PROCEEDINGS OF SCIENCE

Results from charm baryon spectroscopy at LHCb, Belle and BESIII

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The spectroscopy of charm baryons provides a primary tests and inputs to the effective theories of the strong interaction. Many conventional *c*-baryon states have not yet been observed experimentally and properties of many of the observed states are still to be determined. Recent measurements of charmed baryons performed at LHCb, BESIII and Belle are reported.

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1. Introduction

Spectroscopy of baryons with a charm quark is quite intricate but can provide an intererest-ing laboratory for testing Quantum Chromodynamics (QCD). First observations of excited singly-charmed baryons have been performed at the *B*-factories but many excited singly-charmed states and doubly charmed baryons are still missing in the experimental picture. In addition the spin-parity assignments of many of the observed states is still to be determined. The LHCb, Belle and BESIII experiments are the ideal environment to study charmed baryon production and properties.

2. Excited Λ_c^+ states

The mass spectrum of the Λ_c^+ states includes, in addition to the ground state, a P-wave doublet and a D-wave doublet. One of the state of the D-wave doublet could be the $\Lambda_c(2880)^+$ state with $J^P = 5/2^+$ [1] while the other member of the D-wave doublet has not yet been observed. On the other hand two other states, the $\Lambda_c(2765)^+$ [1] and the $\Lambda_c^+(2940)$ [2] states do not have a clear assignment.

LHCb performed an analysis to determine the shape of the differential decay rate of $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}$ [3]. A clear signal of the previously observed $\Lambda_c(2595)^+$, $\Lambda_c(2625)^+$, $\Lambda_c(2765)^+$ and $\Lambda_c(2880)^+$ states is seen in the $\Lambda_c^+\pi^+\pi^-$ invariant mass spectrum as shown in Figure 1.

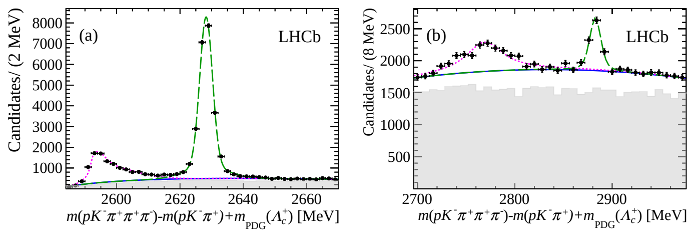

Figure 1: The mass difference $m(pK^-\pi^+\pi^+\pi^-)$-$m(pK^-\pi^+)$ added to the known Λ_c^+ mass distribution. For $m < 2700\,\text{MeV}$, the $\Lambda_c(2595)^+$ is in magenta dashed line, and the $\Lambda_c(2625)^+$ in green long-dashed line (left) and for $m > 2700\,\text{MeV}$, the $\Lambda_c(2765)^+$ is in magenta dashed line, and the $\Lambda_c(2880)^+$ in green long-dashed line (right).

Another analysis, performed at LHCb, searches for excited Λ_c^+ states in the $D^0 p$ channel through an amplitude analysis of $\Lambda_b^0 \to D^0 p \pi^-$ decays [5]. The analysis uses exclusive *b*-decays with the advantages of a well-defined initial state and a low-level background. The full Dalitz plot and a zoom in the near-threshold region of the selected candidates is shown in Figure 2. The $\Lambda_c(2880)^+$ and the $\Lambda_c(2940)^+$ states have been identified. The preferred spin for the $\Lambda_c(2880)^+$ state is found to be $5/2^+$. Mass and width measurements are compatible with PDG and have similar precision. Also for the $\Lambda_c(2940)^+$ state, the spin parity assignment is investigated and the preferred spin is found to be $3/2^-$ but $1/2$ and $7/2$ cannot be ruled out. In addition a near threshold enhancement consistent with a new resonance state, $\Lambda(2860)$, is found. Mass, width and $J^P = 3/2^+$ are measured. Its mass is consistent with the orbital D-wave excitation and the phase motion of the $3/2^+$ component with respect to the non-resonant component is consistent with a resonant behavior.

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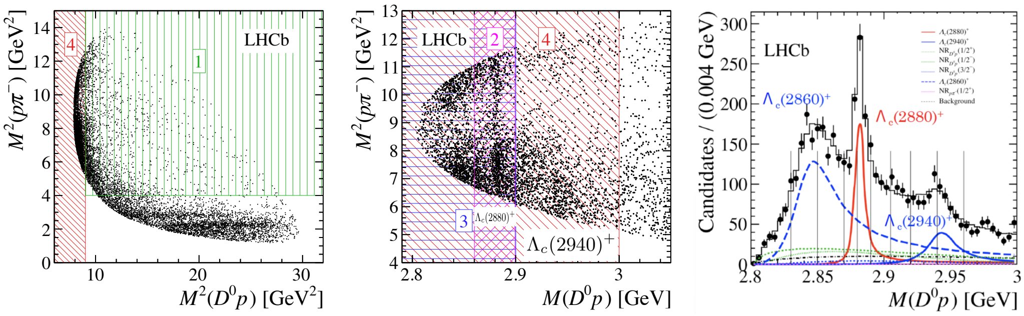

Figure 2: The full Dalitz plot (left) and a zoom near the D^0p threshold (centre) (Region 4) where Λ_c^* resonances are expected. Region 1 does not contain any resonant contribution. Region 2 contains the $\Lambda_c(2880)^+$ state and Region 4 contains the $\Lambda_c(2940)^+$ state. The right plot shows the projection of the fit result in the D^0p invariant mass.

BESIII performed in the last years many measurements of branching fractions of Λ_c decays using a sample of data collected in 2014 above the $\Lambda_c^+\Lambda_c^-$ pair threshold including Cabibbo-suppressed decays [7, 8] and neutron mode decays [6] which were not explored yet. Plans to collect Λ_c^+ data at higher energies are foreseen in the next future.

3. Ω_c^0 baryon lifetime

Charm baryon lifetimes are known much less precisely than the charm meson ones. Lifetime measurements of charm baryon can provide a test of heavy-quark effective theory and in particular on higher-order terms in the heavy-quark expansion. The lifetime of the Ω_c^0 baryon is measured at LHCb with respect to the D^+ lifetime estimated using $D^+ \to K^-\pi^+\pi^+$ to reduce systematic uncertainties [4]. A sample of semileptonic $\Omega_b^- \to \Omega_c^0\mu^-\bar{\nu}_\mu X$ with $\Omega_c^0 \to pK^-K^-\pi^+$ decays is used. The analysis uses full Run1 data. The measured lifetime $\tau_{\Omega_c^0} = (268 \pm 21(\mathrm{stat}) \pm 10(\mathrm{syst}) \pm 2(\mathrm{D}^+))$ fs is four times larger than, ad inconsistent, with the world average value.

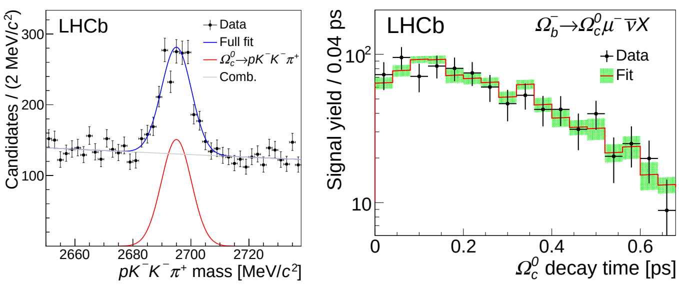

Figure 3: Invariant-mass distribution (left) and decay-time spectrum (right) for Ω_c^0 candidates.

4. Excited Ω_c^0 states

Concerning the Ω_c baryons, the spectrum is almost unexplored. Only the two ground states were known: Ω_c^0 ($J^P = 1/2^+$) and Ω_c^{*0} ($J^P = 3/2^+$). Studies of the strong Ω_c decays into the

$\Xi_c^+(\to pK^-\pi^+)K^-$ final state are performed at LHCb [9]. The analysis is performed using a data sample corresponding to an integrated luminosity of $\sim 3.3\,\mathrm{fb}^{-1}$ including a part of Run2 data with a high-efficiency dedicated trigger. As it can be seen in Figure 4, five narrow peaks, with significances greater than 5σ, are visible in the $\Xi_c^+K^-$ spectrum. In addition a broad state at high mass is visible that can be a superposition of several states. As a cross-check, wrong sign sample combining same-sign $\Xi_c^+K^+$ candidates is inspected together with a sample of Ξ_c sidebands.

Using the entire available data sample of $980\,\mathrm{fb}^{-1}$, excited Ω_c baryons are studied at Belle [10]. The Ξ_c^+ candidates are reconstructed in seven different decay modes. In the fit procedure, masses and widths of the six states are fixed to the LHCb values. The $\Omega_c(3066)$ and the $\Omega_c(3090)$ states are strongly confirmed and their parameters are compatible with LHCb measurement. The $\Omega_c(3000)$ and the $\Omega_c(3050)$ states are also confirmed but with a significance less than 5σ while the $\Omega_c(3119)$ state is not confirmed. In addition, there is an indication that there is a wide excess at higher mass consistent with LHCb. The spectra of the candidates selected at LHCb and at Belle is shown in Figure 4. Most of the theoreticians identified these states as the orbitally or radial excitations [11] of the Ω_c baryon but there are also ideas that they could be pentaquark states [12, 13, 14]. The narrowness of the states might be a hint that it is difficult to get apart the two s quarks in a $c(ss)$ system.

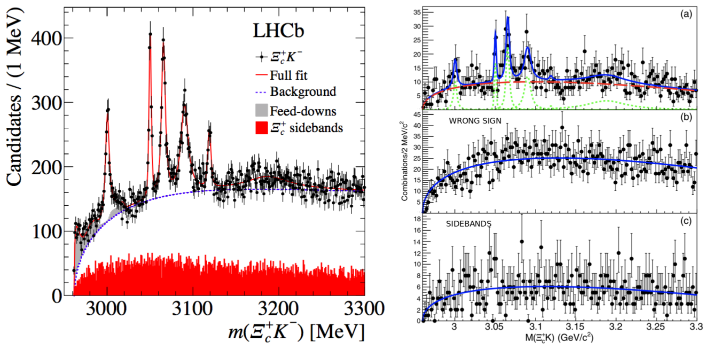

Figure 4: Reconstructed invariant mass $m(\Xi_c^+K^-)$ spectra for the LHCb (left) and Belle (right) candidates.

5. Double-charmed baryons

Doubly heavy baryons predicted by the quark model are a mostly unexplored region. They can provide a unique system for QCD tests with two heavy constituent quarks. The SELEX experiment claimed the observation of the Ξ_{cc}^+ state in $\Lambda_c^+K^-\pi^+$ [15] and in D^+K^-p [16] final states measuring an unexpected short lifetime, $\tau < 33\,\mathrm{fs}$ @ 90% CL. Other experiments did not confirm the existence of this state [17, 18, 19].

The LHCb experiment searched for the $\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^-$ with $\Lambda_c^+ \to pK^-\pi^+$ using $2.0\,\mathrm{fb}^{-1}$ of data collected at 8 TeV (2012) and $1.7\,\mathrm{fb}^{-1}$ collected at 13 TeV (2016) [20]. Using the 2016 data sample, shown in Figure 5, the mass is measured $m(\Xi_c^{++}) = 3621.40 \pm 0.72(stat) \pm 0.27(syst) \pm 0.14(\Lambda_c^+)\,\mathrm{MeV/c^2}$ and it is consistent with the theoretical range of predictions. On the other hand, it is very different from the SELEX measurement being shifted of $\sim 100\,\mathrm{MeV}$. The Ξ_{cc}^+ state observed by SELEX is inconsistent with being the isospin partner of the Ξ_{cc}^{++} state.

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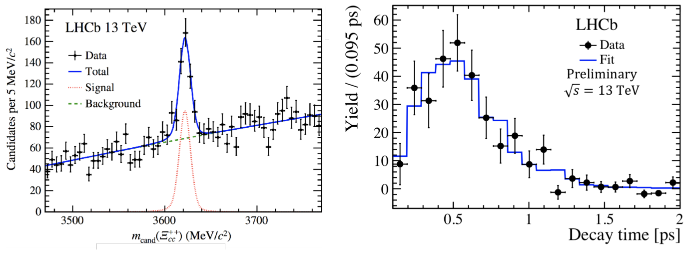

Figure 5: With a yield of 313 ± 33, a highly significant peak (12.9σ) is visible in the Ξ_{cc}^{++} reconstructed invariant mass (left) and the decay time distribution of the Ξ_{cc}^{++} state using $\Xi_c^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decays (right) is shown.

Lifetime measurement is crucial to establish the weak nature of the Ξ_{cc}^{++} decay and for comparison with the short lifetime measured by SELEX and the theoretical predictions. A lifetime measurements is performed using the $\Xi_c^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decay relative to the control channel $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$ using $\sim 1.7\,\mathrm{fb}^{-1}$ collected at 13 TeV [21]. The decay time distribution, shown in Figure 5, is fitted obtaining $\tau_{\Xi_{cc}^{++}} = 0.256^{+0.224}_{-0.022}(stat) \pm 0.014(syst)$ ps, a value compatible with a weak decay and inconsistent with SELEX measurement.

Searching for new decays allows to understand the dynamics of doubly heavy baryons where an interference between the decay amplitudes of the two heavy quark can happen. The search of the $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ decay with $\Xi_c^+ \to pK^- \pi^+$ uses an integrated luminosity of $1.7\,\mathrm{fb}^{-1}$ collected at a centre-of-mass-energy of 13 TeV [22]. With a yield of 91 ± 20 and a significance of 5.9σ, a new decay mode of the Ξ_{cc}^{++} state is observed. The mass is measured and it is compatible with the previous result by LHCb and with theoretical expectations.

The search of $\Xi_{cc}^{++} \to D^+ pK^- \pi^+$ decay with $D^+ \to K^- \pi^+ \pi^+$ is performed at LHCb using $1.7\,\mathrm{fb}^{-1}$ of data collected at 13 TeV [23]. The search of this channel is motivated by the excellent trigger for the $D^+ \to K^- \pi^+ \pi^+$ channel and from the branching fraction of this channel which is expected to be similar to the branching fraction of the $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decay. No signal is observed and un upper limit on the ratio of the branching fraction with respect to the normalizing channel is set. A better understanding of the resonance contributions is necessary, since dynamical effects or spin constraints in the resonance structures could be suppressing this decay.

6. Conclusions

A great interest is active in discovering new baryon states and measuring their properties. There are good experimental prospects with the LHCb upgrade program, with the start of the data taking of Belle II and with a new run at $\Lambda_c^+ \Lambda_c^-$ pair threshold at BESIII.

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