We report new measurements relative to charmed hadron spectroscopy and measurement of charm hadron properties by the LHCb collaboration. Two new $\Xi^+_c$ baryons are observed, and the lifetimes of the $\Lambda^+_c$, $\Xi^0_c$ and $\Xi^+_c$ 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 $\Xi^0_c \to \Lambda^+_c\pi^-$ are observed for the first time. The most precise measurement of $\Xi^{++}_c$ mass and production ratio is performed. Finally, the $\Xi^{++}_c$ baryon is searched for in the $\Lambda^+_cK^-\pi^+$ final state.
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 $\Xi_c^0$ 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 $\Omega_c^0$ 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 $\Lambda_c^+(\rightarrow p K^- \pi^+) K^-$ 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.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass [MeV/$c^2$]</th>
<th>$\Gamma$ [MeV/$c^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi_c(2923)^0$</td>
<td>2923.04 ± 0.25 ± 0.24</td>
<td>7.1 ± 0.8 ± 1.8</td>
</tr>
<tr>
<td>$\Xi_c(2939)^0$</td>
<td>2938.55 ± 0.21 ± 0.22</td>
<td>10.2 ± 0.8 ± 1.1</td>
</tr>
<tr>
<td>$\Xi_c(2965)^0$</td>
<td>2964.88 ± 0.26 ± 0.20</td>
<td>14.1 ± 0.9 ± 1.3</td>
</tr>
</tbody>
</table>

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 $\Xi_c^0$ to $\Lambda_c^+$ baryons $f_{\Xi_c^0}/f_{\Lambda_c^+}$ is estimated as $C \cdot f_{\Xi_b^0}/f_{\Lambda_b^+}$, where $C$ is a correction factor for feed-downs of excited $\Xi_b$ baryons that do not have equal rates to $\Xi_b^-$ and $\Xi_b^0$ final states. The second method uses the branching fraction
of \( \Xi_c^+ \rightarrow pK^−\pi^+ \) measured by Belle [5]. Taking the weighted average value of the two methods, the branching fraction of \( \Xi_c^0 \rightarrow \Lambda_c^+\pi^− \) is determined to be \( \mathcal{B}(\Xi_c^0 \rightarrow \Lambda_c^+\pi^−) = (0.55 \pm 0.02 \text{ (stat)} \pm 0.18 \text{ (syst)})\% \). The \( \mathcal{B}(\Xi_c^+ \rightarrow pK^−\pi^+) \) is determined to be \( (1.135 \pm 0.002 \text{ (stat)} \pm 0.387 \text{ (syst)})\% \) using \( \mathcal{B}(\Lambda_c^+ \rightarrow pK^−\pi^+) \) as normalisation [6].

4. Observation of doubly Cabibbo-suppressed decay \( \Xi_c^+ \rightarrow p\phi \)

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, \( \Lambda_c^+ \rightarrow pK^+\pi^- \), has been observed [8, 9].

In this work the ratio of branching fractions between the \( \Xi_c^+ \rightarrow p\phi \) and \( \Xi_c^+ \rightarrow pK^-\pi^+ \) 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 \( \Xi_c^+ \rightarrow p\phi \) decay, a two-dimensional unbinned extended maximum likelihood fit to the \( m_{pK^-\pi^+} \) and \( m_{K^+\pi^-} \) distributions is performed. The resulting relative branching fraction ratio with respect to the singly Cabibbo-suppressed \( \Xi_c^+ \rightarrow pK^-\pi^+ \) 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 \( \Xi_c^+ \rightarrow p\phi \) decay is observed for the first time, and an evidence at the level of 3.5 \( \sigma \) is found for a non-\( \phi \) contribution to the \( \Xi_c^+ \rightarrow pK^+K^- \) decay.

5. Precision measurement of the \( \Lambda_c^+ \), \( \Xi_c^+ \) and \( \Xi_c^0 \) 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 \( \Omega_c^0 \) lifetime that was nearly four times larger than, and inconsistent with, the world average value [11]. Given the overall relatively poor precision on the \( \Lambda_c^+, \Xi_c^+ \) and \( \Xi_c^0 \) 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 \( \Omega_c^0 \) lifetime measurement, the lifetimes are measured using samples of semileptonic \( H_b \rightarrow H_c\mu\nu_X \) decays, where \( H_b \) represents a \( \Lambda_c^0, \Xi_c^0 \) or \( \Xi_c^- \) baryon and \( H_c \) corresponds to a \( \Lambda_c^+, \Xi_c^+ \) or \( \Xi_c^0 \), 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

\[
\tau_{\Lambda_c^+} = 203.5 \pm 1.0 \pm 1.9 \text{ fs}, \\
\tau_{\Xi_c^+} = 456.8 \pm 3.5 \pm 4.2 \text{ fs}, \\
\tau_{\Xi_c^0} = 154.5 \pm 1.7 \pm 1.9 \text{ fs},
\]

where the first uncertainty is statistical and the second is systematic [12]. The \( \Lambda_c^+ \) and \( \Xi_c^+ \) lifetimes are measured with about 1% precision and are consistent with the existing world averages. The \( \Xi_c^0 \) lifetime is measured with about 1.8% precision, and is 3.3\( \sigma \) larger than the world average value of
112^{+13}_{-10} \text{ 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 $\Xi^{++}_{cc}$ mass

The doubly charmed baryon $\Xi^{++}_{cc}$ (ccu) was first observed by the LHCb collaboration in 2017 via the $\Xi^{++}_{cc} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ decay channel, with $\Lambda_c^+$ decaying to the $p K^- \pi^+$ final state [13]. This observation was then confirmed in another decay channel, $\Xi^{++}_{cc} \rightarrow \Xi^+_c \pi^+$ with $\Xi^+_c$ decaying to $p K^- \pi^+$ final state [14]. The $\Xi^{++}_{cc}$ mass was measured to be 3621.24±0.65 (stat)±0.31 (syst) MeV/c$^2$. Theoretical calculations of the $\Xi^{++}_{cc}$ 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 $\Xi^{++}_{cc}$ mass is still large compared to that of the singly charmed baryons.

In this work, the $\Xi^{++}_{cc}$ mass was measured using the $\Xi^{++}_{cc} \rightarrow \Lambda_c^+(\rightarrow p K^- \pi^+) K^- \pi^+ \pi^+$ and $\Xi^{++}_{cc} \rightarrow \Xi^+_c (\rightarrow p K^- \pi^+) \pi^+$ 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 $\Xi^{++}_{cc}$ mass using the $\Xi^{++}_{cc} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi^{++}_{cc} \rightarrow \Xi^+_c \pi^+$ decay modes are 3621.53±0.24 (stat)±0.29 (syst) MeV/c$^2$, and 3621.95±0.60 (stat)±0.49 (syst) MeV/c$^2$, respectively. By combining these two measurements the $\Xi^{++}_{cc}$ mass is determined to be 3621.55 ± 0.23 (stat) ± 0.30 (syst) MeV/c$^2$ [16]. This is the most precise measurement of the $\Xi^{++}_{cc}$ mass to date.

7. Measurement of $\Xi^{++}_{cc}$ 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 $\Xi^{++}_{cc}$ 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 $\Xi^{++}_{cc} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ decay, is measured relative to the prompt $\Lambda_c^+$ production cross-section, $\sigma(\Lambda_c^+)$, in the transverse momentum range $4 < p_T < 15 \text{ GeV}/c$ and the rapidity range $2.0 < y < 4.5$. The production ratio is defined as

$$R \equiv \frac{\sigma(\Xi^{++}_{cc}) \times B(\Xi^{++}_{cc} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)}.$$

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 $\Xi^{++}_{cc}$ 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 $\Xi^{+}_{cc}$

The doubly charmed baryon $\Xi^{+}_{cc}$ was first reported by the SELEX collaboration with its decays into $\Lambda_c^+ K^- \pi^+$ and $p D^* K^-$ [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 $\Xi^+_c$ search by the LHCb collaboration using only 2011 data [24]. The largest local significance is about 3.1$\sigma$ in region around 3620 MeV$/c^2$. Taking into account the look-elsewhere effect the global significance is about 1.7$\sigma$. Upper limits are set at 95% credibility level on the ratio of the $\Xi^+_c$ production cross-section times the branching fraction to that of the $\Lambda^+ (R(\Lambda^+_c))$ and $\Xi^{++}_c (R(\Xi^{++}_c))$ baryons. The limits are determined as functions of the $\Xi^+_c$ 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 $R(\Lambda^+_c)(R(\Xi^{++}_c))$ depends strongly on the considered mass and lifetime of the $\Xi^+_c$ 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 $\Xi^0_c$ states [3], and the lifetime of $\Lambda^+_c$, $\Xi^0_c$ and $\Xi^+_c$ are measured with significantly improved precision [12], the first observation of suppressed decays of $\Xi^+_c \rightarrow p\phi$ and $\Xi^0_c \rightarrow \Lambda^+_c\pi^-$ [6, 10], and the most precise measurement of $\Xi^{++}_c$ mass and production ratio [16, 18], and last is the search of $\Xi^+_c$ [26]. More results of charm spectroscopy at LHCb are expected soon.

References

[9] Roel Aaij et al. Measurements of the branching fractions of $\Lambda_c^+ \to p\pi^-\pi^+$, $\Lambda_c^+ \to p\pi^-K^+$, and $\Lambda_c^0 \to p\pi^-K^+$. JHEP, 03:043, 2018.

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