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Rare radiative decays at LHCb

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Abstract
Radiative b-hadron decays are sensitive probes of New Physics through the study of branching fractions, CP asymmetries and measurements of the polarization of the photon emitted in the decay. During Run I of the LHC, the LHCb experiment has collected large samples of radiative b-hadron decays. An overview of the LHCb measurements, including results on the time dependence of $B_s^0 \to \phi\gamma$ decays, is presented here. These results help constrain the size of right-handed currents in extensions of the Standard Model.

Keywords
LHCb; Flavour Physics; Rare Decays; Radiative Decays.

1 Introduction

Rare $b \to s\gamma$ flavour-changing neutral-current transitions are forbidden at tree level in the Standard Model (SM) and, as a consequence, are very sensitive to new physics (NP) effects arising from the exchange of new heavy particles in electroweak penguin diagrams. In such cases, the SM predicts that the emitted photon is predominantly left-handed since the recoil s quark that couples to a W boson is left-handed. However, in several NP models, such as the left-right symmetric model [1–4] or the minimal supersymmetric model (MSSM) [5], the photon can acquire a significant right-handed component. Although effects coming from NP are strongly constrained by measurements of inclusive radiative decays, there is still room for contributions that would enhance the right-handed photon polarization component.

The main challenge for the study of b decays with a final state photon at the LHCb experiment [6] is the fact that their mass resolution is significantly worse (a factor 4–5) than that for decays to only charged particles due to the dominance of the photon energy resolution. This issue, combined with the large levels of background expected from a pp machine, makes the identification of signal remarkably difficult. Despite this fact, the LHCb collaboration has a wide program covering b decays with a final state photon, studying not only the polarization of the photon but also other quantities which could be affected by NP effects. This contribution presents the main measurements of rare radiative B decays at LHCb.

2 $B^0 \to K^{*0}\gamma$ and $B_s^0 \to \phi\gamma$

While inclusive decays are theoretically cleaner than exclusive ones—which suffer from large uncertainties due to, e.g., form factors—they are more challenging experimentally, especially in the LHC context. It is possible, however, to find cleaner, form-factor free observables that can be at the same time predicted accurately enough and measured with good precision. Examples of such observables are the ratio of branching fractions of $B^0 \to K^{*0}\gamma$ and $B_s^0 \to \phi\gamma$ decays, with a SM prediction of 1.0 ± 0.2 [7], or the direct CP asymmetry in $B^0 \to K^{*0}\gamma$ decays, predicted to be $(-0.61 \pm 0.43)\%$ [8].

Benefitting from large samples of $B^0 \to K^{*0}\gamma$ and $B_s^0 \to \phi\gamma$ decays corresponding to 1 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV, shown in Fig. 1, the LHCb collaboration measured the ratio of their branching fractions to be [9]

$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.23 \pm 0.06\,(\text{stat}) \pm 0.04\,(\text{syst}) \pm 0.10\,(f_s/f_d), \tag{1}$$

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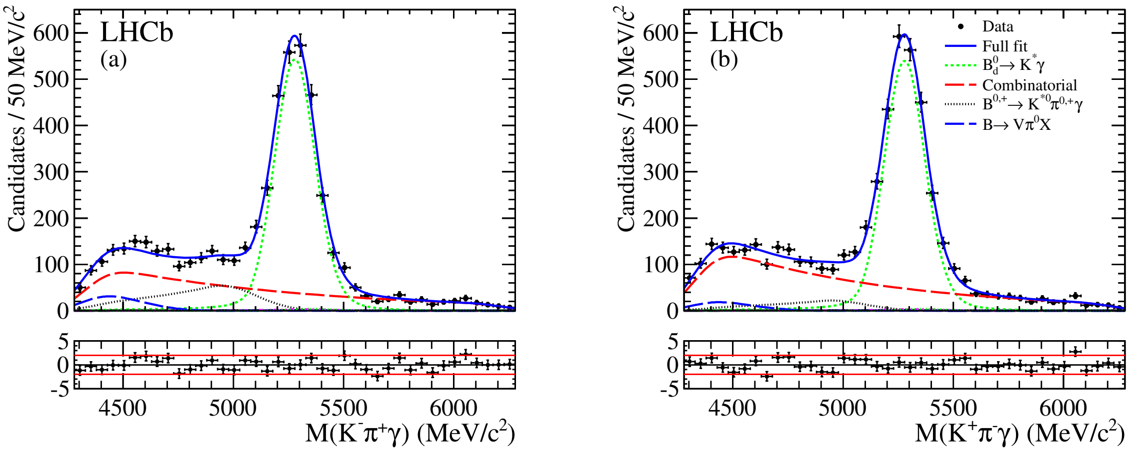

Fig. 1: Invariant mass distributions of the (a) $B^0 \to K^{*0}\gamma$ and (b) $B_s^0 \to \phi\gamma$ decay candidates. The fit result is overlaid as a solid blue line, with the signal component represented as a dashed green line.

which is the most precise measurement to date and is in agreement with the SM prediction. Using the world average value of $\mathcal{B}(B^0 \to K^{*0}\gamma) = (4.5 \pm 0.15) \times 10^{-5}$ [10], the branching fraction of $B_s^0 \to \phi\gamma$ was found to be

$$\mathcal{B}(B_s^0 \to \phi\gamma) = (3.5 \pm 0.4) \times 10^{-5}. \tag{2}$$

The same dataset was used to measure the direct *CP* asymmetry of the $B^0 \to K^{*0}\gamma$ decay, defined as

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\gamma) - \Gamma(B^0 \to K^{*0}\gamma)}{\Gamma(\overline{B}^0 \to \overline{K}^{*0}\gamma) + \Gamma(B^0 \to K^{*0}\gamma)}, \tag{3}$$

to be [9]

$$\mathcal{A}_{CP} = (0.8 \pm 1.7\,(\text{stat}) \pm 0.9\,(\text{syst}))\%, \tag{4}$$

well in agreement with the SM prediction.

Once these two results are updated with the full dataset collected by LHCb, the measurements are expected to reach the systematic limitation.

3 Search for $B_{(s)} \to J/\psi\,\gamma$ decays

Radiative B decays can also be used to test different approaches to the treatment of QCD calculations in theoretical predictions. In particular, the branching fraction predictions for $B_{(s)} \to J/\psi\gamma$ decays, dominated by the W boson exchange diagram shown in Fig. 2, vary one order of magnitude between the QCD factorization and the perturbative QCD approaches, going from $\sim 2 \times 10^{-7}$ [11] to 5×10^{-6} [12], respectively.

Despite not being $b \to s\gamma$ transitions, $B^0 \to J/\psi\gamma$ and $B_s^0 \to J/\psi\gamma$ present similar challenges to other radiative decays, i.e., the large contamination from low-mass backgrounds due to the wide mass resolution and the difficulty to separate π^0 from photons at high transverse energies. In order to distinguish the signal from the large contamination from decays such as $B_{(s)} \to J/\psi\eta(\to \gamma\gamma)$, $B^0 \to J/\psi\pi^0$, $B^0 \to J/\psi K_S^0(\to \pi^0\pi^0)$, and $B^+ \to J/\psi\rho^+(\to \pi^0\pi^+)$, only photons reconstructed as a electron-positron pairs where used; the fact that only the J/ψ meson and one photon are reconstructed was then used to separate these backgrounds from the signal.

Using 1 fb^{-1} of luminosity at $\sqrt{s} = 7$ TeV collected by the LHCb experiment, no significant signal was observed and an upper limit on the branching fractions was set to

$$\mathcal{B}(B^0 \to J/\psi\gamma) < 7.3 \times 10^{-6} \text{ at } 90\% \text{ CL}, \tag{5}$$

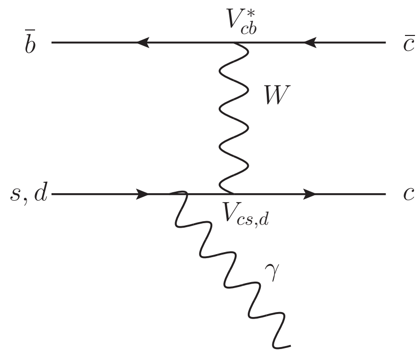

Fig. 2: Feynman diagram of the leading contribution to $B_{(s)} \to J/\psi\,\gamma$ decays, where one quark radiates a photon.

$$\mathcal{B}(B^0_s \to J/\psi\,\gamma) < 1.5 \times 10^{-6} \text{ at } 90\% \text{ CL}. \tag{6}$$

The $B^0 \to J/\psi\,\gamma$ branching fractions is in agreement and competitive with the previous measurement by the BaBar collaboration [13], while the first limit on $B^0_s \to J/\psi\,\gamma$ is close to the sensitivity of the prediction based on perturbative QCD.

4 $B^0_s \to \phi\gamma$ lifetime measurement

The time-dependent decay rate of B^0_s and $\overline{B}{}^0_s$ mesons decaying into a common final state containing a photon, such as $B^0_s \to \phi\gamma$, is proportional to

$$e^{-\Gamma_s t}\left\{\cosh\left(\frac{\Delta\Gamma_s}{2}\right) - \mathcal{A}^\Delta \sinh\left(\frac{\Delta\Gamma_s}{2}\right) \pm \mathcal{C}\cos\left(\Delta m_s t\right) \mp \mathcal{S}\sin\left(\Delta m_s t\right)\right\}, \tag{7}$$

where $\Delta\Gamma_s$ and Δm_s are the width and mass differences between the light and heavy B^0_s mass eigenstates and Γ_s is the mean decay width; the $\mathcal{A}^\Delta$, $\mathcal{C}$ and $\mathcal{S}$ coefficients are functions of the photon polarization. When the initial flavor of the B^0_s meson is unknown, only the $\mathcal{A}^\Delta$, predicted to be $\mathcal{A}^\Delta = 0.047^{+0.029}_{-0.025}$ in the SM [14], is accessible, and can be measured through the study of the $B^0_s \to \phi\gamma$ effective lifetime.

Making use of the full statistics collected in the LHC Run I by the LHCb experiment, corresponding to $1\ \text{fb}^{-1}$ and $2\ \text{fb}^{-1}$ of luminosity collected at center-of-mass energies of 7 and $8\ \text{TeV}$, respectively, the LHCb collaboration performed the first measurement of the $\mathcal{A}^\Delta$ parameter [15]. A value of

$$\mathcal{A}^\Delta = -0.98^{+0.46}_{-0.52}\,(\text{stat})^{+0.23}_{-0.20}\,(\text{syst}), \tag{8}$$

was found through an unbinned simultaneous fit of the $B^0_s \to \phi\gamma$ and $B^0 \to K^{*0}\gamma$ background-subtracted decay-time distributions, shown in Fig. 3, where the latter is used as a control sample. This result is compatible with the SM prediction within two standard deviations.

5 Angular analysis of $B^+ \to K^+\pi^-\pi^+\gamma$

Another way to access the photon polarization is through the decays of B mesons to a photon and a resonance that decays to three particles; information about the polarization of the photon can then be obtained from its direction with respect to the normal to the plane defined by the momenta of the three final-state hadrons in their centre-of-mass frame ($\tilde{\theta}$) [16, 17].

In general, the differential decay rate of $\overline{B} \to P_1P_2P_3\gamma$ going through a single resonance can be written using the helicity amplitude $\mathcal{J}_\mu$ as

$$\frac{\mathrm{d}\Gamma(\overline{B} \to \overline{K}_{\text{res}}\gamma \to P_1P_2P_3\gamma)}{\mathrm{d}s\,\mathrm{d}s_{13}\,\mathrm{d}s_{23}\,\mathrm{d}\cos\tilde{\theta}} \propto |\vec{\mathcal{J}}|^2(1+\cos^2\tilde{\theta}) + \lambda_\gamma\,2\,\mathrm{Im}\left[\vec{n}\cdot(\vec{\mathcal{J}}\times\vec{\mathcal{J}}^*)\right]\cos\tilde{\theta}\,, \tag{9}$$

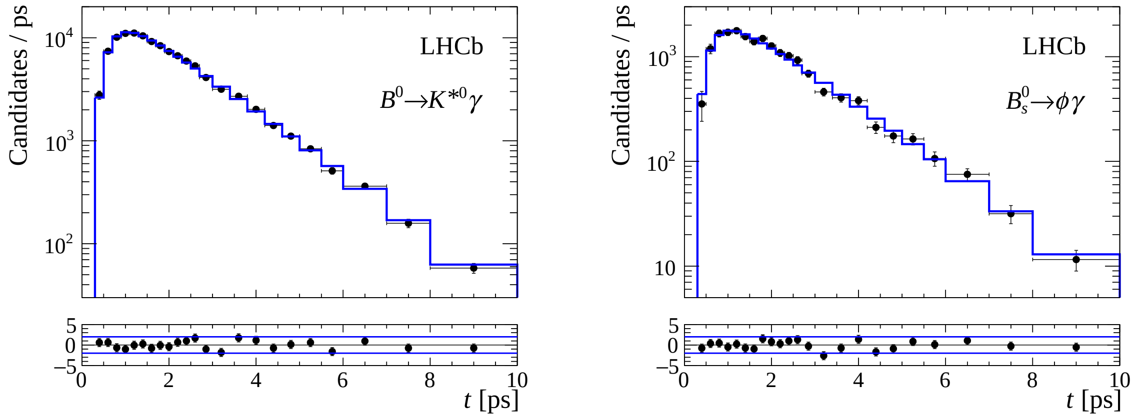

Fig. 3: Background-subtracted decay-time distributions of the (left) $B^0 \to K^{*0}\gamma$ and (right) $B^0_s \to \phi\gamma$ decays. The fit projection is overlaid as a solid blue line.

where s is the invariant mass of the $P_1P_2P_3$ system and s_{ij} the invariant mass of the P_iP_j system. In the case of overlapping intermediate resonances, one needs to consider their interference and Eq. 9 is not valid, leading to more complex dependencies on $\cos\tilde{\theta}$. However, even in the case of multiple resonances one can write the differential decay rate as a function of the even and odd powers of $\cos\tilde{\theta}$ and coefficients $a_j(s_{13}, s_{23})$:

$$\frac{\mathrm{d}\Gamma(\overline{B}\to \overline{K}_{\mathrm{res}}\gamma \to P_1P_2P_3\gamma)}{\mathrm{d}s\,\mathrm{d}s_{13}\,\mathrm{d}s_{23}\,\mathrm{d}\cos\tilde{\theta}} \propto \sum_{j\text{ even}} a_j(s_{13}, s_{23})\cos^j\tilde{\theta} + \lambda_\gamma \sum_{j\text{ odd}} a_j(s_{13}, s_{23})\cos^j\tilde{\theta}. \tag{10}$$

The structure of the decay rate can be exploited to study the photon polarization by constructing the up-down asymmetry

$$\mathcal{A}_{\mathrm{ud}} \equiv \frac{\int_0^1 \mathrm{d}\cos\tilde{\theta}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\tilde{\theta}} - \int_{-1}^0 \mathrm{d}\cos\tilde{\theta}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\tilde{\theta}}}{\int_{-1}^1 \mathrm{d}\cos\tilde{\theta}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\tilde{\theta}}} = C\lambda_\gamma\,, \tag{11}$$

where the constant C takes into account the integral over the Dalitz plot, $a_j(s_{13}, s_{23})$, and the angle $\cos\tilde{\theta}$. If $\mathcal{J}$ is known, C can be calculated and this asymmetry allows the determination of the photon polarization. However, in the case of $B^+ \to K^+\pi^-\pi^+\gamma$ the different resonances in the $K^+\pi^-\pi^+$ spectrum, shown in Fig. 4, cannot be easily separated and therefore the measurement needs to be performed inclusively.

The LHCb collaboration has studied the $\cos\tilde{\theta}$ angular distribution—including the up-down asymmetry in $B^+ \to K^+\pi^-\pi^+\gamma$ decays using 1 fb^{-1} of data collected at $\sqrt{s} = 7$ TeV [18]. The measurement was performed in bins of the $K^+\pi^-\pi^+$ mass, as defined in Fig. 4, in order to separate as much as possible physics effects coming from the dominant resonances.

While the measurements do not allow to determine the photon polarization, the combined significance of the observed up-down asymmetries (shown in Fig. 5) with respect to the no-polarization scenario in which the up-down asymmetry is expected to be zero in every mass interval, was determined to be $5.2\,\sigma$. This is the first observation of non-zero photon polarization.

6 Conclusions

The LHCb collaboration has fulfilled its core radiative B decays programme with data collected in the Run I of the LHC, with most of the presented results being either world's best or very competitive with previous measurements. The great potential of the LHCb experiment for the study of radiative B

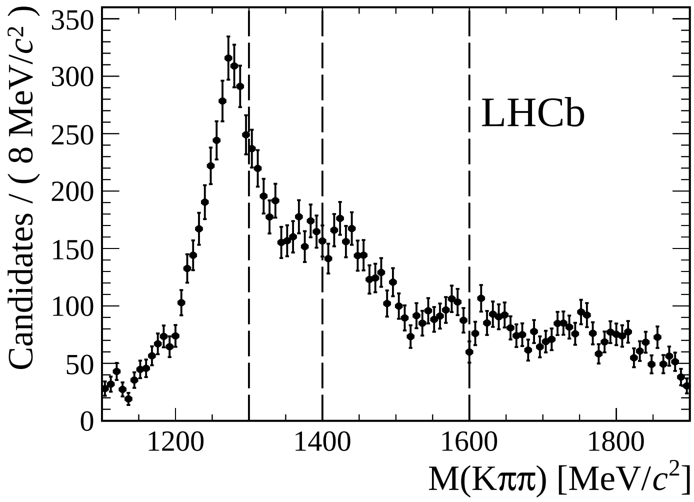

Fig. 4: Background-subtracted $K^+\pi^-\pi^+$ mass distribution of $B^+ \to K^+\pi^-\pi^+\gamma$ candidates. The vertical dashed lines indicate the bin edges used in the angular analysis.

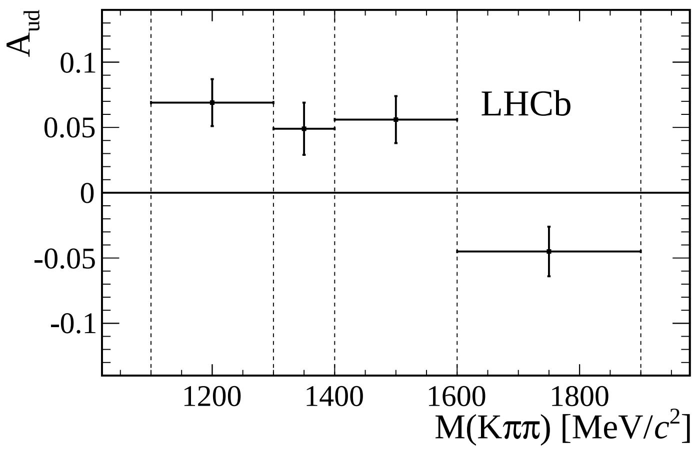

Fig. 5: Up-down asymmetry in bins of $K^+\pi^-\pi^+$ mass measured in $B^+ \to K^+\pi^-\pi^+\gamma$ decays. The vertical dashed lines indicate the bin edges used in the angular analysis.

decays is further showcased through its influence on the global fits of the $C_7^{(\prime)}$ Wilson coefficients (see for example Ref. [19]): thanks to measurements such as the $B_s^0 \to \phi\gamma$ effective lifetime and the angular distribution of the $B^0 \to K^{*0}e^+e^-$ decay [20], combined with other results from the B-factories, the presence of large NP effects $C_7^{(\prime)}$ has almost been ruled out.

The update of the results presented here with data taken in the Run II of the LHC, along with the addition of more complex measurements, such as the B-tagged $B_s^0 \to \phi\gamma$ effective lifetime, b radiative baryon decays, the full amplitude analysis of $B^+ \to K^+\pi^-\pi^+\gamma$ or $b \to d\gamma$ transitions, will improve constraints on NP and will allow to reach an unprecedented knowledge of the polarization of the photon.

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