Studies of $\Xi_c$ baryons at LHCb

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Abstract. The LHCb detector at the Large Hadron Collider is one of the best instruments for charmed baryon spectroscopy available today. Due to its unique design and characteristics as well as stable operation of the LHC, the detector enables measurements of rare and suppressed decays with high accuracy. The report is devoted to the recent observations of the suppressed decays of the baryons $\Xi^+_c$ and $\Xi^0_c$ and search for $CP$ violation in $\Xi^+_c$ baryon decays that were performed by the LHCb collaboration.

1. Introduction
Modern studies in baryon physics are aided by various features of high precision experimental setups. Despite the fact that studies using $e^+e^-$ collisions are the more clean research method, experiments on hadron colliders often provide more data. Moreover, a Lorentz boost provides an opportunity to measure lifetimes of weakly decaying particles, as well as to separate prompt-production and production in decay chains of heavier hadrons. Among the existing detectors on hadron colliders, the LHCb experiment [1] excels due to its excellent particle identification and vertex reconstruction capabilities. This opens up great possibilities for studying rare and suppressed decays, as well as performing baryon spectroscopy in general.

The LHCb detector is located at Large Hadron Collider in CERN. It is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for studies of particles containing $b$ or $c$ quarks. The performance values of LHCb are presented in the table 1.

| Table 1. The LHCb detector performance. |
|----------------------------------------|
| Parameter | Performance value |
| Pseudorapidity: | $2 < \eta < 5$ |
| Polar angle: | $10 < \theta < 250$ mrad |
| Resolution | $\Delta p/p = 0.5\%$ (low p) |
| Trigger efficiency: | $90\%$ for dimuon decays |
| ECAL resolution | $1\% + 10\% / \sqrt{E}$ [GeV] |
| Tracking efficiency: | $96\%$ for long tracks |
| Kaon ID: | $95\%$ for $5\% \pi \rightarrow K$ mis-id |
| Muon ID: | $97\%$ for $1-3\% \pi \rightarrow \mu$ mis-id |
The LHCb experiment collected a data sample corresponding to 9.1 fb\(^{-1}\) of integrated luminosity in two data taking periods, named Run I (2010-12) and Run II (2015-18). This review is devoted to LHCb results for charmed baryons containing both strange and charm quarks (\(\Xi^+_c, \Xi^0_c\) and their excited states).

2. Observation of the doubly Cabibbo-suppressed decay \(\Xi^+_c \rightarrow p\phi\)

Rates of the different decay processes of charm baryons are governed by the elements of the Cabibbo–Kobayashi–Maskawa (CKM) matrix. Among the CKM matrix elements that appear in the corresponding amplitude of the quark transition, \(V_{us}\) and \(V_{cd}\) have smaller magnitudes than \(V_{ud}\) and \(V_{cs}\). This provides a corresponding classification of decays: Cabibbo-favoured (CF), which don’t contain \(u \rightarrow s\) or \(c \rightarrow d\) transitions; singly Cabibbo-suppressed (SCS), containing one of them; and doubly Cabibbo-suppressed (DCS), containing both.

The DCS decays are interesting because they can provide information about a role of non-spectator quark and the hierarchy of the lifetimes of charmed baryons \[^2\]. Prior to 2019 only one DCS decay channel had been observed for the charm baryons \[^3, 4\]. Recently, the LHCb experiment discovered a DCS decay of the \(\Xi^+_c\) baryon into the \(p\phi\) decay channel \[^5\]. The measurement is based on data sample of pp collisions collected in 2012 with the LHCb detector at the centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 2 fb\(^{-1}\). The leading order quark diagram for the \(\Xi^+_c \rightarrow p\phi\) decay is shown in figure 1.

\[
\Xi^+_c \rightarrow p\phi
\]

Figure 1. The \(\Xi^+_c \rightarrow p\phi\) decay diagram.

The branching fraction for the observed \(\Xi^+_c \rightarrow p\phi\) DCS decay has been measured with respect to the \(\Xi^+_c \rightarrow pK^-\pi^+\) decay channel:

\[
R_{p\phi} = \frac{B(\Xi^+_c \rightarrow p\phi)}{B(\Xi^+_c \rightarrow pK^-\pi^+)}.
\]  

The \(pK^+K^-\) final state in a mass region of interest is selected using kinematical and particle identification requirements. The \(\Xi^+_c\) baryon manifests in the \(M_{pK^+K^-}\) spectrum as a peak on top of a smooth background distribution for the candidates with \(M_{K^+K^-}\) around \(\phi\) meson peak (see figure 2(a)). The corresponding spectrum for \(M_{K^+K^-}\) is shown on figure 2(b). The fraction of \(\phi\) component is calculated using maximum likelihood fit of the background subtracted \(M_{K^+K^-}\) spectrum. An sPlot unfolding technique is used for this purpose \[^6\]. The fit model contains \(\phi\) signal, parameterized with a relativistic Breit-Wigner distribution convolved with a detector resolution function and non-\(\phi\) contribution described by a Flatte parameterization of a \(f_0(980)\) lineshape.

The ratio of the branching fractions \(R_{p\phi}\) is measured to be \((19.8 \pm 0.7 \pm 0.9 \pm 0.2) \times 10^{-3}\), where the first uncertainty is statistical, the second is systematic and the third due to the knowledge of the \(\phi \rightarrow K^+K^-\) branching fraction.
3. Observation of new $\Xi^0_c$ baryons decaying to $\Lambda_c^+ K^-$

The LHCb experiment is excellent for baryon spectroscopy studies. An example is the simultaneous discovery of the five new narrow excited states of the $\Omega_c^0$ baryon in the $\Xi_c^0 K^-$ final state [7]. A similar analysis has recently been performed using the the $\Lambda_c^+ K^-$ final state [8] in a mass region close to the $\Xi_c(2930)^0$ baryon announced by Belle experiment [9] and $\Xi_c(2970)^0$ reported by BaBar collaboration [10].

The analysis is performed using a data sample of $pp$ collisions collected by the LHCb detector at the centre-of-mass energy of 13 TeV corresponding to an integrated luminosity of 5.6 fb$^{-1}$. Three peaking contribution as well as couple of additional structures on top of a smooth background distribution are visible in the mass spectrum covering 300 MeV/c$^2$ range above the $\Lambda_c^+ K^-$ threshold (see figure 3).
partially reconstructed the $\Xi_c(3055)^0$, $\Xi_c(3055)^+$, $\Xi_c(3080)^0$ and $\Xi_c(3080)^+$ baryons decays, where the pion is not reconstructed.

A maximum likelihood fit of the mass distribution has been performed to extract masses and widths of the narrow structures, which were parameterized by an S-wave relativistic Breit-Wigner distribution convolved with the detector resolution function. Lineshapes of partially reconstructed contributions were determined from simulations. The mass resolution was estimated from simulations also, and varies from 1.7 to 2.2 MeV/c$^2$ in the mass range of interest.

Measured parameters of resonances are presented in table 2, where the first uncertainties are statistical, second systematic and the third corresponds to the present knowledge of the $\Lambda_c^+$ mass.

### Table 2. Extracted parameters for the observed resonances.

| Resonance     | Peak of $\Delta M$ [MeV] | Mass [MeV] | $\Gamma$ [MeV] |
|---------------|--------------------------|------------|----------------|
| $\Xi_c(2923)^0$ | 142.91 ± 0.25 ± 0.20    | 2923.04 ± 0.20 ± 0.14 | 7.1 ± 0.8 ± 1.8 |
| $\Xi_c(2939)^0$ | 158.45 ± 0.21 ± 0.17    | 2938.55 ± 0.17 ± 0.14 | 10.2 ± 0.8 ± 1.1 |
| $\Xi_c(2965)^0$ | 184.75 ± 0.26 ± 0.14    | 2964.88 ± 0.14 ± 0.14 | 14.1 ± 0.9 ± 1.3 |

The $\Xi_c(2930)^0$ state observed by Belle might be interpreted as an overlap of the states $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$. Parameters of the observed $\Xi_c(2965)^0$ resonance are significantly different with respect to the parameters of the previously reported $\Xi_c(2970)^0$ state. A future investigation using additional final states will probably help to distinguish whether the $\Xi_c(2965)^0$ and $\Xi_c(2970)^0$ states are different baryons.

### 4. First branching fraction measurement for the suppressed decay $\Xi_c^0 \rightarrow \Lambda_c^+\pi^-$

The $\Xi_c^0$ baryon decays via transitions of the charm quark. However, transformations of the $s$ quark are also possible, via the transition $s \rightarrow u\bar{u}d$ and $cs \rightarrow dc$ weak scattering. Quark diagrams corresponding to these amplitudes are shown in figure 4.

![Quark diagrams](image)

**Figure 4.** Decay diagrams for the $\Xi_c^0 \rightarrow \pi^-\Lambda_c^+$ decay. (a) The $s \rightarrow u\bar{u}d$ amplitude. (b) The $cs \rightarrow dc$ amplitude.

A signal interpreted as $\Xi_c^0 \rightarrow \Lambda_c^+\pi^-$ decay was observed by the Belle collaboration [11]. However, no branching fraction measurement was done for this decay channel. Recently, the LHCb collaboration provided the first measurement of the branching fraction for this decay [12].

A measurement this branching ratio is hampered by the lack of accurately measured $\Xi_c^0$ branching fractions to be used for normalization. The LHCb collaboration measured two ratios.
of yield related with the branching fraction of interest:

\[
R_1 = \frac{N(\Xi^0_c)}{N(\Lambda^+_c)} = \frac{f_{\Xi^0_c}}{f_{\Lambda^+_c}} \cdot B(\Xi^0_c \rightarrow \pi^- \Lambda^+_c),
\]

(2)

\[
R_2 = \frac{N(\Xi^0_c)}{N(\Xi^+_c)} = \frac{f_{\Xi^0_c}}{f_{\Xi^+_c}} \cdot \frac{B(\Lambda^+_c \rightarrow pK^- \pi^+)}{B(\Xi^+_c \rightarrow pK^- \pi^+)} \cdot B(\Xi^0_c \rightarrow \pi^- \Lambda^+_c),
\]

(3)

where \(N(Q)\) indicates the efficiency corrected number of signal events for baryon \(Q\), \(f_Q\) indicates the fraction of particle production with respect to total \(c\)- or \(b\)-quark production. Both ratios are measured from signals of promptly produced charm baryons. Corresponding mass spectrum for \(\Xi^0_c\) is presented in the figure 5.

\[\text{Figure 5.} \quad \text{Reconstructed mass distribution and signal fit for the } \Xi^0_c \rightarrow \Lambda^+_c K^- \text{ decay.}\]

The ratio \(f_{\Xi^0_c}/f_{\Lambda^+_c}\) is estimated from recent LHCb measurements for production fractions of beauty baryons and from heavy-quark symmetry \[13\]. According to heavy-quark symmetry, the fragmentation fractions are related as \(f_{\Xi^0_c}/f_{\Lambda^+_c} = CF_{\Xi^0_b}/f_{\Lambda^+_b}\), where \(C\) is a correction for feed-downs from excited \(\Xi_b\) baryons. The ratio \(f_{\Xi^0_c}/f_{\Xi^+_c}\) is considered to be close to the unity by isospin symmetry reason \[14\]. The value of \(B(\Xi^+_c \rightarrow pK^- \pi^+)\) is taken from recent Belle measurement \[15\].

Using this method to normalise the decay rates, the branching fraction \(B(\Xi^0_c \rightarrow \pi^- \Lambda^+_c)\) is determined to be \((0.55 \pm 0.02 \pm 0.18) \times 10^{-2}\), where the first uncertainty is statistical and second systematic.

5. Search for \(CP\) violation in \(\Xi^+_c \rightarrow pK^- \pi^+\) using model-independent techniques

In 2019, the LHCb collaboration reported the observation of \(CP\) violation (\(CPV\)) in the decays of charmed mesons \[16\]. This entailed several analysis searching for \(CPV\) in the decays of charm baryons. For example, no \(CP\) asymmetry was observed in decays of the \(\Lambda^+_c\) baryon into \(pK^- K^-\) and \(p\pi^+ \pi^-\) final states \[17\].

A recent search for \(CPV\) in decays of the \(\Xi^+_c\) baryon to the \(pK^- \pi^+\) final state has also been made \[18\]. The analysis is based on a data sample collected by the LHCb experiment in \(pp\) collisions at 7 and 8 TeV in 2011-12. The search for \(CPV\) in these decays was carried out using model independent approaches through a direct comparison between the Dalitz plots for decays of \(\Xi^+_c\) and \(\Xi^-_c\). The Dalitz plot for the \(\Xi^+_c\) decay is presented in figure 4. The analysis of possible
6. Conclusions

Four analyses, which are presented in this review, clearly demonstrate that the LHCb detector is an excellent and stable tool for precise measurements in the charm physics sector. The experimental mass resolution for charmed baryons is on a few MeV/c² level, which is undoubtedly nice for new baryon states studies. The ability of precise particle identification and huge sample sizes allow to measure a branching fractions for rare decays and suppressed decays with good accuracy. Due to this high performance we can confidently expect more interesting results from LHCb in the future.

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