PROCEEDINGS OF SCIENCE

Radiative decays at LHCb

Pavel Krokovny*
Novosibirsk State University, Novosibirsk, Russia
Budker Institute of Nuclear Physics, Novosibirsk, Russia
E-mail: krokovny@inp.nsk.su

The radiative decay $\Lambda_b^0 \to \Lambda^0\gamma$ is observed for the first time using a data sample of proton-proton collisions corresponding to an integrated luminosity of $1.7\,\mathrm{fb}^{-1}$ collected by the LHCb experiment at a center-of-mass energy of 13 TeV. Its branching fraction is measured to be $\mathscr{B}(\Lambda_b^0 \to \Lambda^0\gamma) = (7.1\pm1.5\pm0.6\pm0.7)\times10^{-6}$, where the quoted uncertainties are statistical, systematic and systematic from external inputs, respectively. A time-dependent analysis of the $B_s^0 \to \phi\gamma$ decay rate is performed to determine the *CP*-violating observables $S_{\phi\gamma}$ and $C_{\phi\gamma}$, and the mixing-induced observable $\mathscr{A}^{\Delta}_{\phi\gamma}$. The measurement is based on a sample of *pp* collision data recorded with the LHCb detector, corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$ at center-of-mass energies of 7 and 8 TeV. The measured values are $S_{\phi\gamma} = 0.43\pm0.30\pm0.11$, $C_{\phi\gamma} = 0.11\pm0.29\pm0.11$, $\mathscr{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41}\pm0.17$, where the first uncertainty is statistical and the second systematic. The results are consistent with the Standard Model predictions.

18th International Conference on B-Physics at Frontier Machines - Beauty2019 -
29 September / 4 October, 2019
Ljubljana, Slovenia

*Speaker.

PoS(Beauty2019)020

1. Introduction

In the Standard Model (SM) of particle physics, the $b \to s\gamma$ transition proceeds via flavour-changing neutral-current loop Feynman diagrams. The polarization of the photon in these processes is predicted to be predominantly left-handed in the SM, due to parity violation in the weak interaction, with a small 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 in mixing-induced CP asymmetries and time-dependent decay rates of radiative B^0 and B_s^0 decays [1, 2, 3].

$\Lambda_b^0 \to \Lambda^0\gamma$ decay can be used for the study of the photon polarization, since the helicity of the Λ^0 baryon can be measured, giving access to the helicity structure of the $b \to s\gamma$ transition [4, 5]. We report on a search of $\Lambda_b^0 \to \Lambda^0\gamma$ decay using a data sample of proton-proton collisions corresponding to an integrated luminosity of $1.7\,\mathrm{fb}^{-1}$ collected by the LHCb experiment at a center-of-mass energy of 13 TeV.

Photon helicity amplitudes and weak phases can be also accessed by measurement of time-dependent rate of $B_s^0 \to \phi\gamma$ decay. We report results of time-dependent analysis of $B_s^0 \to \phi\gamma$ decays using $3\,\mathrm{fb}^{-1}$ data collected by LHCb detector at center-of-mass energies 7 and 8 TeV.

The LHCb detector [6, 7] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$. 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 of the magnet. Charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. The online event selection is performed by a trigger, which 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.

2. First Observation of the Radiative Decay $\Lambda_b^0 \to \Lambda^0\gamma$

Data analysis proceeds in two steps: preliminary requirements are made to reduce backgrounds and then a Boosted Decision Tree (BDT) is used. Λ_b^0 candidates are combined from a Λ^0 baryon and a photon. Good-quality tracks, consistent with the proton and pion hypotheses, with opposite charge and good vertex well separated from any primary vertex (PV) form the Λ^0 candidate. Proton and pion candidates are required have p_T larger than $800\,\mathrm{MeV}/c$ and $300\,\mathrm{MeV}/c$, respectively. The proton-pion system is required to have an invariant mass in the range 1110–1122 MeV/c^2 and $p_\mathrm{T} > 1\,\mathrm{GeV}/c$. Photons are required to have $E_\mathrm{T} > 3\,\mathrm{GeV}$. The sum of the Λ^0 and photon p_T transverse momenta should be larger than $5\,\mathrm{GeV}/c$. The Λ_b^0 transverse momentum is required to be above $4\,\mathrm{GeV}/c$ and its invariant mass within $900\,\mathrm{MeV}/c^2$ of the nominal Λ_b^0 mass [8]. BDT is used to further separate signal from combinatorial background. It is trained on signal simulated events and on data candidates with an invariant mass larger than $6.1\,\mathrm{GeV}/c^2$ as background. A combination of topological and isolation information is used as input for the classifier, including the transverse momentum and the separation from the PV of the different particles, the separation between the Λ^0 decay vertex and the PV and the DOCA between the two tracks and between the Λ_b^0 and Λ^0 trajectories. A two-fold technique is used to avoid overtraining and no correlation is observed between the BDT response and the candidate mass. The requirement on the BDT output is optimized using the Punzi figure of merit [9]. A working point of 0.985 is chosen, which provides a signal efficiency of 33% with a 99.8% background rejection. A separate BDT with the same configuration and input variables is trained to select $B^0 \to K^{*0}\gamma$ candidates. Potential contamination from neutral pions that are reconstructed as a single merged cluster in the electromagnetic calorimeter is suppressed by employing a neural network classifier trained to separate π^0 mesons from photons.

Signal yields are obtained by maximum likelihood simultaneous fit to the invariant-mass distributions of the selected $\Lambda_b^0 \to \Lambda^0\gamma$ and $B^0 \to K^{*0}\gamma$ candidates. The $\Lambda_b^0 \to \Lambda^0\gamma$ signal component is descried with a double-tailed Crystal Ball probability density function (PDF), with power-law tails. The dominant source of background is formed by combinations of a real Λ^0 baryon with a random photon is modeled with an exponential PDF with a free decay parameter.

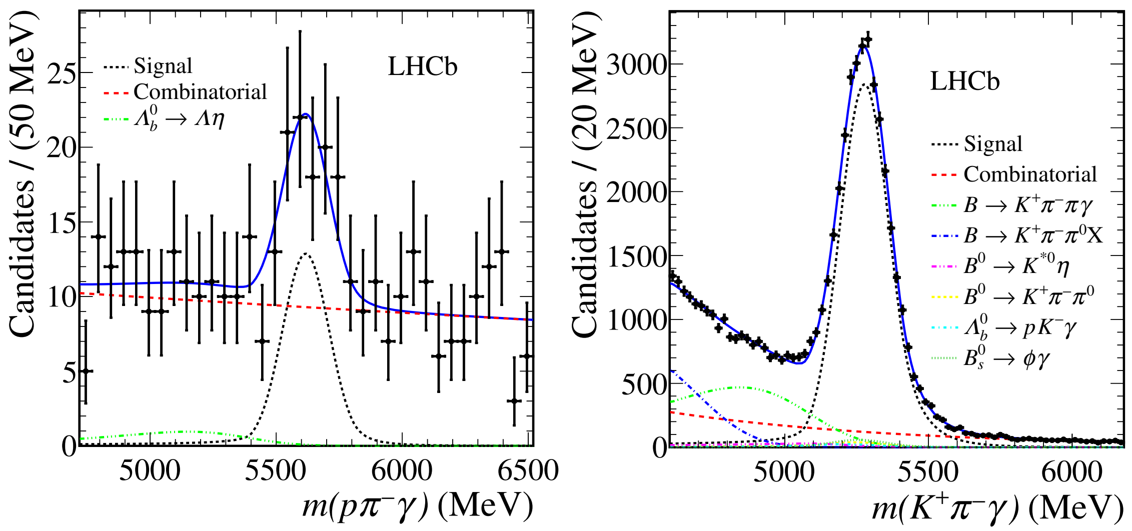

Figure 1: Simultaneous fit to the (left) $\Lambda_b^0 \to \Lambda^0\gamma$ and (right) $B^0 \to K^{*0}\gamma$ invariant-mass distributions of selected candidates. The data are represented by black dots and the result of the fit by a solid blue curve while individual contributions are represented in different line styles (see legend).

The signal yields are found to be 65 ± 13 and 32670 ± 290 for $\Lambda_b^0 \to \Lambda^0\gamma$ and $B^0 \to K^{*0}\gamma$, respectively. The $\Lambda_b^0 \to \Lambda^0\gamma$ decay is observed for the first time with a significance of 5.6σ. The ratio of hadronization and branching fractions is measured to be

$$\frac{f_{\Lambda_b^0}}{f_{B_d}} \times \frac{\mathscr{B}(\Lambda_b^0 \to \Lambda^0\gamma)}{\mathscr{B}(B^0 \to K^{*0}\gamma)} \times \frac{\mathscr{B}(\Lambda^0 \to p\pi^-)}{\mathscr{B}(K^{*0} \to K^+\pi^-)} = (9.9 \pm 2.0) \times 10^{-2},$$

where the uncertainty is statistical only. The $\Lambda_b^0 \to \Lambda^0\gamma$ decay branching fraction is measured $\mathscr{B}(\Lambda_b^0 \to \Lambda^0\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$, where the first uncertainty is statistical, the second systematic and the third is the systematic from external measurements. Our result is in good agreement with the predictions from Refs. [10], [11] and [12], which make use of Light Cone Sum

Rules, the Heavy Quark Limit and the covariant constituent quark model, respectively. This is the first observation of a radiative decay of a beauty baryon.

More details of the analysis can be found in [13].

3. Measurement of *CP*-Violating and Mixing-Induced Observables in $B_s^0 \to \phi\gamma$ Decays

The rate $\mathscr{P}(t)$ at which B_s^0 or $\bar{B}_s^0$ mesons decay into $\phi(1020)\gamma$, depends on the decay time t as [3]

$$\mathscr{P}(t) \propto e^{-\Gamma_s t}\left\{\cosh\left(\Delta\Gamma_s t/2\right) - \mathscr{A}^{\Delta}\sinh\left(\Delta\Gamma_s t/2\right) + \zeta\, C\cos\left(\Delta m_s t\right) - \zeta\, S\sin\left(\Delta m_s t\right)\right\}, \quad (3.1)$$

where $\Delta\Gamma_s$ and Δm_s are the width and mass differences between the B_s^0 mass eigenstates, defined positively, Γ_s is the mean decay width between such eigenstates, and ζ takes the value of $+1$ (-1) for an initial B_s^0 $(\bar{B}_s^0)$ state. The coefficients $\mathscr{A}^{\Delta}$ 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 $\phi\gamma$ decay are close to zero [3].

We report the first measurement of the CP-violating observables S and C from a radiative B_s^0 decay, determined from the time-dependent rate of $\phi\gamma$ decays in which the ϕ meson decays to a K^+K^- pair.

Candidate $\phi\gamma$ decays are reconstructed from two oppositely charged kaons and a photon. Photons required to have E_{T} greater than 3.0 or 4.2 GeV, depending on the trigger selection. Both kaon candidates are required to have $P > 1.0\,\mathrm{GeV}/c$ and $p_{\mathrm{T}} > 0.3\,\mathrm{GeV}/c$, and at least one of them $P > 10\,\mathrm{GeV}/c$ and $p_{\mathrm{T}} > 1.2$ or $1.8\,\mathrm{GeV}/c$, depending on the trigger selection. Kaon candidates are required to come from a common vertex inconsistent with originating from a PV. The K^+K^- invariant mass should be within $15\,\mathrm{MeV}/c^2$ of the nominal $\phi(1020)$ mass [8]. The B_s^0 candidate must be consistent with originating from only one PV, and have a decay time between 0.3 and 10 ps. The cosine of the helicity angle (θ_H), defined as the angle between the momenta of the positively charged kaon and that of the B_s^0 meson in the rest frame of the ϕ meson, is required to be $|cos(\theta_H)| < 0.8$.

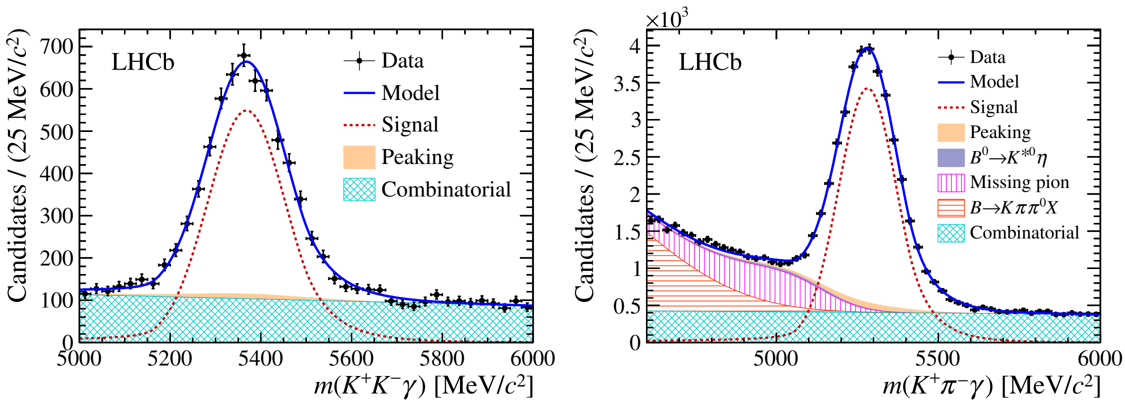

Figure 2: Fits to the mass distributions of the (left) $\phi\gamma$ and (right) $K^{*0}\gamma$ candidates.

The signal yields are obtained from separate extended unbinned maximum-likelihood fits to the $B_s^0 \to \phi\gamma$ and $B^0 \to K^{*0}\gamma$ reconstructed mass distributions shown in Fig. 2. They found to be 5110 ± 90 for $\phi\gamma$ decays and 33860 ± 250 for $K^{*0}\gamma$ decays, where the uncertainties are statistical only.

Flavor-tagging algorithms are applied to identify the initial flavor of the B_s^0 meson. They provide a tag decision q, which takes the value $+1$ if the signal was originally a B_s^0 meson, -1 if it was a $\bar{B}_s^0$ meson, and zero if no decision is given. The effective tagging efficiency, $\varepsilon_{\text{eff}} = (4.99 \pm 0.14)\%$, is the product of the probability to obtain a decision $\varepsilon_{\text{tag}} = (74.5 \pm 0.8)\%$ and the square of the effective dilution $D = 1 - 2\omega = (25.9 \pm 0.3)\%$.

The CP-violating and mixing-induced observables are determined from a weighted unbinned maximum-likelihood fit to the decay-time distributions, performed simultaneously on the $\phi\gamma$ and $K^{*0}\gamma$ samples. The signal PDF of the $\phi\gamma$ decay-time distribution is defined as the decay rate $\mathscr{P}(t)$ in Eq. 3.1, convolved with a resolution function and multiplied by a decay-time-dependent efficiency $\varepsilon(t)$. For the $B^0 \to K^{*0}\gamma$ decay, the time-dependent decay rate is described as a single exponential function. The physics parameters are constrained to the averages from Ref. [14].

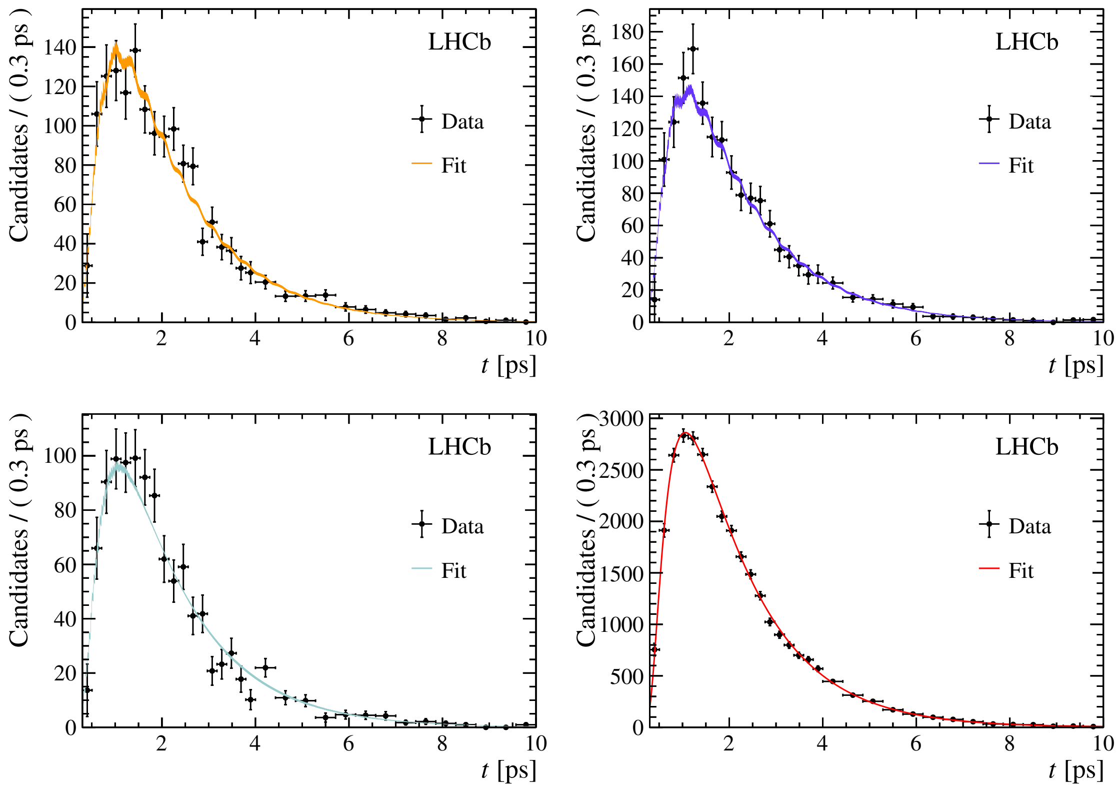

Figure 3: Decay-time fit projections. The top row corresponds to the tagged (left) $\phi\gamma$ and (right) $\bar{B}_s^0 \to \phi\gamma$ candidates, while the bottom plots show the (left) untagged $\phi\gamma$ and (right) $K^{*0}\gamma$ candidates. The line is the result of the fit described in the text, including statistical uncertainties.

The decay-time distributions and the corresponding fit projections are shown in Fig. 3. The fitted values are $S_{\phi\gamma} = 0.43 \pm 0.30$, $C_{\phi\gamma} = 0.11 \pm 0.29$ and $\mathscr{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41}$, with a small correlation of -0.04 between each pair of observables. The statistical uncertainty includes the uncertainty from the physics parameters taken from external measurements. The total systematic uncertainties are 0.11 for $S_{\phi\gamma}$ and $C_{\phi\gamma}$, and 0.17 for $\mathscr{A}^{\Delta}_{\phi\gamma}$. The results are compatible with the SM expectation [3] within 1.3, 0.3 and 1.7 standard deviations, respectively. This is the first measurement of the observables S and C in radiative B^0_s decays.

More details of the analysis can be found in [15].

4. Conclusion

A search for the b-baryon flavour-changing neutral-current radiative decay $\Lambda^0_b \to \Lambda^0\gamma$ is performed with a data sample corresponding to an integrated luminosity of $1.7\,\text{fb}^{-1}$ collected in pp collisions at a center-of-mass energy of 13 TeV with the LHCb detector. A signal of 65 ± 13 events is observed for a first time with a significance of 5.6σ. This is the first step towards the study of the photon polarization in radiative decays of b-baryons with a larger dataset. Exploiting the well-known $B^0 \to K^{*0}\gamma$ mode as a normalization channel, the branching fraction of the $\Lambda^0_b \to \Lambda^0\gamma$ decay is measured, $\mathscr{B}(\Lambda^0_b \to \Lambda^0\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$, where the first uncertainty is statistical, the second systematic and the third is the systematic from external measurements. Our result is in good agreement with the predictions from Refs. [10], [11] and [12], which make use of Light Cone Sum Rules, the Heavy Quark Limit and the covariant constituent quark model, respectively.

The *CP*-violating and mixing-induced observables $S_{\phi\gamma}$, $C_{\phi\gamma}$ and $\mathscr{A}^{\Delta}_{\phi\gamma}$ are measured from a time-dependent analysis of $B^0_s \to \phi\gamma$ decays, using a data sample corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$ collected with the LHCb experiment in pp collisions at a center-of-mass energies of 7 and 8 TeV. More than 5000 $B^0_s \to \phi\gamma$ decays are reconstructed. A sample of $B^0 \to K^{*0}\gamma$ decays, which is six times larger, is used for the calibration of the time-dependent efficiency. From a simultaneous unbinned fit to the $B^0_s \to \phi\gamma$ and $B^0 \to K^{*0}\gamma$ data samples, the values $S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11$, $C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11$, $\mathscr{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17$ are measured, where the first uncertainty is statistical and the second systematic. The results are compatible with the SM expectation [3] within 1.3, 0.3 and 1.7 standard deviations, respectively.

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