RARE AND RADIATIVE DECAYS AT LHCb

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Abstract

Rare and radiative b-hadron decays are sensitive probes of New Physics (NP). One sensitive measurement is the polarisation of the photon emitted in a $b \to s \gamma$ transition, predominantly left-handed in the Standard Model (SM). Recent results by the LHCb collaboration are presented: the first observation of $\Lambda_0 \to \Lambda \gamma$ and the time-dependent analysis of $B^0_s \to \phi \gamma$, which provides constraints on right-handed currents contribution.

1 Introduction

In the Standard Model (SM) of particle physics, the radiative $b \to s \gamma$ transitions proceed via loop Feynman diagrams. The small size of the SM amplitude makes such process sensitive to the contribution of possible new virtual particles that can modify the decay rate or the helicity structure of the vertex. The emitted photons are produced predominantly with left-handed helicity in the SM due to parity violation in the weak interaction, with a small relative right-handed component proportional to the ratio of $s$- to $b$-quark masses. In many extensions of the SM, the right-handed component can be enhanced, leading to observable effects, for instance, in mixing-induced CP asymmetries and time-dependent decay rates of radiative $B^0$ and $B^0_s$ decays $1, 2, 3$. Figure 1 shows the dominant SM contribution as well as possible NP contributions.

The LHCb experiment has collected data in the first two runs of the Large Hadron Collider (LHC), during 2010-12 (Run 1) and 2015-18 (Run 2). In Run 1, the data sample corresponds to an integrated luminosity around 3 fb$^{-1}$ collected in proton-proton ($pp$) collisions at center-of-mass energies of 7 and 8 TeV. For Run 2, the integrated luminosity is approximately 6 fb$^{-1}$ and the $pp$ collisions were at 13 TeV. The detector is ideally suited for b-hadron decay measurements due to its high trigger efficiency on the
high $E_T$ decay products and displaced vertices, as well as excellent tracking and particle identification performance $^4$.

Previous LHCb measurements regarding the photon polarisation with radiative decays are: the first observation of photon polarisation in $B^+ \to K^+\pi^+\pi^-\gamma$ decays $^5$; the angular analysis of $B^0 \to K^{*0}e^+e^-$ in the low-$q^2$ region, where the virtual photon contribution is dominant $^6$, and the time-dependent analysis of $B^0_s \to \phi \gamma$ decays $^7$. Here the two most recent results from the LHCb collaboration are presented: the first observation of $\Lambda^0_b \to \Lambda \gamma$ decays $^8$ and an update of the time-dependent analysis of $B^0_s \to \phi \gamma$ decays $^9$.

2 First observation of $\Lambda^0_b \to \Lambda \gamma$

Radiative $b$-baryon decays had never been observed so far. The study of these transitions offers a unique benchmark to measure the photon polarization due to the non-zero spin of the initial particle $^{10}$. In particular, the $\Lambda^0_b \to \Lambda \gamma$ decay has been proposed as a suitable mode for the study of the photon polarization $^{11}, 12$.

The $\Lambda^0_b \to \Lambda \gamma$ decay is experimentally challenging to reconstruct. At hadron colliders the $\Lambda^0_b$ decay vertex cannot be determined directly due to the long lifetime of the weakly decaying $\Lambda$ baryon and the unknown photon direction.

The SM prediction of the branching fraction lies in the range $(6–100) \times 10^{-7}$, where the large variation is due to different computations of the $\Lambda^0_b \to \Lambda$ form factors at the photon pole $^{13}, 14, 15, 16$). A precise measurement of the $\Lambda^0_b \to \Lambda \gamma$ branching fraction allows discrimination between different approaches to the form-factor computation, and is an important step towards the measurement of the photon polarization in radiative $b$-baryon decays $^{17}$.

Here the first observation of $\Lambda^0_b \to \Lambda \gamma$ decays is presented, with $\Lambda$ reconstructed as $p\pi$. The $B^0 \to K^{*0}\gamma$ decay is used as a normalization mode to measure the branching fraction, with $K^{*0}$ reconstructed in the $K^+\pi^-$ final state. The data sample used in this work corresponds to $1.7 \text{ fb}^{-1}$ of integrated luminosity collected by the LHCb experiment in 13 TeV $pp$ collisions during 2016. A dedicated reconstruction has been developed to study this mode and a Boosted Decision Tree algorithm is used to reduce the large combinatorial background.

Normalization and signal yields are obtained from a simultaneous extended unbinned maximum likelihood fit to data, shown in Fig. 2. The yields are found to be $65 \pm 13$ and $32670 \pm 290$ for $\Lambda^0_b \to \Lambda \gamma$ and $B^0 \to K^{*0}\gamma$, respectively. The ratio of yields is given by the expression

$$\frac{N(\Lambda^0_b \to \Lambda \gamma)}{N(B^0 \to K^{*0}\gamma)} = \frac{f_{\Lambda_b}}{f_{B_d}} \times \frac{\mathcal{B}(\Lambda^0_b \to \Lambda \gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} \times \frac{\mathcal{B}(\Lambda \to p\pi)}{\mathcal{B}(K^{*0} \to K^\pi)} \times \frac{\epsilon(\Lambda^0_b \to \Lambda \gamma)}{\epsilon(B^0 \to K^{*0}\gamma)}$$ (1)
where \( f_{\Lambda_b}/f_{B_d} \) is the ratio of hadronisation fractions \(^{18}\), \( \mathcal{B} \) is the branching fraction \(^{19}\) and \( \epsilon \) is the combined reconstruction and selection efficiency for the given decay computed from simulation and calibration samples.

The branching fraction of the \( \Lambda_0^b \to \Lambda\gamma \) decay is measured for the first time,

\[
\mathcal{B}(\Lambda_0^b \to \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6},
\]

where the first uncertainty is statistical, the second systematic and the third is the systematic from external measurements, dominated by the ratio of hadronisation fractions. The significance for \( \Lambda_0^b \to \Lambda\gamma \) decays is found to be 5.6 standard deviations.

### 3 Time-dependent analysis of \( B_0^s \to \phi\gamma \)

The decay rate of \( B_0^s \) or \( \bar{B}_0^s \) mesons to a CP even final state is given by:

\[
P(t) \propto e^{-\Gamma_s t} \left\{ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - A^\Delta \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) + \zeta C \cos \left( \Delta m_s t \right) - \zeta S \sin \left( \Delta m_s t \right) \right\},
\]

where \( \Delta \Gamma_s \) and \( \Delta m_s \) are the width and mass differences between the \( B_0^s \) mass eigenstates, defined positively, \( \Gamma_s \) is the mean decay width between such eigenstates, and \( \zeta \) takes the value of +1 (-1) for an initial \( B_0^s \) (\( \bar{B}_0^s \)) state. The coefficients \( A^\Delta \) and \( S \) are sensitive to the photon helicity amplitudes and weak phases, while \( C \) is related to CP violation in the decay. The SM predictions for the three coefficients in the \( B_0^s \to \phi\gamma \) decay are close to zero \(^3\). The LHCb collaboration had previously measured \( A^\Delta = -0.98^{+0.46}_{-0.52} +0.23 \) from a time-dependent flavour-untagged analysis \(^7\), which is compatible with the SM within two standard deviations.

This new analysis represents the first measurement of the CP-violating observables \( S \) and \( C \) from a radiative \( B_0^s \) decay. An update of the \( A^\Delta \) coefficient measurement is also provided. Results are based on data collected with the LHCb detector in \( pp \) collisions at center-of-mass energies of 7 and 8 TeV during the years 2011 and 2012, respectively, corresponding to an integrated luminosity of 3 fb\(^{-1}\). Compared
to the previous measurement, the current analysis benefits from a 20% higher event selection efficiency, a reoptimized calorimeter reconstruction and a new photon identification algorithm. Flavour-tagging algorithms \(^{20, 21}\) are applied to determine the flavour of the initial eigenstate (\(B^+_s\) or \(\bar{B}^+_s\)), which is essential to measure the \(S\) and \(C\) observables. The background is subtracted from a fit to the mass distribution of the \(B^0_s\) candidates. A sample of untagged \(B^0 \rightarrow K^{*0}(892)\gamma\) decays, reconstructed in the flavour-specific \(K^{*0} \rightarrow K^+\pi^-\) final state, is used to control the decay-time-dependent efficiency, since its lifetime is well measured. Figure 3 shows the mass-fit of the signal and control mode candidates. A total of \(5110 \pm 90\) \(B^0_s \rightarrow \phi\gamma\) and \(33860 \pm 250\) \(B^0 \rightarrow K^{*0}\gamma\) candidates are found.

**Figure 3:** Fits to the mass distributions of the (left) \(B^0_s \rightarrow \phi\gamma\) and (right) \(B^0 \rightarrow K^{*0}\gamma\) candidates.

From a simultaneous unbinned fit to the decay-time distributions of \(B^0_s \rightarrow \phi\gamma\) and \(B^0 \rightarrow K^{*0}\gamma\) data samples, the following values are measured

\[
S = 0.43 \pm 0.30 \pm 0.11, \\
C = 0.11 \pm 0.29 \pm 0.11, \\
A^\Delta = -0.67^{+0.37}_{-0.47} \pm 0.17,
\]

where the first uncertainty is statistical (including the external parameters) and the second systematic. The larger systematic uncertainty for \(A^\Delta\) is from the background modelling. For \(S\) and \(C\) parameters, the larger systematic uncertainties come from the decay-time resolution and the calibration of flavour-tagging algorithms. The fit projections are shown in Fig. 4. The results are compatible with the SM expectation \(^3\) within 1.3, 0.3 and 1.7 standard deviations, respectively. The observables \(A^\Delta\) and \(S\) provide constraints on the right-handed currents contribution in \(b \rightarrow s\) transitions.

4 Summary

Radiative \(b\)-decays allow to probe NP at large energy scales through indirect measurements. The photon polarisation can be measured in several ways and allows to puts constraints on righ-handed components. The two lastest results from LHCb have been presented. The branching fraction of the \(\Lambda^0_b \rightarrow \Lambda\gamma\) decay is measured for the first time, opening the possibility of measuring the photon polarisation in \(b\)-baryon decays. Moreover, the CP-violating and mixing-induced observables \(S\), \(C\) and \(A^\Delta\) are measured from a time-dependent analysis of \(B^0_s \rightarrow \phi\gamma\) decay, and they are compatible with SM expectations.
Figure 4: Decay-time fit projections. The top row corresponds to the tagged (left) $B^0_s \to \phi\gamma$ and (right) $B^0_\bar{s} \to \phi\gamma$ candidates, while the bottom plots show the (left) untagged $B^0_s \to \phi\gamma$ and (right) $B^0 \to K^{*0}\gamma$ candidates. The line is the result of the fit including statistical uncertainties.

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