CP and up-down asymmetries in $B^{\pm} \to K^{\pm} \pi^{\mp} \pi^{\pm} \gamma$ decays

The LHCb collaboration †

Abstract

We present the first study of the flavour-changing neutral-current radiative $B^{+} \to K^{+} \pi^{-} \pi^{+} \gamma$ decay at LHCb. More than 8000 signal events are reconstructed and selected using a data sample corresponding to an integrated luminosity of $2 \text{ fb}^{-1}$, collected in $pp$ collisions at $\sqrt{s} = 8 \text{ TeV}$ in 2012. The signal sample contains all possible intermediate resonances that exist in the hadronic $K^{+} \pi^{-} \pi^{+}$ system. We measure the CP asymmetry to be $A_{CP} = -0.007 \pm 0.015 \text{ (stat)} \pm 0.008 \text{ (syst)}$. The up-down asymmetry, obtained from the photon direction with respect to the plane defined by the hadronic system, is measured in a range of interest for the mass of the hadronic system and found to be $A_{ud} = -0.085 \pm 0.019 \text{ (stat)} \pm 0.003 \text{ (syst)}$. Evidence of parity violation with significance of $4.6\sigma$ is found.

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1 Introduction

Rare $b \to s \gamma$ flavour-changing neutral-current transitions are forbidden at tree level and therefore are very sensitive to new physics (NP) effects arising from the exchange of new heavy particles in electroweak penguin diagrams. The Standard Model (SM) predicts that the photon emitted in such decays is predominantly left-handed, since the recoil $s$ quark that couples to a $W$ boson is left-handed. However, while measurements of the inclusive rate agree with SM calculations, this predominance has not yet been observed. Several models beyond the SM, such as the left-right symmetric model [1] and the minimal supersymmetric model (MSSM) [2], predict the photon to acquire a significant right-handed component due to the exchange of a heavy fermion in the electroweak penguin loop [3]. Although measurements of inclusive radiative decays strongly constrain possible NP effects, there is still room for a non-SM photon polarization.

In the present work, the inclusive radiative decay $B^+ \to K^+ \pi^- \pi^+ \gamma$ is studied. This decay has already been observed at the $B$ factories with branching fraction $\mathcal{B} = (27.6 \pm 1.8) \times 10^{-6}$ [4–6]. Some exclusive decay modes have also been observed, such as $B^+ \to K_1(1270)^+ \gamma$, with $\mathcal{B} = (43 \pm 12) \times 10^{-6}$ [7], or $B^+ \to K_2^*(1430)^+ \gamma$ through the $B^+ \to K_2^*(1430)^+ \gamma \to K^+ \pi^-$ channel, with $\mathcal{B} = (14.5 \pm 4.3) \times 10^{-6}$ [4, 8]. Upper limits have been set for some other intermediate resonances, such as $K_1(1400)^+$ ($\mathcal{B} \leq 1.5 \times 10^{-5}$ at 90% confidence level) [7].

The presence of three hadrons in the $K^+ \pi^- \pi^+ \gamma$ final state allows to build a parity-odd triple product that can be used to describe the photon helicity through simple kinematic considerations. It is then possible to obtain information about the photon polarization from the angular correlations between the three hadrons in the decay plane of the hadronic $K^+ \pi^- \pi^+$ system, since the kinematic distribution of this three-body decay carries the polarization information.

The aim of this study is to observe the $B^+ \to K^+ \pi^- \pi^+ \gamma$ decay, to measure its charge and up-down asymmetries (the latter being proportional to the photon polarization) in interesting ranges of the $K^\pm \pi^- \pi^+$ invariant mass. This represents a simplified approach with respect to the full angular study for determining the photon polarization (see Ref. [9]). The lack of theoretical predictions makes it challenging, at present, to translate the measured up-down asymmetry into an actual photon polarization value. Therefore, this study concentrates on the significance of such asymmetry, since measuring an up-down asymmetry different from zero corresponds to demonstrating that the photon is polarized or, equivalently, that parity is violated in radiative $B$ decays.

2 Photon polarization in $B^+ \to K^+ \pi^- \pi^+ \gamma$ decays

We consider decays of the type $\bar{B} \to K_{\text{res}} \gamma \to P_1 P_2 P_3 \gamma$, where $K_{\text{res}}$ is a kaon resonance and $P_1$, $P_2$, $P_3$ are three pseudoscalar mesons. We denote the weak $\bar{B} \to K_{\text{res}} \gamma$ amplitudes involving left- and right-handed photons as $c_L$ and $c_R$, and the corresponding strong decay amplitudes of the resonance as $M_L$ and $M_R$, respectively. In the SM the photon
from radiative $\bar{B}$ ($B$) decays is predominantly left- (right-) handed, i.e. $|c_L|^2 \gg |c_R|^2$ ($|c_L|^2 \ll |c_R|^2$). Defining the photon polarization parameter $\lambda_\gamma$ as

$$\lambda_\gamma \equiv \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2},$$  \hfill (1)$$

the SM implies $\lambda_\gamma \simeq -1$ (+1) for radiative $\bar{B}$ ($B$) decays, with corrections up to 10% [9,10].

Taking the final-state momenta $\tilde{p}_i$ ($i = 1, 2, 3$) and $\tilde{p}_\gamma$ in the $K_{\text{res}}$ rest frame (see Fig. 1), one defines

$$\cos \theta \equiv -\frac{\tilde{p}_\gamma \cdot \hat{n}}{|\tilde{p}_\gamma|},$$  \hfill (2)$$

where the unit vector $\hat{n}$ normal to the $K_{\text{res}}$ decay plane is taken as

$$\hat{n} \equiv \frac{\tilde{p}_1\times\tilde{p}_2}{|\tilde{p}_1\times\tilde{p}_2|}. \hfill (3)$$

The differential decay width of the subsequent $K_{\text{res}} \to P_1P_2P_3$ process can be described with the helicity amplitude $\mathcal{J}_\mu$,

$$\mathcal{M}(K_{\text{res}},\text{pol} \to P_1P_2P_3) = \epsilon^\mu_{\text{pol}} \mathcal{J}_\mu,$$  \hfill (4)$$

where $\epsilon^\mu_{\text{pol}}$ are the circular polarization 4-vectors (pol = L, R). Then, in the $K_{\text{res}}$ rest frame, the differential decay rate of $\bar{B} \to P_1P_2P_3\gamma$ going through a single resonance can be written as [9]

$$\frac{d\Gamma(\bar{B} \to K_{\text{res}}\gamma \to P_1P_2P_3\gamma)}{ds_1 ds_2 ds_3 ds_{13} ds_{23} d\cos \theta} \propto |\mathcal{F}|^2 (1 + \cos^2 \theta) + \lambda_\gamma 2 \, \text{Im} \left[ \hat{n} \cdot (\mathcal{F} \times \mathcal{F}^*) \right] \cos \theta,$$  \hfill (5)$$
where \( s_{ij} = (p_i + p_j)^2 \) and \( s = (p_1 + p_2 + p_3)^2 \). In the case of overlapping intermediate resonances, it becomes necessary to consider the interference between them, and Eq. 5 is no longer valid, leading to more complex dependencies on \( \cos \theta \) \cite{11}.

For the \( B^+ \rightarrow K^+ \pi^- \pi^+ \gamma \) decay, \( P_1 = \pi^+ \), \( P_2 = \pi^- \) and \( P_3 = K^+ \), while for the \( B^- \rightarrow K^- \pi^+ \pi^- \) decay we have \( P_1 = \pi^- \), \( P_2 = \pi^+ \) and \( P_3 = K^- \) (inclusion of charge conjugate processes is be implied throughout this report, unless explicitly stated). In this case, since the \( \cos \theta \) variable changes sign under the exchange of \( s_{13} \) and \( s_{23} \), we replace it with a new angular variable independent of \( s_{13} \) and \( s_{23} \), \( \cos \tilde{\theta} \equiv \text{sign}(s_{12} - s_{23}) \cos \theta \), following the convention in Ref. \cite{11}. This is equivalent to state that \( \tilde{\theta} \) is the angle between \(-\vec{p}_s\) and the normal to the decay plane defined by \( \vec{p}_{\text{slow}} \times \vec{p}_{\text{fast}} \), where \( \vec{p}_{\text{slow}} \) and \( \vec{p}_{\text{fast}} \) correspond to the momenta of the slower and faster pions, respectively.

### 2.1 Up-down asymmetry

In Refs. \cite{11,12}, the up-down asymmetry is defined as

\[
\mathcal{A}_{\text{ud}} \equiv \frac{\int_0^1 d\cos \tilde{\theta} \frac{d\Gamma}{d\cos \tilde{\theta}} - \int_{-1}^0 d\cos \tilde{\theta} \frac{d\Gamma}{d\cos \tilde{\theta}}}{\int_{-1}^1 d\cos \tilde{\theta} \frac{d\Gamma}{d\cos \tilde{\theta}}} = \frac{3}{4} \lambda_{\gamma} \frac{\int d\tau d\tau_1 d\tau_2 \text{Im} \left[ \hat{n} \cdot (\hat{J} \times \hat{J}^*) \right]}{\int d\tau d\tau_1 d\tau_2 |J|^2}.
\]

(6)

As this asymmetry is proportional to \( \lambda_{\gamma} \), if \( J \) is known, its measurement allows the determination of the photon polarization.

In the case of the \( B^+ \rightarrow K^+ \pi^- \pi^+ \gamma \) decay, one has to take into account that different resonances in the \( K^+ \pi^- \pi^+ \) spectrum cannot be easily distinguished because they overlap. Each of these resonances has its own Dalitz plot and thus can contribute differently to the inclusive up-down asymmetry. Moreover, the interference between overlapping resonances can enhance or dilute the asymmetry. A detailed study of the case of \( K_1(1400), K_2^*(1430) \) and \( K^*(1410) \), which illustrates the nature of the problem, can be found in Ref. \cite{11}. As a consequence of this, it is not possible to determine the value of the photon polarization from the inclusive up-down asymmetry without a precise theoretical calculation and knowledge of the proportions between the different resonances in the studied region.

However, a measurement of a non-zero up-down asymmetry would constitute a proof of photon polarization, since this asymmetry is proportional to the photon polarization. In this study, the combination of two regions in the \( K^+ \pi^- \pi^+ \) mass spectrum is used, \([1100,1300] \cup [1400,1600] \) MeV/c\(^2\), following the recommendation from Ref. \cite{11}. The first region is dominated by the \( K_1(1270) \) resonance. The second mainly includes the \( K_1(1400), K_2^*(1430) \) and \( K^*(1410) \) resonances, with strong, small and null expected up-down asymmetries, respectively; it also avoids the upper tail of the \( K_1(1270) \), which would interfere with the dominant \( K_1(1400) \).

### 3 Detector and software description

The LHCb detector \cite{13} 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. The combined tracking system has momentum resolution $\Delta p/p$ that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, and impact parameter resolution of 20 $\mu$m for tracks with high transverse momentum. Charged hadrons are identified using two ring-imaging Cherenkov detectors. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter (ECAL) and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers. The trigger [14] 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.

In the simulation, pp collisions are generated using PYTHIA 6.4 [15] with a specific LHCB configuration [16]. Decays of hadronic particles are described by EVTGEN [17], in which final state radiation is generated using PHOTOS [18]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [19] as described in Ref. [20].

4 Event selection

For this analysis, pp collision data corresponding to an integrated luminosity of 2 fb$^{-1}$, recorded by the LHCb detector at $\sqrt{s} = 8$ TeV, have been used.

Signal $B \rightarrow K_{\text{res}}\gamma \rightarrow K^+\pi^-\pi^+\gamma$ candidates are built from a $K$ resonance, made of three charged tracks, and one photon. At first, three charged tracks with a total positive or negative unit charge are combined to form the $K$ resonance vertex. Afterwards, this resonance is combined with a high transverse energy ($E_T$) photon to build a $B$ candidate.

Track quality is ensured by requiring a good track fit and a low probability that the track is actually made of pseudorandom combinations of hits. All tracks are required to have minimum transverse momentum ($p_T$) of 500 MeV/c and at least one of them needs to have $p_T$ above 1200 MeV/c. In addition, their impact parameter $\chi^2$ ($\chi^2_{IP}$), defined as the difference between the $\chi^2$ of a primary vertex (PV) reconstructed with and without the considered track, is required to be larger than 25. Particle identification likelihoods for several hypotheses are formed, and the differences in the logarithms of these likelihoods are used to identify the considered tracks as pions or kaons [21].

The vertex corresponding to the intermediate resonance is built from three tracks, one identified as kaon and two oppositely-charged pions, with the requirement that the $\chi^2$ over degrees of freedom of the vertex fit is below 9. In addition, this resonance is required to be isolated from other charged tracks in the event by comparing the $\chi^2$ of the three-track fit and the $\chi^2$ of all possible vertices that can be obtained by adding an extra track to the original vertex; the minimal difference in $\chi^2$ is required to be above 4 units.

Photons are built from energy depositions in the ECAL and are required to have
$E_T$ above 3 GeV. Anticoincidence with tracks pointing to the calorimeter is applied to distinguish neutral from charged electromagnetic particles and a multivariate tool based on the cluster shape parameters is used to separate photons from $\pi^0 \rightarrow \gamma\gamma$ in the case where the two photons form a single cluster in the calorimeter.

The intermediate resonance vertex, with a $B$ mass-constrained invariant mass between 1100 and 1900 MeV/$c^2$, is combined with the photon to build the $B$ candidate. The $B$ candidate is required to point to the PV by means of a cut on its $\chi^2_{IP}$, which has to be less than 9. Good reconstruction of the $B$ vertex is ensured by requiring that the cosine of the angle between the reconstructed $B$ momentum and the direction defined by the PV and the $B$ vertex is above 0.9998. The relatively long lifetime of $B$ mesons is exploited to remove background coming from particles produced in the PV by requiring that the flight distance $\chi^2$ exceeds a hundred units. Finally, only candidates in the [4279, 6829] MeV/$c^2$ invariant mass range are kept.

The $B^+ \rightarrow \bar{D}^0 \rho^+$ background, with $\bar{D}^0 \rightarrow K^+\pi^- (\rightarrow \pi^-\pi^0)$ and $\rho^+ \rightarrow \pi^+\pi^0$, is a potentially dangerous background when one of the neutral pions is not reconstructed and the other is misreconstructed as a photon. Vetos on the $K^+\pi^-\pi^0$ mass and in the $\pi^+\pi^0$ mass ($\gamma$ reconstructed as $\pi^0$) mass, above the $\bar{D}^0$ and the $\rho$ mass, respectively, allow to completely remove this background without suppressing any signal event.

The presence of the magnetic field in the $y$ direction causes some tracks to leave the detector acceptance for a given magnet polarity, leading to a charge-dependent acceptance that generates an artificially large (up to 100%) charge asymmetry in the lower-edge regions of the momentum distributions of the final state hadrons. In $CP$ violation studies this effect is suppressed by applying a fiducial requirement on the track momentum, such that $|p_x| \leq 0.317(p_z - 2400)$ (MeV/$c$), where the $z$ direction is defined along the beam axis.

Finally, events with multiple $B$ candidates (about 2.5%) are not considered. This helps removing those events with double misidentification ($K \rightarrow \pi$ and $\pi \rightarrow K$) in which both candidates pass the particle identification requirements, and which potentially dilute the up-down asymmetry.

## 5 Fit description

Several fits to the $B$ candidate invariant mass distributions, in different $K^+\pi^-\pi^+$ invariant mass ranges and with or without applying the fiducial requirement, are performed in order to determine signal yield, charge asymmetry and up-down asymmetry. The signal is modelled with a double-tail Crystal Ball (CB) function [22], with the four tail parameters fixed from simulation. Included backgrounds are combinatorial, partially reconstructed background in which the missing particle is a pion and partially reconstructed background with more than one missing particle or with one missing particle and misidentification. The first is modelled with an exponential function, the second is modelled with an ARGUS function [23] (with parameters fixed from simulation and endpoint fixed to the $B$ mass minus the $\pi$ mass) convolved with a Gaussian resolution with the same width as the signal,
and the third is modelled with an ARGUS function with free power parameter (with endpoint fixed to the $B$ mass minus twice the $\pi$ mass), also convolved with a Gaussian resolution with the same width as the signal.

The contamination from other backgrounds, such as the neutral $B^0 \to (K\pi\pi)^0 \gamma$ decay, the $b \to d\gamma$ transition $B^+ \to \pi^+\pi^-\pi^+\gamma$ with a misidentified pion, $B^+ \to K^+\pi^-\pi^+\eta(\to \gamma\gamma)$ with one missing photon, and $B^+ \to D^+(-\to K^+\pi^-\pi^0)\pi^+$ and $B^+ \to K^+\pi^0(\to K^+\pi^0)\pi^+\pi^-$ decays, has been studied in simulation and found to be negligible.

With this invariant mass description, three different fits are performed to the 2012 data:

- A fit to the full data sample to get the signal yield.
- A simultaneous fit to two samples split according to the $B$ candidate charge, for the determination of the raw charge asymmetry and signal yield, performed on the full $K^+\pi^-\pi^+$ spectrum, including the fiducial requirement. The mean and width of the signal mass distributions are free but shared between the two categories, as well as the partially reconstructed background shape parameters. Relative fractions of the backgrounds are left free, allowing for possible charge asymmetries in the background.
- A simultaneous fit to four samples split according to the $B$ candidate charge and photon direction (up or down), for the determination of the raw charge asymmetry, $B^+$ and $B^-$ up-down asymmetries\footnote{In this fit, we define the up-down asymmetry for $B^+$ as $A^+ = A_{ud}$ (as given in Eq. 6) and the up-down asymmetry for $B^-$ as $A^- = -A_{ud}$ because we expect the photon polarization to have opposite sign for $B^+$ and $B^-$.} and the total signal yield, performed on the $[1100, 1300] \cup [1400, 1600]$ MeV/$c^2$ mass range in the $K^+\pi^-\pi^+$ spectrum, also with the fiducial requirement applied. As in the previous fit, the mean and width of the signal mass distributions are free and shared by all categories, as well as the partially reconstructed background shape parameters. The shape of the combinatorial background is shared between same-sign categories. Relative fractions of the backgrounds are left free, allowing for $CP$ violation in the background.

\section{Fit results}

The mass fit to the full dataset is shown in Fig. 2, while the background-subtracted invariant mass distribution of the $K^+\pi^-\pi^+$ system, showing the contributions from several intermediate kaon resonances, is shown in Fig. 3. The total number of $B^+ \to K^+\pi^-\pi^+\gamma$ events determined from the fit is $8189 \pm 136$. Even though it is an unbinned fit, a binned goodness of fit is used to assess its quality; the fit $\chi^2$ per number of degrees of freedom is 33.4/41, which corresponds to a p-value of $\sim 80\%$.

After the first mass fit, an unbinned extended maximum likelihood fit is performed to extract the charge asymmetry of the inclusive $B^+ \to K^+\pi^-\pi^+\gamma$ decay. Fit results on
Figure 2: Invariant $K\pi\pi\gamma$ mass with the results of the fit on the full data sample overlaid, along with their normalized residuals (lower plot). The fitted values for the total yield and for the mean and the width of the double tail CB signal are shown in the legend. The signal component is shown in red (solid), combinatorial background in green (dotted), missing pion background in black (dashed) and partially reconstructed background in purple (dot-dashed).

the $B^+$ and $B^-$ subsamples of the full dataset are shown in Fig. 4. The stability of the fit has been confirmed by a large number of pseudoexperiments and by studying the log likelihood profiles of the fitted parameters.

A raw charge asymmetry of $-0.022 \pm 0.015$ is measured, where the error is statistical only. The combinatorial background presents a charge asymmetry of $0.01 \pm 0.05$, while both the partial and the missing pion backgrounds exhibit asymmetries of $0.04 \pm 0.03$.

For the full asymmetry fit including the additional up-down asymmetries, candidates having $B$ mass-constrained $K^+\pi^-\pi^+$ invariant mass in the $[1100, 1300] \cup [1400, 1600]$ MeV/$c^2$ range are split into four subsamples according to the charge of the $B$ meson and to the sign of $\cos \tilde{\theta}$. The result of the maximum likelihood fit is shown in Fig. 5. Again, the stability of the fit has been confirmed with a large number of pseudoexperiments and by studying the log likelihood profiles of the fitted parameters. The fit in the two $K^+\pi^-\pi^+$ mass sub-regions is also performed independently, in order to check if the different resonance contributions affect the up-down asymmetry.

The signal yield in the region of interest is approximately half of that in the full data
Figure 3: Background-subtracted $K^+\pi^-\pi^+$ invariant mass distribution, obtained using the sPlot technique [24].

Figure 4: Invariant $K\pi\pi\gamma$ mass for $B^+$ (left) and $B^-$ (right) candidates with the result of the simultaneous fit overlaid. The signal component is shown in red (solid), combinatorial background in green (dotted), missing pion background in black (dashed) and partially reconstructed background in purple (dot-dashed).

As expected, the up-down asymmetries obtained for $B^+$ and $B^-$ are compatible, $-0.084 \pm 0.026$ and $-0.086 \pm 0.025$, respectively, where uncertainties are statistical only.
Figure 5: Invariant $K\pi\pi$ mass for $B^+$ (left) and $B^-$ (right) candidates and up (top) and down (bottom) subsamples, for $1100 < m_{K^+\pi^-\pi^+} < 1300$ MeV/c^2 and $1400 < m_{K^+\pi^-\pi^+} < 1600$ MeV/c^2. The result of the simultaneous fit is superimposed. The intermediate $m_{K^+\pi^-\pi^+}$ mass region is not considered because of the interferences between the two possible $K_1$ resonances.

The signal component is shown in red (solid), combinatorial background in green (dotted), missing pion background in black (dashed) and partially reconstructed background in purple (dot-dashed).

7 Results

7.1 Charge asymmetry

A measure of CP violation in the inclusive $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ channel is determined from the observed raw charge asymmetry, which is related to the physical CP-violating asymmetry
\( \mathcal{A}_{\text{CP}} \) through
\[
\mathcal{A}_{\text{CP}} = \mathcal{A}_{\text{CP}}^{\text{raw}} - \mathcal{A}_{\text{P}} - \mathcal{A}_{\text{D}} + \Delta \mathcal{A}_{\text{CP}}^{\text{raw}},
\]
where \( \mathcal{A}_{\text{P}} \) is the asymmetry in the production of \( B^+ \) and \( B^- \) in \( pp \) collisions, \( \mathcal{A}_{\text{D}} \) is the asymmetry due to the differences between positive and negative particles that arise in the interaction with matter, detector acceptance, and reconstruction, and \( \Delta \mathcal{A}_{\text{CP}}^{\text{raw}} \) is the instrumental bias induced by non-uniformities in the detector in the presence of a magnetic field.

The detection and production asymmetries in \( B^+ \to K^+\pi^+\pi^-\gamma \) decays are determined from the \( B^+ \to J/\psi K^+ \) control channel, which has a small and well measured \( CP \) asymmetry \( \mathcal{A}_{\text{CP}}^{B^+\to J/\psi K^+} = 0.001 \pm 0.007 \) [25], and are found to be \( \mathcal{A}_{\text{D}} + \mathcal{A}_{\text{P}} = -0.013 \pm 0.008 \). Since both signal and control channels involve a charged \( B \) meson, the asymmetries arising from \( B \) meson from production are equal between them. In addition, both decays have one kaon, so asymmetries from kaon interaction with matter and reconstruction are considered to be the same; the difference in kaon momentum spectra between signal and \( B^+ \to J/\psi K^+ \), which could cause different \( \mathcal{A}_{\text{D}} \), is considered as a possible source of systematic uncertainty, but its effect is found to be negligible.

The presence of the magnetic field, which spreads oppositely-charged particles to different regions of the LHCb detector, introduces an additional source of instrumental bias. Non-uniformities in the detector performance can induce a bias in the asymmetry measurement, which is experimentally reduced by regularly flipping the magnet polarity during data taking. To estimate the instrumental bias \( \Delta \mathcal{A}_{\text{CP}}^{\text{raw}} \), a separate \( \mathcal{A}_{\text{CP}} \) fit is performed for each of the magnet polarities. Taking into account the imbalance in luminosity between the two magnet polarities, the correction is found to be \( \Delta \mathcal{A}_{\text{CP}}^{\text{raw}} = 0.002 \pm 0.001 \).

Systematic uncertainties associated with the fit parameters that are fixed from simulation are assessed by means of a large number of fits, which are performed on the same data sample and where the fixed shape parameters are varied randomly within their simulation uncertainties. The systematic uncertainty associated to the fit model is assessed by using different parameterizations of mass shapes, both for the signal and each of the backgrounds, and by varying the \( B \) mass window. The contributions from each of the fit components are added in quadrature.

Taking the intermediate results and systematic uncertainties, summarized in Table 1, and making use of Eq. 7, the \( CP \) asymmetry in the inclusive \( B^+ \to K^+\pi^+\pi^-\gamma \) decay is found to be
\[
\mathcal{A}_{\text{CP}} = -0.007 \pm 0.015 \text{ (stat)} \pm 0.008 \text{ (syst)}.
\]

### 7.2 Up-down asymmetry

Two independent measurements of the up-down asymmetry are obtained from the full asymmetry fit, one for each charge of the \( B \) meson.

Systematic uncertainties associated to the parameters fixed from simulation and to the fit model are evaluated in the same way as in the case of the charge asymmetry. In
Table 1: Contributions to the value and uncertainty of $A_{CP}$. The $A_{CP}^{\text{raw}}$ uncertainty is statistical, while the rest are included in the systematic uncertainty. The total systematic uncertainty is obtained by summing these contributions in quadrature.

<table>
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<th>Contribution</th>
<th>Value</th>
<th>Error</th>
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<tbody>
<tr>
<td>$A_{CP}^{\text{raw}}$</td>
<td>-0.022</td>
<td>0.015</td>
</tr>
<tr>
<td>$A_D$ and $A_P$</td>
<td>0.013</td>
<td>0.008</td>
</tr>
<tr>
<td>$\Delta A_{CP}^{\text{raw}}$</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>Simulation parameters</td>
<td>0.000</td>
<td>$^{+0.001}_{-0.000}$</td>
</tr>
<tr>
<td>Fit model</td>
<td>0.000</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Table 2: Contributions to the systematic uncertainty of the up-down asymmetries. The total systematic uncertainty is obtained by summing all contributions in quadrature.

<table>
<thead>
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<th>Contribution</th>
<th>$\sigma(A^+)$</th>
<th>$\sigma(A^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation parameters</td>
<td>$^{+0.002}_{-0.001}$</td>
<td>$^{+0.001}_{-0.000}$</td>
</tr>
<tr>
<td>Fit model</td>
<td>$^{+0.003}_{-0.000}$</td>
<td>$^{+0.002}_{-0.000}$</td>
</tr>
<tr>
<td>Detector resolution</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>$^{+0.004}_{-0.003}$</td>
<td>$^{+0.002}_{-0.000}$</td>
</tr>
</tbody>
</table>

addition, the effect of detector resolution on $\cos \tilde{\theta}$, which can cause candidates with a photon almost parallel to the $K^+\pi^-\pi^+$ plane to be wrongly assigned to the up or down categories, is assessed by fitting the up-down asymmetries only for events with $|\cos \tilde{\theta}|$ larger than the resolution obtained from simulation. This effect is found to be negligible.

Including the systematic uncertainties, summarized in Table 2, the up-down asymmetry for each of the charges of the $B$ meson is found to be

\[
A^+ = -0.084 \pm 0.026 \text{ (stat)} ^{+0.004}_{-0.003} \text{ (syst)}, \\
A^- = -0.086 \pm 0.025 \text{ (stat)} \pm 0.002 \text{ (syst)} .
\]  

(9)

Since $A^+$ and $A^-$ are independent measurements of the same quantity, the up-down asymmetry $A_{ud}$, their likelihood profiles are combined to obtain

\[
A_{ud} = -0.085 \pm 0.019 \text{ (stat)} \pm 0.003 \text{ (syst)},
\]  

(10)

where the systematic uncertainty is calculated as half the sum in quadrature of the $A^\pm$ systematic uncertainties. The overall significance with respect to zero, equivalent to parity violation, is found to be 4.6$\sigma$. This result is consistent with the expected significance obtained from pseudoexperiments.
8 Conclusions

The inclusive $B^\pm \to K^\pm \pi^\pm \pi^\pm \gamma$ decay, with a $K^+\pi^-\pi^+$ mass in the 1.1–1.9 GeV/c$^2$ range, has been studied with a data sample corresponding to 2 fb$^{-1}$ collected by the LHCb detector at $\sqrt{s} = 8$ TeV. A total of $8189 \pm 140$ (stat) $^{+450}_{-390}$ (syst) signal events have been observed.

The $CP$ asymmetry of this decay mode has been determined for the first time, and has been found to be compatible with zero:

$$A_{CP} = -0.007 \pm 0.015 \text{ (stat)} \pm 0.008 \text{ (syst)}.$$  \hspace{1cm} (11)

Finally, the up-down asymmetry, which is proportional to the photon polarization parameter $\lambda_\gamma$, has been studied for the first time in the $[1100, 1300] \cup [1400, 1600]$ MeV/c$^2$ mass range in the $K^+\pi^-\pi^+$ spectrum, separately for $B^+$ and $B^-$ decays. A combined value of

$$A_{ud} = -0.085 \pm 0.019 \text{ (stat)} \pm 0.003 \text{ (syst)},$$  \hspace{1cm} (12)

has been found, 4.6$\sigma$ away from zero, showing evidence for photon polarization in $b \to s \gamma$ transitions; this is equivalent to stating that evidence has been found for parity violation in such decays.

The measured up-down asymmetry may be used, if theoretical predictions become available, to determine a value for the photon polarization. This would be the first measurement of such a quantity, which could eventually help in constraining the effects of non-SM physics in the $b \to s \gamma$ sector.
References


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