PROCEEDINGS OF SCIENCE

Rare Radiative decays at LHCb

M. Vieites Díaz, on behalf of LHCb collaboration[a,*]

[a] *Laboratoire de Physique des Hautes Énergies,*
École Polytechnique Fédérale de Lausanne,
BSP 619 Cubotron, Rte de la Sorge, CH-1015 Lausanne

E-mail: maria.vieites.diaz@cern.ch

Radiative rare b-hadron decays are sensitive probes of New Physics through the study of branching fractions, angular observables, $C\mathcal{P}$ asymmetries and measurements of the polarisation of the photon emitted in the decay. The recent LHCb results on the first direct measurement of the photon polarisation using $\Lambda_b^0 \to \Lambda\gamma$ decays and on the search for the rare $\Xi_b^- \to \Xi^-\gamma$ decay are reported.

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*Speaker

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1. Introduction

The term 'Radiative decays' is often used to describe quark level transitions of the form $b \to s\gamma$. The hard (real) photon in the final state provides a clear experimental signature which features a prominent role in the event selections. Interest in these decays stems from the $b \to s\gamma$ process being a flavour changing neutral current (FCNC), which implies that these decays can only proceed within the Standard Model (SM) via loop or penguin diagrams. Given that there is no restriction as to which particles may run in these loops, FCNC processes define an interesting benchmark to perform precision tests of the SM.

The effective Hamiltonian describing $b \to s\gamma$ transitions at leading order is given by

$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} (C_7 O_7 + C_7' O_7'),$$

where $O_7^{(\prime)}$ is the left (right) projection of the electromagnetic penguin operator and C_7 and C_7' are the Wilson coefficients associated to each operator. The polarisation of the emitted photons, defined as the ratio between the number of left- (γ_L) and right-handed (γ_R) emitted photons, $\alpha_\gamma = \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R}$, gives access to the value of the aforementioned Wilson coefficients, as the handedness of the emitted photon correlates to that of the projection of the electromagnetic penguin operator.

The leading order SM prediction for the photon polarisation is $\alpha = \frac{1-|r|^2}{1+|r|^2}$ [1], with r being approximately ratio between the s and b quark masses. In b-decays, the expectation is therefore for predominately left-handed photons to be emitted and any significant deviations from this expectation would imply the presence of sizeable contributions from right handed currents that would hint to New Physics phenomena.

2. Measurement of the polarisation in $\Lambda_b^0 \to \Lambda\gamma$

Weak decays of b-baryons can be used to probe the helicity structure of $b \to s\gamma$ transitions, thanks to the non-zero spin of the initial- and final-state particles. In particular, the $\Lambda_b^0 \to \Lambda(\to p\pi^-)\gamma$ process can be used to directly measure the photon polarisation by analysing its decay rate as a function of the helicity angle of the proton in the final state (see Fig. 1 for a graphical definition of θ_p and θ_Λ, the helicity angles in the decay). The decay rate is integrated over θ_Λ in order to remove the dependence on the initial polarisation of the Λ_b baryon, which leads to:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}(\cos\theta_\mathrm{p})} \propto 1 - \alpha_\Lambda \alpha_\gamma \cos\theta_p, \tag{1}$$

from where one can access the value of α_γ up to the knowledge on the α_Λ, the Λ baryon weak decay parameter. The recent BESIII results [2] are used as external input to fix the flavour-specific α_Λ and $\alpha_{\overline{\Lambda}}$ parameters to their best known values.

The presented LHCb analysis [3] uses a data sample corresponding to an integrated luminosity of 6 fb^{-1} collected by the LHCb experiment in proton-proton (pp) collisions at a center-of-mass energy of 13 TeV during 2015–2018. The first measurement of the photon polarisation in $\Lambda_b^0 \to \Lambda\gamma$ decays, as well as the first study of $C\mathcal{P}$ asymmetries in angular distributions of $b \to s\gamma$ processes are reported.

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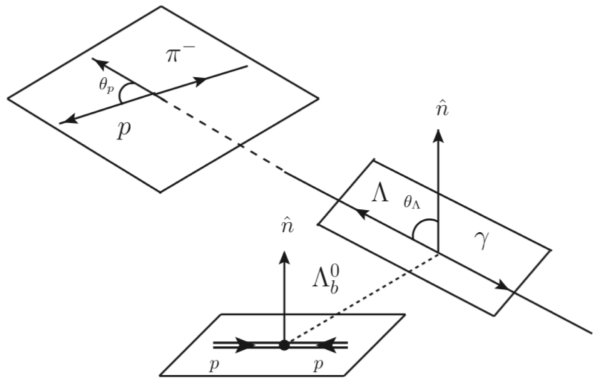

Figure 1: Schematic definition of the helicity angles in the $\Lambda_b^0 \to \Lambda(\to p\pi^-)\gamma$ decay [4].

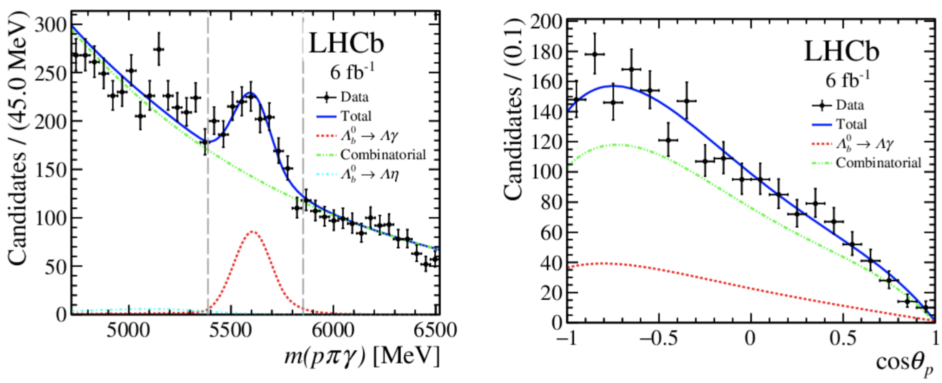

Figure 2: Left: Invariant mass distribution of selected $(p\pi\gamma)$ candidates. The (solid blue line) fit model encompasses the contributions from (dashed green line) the combinatorial background, (dashed cyan) the partially reconstructed $\Lambda_b^0 \to \Lambda\eta(\to\gamma\gamma)$ candidates and (dotted red) the $\Lambda_b^0 \to \Lambda\gamma$ signal component. Data is represented by the black dots. The signal region is shown delimited by dashed grey vertical lines. Right: $\cos\theta_p$ distribution of events in the signal region, with the total fit model overlaid.

The measurement of the photon polarisation is achieved by performing a maximum likelihood fit to the $\cos\theta_p$ distribution of selected $\Lambda_b^0 \to \Lambda\gamma$ candidates in the signal region ($m(p\pi\gamma) \in [5387.1, 5852.1]$ MeV). Both a signal and a background component are included in this fit, their respective yields being determined from the fit to the invariant mass distribution of the $(p\pi\gamma)$ candidates, shown in Fig. 2 (left). The model used to describe the $(p\pi\gamma)$ invariant mass spectrum accounts for three components, namely: a background contribution originating from random combination of a Λ and a photon candidates, a second background source from partially reconstructed $\Lambda_b^0 \to \Lambda\eta(\to\gamma\gamma)$ candidates (where one of the photons from the η decay is not reconstructed), and lastly, for the $\Lambda_b^0 \to \Lambda\gamma$ signal component. The obtained yields in the signal region are 440 ± 40 for the signal contribution, 1460 ± 23 for the combinatorial background and 10 ± 4 for the partially reconstructed $\Lambda_b^0 \to \Lambda\eta(\to\gamma\gamma)$ background.

The model used to describe the signal component in the $\cos\theta_p$ distribution of selected $(p\pi\gamma)$ candidates is obtained by multiplying the decay rate shown in Eq. 1 by an acceptance function,

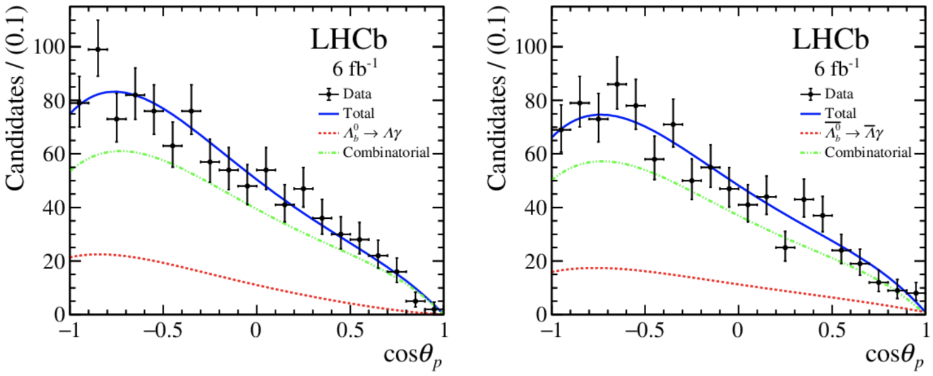

Figure 3: Distribution of $\cos\theta_p$ for events in the signal region, split according to the charge of the final state pion to define the Λ_b^0 (left) and $\overline{\Lambda}_b^0$ (right) sub-samples.

which describes the distortion induced in the expected distribution due to the geometrical acceptance of the LHCb detector and the biases imposed by the reconstruction and selection requirements. This function is obtained from simulated data and is described with a fourth-order polynomial in $\cos\theta_p$. The reliability of the simulation for this description is validated using $\Lambda_b^0 \to \Lambda J/\psi$ candidates from real and simulated data, as the key features of this function are dominated by the presence of the $(p\pi^-)$ system in the final state, common in both decays. The shape of the background component, accounting both the combinatorial and the $\Lambda_b^0 \to \Lambda\eta(\to \gamma\gamma)$ backgrounds, is obtained from the control region defined by the high and low mass side-bands ($[4719.6, 5382.1] \cup [5857.1, 6519.6]$ MeV) of the $(p\pi\gamma)$ invariant mass spectrum. The projection of this fit is shown in Fig. 2 (right) and from it, the photon polarisation is measured to be

$$\alpha_\lambda = 0.82^{+0.17}_{-0.26}(stat.)^{+0.04}_{-0.13}(syst.),$$

where the confidence intervals (enforcing the physical boundary of [-1,1] for α_λ) have been determined using the Feldman-Cousins technique.

As the $\Lambda \to p\pi^-$ decay is self-tagged, the selected data sample can be split according to the charge of the final state pion to disentangle the $\Lambda_b^0 \to \Lambda\gamma$ and $\overline{\Lambda}_b^0 \to \overline{\Lambda}\gamma$ decays and perform flavour-specific measurements. Applying the same technique as described earlier for the combined data sample, the photon polarisation is measured in each of these sub-samples, yielding the results shown in Fig. 3, and obtaining

$$\alpha_\lambda^- > 0.56\ (0.44) \text{ at } 90\%(95\%) \text{ CL}$$

$$\alpha_\lambda^+ = -0.56^{+0.36}_{-0.33}(stat.)^{+0.16}_{-0.09}(syst.)$$

where α_λ^- (α_λ^+) is measured using the Λ_b^0 ($\overline{\Lambda}_b^0$) sample and both are expected to have the same absolute value with opposite sign in the absence of $\mathcal{CP}$ violation.

3. Search for the radiative $\Xi_b^- \to \Xi^-\gamma$ decay

As introduced earlier, the presence of right-handed currents, and thus, of beyond the SM phenomena, can be tested with precision measurements of processes involving $b \to s\gamma$ transitions.

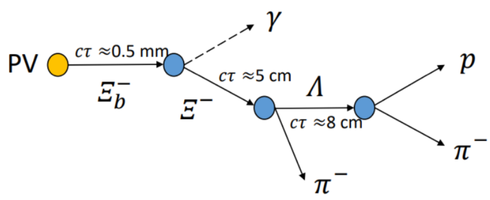

Figure 4: Schematic view of the $\Xi_b^- \to \Xi^-\gamma$ decay chain.

Measuring branching ratios, while experimentally challenging, provides very valuable constraints to possible new physics contributions. The $\Xi_b^- \to \Xi^-\gamma$ process has yet to be observed experimentally, however, its predicted branching ratio within the SM being $\mathcal{B}(\Xi_b^- \to \Xi^-\gamma) = (3.03 \pm 0.10) \times 10^{-4}$ [5], this observation could be within reach of the LHCb experiment. The presented work [6] documents the search for this decay, for which a data sample corresponding to an integrated luminosity of 5.4 fb^{-1} of pp collisions at a center-of-mass energy of 13 TeV, collected by the LHCb detector, was analysed.

The analysed data sample is restricted (due to trigger limitations) to candidates that undergo the full decay chain inside the vertex detector of the LHCb experiment. As shown in Fig. 4, this chain involves 3 decay vertices, from which the one involving the photon can not be reconstructed in LHCb. Backgrounds originating from the random combination of tracks have therefore to be very well controlled (by means of a dedicated multivariate discriminator). Tight invariant-mass windows are placed around the best known values of each of the masses of the Λ, Ξ^- and Ξ_b^- resonances in the corresponding invariant mass spectra. The $\Xi_b^- \to \Xi^- J/\psi(\to \mu^+\mu^-)$ decay mode is used as normalisation channel for the branching fraction measurement, due to the similarity between the hadronic parts of both channels. A simultaneous unbinned maximum likelihood fit is performed on the candidates passing the selections for the signal and normalisation channels, respectively. The results of this fit are shown in Fig. 5 and are translated into an upper limit for this decay mode using the Feldman-Cousins approach:

$$\mathcal{B}(\Xi_b^- \to \Xi^-\gamma) < 1.3(0.6) \times 10^{-4} \text{ at } 95\% \text{ } (90\%) \text{ CL}.$$

The dominant systematic uncertainty arises from the poor knowledge of the absolute branching fraction of the control channel. For this reason, the ratio of branching fractions is computed explicitly:

$$\frac{\mathcal{B}(\Xi_b^- \to \Xi^-\gamma)}{\mathcal{B}(\Xi_b^- \to \Xi^- J/\psi)} < 0.12(0.08) \text{ at } 95\% \text{ } (90\%) \text{ CL}.$$

4. Conclusions

The most recent results by the LHCb collaboration on rare radiative decays of b-baryons have been presented. These include the first measurement of the photon polarisation in $b \to s\gamma$ transitions using $\Lambda_b^0 \to \Lambda\gamma$ decays and the first flavour-specific measurements on this observable. The search for the rare $\Xi_b^- \to \Xi^-\gamma$ decay mode was also presented. All results are in agreement with expectations from the SM.

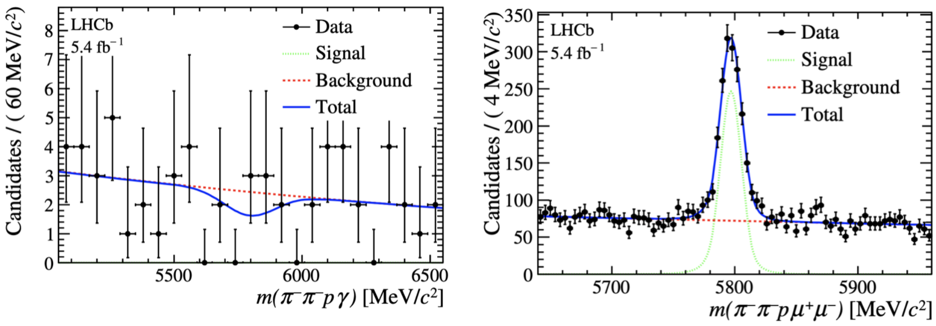

Figure 5: Invariant mass distribution of the (left) $\pi^-\pi^- p\gamma$ and (right) $\pi^-\pi^- p\mu^+\mu^-$ selected candidates, corresponding to the signal and the normalisation mode, respectively. Data is represented with black dots, the total fit model is shown with a solid blue line and accounts for the (dashed green line) signal and (dashed red line) combinatorial background contributions.

Acknowledgements

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