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Radiative B decays at LHCb

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Radiative B decays are sensitive probes of New Physics. We present the latest results on these decays from the LHCb experiment. Results include first measurements of new decay modes and studies sensitive to physics beyond the Standard Model that may affect the polarisation of the emitted photon in radiative B decays.

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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. 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. Although measurements of inclusive radiative decays agree with SM calculations and strongly constrain possible NP effects, there is still room for a non-SM photon polarization, as the predominance of left-handed photons has not yet been observed.

The inclusive radiative decay $B^+ \to K^+\pi^-\pi^+\gamma$ has already been observed at the B factories with branching fraction $\mathscr{B} = (27.6 \pm 1.8) \times 10^{-6}$ [3–5]. Some exclusive decay modes have also been observed, such as $B^+ \to K_1(1270)^+\gamma$ [6] or $B^+ \to K_2^*(1430)^+\gamma$ [3, 7]. Upper limits have been set for some other intermediate resonances, such as $K_1(1400)^+$ [6].

The observation of $B^+ \to K^+\pi^-\pi^+\gamma$, as well as the measurement of its charge and up-down asymmetries is presented, based on the study performed by LHCb [8]. This represents a simplified approach with respect to the full angular study for determining the photon polarization [9].

The lack of theoretical predictions makes impedes, at present, translating 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 $\bar{B} \to \bar{K}_{\rm res}\gamma \to P_1P_2P_3\gamma$, where $\bar{K}_{\rm res}$ is a kaon resonance and P_1, P_2, P_3 are three pseudoscalar mesons[1]. We denote the weak $\bar{B} \to \bar{K}_{\rm res}\gamma$ amplitudes involving left- and right-handed photons as $c_{\rm L}$ and $c_{\rm R}$, and the corresponding strong decay amplitudes of the resonance as $\mathscr{M}_{\rm L}$ and $\mathscr{M}_{\rm R}$, respectively. The differential decay width of the subsequent $\bar{K}_{\rm res} \to P_1P_2P_3$ process can be described with the helicity amplitude $\mathscr{J}_\mu$.

In the SM the photon from radiative $\bar{B}$ (B) decays is predominantly left- (right-) handed. ($|c_{\rm L}|^2 \ll |c_{\rm R}|^2$). Defining the photon polarization parameter λ_γ as

$$\lambda_\gamma \equiv \frac{|c_{\rm R}|^2 - |c_{\rm L}|^2}{|c_{\rm R}|^2 + |c_{\rm L}|^2}, \tag{2.1}$$

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 $\vec{p}_i$ $(i = 1, 2, 3)$ and $\vec{p}_\gamma$ in the $\bar{K}_{\rm res}$ rest frame, and defining

$$\cos\theta \equiv -\frac{\vec{p}_\gamma}{|\vec{p}_\gamma|} \cdot \hat{n}, \text{ with } \hat{n} \equiv \frac{\vec{p}_1 \times \vec{p}_2}{|\vec{p}_1 \times \vec{p}_2|}, \tag{2.2}$$

[1] For the $B^+ \to K^+\pi^-\pi^+\gamma$ decay, $P_1 = \pi^+$, $P_2 = \pi^-$ and $P_3 = K^+$, while for the $B^- \to K^-\pi^+\pi^-$ decay we have $P_1 = \pi^-$, $P_2 = \pi^+$ and $P_3 = K^-$ (inclusion of charge conjugate processes is implied throughout this report, unless explicitly stated).

the differential decay rate of $\bar{B}\to P_1P_2P_3\gamma$ going through a single resonance can be written as [9]

$$\frac{\mathrm{d}\Gamma(\bar{B}\to \bar{K}_{\mathrm{res}}\gamma\to P_1P_2P_3\gamma)}{\mathrm{d}s\,\mathrm{d}s_{13}\,\mathrm{d}s_{23}\,\mathrm{d}\cos\theta} \propto |\vec{\mathscr{J}}|^2(1+\cos^2\theta)+\lambda_\gamma 2\,\mathrm{Im}\left[\vec{n}\cdot(\vec{\mathscr{J}}\times\vec{\mathscr{J}}^*)\right]\cos\theta\,, \tag{2.3}$$

where s_{ij} and s are the invariant masses of the P_iP_j and $P_1P_2P_3$ systems, respectively. In the case of overlapping intermediate resonances, it becomes necessary to consider the interference between them, and Eq. 2.3 is no longer valid, leading to more complex dependencies on $\cos\theta$ [11].

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}, $\cos\tilde{\theta}\equiv \mathrm{sign}(s_{12}-s_{23})\cos\theta$. Then, the up-down asymmetry is defined as [11, 12]

$$\mathscr{A}_{\mathrm{ud}} \equiv \frac{\int_0^1 \mathrm{d}\cos\tilde{\theta}\,\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\tilde{\theta}} - \int_{-1}^0 \mathrm{d}\cos\tilde{\theta}\,\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\tilde{\theta}}}{\int_{-1}^1 \mathrm{d}\cos\tilde{\theta}\,\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\tilde{\theta}}} = \frac{3}{4}\lambda_\gamma \frac{\int \mathrm{d}s\,\mathrm{d}s_{13}\,\mathrm{d}s_{23}\mathrm{Im}\left[\vec{n}\cdot(\vec{\mathscr{J}}\times\vec{\mathscr{J}}^*)\right]}{\int \mathrm{d}s\,\mathrm{d}s_{13}\,\mathrm{d}s_{23}|\vec{\mathscr{J}}|^2}\,. \tag{2.4}$$

If $\vec{\mathscr{J}}$ is known, measuring this asymmetry allows the determination of the photon polarization.

In the case of the $B^+\to K^+\pi^-\pi^+\gamma$ decay, one has to take into account that different resonances in the $K^+\pi^-\pi^+$ spectrum cannot be easily separated. Each of these resonances has its own Dalitz plot and thus contributes differently to the inclusive up-down asymmetry, with additional enhancement or dilution due to interference patterns.

Currently, it is not possible to determine the value of the photon polarization from the inclusive up-down asymmetry due to the lack of precise theoretical calculations and of 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, given their proportionality relationship.

3. 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 $B\to K_{\mathrm{res}}\gamma\to K^+\pi^-\pi^+\gamma$ 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. 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}) and to have a large impact parameter χ^2 (χ^2_{IP}), defined as the difference between the χ^2 of a primary vertex (PV) reconstructed with and without the considered track. The difference between the logarithms of the particle identification likelihoods for several hypotheses are used to identify the tracks as pions or kaons [13].

The vertex corresponding to the intermediate resonance is required to have a good χ^2 and to be isolated from other charged tracks in the event by comparing the χ^2 of the three-track fit and the χ^2 of all possible vertices that can be obtained by adding an extra track to the original vertex.

Finally, this $K^+\pi^-\pi^+$ resonance is combined with a high transverse energy (E_{T}) photon ($E_{\mathrm{T}}>3$ GeV) to build a B candidate. Anticoincidence with tracks pointing to the calorimeter is applied to distinguish neutral from charged electromagnetic particles and a multivariate tool based

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on the cluster shape parameters is used to separate photons from $\pi^0 \to \gamma\gamma$ in the case where the two photons form a single cluster in the calorimeter.

The B candidate is required to point to the PV by means of a cut on its χ^2_{IP}, the good reconstruction of its 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, and 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 χ^2 exceeds a hundred units. Only candidates in the $4279 - 6829$ MeV/c^2 invariant mass range are kept.

The background coming from $B^+ \to \bar{D}^0\rho^+$ ($\bar{D}^0 \to K^+\rho^-(\to \pi^-\pi^0)$ and $\rho^+ \to \pi^+\pi^0$), which requires $\gamma \to \pi^0$ misidentification, is vetoed by means of cuts on the $K^+\ \pi^-\ \pi^0$ mass and in the π^+ π^0 mass (γ reconstructed as π^0) mass, above the $\bar{D}^0$ and the ρ mass, respectively.

The presence of the magnetic field causes some tracks to leave the detector acceptance for a given magnet polarity, leading to a charge-dependent acceptance that generates an artificially large 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.

4. Fit

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 the signal yield, the charge asymmetry and the up-down asymmetry. The signal is modelled with a double-tail Crystal Ball (CB) function [14], 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, misidentified particle. The first is modelled with an exponential function, the second is modelled with an ARGUS function [15] (with parameters fixed from simulation and endpoint fixed to the B mass minus the π 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 π mass), also convolved with a Gaussian resolution with the same width as the signal. The contamination from other exclusive backgrounds 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. The total number of $B^+ \to K^+\pi^-\pi^+\gamma$ events determined from the fit is 8189 ± 136.
- A simultaneous fit to two samples split according to the B candidate charge, for the determination of the raw charge asymmetry and total signal yield, performed on the full $K^+\pi^-\pi^+$ spectrum, including the fiducial requirement. Relative fractions of the backgrounds are left free, allowing for possible charge asymmetries in the background. A raw charge asymmetry of -0.022 ± 0.015 is measured, where the error is statistical only.
- 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[2] 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 (Fig. 1). The intermediate $m_{K^+\pi^-\pi^+}$ mass region is not considered because of the possible interference between the two K_1 resonances. Like in the previous fit, relative fractions of the backgrounds are left free. As expected, the up-down asymmetries obtained for B^+ and B^- are compatible, -0.084 ± 0.026 and -0.086 ± 0.025, respectively, where uncertainties are statistical only.

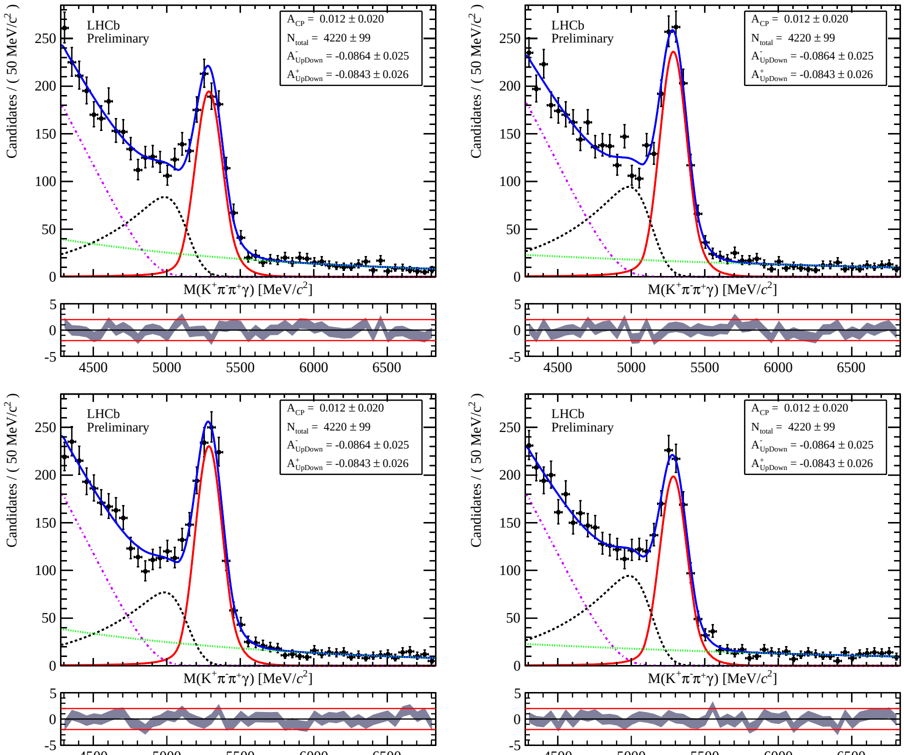

Figure 1: Invariant $K\pi\pi\gamma$ mass for B^+ (left) and B^- (right) candidates and up (top) and down (bottom) subsamples, for $m_{K^+\pi^-\pi^+}$ in $[1100,1300]\cup[1400,1600]$ MeV/c^2. The result of the simultaneous fit is superimposed. The signal component is shown in red (solid), combinatorial background in green (dotted), missing pion background in black (dashed) and partially reconstructed background in purple (dot-dashed).

5. Results

The *CP* violation in the inclusive $B^+\to K^+\pi^-\pi^+\gamma$ channel is determined from the observed raw charge asymmetry, which is related to the physical *CP*-violating asymmetry $\mathscr{A}_{CP}$ through

$$\mathscr{A}_{CP} = \mathscr{A}_{CP}^{\text{raw}} - \mathscr{A}_{\text{P}} - \mathscr{A}_{\text{D}} + \Delta\mathscr{A}_{CP}^{\text{raw}}, \tag{5.1}$$

where $\mathscr{A}_{\text{P}}$ is the asymmetry in the production of B^+ and B^- in pp collisions, $\mathscr{A}_{\text{D}}$ is the asymmetry due to the differences between positive and negative particles that arise in the interaction with

[2] In this fit, we define the up-down asymmetry for B^+ as $\mathscr{A}^+ = \mathscr{A}_{\text{ud}}$ (as given in Eq. 2.4) and the up-down asymmetry for B^- as $\mathscr{A}^- = -\mathscr{A}_{\text{ud}}$ because we expect the photon polarization to have opposite signs for B^+ and B^-.

matter, detector acceptance, and reconstruction, and $\Delta\mathscr{A}_{CP}^{\rm raw}$ is the bias induced by non-uniformities in the detector in the presence of a magnetic field, which spreads oppositely-charged particles to different regions of the detector. The detection and production asymmetries are determined from the $B^+ \to J/\psi K^+$ control channel, which has a small and well measured *CP* asymmetry of 0.001 ± 0.007 [16], and are found to be $\mathscr{A}_{\rm D} + \mathscr{A}_{\rm P} = -0.013 \pm 0.008$. A separate $\mathscr{A}_{CP}$ fit is performed for each of the magnet polarities and the correction due to the non-uniformities of the detector is found to be $\Delta\mathscr{A}_{CP}^{\rm raw} = 0.002 \pm 0.001$.

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 central interval criterion yields an asymmetric uncertainty of ${}^{+0.001}_{-0.000}$.

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 for a total systematic uncertainty of ± 0.002.

In addition to the *CP* 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, and are found to be ${}^{+0.002}_{-0.001}\,(\pm 0.001)$ and $\pm 0.003\,(\pm 0.002)$ for $\mathscr{A}^+$ $(\mathscr{A}^-)$, respectively. In 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 studied and found to be negligible.

Including the systematic uncertainties, the two up-down asymmetries are found to be

$$\begin{aligned} \mathscr{A}^+ &= -0.084 \pm 0.026\,(\text{stat})\ {}^{+0.004}_{-0.003}\,(\text{syst})\,, \\ \mathscr{A}^- &= -0.086 \pm 0.025\,(\text{stat}) \pm 0.002\,(\text{syst})\,. \end{aligned} \tag{5.2}$$

6. Conclusions

The inclusive $B^\pm \to K^\pm\pi^\mp\pi^\pm\gamma$ decay, with a $K^+\pi^-\pi^+$ mass in the $1.1 - 1.9\ \text{GeV}/c^2$ range, has been studied with a data sample corresponding to 2 fb^{-1} collected with the LHCb detector at $\sqrt{s} = 8\,\text{TeV}$. A total of $8190 \pm 140\,(\text{stat})\,{}^{+450}_{-390}\,(\text{syst})$ 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:

$$\mathscr{A}_{CP} = -0.007 \pm 0.015\,(\text{stat}) \pm 0.008\,(\text{syst})\,. \tag{6.1}$$

Finally, the up-down asymmetry, which is proportional to the photon polarization parameter λ_γ, has been studied for the first time in the $[1100, 1300] \cup [1400, 1600]\ \text{MeV}/c^2$ mass range in the $K^+\pi^-\pi^+$ spectrum, separately for B^+ and B^- decays. Since $\mathscr{A}^+$ and $\mathscr{A}^-$ are independent measurements of the same quantity, the up-down asymmetry $\mathscr{A}_{\rm ud}$, their likelihood profiles are combined to obtain

$$\mathscr{A}_{\rm ud} = -0.085 \pm 0.019\,(\text{stat}) \pm 0.003\,(\text{syst})\,, \tag{6.2}$$

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4.6σ 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 quantity, which could eventually help in constraining the effects of NP in the $b \to s\gamma$ sector.

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