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LHCb results in charm baryons

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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 reported.

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1. Introduction

The LHCb experiment collected an unprecedented number of charmed hadrons during LHC Run 1 and Run 2, thanks to the large production cross section at hadron colliders and the excellent performance of the LHCb detector [1, 2] and trigger system [3, 4]. 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 reported.

2. Lifetimes of singly charmed baryons

There are four singly charmed baryons which decay weakly, including Λ_c^+, Ξ_c^0, Ξ_c^+ and Ω_c^0 baryon. Their lifetime hierarchy was measured to be $\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$ [5], which remains stable in the past twenty years and was understood qualitatively by heavy quark expansion theory. However, this hierarchy changed dramatically into $\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$ when LHCb reported a series of measurements using sigals from semileptonic b-decays [6, 7]. The Ω_c^0 lifetime becomes four times larger than previous world average, leading to a larger lifetime than that of the Λ_c^+ baryon. In addition, the Ξ_c^0 lifetime is larger than previous world average beyond 3σ. Independent measurements are helpful to understand the large discrepancy.

A new measurement of Ω_c^0 and Ξ_c^0 lifetimes is performed at LHCb based on a sample of Ω_c^0 and Ξ_c^0 baryons promptly produced in pp collisions at a centre-of-mass energy of 13 TeV [8]. The Ω_c^0 and Ξ_c^0 signals are reconstructed in the $pK^-K^-\pi^+$ final state. The four body decay of $D^0 \to K^-K^+\pi^-\pi^+$ is used as a control mode to validate the analysis procedure and reduce systematic uncertainties. Prompt signal yields are determined in decay-time intervals using the extended maximum likelihood fit to the two dimensional distribution of the invariant mass of the charmed hadron and the logarithm of the significance of its impact parameter. The later is used to discriminate between signals produced directly from pp collisions and from b-decays. The χ^2 fits are performed to obtain the lifetimes. The decay-time distributions for Ω_c^0 and Ξ_c^0 baryons are shown in Fig. 1, along with the fit results. The measured lifetimes are

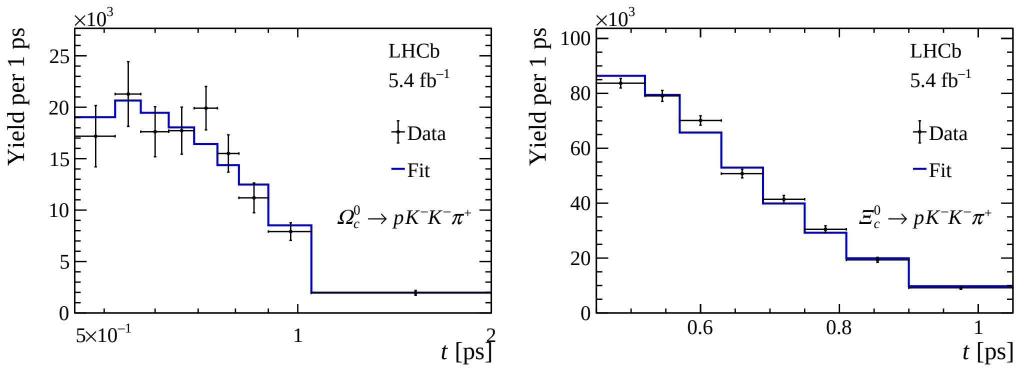

Figure 1: Decay-time distributions for the (left) Ω_c^0 mode and the (right) Ξ_c^0 mode with the χ^2 fit superimposed. The uncertainty on the data distribution is statistical only.

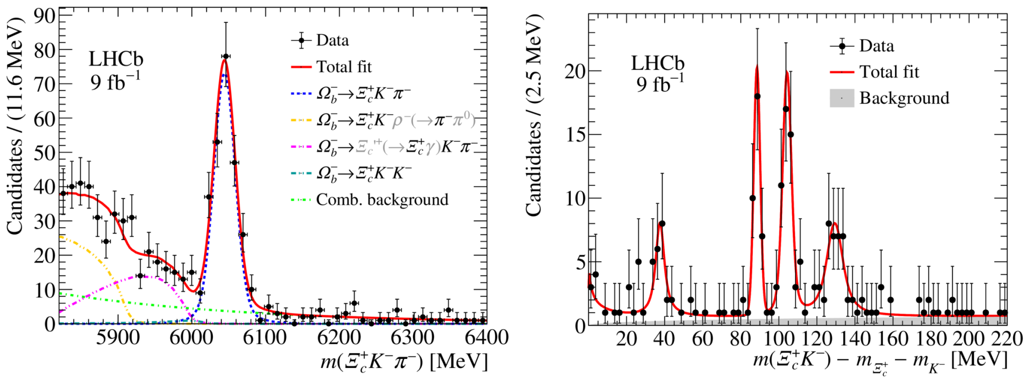

Figure 2: Distribution of the reconstructed invariant mass (left) $m(\Xi_c^+ K^- \pi^-)$ and (right) the reconstructed mass difference between the $m(\Xi_c^+ K^-)$ invariant mass and the Ξ_c^+ and K^- masses.

$$\tau_{\Omega_c^0} = 276.5 \pm 13.4 \pm 4.4 \pm 0.7 \text{ fs},$$
$$\tau_{\Xi_c^0} = 148.0 \pm 2.3 \pm 2.2 \pm 0.2 \text{ fs},$$

where the uncertainties are statistical, systematic and due to the limited knowledge of the D^0 lifetime. The dominant systematic uncertainties stem from the fit model and the difference between data and simulation in kinematic distributions and decay-time resolution. This result is in good agreement with previous LHCb measurements [6, 7]. The precision of the Ω_c^0 lifetime is improved by a factor of two. The new lifetime pattern established by previous LHCb measurements is confirmed. This interesting pattern motivates the reconsideration of the validity of heavy quark expansion in the Ω_c^0 system.

3. Observations of excited charmed baryons

In 2017 LHCb reported an observation of five narrow structures in the $\Xi_c^+ K^-$ invariant mass spectrum in prompt production, denoted as $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$ and $\Omega_c(3120)^0$ [9]. In addition, an enhancement near the threshold is noticed, which is described by the feed-down contributions $\Omega_c^{**0} \to \Xi_c'^+(\to \Xi_c^+ \gamma) K^-$ from the observed resonances, where the γ escapes detection. The masses and widths of Ω_c^{**0} states are measured. However, further experimental inputs of quantum numbers are important for the interpretation of their nature.

Recently LHCb reported the observation of Ω_c^{**0} states in exclusive $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays [10]. The invariant mass distribution of Ω_b^- and the $\Xi_c^+ K^-$ mass projection of Ω_b^- are shown in Fig. 2, along with the fit results. Four significant narrow structures are observed in the $\Xi_c^+ K^-$ mass projection, which are in good agreement with $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, and $\Omega_c(3090)^0$ observed in the prompt production. No structure corresponding to $\Omega_c(3120)^0$ is observed. It is noticed that the threshold enhancement persists, which can not be ascribed to partial reconstructions and needs to be further understood with larger data samples.

Thanks to the exclusive production environment, the spin of Ω_c^{**0} states can be tested for each resonance with helicity angle distributions. The likelihood-ratio test statistic based on the angular density distribution is built to discriminate between different spin hypotheses. As an illustration, the helicity angle distributions for $\Omega_c(3050)^0$ and $\Omega_c(3065)^0$ are shown in Fig. 3. The $J = 1/2$

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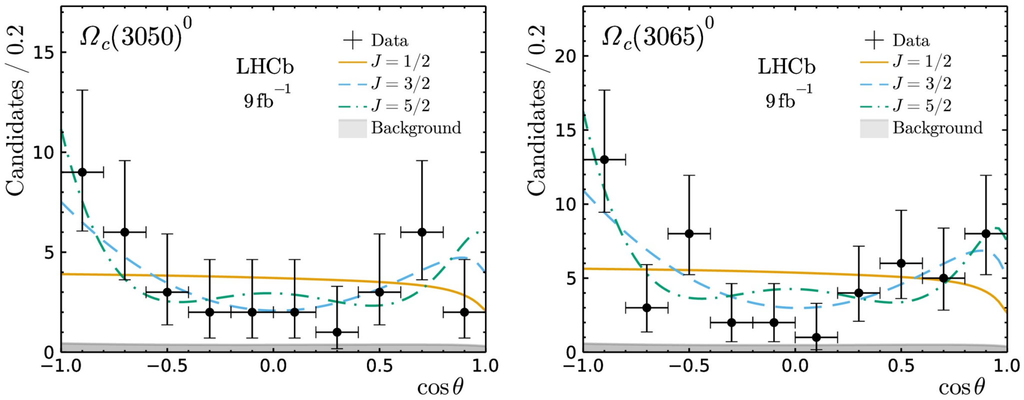

Figure 3: Helicity angle distributions for (left) $\Omega_c(3050)^0$ and (right) $\Omega_c(3065)^0$ in the Ω_b^- decay. Solid, dashed and dot-dashed lines indicate the expectations under the spin hypotheses, $J = 1/2$, $3/2$, and $5/2$, respectively.

is rejected at 2.2σ (3.6σ) for $\Omega_c(3050)^0$ ($\Omega_c(3065)^0$) state. A collective spin hypothesis is also tested, in which the natural order of $J = 1/2, 1/2, 3/2, 3/2$ is rejected beyond 3σ, while data is consistent with $J = 1/2, 3/2, 3/2, 5/2$ assignment. A larger data sample is necessary to pin down the quantum numbers of Ω_c^{**0} states.

4. Searches for doubly charmed baryons

The constituent quark model [11, 12] predicts the existence of doubly charmed baryons, which are composed of two c quarks and a light quark. These states form one isospin doublet Ξ_{cc} ($\Xi_{cc}^+ = ccd$ and $\Xi_{cc}^{++} = ccu$) and one isospin singlet Ω_{cc} ($\Omega_{cc}^+ = ccs$). The Ξ_{cc}^{++} baryon has been observed and extensively studied at LHCb. It is measured to be a weakly decaying baryon with a mass around 3.62 GeV [13, 14], and its production cross-section is about 10^{-4} w.r.t that of the Λ_c^+ baryon [15] and several of its decay modes have been observed [13, 16, 17]. However, the Ξ_{cc}^+ and Ω_{cc}^+ baryons are not observed, although two searches for $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ decay have been performed at LHCb [18, 19].

A search for Ξ_{cc}^+ baryon in the $\Xi_c^+\pi^+\pi^-$ final state is performed, using a data sample corresponding to an integrated luminosity of 5.4 fb^{-1} [20]. The Ξ_c^+ baryon is reconstructed in the $pK^-\pi^+$ final state. No significant signals are observed. The upper limits on the production ratio, which is defined as the production cross section times branching fraction w.r.t. the $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$ decay mode, are set at different mass values for different lifetime hypotheses, as shown in Fig. 4.

The first search for Ω_{cc}^+ baryon in the $\Xi_c^+\pi^+K^-$ final state is performed, using a data sample corresponding to an integrated luminosity of 5.4 fb^{-1} [21]. The Ξ_c^+ baryon is reconstructed in the $pK^-\pi^+$ final state. No significant signals are observed. The upper limits on the production ratio, which is defined as the production cross section times branching fraction w.r.t. the $\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$ decay mode, are set at different mass values for different lifetime hypotheses, as shown in Fig. 5.

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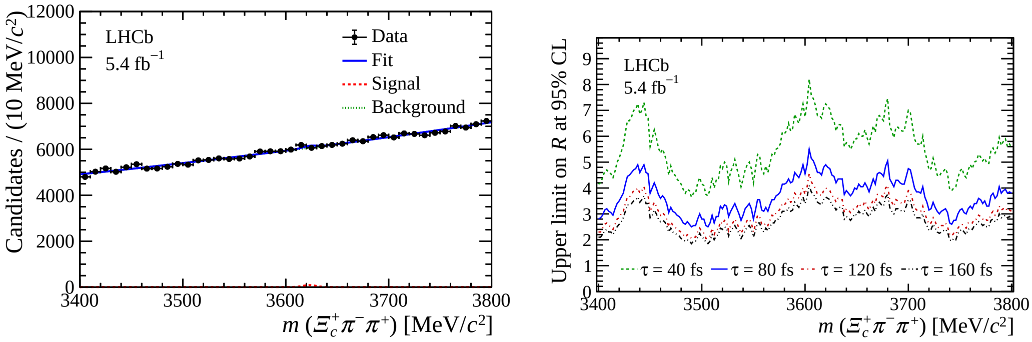

Figure 4: The (left) invariant mass distributions of $\Xi_c^+\pi^+\pi^-$ and (right) the upper limits at different mass values for different lifetime hypotheses.

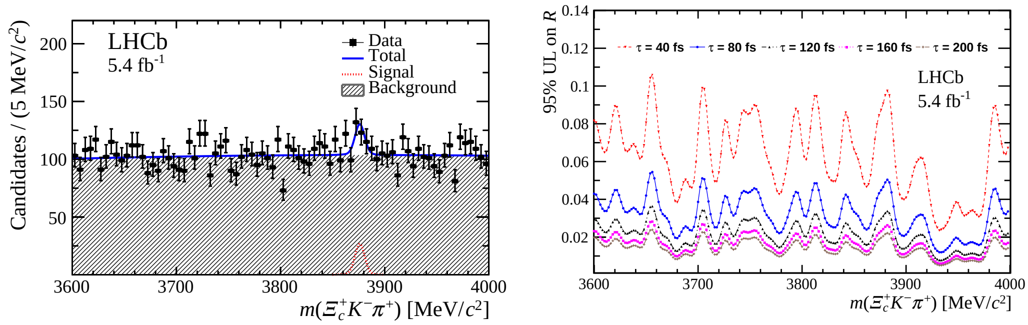

Figure 5: The (left) invariant mass distributions of $\Xi_c^+\pi^+K^-$ and (right) the upper limits at different mass values for different lifetime hypotheses.

5. Summary and prospects

In this article we report recent measurements by the LHCb experiment on charmed baryons. The total data samples collected during LHC Run 1 and Run 2 are still being exploited. In the upcoming Run 3, the increased integrated luminosity and efficiency will boost the sample size to a new level, which enables us to perform even more precise measurements and discover more unobserved states.

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