Search for CP violation using triple product asymmetries in 
\( \Lambda_c^0 \rightarrow pK^−\pi^+\pi^− \), \( \Lambda_c^0 \rightarrow pK^-K^+K^- \) and \( \Xi_b^0 \rightarrow pK^-K^-\pi^+ \) decays

LHCb collaboration

Abstract

A search for CP and P violation using triple-product asymmetries is performed with \( \Lambda_c^0 \rightarrow pK^-\pi^+\pi^- \), \( \Lambda_c^0 \rightarrow pK^-K^+K^- \) and \( \Xi_b^0 \rightarrow pK^-K^-\pi^+ \) decays. The data sample corresponds to integrated luminosities of 1.0 fb\(^{-1}\) and 2.0 fb\(^{-1}\), recorded with the LHCb detector at centre-of-mass energies of 7 TeV and 8 TeV, respectively. The CP- and P-violating asymmetries are measured both integrating over all phase space and in specific phase-space regions. No significant deviation from CP or P symmetry is found. The first observation of \( \Lambda_c^0 \rightarrow pK^-\chi_c(1P)(\rightarrow \pi^+\pi^-, K^+K^-) \) decay is also reported.

Published in JHEP 08 (2018) 039

© 2018 CERN for the benefit of the LHCb collaboration. CC-BY-4.0 licence

†Authors are listed at the end of this paper.
1 Introduction

The study of matter-antimatter asymmetries in $B$-meson decays contributed to establishing the validity of the Cabibbo-Kobayashi-Maskawa (CKM) mechanism for $CP$ violation in the Standard Model (SM). By contrast, no $CP$ violation has been observed in the baryon sector to date. However, sizeable $CP$-violating asymmetries of up to 20% are expected in certain $b$-baryon decays \[1\], and a systematic study will either confirm the CKM mechanism in baryon decays, or will bring insights into new sources of $CP$ violation. Recently the first evidence for $CP$ violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays has been reported by the LHCb collaboration, with a statistical significance corresponding to 3.3 standard deviations \[2\].

In this article, a search for $CP$ violation based on triple-product asymmetries in charmless $\Lambda_b^0 \to pK^−\pi^+\pi^−$, $\Lambda_b^0 \to pK^−K^+K^−$ and $\Xi_b^0 \to pK^−K^−\pi^+$ decays is presented.\[3\] In all of these decays, the transitions are mainly mediated by $b \to us\bar{u}$ tree and $b \to s\bar{u}u$ penguin diagrams, with a relative weak phase, $\arg(V_{ub}V_{us}^*/V_{tb}V_{ts}^*)$, that in the SM is dominated by the CKM angle $\gamma$ \[3\]. With this relative phase, $CP$ violation could arise from the interference of these amplitudes, with the sensitivity enhanced by the rich resonant structure in $\Lambda_b^0$ and $\Xi_b^0$ four-body decays. The symbol $X_b^0$ is used throughout this article to refer to both $\Lambda_b^0$ and $\Xi_b^0$ baryons.

Asymmetries in the triple products of final-state momenta are expected to be sensitive to new physics \[4\]–\[6\]. The triple product of final-state particle momenta in the $X_b^0$ centre-of-mass frame is defined as $C_T = \vec{p}_f \cdot (\vec{p}_{h1} \times \vec{p}_{h2})$, where $h_1 = K^-$, $h_2 = \pi^+$ for the $\Lambda_b^0 \to pK^−\pi^+\pi^−$ decay, $h_1 = K_{fast}^−$, $h_2 = K^+$ for the $\Lambda_b^0 \to pK^−K^+K^−$ decay and $h_1 = K_{fast}^−$, $h_2 = \pi^+$ for the $\Xi_b^0 \to pK^−K^−\pi^+$ decay. The kaon labelled as “fast (slow)” is that with the highest (lowest) momentum among those with the same charge. The triple product $C_T$ is defined similarly for $\Xi_b^0$ baryons using the momenta of the charge conjugate particles.

Two $T$-odd asymmetries are defined based on the operator $\hat{T}$ that reverses the spin and the momentum of the particles \[7\]–\[12\]. This operator is different from the time-reversal operator, which reverses also the initial and final state. The asymmetries are defined as

$$A_T = \frac{N(C_T > 0) - N(C_T < 0)}{N(C_T > 0) + N(C_T < 0)},$$

$$\bar{A}_T = \frac{N(-C_T > 0) - N(-C_T < 0)}{N(-C_T > 0) + N(-C_T < 0)},$$

where $N$ and $\bar{N}$ are the numbers of $X_b^0$ and $\bar{X}_b^0$ decays. The $P$- and $CP$-violating observables are defined as

$$a_P^{T-{	ext{odd}}} = \frac{1}{2} (A_T + \bar{A}_T), \quad a_P^{T-{	ext{odd}}} = \frac{1}{2} (A_T - \bar{A}_T),$$

and a significant deviation from zero in these observables would indicate $P$ violation and $CP$ violation, respectively. In contrast to the asymmetry between the phase-space integrated rates, $a_P^{T-{	ext{odd}}}$ is sensitive to the interference of $\hat{T}$-even and $\hat{T}$-odd amplitudes and has a different sensitivity to strong phases \[13\]–\[14\]. The observables $A_T$, $\bar{A}_T$, $a_P^{T-{	ext{odd}}}$ and $a_P^{T-{	ext{odd}}}$ are, by construction, largely insensitive to $X_b^0/\bar{X}_b^0$ production asymmetries.

\[1\]Unless stated otherwise, charge-conjugated modes are implicitly included throughout this article.
and detector-induced charge asymmetries of the final-state particles [15]. In the present paper, these quantities are measured integrated over all the phase space and in specific phase-space regions.

2 Detector and simulation

The LHCb detector [16, 17] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing $b$ or $c$ 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 magnetic field is reversed periodically in order to cancel detection asymmetries. The tracking system provides a measurement of momentum, $p$, of charged particles with a relative uncertainty that varies from 0.5% at 5 GeV/$c$ to 1.0% at 200 GeV/$c$. The minimum distance of a track to a primary vertex, the impact parameter, is measured with a resolution of $(15 + 29/p_T)$ µm, 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 calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The online event selection is performed by a trigger, which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. Candidates are required to pass both hardware and software trigger selections. The hardware trigger identifies the hadron daughters of the $X^0_b$ or events containing candidates generated from hard $pp$ scattering collisions. The software trigger identifies four-body decays that are consistent with a $b$-hadron decay topology, and which have final-state tracks originating from a secondary vertex detached from the primary $pp$ collision point.

In the simulation, $pp$ collisions are generated using Pythia [18] with a specific LHCb configuration [19]. Decays of hadronic particles are described by EvtGen [20], in which final-state radiation is generated using Photos [21]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [22] as described in Ref. [23].

3 Candidate selection

The analysis is based on data recorded with the LHCb detector at centre-of-mass energies of 7 TeV and 8 TeV, corresponding to integrated luminosities of 1.0 fb$^{-1}$ and 2.0 fb$^{-1}$, respectively.

The $X^0_b$ candidates are formed from combinations of tracks that originate from a good quality common vertex. The tracks are identified as $p$, $K$ or $\pi$ candidates with loose particle identification (PID) requirements providing proton, kaon, and pion identification efficiency of 94%, 96% and 99%, respectively, with a pion misidentification rate to proton (kaon) of 5% (9%) and a kaon misidentification rate to pion of 30%. The proton or
antiproton identifies the candidate as a $X^0_b$ baryon or $\bar{X}^0_b$ antibaryon. Reconstructed tracks are required to have $p_T > 250$ MeV/$c$ and $p > 1.5$ GeV/$c$, and are required to be displaced from any primary vertex. The latter requirement is imposed by selecting tracks with $\chi^2_{IP} > 16$, where $\chi^2_{IP}$ is the change of the primary-vertex fit $\chi^2$ when including the considered track. Only $X^0_b$ candidates with a transverse momentum $p_T > 1.5$ GeV/$c$ are retained. To ensure that the $X^0_b$ baryon is produced in the primary interaction, it is required that $\chi^2_{IP}(X^0_b) < 16$, and the flight direction of the $X^0_b$ decay, calculated from its associated primary vertex, defined as that with minimum $\chi^2_{IP}(X^0_b)$, and the decay vertex, must align with the reconstructed particle momentum with an angle that satisfies $\cos \theta > 0.9999$.

Decays of $X^0_b$ baryons to charm hadrons represent a source of background that originates from $b \to c$ transitions. Such background is vetoed by rejecting candidates with combinations of two or three final-state particles that have reconstructed invariant masses compatible with weakly decaying charm hadron states or with the $J/\psi$ resonance. Among the vetoed candidates, those listed in Table 1 are used for assessing systematic uncertainties and for selection criteria optimization. Backgrounds from a pion or a kaon misidentified as a proton originating from $B^0$ and $B^0$ decays with a $\phi$ or $K^*(892)^0$ resonance are suppressed by vetoing the region within 10 and 70 MeV/$c^2$ of the $\phi$ and $K^*(892)^0$ invariant masses, respectively, after applying the relevant substitution of the particle mass hypotheses.

Table 1: Selection window for control samples used to assess systematic uncertainties and for selection criteria optimization.

<table>
<thead>
<tr>
<th>Decay</th>
<th>Selection window</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A^0_b \to A^+_c (\to pK^-\pi^+)\pi^-\pi^-$</td>
<td>$2.23 &lt; m(pK^-\pi^+) &lt; 2.31$ GeV/$c^2$ ($[-7.5\sigma, 4.5\sigma]$)</td>
</tr>
<tr>
<td>$A^0_b \to D^0 (\to K^-\pi^+)p\pi^-$</td>
<td>$1.832 &lt; m(K^-\pi^+) &lt; 1.844$ GeV/$c^2$ ($[-3\sigma, 3\sigma]$)</td>
</tr>
</tbody>
</table>

A boosted decision tree (BDT) classifier [24] is used to suppress combinatorial background. Background from other $b$ hadrons is suppressed by means of PID requirements. The $A^0_b \to pK^-\pi^+\pi^-$ decay, which is the final state of interest with the largest yield, is used to train the classifier, since its kinematics and topology are very similar to those of $A^0_b \to pK^-K^+\pi^-$ and $\Xi^0_b \to pK^-K^-\pi^+$ decays. The signal training sample is obtained by subtracting the background using the sPlot technique and a fit to the invariant mass distribution [25]. The candidates from the sideband, $5.85 < m(pK^-\pi^+\pi^-) < 6.40$ GeV/$c^2$, are selected as the background training sample. The discriminating variables included in the BDT are the proton transverse and longitudinal momenta $p_T$ and $p_z$; the impact parameter of the $K$ and $\pi$ candidate tracks with respect to the $X^0_b$ primary vertex; the $\chi^2$ of the $X^0_b$ decay vertex fit; the angle between the $X^0_b$ momentum and its flight direction; the $X^0_b$ IP; the asymmetry between the transverse momentum of the $X^0_b$ and that of the charged tracks contained in a region defined as $\sqrt{\Delta \eta^2 + \Delta \phi^2} < 1.0$, where $\Delta \eta$ ($\Delta \phi$) is the difference of pseudorapidity (azimuthal angle) between the candidate and the charged tracks. The most important discriminating variables are the proton transverse and longitudinal momentum, and the angle between the $X^0_b$ momentum and its flight direction. No correlation is found between the discriminating variables or between the BDT output and the reconstructed $b$-baryon candidate mass. The signal and background training samples are divided into three statistically independent subsamples with equal
number of candidates, on which k-fold cross-validation is applied [26]. The BDT selection criteria are optimised by maximising $S/\sqrt{S + B}$, where $S$ ($B$) is the expected signal (background) yield. The expected yield is estimated using $S = \epsilon_S S_0$ ($B = \epsilon_B B_0$), where the signal (background) efficiency $\epsilon_S$ ($\epsilon_B$) of each BDT selection requirement is evaluated using $A^0_b \rightarrow pK^-\pi^+\pi^-$ (data sideband) control samples; the reference signal (background) yield, $S_0$ ($B_0$), is obtained from a fit to the reconstructed invariant mass in the range [5.5 – 5.7] GeV/$c^2$ before applying the BDT selection.

The $A^0_b \rightarrow pD^0(\rightarrow K^-\pi^+)\pi^-$ sample is employed to optimise the PID selection since the momentum and pseudorapidity distributions of its final-state particles are similar to those of $A^0_b \rightarrow pK^-\pi^+\pi^-$, $A^0_b \rightarrow pK^-K^+K^-$ and $\Xi_b^0 \rightarrow pK^-\pi^+$ decays. The figure of merit that is maximised is defined as

$$S_{\text{PID}} = \frac{\epsilon_S(\text{PID}) \cdot N_S}{\sqrt{\epsilon_S(\text{PID}) \cdot N_S + \epsilon_B(\text{PID}) \cdot N_B}},$$

where the signal and background efficiencies of the PID selection criteria, $\epsilon_S(\text{PID})$ and $\epsilon_B(\text{PID})$, respectively, are determined using the $A^0_b \rightarrow pD^0(\rightarrow K^-\pi^+)\pi^-$ sample; $N_S$ ($N_B$) is the number of signal (background) candidates after applying the BDT selection. Multiple candidates are reconstructed in less than 1% of the selected events, and in such cases a single candidate is retained with a random but reproducible choice.

There are three main categories of background considered in the optimization process. Background from partially reconstructed decays is localised in the region at low invariant mass, and originates from $A^0_b \rightarrow p\pi^+K^-\rho^-(\rightarrow \pi^-\pi^0)$, $A^0_b \rightarrow p\pi^+\pi^-K^-\rho^-(\rightarrow \pi^-\pi^0)$ and similar decays, where the $\pi^0$ meson is not reconstructed. The background from misidentified final-state particles, called cross-feed in the following, consists of four-body decays, where one of them is reconstructed with the wrong mass hypothesis. The combinatorial background results from random combinations of tracks in the event.

4 Measurement of the CP-violating asymmetries

For each signal mode, the selected data sample is split into four subsamples according to the $X^0_b$ or $\overline{X}^0_b$ flavour and the sign of $C_T$ or $\overline{C}_T$. Simulated events and the $A^0_b \rightarrow A^+ (pK^-\pi^+)\pi^-$ control sample indicate that the reconstruction efficiencies for candidates with $C_T > 0$ ($-\overline{C}_T > 0$) and $C_T < 0$ ($-\overline{C}_T < 0$) are equal, within statistical uncertainties. For each final state, a simultaneous maximum likelihood fit to the $m(pK^-h^+h^-)$ distribution of the four subsamples is used to determine the number of signal and background yields and the asymmetries $A_T$ and $\overline{A}_T$. The $P$- and CP-violating asymmetries, $a_{T,\text{odd}}$ and $a_{CP,\text{odd}}$, are then obtained according to Eq. (3).

The invariant-mass distribution of the $X^0_b$ signal is modelled by the sum of two Crystal Ball functions [27] that share the peak value and width but have tails on opposite sides of the peak. The parameters related to the tails and the relative fraction of the two Crystal Ball functions are determined from fits to simulated samples, and are fixed in fits made to data. The $\Xi^0_b$ signal is also visible in the $m(pK^-\pi^+\pi^-)$ and $m(pK^-K^+K^-)$ invariant-mass distributions, and its peak value is fitted by imposing a Gaussian constraint using the known value of the mass difference of the $\Xi^0_b$ and $A^0_b$ baryons, 174.8 $\pm$ 2.5 MeV/$c^2$ [28]. The combinatorial background distribution is modelled by an exponential function with the rate parameter determined from the data. Partially reconstructed $A^0_b$ decays are described
The results of the first approach are obtained by fitting the full data sample and found to be compatible with the previously measured branching fractions \( \lambda \), once the selection efficiencies are taken into account. In the \( \Lambda^0_b \to pK^-\pi^+\pi^- \) and the \( \Lambda^0_b \to pK^-K^+K^- \) decay modes, signals consistent with the \( \chi_{c0}(1P) \) charmonium resonance are observed in the \( \pi^+\pi^- \) and the \( K^+K^- \) invariant-mass distributions, which are shown in Figs. 1, 2, and 3 respectively. The signal yields, 19,877 \( \pm \) 195, 5,297 \( \pm \) 83, and 709 \( \pm \) 45, respectively, are considered uncorrelated among the bins, while systematic uncertainties are assumed for all bins. The statistical uncertainty is the sum of the statistical and systematic covariance matrices. An average systematic uncertainty, discussed in Section 5, is assumed for all bins. The statistical uncertainties may have better sensitivity to \( CP \) violation. Therefore, measurements in specific phase-space regions and measurements in specific phase-space regions. The results of the first approach are obtained by fitting the full data sample and found to be compatible with \( P \) and \( CP \) symmetries, as shown in Table 2.

Two different approaches have been used to search for \( CP \) violation: a measurement integrated over the phase space and measurements in specific phase-space regions. The results of the first approach are obtained by fitting the full data sample and found to be compatible with \( P \) and \( CP \) symmetries, as shown in Table 2.

The \( CP \)-violating asymmetries may vary over the phase space due to the interference between resonant contributions. Therefore, measurements in specific phase-space regions may have better sensitivity to \( CP \) violation. In order to avoid biases, the binning schemes used to divide up the phase space were chosen before examining the data. Two binning schemes are used for the \( \Lambda^0_b \to pK^-\pi^+\pi^- \) \( \Lambda^0_b \to pK^-K^+K^- \) decay. Schemes A and B (C and D) are designed to isolate regions of phase space according to the dominant resonant contributions and to exploit the potential interference of contributions as a function of the angle \( \Phi \) between the decay planes formed by the \( pK^- \) \( (pK^-) \) and the \( \pi^+\pi^- \) \( (K^+K^-) \) systems, respectively. Scheme A (C) is defined in Table 4 in Appendix B, while scheme B (D) has twelve (ten) nonoverlapping bins of width \( \pi/12 \) \( (\pi/10) \) in \( \Phi \). The size of the bins, and the resulting statistical uncertainty, is chosen to have sensitivity at the level of a few percent. The same fit model used for the integrated measurement is employed to fit each phase-space region. The distribution of asymmetries for the \( \Lambda^0_b \to pK^-\pi^+\pi^- \) \( \Lambda^0_b \to pK^-K^+K^- \) decay is shown in Fig. 4 (5), and the results are reported in Table 5 (6) in Appendix B.

The compatibility with the \( CP \)-symmetry \((P\)-symmetry\) hypothesis is tested for each scheme individually by means of a \( \chi^2 \) test, where the \( \chi^2 \) is defined as \( R^TV^{-1}R \), with \( R \) the array of \( a^P_{\text{odd}} \) \( (a^P_{\text{odd}}) \) measurements and \( V^{-1} \) the inverse of the covariance matrix, which is the sum of the statistical and systematic covariance matrices. An average systematic uncertainty, discussed in Section 5, is assumed for all bins. The statistical uncertainties are considered uncorrelated among the bins, while systematic uncertainties are assumed to be fully correlated. The results are consistent with the \( CP \)-symmetry hypothesis with a \( p \)-value of 0.93 \( (0.55) \), based on \( \chi^2/\text{ndf} = 7.2/14 \) \( (10.8/12) \) for scheme A (B) and a \( p \)-value of 0.95 \( (0.99) \), based on \( \chi^2/\text{ndf} = 2.1/7 \) \( (2.2/10) \) for scheme C (D). A similar \( \chi^2 \) test is performed on the \( a^P_{\text{odd}} \) measurements. The results are consistent with the \( P \)-symmetry hypothesis with a \( p \)-value of 0.53 \( (0.80) \), based on \( \chi^2/\text{ndf} = 13.0/14 \) \( (7.8/12) \) for scheme A.
Table 2: Measurements of the CP- and P-violating observables $a^\text{P-odd}_{CP}$ and $a^\text{P-odd}_P$, together with their statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th></th>
<th>$\Lambda^0_b \to pK^+\pi^+\pi^-$</th>
<th>$\Lambda^0_b \to pK^-K^+K^-$</th>
<th>$\Sigma^0_b \to pK^-K^-\pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a^\text{P-odd}_{CP}$ (%)</td>
<td>$-0.60 \pm 0.84 \pm 0.31$</td>
<td>$-1.56 \pm 1.51 \pm 0.32$</td>
<td>$-3.04 \pm 5.19 \pm 0.36$</td>
</tr>
<tr>
<td>$a^\text{P-odd}_P$ (%)</td>
<td>$-0.81 \pm 0.84 \pm 0.31$</td>
<td>$1.12 \pm 1.51 \pm 0.32$</td>
<td>$-3.58 \pm 5.19 \pm 0.36$</td>
</tr>
</tbody>
</table>

Figure 1: Distributions of the $pK^-\pi^+\pi^-$ invariant mass in the four samples defined by the $\Lambda^0_b$ ($\bar{\Lambda}^0_b$) flavour and the sign of $C_\bar{\rho}$ ($C_{\bar{\rho}}$). The results of the fit are overlaid as described in the legend. The contribution of the cross-feeds to the fit results is barely visible but is found to be nonnegligible.

(B) and a $p$-value of 0.18 (0.73), based on $\chi^2/\text{ndf}= 10.1/7$ (6.9/10) for scheme C (D).
which is assigned as a systematic uncertainty for the measured asymmetry is consistent with zero with a statistical uncertainty of 0.31%.

To assess the systematic uncertainty for the measurements in regions of the phase space, the $\Lambda^0_b \rightarrow \Lambda^+_c (\rightarrow pK^−\pi^+)\pi^−$ control sample is split in ten bins of the angle $\Phi$ between the

5 Evaluation of systematic uncertainties

The sources of systematic uncertainty and their relative contributions to the total uncertainty are listed in Table 3. The main source of systematic uncertainty is due to the experimental reconstruction and analysis technique, which could introduce potential biases in the measured asymmetries. This is tested by measuring the asymmetry $a_{CP}^{T,\text{odd}}(\Lambda^+_c\pi^-)$ for the Cabibbo-favoured $\Lambda^0_b \rightarrow \Lambda^+_c\pi^-\pi^−$ decay mode, where negligible $CP$ violation is expected. The measured asymmetry is consistent with zero with a statistical uncertainty of 0.31%, which is assigned as a systematic uncertainty for $a_{CP}^{T,\text{odd}}$ for the integrated measurement over the full phase space. The systematic uncertainty on $a_{CP}^{T,\text{odd}}$ is identical to that on $a_{CP}^{T,\text{odd}}$, as follows from Eq. 3.

To assess the systematic uncertainty for the measurements in regions of the phase space, the $\Lambda^0_b \rightarrow \Lambda^+_c (\rightarrow pK^−\pi^+)\pi^−$ control sample is split in ten bins of the angle $\Phi$ between the
within statistical uncertainties of the control sample and the signal MC, and likewise for the bins, is estimated from simulated samples of the asymmetry measurements. Similarly, the reconstruction efficiencies over $|\hat{T}|$ and $|\hat{\Delta}|$ cross-feed to the fit results is barely visible but is found to be nonnegligible.

decay planes of $pK^-$ and $\pi^+\pi^-$. The resulting distribution of $d_{CP}^{\text{odd}}$ is fitted with various models, all of which give results consistent with no asymmetry with a statistical precision of 0.6%. This statistical precision is assigned as a systematic uncertainty in each bin of the different binning schemes A, B, C and D.

The reconstruction efficiencies for signal candidates of opposite sign of $C_{\vec{\tau}}$ are identical within statistical uncertainties of the control sample and the signal MC, and likewise for $C_{\vec{\tau}}$, which indicates that the detector and the reconstruction technique do not bias the asymmetry measurements. Similarly, the reconstruction efficiencies over $|\hat{\Phi}|$ and four-body phase space are also identical for events with opposite sign of $C_{\vec{\tau}}$ and $C_{\vec{\tau}}$. For the measurements of the triple products $C_{\vec{\tau}}$ and $C_{\vec{\tau}}$, the systematic uncertainty from detector-resolution effects, which could introduce a migration of signal decays between the bins, is estimated from simulated samples of $A_\theta^0 \rightarrow pK^-\pi^+\pi^-$, $A_\theta^0 \rightarrow pK^-K^+K^-$ and $\Xi_b^0 \rightarrow pK^-K^+\pi^-$ decays, where neither $P$- nor $CP$-violating effects are present. The

Figure 3: Distributions of the $pK^-K^-\pi^+$ invariant mass in the four samples defined by the $\Xi_b^0$ ($\Xi_b^0$) flavour and the sign of $C_{\vec{\tau}}$ ($C_{\vec{\tau}}$). The results of the fit are overlaid as described in the legend. The contribution of the $B^0 \rightarrow K^-K^+\pi^-$ cross-feed to the fit results is barely visible but is found to be nonnegligible.
Asymmetries [%]

Phase space region

0 5 10 20

\( a^{T}_{P} \) $\chi^2$/ndf=7.2/14

20

LHCb

Asymmetries [%]

Phase space region

0 5 10 20

\( a^{T}_{CP} \) $\chi^2$/ndf=13.0/14

20

LHCb

Asymmetries [%]

Phase space region

0 1 2 3

\( a^{T}_{P} \) $\chi^2$/ndf=2.1/7

20

LHCb

Asymmetries [%]

Phase space region

0 1 2 3

\( a^{T}_{CP} \) $\chi^2$/ndf=6.9/10

20

LHCb

Figure 4: The asymmetries using binning schemes (left) A and (right) B for the \( \Lambda_0^0 \to pK^-\pi^+\pi^- \) decay. For \( a^{T}_{P \text{-odd}} \) \( (a^{T}_{CP \text{-odd}}) \), the values of the $\chi^2$/ndf for the $P$-symmetry ($CP$-symmetry) hypothesis, represented by a dashed line, are quoted.

Figure 5: The asymmetries using binning schemes (left) C and (right) D for \( \Lambda_0^0 \to pK^-K^+K^- \) decay. For \( a^{T}_{P \text{-odd}} \) \( (a^{T}_{CP \text{-odd}}) \), the values of the $\chi^2$/ndf for the $P$-symmetry ($CP$-symmetry) hypothesis, represented by a dashed line, are quoted.

difference between the reconstructed and generated asymmetry is taken as systematic uncertainty and is less than 0.05% in all cases.

The systematic uncertainties related to the choice of model for the signal and background components of the fits are evaluated by using alternative models that have comparable fit quality. The signal shape is varied by weighting the simulated sample with the PID efficiencies determined from data in order to account for possible discrepancies between data and simulation. The power and the threshold parameters of the empirical function for the partially reconstructed \( \Lambda_0^0 \) shape in the \( \Lambda_0^0 \to pK^-\pi^+\pi^- \) decay are floated in the alternative fit to data. The cross-feed backgrounds are described with one or two
Crystal Ball functions with the tail and fraction parameters fixed from fits to simulated samples. Ten thousand pseudoexperiments are generated using the alternative models with the same event yields determined in the fits to data. The nominal model is then fitted to each generated sample and the asymmetry parameters are extracted. As the bias observed is not significantly different from zero, the statistical uncertainty on the mean of the pulls is taken as the systematic uncertainty due to the model.

Further cross-checks are made to test the stability of the results with respect to different periods of data-taking, the different magnet polarities, the choice made in the selection of multiple candidates, and the effect of the trigger and selection criteria. The results of these checks are all statistically compatible with the nominal results, and no systematic uncertainty is assigned.

Table 3: Sources of systematic uncertainty and their relative contributions to the total uncertainty. Where present, the value in brackets shows the systematic uncertainty assigned to the measurement in specific phase-space regions.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>$\Lambda_b^0 \to pK^-\pi^+\pi^-(%)$</th>
<th>$\Lambda_b^0 \to pK^-K^+K^-(%)$</th>
<th>$\Xi_b^0 \to pK^-K^-\pi^+(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental bias</td>
<td>$\pm0.31$ ($\pm0.60$)</td>
<td>$\pm0.31$ ($\pm0.60$)</td>
<td>$\pm0.31$</td>
</tr>
<tr>
<td>$C_P$ resolution</td>
<td>$\pm0.01$</td>
<td>$\pm0.05$</td>
<td>$\pm0.02$</td>
</tr>
<tr>
<td>Fit model</td>
<td>$\pm0.03$</td>
<td>$\pm0.08$</td>
<td>$\pm0.19$</td>
</tr>
<tr>
<td>Total</td>
<td>$\pm0.31$ ($\pm0.60$)</td>
<td>$\pm0.32$ ($\pm0.61$)</td>
<td>$\pm0.36$</td>
</tr>
</tbody>
</table>

6 Conclusions

A search for $P$ and $CP$ violation is performed in four-body $\Lambda_b^0$ decays. Candidates are reconstructed in a data sample of $pp$ collisions collected with the LHCb detector in 2011 and 2012, corresponding to an integrated luminosity of 3 fb$^{-1}$. Samples of $\Lambda_b^0 \to pK^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^-K^+K^-$ and $\Xi_b^0 \to pK^-K^-\pi^+$ decays are reconstructed, yielding 19877 $\pm$ 195, 5297 $\pm$ 83 and 709 $\pm$ 45 signal candidates, respectively. Two different measurements are made: one integrated over the phase space, and the other in specific phase-space regions.

No significant asymmetry is observed in the integrated measurements with a sensitivity of 0.8% in $\Lambda_b^0 \to pK^-\pi^+\pi^-$, 1.5% in $\Lambda_b^0 \to pK^-K^+K^-$ and 5.2% in $\Xi_b^0 \to pK^-K^-\pi^+$ decays, where the uncertainty is combined between statistical and systematic. The measurements in regions of the phase space for $\Lambda_b^0 \to pK^-\pi^+\pi^-$ and $\Lambda_b^0 \to pK^-K^+K^-$ decays are also all found to be consistent with conservation of both $P$ symmetry and $CP$ symmetry.

The $\Lambda_b^0 \to pK^-\chi_c(1P)(\to \pi^+\pi^-)$ and $\Lambda_b^0 \to pK^-\chi_c(1P)(\to K^+K^-)$ decays are observed for the first time. The yields and the corresponding statistical uncertainties are 336 $\pm$ 25 and 332 $\pm$ 23, respectively.

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 (The Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MinES and FASO (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (The 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 Skłodowska-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 and Yandex LLC (Russia), GVA, XuntaGal and GENCAT (Spain), Herchel Smith Fund, the Royal Society, the English-Speaking Union and the Leverhulme Trust (United Kingdom).
Appendices

A  Observation of the $\Lambda^0_b \rightarrow \chi_{c0}(1P)pK^-$ decay

The $\pi^+\pi^-$ and $K^+K^-\text{fast}$ invariant-mass distributions, obtained by selecting $\Lambda^0_b$ candidates within a signal window of $\pm2\sigma$ with respect to the reconstructed $\Lambda^0_b$ mass peak, are shown in Fig. 6. The invariant mass distributions of the $\chi_{c0}(1P)$ and $\chi_{c2}(1P)$ signals are modelled by nonrelativistic Breit-Wigner functions convolved with a Gaussian function to account for the detector resolution. The mean and width of the signal Breit-Wigner functions are fixed to known values [28], while the detector resolution, identical for the $\chi_{c0}(1P)$ and $\chi_{c2}(1P)$ signals, is determined from the data. The background, from random combinations of tracks and from $\Lambda^0_b$ decays that do not proceed via the $\chi_{c0}(1P)$ states, is modelled by an exponential function. An unbinned extended maximum likelihood fit is performed for $\pi^+\pi^-$ and $K^+K^-\text{fast}$ invariant mass distributions. The signal yield for the $\Lambda^0_b \rightarrow pK^-\chi_{c0}(1P)(\rightarrow \pi^+\pi^-)$ decay is $336 \pm 25$, and for $\Lambda^0_b \rightarrow pK^-\chi_{c2}(1P)(\rightarrow K^+K^-\text{fast})$ decay is $332 \pm 23$, where the uncertainty is statistical only. This represents the first observation of these decays. The signal yield and the statistical uncertainty for the $\Lambda^0_b \rightarrow pK^-\chi_{c2}(1P)(\rightarrow \pi^+\pi^-)$ decay is $36 \pm 12$, and for $\Lambda^0_b \rightarrow pK^-\chi_{c2}(1P)(\rightarrow K^+K^-\text{fast})$ decay is $19 \pm 9$.

![Figure 6](image.png)

Figure 6: The left (right) plot shows the distribution of the $\pi^+\pi^-$ ($K^+K^-\text{fast}$) reconstructed invariant mass for $\Lambda^0_b$ candidates selected within $\pm2\sigma$ of the $\Lambda^0_b$ mass peak. The results of the fit for different signal and background components are overlaid as described in the legend.

B  Measured asymmetries in regions of phase space

The definitions of the 14 (7) regions that form the binning scheme A (C) for the $\Lambda^0_b \rightarrow pK^-\pi^+\pi^-$ ($\Lambda^0_b \rightarrow pK^-K^+K^-$) decay are reported in Table 4 (6). The measurements of $a^{T\text{-odd}}_{CP}$ and $a^{T\text{-odd}}_P$ in specific phase-space regions are reported in Table 5 (7).
Table 4: Definition of the 14 regions that form scheme A for the $A_0^b \to pK^-\pi^+\pi^-$ decay. Bins 1 – 4 focus on the region dominated by the $\Delta(1232)^{++} \to p\pi^+$ resonance. The other 10 bins are defined to study regions where $pK^-$ resonances are present on either side of the $f_0(980) \to \pi^+\pi^-$ or $K^*(892)^0 \to K^-\pi^+$ resonances. Further splitting depending on $|\Phi|$ is performed to reduce potential dilution of asymmetries, as suggested in Ref. [14]. Masses are in units of GeV/c^2.

| Region | $m(p\pi^+)$ | $m(pK^-)$ | $m(\pi^+\pi^-)$ | $m(K^-\pi^+)$ | $|\Phi|$ |
|--------|-------------|------------|-----------------|----------------|--------|
| 1      | (1.00, 1.23) |            |                 |                | (0, π) |
| 2      | (1.00, 1.23) |            |                 |                | (0, π) |
| 3      | (1.23, 1.35) |            |                 |                | (0, π) |
| 4      | (1.23, 1.35) |            |                 |                | (0, π) |
| 5      | (1.35, 5.40) | (1.00, 2.00) | 0.27, 0.99     |                | (0, π) |
| 6      | (1.35, 5.40) | (1.00, 2.00) | 0.27, 0.99     |                | (0, π) |
| 7      | (1.35, 5.40) | (1.00, 2.00) | 0.99, 4.50     |                | (0, π) |
| 8      | (1.35, 5.40) | (1.00, 2.00) | 0.99, 4.50     |                | (0, π) |
| 9      | (1.35, 5.40) | (2.00, 5.00) | 0.27, 0.99     | 0.63, 0.89     | (0, π) |
| 10     | (1.35, 5.40) | (2.00, 5.00) | 0.27, 0.99     | 0.89, 4.50     | (0, π) |
| 11     | (1.35, 5.40) | (2.00, 5.00) | 0.27, 0.99     |                | (0, π) |
| 12     | (1.35, 5.40) | (2.00, 5.00) | 0.99, 4.50     | 0.63, 0.89     | (0, π) |
| 13     | (1.35, 5.40) | (2.00, 5.00) | 0.99, 4.50     | 0.89, 4.50     | (0, π) |
| 14     | (1.35, 5.40) | (2.00, 5.00) | 0.99, 4.50     |                | (0, π) |

C Background-subtracted distributions in phase space

The background-subtracted distributions for $A_0^b$ ($\overline{A}_b^0$) with $C_T > 0$ and $C_{\overline{T}} < 0$ (−$C_{\overline{T}} > 0$ and −$C_T < 0$ ) in different regions of phase space of the $A_0^b \to pK^-\pi^+\pi^-$ ($\overline{A}_b^0 \to pK^-K^+K^-$) decay are shown in Figs. [7, 8, 9, 10]. The distributions are made using the $s$Plot technique [25].
Table 5: Measurements of $a_P^{T,\text{odd}}$ and $a_{CP}^{T,\text{odd}}$ in specific phase-space regions for the $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ decay. Each value is obtained through an independent fit to the candidates in the corresponding region of the phase space. Scheme A is defined in Table 4 and divides the phase space according to dominant resonant contributions, while scheme B consists of twelve non-overlapping bins of width $\pi/12$ in $|\Phi|$.

<table>
<thead>
<tr>
<th>Scheme A</th>
<th>$a_P^{T,\text{odd}}$ (%)</th>
<th>$a_{CP}^{T,\text{odd}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-8.3 \pm 7.2 \pm 0.6$</td>
<td>$-6.5 \pm 7.2 \pm 0.6$</td>
</tr>
<tr>
<td>2</td>
<td>$-4.2 \pm 3.2 \pm 0.6$</td>
<td>$-0.6 \pm 3.2 \pm 0.6$</td>
</tr>
<tr>
<td>3</td>
<td>$7.7 \pm 5.8 \pm 0.6$</td>
<td>$-7.8 \pm 5.8 \pm 0.6$</td>
</tr>
<tr>
<td>4</td>
<td>$-9.1 \pm 4.3 \pm 0.6$</td>
<td>$-2.2 \pm 4.3 \pm 0.6$</td>
</tr>
<tr>
<td>5</td>
<td>$2.1 \pm 4.9 \pm 0.6$</td>
<td>$-0.4 \pm 4.9 \pm 0.6$</td>
</tr>
<tr>
<td>6</td>
<td>$-2.3 \pm 5.0 \pm 0.6$</td>
<td>$-0.5 \pm 5.0 \pm 0.6$</td>
</tr>
<tr>
<td>7</td>
<td>$-1.0 \pm 3.0 \pm 0.6$</td>
<td>$-0.1 \pm 3.0 \pm 0.6$</td>
</tr>
<tr>
<td>8</td>
<td>$4.2 \pm 3.7 \pm 0.6$</td>
<td>$-1.3 \pm 3.7 \pm 0.6$</td>
</tr>
<tr>
<td>9</td>
<td>$-1.4 \pm 5.1 \pm 0.6$</td>
<td>$-0.3 \pm 5.1 \pm 0.6$</td>
</tr>
<tr>
<td>10</td>
<td>$-0.8 \pm 2.7 \pm 0.6$</td>
<td>$-3.0 \pm 2.7 \pm 0.6$</td>
</tr>
<tr>
<td>11</td>
<td>$-0.9 \pm 2.5 \pm 0.6$</td>
<td>$3.5 \pm 2.5 \pm 0.6$</td>
</tr>
<tr>
<td>12</td>
<td>$-3.2 \pm 2.9 \pm 0.6$</td>
<td>$-3.0 \pm 2.9 \pm 0.6$</td>
</tr>
<tr>
<td>13</td>
<td>$0.7 \pm 1.5 \pm 0.6$</td>
<td>$-0.9 \pm 1.5 \pm 0.6$</td>
</tr>
<tr>
<td>14</td>
<td>$1.4 \pm 2.8 \pm 0.6$</td>
<td>$-0.3 \pm 2.8 \pm 0.6$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scheme B</th>
<th>$a_P^{T,\text{odd}}$ (%)</th>
<th>$a_{CP}^{T,\text{odd}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$0.6 \pm 2.1 \pm 0.6$</td>
<td>$-3.5 \pm 2.1 \pm 0.6$</td>
</tr>
<tr>
<td>2</td>
<td>$-0.3 \pm 2.2 \pm 0.6$</td>
<td>$1.8 \pm 2.2 \pm 0.6$</td>
</tr>
<tr>
<td>3</td>
<td>$-2.8 \pm 2.5 \pm 0.6$</td>
<td>$-1.4 \pm 2.5 \pm 0.6$</td>
</tr>
<tr>
<td>4</td>
<td>$2.9 \pm 2.9 \pm 0.6$</td>
<td>$-4.7 \pm 2.9 \pm 0.6$</td>
</tr>
<tr>
<td>5</td>
<td>$-3.3 \pm 3.0 \pm 0.6$</td>
<td>$-4.1 \pm 3.0 \pm 0.6$</td>
</tr>
<tr>
<td>6</td>
<td>$0.3 \pm 3.1 \pm 0.6$</td>
<td>$1.4 \pm 3.1 \pm 0.6$</td>
</tr>
<tr>
<td>7</td>
<td>$-2.6 \pm 3.3 \pm 0.6$</td>
<td>$3.8 \pm 3.3 \pm 0.6$</td>
</tr>
<tr>
<td>8</td>
<td>$4.1 \pm 3.6 \pm 0.6$</td>
<td>$-2.8 \pm 3.6 \pm 0.6$</td>
</tr>
<tr>
<td>9</td>
<td>$-2.6 \pm 3.2 \pm 0.6$</td>
<td>$1.7 \pm 3.2 \pm 0.6$</td>
</tr>
<tr>
<td>10</td>
<td>$0.1 \pm 3.1 \pm 0.6$</td>
<td>$-0.7 \pm 3.1 \pm 0.6$</td>
</tr>
<tr>
<td>11</td>
<td>$-0.7 \pm 3.2 \pm 0.6$</td>
<td>$-2.2 \pm 3.2 \pm 0.6$</td>
</tr>
<tr>
<td>12</td>
<td>$-4.6 \pm 3.2 \pm 0.6$</td>
<td>$1.3 \pm 3.2 \pm 0.6$</td>
</tr>
</tbody>
</table>

Table 6: Definition of the seven regions that form scheme C for the $\Lambda_b^0 \rightarrow pK^-K^+K^-$ decay. The scheme is defined to study regions where $pK^-$ resonances are present (1 – 3) on either side of the $\Phi \rightarrow K^+K^-$ resonances. Masses are in units of GeV/c².

| Region | $m(pK^-_{\text{slow}})$ | $m(K^+K^-_{\text{slow}}), m(K^+K^-_{\text{fast}})$ | $|\Phi|$ |
|--------|-------------------------|---------------------------------|--------|
| 1      | (0.9, 2.0)              | $m(K^+K^-_{\text{slow}}) < 1.02$ or $m(K^+K^-_{\text{fast}}) < 1.02$ |        |
| 2      | (0.9, 2.0)              | $m(K^+K^-_{\text{slow}}) > 1.02$ and $m(K^+K^-_{\text{fast}}) > 1.02$ | (0, $\frac{\pi}{2}$) |
| 3      | (0.9, 2.0)              | $m(K^+K^-_{\text{slow}}) > 1.02$ and $m(K^+K^-_{\text{fast}}) > 1.02$ | ($\frac{\pi}{2}, \pi$) |
| 4      | (2.0, 4.0)              | $m(K^+K^-_{\text{slow}}) < 1.02$ or $m(K^+K^-_{\text{fast}}) < 1.02$ | (0, $\frac{\pi}{2}$) |
| 5      | (2.0, 4.0)              | $m(K^+K^-_{\text{slow}}) < 1.02$ or $m(K^+K^-_{\text{fast}}) < 1.02$ | ($\frac{\pi}{2}, \pi$) |
| 6      | (2.0, 4.0)              | $m(K^+K^-_{\text{slow}}) > 1.02$ and $m(K^+K^-_{\text{fast}}) > 1.02$ | (0, $\frac{\pi}{2}$) |
| 7      | (2.0, 4.0)              | $m(K^+K^-_{\text{slow}}) > 1.02$ and $m(K^+K^-_{\text{fast}}) > 1.02$ | ($\frac{\pi}{2}, \pi$) |
Table 7: Measurements of $a_T^{P,\text{odd}}$ and $a_T^{CP,\text{odd}}$ in specific phase-space regions for the $\Lambda_b^0 \rightarrow pK^-K^+K^-$ decay. Each value is obtained through an independent fit to the candidates in the corresponding region of the phase space. Scheme C is defined in Table 6 and divides the phase space according to dominant resonant contributions, while scheme D consists of ten non-overlapping bins of width $\pi/10$ in $|\Phi|$.

<table>
<thead>
<tr>
<th>Scheme C</th>
<th>$a_T^{P,\text{odd}}$ (%)</th>
<th>$a_T^{CP,\text{odd}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.8 ± 5.2 ± 0.6</td>
<td>6.0 ± 5.2 ± 0.6</td>
</tr>
<tr>
<td>2</td>
<td>-2.8 ± 2.5 ± 0.6</td>
<td>1.7 ± 2.5 ± 0.6</td>
</tr>
<tr>
<td>3</td>
<td>0.2 ± 4.9 ± 0.6</td>
<td>0.2 ± 4.9 ± 0.6</td>
</tr>
<tr>
<td>4</td>
<td>-15.8 ± 6.3 ± 0.6</td>
<td>0.4 ± 6.3 ± 0.6</td>
</tr>
<tr>
<td>5</td>
<td>4.6 ± 5.9 ± 0.6</td>
<td>-2.5 ± 5.9 ± 0.6</td>
</tr>
<tr>
<td>6</td>
<td>2.8 ± 3.7 ± 0.6</td>
<td>0.9 ± 3.7 ± 0.6</td>
</tr>
<tr>
<td>7</td>
<td>-2.7 ± 3.4 ± 0.6</td>
<td>1.5 ± 3.4 ± 0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scheme D</th>
<th>$a_T^{P,\text{odd}}$ (%)</th>
<th>$a_T^{CP,\text{odd}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.1 ± 3.0 ± 0.6</td>
<td>-0.1 ± 3.0 ± 0.6</td>
</tr>
<tr>
<td>2</td>
<td>-3.2 ± 4.2 ± 0.6</td>
<td>2.3 ± 4.2 ± 0.6</td>
</tr>
<tr>
<td>3</td>
<td>-5.5 ± 4.4 ± 0.6</td>
<td>1.7 ± 4.4 ± 0.6</td>
</tr>
<tr>
<td>4</td>
<td>-2.0 ± 5.1 ± 0.6</td>
<td>4.3 ± 5.1 ± 0.6</td>
</tr>
<tr>
<td>5</td>
<td>-2.0 ± 5.8 ± 0.6</td>
<td>1.5 ± 5.8 ± 0.6</td>
</tr>
<tr>
<td>6</td>
<td>3.1 ± 5.5 ± 0.6</td>
<td>-0.9 ± 5.5 ± 0.6</td>
</tr>
<tr>
<td>7</td>
<td>3.6 ± 5.8 ± 0.6</td>
<td>2.5 ± 5.8 ± 0.6</td>
</tr>
<tr>
<td>8</td>
<td>-6.6 ± 5.9 ± 0.6</td>
<td>-0.5 ± 5.9 ± 0.6</td>
</tr>
<tr>
<td>9</td>
<td>-6.6 ± 5.6 ± 0.6</td>
<td>-2.8 ± 5.6 ± 0.6</td>
</tr>
<tr>
<td>10</td>
<td>6.2 ± 5.7 ± 0.6</td>
<td>4.3 ± 5.7 ± 0.6</td>
</tr>
</tbody>
</table>
Figure 7: Background-subtracted distributions of $A_b^0$ ($\bar{A}_b^0$) candidates in different regions of phase space of the $A_b^0 \rightarrow pK^-\pi^+\pi^-$ decay for different values of $C_\perp$ ($\bar{C}_\perp$). The background subtraction is performed using the sPlot technique [25].
Figure 8: Background-subtracted distributions of $A_b^0$ ($\bar{A}_b^0$) candidates in different regions of phase space of the $A_b^0 \to pK^-\pi^+\pi^-$ decay for different values of $C_T$ ($\bar{C}_T$). The background subtraction is performed using the sPlot technique \cite{25}. 
Figure 9: Background-subtracted distributions of $A^0_b$ ($\bar{A}^0_b$) candidates in different regions of phase space of the $A^0_b \rightarrow pK^-K^+K^-$ decay for different values of $C_\tau$ ($\bar{C}_\tau$). The background subtraction is performed using the sPlot technique [25].
Figure 10: Background-subtracted distributions of $A_b^0$ ($\overline{A}_b^0$) candidates in different regions of phase space of the $A_b^0 \rightarrow pK^-K^+K^-$ decay for different values of $C_T$ ($\overline{C}_T$). The background subtraction is performed using the sPlot technique [25].
References


LHCb collaboration

R. Aaij, B. Adeva, M. Adinolfi, A. Alfonso Albero, S. Ali, G. Alkhazov, P. Alvarez Cartelle,
A.A. Alves Jr, S. Amato, S. Amerio, Y. An, L. Anderlini, G. Andreassi, M. Andreotti, J.E. Andrews, R.B. Appleby, F. Archilli, P. d’Argent,
J. Arnau Romeu, A. Artamonov, M. Artuso, E. Aslanides, M. Atzeni, G. Auriemma, I. Babuschkin, S. Bachmann, J.J. Back,
A. Badalov, C. M. Baesso, S. Bakes, V. Balalagua, W. Baldini, A. Baranov, R.J. Barlow, C. Barschel, S. Barsuk,
W. Barter, F. Baryshnikov, V. Batozska, V. Battista, A. Bay, J. Bedford, F. Bedeschi, I. Bediaga,
A. Beiter, L.J. Bei, N. Beliy, V. Bellec, N. Belloli, K. Belous, I. Belyaev, E. Ben-Haim, G. Bencivenni, S. Benson, S. Beranek,
A. Berezin, R. Bernet, D. Berthinghoff, E. Bertholet, A. Bertolin, C. Betancourt, F. Betti, M.O. Bettler,
M. Borsato, F. Bossu, M. Boudoir, T.J.V. Bowcock, E. Bowen, C. Bozzi, S. Braun, J. Brodzicka,
D. Brundu, E. Buchanan, C. Burr, A. Bursche, J. Buytaert, W. Byczynski, S. Cadeddu, H. Cat, R. Calabrese,
R. Calladine, M. Calvi, M. Calvo Gomez, A. Camboni, P. Campana, D.H. Campora Perez, L. Capriotti,
A. Carboni, G. Carboni, G. Cardinale, A. Cardinelli, P. Carulli, L. Carson,
K. Carvalho Akiba, G. Casse, L. Cassina, M. Cattaneo, G. Cavallero, T. Cenci,
D. Chamont, M.G. Chapman, M. Charles, Ph. Charpentier, G. Chatzikonstantinidis,
M. Chefdeville, S. Chen, S.F. Cheung, S.-G. Chitic, V. Chobanova, M. Chrzaszcz,
A. Chubynsky, P. Ciambone, X. Cid Vidal, G. Ciezarek, P.E.L. Clarke,
M. Clemencic, H.V. Clift, J. Cleisier, V. Coco, J. Cogan, E. Cogneras, V. Cogoni,
L. Cojocariu, P. Collins, T. Colombo, A. Comerma-Montells, A. Contu, G. Coombs,
S. Coqueur, G. Corti, M. Corvo, C.M. Costa Soldani, B. Couturier, G.A. Cowan,
D.C. Craik, A. Crocombe, M. Cruz Torres, R. Currie, D. C’Ambrosio,
F. Da Cunha Marinho, C.L. Da Silva, E. Dall’Occo, J. Dalseno, A. Davis,
O. De Aguiar Francisco, K. De Bruyn, S. De Capua, M. De Cian, J.M. De Miranda,
L. De Paula, M. De Serio, P. De Simone, C.T. Dean, D. Decamp, L. Del Buono,
B. Delany, H.-P. Dembinski, M. Demmer, A. Dendek, D. Derkach, O. Deschamps,
F. Dettori, B. Dey, M. Di Canto, P. Di Nezza, H. Dijkstra, F. Dordei, M. Dorigo,
A. Dosil Suárez, L. Douglas, A. Dovbnya, A. Druskovic, K. Dreimanis,
L. Dufou, G. Ducatillon, P. Durante, J.M. Durham, D. Dutta, R. Dzhelyadin,
M. Dziewiecki, A. Dziurda, A. Dzyuba, S. Easo, U. Egede, E. Egorychev,
S. Eidelman, S. Eisenhardt, U. Eitschberger, R. Ekelhof, L. Eklund, S. Ely, A. Ene,
S. Esen, H.M. Evans, T. Evans, A. Falabella, N. Farley, S. Farry, D. Fazzini, L. Federici,
P. Fernandez Declara, A. Fernandez Prieto, F. Ferrari, L. Ferreira Lopes,
F. Ferreira Rodrigues, M. Ferro-Luzzi, S. Filipov, R.A. Fini, M. Fiorini, G. Firlej,
C. Fitzpatrick, T. Fiutowski, F. Fleuret, M. Fontana, F. Fontanelli, R. Forty,
V. Franco Lima, M. Frank, C. Frei, J. Fu, W. Funk, E. Furfaro, C. Färber,
E. Gabriel, A. Gallas Torreira, D. Galli, S. Gallorini, S. Gambetta, M. Gandelman,
P. Gandini, Y. Gao, L.M. Garcia Martin, J. Garcia Pardiñas, J. Garra Tico,
L. Garrido, D. Gascon, C. Gaspar, L. Gavardi, G. Gazzoni, D. Gerick,
E. Gersabeck, M. Gersabeck, T. Gershon, L. Gavardi, E. Graugé,
E. Graverini, B. Grech, J. Grecu, R. Greim.

1Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil
2Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
3Center for High Energy Physics, Tsinghua University, Beijing, China
4Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France
5Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France
6Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
7LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
8LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France
9F. Physikalisches Institut, RWTH Aachen University, Aachen, Germany
10Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
11Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
12Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
13School of Physics, University College Dublin, Dublin, Ireland
14INFN Sezione di Bari, Bari, Italy
15INFN Sezione di Bologna, Bologna, Italy
16INFN Sezione di Ferrara, Ferrara, Italy
INFN Sezione di Firenze, Firenze, Italy
INFN Laboratori Nazionali di Frascati, Frascati, Italy
INFN Sezione di Genova, Genova, Italy
INFN Sezione di Milano-Bicocca, Milano, Italy
INFN Sezione di Milano, Milano, Italy
INFN Sezione di Cagliari, Monserrato, Italy
INFN Sezione di Padova, Padova, Italy
INFN Sezione di Pisa, Pisa, Italy
INFN Sezione di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma La Sapienza, Roma, Italy
Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
National Center for Nuclear Research (NCBJ), Warsaw, Poland
Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
Petersburge Nuclear Physics Institute (PNPI), Gatchina, Russia
Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia
Yandex School of Data Analysis, Moscow, Russia
Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia
Institute for High Energy Physics (IHEP), Protvino, Russia
ICCB, Universitat de Barcelona, Barcelona, Spain
Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
European Organization for Nuclear Research (CERN), Geneva, Switzerland
Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
Physik-Institut, Universität Zürich, Zürich, Switzerland
Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands
NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
University of Birmingham, Birmingham, United Kingdom
H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, University of Warwick, Coventry, United Kingdom
STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Imperial College London, London, United Kingdom
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
Department of Physics, University of Oxford, Oxford, United Kingdom
Massachusetts Institute of Technology, Cambridge, MA, United States
University of Cincinnati, Cincinnati, OH, United States
University of Maryland, College Park, MD, United States
Syracuse University, Syracuse, NY, United States
Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to 2
University of Chinese Academy of Sciences, Beijing, China, associated to 3
School of Physics and Technology, Wuhan University, Wuhan, China, associated to 3
Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China, associated to 3
Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia, associated to 8
Institut für Physik, Universität Rostock, Rostock, Germany, associated to 12
National Research Centre Kurchatov Institute, Moscow, Russia, associated to 32
National University of Science and Technology "MISIS", Moscow, Russia, associated to 32
National Research Tomsk Polytechnic University, Tomsk, Russia, associated to
Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain, associated to
Van Swinderen Institute, University of Groningen, Groningen, The Netherlands, associated to
Los Alamos National Laboratory (LANL), Los Alamos, United States, associated to

Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil
Laboratoire Leprince-Ringuet, Palaiseau, France
P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia
Università di Bari, Bari, Italy
Università di Bologna, Bologna, Italy
Università di Cagliari, Cagliari, Italy
Università di Ferrara, Ferrara, Italy
Università di Genova, Genova, Italy
Università di Milano Bicocca, Milano, Italy
Università di Roma Tor Vergata, Roma, Italy
Università di Roma La Sapienza, Roma, Italy
AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland
LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain
Hanoi University of Science, Hanoi, Vietnam
Università di Pisa, Pisa, Italy
Università degli Studi di Milano, Milano, Italy
Università di Urbino, Urbino, Italy
Università della Basilicata, Potenza, Italy
Scuola Normale Superiore, Pisa, Italy
Università di Modena e Reggio Emilia, Modena, Italy
MSU - Iligan Institute of Technology (MSU-IIT), Iligan, Philippines
Novosibirsk State University, Novosibirsk, Russia
National Research University Higher School of Economics, Moscow, Russia
Escuela Agrícola Panamericana, San Antonio de Oriente, Honduras
Deceased