world average. The combined LHCb results are shown in colored bands. The figure is cited from Ref [20].

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