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Search for *CP* violation using triple-product asymmetries in $\Lambda_b^0 \to ph^-h^+h^-$ and $\Xi_b^0 \to ph^-h^+h^-$ decays

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Summary. — We present the measurement of *CP*-violating asymmetries in bottom baryon decays, using $\Lambda_b^0 \to ph^-h^+h^-$ and $\Xi_b^0 \to ph^-h^+h^-$ decays, where $h = K, \pi$. The analysis is based on a data sample collected by the LHCb experiment in proton-proton collisions at centre-of-mass energies of 7 TeV and 8 TeV in 2011 and 2012, corresponding to integrated luminosities of about $1.0\,\mathrm{fb}^{-1}$ and $2.0\,\mathrm{fb}^{-1}$, respectively. The *CP*-violating asymmetries, based on triple products, are measured in different regions of phase space and also integrated over the phase space. We reach a sensitivity of 1% on *CP*-violating asymmetries, the most precise measurement in bottom baryon decays to date.

1. – Introduction

Flavour physics has historically driven indirect discoveries of new physics, through precision measurements when the available energy was not sufficient to produce new particles. Notable examples are the discoveries of *CP* violation (*CPV*) [1] which led to the explanation of flavour mixing with three families of quarks, the absence of $K_L^0 \to \mu^+\mu^-$ decay to the prediction of the c quark as explained by the GIM mechanism [2] and the measurement of B^0 mixing [3] leading to the prediction of the top quark mass. The "B-factories" BaBar and Belle have studied in detail the B^0 and $B^{\pm}$ decays, however the heavy-baryon sector (*i.e.* containing the b quark) still remains largely unexplored. Given the copious production of heavy baryons at the LHC, precision measurements have become possible in this field and the interest of the scientific community is growing. Recently, studies of heavy baryons led to the measurement of $|V_{ub}|$ using $\Lambda_b^0 \to p\mu^-\overline{\nu}$ decays [4] and the discovery of a pentaquark using $\Lambda_b^0 \to J/\psi pK^-$ decays [5]. In the Standard Model (SM), *CPV* is predicted to be particularly suppressed, as explained by the CKM flavour-mixing mechanism [6, 7]. A significant excess of *CPV* with respect to the theoretical predictions would represent a proof of new physics beyond the SM [8]. We know that *CPV* is a key ingredient for baryogenesis [9], but can not be explained quantitatively with the CKM mechanism [10, 11]. New sources of *CPV* are necessary to explain baryogenesis. Within the mesonic sector, the CKM matrix in the Standard Model describes the CPV results for B and K mesons quite well. It is important to test *CPV* also in baryon decays to verify if the mechanism through which it is generated is the same as for mesons.

2. – Measuring *CP*-violating asymmetries in bottom baryons decays

A measurable amount of *CPV* is expected in the decays of bottom baryons. The $\Lambda_b^0(\Xi_b^0) \to ph^+h^-h^+$ decays proceed via tree $b \to uq\overline{q}$ transitions and penguin $b \to sq\overline{q}$, $b \to dq\overline{q}$ transitions and *CPV* could arise from the interference of tree and penguin amplitudes, as shown in fig. 1. In addition, new physics effects could be originated from new particles contributing to penguin loop diagrams.

The study of triple-product asymmetries, defined in eqs. (5) and (6), in Λ_b^0 decays is particularly sensitive to new physics effects. Triple-product asymmetries which are expected to vanish in the SM can be very large (up to 50%) in the presence of new physics [12]. This technique for searching for *CPV* is very promising in the baryon sector expecially from an experimental point of view [13]. The triple-product asymmetries are by construction insensitive to production and detection asymmetries. The former property is particularly important in a $p\ p$ collider where $\Lambda_b^0/\overline{\Lambda}_b^0(\Xi_b^0/\overline{\Xi}_b^0)$ production asymmetry can arise, and the latter is crucial in the baryon sector since, in addition to meson/antimeson detection efficiency asymmetries, we have to deal with $p/\overline{p}$ interactions with matter which are quite different for different kinematic regimes.

Consequently, the systematic uncertainties are relatively small for this analysis and have been proved to be small for other triple-product analyses in LHCb [14], representing an interesting technique also for future measurements with larger data samples.

The Λ_b^0 baryon ($u\ d\ b$) is the lightest baryon containing a b quark with a mass of $5619.5 \pm 0.4\,\mathrm{MeV}$ [15]. The Ξ_b^0 baryon ($u\ s\ b$) is heavier with a mass of $5793.1 \pm 2.5\,\mathrm{MeV}$ [15].

The Λ_b^0 particle was discovered at UA1 experiment [16] and DØ and CDF were the first experiments to perform systematic studies on Λ_b^0 decays [17]. Precise measurements of its mass [18] and lifetime [19] have been performed by LHCb experiment.

The Ξ_b^0 baryon was discovered by the CDF experiment [20]. Precise measurements of the Ξ_b^0 baryon mass and lifetime have been recently performed by LHCb experiment [21]. The relative production rate of Ξ_b^0 to Λ_b^0 inside the LHCb acceptance is estimated to be $\frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} \approx 0.2$ [21].

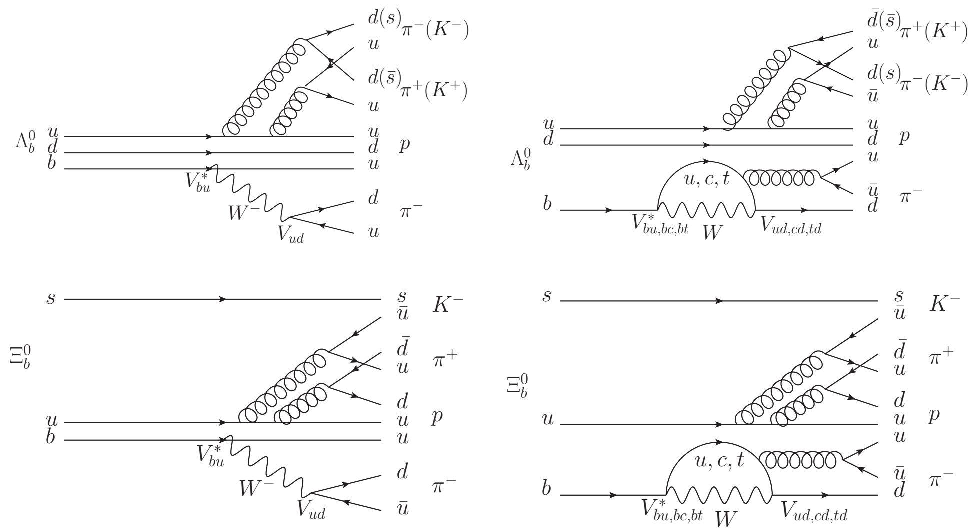
The CDF experiment searched for *CPV* in $\Lambda_b^0 \to pK^-$, $p\pi^-$ decays [22], measuring $\mathcal{A}_{CP} = \frac{N(\Lambda_b^0 \to f) - N(\overline{\Lambda}_b^0 \to \bar{f})}{N(\Lambda_b^0 \to f) + N(\overline{\Lambda}_b^0 \to \bar{f})}$ where f is the final state and $\bar{f}$ is the charge-conjugate state, to be compatible with zero:

$$\mathcal{A}_{CP}(\Lambda_b^0 \to pK^-) = -0.10 \pm 0.08(stat) \pm 0.04(syst), \tag{1}$$

$$\mathcal{A}_{CP}(\Lambda_b^0 \to p\pi^-) = +0.06 \pm 0.07(stat) \pm 0.03(syst). \tag{2}$$

The LHCb experiment recently measured *CP*-violating asymmetries in the decay $\Lambda_b^0 \to \overline{K}^0 p\pi^-$ to be

$$\mathcal{A}_{CP}(\Lambda_b^0 \to \overline{K}^0 p\pi^-) = 0.22 \pm 0.13(stat) \pm 0.03(syst), \tag{3}$$



(a) Tree diagram $\alpha\ V_{bu}^* \cdot V_{ud}\ \lambda^3$ (b) Penguin diagram $\alpha\ \Sigma_{x=u,c,t}\, V_{bx}^* V_{xd} \cdot \lambda^3$

Fig. 1. – Examples of tree (left) and penguin (right) diagrams for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-(\Lambda_b^0 \to pK^+K^-\pi^-)$ (above) and $\Xi_b^0 \to pK^-\pi^+\pi^-$ (below) decays. The tree and penguin diagrams have the same magnitude and large interference is possible.

consistent with the no *CPV* hypothesis [23]. More recently the difference of *CP*-violating asymmetries between $\Lambda_b^0 \to J/\psi p\pi^-$ and $\Lambda_b^0 \to J/\psi pK^-$ decays has been measured by the LHCb experiment to be

$$\mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi p\pi^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi pK^-) = [5.7 \pm 2.4(stat) \pm 1.2(syst)]\%, \tag{4}$$

which is compatible with the *CP* conservation hypothesis at 2.2σ level [24]. No searches for *CPV* in Ξ_b^0 decays have been performed to date.

LHCb is the first experiment which has the opportunity to study heavy baryons with good precision thanks to its optimization for flavour physics and to a copious production of baryons, opening new possibilities for this research.

3. – *CPV* using triple-product asymmetries

3·1. *Definition of the triple-product observables.* – In this work, the momenta of the final-state particles are used to define the triple products and are calculated in the mother baryon rest frame. The triple products are C_T for Λ_b^0 (Ξ_b^0) and $\overline{C}_T$ for $\overline{\Lambda}_b^0$ ($\overline{\Xi}_b^0$), defined as

- $\Lambda_b^0 \to pK^-\pi^+\pi^-$ ($\Xi_b^0 \to pK^-\pi^+\pi^-$): $C_T \equiv \vec{p}_p\cdot(\vec{p}_{K^-}\times\vec{p}_{\pi^+})$, $\overline{C}_T \equiv \vec{p}_{\overline{p}}\cdot(\vec{p}_{K^+}\times\vec{p}_{\pi^-})$,
- $\Lambda_b^0 \to pK^+K^-\pi^-$: $C_T \equiv \vec{p}_p\cdot(\vec{p}_{\pi^-}\times\vec{p}_{K^+})$, $\overline{C}_T \equiv \vec{p}_{\overline{p}}\cdot(\vec{p}_{\pi^+}\times\vec{p}_{K^-})$,
- $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$: $C_T \equiv \vec{p}_p\cdot(\vec{p}_{\pi^-{}_{fast}}\times\vec{p}_{\pi^+})$, $\overline{C}_T \equiv \vec{p}_{\overline{p}}\cdot(\vec{p}_{\pi^+{}_{fast}}\times\vec{p}_{\pi^-})$,
- $\Lambda_b^0 \to pK^-K^+K^-$: $C_T \equiv \vec{p}_p\cdot(\vec{p}_{K^-{}_{fast}}\times\vec{p}_{K^+})$, $\overline{C}_T \equiv \vec{p}_{\overline{p}}\cdot(\vec{p}_{K^+{}_{fast}}\times\vec{p}_{K^-})$,
- $\Xi_b^0 \to pK^-K^-\pi^+$: $C_T \equiv \vec{p}_p\cdot(\vec{p}_{K^-{}_{fast}}\times\vec{p}_{\pi^+})$, $\overline{C}_T \equiv \vec{p}_{\overline{p}}\cdot(\vec{p}_{K^+{}_{fast}}\times\vec{p}_{\pi^-})$,

where π_{fast} (K_{fast}) indicates the highest momentum π (K) among those of identical charge in the final state in the mother rest frame.

It is useful to introduce the motion-reversal operator indicated as $\widehat{T}$ which reverses both momentum and spin three-vectors but contrarily to the time-reversal operator T does not interchange final states into initial states [25]. The triple-products observables C_T and $\overline{C}_T$ are $\widehat{T}$-odd and also P-odd. These variables are used to define the asymmetry parameters $A_{\widehat{T}}$ and $\overline{A}_{\widehat{T}}$

$$A_{\widehat{T}} \equiv \frac{N(C_T > 0) - N(C_T < 0)}{N(C_T > 0) + N(C_T < 0)}, \qquad \overline{A}_{\widehat{T}} \equiv \frac{N(-\overline{C}_T > 0) - N(-\overline{C}_T < 0)}{N(-\overline{C}_T > 0) + N(-\overline{C}_T < 0)}. \tag{5}$$

Finally the CP-violating asymmetry parameter is measured as follows:

$$a_{CP}^{\widehat{T}\text{-odd}} = \frac{1}{2}(A_{\widehat{T}} - \overline{A}_{\widehat{T}}). \tag{6}$$

3˙2. *Sensitivity to CP violation.* – The triple-product asymmetry technique provides an alternative and complementary way to search for CPV with respect to the CP-violating asymmetry based on the difference of the yields between particles and antiparticles $\mathcal{A}_{CP}$.

The use of triple product asymmetries for searching for CPV is described for example in ref. [26, 12, 27]. $A_{\widehat{T}}$ and $\overline{A}_{\widehat{T}}$ are P-odd therefore they are sensitive to P violation. Nevertheless, as reported in [28], $A_{\widehat{T}}$ and $\overline{A}_{\widehat{T}}$ observables are affected by final-state interaction effects and strong phases, as can be seen in eqs. (7) and (8), and cannot be calculated. They are not CP-odd and therefore not sensitive to CPV. The CP-odd observable is $a_{CP}^{\widehat{T}\text{-odd}}$, defined in eq. (9), implying that a non zero value is a clean signal of CPV.

As pointed out in several papers [29,30,28], CP-violating asymmetries based on triple products are different and complementary observables with respect to $\mathcal{A}_{CP}$. In particular

$$A_{\widehat{T}} \propto \sin(\delta' + \phi'), \tag{7}$$

$$\overline{A}_{\widehat{T}} \propto \sin(\delta' - \phi'), \tag{8}$$

$$a_{CP}^{\widehat{T}\text{-odd}} \propto \sin\phi' \cos\delta', \tag{9}$$

while the CP-violating asymmetry based on the yields is

$$\mathcal{A}_{CP} \propto \sin\phi \sin\delta. \tag{10}$$

Here, ϕ is the relative weak phase and δ is the strong phase between two interfering decay amplitudes, and ϕ' is the relative weak phase and δ' is the strong phase between the $\widehat{T}$-odd and $\widehat{T}$-even part of the decay amplitudes [28]. Furthermore, the strong phases vary over the phase space, therefore the different regions of the phase space provide different sensitivity to CPV depending on their values.

Comparing eq. (9) and eq. (10), the observable $a_{CP}^{\widehat{T}\text{-odd}}$ has therefore different sensitivity to CPV with respect to $\mathcal{A}_{CP}$.

4. – The LHCb experiment

The LHCb detector [31] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, primarily 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 [32], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about $4\,\mathrm{T\,m}$, and three stations of silicon-strip detectors and straw drift tubes [33] placed downstream of the magnet. The tracking system provides a measurement of momentum, p, with a relative uncertainty that varies from 0.4% at low momentum to 0.6% at $100\,\mathrm{GeV}/c$. The minimum distance of a track to a primary vertex, the impact parameter, is measured with a resolution of $(15 + 29/p_{\mathrm{T}})\,\mu\mathrm{m}$ where p_{T} is the component of p transverse to the beam in GeV/c. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [34]. Photon, electron and hadron candidates 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 trigger [35] 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.

Events are required to pass both hardware and software trigger selections. The software trigger requires a secondary vertex with a significant displacement from the primary pp interaction vertices. At least one charged particle must have a transverse momentum $p_{\mathrm{T}} > 1.7\,\mathrm{GeV}/c$ and be inconsistent with originating from the primary vertex. A multivariate algorithm [36] is used for the identification of secondary vertices consistent with the decay of a b hadron.

5. – Analysis technique

This analysis is based on a data sample collected by the LHCb Collaboration in pp collisions at a centre of mass energies of 7 TeV and 8 TeV in 2011 and 2012 corresponding to integrated luminosities of about $1.0\,\mathrm{fb}^{-1}$ and $2.0\,\mathrm{fb}^{-1}$, respectively.

5·1. *Selection of signal events.* – The signal candidates are formed from combinations of four tracks. The candidates are selected by requiring a four-track secondary vertex with a sum of transverse momentum (p_{T}) of the tracks greater than $3.5\,\mathrm{GeV}/c$ and p_{T} for the combination greater than $1.5\,\mathrm{GeV}/c$. The daughters are required to have $p_{\mathrm{T}} > 250\,\mathrm{MeV}/c$ and a momentum $p > 1.5\,\mathrm{GeV}/c$. Tracks have to be compatible with a detached decay vertex with a $\chi^2_{\mathrm{vtx}} < 20$. Therefore, a requirement is imposed on the tracks on the $\chi^2_{\mathrm{IP}} > 16$, *i.e.* the difference in χ^2 of a given primary vertex reconstructed with and without the considered particle. On the contrary, the reconstructed mother is required to be produced at the primary vertex, *i.e.* $\chi^2_{\mathrm{IP}} < 16$.

Since we are interested in Cabibbo suppressed processes mediated by V_{ub} and penguin diagrams as shown in fig. 1, we apply a veto on the more abundant Cabibbo favored decays mediated via V_{cb} which do not contain any weak phase. In particular, the charm resonances, such as $\Lambda_c^+, \Xi_c^0, D^0, D^+, D_s^+$ are vetoed by requiring the reconstructed invariant mass of the Λ_b^0 (Ξ_b^0) daughters is more than 3σ away from the fitted peaks, where σ is the resolution of the reconstructed invariant mass. We veto also the J/ψ resonance, mainly due to $\pi \to \mu$ misidentification. In order to further reduce cross-feed from B^0 and B_s^0 decays, we veto also events with ϕ and K^* resonances reconstructed using the

K or π mass hypothesis for the p candidate track. No contamination from light-quark long-lived particles, such as $\mathit{\Lambda}$ and K^0_S, is found in the data sample since the typical flight length $c\tau \approx \mathcal{O}(1\ \text{cm})$ is not compatible with the requirement of a four-track secondary vertex. Strongly decaying resonances are part of the signal.

We use a boosted decision tree (BDT) [37] to separate signal from background, trained and validated with the k-folding technique [38] ($k = 3$ in our case). To train the classifiers we use information on the vertex χ^2 and its isolation with respect to the other tracks in the event, proton momenta, tracks and Λ^0_b ($\mathit{\Xi}^0_b$) candidate impact parameter. We consider also the angle between the Λ^0_b ($\mathit{\Xi}^0_b$) candidate momenta and the pointing vector, *i.e.* the vector from the primary vertex to the secondary vertex. The optimal cuts are obtained maximizing the significance obtaining a signal efficiency of 90% and a background rejection of 90%.

We further optimize the selection using PID information from the Cherenkov detectors, calorimeters and muon system. We perform the optimization on the previously vetoed data samples.

5˙2. *Extraction of signal yields*. – The invariant mass signal shape is determined by using $\Lambda^0_b \to ph^-h^+h^-$ simulated MC decays and is modeled by using the sum of two Crystal Ball (CB) functions [39]. The mean of the $\mathit{\Xi}^0_b$ signal peak is fitted with a Gaussian constraint on the mass difference, taken from the PDG [15], with respect to the Λ^0_b mass. In the fit to the data the mean μ and the σ of the signal distributions are free to vary for obtaining optimal fit results.

Three main categories of background can be identified in this analysis.

– Partially reconstructed decays: these are localized in the region at low invariant mass and include feed down from $\Lambda^0_b \to ph^+h^-\rho^-(\rho^- \to \pi^-\pi^0)$ or $\Lambda^0_b \to ph^+h^-K^{*-}(K^{*-} \to K^-\pi^0)$ and similar decays, in which the π^0 is not reconstructed (*five-body background*). These candidates appear as a shoulder on the low-energy side of the mass distribution. The distribution of the partial reconstructed background can be empirically modeled by an ARGUS function convoluted with a Gaussian resolution function.

– Cross-feed background: these are mainly due to four-body Λ^0_b, B^0 and B^0_s decays where one of the daughter particles has been misidentified and reconstructed with a wrong mass hypothesis. This background can be reduced using adequate PID requirements and *ad hoc* resonance vetoes, *e.g.* veto $\phi(1020)$ or $K^{*0}(892)$ resonance once reconstructing the decay with different mass hypotheses for the proton candidate. This background is potentially dangerous since it is due to b-hadron decays that in principle can violate *CP* and also it has a distribution that is close, and in some cases overlapping, with the signal shape. It can be considered as a peaking background source in the invariant-mass spectrum. The distributions of the cross-feed backgrounds are parametrized with kernel estimated probability density functions [40] by modeling the signal Monte Carlo invariant-mass distributions under the wrong mass hypothesis for daughter particles.

– Combinatorial background: this source of background is mainly due to random combinations of charged tracks in the event. This source can be reduced by requiring good-quality tracks to be compatible with displaced vertices of Λ^0_b hadrons.

An unbinned maximum-likelihood fit to the reconstructed invariant mass spectra $m(ph^-h^+h^-)$ is performed using the signal and background shapes described above.

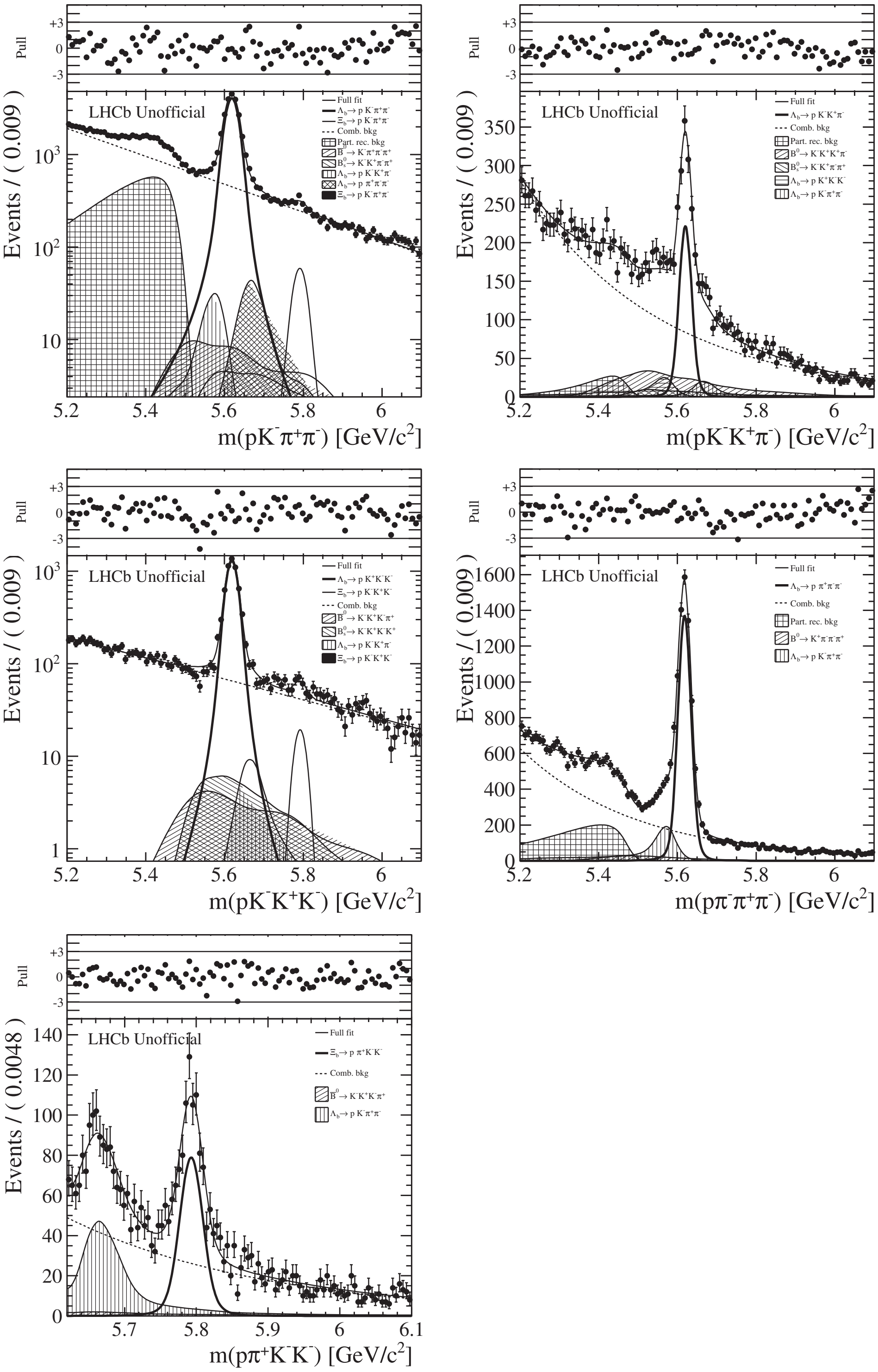


Fig. 2. – Reconstructed invariant-mass distribution for $\Lambda_b^0(\Xi_b^0) \to ph^-h^+h^-$ signal candidates. A fit is overlaid as described in the text.

The yields of cross-feed backgrounds from B^0, B_s^0 and other Λ_b^0 decays are estimated directly on data by fitting the invariant mass spectrum obtained when using different mass hypotheses for final-state particles. The results are then applied as Gaussian constraints on cross-feed background yields in the nominal fit for Λ_b^0 and Ξ_b^0 signal and background estimation. The results of the fits to date are shown in fig. 2. We obtain the following signal yields: 19877 ± 195 for $\Lambda_b^0 \to pK^-\pi^+\pi^-$, 287 ± 51 for $\Xi_b^0 \to pK^-\pi^+\pi^-$, 5297 ± 83 for $\Lambda_b^0 \to pK^-K^+K^-$, 83 ± 20 for $\Xi_b^0 \to pK^-K^+K^-$, 6646 ± 105 for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$, 1030 ± 56 for $\Lambda_b^0 \to pK^+K^-\pi^-$, 709 ± 45 for $\Xi_b^0 \to pK^-K^-\pi^+$ decays. These represent the first observations for all these decay modes.

6. – Results

6·1. *Asymmetry measurements.* – The selected data samples are split into four subsamples according to the charge of the proton which determines the flavor of the Λ_b^0 (Ξ_b^0) candidate, and the sign of C_T ($\overline{C}_T$). The reconstruction efficiencies are identical, within their uncertainties, for $C_T > 0$ ($-\overline{C}_T > 0$) and $C_T < 0$ ($-\overline{C}_T < 0$) according to studies based on simulated events and on the $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$ control sample. A simultaneous maximum likelihood fit to the $m(ph^-h^+h^-)$ reconstructed invariant mass distribution of the four subsamples is used to determine the number of signal and background events and the asymmetries $A_{\widehat{T}}$, $\overline{A}_{\widehat{T}}$. Negligible correlation is found between the two asymmetries.

Two different approaches have been followed to search for *CPV*: a measurement integrated over phase space and measurements in different regions of phase space. At the time of the writing of this article the analysis is still under review and results are kept blind to prevent any possible bias. The blind results of the first approach are obtained by fitting the full data samples and are listed in table I.

The measurements in regions of phase space are performed by dividing the sample according to a binning scheme based on the variables m_{ph^-}, $m_{h^+h'^-}$, $\cos\theta_{ph^-}$, $\cos\theta_{h^+h'^-}$, Φ, defined as the $p\,h^-$ and $h^+h'^-$ invariant masses, the cosine of the p (h^+) helicity angle and the angle between the decay planes described by the $p\,h^-$ and $h^+h'^-$ combinations, respectively. We perform measurements in regions of phase space in order to improve the sensitivity to *CPV*. We try different binning schemes dividing the regions of the phase space according to structures found in the decay, trying to separate the resonant low mass region and the high non resonant mass region. We also divide the phase space in different ways, splitting it with boundaries at mass peak of resonances of two daughter particles and defining 10 different bins in the Φ distribution folded between $(0, \pi)$. The accuracy on *CP*-violating asymmetries varies over phase space, depending on the statistics, ranging from 2% to 10%.

TABLE I. – *Blind results for asymmetries integrated over phase space for each decay mode analyzed.*

Decay	A_T (%)	$\bar{A}_T$ (%)	$a_{CP}^{T\text{-odd}}$ (%)
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$x \pm 1.12_{\text{stat}} \pm 0.44_{\text{syst}}$	$x \pm 1.18_{\text{stat}} \pm 0.44_{\text{syst}}$	$x \pm 0.81_{\text{stat}} \pm 0.31_{\text{syst}}$
$\Lambda_b^0 \to pK^-K^+K^-$	$x \pm 2.10_{\text{stat}} \pm 0.47_{\text{syst}}$	$x \pm 2.14_{\text{stat}} \pm 0.45_{\text{syst}}$	$x \pm 1.50_{\text{stat}} \pm 0.32_{\text{syst}}$
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	$x \pm 2.06_{\text{stat}} \pm 0.45_{\text{syst}}$	$x \pm 2.06_{\text{stat}} \pm 0.44_{\text{syst}}$	$x \pm 1.45_{\text{stat}} \pm 0.32_{\text{syst}}$
$\Lambda_b^0 \to pK^+K^-\pi^-$	$x \pm 6.78_{\text{stat}} \pm 0.85_{\text{syst}}$	$x \pm 6.08_{\text{stat}} \pm 0.52_{\text{syst}}$	$x \pm 4.55_{\text{stat}} \pm 0.42_{\text{syst}}$
$\Xi_b^0 \to pK^-K^-\pi^+$	$x \pm 7.46_{\text{stat}} \pm 0.46_{\text{syst}}$	$x \pm 6.83_{\text{stat}} \pm 0.54_{\text{syst}}$	$x \pm 5.06_{\text{stat}} \pm 0.36_{\text{syst}}$

6·2. *Systematic uncertainties.* – This analysis technique is by construction insensitive to production and reconstruction asymmetries, validated using Monte Carlo simulated events and the $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$ control sample. A few sources of systematic uncertainties have been identified:

– experimental bias: possible bias introduced by the experimental acceptance, reconstruction and analysis technique;

– detector resolution: due to the resolution on triple products C_T and $\overline{C}_T$ which might introduce signal migration between the categories;

– fit model: due to the uncertainty on signal and background models.

We estimate the experimental bias using the Cabibbo-favoured $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$ control sample. In this case *CP*-violating effects are expected to be negligible. Any deviation from zero of the *CP*-violating asymmetry measured in this decay is considered as an experimental bias. We measure $a_{CP}^{\widehat{T}\text{-odd}}$ to be compatible with zero, $a_{CP}^{\widehat{T}\text{-odd}}(\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-) = (0.15 \pm 0.31)\%$, and assign the statistical error as a systematic bias. Since parity violation and final-state interaction can introduce asymmetries in $A_{\widehat{T}}$ and $\overline{A}_{\widehat{T}}$, we cannot verify their values on the control sample. Assuming they have a similar error, as seen from data, we propagate the statistical error from $a_{CP}^{\widehat{T}\text{-odd}}$ and estimate ± 0.44 as systematic uncertainties for $A_{\widehat{T}}$ and $\overline{A}_{\widehat{T}}$.

We evaluated the effect of the C_T resolution on the asymmetries using Monte Carlo signal events. We measure $A_{\widehat{T}}$, $\overline{A}_{\widehat{T}}$ and $a_{CP}^{\widehat{T}\text{-odd}}$ using the generated values and the reconstructed and the difference is assigned as a systematic uncertainty due to the detector resolution on C_T ($\overline{C}_T$). The systematic uncertainty is estimated to be in the range [0.01–0.05]% on the asymmetries, depending on the decay mode.

In order to estimate the systematic uncertainty due to the fit model, 10000 pseudo-experiments have been generated according to data. The number of generated events is the same as the one observed in data. An unbinned maximum likelihood fit is performed for each pseudo-experiment using the nominal model. The residual distribution for fit results with respect to generated events are then fit to a Gaussian to estimate any possible bias, assigned as systematic uncertainty. If no bias is observed, the error on the mean is assigned as systematic uncertainty. The systematic uncertainty is estimated to be in the range $[0.03 - 0.3]\%$, depending on the decay mode.

We sum in quadrature all the contributions to systematic uncertainty. The main contribution is due to the experimental bias. The results are shown in table I.

7. – Conclusion

In this work we report the first observation of $\Lambda_b^0 \to pK^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^+K^-\pi^-$, $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^-K^+K^-$, $\Xi_b^0 \to pK^-K^-\pi^+$, $\Xi_b^0 \to pK^-\pi^+\pi^-$, $\Xi_b^0 \to pK^-K^+K^-$ decays. *CPV* is searched for only in the first five listed decays, that are the most abundant. Two different approaches have been followed to exploit the full potential of the data sample: measurement integrated over phase space and measurements in bins of phase space. In the best case we reach a sensitivity of 1%, which represents the most precise measurement on *CP*-violating asymmetries in bottom baryons. The obtained sensitivity to *CPV*, listed in table I, is much improved with respect to what has been done in the past in the Λ_b^0 sector while no *CPV* measurement has been performed so far for Ξ_b^0. Nevertheless, this is the first time that *CPV* is searched for in baryon decays using the $\widehat{T}$-odd correlations method, a technique particularly suited for this measurement due to its insensitivity to reconstruction and detection asymmetries. Finally, the very low systematic uncertainty and the possibility of relying on a large control sample, *e.g.* the Cabibbo favoured $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$, for their estimate, makes this analysis particularly promising also for the future.

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