



Search for CP violation using triple product asymmetries in $\Lambda_b^0 \rightarrow pK^- \pi^+ \pi^-$, $\Lambda_b^0 \rightarrow pK^- K^+ K^-$ 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 $\Lambda_b^0 \rightarrow pK^- \pi^+ \pi^-$, $\Lambda_b^0 \rightarrow pK^- K^+ K^-$ 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 $\Lambda_b^0 \rightarrow pK^- \chi_{c0}(1P)(\rightarrow \pi^+ \pi^-, K^+ K^-)$ 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 $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ 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 $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$, $\Lambda_b^0 \rightarrow pK^-K^+K^-$ and $\Xi_b^0 \rightarrow pK^-K^-\pi^+$ decays is presented.¹ In all of these decays, the transitions are mainly mediated by $b \rightarrow us\bar{u}$ tree and $b \rightarrow su\bar{u}$ 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 γ [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 Λ_b^0 and Ξ_b^0 four-body decays. The symbol X_b^0 is used throughout this article to refer to both Λ_b^0 and Ξ_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 $C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1} \times \vec{p}_{h_2})$, where $h_1 = K^-$, $h_2 = \pi^+$ for the $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ decay, $h_1 = K_{\text{fast}}^-$, $h_2 = K^+$ for the $\Lambda_b^0 \rightarrow pK^-K^+K^-$ decay and $h_1 = K_{\text{fast}}^-$, $h_2 = \pi^+$ for the $\Xi_b^0 \rightarrow pK^-K^-\pi^+$ decay. The kaon labelled as “fast (slow)” is that with the highest (lowest) momentum among those with the same charge. The triple product $\bar{C}_{\hat{T}}$ is defined similarly for \bar{X}_b^0 baryons using the momenta of the charge conjugate particles.

Two \hat{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

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}, \quad (1)$$

$$\bar{A}_{\hat{T}} = \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_{\hat{T}} < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)}, \quad (2)$$

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

$$a_P^{\hat{T}\text{-odd}} = \frac{1}{2} (A_{\hat{T}} + \bar{A}_{\hat{T}}), \quad a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2} (A_{\hat{T}} - \bar{A}_{\hat{T}}), \quad (3)$$

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, $a_{CP}^{\hat{T}\text{-odd}}$ 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 $A_{\hat{T}}$, $\bar{A}_{\hat{T}}$, $a_P^{\hat{T}\text{-odd}}$ and $a_{CP}^{\hat{T}\text{-odd}}$ are, by construction, largely insensitive to X_b^0/\bar{X}_b^0 production asymmetries

¹Unless 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 $(15 + 29/p_T) \mu\text{m}$, 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 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_b^0 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_b^0 candidates are formed from combinations of tracks that originate from a good quality common vertex. The tracks are identified as p , K or π 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

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

Decay	Selection window
$\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow pK^-\pi^+)\pi^-$	$2.23 < m(pK^-\pi^+) < 2.31 \text{ GeV}/c^2$ ($[-7.5\sigma, 4.5\sigma]$)
$\Lambda_b^0 \rightarrow D^0(\rightarrow K^-\pi^+)p\pi^-$	$1.832 < m(K^-\pi^+) < 1.844 \text{ GeV}/c^2$ ($[-3\sigma, 3\sigma]$)

antiproton identifies the candidate as a X_b^0 baryon or \bar{X}_b^0 antibaryon. Reconstructed tracks are required to have $p_T > 250 \text{ MeV}/c$ and $p > 1.5 \text{ GeV}/c$, and are required to be displaced from any primary vertex. The latter requirement is imposed by selecting tracks with $\chi_{\text{IP}}^2 > 16$, where χ_{IP}^2 is the change of the primary-vertex fit χ^2 when including the considered track. Only X_b^0 candidates with a transverse momentum $p_T > 1.5 \text{ GeV}/c$ are retained. To ensure that the X_b^0 baryon is produced in the primary interaction, it is required that $\chi_{\text{IP}}^2(X_b^0) < 16$, and the flight direction of the X_b^0 decay, calculated from its associated primary vertex, defined as that with minimum $\chi_{\text{IP}}^2(X_b^0)$, and the decay vertex, must align with the reconstructed particle momentum with an angle that satisfies $\cos\theta > 0.9999$.

Decays of X_b^0 baryons to charm hadrons represent a source of background that originates from $b \rightarrow c$ 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/ψ 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_s^0 decays with a ϕ or $K^*(892)^0$ resonance are suppressed by vetoing the region within 10 and 70 MeV/c^2 of the ϕ and $K^*(892)^0$ invariant masses, respectively, after applying the relevant substitution of the particle mass hypotheses.

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 $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ 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 $\Lambda_b^0 \rightarrow pK^-K^+K^-$ and $\Xi_b^0 \rightarrow pK^-K^-\pi^+$ 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, $5.85 < m(pK^-\pi^+\pi^-) < 6.40 \text{ GeV}/c^2$, 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 π candidate tracks with respect to the X_b^0 primary vertex; the χ^2 of the X_b^0 decay vertex fit; the angle between the X_b^0 momentum and its flight direction; the X_b^0 χ_{IP}^2 ; the asymmetry between the transverse momentum of the X_b^0 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_b^0 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 ϵ_S (ϵ_B) of each BDT selection requirement is evaluated using $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ (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 $[5.5 - 5.7] \text{ GeV}/c^2$ before applying the BDT selection.

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

$$\mathcal{S}_{\text{PID}} = \frac{\epsilon_S(\text{PID}) \cdot N_S}{\sqrt{\epsilon_S(\text{PID}) \cdot N_S + \epsilon_B(\text{PID}) \cdot N_B}}, \quad (4)$$

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 $\Lambda_b^0 \rightarrow pD^0(\rightarrow K^-\pi^+)\pi^-$ 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 $\Lambda_b^0 \rightarrow p\pi^+K^-\rho^-(\rightarrow \pi^-\pi^0)$, $\Lambda_b^0 \rightarrow p\pi^+\pi^-K^{*-}(\rightarrow K^-\pi^0)$ and similar decays, where the π^0 meson is not reconstructed. The background from misidentified final-state particles, called cross-feed in the following, consists of four-body Λ_b^0 , B^0 and B_s^0 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_b^0 or \bar{X}_b^0 flavour and the sign of $C_{\hat{\tau}}$ or $\bar{C}_{\hat{\tau}}$. Simulated events and the $\Lambda_b^0 \rightarrow \Lambda_c^+(pK^-\pi^+)\pi^-$ control sample indicate that the reconstruction efficiencies for candidates with $C_{\hat{\tau}} > 0$ ($-\bar{C}_{\hat{\tau}} > 0$) and $C_{\hat{\tau}} < 0$ ($-\bar{C}_{\hat{\tau}} < 0$) 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 $A_{\hat{\tau}}$ and $\bar{A}_{\hat{\tau}}$. The P - and CP -violating asymmetries, $a_P^{\hat{\tau}\text{-odd}}$ and $a_{CP}^{\hat{\tau}\text{-odd}}$, are then obtained according to Eq. (3).

The invariant-mass distribution of the X_b^0 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 Ξ_b^0 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 Ξ_b^0 and Λ_b^0 baryons, $174.8 \pm 2.5 \text{ MeV}/c^2$ [28]. The combinatorial background distribution is modelled by an exponential function with the rate parameter determined from the data. Partially reconstructed Λ_b^0 decays are described

by a threshold function [29] convolved with a Gaussian function to account for resolution effects, the parameters of which are determined from the fit. The shapes of cross-feed backgrounds are modelled using non-parametric functions [30] based on simulated events. The fit results for $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$, $\Lambda_b^0 \rightarrow pK^-K^+K^-$, and $\Xi_b^0 \rightarrow pK^-K^-\pi^+$ decays are shown in Figs. 1, 2, and 3, respectively. The signal yields, 19877 ± 195 , 5297 ± 83 , and 709 ± 45 , respectively, are compatible with the previously measured branching fractions [31], once the selection efficiencies are taken into account. In the $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ and the $\Lambda_b^0 \rightarrow pK^-K^+K^-$ decay modes, signals consistent with the $\chi_{c0}(1P)$ charmonium resonance are observed in the $\pi^+\pi^-$ and the $K^+K_{\text{fast}}^-$ invariant-mass distributions, which are shown in Fig. 6 in Appendix A. The signal yield and the corresponding statistical uncertainty for the $\Lambda_b^0 \rightarrow pK^-\chi_{c0}(1P)(\rightarrow \pi^+\pi^-)$ decay is 336 ± 25 , and for the $\Lambda_b^0 \rightarrow pK^-\chi_{c0}(1P)(\rightarrow K^+K^-)$ decay is 332 ± 23 , representing the first observation of these decays. The $\Lambda_b^0 \rightarrow pK^-\chi_{c0}(1P)$ candidates have an identical final state to the $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ and $\Lambda_b^0 \rightarrow pK^-K^+K^-$ signal decays and can potentially contribute to CP violation. These candidates are retained, together with the charmless 4-body decays, for the measurements of the asymmetries described below. Similar decays from $\Lambda_b^0 \rightarrow pK^-J/\psi$ with $J/\psi \rightarrow \pi^+\pi^-$ are removed due to the significant background from misidentified $J/\psi \rightarrow \mu^+\mu^-$ decays.

Two different approaches have been used to search for P and 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 $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ ($\Lambda_b^0 \rightarrow pK^-K^+K^-$) 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 Φ between the decay planes formed by the pK^- (pK_{fast}^-) and the $\pi^+\pi^-$ ($K^+K_{\text{slow}}^-$) systems, respectively. Scheme A (C) is defined in Table 4 (6) 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 $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ ($\Lambda_b^0 \rightarrow pK^-K^+K^-$) decay is shown in Fig. 4 (5), and the results are reported in Table 5 (7) in Appendix B.

The compatibility with the CP -symmetry (P -symmetry) hypothesis is tested for each scheme individually by means of a χ^2 test, where the χ^2 is defined as $R^T V^{-1} R$, with R the array of $a_{CP}^{\hat{T}\text{-odd}}$ ($a_P^{\hat{T}\text{-odd}}$) 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 χ^2 test is performed on the $a_P^{\hat{T}\text{-odd}}$ 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

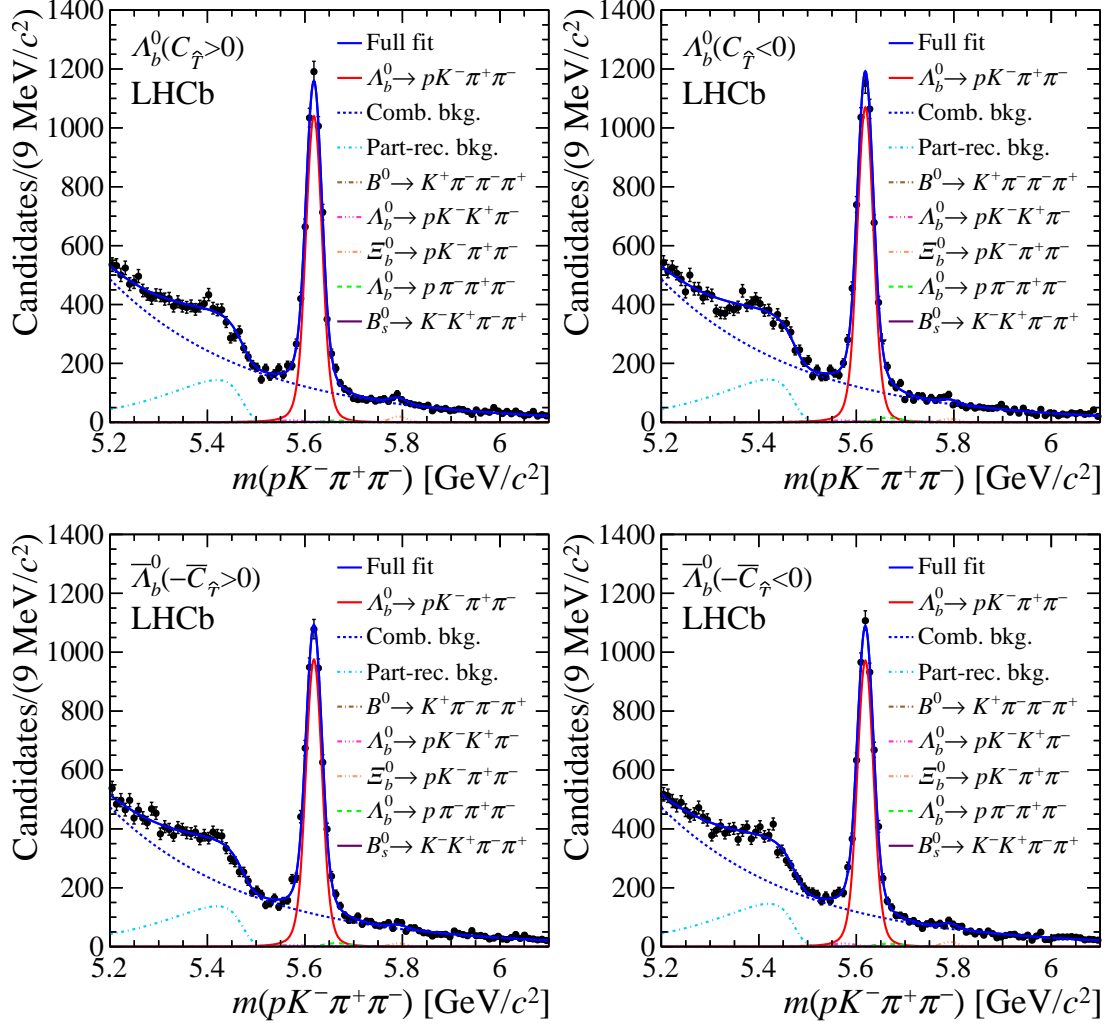


Figure 1: Distributions of the $pK^-\pi^+\pi^-$ invariant mass in the four samples defined by the Λ_b^0 ($\bar{\Lambda}_b^0$) flavour and the sign of $C_{\hat{T}}$ ($\bar{C}_{\hat{T}}$). The results of the fit are overlaid as described in the legend. The contribution of the cross-feeds to the fit results 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).

Table 2: Measurements of the CP - and P -violating observables $a_{CP}^{\hat{T}\text{-odd}}$ and $a_P^{\hat{T}\text{-odd}}$, together with their statistical and systematic uncertainties.

	$\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$	$\Lambda_b^0 \rightarrow pK^-K^+K^-$	$\Xi_b^0 \rightarrow pK^-K^-\pi^+$
$a_P^{\hat{T}\text{-odd}}$ (%)	$-0.60 \pm 0.84 \pm 0.31$	$-1.56 \pm 1.51 \pm 0.32$	$-3.04 \pm 5.19 \pm 0.36$
$a_{CP}^{\hat{T}\text{-odd}}$ (%)	$-0.81 \pm 0.84 \pm 0.31$	$1.12 \pm 1.51 \pm 0.32$	$-3.58 \pm 5.19 \pm 0.36$

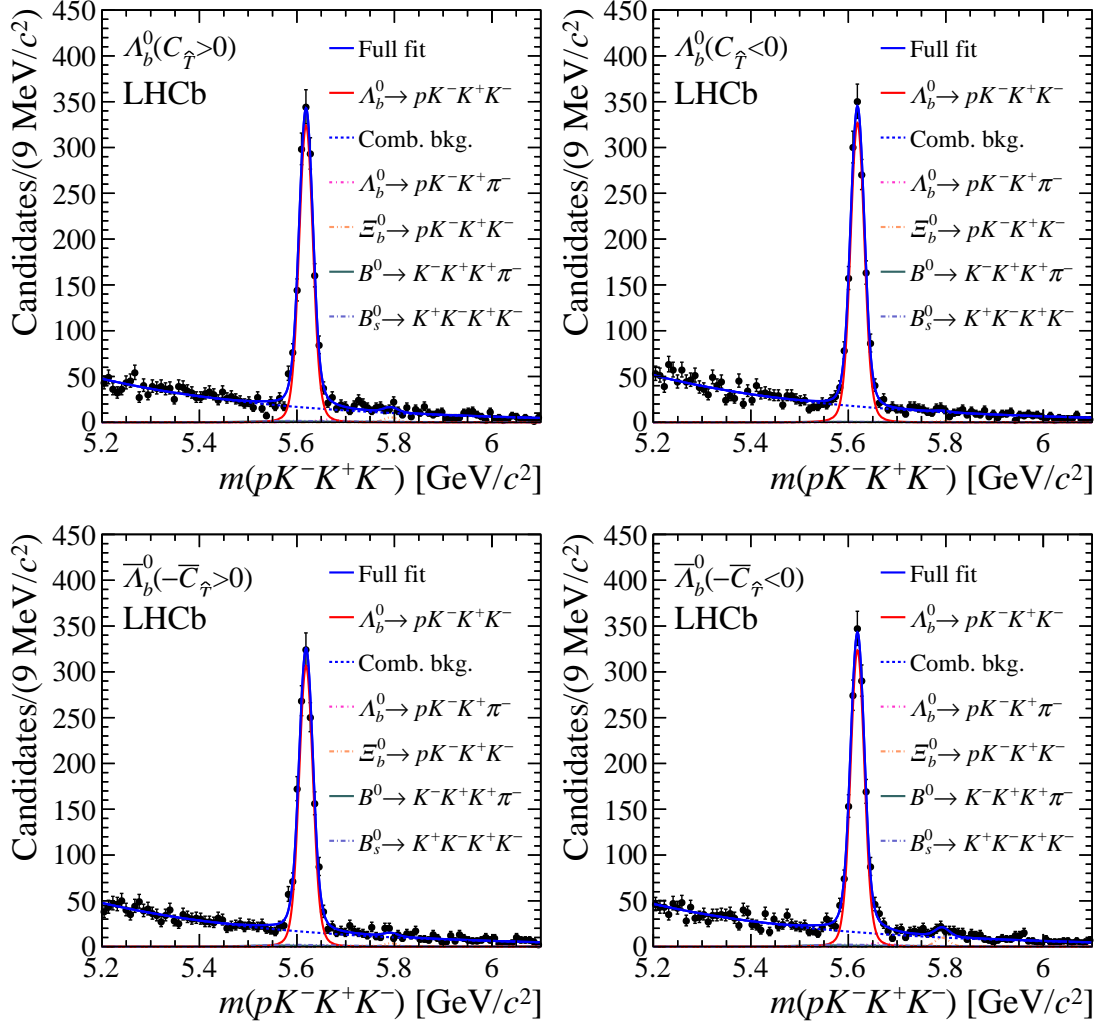


Figure 2: Distributions of the $pK^-K^+K^-$ invariant mass in the four samples defined by the Λ_b^0 ($\bar{\Lambda}_b^0$) flavour and the sign of $C_{\hat{T}}$ ($\bar{C}_{\hat{T}}$). The results of the fit are overlaid as described in the legend. The contribution of the cross-feeds to the fit results is barely just visible but is found to be nonnegligible.

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 $a_{CP}^{\hat{T}\text{-odd}}(\Lambda_c^+\pi^-)$ for the Cabibbo-favoured $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ 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 $a_{CP}^{\hat{T}\text{-odd}}$ for the integrated measurement over the full phase space. The systematic uncertainty on $a_{CP}^{\hat{T}\text{-odd}}$ is identical to that on $a_{CP}^{\hat{T}\text{-odd}}$, as follows from Eq. 3.

To assess the systematic uncertainty for the measurements in regions of the phase space, the $\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow pK^-\pi^+)\pi^-$ control sample is split in ten bins of the angle Φ between the

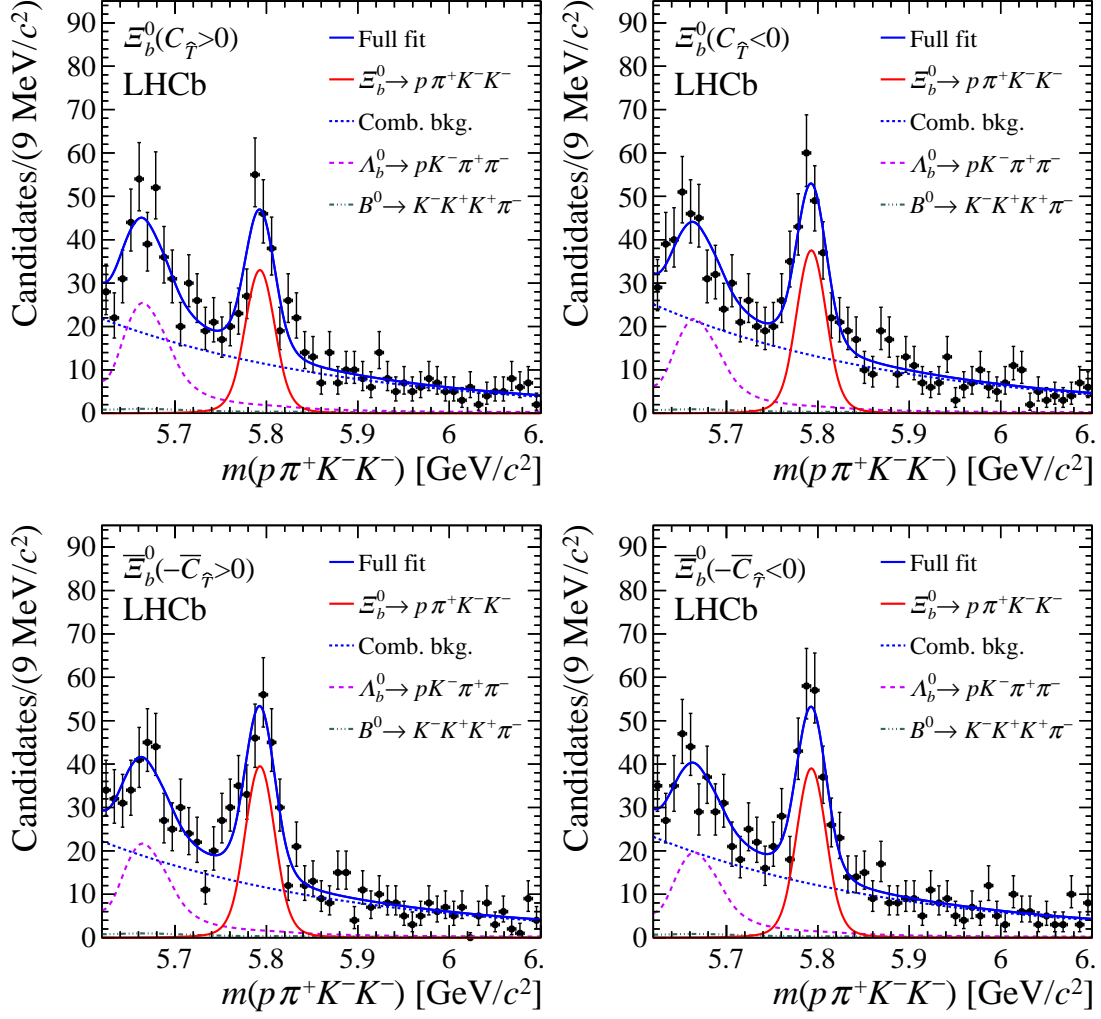


Figure 3: Distributions of the $pK^-K^-\pi^+$ invariant mass in the four samples defined by the Ξ_b^0 (Ξ_b^0) flavour and the sign of $C_{\hat{T}}$ ($\bar{C}_{\hat{T}}$). The results of the fit are overlaid as described in the legend. The contribution of the $B^0 \rightarrow K^-K^+K^+\pi^-$ cross-feed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

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

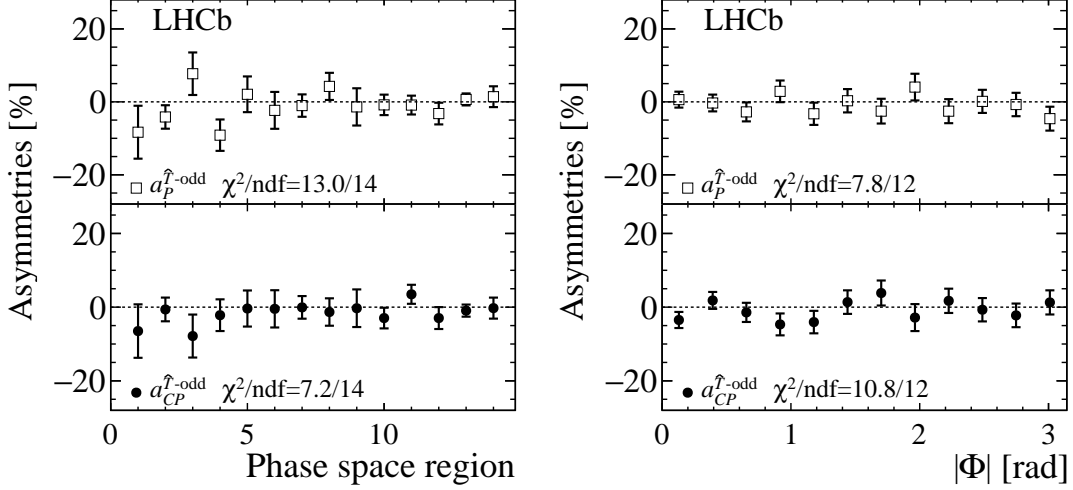


Figure 4: The asymmetries using binning schemes (left) A and (right) B for the $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ decay. For $a_P^{\hat{T}\text{-odd}}$ ($a_{CP}^{\hat{T}\text{-odd}}$), the values of the χ^2/ndf for the P -symmetry (CP -symmetry) hypothesis, represented by a dashed line, are quoted.

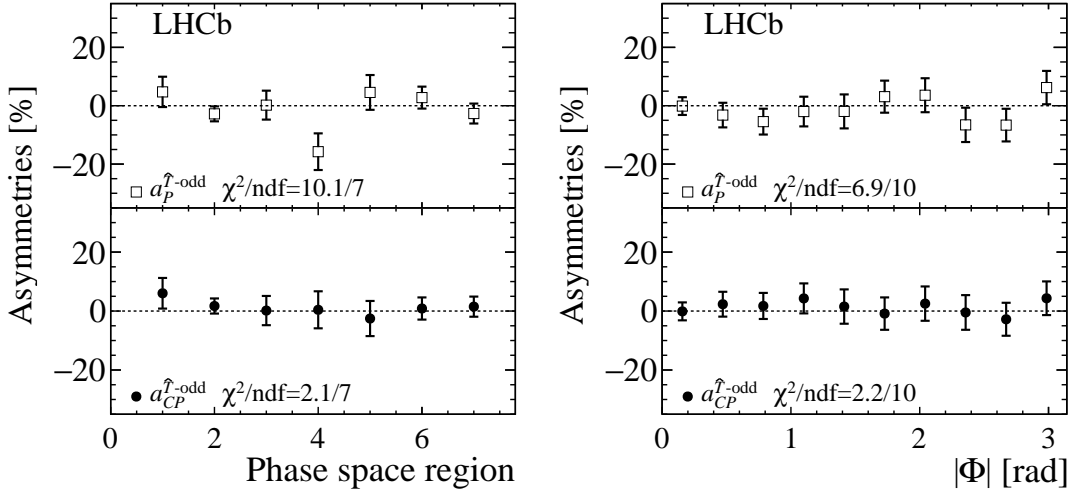


Figure 5: The asymmetries using binning schemes (left) C and (right) D for $\Lambda_b^0 \rightarrow pK^-K^+K^-$ decay. For $a_P^{\hat{T}\text{-odd}}$ ($a_{CP}^{\hat{T}\text{-odd}}$), the values of the χ^2/ndf for the P -symmetry (CP -symmetry) hypothesis, represented by a dashed line, are quoted.

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 Λ_b^0 shape in the $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ 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.

Contribution	$\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ (%)	$\Lambda_b^0 \rightarrow pK^-K^+K^-$ (%)	$\Xi_b^0 \rightarrow pK^-K^-\pi^+$ (%)
Experimental bias	± 0.31 (± 0.60)	± 0.31 (± 0.60)	± 0.31
$C_{\hat{T}}$ resolution	± 0.01	± 0.05	± 0.02
Fit model	± 0.03	± 0.08	± 0.19
Total	± 0.31 (± 0.60)	± 0.32 (± 0.61)	± 0.36

6 Conclusions

A search for P and CP violation is performed in four-body Λ_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 $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$, $\Lambda_b^0 \rightarrow pK^-K^+K^-$ and $\Xi_b^0 \rightarrow pK^-K^-\pi^+$ decays are reconstructed, yielding 19877 ± 195 , 5297 ± 83 and 709 ± 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 $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$, 1.5% in $\Lambda_b^0 \rightarrow pK^-K^+K^-$ and 5.2% in $\Xi_b^0 \rightarrow pK^-K^-\pi^+$ decays, where the uncertainty is combined between statistical and systematic. The measurements in regions of the phase space for $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ and $\Lambda_b^0 \rightarrow pK^-K^+K^-$ decays are also all found to be consistent with conservation of both P symmetry and CP symmetry.

The $\Lambda_b^0 \rightarrow pK^-\chi_{c0}(1P)(\rightarrow \pi^+\pi^-)$ and $\Lambda_b^0 \rightarrow pK^-\chi_{c0}(1P)(\rightarrow K^+K^-)$ decays are observed for the first time. The yields and the corresponding statistical uncertainties are 336 ± 25 and 332 ± 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 $\Lambda_b^0 \rightarrow \chi_{c0}(1P)pK^-$ decay

The $\pi^+\pi^-$ and $K^+K_{\text{fast}}^-$ invariant-mass distributions, obtained by selecting Λ_b^0 candidates within a signal window of $\pm 2\sigma$ with respect to the reconstructed Λ_b^0 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 Λ_b^0 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 $\Lambda_b^0 \rightarrow pK^-\chi_{c0}(1P)(\rightarrow \pi^+\pi^-)$ decay is 336 ± 25 , and for $\Lambda_b^0 \rightarrow pK_{\text{slow}}^-\chi_{c0}(1P)(\rightarrow K^+K_{\text{fast}}^-)$ decay is 332 ± 23 , where the uncertainty is statistical only. This represents the first observation of these decays. The signal yield and the statistical uncertainty for the $\Lambda_b^0 \rightarrow pK^-\chi_{c2}(1P)(\rightarrow \pi^+\pi^-)$ decay is 36 ± 12 , and for $\Lambda_b^0 \rightarrow pK_{\text{slow}}^-\chi_{c2}(1P)(\rightarrow K^+K_{\text{fast}}^-)$ decay is 19 ± 9 .

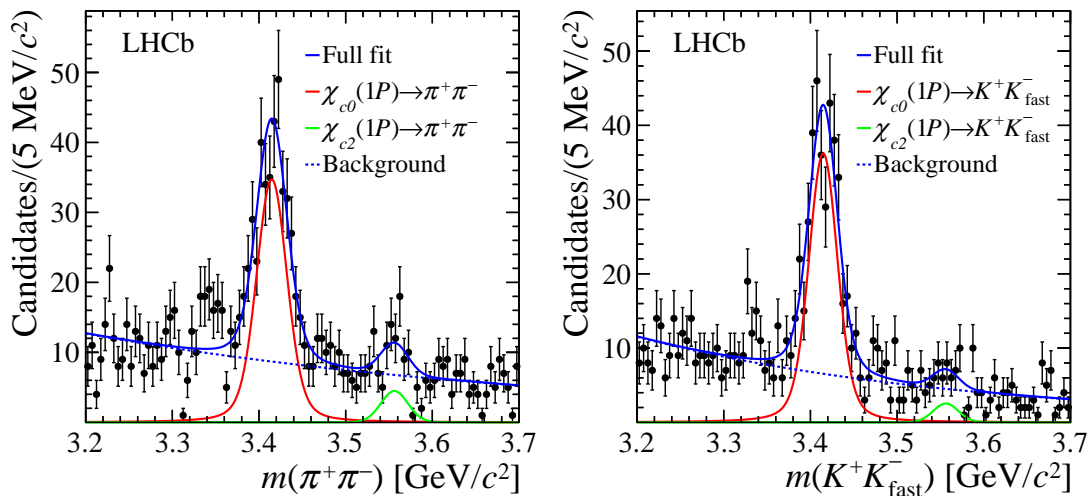


Figure 6: The left (right) plot shows the distribution of the $\pi^+\pi^-$ ($K^+K_{\text{fast}}^-$) reconstructed invariant mass for Λ_b^0 candidates selected within $\pm 2\sigma$ of the Λ_b^0 mass peak. The results of the fit for different signal and background components are overlaid as described in 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 $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ ($\Lambda_b^0 \rightarrow pK^-K^+K^-$) decay are reported in Table 4 (6). The measurements of $a_{CP}^{\hat{T}\text{-odd}}$ and $a_P^{\hat{T}\text{-odd}}$ in specific phase-space regions are reported in Table 5 (7).

Table 4: Definition of the 14 regions that form scheme A for the $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ decay. Bins 1 – 4 focus on the region dominated by the $\Delta(1232)^{++} \rightarrow p\pi^+$ resonance. The other 10 bins are defined to study regions where pK^- resonances are present on either side of the $f_0(980) \rightarrow \pi^+\pi^-$ or $\bar{K}^*(892)^0 \rightarrow K^-\pi^+$ 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)				$(0, \frac{\pi}{2})$
2	(1.00, 1.23)				$(\frac{\pi}{2}, \pi)$
3	(1.23, 1.35)				$(0, \frac{\pi}{2})$
4	(1.23, 1.35)				$(\frac{\pi}{2}, \pi)$
5	(1.35, 5.40)	(1.00, 2.00)	(0.27, 0.99)		$(0, \frac{\pi}{2})$
6	(1.35, 5.40)	(1.00, 2.00)	(0.27, 0.99)		$(\frac{\pi}{2}, \pi)$
7	(1.35, 5.40)	(1.00, 2.00)	(0.99, 4.50)		$(0, \frac{\pi}{2})$
8	(1.35, 5.40)	(1.00, 2.00)	(0.99, 4.50)		$(\frac{\pi}{2}, \pi)$
9	(1.35, 5.40)	(2.00, 5.00)	(0.27, 0.99)	(0.63, 0.89)	$(0, \frac{\pi}{2})$
10	(1.35, 5.40)	(2.00, 5.00)	(0.27, 0.99)	(0.89, 4.50)	$(0, \frac{\pi}{2})$
11	(1.35, 5.40)	(2.00, 5.00)	(0.27, 0.99)		$(\frac{\pi}{2}, \pi)$
12	(1.35, 5.40)	(2.00, 5.00)	(0.99, 4.50)	(0.63, 0.89)	$(0, \frac{\pi}{2})$
13	(1.35, 5.40)	(2.00, 5.00)	(0.99, 4.50)	(0.89, 4.50)	$(0, \frac{\pi}{2})$
14	(1.35, 5.40)	(2.00, 5.00)	(0.99, 4.50)		$(\frac{\pi}{2}, \pi)$

C Background-subtracted distributions in phase space

The background-subtracted distributions for Λ_b^0 ($\bar{\Lambda}_b^0$) with $C_{\hat{T}} > 0$ and $C_{\hat{T}} < 0$ ($-\bar{C}_{\hat{T}} > 0$ and $-\bar{C}_{\hat{T}} < 0$) in different regions of phase space of the $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ ($\bar{\Lambda}_b^0 \rightarrow pK^-K^+K^-$) decay are shown in Figs. 7, 8 (9, 10). The distributions are made using the *sPlot* technique [25].

Table 5: Measurements of $a_{\hat{P}}^{\hat{T}\text{-odd}}$ and $a_{\hat{CP}}^{\hat{T}\text{-odd}}$ 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 $|\Phi|$.

Scheme A	$a_{\hat{P}}^{\hat{T}\text{-odd}}$ (%)	$a_{\hat{CP}}^{\hat{T}\text{-odd}}$ (%)
1	$-8.3 \pm 7.2 \pm 0.6$	$-6.5 \pm 7.2 \pm 0.6$
2	$-4.2 \pm 3.2 \pm 0.6$	$-0.6 \pm 3.2 \pm 0.6$
3	$7.7 \pm 5.8 \pm 0.6$	$-7.8 \pm 5.8 \pm 0.6$
4	$-9.1 \pm 4.3 \pm 0.6$	$-2.2 \pm 4.3 \pm 0.6$
5	$2.1 \pm 4.9 \pm 0.6$	$-0.4 \pm 4.9 \pm 0.6$
6	$-2.3 \pm 5.0 \pm 0.6$	$-0.5 \pm 5.0 \pm 0.6$
7	$-1.0 \pm 3.0 \pm 0.6$	$-0.1 \pm 3.0 \pm 0.6$
8	$4.2 \pm 3.7 \pm 0.6$	$-1.3 \pm 3.7 \pm 0.6$
9	$-1.4 \pm 5.1 \pm 0.6$	$-0.3 \pm 5.1 \pm 0.6$
10	$-0.8 \pm 2.7 \pm 0.6$	$-3.0 \pm 2.7 \pm 0.6$
11	$-0.9 \pm 2.5 \pm 0.6$	$3.5 \pm 2.5 \pm 0.6$
12	$-3.2 \pm 2.9 \pm 0.6$	$-3.0 \pm 2.9 \pm 0.6$
13	$0.7 \pm 1.5 \pm 0.6$	$-0.9 \pm 1.5 \pm 0.6$
14	$1.4 \pm 2.8 \pm 0.6$	$-0.3 \pm 2.8 \pm 0.6$
Scheme B	$a_{\hat{P}}^{\hat{T}\text{-odd}}$ (%)	$a_{\hat{CP}}^{\hat{T}\text{-odd}}$ (%)
1	$0.6 \pm 2.1 \pm 0.6$	$-3.5 \pm 2.1 \pm 0.6$
2	$-0.3 \pm 2.2 \pm 0.6$	$1.8 \pm 2.2 \pm 0.6$
3	$-2.8 \pm 2.5 \pm 0.6$	$-1.4 \pm 2.5 \pm 0.6$
4	$2.9 \pm 2.9 \pm 0.6$	$-4.7 \pm 2.9 \pm 0.6$
5	$-3.3 \pm 3.0 \pm 0.6$	$-4.1 \pm 3.0 \pm 0.6$
6	$0.3 \pm 3.1 \pm 0.6$	$1.4 \pm 3.1 \pm 0.6$
7	$-2.6 \pm 3.3 \pm 0.6$	$3.8 \pm 3.3 \pm 0.6$
8	$4.1 \pm 3.6 \pm 0.6$	$-2.8 \pm 3.6 \pm 0.6$
9	$-2.6 \pm 3.2 \pm 0.6$	$1.7 \pm 3.2 \pm 0.6$
10	$0.1 \pm 3.1 \pm 0.6$	$-0.7 \pm 3.1 \pm 0.6$
11	$-0.7 \pm 3.2 \pm 0.6$	$-2.2 \pm 3.2 \pm 0.6$
12	$-4.6 \pm 3.2 \pm 0.6$	$1.3 \pm 3.2 \pm 0.6$

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_{slow}^- resonances are present (1 – 3) on either side of the $\Phi \rightarrow K^+K^-$ resonances. Masses are in units of GeV/c^2 .

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 $a_P^{\widehat{T}\text{-odd}}$ and $a_{CP}^{\widehat{T}\text{-odd}}$ in specific phase-space regions for the $A_b^0 \rightarrow pK^-K^+K^-$ 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 $|\Phi|$.

Scheme C	$a_P^{\widehat{T}\text{-odd}}$ (%)	$a_{CP}^{\widehat{T}\text{-odd}}$ (%)
1	$4.8 \pm 5.2 \pm 0.6$	$6.0 \pm 5.2 \pm 0.6$
2	$-2.8 \pm 2.5 \pm 0.6$	$1.7 \pm 2.5 \pm 0.6$
3	$0.2 \pm 4.9 \pm 0.6$	$0.2 \pm 4.9 \pm 0.6$
4	$-15.8 \pm 6.3 \pm 0.6$	$0.4 \pm 6.3 \pm 0.6$
5	$4.6 \pm 5.9 \pm 0.6$	$-2.5 \pm 5.9 \pm 0.6$
6	$2.8 \pm 3.7 \pm 0.6$	$0.9 \pm 3.7 \pm 0.6$
7	$-2.7 \pm 3.4 \pm 0.6$	$1.5 \pm 3.4 \pm 0.6$
Scheme D	$a_P^{\widehat{T}\text{-odd}}$ (%)	$a_{CP}^{\widehat{T}\text{-odd}}$ (%)
1	$-0.1 \pm 3.0 \pm 0.6$	$-0.1 \pm 3.0 \pm 0.6$
2	$-3.2 \pm 4.2 \pm 0.6$	$2.3 \pm 4.2 \pm 0.6$
3	$-5.5 \pm 4.4 \pm 0.6$	$1.7 \pm 4.4 \pm 0.6$
4	$-2.0 \pm 5.1 \pm 0.6$	$4.3 \pm 5.1 \pm 0.6$
5	$-2.0 \pm 5.8 \pm 0.6$	$1.5 \pm 5.8 \pm 0.6$
6	$3.1 \pm 5.5 \pm 0.6$	$-0.9 \pm 5.5 \pm 0.6$
7	$3.6 \pm 5.8 \pm 0.6$	$2.5 \pm 5.8 \pm 0.6$
8	$-6.6 \pm 5.9 \pm 0.6$	$-0.5 \pm 5.9 \pm 0.6$
9	$-6.6 \pm 5.6 \pm 0.6$	$-2.8 \pm 5.6 \pm 0.6$
10	$6.2 \pm 5.7 \pm 0.6$	$4.3 \pm 5.7 \pm 0.6$

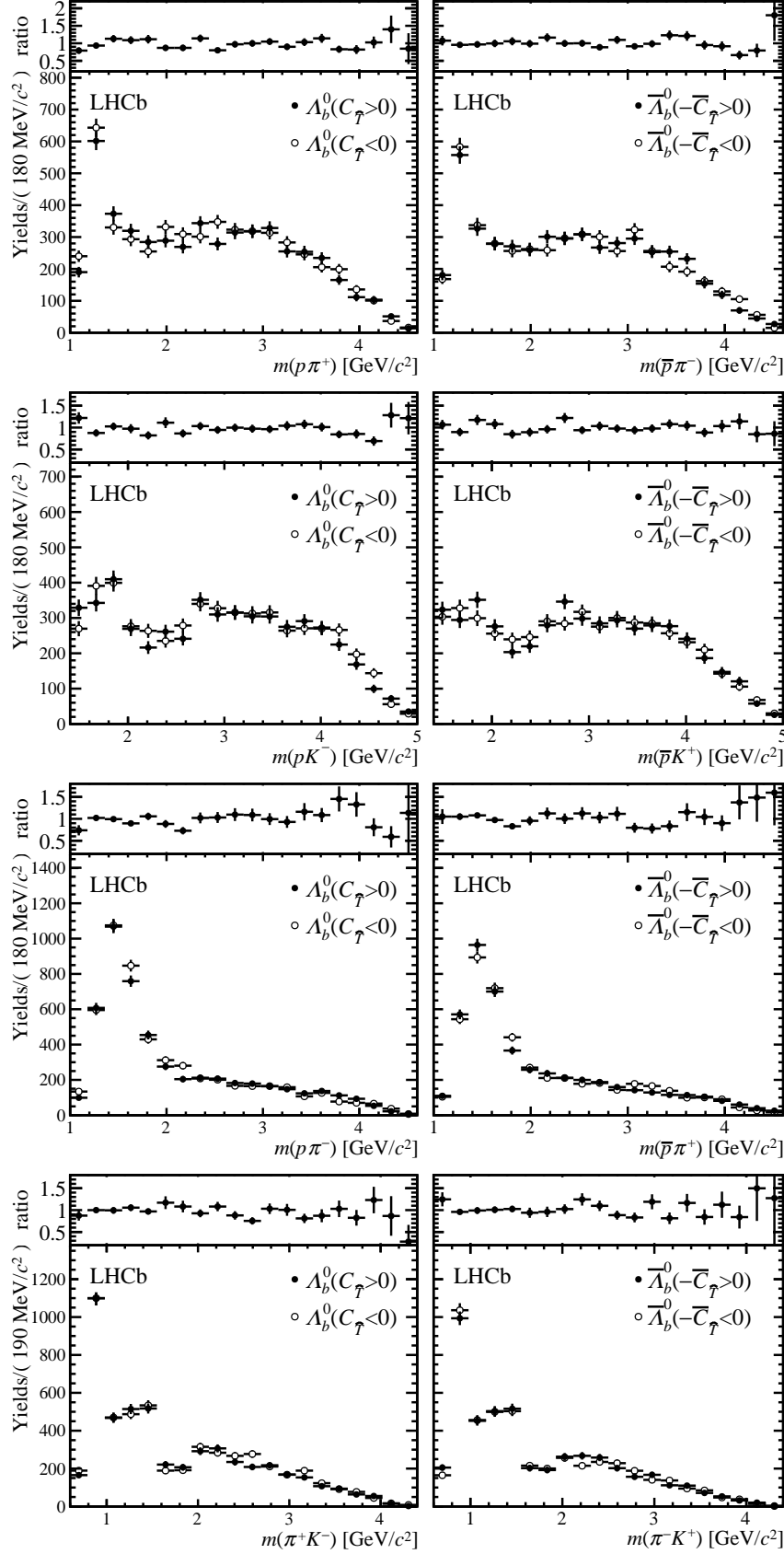


Figure 7: Background-subtracted distributions of Λ_b^0 ($\bar{\Lambda}_b^0$) candidates in different regions of phase space of the $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ decay for different values of $C_{\hat{T}}$ ($\bar{C}_{\hat{T}}$). The background subtraction is performed using the *sPlot* technique [25].

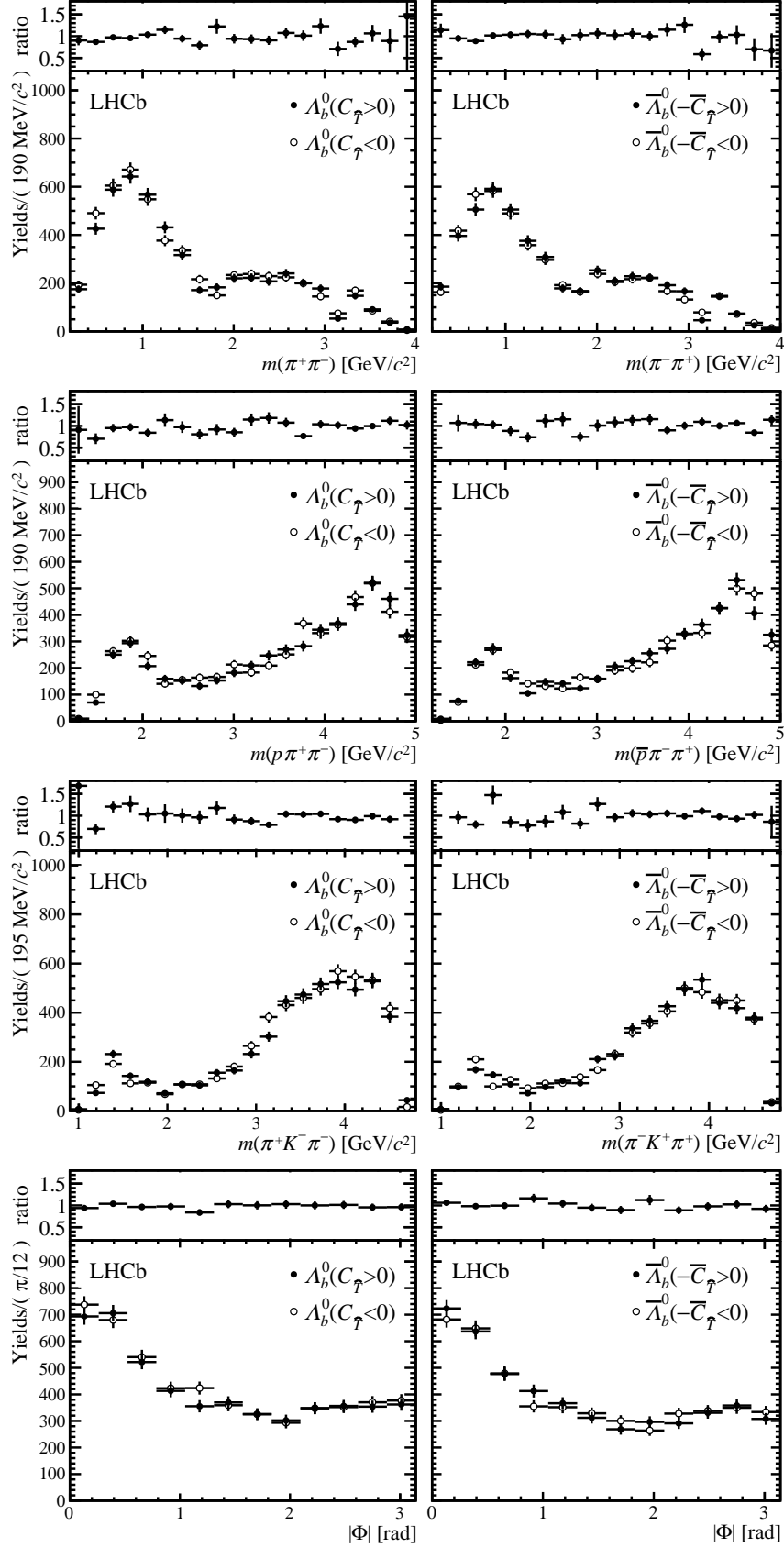


Figure 8: Background-subtracted distributions of Λ_b^0 ($\bar{\Lambda}_b^0$) candidates in different regions of phase space of the $\Lambda_b^0 \rightarrow p K^- \pi^+ \pi^-$ decay for different values of $C_{\hat{T}}$ ($\bar{C}_{\hat{T}}$). The background subtraction is performed using the *sPlot* technique [25].

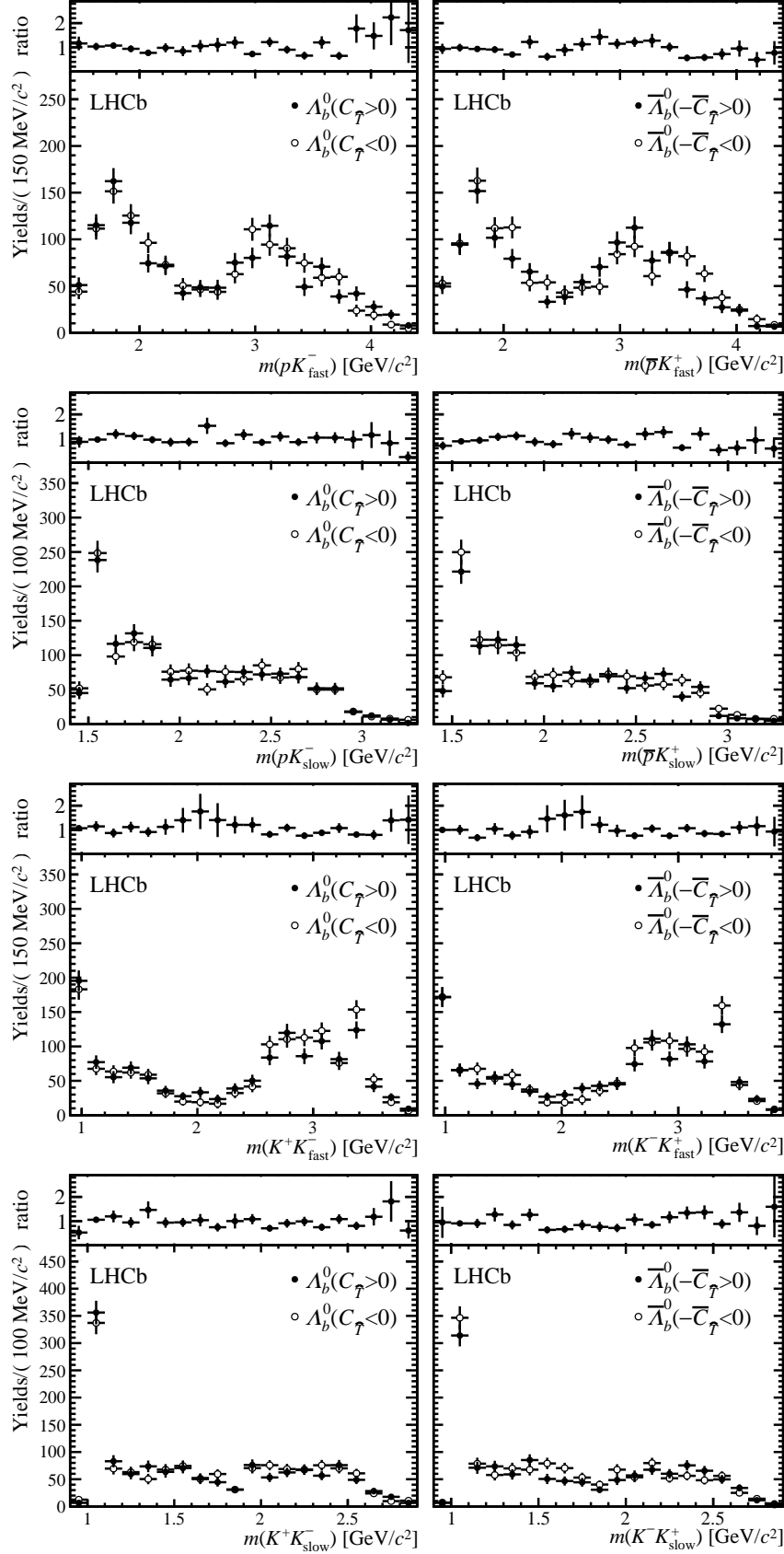


Figure 9: Background-subtracted distributions of Λ_b^0 ($\bar{\Lambda}_b^0$) candidates in different regions of phase space of the $\Lambda_b^0 \rightarrow p K^- K^+ K^-$ decay for different values of $C_{\hat{T}}$ ($\bar{C}_{\hat{T}}$). The background subtraction is performed using the *sPlot* technique [25].

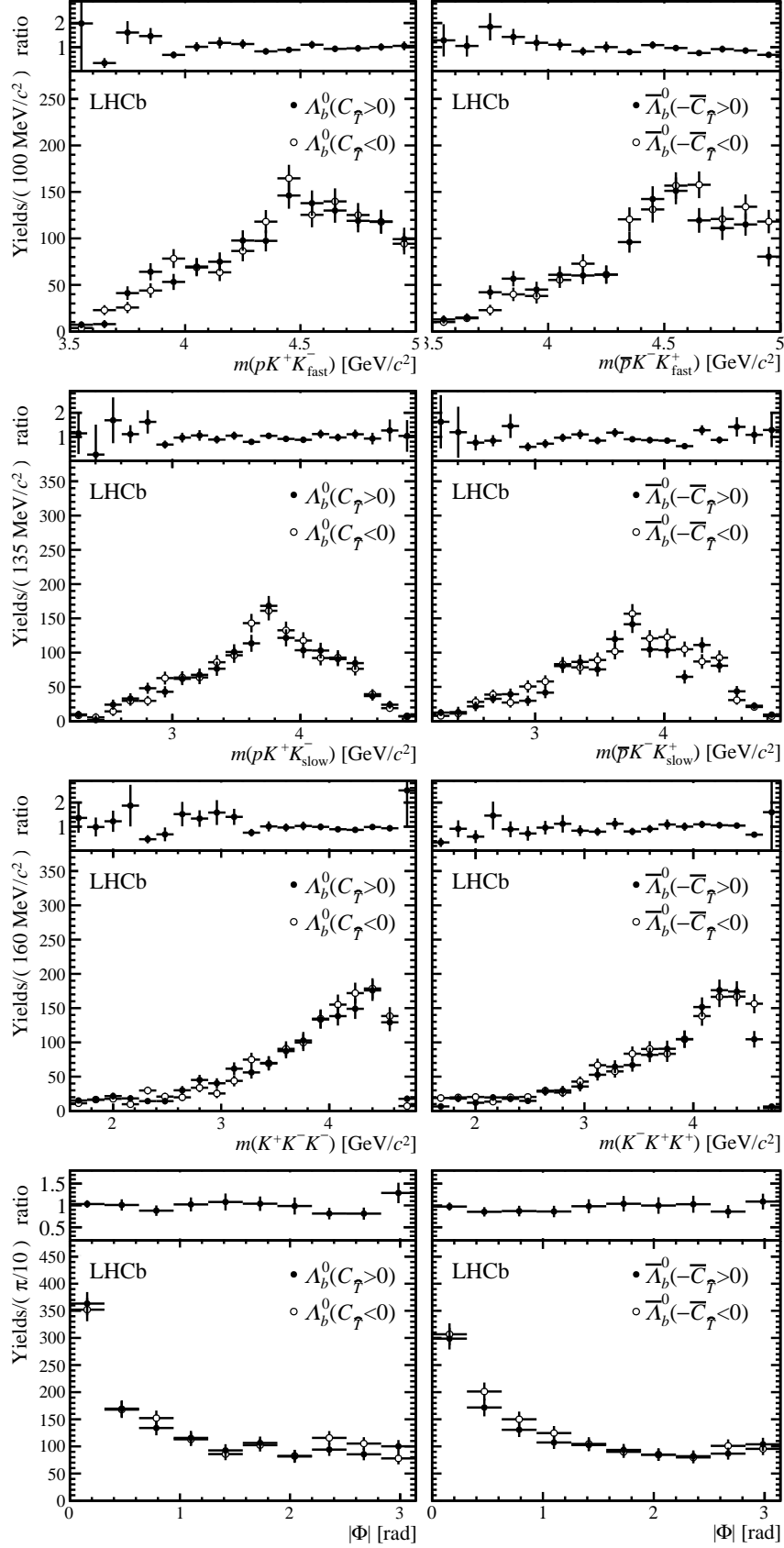


Figure 10: Background-subtracted distributions of Λ_b^0 ($\bar{\Lambda}_b^0$) candidates in different regions of phase space of the $\Lambda_b^0 \rightarrow p K^- K^+ K^-$ decay for different values of $C_{\hat{T}}$ ($\bar{C}_{\hat{T}}$). The background subtraction is performed using the *sPlot* technique [25].

References

- [1] Y. K. Hsiao and C. Q. Geng, *Direct CP violation in Λ_b^0 decays*, Phys. Rev. **D91** (2015) 116007, [arXiv:1412.1899](#).
- [2] LHCb collaboration, R. Aaij *et al.*, *Measurement of matter-antimatter differences in beauty baryon decays*, Nature Physics **13** (2017) 391, [arXiv:1609.05216](#).
- [3] M. Gronau and J. L. Rosner, *Triple product asymmmetries in Λ_b^0 and Ξ_b^0 decays*, Phys. Lett. **B749** (2015) 104, [arXiv:1506.01346](#).
- [4] E. Golowich and G. Valencia, *Triple Product Correlations in Semileptonic B^\pm Decays*, Phys. Rev. **D40** (1989) 112.
- [5] W. Bensalem, A. Datta, and D. London, *New physics effects on triple-product correlations in Λ_b^0 decays*, Phys. Rev. **D66** (2002) 094004.
- [6] A. Datta, M. Duraisamy, and D. London, *Searching for New Physics with B-Decay Fake Triple Products*, Phys. Lett. **B701** (2011) 357, [arXiv:1103.2442](#).
- [7] I. I. Y. Bigi, *Charm Physics: Like Botticelli in the Sistine Chapel*, in *KAON2001: International Conference on CP violation Pisa, Italy, June 12-17, 2001*, 2001. [arXiv:hep-ph/0107102](#).
- [8] BaBar collaboration, P. del Amo Sanchez *et al.*, *Search for CP violation using T-odd correlations in $D^0 \rightarrow K^+K^-\pi^+\pi^-$ decays*, Phys. Rev. **D81** (2010) 111103, [arXiv:1003.3397](#).
- [9] BaBar collaboration, J. P. Lees *et al.*, *Search for CP violation using T-odd correlations in $D^+ \rightarrow K^+K_S^0\pi^+\pi^-$ and $D_s^+ \rightarrow K^+K_S^0\pi^+\pi^-$ decays*, Phys. Rev. **D84** (2011) 031103, [arXiv:1105.4410](#).
- [10] M. Gronau and J. L. Rosner, *Triple product asymmetries in K , $D_{(s)}$ and $B_{(s)}$ decays*, Phys. Rev. **D84** (2011) 096013, [arXiv:1107.1232](#).
- [11] G. Durieux and Y. Grossman, *CP violation: Another piece of the puzzle*, Nature Physics **13** (2017) 322.
- [12] Belle collaboration, K. Prasanth *et al.*, *First measurement of T-odd moments in $D^0 \rightarrow K_S^0\pi^+\pi^-\pi^0$ decays*, Phys. Rev. **D95** (2017) 091101, [arXiv:1703.05721](#).
- [13] G. Valencia, *Angular correlations in the decay $B \rightarrow VV$ and CP violation*, Phys. Rev. **D39** (1989) 3339.
- [14] G. Durieux and Y. Grossman, *Probing CP violation systematically in differential distributions*, Phys. Rev. **D92** (2015) 076013, [arXiv:1508.03054](#).
- [15] LHCb collaboration, R. Aaij *et al.*, *Search for CP violation using T-odd correlations in $D^0 \rightarrow K^+K^-\pi^+\pi^-$ decays*, JHEP **10** (2014) 005, [arXiv:1408.1299](#).
- [16] LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.

- [17] LHCb collaboration, R. Aaij *et al.*, *LHCb detector performance*, Int. J. Mod. Phys. **A30** (2015) 1530022, arXiv:1412.6352.
- [18] T. Sjöstrand, S. Mrenna, and P. Skands, *PYTHIA 6.4 physics and manual*, JHEP **05** (2006) 026, arXiv:hep-ph/0603175; T. Sjöstrand, S. Mrenna, and P. Skands, *A brief introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178** (2008) 852, arXiv:0710.3820.
- [19] I. Belyaev *et al.*, *Handling of the generation of primary events in Gauss, the LHCb simulation framework*, J. Phys. Conf. Ser. **331** (2011) 032047.
- [20] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. **A462** (2001) 152.
- [21] P. Golonka and Z. Was, *PHOTOS Monte Carlo: A precision tool for QED corrections in Z and W decays*, Eur. Phys. J. **C45** (2006) 97, arXiv:hep-ph/0506026.
- [22] Geant4 collaboration, J. Allison *et al.*, *Geant4 developments and applications*, IEEE Trans. Nucl. Sci. **53** (2006) 270; Geant4 collaboration, S. Agostinelli *et al.*, *Geant4: A simulation toolkit*, Nucl. Instrum. Meth. **A506** (2003) 250.
- [23] M. Clemencic *et al.*, *The LHCb simulation application, Gauss: Design, evolution and experience*, J. Phys. Conf. Ser. **331** (2011) 032023.
- [24] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification and regression trees*, Wadsworth international group, Belmont, California, USA, 1984.
- [25] M. Pivk and F. R. Le Diberder, *sPlot: A statistical tool to unfold data distributions*, Nucl. Instrum. Meth. **A555** (2005) 356, arXiv:physics/0402083.
- [26] S. Arlot and A. Celisse, *A survey of cross-validation procedures for model selection*, Statist. Surv. **4** (2010) 40.
- [27] T. Skwarnicki, *A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances*, PhD thesis, Institute of Nuclear Physics, Krakow, 1986, DESY-F31-86-02.
- [28] Particle Data Group, K. A. Olive *et al.*, *Review of particle physics*, Chin. Phys. **C38** (2014) 090001.
- [29] ARGUS collaboration, H. Albrecht *et al.*, *Search for hadronic $b \rightarrow u$ decays*, Phys. Lett. **B241** (1990) 278.
- [30] K. S. Cranmer, *Kernel estimation in high-energy physics*, Comput. Phys. Commun. **136** (2001) 198, arXiv:hep-ex/0011057.
- [31] LHCb collaboration, R. Aaij *et al.*, *Measurement of branching fractions of charmless four-body Λ_b^0 and Ξ_b^0 decays*, JHEP **1802** (2018) 098, arXiv:1711.05490.

LHCb collaboration

R. Aaij⁴⁰, B. Adeva³⁹, M. Adinolfi⁴⁸, Z. Ajaltouni⁵, S. Akar⁵⁹, J. Albrecht¹⁰, F. Alessio⁴⁰, M. Alexander⁵³, A. Alfonso Alberio³⁸, S. Ali⁴³, G. Alkhazov³¹, P. Alvarez Cartelle⁵⁵, A.A. Alves Jr⁵⁹, S. Amato², S. Amerio²³, Y. Amhis⁷, L. An³, L. Anderlini¹⁷, G. Andreassi⁴¹, M. Andreotti^{16,g}, J.E. Andrews⁶⁰, R.B. Appleby⁵⁶, F. Archilli⁴³, P. d'Argent¹², J. Arnau Romeu⁶, A. Artamonov³⁷, M. Artuso⁶¹, E. Aslanides⁶, M. Atzeni⁴², G. Auremma²⁶, I. Babuschkin⁵⁶, S. Bachmann¹², J.J. Back⁵⁰, A. Badalov^{38,m}, C. Baesso⁶², S. Baker⁵⁵, V. Balagura^{7,b}, W. Baldini¹⁶, A. Baranov³⁵, R.J. Barlow⁵⁶, C. Barschel⁴⁰, S. Barsuk⁷, W. Barter⁵⁶, F. Baryshnikov³², V. Batozskaya²⁹, V. Battista⁴¹, A. Bay⁴¹, J. Beddow⁵³, F. Bedeschi²⁴, I. Bediaga¹, A. Beiter⁶¹, L.J. Bel⁴³, N. Bely⁶³, V. Belle⁴¹, N. Belloli^{20,i}, K. Belous³⁷, I. Belyaev^{32,40}, E. Ben-Haim⁸, G. Bencivenni¹⁸, S. Benson⁴³, S. Beranek⁹, A. Berezhnoy³³, R. Bernet⁴², D. Berninghoff¹², E. Bertholet⁸, A. Bertolin²³, C. Betancourt⁴², F. Betti¹⁵, M.O. Bettler⁴⁰, M. van Beuzekom⁴³, I.a. Bezshyiko⁴², S. Bifani⁴⁷, P. Billoir⁸, A. Birnkraut¹⁰, A. Bizzeti^{17,u}, M. Bjørn⁵⁷, T. Blake⁵⁰, F. Blanc⁴¹, S. Blusk⁶¹, V. Bocci²⁶, T. Boettcher⁵⁸, A. Bondar^{36,w}, N. Bondar³¹, I. Bordyuzhin³², S. Borghi^{56,40}, M. Borisyak³⁵, M. Borsato³⁹, F. Bossu⁷, M. Boubdir⁹, T.J.V. Bowcock⁵⁴, E. Bowen⁴², C. Bozzi^{16,40}, S. Braun¹², J. Brodzicka²⁷, D. Brundu²², E. Buchanan⁴⁸, C. Burr⁵⁶, A. Bursche^{22,f}, J. Buytaert⁴⁰, W. Byczynski⁴⁰, S. Cadeddu²², H. Cai⁶⁴, R. Calabrese^{16,g}, R. Calladine⁴⁷, M. Calvi^{20,i}, M. Calvo Gomez^{38,m}, A. Camboni^{38,m}, P. Campana¹⁸, D.H. Campora Perez⁴⁰, L. Capriotti⁵⁶, A. Carbone^{15,e}, G. Carboni^{25,j}, R. Cardinale^{19,h}, A. Cardini²², P. Carniti^{20,i}, L. Carson⁵², K. Carvalho Akiba², G. Casse⁵⁴, L. Cassina²⁰, M. Cattaneo⁴⁰, G. Cavallero^{19,40,h}, R. Cenci^{24,t}, D. Chamont⁷, M.G. Chapman⁴⁸, M. Charles⁸, Ph. Charpentier⁴⁰, G. Chatzikonstantinidis⁴⁷, M. Chefdeville⁴, S. Chen²², S.F. Cheung⁵⁷, S.-G. Chitic⁴⁰, V. Chobanova³⁹, M. Chruszcz⁴⁰, A. Chubykin³¹, P. Ciambone¹⁸, X. Cid Vidal³⁹, G. Ciezarek⁴⁰, P.E.L. Clarke⁵², M. Clemencic⁴⁰, H.V. Cliff⁴⁹, J. Closier⁴⁰, V. Coco⁴⁰, J. Cogan⁶, E. Cogneras⁵, V. Cogoni^{22,f}, L. Cojocariu³⁰, P. Collins⁴⁰, T. Colombo⁴⁰, A. Comerma-Montells¹², A. Contu²², G. Coombs⁴⁰, S. Coquereau³⁸, G. Corti⁴⁰, M. Corvo^{16,g}, C.M. Costa Sobral⁵⁰, B. Couturier⁴⁰, G.A. Cowan⁵², D.C. Craik⁵⁸, A. Crocombe⁵⁰, M. Cruz Torres¹, R. Currie⁵², C. D'Ambrosio⁴⁰, F. Da Cunha Marinho², C.L. Da Silva⁷³, E. Dall'Occo⁴³, J. Dalseno⁴⁸, A. Davis³, O. De Aguiar Francisco⁴⁰, K. De Bruyn⁴⁰, S. De Capua⁵⁶, M. De Cian¹², J.M. De Miranda¹, L. De Paula², M. De Serio^{14,d}, P. De Simone¹⁸, C.T. Dean⁵³, D. Decamp⁴, L. Del Buono⁸, B. Delaney⁴⁹, H.-P. Dembinski¹¹, M. Demmer¹⁰, A. Dendek²⁸, D. Derkach³⁵, O. Deschamps⁵, F. Dettori⁵⁴, B. Dey⁶⁵, A. Di Canto⁴⁰, P. Di Nezza¹⁸, H. Dijkstra⁴⁰, F. Dordei⁴⁰, M. Dorigo⁴⁰, A. Dosil Suárez³⁹, L. Douglas⁵³, A. Dovbnya⁴⁵, K. Dreimanis⁵⁴, L. Dufour⁴³, G. Dujany⁸, P. Durante⁴⁰, J.M. Durham⁷³, D. Dutta⁵⁶, R. Dzhelyadin³⁷, M. Dziwiecki¹², A. Dziurda⁴⁰, A. Dzyuba³¹, S. Easo⁵¹, U. Egede⁵⁵, V. Egorychev³², S. Eidelman^{36,w}, S. Eisenhardt⁵², U. Eitschberger¹⁰, R. Ekelhof¹⁰, L. Eklund⁵³, S. Ely⁶¹, A. Ene³⁰, S. Esen⁴³, H.M. Evans⁴⁹, T. Evans⁵⁷, A. Falabella¹⁵, N. Farley⁴⁷, S. Farry⁵⁴, D. Fazzini^{20,i}, L. Federici²⁵, G. Fernandez³⁸, P. Fernandez Declara⁴⁰, A. Fernandez Prieto³⁹, F. Ferrari¹⁵, L. Ferreira Lopes⁴¹, F. Ferreira Rodrigues², M. Ferro-Luzzi⁴⁰, S. Filippov³⁴, R.A. Fini¹⁴, M. Fiorini^{16,g}, M. Firlej²⁸, C. Fitzpatrick⁴¹, T. Fiutowski²⁸, F. Fleuret^{7,b}, M. Fontana^{22,40}, F. Fontanelli^{19,h}, R. Forty⁴⁰, V. Franco Lima⁵⁴, M. Frank⁴⁰, C. Frei⁴⁰, J. Fu^{21,g}, W. Funk⁴⁰, E. Furfaro^{25,j}, C. Färber⁴⁰, E. Gabriel⁵², A. Gallas Torreira³⁹, D. Galli^{15,e}, S. Gallorini²³, S. Gambetta⁵², M. Gandelman², P. Gandini²¹, Y. Gao³, L.M. Garcia Martin⁷¹, J. García Pardiñas³⁹, J. Garra Tico⁴⁹, L. Garrido³⁸, D. Gascon³⁸, C. Gaspar⁴⁰, L. Gavardi¹⁰, G. Gazzoni⁵, D. Gerick¹², E. Gersabeck⁵⁶, M. Gersabeck⁵⁶, T. Gershon⁵⁰, Ph. Ghez⁴, S. Giani⁴¹, V. Gibson⁴⁹, O.G. Girard⁴¹, L. Giubega³⁰, K. Gizdov⁵², V.V. Gligorov⁸, D. Golubkov³², A. Golutvin^{55,69}, A. Gomes^{1,a}, I.V. Gorelov³³, C. Gotti^{20,i}, E. Govorkova⁴³, J.P. Grabowski¹², R. Graciani Diaz³⁸, L.A. Granado Cardoso⁴⁰, E. Graugés³⁸, E. Graverini⁴², G. Graziani¹⁷, A. Greco³⁰, R. Greim⁹,

P. Griffith²², L. Grillo⁵⁶, L. Gruber⁴⁰, B.R. Gruberg Cazon⁵⁷, O. Grünberg⁶⁷, E. Gushchin³⁴,
 Yu. Guz³⁷, T. Gys⁴⁰, C. Göbel⁶², T. Hadavizadeh⁵⁷, C. Hadjivasilou⁵, G. Haefeli⁴¹, C. Haen⁴⁰,
 S.C. Haines⁴⁹, B. Hamilton⁶⁰, X. Han¹², T.H. Hancock⁵⁷, S. Hansmann-Menzemer¹²,
 N. Harnew⁵⁷, S.T. Harnew⁴⁸, C. Hasse⁴⁰, M. Hatch⁴⁰, J. He⁶³, M. Hecker⁵⁵, K. Heinicke¹⁰,
 A. Heister⁹, K. Hennessy⁵⁴, P. Henrard⁵, L. Henry⁷¹, E. van Herwijnen⁴⁰, M. Heß⁶⁷,
 A. Hicheur², D. Hill⁵⁷, P.H. Hopchev⁴¹, W. Hu⁶⁵, W. Huang⁶³, Z.C. Huard⁵⁹, W. Hulsbergen⁴³,
 T. Humair⁵⁵, M. Hushchyn³⁵, D. Hutchcroft⁵⁴, P. Ibis¹⁰, M. Idzik²⁸, P. Ilten⁴⁷, R. Jacobsson⁴⁰,
 J. Jalocha⁵⁷, E. Jans⁴³, A. Jawahery⁶⁰, F. Jiang³, M. John⁵⁷, D. Johnson⁴⁰, C.R. Jones⁴⁹,
 C. Joram⁴⁰, B. Jost⁴⁰, N. Jurik⁵⁷, S. Kandybei⁴⁵, M. Karacson⁴⁰, J.M. Kariuki⁴⁸, S. Karodia⁵³,
 N. Kazeev³⁵, M. Kecke¹², F. Keizer⁴⁹, M. Kelsey⁶¹, M. Kenzie⁴⁹, T. Ketel⁴⁴, E. Khairullin³⁵,
 B. Khanji¹², C. Khurewathanakul⁴¹, K.E. Kim⁶¹, T. Kirn⁹, S. Klaver¹⁸, K. Klimaszewski²⁹,
 T. Klimkovich¹¹, S. Koliiev⁴⁶, M. Kolpin¹², R. Kopečna¹², P. Koppenburg⁴³, A. Kosmyntseva³²,
 S. Kotriakhova³¹, M. Kozeiha⁵, L. Kravchuk³⁴, M. Kreps⁵⁰, F. Kress⁵⁵, P. Krokovny^{36,w},
 W. Krzemien²⁹, W. Kucewicz^{27,l}, M. Kucharczyk²⁷, V. Kudryavtsev^{36,w}, A.K. Kuonen⁴¹,
 T. Kvaratskheliya^{32,40}, D. Lacarrere⁴⁰, G. Lafferty⁵⁶, A. Lai²², G. Lanfranchi¹⁸,
 C. Langenbruch⁹, T. Latham⁵⁰, C. Lazzeroni⁴⁷, R. Le Gac⁶, A. Leflat^{33,40}, J. Lefrançois⁷,
 R. Lefèvre⁵, F. Lemaitre⁴⁰, O. Leroy⁶, T. Lesiak²⁷, B. Leverington¹², P.-R. Li⁶³, T. Li³, Y. Li⁷,
 Z. Li⁶¹, X. Liang⁶¹, T. Likhomanenko⁶⁸, R. Lindner⁴⁰, F. Lionetto⁴², V. Lisovskyi⁷, X. Liu³,
 D. Loh⁵⁰, A. Loi²², I. Longstaff⁵³, J.H. Lopes², D. Lucchesi^{23,o}, M. Lucio Martinez³⁹,
 A. Lupato²³, E. Luppi^{16,g}, O. Lupton⁴⁰, A. Lusiani²⁴, X. Lyu⁶³, F. Machefert⁷, F. Maciuc³⁰,
 V. Macko⁴¹, P. Mackowiak¹⁰, S. Maddrell-Mander⁴⁸, O. Maev^{31,40}, K. Maguire⁵⁶,
 D. Maisuzenko³¹, M.W. Majewski²⁸, S. Malde⁵⁷, B. Malecki²⁷, A. Malinin⁶⁸, T. Maltsev^{36,w},
 G. Manca^{22,f}, G. Mancinelli⁶, D. Marangotto^{21,q}, J. Maratas^{5,v}, J.F. Marchand⁴, U. Marconi¹⁵,
 C. Marin Benito³⁸, M. Marinangeli⁴¹, P. Marino⁴¹, J. Marks¹², G. Martellotti²⁶, M. Martin⁶,
 M. Martinelli⁴¹, D. Martinez Santos³⁹, F. Martinez Vidal⁷¹, A. Massafferri¹, R. Matev⁴⁰,
 A. Mathad⁵⁰, Z. Mathe⁴⁰, C. Matteuzzi²⁰, A. Mauri⁴², E. Maurice^{7,b}, B. Maurin⁴¹,
 A. Mazurov⁴⁷, M. McCann^{55,40}, A. McNab⁵⁶, R. McNulty¹³, J.V. Mead⁵⁴, B. Meadows⁵⁹,
 C. Meaux⁶, F. Meier¹⁰, N. Meinert⁶⁷, D. Melnychuk²⁹, M. Merk⁴³, A. Merli^{21,40,q},
 E. Michielin²³, D.A. Milanes⁶⁶, E. Millard⁵⁰, M.-N. Minard⁴, L. Minzoni^{16,g}, D.S. Mitzel¹²,
 A. Mogini⁸, J. Molina Rodriguez^{1,y}, T. Mombächer¹⁰, I.A. Monroy⁶⁶, S. Monteil⁵,
 M. Morandin²³, M.J. Morello^{24,t}, O. Morgunova⁶⁸, J. Moron²⁸, A.B. Morris⁶, R. Mountain⁶¹,
 F. Muheim⁵², M. Mulder⁴³, D. Müller⁴⁰, J. Müller¹⁰, K. Müller⁴², V. Müller¹⁰, P. Naik⁴⁸,
 T. Nakada⁴¹, R. Nandakumar⁵¹, A. Nandi⁵⁷, I. Nasteva², M. Needham⁵², N. Neri^{21,40},
 S. Neubert¹², N. Neufeld⁴⁰, M. Neuner¹², T.D. Nguyen⁴¹, C. Nguyen-Mau^{41,n}, S. Nieswand⁹,
 R. Niet¹⁰, N. Nikitin³³, T. Nikodem¹², A. Nogay⁶⁸, D.P. O’Hanlon⁵⁰, A. Oblakowska-Mucha²⁸,
 V. Obraztsov³⁷, S. Ogilvy¹⁸, R. Oldeman^{22,f}, C.J.G. Onderwater⁷², A. Ossowska²⁷,
 J.M. Otalora Goicochea², P. Owen⁴², A. Oyanguren⁷¹, P.R. Pais⁴¹, A. Palano¹⁴, M. Palutan^{18,40},
 G. Panshin⁷⁰, A. Papanestis⁵¹, M. Pappagallo⁵², L.L. Pappalardo^{16,g}, W. Parker⁶⁰, C. Parkes⁵⁶,
 G. Passaleva^{17,40}, A. Pastore¹⁴, M. Patel⁵⁵, C. Patrignani^{15,e}, A. Pearce⁴⁰, A. Pellegrino⁴³,
 G. Penso²⁶, M. Pepe Altarelli⁴⁰, S. Perazzini⁴⁰, D. Pereima³², P. Perret⁵, L. Pescatore⁴¹,
 K. Petridis⁴⁸, A. Petrolini^{19,h}, A. Petrov⁶⁸, M. Petruzzo^{21,q}, E. Picatoste Olloqui³⁸,
 B. Pietrzyk⁴, G. Pietrzyk⁴¹, M. Pikiés²⁷, D. Pinci²⁶, F. Pisani⁴⁰, A. Pistone^{19,h}, A. Piucci¹²,
 V. Placinta³⁰, S. Playfer⁵², M. Plo Casasus³⁹, F. Polci⁸, M. Poli Lener¹⁸, A. Poluektov⁵⁰,
 I. Polyakov⁶¹, E. Polcarpo², G.J. Pomery⁴⁸, S. Ponce⁴⁰, A. Popov³⁷, D. Popov^{11,40},
 S. Poslavskii³⁷, C. Potterat², E. Price⁴⁸, J. Prisciandaro³⁹, C. Prouve⁴⁸, V. Pugatch⁴⁶,
 A. Puig Navarro⁴², H. Pullen⁵⁷, G. Punzi^{24,p}, W. Qian⁵⁰, J. Qin⁶³, R. Quagliani⁸, B. Quintana⁵,
 B. Rachwal²⁸, J.H. Rademacker⁴⁸, M. Rama²⁴, M. Ramos Pernas³⁹, M.S. Rangel², I. Raniuk^{45,†},
 F. Ratnikov^{35,x}, G. Raven⁴⁴, M. Ravonel Salzgeber⁴⁰, M. Reboud⁴, F. Redi⁴¹, S. Reichert¹⁰,
 A.C. dos Reis¹, C. Remon Alepuz⁷¹, V. Renaudin⁷, S. Ricciardi⁵¹, S. Richards⁴⁸, M. Rihl⁴⁰,
 K. Rinnert⁵⁴, P. Robbe⁷, A. Robert⁸, A.B. Rodrigues⁴¹, E. Rodrigues⁵⁹,

J.A. Rodriguez Lopez⁶⁶, A. Rogozhnikov³⁵, S. Roiser⁴⁰, A. Rollings⁵⁷, V. Romanovskiy³⁷, A. Romero Vidal^{39,40}, M. Rotondo¹⁸, M.S. Rudolph⁶¹, T. Ruf⁴⁰, P. Ruiz Valls⁷¹, J. Ruiz Vidal⁷¹, J.J. Saborido Silva³⁹, E. Sadykhov³², N. Sagidova³¹, B. Saitta^{22,f}, V. Salustino Guimaraes⁶², C. Sanchez Mayordomo⁷¹, B. Sanmartin Sedes³⁹, R. Santacesaria²⁶, C. Santamarina Rios³⁹, M. Santimaria¹⁸, E. Santovetti^{25,j}, G. Sarpis⁵⁶, A. Sarti^{18,k}, C. Satriano^{26,s}, A. Satta²⁵, D.M. Saunders⁴⁸, D. Savrina^{32,33}, S. Schael⁹, M. Schellenberg¹⁰, M. Schiller⁵³, H. Schindler⁴⁰, M. Schmelling¹¹, T. Schmelzer¹⁰, B. Schmidt⁴⁰, O. Schneider⁴¹, A. Schopper⁴⁰, H.F. Schreiner⁵⁹, M. Schubiger⁴¹, M.H. Schune⁷, R. Schwemmer⁴⁰, B. Sciascia¹⁸, A. Sciubba^{26,k}, A. Semennikov³², E.S. Sepulveda⁸, A. Sergi⁴⁷, N. Serra⁴², J. Serrano⁶, L. Sestini²³, P. Seyfert⁴⁰, M. Shapkin³⁷, Y. Shcheglov^{31,†}, T. Shears⁵⁴, L. Shekhtman^{36,w}, V. Shevchenko⁶⁸, B.G. Siddi¹⁶, R. Silva Coutinho⁴², L. Silva de Oliveira², G. Simi^{23,o}, S. Simone^{14,d}, N. Skidmore⁴⁸, T. Skwarnicki⁶¹, I.T. Smith⁵², J. Smith⁴⁹, M. Smith⁵⁵, I. Soares Lavra¹, M.D. Sokoloff⁵⁹, F.J.P. Soler⁵³, B. Souza De Paula², B. Spaan¹⁰, P. Spradlin⁵³, F. Stagni⁴⁰, M. Stahl¹², S. Stahl⁴⁰, P. Stefko⁴¹, S. Stefkova⁵⁵, O. Steinkamp⁴², S. Stemmler¹², O. Stenyakin³⁷, M. Stepanova³¹, H. Stevens¹⁰, S. Stone⁶¹, B. Storaci⁴², S. Stracka^{24,p}, M.E. Stramaglia⁴¹, M. Straticiuc³⁰, U. Straumann⁴², S. Strokov⁷⁰, J. Sun³, L. Sun⁶⁴, K. Swientek²⁸, V. Syropoulos⁴⁴, T. Szumlak²⁸, M. Szymanski⁶³, S. T’Jampens⁴, Z. Tang³, A. Tayduganov⁶, T. Tekampe¹⁰, G. Tellarini^{16,g}, F. Teubert⁴⁰, E. Thomas⁴⁰, J. van Tilburg⁴³, M.J. Tilley⁵⁵, V. Tisserand⁵, M. Tobin⁴¹, S. Tolck⁴⁹, L. Tomassetti^{16,g}, D. Tonelli²⁴, R. Tourinho Jadallah Aoude¹, E. Tournefier⁴, M. Traill⁵³, M.T. Tran⁴¹, M. Tresch⁴², A. Trisovic⁴⁹, A. Tsaregorodtsev⁶, P. Tsopelas⁴³, A. Tully⁴⁹, N. Tuning^{43,40}, A. Ukleja²⁹, A. Usachov⁷, A. Ustyuzhanin³⁵, U. Uwer¹², C. Vacca^{22,f}, A. Vagner⁷⁰, V. Vagnoni^{15,40}, A. Valassi⁴⁰, S. Valat⁴⁰, G. Valenti¹⁵, R. Vazquez Gomez⁴⁰, P. Vazquez Regueiro³⁹, S. Vecchi¹⁶, M. van Veghel⁴³, J.J. Velthuis⁴⁸, M. Veltri^{17,r}, G. Veneziano⁵⁷, A. Venkateswaran⁶¹, T.A. Verlage⁹, M. Vernet⁵, M. Vesterinen⁵⁷, J.V. Viana Barbosa⁴⁰, D. Vieira⁶³, M. Vieites Diaz³⁹, H. Viemann⁶⁷, X. Vilasis-Cardona^{38,m}, A. Vitkovskiy⁴³, M. Vitti⁴⁹, V. Volkov³³, A. Vollhardt⁴², B. Voneki⁴⁰, A. Vorobyev³¹, V. Vorobyev^{36,w}, C. Voß⁹, J.A. de Vries⁴³, C. Vázquez Sierra⁴³, R. Waldi⁶⁷, J. Walsh²⁴, J. Wang⁶¹, M. Wang³, Y. Wang⁶⁵, D.R. Ward⁴⁹, H.M. Wark⁵⁴, N.K. Watson⁴⁷, D. Websdale⁵⁵, A. Weiden⁴², C. Weisser⁵⁸, M. Whitehead⁴⁰, J. Wicht⁵⁰, G. Wilkinson⁵⁷, M. Wilkinson⁶¹, M.R.J. Williams⁵⁶, M. Williams⁵⁸, T. Williams⁴⁷, F.F. Wilson^{51,40}, J. Wimberley⁶⁰, M. Winn⁷, J. Wishahi¹⁰, W. Wislicki²⁹, M. Witek²⁷, G. Wormser⁷, S.A. Wotton⁴⁹, K. Wyllie⁴⁰, Y. Xie⁶⁵, M. Xu⁶⁵, Q. Xu⁶³, Z. Xu³, Z. Xu⁴, Z. Yang³, Z. Yang⁶⁰, Y. Yao⁶¹, H. Yin⁶⁵, J. Yu⁶⁵, X. Yuan⁶¹, O. Yushchenko³⁷, K.A. Zarebski⁴⁷, M. Zavertyaev^{11,c}, L. Zhang³, Y. Zhang⁷, A. Zhelezov¹², Y. Zheng⁶³, X. Zhu³, V. Zhukov^{9,33}, J.B. Zonneveld⁵², S. Zucchelli¹⁵.

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

⁹I. 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

- ¹⁷ INFN Sezione di Firenze, Firenze, Italy
- ¹⁸ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ¹⁹ INFN Sezione di Genova, Genova, Italy
- ²⁰ INFN Sezione di Milano-Bicocca, Milano, Italy
- ²¹ INFN Sezione di Milano, Milano, Italy
- ²² INFN Sezione di Cagliari, Monserrato, Italy
- ²³ INFN Sezione di Padova, Padova, Italy
- ²⁴ INFN Sezione di Pisa, Pisa, Italy
- ²⁵ INFN Sezione di Roma Tor Vergata, Roma, Italy
- ²⁶ INFN Sezione di Roma La Sapienza, Roma, Italy
- ²⁷ Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
- ²⁸ AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
- ²⁹ National Center for Nuclear Research (NCBJ), Warsaw, Poland
- ³⁰ Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
- ³¹ Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
- ³² Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ³³ Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
- ³⁴ Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia
- ³⁵ Yandex School of Data Analysis, Moscow, Russia
- ³⁶ Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia
- ³⁷ Institute for High Energy Physics (IHEP), Protvino, Russia
- ³⁸ ICCUB, Universitat de Barcelona, Barcelona, Spain
- ³⁹ Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
- ⁴⁰ European Organization for Nuclear Research (CERN), Geneva, Switzerland
- ⁴¹ Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
- ⁴² Physik-Institut, Universität Zürich, Zürich, Switzerland
- ⁴³ Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
- ⁴⁴ Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands
- ⁴⁵ NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
- ⁴⁶ Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
- ⁴⁷ University of Birmingham, Birmingham, United Kingdom
- ⁴⁸ H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
- ⁴⁹ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ⁵⁰ Department of Physics, University of Warwick, Coventry, United Kingdom
- ⁵¹ STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
- ⁵² School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁵³ School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁴ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁵⁵ Imperial College London, London, United Kingdom
- ⁵⁶ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁵⁷ Department of Physics, University of Oxford, Oxford, United Kingdom
- ⁵⁸ Massachusetts Institute of Technology, Cambridge, MA, United States
- ⁵⁹ University of Cincinnati, Cincinnati, OH, United States
- ⁶⁰ University of Maryland, College Park, MD, United States
- ⁶¹ Syracuse University, Syracuse, NY, United States
- ⁶² Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to ²
- ⁶³ University of Chinese Academy of Sciences, Beijing, China, associated to ³
- ⁶⁴ School of Physics and Technology, Wuhan University, Wuhan, China, associated to ³
- ⁶⁵ Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China, associated to ³
- ⁶⁶ Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia, associated to ⁸
- ⁶⁷ Institut für Physik, Universität Rostock, Rostock, Germany, associated to ¹²
- ⁶⁸ National Research Centre Kurchatov Institute, Moscow, Russia, associated to ³²
- ⁶⁹ National University of Science and Technology "MISIS", Moscow, Russia, associated to ³²

- ⁷⁰ *National Research Tomsk Polytechnic University, Tomsk, Russia, associated to* ³²
- ⁷¹ *Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain, associated to* ³⁸
- ⁷² *Van Swinderen Institute, University of Groningen, Groningen, The Netherlands, associated to* ⁴³
- ⁷³ *Los Alamos National Laboratory (LANL), Los Alamos, United States, associated to* ⁶¹
- ^a *Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil*
- ^b *Laboratoire Leprince-Ringuet, Palaiseau, France*
- ^c *P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia*
- ^d *Università di Bari, Bari, Italy*
- ^e *Università di Bologna, Bologna, Italy*
- ^f *Università di Cagliari, Cagliari, Italy*
- ^g *Università di Ferrara, Ferrara, Italy*
- ^h *Università di Genova, Genova, Italy*
- ⁱ *Università di Milano Bicocca, Milano, Italy*
- ^j *Università di Roma Tor Vergata, Roma, Italy*
- ^k *Università di Roma La Sapienza, Roma, Italy*
- ^l *AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland*
- ^m *LIFAEELS, La Salle, Universitat Ramon Llull, Barcelona, Spain*
- ⁿ *Hanoi University of Science, Hanoi, Vietnam*
- ^o *Università di Padova, Padova, Italy*
- ^p *Università di Pisa, Pisa, Italy*
- ^q *Università degli Studi di Milano, Milano, Italy*
- ^r *Università di Urbino, Urbino, Italy*
- ^s *Università della Basilicata, Potenza, Italy*
- ^t *Scuola Normale Superiore, Pisa, Italy*
- ^u *Università di Modena e Reggio Emilia, Modena, Italy*
- ^v *MSU - Iligan Institute of Technology (MSU-IIT), Iligan, Philippines*
- ^w *Novosibirsk State University, Novosibirsk, Russia*
- ^x *National Research University Higher School of Economics, Moscow, Russia*
- ^y *Escuela Agrícola Panamericana, San Antonio de Oriente, Honduras*
- [†] *Deceased*