CHARMED BARYONS AT THE LHCb*

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The LHCb experiment has collected the world's largest sample of charmed hadrons during the LHC periods: Run 1 and Run 2. Based on these data, the LHCb experiment provides the world's most precise measurements of properties, including searches for CP violation and branching ratios of the known charmed baryons, as well as discovering many unobserved states till now. The latest results from the LHCb Collaboration on charmed baryons are reviewed in this manuscript, focusing on searches for CP violation.

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1. Introduction

The Standard Model (SM) successfully describes various properties of the elementary particles as well as their interactions. Although, there are still phenomena therein which are not fully understood. One of those issues is related with matter dominance over antimatter in our universe. The known value of CP violation (CPV), which is expected to be less than 10^{-3} [1], is not enough to explain observed particles and antiparticles discrepancies. It suggests the existence of additional sources of CPV beyond those discovered in the SM. On this basis, the searches for CPV can be treated as probes for new physics effects. Apart from searching for CPV in charmed baryons decays, the LHCb Collaboration is also concerned about properties of charmed baryons, such as lifetimes and branching ratios, and finding new exotic states. The LHCb's physicists use those very precise measurements to test the SM with the highest until now possible accuracy.

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2. CPV in CP asymmetry difference between $\Lambda_c^+ \to pK^-K^+$ and $p\pi^-\pi^+$ decays

Using the LHCb detector, the samples of charm hadrons have been collected in 2011 and 2012 at the centre-of-mass energy of 7 and 8 TeV, respectively, corresponding to an integrated luminosity of 3 fb^{-1}. The total yields of those decays are about 25×10^3 pK^-K^+ and 187×10^3 $p\pi^-\pi^+$ candidates. The reconstructed mass distributions are presented in Fig. 1.

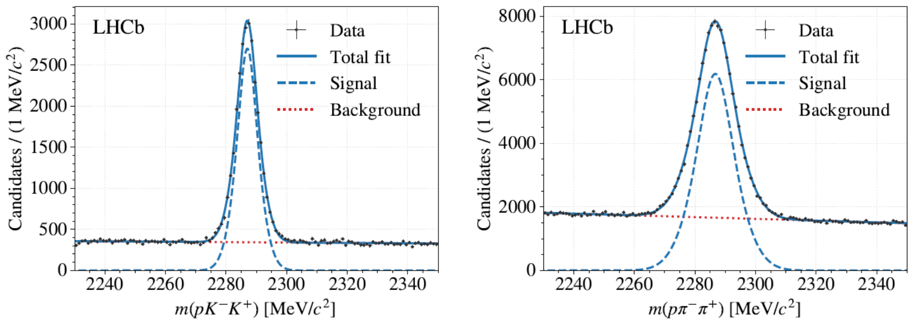

Fig. 1. Mass distributions for (left) $\Lambda_c^+ \to pK^-K^+$ and (right) $p\pi^-\pi^+$ decays.

The CP asymmetry ($A_{\mathrm{CP}}(f)$) in the decays of Λ_c^+ to a given final state (f) is defined as

$$A_{\mathrm{CP}}(f) = \frac{\Gamma(f) - \Gamma\left(\bar{f}\right)}{\Gamma(f) + \Gamma\left(\bar{f}\right)}\,, \tag{1}$$

where $\Gamma(f)$ stands for the decay rate of the $\Lambda_c^+ \to f$ decay. The measured difference in the CP asymmetries between two distinct Λ_c^+ modes is defined as

$$\begin{aligned}\Delta A_{\mathrm{CP}}^{\mathrm{wgt}} &= A_{\mathrm{CP}}(pK^-K^+) - A_{\mathrm{CP}}^{\mathrm{wgt}}(p\pi^-\pi^+)\\ &\approx A_{\mathrm{raw}}\left(pK^-K^+\right) - A_{\mathrm{raw}}^{\mathrm{wgt}}\left(p\pi^-\pi^+\right)\,,\end{aligned} \tag{2}$$

where A_{raw} is so-called raw (total) asymmetry and the sum of all existing asymmetries, and it can be written as $A_{\mathrm{raw}}(f) = A_{\mathrm{CP}}(f) + A_{\mathrm{P}}^{\Lambda_b^0}(f\mu) + A_{\mathrm{D}}^{\mu}(\mu) + A_{\mathrm{D}}^{f}(f)$, where A_{D} and A_{P} are detector and production asymmetries, respectively If data sets with $p\pi^-\pi^+$ and pK^-K^+ kinematically agree by the weighting procedure, then the pollution asymmetries cancel in subtraction of two CP asymmetries. Hence, ΔA_{CP} is measured. Another advantage of this approach is that these observable and raw asymmetries are easier to obtain than single CP asymmetries.

The $\Delta A_{\rm CP}$ is obtained to be [2]

$$\Delta A_{\rm CP}^{\rm wgt} = (0.30 \pm 0.91 \pm 0.61)\% \,. \tag{3}$$

This is the first measurement of the CP-violating parameter in Λ_c^+ decays. The central value is consistent with zero.

3. The CPV search in $\Xi_c^+ \to pK^-\pi^+$

Till now, CPV has not been observed in any baryon decays. In the charm sector, the $\Xi_c^+ \to pK^-\pi^+$ channel seems to be worth investigating. The first studies were conducted using data taken in Run 1, corresponding to an integrated luminosity of 3 fb^{-1}. The two model-independent tests were introduced: the binned $S_{\rm CP}$ [3] method and the unbinned k-nearest neighbours (kNN) [4] technique [10]. Since in one region of the phase space, the difference between Ξ^+ and Ξ^- is 2.7 standard deviations, this study is continued. Data collected in Run 2 are being analysed and two other approaches were taken into consideration: the Energy Test (ET) [5–8] and the Kernel Density Estimation (KDE) [9] technique.

3.1. $S_{\rm CP}$ method

The binned $S_{\rm CP}$ (also called *Miranda*) method is based on dividing the whole phase space, in this case the Dalitz plot, into a given number of bins. For each $i^{\rm th}$ bin, the significance of the difference between particles (N_+^i) and antiparticles (N_-^i) is calculated using the following expression:

$$S_{\rm CP}^i = \frac{N_+^i - \alpha N_-^i}{\sqrt{\alpha(N_+^i + N_-^i)}} \,, \tag{4}$$

where $\alpha = N_+/N_-$ is a normalization factor accounting for production asymmetry. When all of the $S_{\rm CP}^i$ are obtained, the χ^2 test ($\chi^2 \sum (S_{\rm CP}^i)^2$) is performed to find the probability of agreement with the null hypothesis (p-value), meaning the CP symmetry. In the case of CPV, the p-value is equivalent to the significance at least at the level of 5σ. Without local asymmetries, the $S_{\rm CP}$ distribution agrees with the normal distribution with mean, μ, equals 0 and standard deviation, σ, equals 1. The results are consistent with the CP symmetry.

3.2. kNN technique

The model-independent kNN technique tests whether baryons and antibaryons share the same parent distribution function. The test statistics T is defined as

$$T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i,k)\,, \tag{5}$$

where $I(i,k) = 1$ if the $i^{\rm th}$ candidate and its $k^{\rm th}$ nearest neighbour have the same charge and $I(i,k) = 0$, otherwise the n_k is the number of neighbours, and n_+ and n_- are total number of particles and antiparticles, respectively. Under the null hypothesis, T follows a normal distribution with mean, μ_T, and standard deviation, σ_T, which are calculated each time for a given statistics. The results are consistent with the absence of CPV in $\Xi_c^+ \to pK^-\pi^+$ decays.

4. Lifetimes of Ω_c^0 and Ξ_c^0

The samples of the Ω_c^0 and Ξ_c^0 decays were collected using pp collision at a centre-of-mass energy of 13 TeV and correspond to an integrated luminosity of 5.4 fb^{-1}. The decays were produced directly in pp interactions and reconstructed in the $pK^-K^-\pi^+$ final states. The lifetimes of the Ω_c^0 and Ξ_c^0 baryons are determined from a χ^2 fit, which is presented in Fig. 2. The lifetimes of Ω_c^0 and Ξ_c^0 baryons, after combining with the previous LHCb measurements, are found to be [11]

$$\tau_{\Omega_c^0} = 274.5 \pm 12.4 \text{ fs}\,, \qquad \tau_{\Xi_c^0} = 152.0 \pm 2.0 \text{ fs}\,. \tag{6}$$

The uncertainties consist of both statistical and systematic uncertainties.

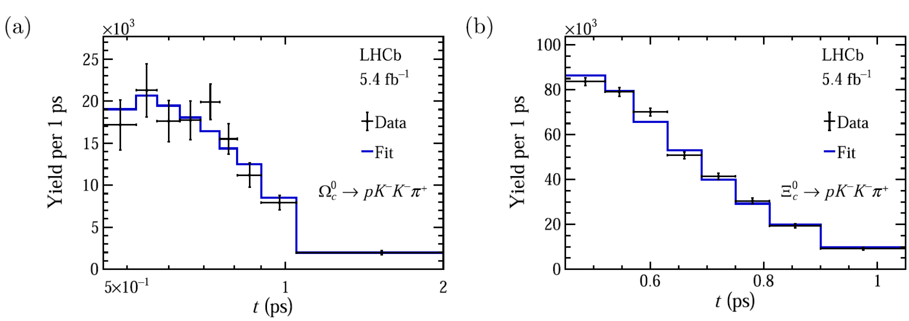

Fig. 2. Decay-time distributions for the (a) Ω_c^0 and the (b) Ξ_c^0 with the χ^2 fit superimposed. The uncertainty on the data distribution is statistical only.

5. Excited Ω_c^0 in $\Omega_b^- \to \Xi_c^+ \to pK^-\pi^+$ decays

The $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays were observed for the first time using *pp*-collision data at the centre-of-mass energies of 7, 8, and 13 TeV collected in the LHCb experiment, which correspond to an integrated luminosity of 9 fb^{-1} [12]. Apart from that, four excited Ω_c^0 baryons are observed, with the significance of each exceeding five standard deviations. Results are presented in Fig. 3. Moreover, a precise measurement of the Ω_b^- mass of $6044.3 \pm 1.2 \pm 1.1^{+0.19}_{-0.22}$ MeV is obtained.

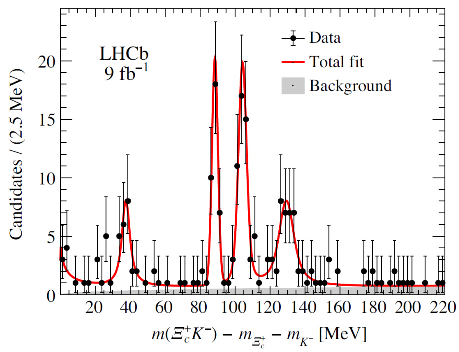

Fig. 3. Distribution of the reconstructed mass difference between the $\Xi_c^+ K^-$ invariant mass and the Ξ_c^+ and K^- masses. The four peaking structures are consistent with observed $\Omega_c^0(3000)$, $\Omega_c^0(3050)$, $\Omega_c^0(3065)$, and $\Omega_c^0(3090)$ baryons.

6. Doubly charmed $\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+$ states

The $\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+$ decay is observed in data collected in the LHCb experiment at a centre-of-mass energy of 13 TeV and corresponds to an integrated luminosity of 5.4 fb^{-1} [13]. Its branching fraction relative to that of the $\Xi_{cc}^+ \to \Xi_c^+ \pi^+$ transition is measured to be $1.41 \pm 0.17 \pm 0.10$, where the

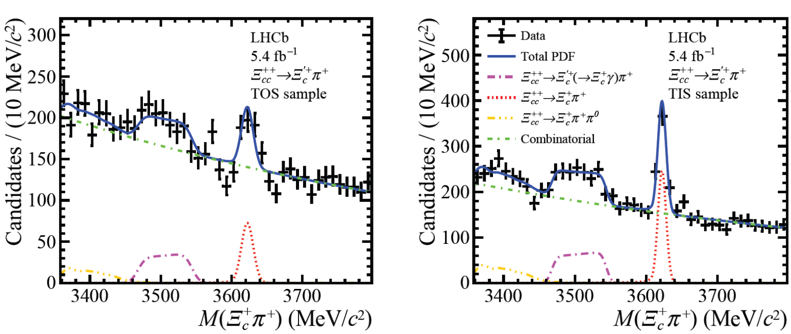

Fig. 4. The mass distributions of the Ξ_{cc}^{++} candidates from the (left) TOS and (right) TIS with the results of the fit overlaid. The $\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+$ component is shown as a purple dashed line

first uncertainty is statistical and the second systematic. The $\Xi_c^+\pi^+$ mass spectra, separated for triggered on signal (TOS) and triggered independently of samples (TIS), are presented in Fig. 4.

7. Doubly charmed Ξ_{cc}^+ in $\Xi_c^+\pi^-\pi^+$

A search for the doubly charmed baryon Ξ_{cc}^+ was conducted in the $\Xi_c^+\pi^-\pi^+ +$ mass spectrum. The *pp*-collision data collected with the LHCb detector at a centre-of-mass energy of 13 TeV corresponding to a total integrated luminosity of 5.4 fb^{-1} were used. Test statistics $q_\pm$ [14] was introduced to determine *p*-values, the scan of which is shown in Fig. 5 as the function of the mass. The minimum *p*-values were calculated to be 0.0108 (0.0024) at the mass of 3 617 (3 452) MeV/c^2 corresponding to 2.3σ (2.8σ) [15].

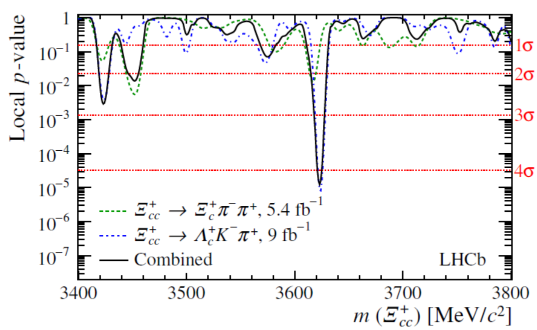

Fig. 5. Local *p*-values as the function of the Ξ_{cc}^+ invariant mass, for Ξ_{cc}^+ baryon decays reconstructed in the $\Xi_c^+\pi^-\pi^+$ (green curve) and $\Lambda_c^+ \to pK^-pi^+$ (blue curve) modes, or combining the two modes (black curve).

8. Conclusions

This article presents the recently measured properties of baryons and results of searches for CP violation. The lifetimes of Ω_c^0 and Ξ_c^0 were measured. The $\Omega_b^- \to \Xi_c^+K^-\pi^-$ decays were observed for the first time, and their mass was measured with great precision. Four excited Ω_c^0 baryons are observed with significance at a level greater than 5σ. Also, the new decay mode $\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$ was found. Searches for the CP violation in charm baryons are being continued as CP asymmetry has not been observed yet. Local asymmetry on the level of 2.7σ between particles and antiparticles is seen.

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