Search for $CP$ violation in $\Xi_c^+ \rightarrow pK^-\pi^+$ decays using model-independent techniques

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Abstract

A first search for $CP$ violation in the Cabibbo-suppressed $\Xi_c^+ \rightarrow pK^-\pi^+$ decay is performed using both a binned and an unbinned model-independent technique in the Dalitz plot. The studies are based on a sample of proton-proton collision data, corresponding to an integrated luminosity of 3.0 fb$^{-1}$, and collected by the LHCb experiment at centre-of-mass energies of 7 and 8 TeV. The data are consistent with the hypothesis of no $CP$ violation.

Submitted to Eur. Phys. J. C

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1 Introduction

The non-invariance of fundamental interactions under the combination of charge conjugation and parity transformation, known as CP violation (CPV), is a key requirement for the generation of the baryon-antibaryon asymmetry in the early Universe [1,2]. In the Standard Model (SM) of particle physics, CPV is included through the introduction of a single irreducible complex phase in the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix [3,4]. The amount of CPV predicted by the CKM mechanism is not sufficient to explain a matter-dominated universe [5,6] and other sources of CPV are required. The realization of CPV in nature has been well established in the K- and B-meson systems by several experiments [7–13]. The LHCb experiment has observed for the first time CPV in the charm-meson sector as the difference of the CP asymmetries between the two-body decays $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ [14]. A similar study using $\Lambda_c^+ \rightarrow pK^- \pi^+$ has found no evidence for CPV [15]. Indeed, so far CPV has never been observed in any baryon system. Evidence for CPV in the b baryon sector reported by the LHCb collaboration in [16] has not been confirmed with more data [17]. Further measurements of processes involving the decay of charm hadrons can shed light on the origin and magnitude of CPV mechanisms within the SM and beyond.

In two-body decays of charm hadrons, CPV can manifest itself as an asymmetry between partial decay rates. Multi-body decays offer access to more observables which are sensitive to CP-violating effects. For a three-body baryon decay the kinematics can be characterised by three Euler angles and two squared invariant masses forming the Dalitz plot [18]. The Euler angles are redundant if all initial spin states are integrated over. Interference effects in the Dalitz plot probe CP asymmetries in both the magnitudes and phases of the amplitudes. In three-body decays there can be large local CP asymmetries in the Dalitz plot, even when no significant global CPV exists. A recent example has been measured in the decay $B^+ \rightarrow \pi^+ \pi^- \pi^+$ [19].

In the SM, CPV asymmetries in the charm sector are expected at the order of $10^{-3}$ or less [20] for singly Cabibbo-suppressed (SCS) decays. New physics (NP) contributions can enhance CP-violating effects up to $10^{-2}$ [21–29]. Searches for CPV in $\Xi_c^+$ baryon decays [3] provide a test of the SM and place constraints on NP parameters [30–34]. In contrast to SCS decays, in Cabibbo-favoured (CF) charm-quark transitions, such as $\Lambda_c^+ \rightarrow pK^- \pi^+$ decays, there is only one dominant amplitude in the SM, resulting in no CP-violating effects.

This article describes searches for direct CPV in the SCS decay $\Xi_c^+ \rightarrow pK^- \pi^+$ produced promptly in $pp$ collisions. The $\Lambda_c^+ \rightarrow pK^- \pi^+$ decay is used as a control mode to study on data the level of experimental asymmetries that pollute the measurement. In this paper, the symbol $H_c^+$ is used to refer to both $\Xi_c^+$ and $\Lambda_c^+$. It is assumed that the polarisation of charm baryons produced in $pp$ collisions is sufficiently small to justify the integration over the Euler angles. This measurement uses $pp$ collision data, corresponding to an integrated luminosity of 3 fb$^{-1}$, recorded by the LHCb detector in Run 1. About 1 fb$^{-1}$ is collected in 2011 at a centre-of-mass energy of 7 TeV and 2 fb$^{-1}$ are collected in 2012 at a centre-of-mass energy of 8 TeV. The magnetic field polarity is reversed regularly during the data taking in order to minimise effects of charged particle and antiparticle detection asymmetries. Approximately half of the data are collected with each polarity.

1Unless stated explicitly, the inclusion of charge-conjugate states is implied throughout.
There is presently no successful method for computing decay amplitudes in multi-body charm decays, which could provide reliable predictions on how the CP asymmetries vary over the phase space of the decay. This situation favours a model-independent approach, which looks for differences between multivariate density distributions for baryons and antibaryons. Therefore, in this article searches for CPV are performed through a direct comparison between the Dalitz plots of \( \Xi^{-} \) and \( \Xi^{+} \) decays using a binned significance \((S_{CP})\) method \cite{35} and an unbinned k-nearest neighbour method (kNN) \cite{36-39}, both of which are model independent.

2 Detector and simulation

The LHCb detector \cite{40,41} is a single-arm forward spectrometer covering the pseudorapidity range \( 2 < \eta < 5 \). It is designed for the study of particles containing \( b \) and \( c \) quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the \( pp \) interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The tracking system provides a measurement of the momentum, \( p \), of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/c. The minimum distance of a track to a primary vertex (PV), the impact parameter (IP), is measured with a resolution of \((15 + 29/p_{T})\) \( \mu m \), where \( p_{T} \) is the component of the momentum transverse to the beam, in GeV/c. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadron calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

Samples of simulated events are used to optimise the signal selection, to derive the angular efficiency and to correct the decay-time efficiency. In the simulation, \( pp \) collisions are generated using PYTHIA \cite{42} with a specific LHCb configuration \cite{43}. Decays of hadronic particles are described by EVTGEN \cite{44}, in which final-state radiation is generated using PHOTOS \cite{45}. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit \cite{46} as described in Ref. \cite{47}.

3 Selection of signal candidates

The online event selection is performed by a trigger consisting of a hardware stage, based on information from the calorimeter and muon systems, followed by two software stages. At the hardware trigger stage, events are required to have either muons with high \( p_{T} \) or hadrons, photons or electrons with a high transverse-energy deposit in the calorimeters. In the first software trigger stage at least one good-quality track with a large \( p_{T} \) is required. In the second software trigger stage, an \( H_{c}^{+} \) candidate is fully reconstructed by the association of three high-quality tracks forming a secondary vertex of the \( H_{c}^{+} \) candidate (SV) which must be well separated from any PV, and the tracks should not pointing to any PV. Requirements are also placed on \( p \) and \( p_{T} \) of the \( H_{c}^{+} \) candidate; on
the scalar sum of $p_T$ for the three tracks; on the particle identification criteria of the tracks; and on the direction vector from the associated PV to the $H_c^+$ candidate decay vector and the SV, where the associated PV is that with the least IP $\chi^2$ with respect to the $H_c^+$ candidate.

In the offline analysis, tighter selection requirements are placed on the track-reconstruction quality, the $p_T$ and $p$ of the final-state particles. Additional requirements are also made on the SV fit quality, and the minimum significance of the displacement from the SV to any PV in the event. This reduces the contribution of charm baryons from $b$-hadron decays to less than 5% of the prompt signal. Fiducial requirements are imposed to exclude kinematic regions characterised by large detection asymmetries between particles and antiparticles. Reconstructed particles are accepted if their momenta are within a region defined by $|p_x| < 0.2p_z$ and $|p_x| > 0.01p_z$, where $p_x$ and $p_z$ are the momentum components along the $x$ and $z$ axes. Large detection asymmetries occur in certain kinematic regions because, for a given magnet polarity, particles of one charge with low $p$ or flying with small polar angles may be deflected outside of the detector acceptance or into the LHC beam pipe, whereas particles of the opposite charge remain within the LHCb detector acceptance. About 25% of the selected charm-baryon candidates are rejected by these fiducial requirements. Differences in reconstruction efficiencies are also observed for candidates where $p < 20$ GeV/c for all charged tracks. These differences do not cancel by simply averaging the data acquired with opposite magnet polarities. To minimise the difference of the reconstruction efficiency for particles and anti-particles, the momentum of all tracks is required to be greater than 20 GeV/c. This requirement rejects about 20% of the selected charm-baryon candidates.

The distributions of the invariant-mass, $M(pK^−\pi^+)$, of selected $\Lambda_c^+$ and $\Xi_c^+$ candidates are presented in Figs. 1 and 2, respectively. The fitted curves are overlaid. The model comprises a sum of two Gaussian functions describing the signal and a second-order Chebyshev polynomial function describing the combinatorial background. No additional source of background is found to contribute significantly.

The final samples used for the $CPV$ search comprise all candidates with $M(pK^−\pi^+)$ within $±3\sigma$ around $m(\Lambda_c^+)$ or $m(\Xi_c^+)$, where $\sigma$ is the weighted average of the two fitted Gaussian widths and $m(\Lambda_c^+)$ and $m(\Xi_c^+)$ are the masses of the $\Lambda_c^+$ and $\Xi_c^+$ baryons. There are approximately 2.0 million $\Lambda_c^+$ candidates (0.4 million in the 2011 and 1.6 million in the 2012 data sample) and 0.25 million $\Xi_c^+$ candidates (0.05 million in the 2011 and 0.2 million in the 2012 data sample). The purity for $\Lambda_c^+$ decays is 94% for 2011 and 98% for 2012 and that for $\Xi_c^+$ decays is 77% for 2011 and 78% for 2012.

4 Methods

The Dalitz plot for $H_c^+ \rightarrow pK^−\pi^+$ is described by the squares of the invariant masses of two pairs of the decay products: $M^2(K^−\pi^+)$ and $M^2(pK^-)$. Polarisation effects for the $H_c^+$ baryons are neglected. Comparisons of the Dalitz plots of $H_c^+$ and $H_c^−$ candidates are performed using the binned $S_{CP}$ and the unbinned $kNN$ methods, described in the following. For both the binned $S_{CP}$ and unbinned $kNN$ methods, a signal of $CPV$ is
established if a $p$-value lower then $3 \times 10^{-7}$ is found, corresponding to an exclusion of $CP$ symmetry with a significance of five standard deviations. However, in case that no CPV is found, there is no model-independent mechanism for setting an upper limit on the amount of CPV in the Dalitz plot.
4.1 Binned \( S_{CP} \) method

In the \( S_{CP} \) method the Dalitz plots of particles and antiparticles are divided using an identical binning. The \( S_{CP} \) method [35] has been used before for hypothesis testing in charm and beauty decays [39, 49–52]. This method is used to search for localised asymmetries in the phase space of the decay \( H_+^c \rightarrow pK^--\pi^+ \) and is based on a bin-by-bin comparison between the Dalitz plots of baryons, \( H_+^c \), and antibaryons, \( H_+^c \). For each bin \( i \) of the Dalitz plot, the significance of the difference between the number of \( H_+^c \) (\( n_+^i \)) and \( H_+^c \) (\( n_-^i \)) candidates, \( S_{CP}^i \), is computed as

\[
S_{CP}^i = \frac{n_+^i - \alpha n_-^i}{\sqrt{\alpha(n_+^i + n_-^i)}},
\]

where the factor \( \alpha \) is defined as \( \alpha = \frac{n_+}{n_-} \) and \( n_+ \), \( n_- \) are the total number of \( \Lambda_c^+ \) (\( \Xi_c^+ \)), \( \Lambda_c^- \) (\( \Xi_c^- \)) candidates. This factor accounts for spurious asymmetries arising in the production of \( \Lambda_c^+ \) or \( \Xi_c^+ \) baryons, as well as in the detection of the final-state particles. The production and global detection asymmetries are assumed not to depend on the Dalitz plot position.

A numerical comparison between the Dalitz plots of the \( H_+^c \) and \( H_+^c \) candidates is made using a \( \chi^2 \) test defined as

\[
\chi^2 \equiv \Sigma(S_{CP}^i)^2.
\]

This test is performed using a minimum of 10 \( H_+^c \) and 10 \( H_+^c \) candidates in each bin. A \( p \)-value for the hypothesis of no CPV is obtained considering that the number of degrees of freedom is equal to the total number of bins minus one, due to the constraint on the factor \( \alpha \) of the overall \( H_+^c \) and \( H_+^c \) normalisation.

In the hypothesis of no CPV, the \( S_{CP} \) values are expected to be distributed according to the normal distribution with a mean of zero and a standard deviation of unity. In case of CPV, a deviation from the normal distribution is expected, generating a \( p \)-value close to zero.

4.2 Unbinned kNN method

The kNN method is based on the concept of a set of nearest neighbour candidates (\( n_k \)) in a combined sample of two data sets: baryons and antibaryons. As an unbinned method, the kNN approach is more sensitive to a CPV search in a sample with limited data, compared to that of the binned \( S_{CP} \) method. The kNN method is used here to test whether baryons and antibaryons share the same parent distribution function [36, 38]. To find the \( n_k \) nearest neighbour events of each \( H_+^c \) and \( H_+^c \) candidates, an Euclidean distance between closest points in the Dalitz plot is used. A test statistic \( T \) for the null hypothesis is defined as

\[
T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i, k),
\]

where \( I(i, k) = 1 \) if the \( i \)th candidate and its \( k \)th nearest neighbour belong to the same sample of \( H_+^c \) or \( H_+^c \) candidates and \( I(i, k) = 0 \) otherwise.

The test statistic \( T \) is the mean fraction of like-charged neighbour pairs in the sample of \( H_+^c \) and \( H_+^c \) decays. The advantage of the kNN method, in comparison with other proposed methods for unbinned analyses [36], is that the calculation of \( T \) is simple and
fast and the expected distribution of $T$ is well known. Under the hypothesis of no CPV, $T$ follows a normal distribution with a mean, $\mu_T$, and a variance, $\sigma_T$, where

$$\mu_T = \frac{n_+(n_+ - 1) + n_-(n_- - 1)}{n(n - 1)},$$

$$\lim_{n,n_k,D \to \infty} \sigma_T^2 = \frac{1}{nn_k} \left( \frac{n_+n_-}{n^2} + 4 \frac{n_2^2n_2^2}{n^4} \right),$$

with $n = n_+ + n_-$ and $D = 2$ is the dimensionality of the tested distribution. The convergence of the limit is so fast that it can be used to obtain a good approximation of $\sigma_T$ even for $D = 2$ for certain values of $n_+$, $n_-$ and $n_k \geq 36$.

For $n_+ = n_-$ the mean $\mu_T$ can be expressed as

$$\mu_{TR} = \frac{1}{2} \left( \frac{n - 2}{n - 1} \right)$$

and is called the reference value, $\mu_{TR}$. For large $n$, $\mu_{TR}$ asymptotically tends to 0.5.

To increase the power of the kNN method, the Dalitz plot is divided into regions defined around the expected resonances. The Dalitz plot is partitioned into six regions for the decays of the $\Lambda_c^+$ control mode and eleven regions for signal $\Xi_c^+$ decays according to the present of resonances of the phase space, as shown in Fig. 3. For $\Lambda_c^+$ decays the $K^{*}(892)$, $K^{*}(1430)$, $\Lambda(1232)$, $\Lambda(1520)$, $\Lambda(1670)$, $\Lambda(1690)$ resonances are seen in data, whilst for $\Xi_c^+$ decays additional resonances are seen, namely $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1710)$, $\Lambda(1800)$, $\Lambda(1810)$, $\Lambda(1820)$, $\Lambda(1830)$, $\Lambda(1890)$, $\Delta(1600)$, $\Delta(1620)$ and $\Delta(1700)$. For $\Lambda_c^+$ decays there are four independent regions (R1–R4), whilst the region R2 is further split into the high $M^2(pK^-)$ region (R6) and the low $M^2(pK^-)$ region (R5). For $\Xi_c^+$ there are seven independent regions (R1–R7), whilst the region R2 is split in mass $M^2(pK^-)$ in two regions at larger mass (R9) and smaller mass (R8), R2=R8∪R9, similarly for R10 and R11, where R10=R4∪R5, and R11=R4∪R5∪R6∪R7. Region R0 is the full Dalitz plot. The definitions of the regions are given in Tables 1 and 2 for $\Lambda_c^+$ and $\Xi_c^+$ baryons, respectively.

| Region | Definition |
|--------|------------|
| R0     | Full Dalitz plot |
| R1     | $M^2(K^-\pi^+) < 0.7 \text{ GeV}^2/c^4$ |
| R2     | $0.7 \leq M^2(K^-\pi^+) < 0.9 \text{ GeV}^2/c^4$ |
| R3     | $M^2(K^-\pi^+) \geq 0.9 \text{ GeV}^2/c^4$, $M^2(pK^-) < 2.8 \text{ GeV}^2/c^4$ |
| R4     | $M^2(K^-\pi^+) \geq 0.9 \text{ GeV}^2/c^4$, $M^2(pK^-) \geq 2.8 \text{ GeV}^2/c^4$ |
| R5     | $0.7 \leq M^2(K^-\pi^+) < 0.9 \text{ GeV}^2/c^4$, $M^2(pK^-) < 3.2 \text{ GeV}^2/c^4$ |
| R6     | $0.7 \leq M^2(K^-\pi^+) < 0.9 \text{ GeV}^2/c^4$, $M^2(pK^-) \geq 3.2 \text{ GeV}^2/c^4$ |
The measured total raw asymmetry is defined as

$$A_{\text{Raw}} = \frac{n_- - n_+}{n_- + n_+},$$

(7)

Table 2: Definitions of the Dalitz plot regions for $\Xi_c^+ \to pK^+\pi^+$ decays.

| Region | Definition |
|--------|------------|
| R0     | Full Dalitz plot |
| R1     | $M^2(K^-\pi^+) < 0.7 \text{ GeV}^2/c^4$ |
| R2     | $0.7 \leq M^2(K^-\pi^+) < 0.9 \text{ GeV}^2/c^4$ |
| R3     | $0.9 \leq M^2(K^-\pi^+) < 1.3 \text{ GeV}^2/c^4$ |
| R4     | $M^2(K^-\pi^+) \geq 1.3 \text{ GeV}^2/c^4$, $M^2(pK^-) < 2.4 \text{ GeV}^2/c^4$ |
| R5     | $M^2(K^-\pi^+) \geq 1.3 \text{ GeV}^2/c^4$, $2.4 \leq M^2(pK^-) < 3.2 \text{ GeV}^2/c^4$ |
| R6     | $M^2(K^-\pi^+) \geq 1.3 \text{ GeV}^2/c^4$, $3.2 \leq M^2(pK^-) < 3.8 \text{ GeV}^2/c^4$ |
| R7     | $M^2(K^-\pi^+) \geq 1.3 \text{ GeV}^2/c^4$, $M^2(pK^-) \geq 3.8 \text{ GeV}^2/c^4$ |
| R8     | $0.7 \leq M^2(K^-\pi^+) < 0.9 \text{ GeV}^2/c^4$, $M^2(pK^-) < 4 \text{ GeV}^2/c^4$ |
| R9     | $0.7 \leq M^2(K^-\pi^+) < 0.9 \text{ GeV}^2/c^4$, $M^2(pK^-) \geq 4 \text{ GeV}^2/c^4$ |
| R10    | $M^2(K^-\pi^+) \geq 1.3 \text{ GeV}^2/c^4$, $M^2(pK^-) < 3.2 \text{ GeV}^2/c^4$ |
| R11    | $M^2(K^-\pi^+) \geq 1.3 \text{ GeV}^2/c^4$ |

5 Control mode, background and sensitivity studies

The $S_{\text{CP}}$ and kNN methods are tested using the $A_c^+ \to pK^+\pi^+$ control mode where the $CP$ asymmetry is expected to be null. The sidebands of $\Xi_c^+ \to pK^+\pi^+$ candidates in the mass regions $2320 < M(pK^-\pi^+) < 2445 \text{ MeV}/c^2$ and $2490 < M(pK^-\pi^+) < 2650 \text{ MeV}/c^2$ are used to check that the background does not introduce spurious asymmetries. The sensitivity of the methods is estimated using pseudoexperiments. Both the $S_{\text{CP}}$ and kNN methods are checked to fulfill the following requirements: the method should not indicate the presence of a spurious asymmetry and confirm such a signal if present.

The measured total raw asymmetry is defined as

$$A_{\text{Raw}} = \frac{n_- - n_+}{n_- + n_+},$$

(7)
and it depends on the production asymmetry of $H_{c}^{+}$ baryons and on the detection asymmetries that arise through charge-dependent selection efficiencies due to track reconstruction, trigger selection and particle identification. The measured value of $A_{\text{Raw}}$ in each region of the Dalitz plot of $\Lambda_{c}^{+} \rightarrow pK^{-}\pi^{+}$ decays is presented in Fig. 4. The measured $A_{\text{Raw}}$ value integrated over the Dalitz plot equals to $-0.0230 \pm 0.0016$ and $-0.0188 \pm 0.0008$ in the 2011 and 2012 data samples, where the uncertainties are statistical only. Within uncertainties, $A_{\text{Raw}}$ in all regions amounts to about $-2\%$. There is no significant difference between the 2011 and 2012 data samples. Since the production and detection asymmetries of $\Lambda_{c}^{+}$ baryons can depend on the baryon pseudorapidity, $\eta$, and $p_{T}$, the dependence of $A_{\text{Raw}}$ in regions of the Dalitz plot is checked in bins of $\eta$ and $p_{T}$ of the $\Lambda_{c}$ candidates, but for a given bin of $\eta$ and $p_{T}$ a constant behaviour of $A_{\text{Raw}}$ in regions of the Dalitz plot is obtained.

In the $S_{\text{CP}}$ method the production asymmetry and all global effects are considered by introducing the $\alpha$ factor, following the strategy described in Sec. 4.1. The $p$-values obtained are larger than 58\%, consistent with the absence of localised asymmetries. As an example, Fig. 3 shows the distribution of $S_{\text{CP}}$ for $\Lambda_{c}^{+} \rightarrow pK^{-}\pi^{+}$ decays considering uniform binning, and for two granularities of the Dalitz plot: 28 and 106 bins in the 2012 sample. Alternatively the Dalitz plot is divided into different size bins with the same population size in each bin. Typically, the $p$-values obtained are larger than 34\%, consistent with the hypothesis of absence of localised asymmetries.

Following the strategy described in Sec. 4.2, the results of the kNN method in regions of the Dalitz plot for the $\Lambda_{c}^{+} \rightarrow pK^{-}\pi^{+}$ control mode are presented in Fig. 6 for $n_{k} = 50$. The pulls, $(\mu - \mu_{T})/\Delta(\mu - \mu_{T})$, where $\Delta(\mu - \mu_{T})$ is the uncertainty on the difference $(\mu - \mu_{T})$, are different from zero in all regions. The largest effect is observed when integrated over the full Dalitz plot. This asymmetry is an effect of a nonzero production asymmetry that is presented in Fig. 4 and discussed above. Pulls of the test statistic $T$, $(T_{T}/\sigma_{T})$, vary within $-3$ and $+3$, consistent with the hypothesis of absence of localised asymmetries in any region. The difference among data-taking years are consistent with statistical fluctuations. The signal yield in 2012 is twice than that in 2011. Figure 6
Figure 5: Distributions of $S^i_{CP}$ and corresponding one-dimensional distributions for $\Lambda_c^+ \to pK^−\pi^+$ decays for the data collected in the 2012 data sample: (top row) 28 same-size bins and (bottom row) 106 same-size bins of the Dalitz plot. The number of analysed bins, nbins, and the $p$-values are given.

illustrates how the larger 2012 data sample improves the power of the kNN method. In Run 2 (years of data taking 2016, 2017 and 2018) the yield is expected to be about three times larger than that from Run 1.

The interaction cross-section of charged hadrons with matter depends on the charged hadron momentum. As such, the detection asymmetries of the proton and kaon-pion systems are momentum dependent. Pseudoexperiments are performed to check whether the detection asymmetries related to particles reconstructed in the final state are or not generating a spurious $CP$ asymmetry. The proton detection asymmetry varies from about 5% at low momentum to 1% at 100 GeV/c and is estimated using simulations. The kaon-pion detection asymmetry and its dependence on the kaon momentum is measured to vary from $-1.4\%$ at low momentum to $-0.7\%$ at 60 GeV/c [53]. The combined effect of the two asymmetries is found to cancel approximately and does not generate a spurious asymmetry.

These studies are repeated using the candidates in the sideband of the $\Xi_c^+ \to pK^−\pi^+$ mass distribution. No spurious $CP$ asymmetry is found for both methods. For further cross-checks, the control samples are divided according to the polarity of the magnetic
Figure 6: (Top left) pulls, \((\mu_T - \mu_{TR})/\Delta (\mu_T - \mu_{TR})\), and (top right) the corresponding \(p\)-values, (bottom left) pull values of the test statistic \(T\) and (bottom right) the corresponding \(p\)-values in a given region for control \(\Lambda_c^+ \rightarrow pK^-\pi^+\) candidate decays obtained using the kNN method with \(n_k = 50\) for data collecting in 2011 (stars) and 2012 (dots). The horizontal lines in the left figures represent -3 and +3 pull values. R0 corresponds to full Dalitz plot and R2 is separated into R5 and R6, and these regions are correlated and separated by dashed lines.

The expected statistical power of both methods is obtained by performing pseudoexperiments. A total one hundred samples of \(\Xi_c^+ \rightarrow pK^-\pi^+\) decays are generated each with a yield and purity equivalent to that observed in the combined 2011 and 2012 data samples, resulting in 200 000 \(\Xi_c^+\) decays generated in each pseudoexperiment. In this model, the two-dimensional Dalitz plots are generated assuming that the \(\Xi_c^+\) baryons are produced unpolarised. The model for \(\Xi_c^+ \rightarrow pK^-\pi^+\) decays is built by including the resonances observed in the data, using the same software as in Ref. [54]. The same resonances as described in Sec. 4.2 are included. The statistical powers of the two methods are found to be comparable. Both methods are sensitive to a 5\% \(CP\) asymmetry in the \(K^+(892)\) and \(\Delta(1232)\) resonance regions, and signals with 3 and 5 sigma significances would be observed in 69\% and 10\% of the cases for the kNN method and 17\% and 10\% of the cases for the \(S_{CP}\) method, respectively.
\begin{align*}
M(pK^-) \text{[GeV/c]} & = 2 \text{GeV/c}^2 \\
M^2(K\pi^+) \text{[GeV/c]} & = 2 \text{GeV/c}^2
\end{align*}

Figure 7: Distributions of $S_{CP}$ and corresponding one-dimensional distributions for $\Xi_c^+ \rightarrow pK^-\pi^+$ decays for the combined data collected 2011 and 2012: (top row) 29 uniform bins and (bottom row) 111 uniform bins of the Dalitz plot. The number of analysed bins and the $p$-values are given.

6 Results

6.1 Binned $S_{CP}$ method

The binned $S_{CP}$ method is applied to look for local CP asymmetries in $\Xi_c^+ \rightarrow pK^-\pi^+$ decays following the strategy described in Sec. 4.1. The measured $p$-values as well as the $S_{CP}$ distributions are shown in Fig. 7 for the combined 2011 and 2012 data samples. Two binning schemes are tested: 29 and 111 uniform bins. The normalization factor $\alpha$, defined in Eq. 1, is determined to be $1.029 \pm 0.004$. The measured $p$-values using a $\chi^2$ test are larger than 32%, consistent with no evidence for CPV. The obtained $S_{CP}$ distributions agree with a normal distribution. It is also checked that the results in the 2011 and 2012 data samples are consistent with each other.
6.2 Unbinned kNN method

The unbinned kNN method is applied to look for $CP$ asymmetry in $\Xi^+_c \rightarrow pK^-\pi^+$ decays, following the strategy described in Sec. 4.2. The results are presented in Fig. 8 for $n_k = 50$ for the merged 2011 and 2012 data samples. The measured pull values, $((\mu_T - \mu_{TR})/\Delta(\mu_T - \mu_{TR}))$, are different from zero. The largest effect is observed integrated over the full Dalitz plot. This is due to the expected nonzero production and detector asymmetries, that is presented in Fig. 9. The measured $A_{Raw}$ is constant within uncertainties in all regions.

The pulls of the test statistic $T$, $((T - \mu_T)/\sigma_T)$, shown in Fig. 8 vary within $-3$ and $+3$, consistent with the hypothesis of absence of localised asymmetries. To check for any systematic effects the kNN test is repeated for the individual 2011 and 2012 data samples as well as for samples separated according to the polarity of the magnetic field. All obtained results are compatible within uncertainties and no systematic effects are observed.

Since the sensitivity of the method can depend on the $n_k$ parameter, the analysis is repeated with different values of $n_k$ from 10 up to 3000. Only $T$ and $\sigma_T$ depend on $n_k$. Pulls of statistic $T$ are shown in Fig. 10. All results show no significant deviation from the hypothesis of $CP$ symmetry.

7 Conclusions

Model-independent searches for $CP$ violation in $\Xi^+_c \rightarrow pK^-\pi^+$ decays are presented using the binned $S_{CP}$ and the unbinned kNN methods. The $\Lambda^+_c \rightarrow pK^-\pi^+$ candidates and the sideband regions of $\Xi^+_c \rightarrow pK^-\pi^+$ candidates are used to ensure that no spurious charge asymmetries affect the methods. Both methods are sensitive to $CP$ asymmetry larger than a 5% in the regions around the $K^*(892)$ and the $\Delta(1232)$. The obtained results are consistent with the absence of $CP$ violation in $\Xi^+_c \rightarrow pK^-\pi^+$ decays.

Acknowledgements

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MSHE (Russia); MinECo (Spain); SNSF and SER (Switzerland); STFC (United Kingdom); NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and OSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from AvH Foundation (Germany); EPLANET, Marie Sklodowska-Curie Actions and ERC (European Union); ANR, Labex P2IO and OCEVU, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, and the Thousand Talents Program (China); RFBR, RSF
Figure 8: (Top left) pulls, $(\mu_T - \mu_{TR})/\Delta(\mu_T - \mu_{TR})$, and (top right) the corresponding $p$-values; (bottom left) pull values of the test statistic $T$ and (bottom right) the corresponding $p$-values for a given region for signal $\Xi_c^+ \rightarrow pK^-\pi^+$ candidate decays obtained using the kNN method with $n_k = 50$ for combined data collected 2011 and 2012. The horizontal lines in the left figures represent $-3$ and $+3$ pull values. R0 corresponds to full Dalitz plot and R2 is separated into R8 and R9, R10 is separated into R4 and R5, R11 is separated into R4, R5, R6 and R7, and these regions are correlated and separated by dashed lines.

and Yandex LLC (Russia); GVA, XuntaGal and GENCAT (Spain); the Royal Society and the Leverhulme Trust (United Kingdom); Laboratory Directed Research and Development program of LANL (USA).
Figure 9: The measured $A_{\text{Raw}}$ in regions in signal $\Xi^+_c \rightarrow pK^-\pi^+$ candidate decays for the combined data collected in 2011 and 2012. R0 corresponds to full Dalitz plot and R2 is separated into R8 and R9, R10 is separated into R4 and R5, R11 is separated into R4, R5, R6 and R7, and these regions are correlated and separated by dashed lines.

Figure 10: (Left) the pull values of the test statistic $T$ and (right) the corresponding $p$-value dependence on the $n_k$ parameter for the whole Dalitz plot (region R0) for $\Xi^+_c \rightarrow pK^-\pi^+$ candidate decays obtained using the kNN method for the combined data collected in 2011 and 2012. The horizontal lines in the left figures represent $-3$ and $+3$ pull values. The points are determined with different $n_k$ using same data sample, therefore are correlated.
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23 INFN Sezione di Genova, Genova, Italy
24 INFN Sezione di Milano-Bicocca, Milano, Italy
25 INFN Sezione di Milano, Milano, Italy
26 INFN Sezione di Cagliari, Monserrato, Italy
27 INFN Sezione di Padova, Padova, Italy
28 INFN Sezione di Pisa, Pisa, Italy
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40 Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia
41 Yandex School of Data Analysis, Moscow, Russia
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