Letter

Measurement of the photon polarization in $\Lambda_b^0 \to \Lambda\gamma$ decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 23 November 2021; accepted 18 February 2022; published 23 March 2022)

The photon polarization in $b \to s\gamma$ transitions is measured for the first time in radiative b-baryon decays exploiting the unique spin structure of $\Lambda_b^0 \to \Lambda\gamma$ decays. A data sample corresponding to an integrated luminosity of 6 fb^{-1} collected by the LHCb experiment in pp collisions at a center-of-mass energy of 13 TeV is used. The photon polarization is measured to be $\alpha_\gamma = 0.82^{+0.17+0.04}_{-0.26-0.13}$, where the first uncertainty is statistical and the second systematic. This result is in agreement with the Standard Model prediction and previous measurements in b-meson decays. Charge-parity breaking effects are studied for the first time in this observable and found to be consistent with CP symmetry.

DOI: 10.1103/PhysRevD.105.L051104

Rare decays of hadrons containing b-quarks mediated by flavor-changing neutral currents (FCNC) are suppressed in the Standard Model (SM) since they occur only at higher order in the perturbative expansion. They are sensitive to physics beyond the SM (BSM) which can give additional contributions and alter the decay properties. Radiative decays of the type $b \to s\gamma$ are FCNC, mediated by electroweak-loop transitions which produce a final state photon. In the SM, due to the chirality of the electroweak interaction, the emitted photons are polarized. The photon polarization is defined as the normalized difference between the number of left-handed (γ_L) and right-handed (γ_R) photons produced in radiative decays,

$$\alpha_\gamma \equiv \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R}, \qquad (1)$$

with photons emitted in b decays being predominantly left handed. Right-handed contributions arise only due to chirality flips in the outgoing s-quark line of the Feynman diagram, which are suppressed by the ratio of the s and b quark masses. At leading order in the SM, the photon polarization is predicted to be $\alpha_\gamma = (1 - |r|^2)/(1 + |r|^2)$, with $|r| \approx m_s/m_b$ [1–3]. Effects arising at next-to-leading order are estimated to be at the percent level [2]. Therefore, a larger right-handed polarization, which would lower the value of α_γ, could be a clear indication of BSM physics [1,4].

The photon polarization in $b \to s\gamma$ transitions has been indirectly probed by the BaBar, Belle, and LHCb experiments through the measurement of mixing-induced charge-parity (CP) asymmetries in B^0 and B_s^0 decays [5–7] and through the angular analysis of $B^0 \to K^{*0}e^+e^-$ decays at very low dielectron mass [8], with the latter providing the strongest constraints on right-handed currents. Radiative decays of b baryons offer a unique opportunity for a direct measurement of the photon polarization due to the nonzero spin of the initial- and final-state particles [9]. The $\Lambda_b^0 \to \Lambda\gamma$ decay[1] is of special interest due to the weak decay of the Λ baryon, which probes the helicity structure of the $b \to s\gamma$ transition through the measurement of the Λ helicity [2,10]. The $\Lambda_b^0 \to \Lambda\gamma$ decay was first observed in data recorded by LHCb during 2016 [11]. The photon-polarization sensitivity using this decay was estimated in Ref. [12].

The angular distribution of $\Lambda_b^0 \to \Lambda\gamma$ decays, where the Λ baryon decays into a proton and a pion, is given by the differential width [3]

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}(\cos\theta_p)} \propto 1 - \alpha_\gamma \alpha_\Lambda \cos\theta_p, \qquad (2)$$

where α_Λ is the Λ weak-decay parameter, which describes the interference between the parity-violating s-wave and parity-conserving p-wave of the $\Lambda \to p\pi^-$ decay [13], and θ_p is the angle between the proton momentum and the negative Λ_b^0 momentum in the Λ rest frame. The photon direction is integrated over in this study since the distribution in this variable is flat for unpolarized Λ_b^0 baryons, as produced at the LHC [14,15].

[*]Full author list given at the end of the article.

[1]The inclusion of charge-conjugate processes is implied throughout, except in the discussion of asymmetries.

Contrary to b decays, photons produced in $\bar{b}$ decays are expected to be predominantly right handed in the SM, resulting in a photon polarization of $\alpha_\gamma = -1$. A discrepancy in the absolute value of the photon polarization in b and $\bar{b}$ decays would be a hint of CP asymmetry in these transitions. In the SM, CP asymmetries in $b \to s\gamma$ decays are estimated to be less than $\mathcal{O}(1\%)$ [2]. However, new CP-violating BSM contributions can produce asymmetries of $\mathcal{O}(10\%)$ [2]. Experimentally, the strongest constraint on direct CP violation in $b \to s\gamma$ transitions is from $B^0 \to K^{*0}\gamma$ decays [16]. Measurements of angular asymmetries and CP-conjugated decay branching ratios can separate the CP-odd and CP-even components of both the SM and opposite chirality contributions to the $\Lambda_b^0 \to \Lambda\gamma$ decay rate [2].

This paper reports the first measurement of the photon polarization in $\Lambda_b^0 \to \Lambda\gamma$ decays, with $\Lambda \to p\pi^-$, using 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. Additionally, the first study of CP angular asymmetries in $b \to s\gamma$ decays is performed.

The LHCb detector [17,18] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector elements that are relevant for this analysis are; a silicon-strip vertex detector surrounding the pp interaction region that allows c and b hadrons to be identified from their characteristically long flight distance, a tracking system that provides a measurement of the momentum of charged particles, two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons, a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter (ECAL) and a hadronic calorimeter that enables the reconstruction and identification of photons, electrons, and hadrons, and a muon system composed of alternating layers of iron and multiwire proportional chambers.

Charged and neutral clusters in the ECAL are separated by extrapolating reconstructed tracks to the ECAL; photons and neutral pions are distinguished by their cluster shape and energy distribution. For decays with high-energy photons in the final state, e.g., $\Lambda_b^0 \to \Lambda\gamma$, a mass resolution around 100 MeV is achieved[2] [19,20], dominated by the photon energy resolution. The online event selection is performed by a trigger [21], consisting of a hardware stage followed by a software stage which fully reconstructs the event. The hardware trigger requires events to have an ECAL cluster with an energy component transverse to the beam, E_T, above a threshold varying between 2.1 GeV–3.0 GeV. The software trigger first requires at least one charged particle to have transverse momentum $p_\mathrm{T} > 1$ GeV and to be inconsistent with originating from any primary pp collision vertex (PV). Subsequently, Λ candidates are formed from two tracks significantly displaced from any PV, and combined with a high-E_T photon to identify decays consistent with the signal mode. In the offline selection, trigger signals are associated with reconstructed particles and only events where the trigger was activated by the decay products of the signal candidate are kept.

Simulated events are used to model the effects of the detector geometry and the selection requirements. In the simulation, pp collisions are generated using PYTHIA [22] with a specific LHCb configuration [23]. Decays of unstable particles are described by EvtGen [24], in which final-state radiation is generated using PHOTOS [25]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [26] as described in Ref. [27]. The signal sample is generated with unpolarized Λ_b^0 decays and only a left-handed photon contribution. The simulation is validated using the $\Lambda_b^0 \to pK^-J/\psi$ and $\Lambda_b^0 \to \Lambda J/\psi$, with $J/\psi \to \mu^+\mu^-$, control modes in the data. The $\Lambda_b^0 \to pK^-J/\psi$ mode is selected according to Ref. [28], while the $\Lambda_b^0 \to \Lambda J/\psi$ mode is selected with the strategy described for the signal mode below. The Λ_b^0 momentum distribution of all simulated samples with Λ_b^0 decays is corrected to data in two-dimensional intervals of Λ_b^0 transverse momentum and pseudorapidity, $p_\mathrm{T}(\Lambda_b^0)$ and $\eta(\Lambda_b^0)$, using $\Lambda_b^0 \to pK^-J/\psi$ background-subtracted data and simulated candidates.

Offline signal candidates are reconstructed from the combination of a Λ baryon and a high-energy photon candidate. Opposite-charge good-quality track pairs, well separated from any PV, are combined to form Λ candidates, where one track is consistent with the proton hypothesis and the other with the pion hypothesis. Proton and pion candidates are required to have p_T larger than 800 MeV and 300 MeV, respectively. The Λ candidate must form a good-quality vertex that is well separated from the nearest PV and have a mass in the range 1110 MeV–1122 MeV. Only Λ candidates that decay in the central part of the vertex detector ($z < 270$ mm) and have a p_T larger than 1 GeV are retained for further study. Photons, reconstructed from clusters in the ECAL, must have $E_\mathrm{T} > 3$ GeV and be inconsistent with the extrapolation of reconstructed tracks to the ECAL. Since the Λ_b^0 decay vertex cannot be reconstructed in this mode, the photon is assumed to originate from the pp interaction region. The sum of the Λ p_T and the photon E_T must be larger than 5 GeV. The Λ_b^0 candidate must have a transverse momentum above 4 GeV and a mass within 900 MeV of the known Λ_b^0 mass [29]. The distance of closest approach between the Λ_b^0 and Λ trajectories is required to be small; the Λ_b^0 trajectory is assumed to originate from the PV closest to the Λ trajectory

[2]Natural units with $\hbar = c = 1$ are used throughout.

A boosted decision tree (BDT) [30], implementing the XGBoost algorithm [31], used within the Scikit-learn library [32], separates signal from combinatorial background, which is formed by combinations of a real Λ baryon with a random photon. The BDT classifier is trained on a signal sample of $\Lambda_b^0 \to \Lambda\gamma$ simulated events and a background sample from data candidates with a mass larger than 6.1 GeV. The same variables of Ref. [11], with the addition of the photon pseudorapidity, are used as input for the classifier. To maximize sensitivity to the photon polarization, the BDT threshold is selected to reject 99% of background and retain around 50% of signal candidates.

The mass distribution of the selected candidates is shown in Fig. 1. A fit to this mass distribution is used to determine the signal and background yields. The $\Lambda_b^0 \to \Lambda\gamma$ signal component is modeled with a Crystal Ball [33] probability density function (PDF), with power-law tails above and below the Λ_b^0 mass. The tail parameters and the width of the signal peak are fixed to values determined from simulation while the mean is allowed to vary freely in the fit to data. A comprehensive set of background contributions is investigated but only two are found to be significant [11]. The dominant contribution is from combinatorial background which is modeled by an exponential PDF with a freely varying slope. A small contamination from $\Lambda_b^0 \to \Lambda\eta$ decays with $\eta \to \gamma\gamma$, where one of the photons is not reconstructed, is also expected and is described with the shape determined from simulation. The signal and combinatorial background yields vary freely in the fit to data, while the yield of $\Lambda_b^0 \to \Lambda\eta$ is constrained to its expected value, obtained from its measured branching fraction [29] and reconstruction and selection efficiencies determined from simulation.

The signal and background yields are obtained from an extended unbinned maximum likelihood fit to data, as shown in Fig. 1 (left). In the signal region, [5387.1, 5852.1] MeV, the signal yield is 440 ± 40, with 1460 ± 23 and 10 ± 4 combinatorial and $\Lambda_b^0 \to \Lambda\eta$ decays, respectively.

The photon polarization is measured with an unbinned maximum likelihood fit to the $\cos\theta_p$ distribution for events in the signal region, as shown in Fig. 1 (right). The signal is described by the PDF in Eq. (2) multiplied by an acceptance function, which accounts for the effect of the detector geometry, reconstruction and selection requirements. The photon polarization parameter, α_γ, is allowed to vary freely in the fit to data, whereas the physical boundary $[-1, 1]$ on this parameter is imposed later using the Feldman-Cousins technique [34]. The Λ weak decay parameter, α_Λ, is fixed to the average of the values measured by BESIII in Λ and $\bar{\Lambda}$ decays, $\alpha_\Lambda = 0.754 \pm 0.004$ [35]. The shape of the acceptance in $\cos\theta_p$ is determined from simulation and is parametrized as a fourth-order polynomial. It is dominated by the impact parameter and transverse momentum requirements on the proton and the pion. The correct description of the acceptance in simulation is validated using $\Lambda_b^0 \to \Lambda J/\psi$ decays, which are reconstructed without using information from the J/ψ vertex. This decay mode, with higher yield and purity than that of the signal mode, has the same final-state hadrons. The combinatorial and $\Lambda_b^0 \to \Lambda\eta$ components are described together by a fourth-order polynomial, with the coefficients determined from a fit to the candidates in the Λ_b^0 mass control region $[4719.6, 5382.1]$ MeV $\cup$ $[5857.1, 6519.6]$ MeV. The values of these coefficients are found to be consistent for candidates below and above the signal region. The ratio between signal and background decays is constrained by the yields obtained from the mass fit. The fit stability is validated with pseudoexperiments and the results were only examined after all analysis procedures had been finalized in order to avoid experimenter's bias. The result of the fit to data candidates is $\alpha_\gamma = 0.82 \pm 0.23$, where the uncertainty is obtained from the Hessian matrix.

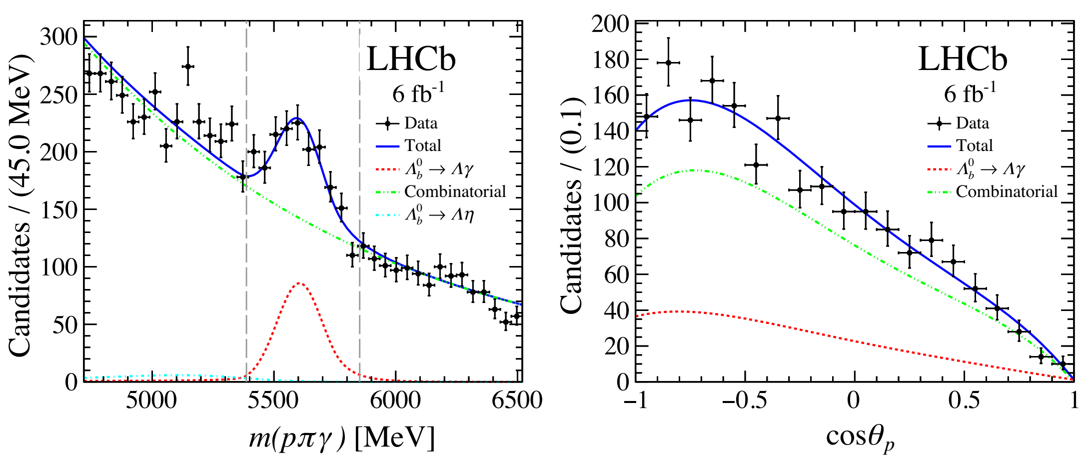

FIG. 1. Distribution of (left) mass, $m(p\pi\gamma)$, and (right) $\cos\theta_p$ for $\Lambda_b^0 \to \Lambda\gamma$ candidates. The latter shows the subset of candidates in the signal region $m(p\pi\gamma) \in [5387.1, 5852.1]$ MeV, delimited by dashed vertical lines in the former. The results of the fits are overlaid as well as the individual contributions.

The data are separated into $\Lambda_b^0 \to \Lambda\gamma$ and $\bar{\Lambda}_b^0 \to \bar{\Lambda}\gamma$ by the charge of the final-state pion and potential *CP* breaking effects on the photon polarization are studied. The photon polarization values in $\Lambda_b^0 \to \Lambda\gamma$ and $\bar{\Lambda}_b^0 \to \bar{\Lambda}\gamma$ decays, denoted as α_γ^- and α_γ^+, are expected to have the same absolute value with opposite sign in the absence of *CP* violation. Both values are measured independently for Λ_b^0 and $\bar{\Lambda}_b^0$ decays following the same strategy as described for the combined sample. The shape of the mass distribution for Λ_b^0 and $\bar{\Lambda}_b^0$ decays is studied in simulation and is compatible, for both signal and $\Lambda_b^0 \to \Lambda\eta$ decays, therefore the shape from the combined sample is used in the fit of the two data sets. In the signal region, 233 ± 32 $\Lambda_b^0 \to \Lambda\gamma$ and 210 ± 30 $\bar{\Lambda}_b^0 \to \bar{\Lambda}\gamma$ decays are found. These yields are affected by production and detection asymmetries [36] and cannot be directly interpreted as a measurement of *CP*-violation effects. The Λ and $\bar{\Lambda}$ weak-decay parameters measured by BESIII [35], $\alpha_\Lambda^- = 0.750 \pm 0.009 \pm 0.004$ and $\alpha_\Lambda^+ = -0.758 \pm 0.010 \pm 0.007$, are used in the angular fit for $\Lambda_b^0 \to \Lambda\gamma$ and $\bar{\Lambda}_b^0 \to \bar{\Lambda}\gamma$, respectively. Due to the limited sample size, the acceptance and background shapes are taken from the combined sample. The fit to data candidates yields $\alpha_\gamma^- = 1.26 \pm 0.42$ and $\alpha_\gamma^+ = -0.55 \pm 0.32$, where the uncertainty is statistical only. The results of the angular fits are shown in Fig. 2. The measured value of α_γ^- is found to be affected by a 5% bias and a 13% over-coverage driven by boundary effects in this observable.

Systematic uncertainties associated with the determination of the signal and background yields in the mass fit, the modeling of the background shape and signal acceptance and the finite precision on the external parameter α_Λ are evaluated. These uncertainties are determined by fitting pseudosamples, generated by an alternative model, with the default model. The limited data size from the mass control region used to determine the background angular shape dominates this uncertainty and is evaluated by varying the background shape parameters. The systematic uncertainty of the background parameterization is evaluated using a third- and fifth-degree polynomial. The acceptance uncertainty is evaluated by considering the limited size of the simulation, using alternative fifth- and third-degree parametrizations, and removing the Λ_b^0 kinematic corrections. The mass-fit uncertainty is determined with pseudoexperiments using an alternative model with a variable signal width. Finally, the limited precision of the Λ decay parameter introduces a small systematic uncertainty. The photon polarization, with all systematic uncertainties included, is $\alpha_\gamma = 0.82 \pm 0.23 \pm 0.13$.

For the *CP* asymmetry measurement, the uncertainties described above are 100% correlated and sum to 0.13 and 0.11 for α_γ^- and α_γ^+, respectively. Additional uncertainties arise from potential differences in the background shape and signal acceptance between Λ_b^0 and $\bar{\Lambda}_b^0$ decays. Fits are performed with the default combined model to pseudosamples generated with alternative models obtained independently for Λ_b^0 and $\bar{\Lambda}_b^0$ candidates, to estimate this effect. These uncertainties are uncorrelated and are 0.15 and 0.12 for α_γ^- and α_γ^+, respectively, resulting in $\alpha_\gamma^- = 1.26 \pm 0.42 \pm 0.20$ and $\alpha_\gamma^+ = -0.55 \pm 0.32 \pm 0.16$.

Confidence intervals on the photon polarization are set within the physical limits of $[-1, 1]$, see Eq. (1), using the Feldman-Cousins technique, the fit result, and the relation between the true and measured values obtained from pseudoexperiments, including both statistical and systematic uncertainties. The photon polarization in $\Lambda_b^0 \to \Lambda\gamma$ decays is found to be

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

which is compatible with the SM prediction. This result excludes two regions allowed by previous measurements for the Wilson coefficients of the effective Hamiltonian of the $b \to s\gamma$ transition (see the Supplemental material to this paper [37] for details).

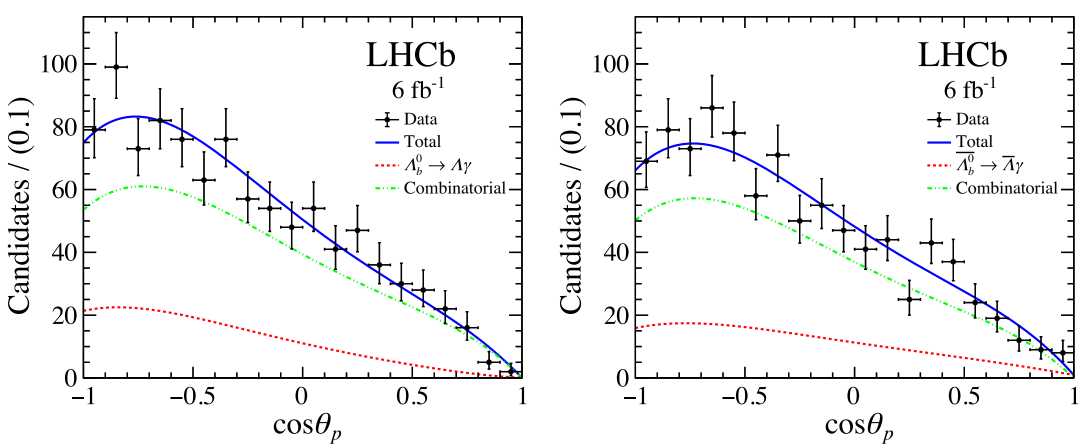

FIG. 2. Distribution of $\cos\theta_p$ for selected (left) $\Lambda_b^0 \to \Lambda\gamma$ and (right) $\bar{\Lambda}_b^0 \to \bar{\Lambda}\gamma$ candidates as well as the individual contributions.

The Feldman-Cousins technique is also applied to the photon polarization measurements in $\Lambda_b^0 \to \Lambda\gamma$ and $\bar{\Lambda}_b^0 \to \bar{\Lambda}\gamma$ decays, which are found to be

$$\alpha_\gamma^- > 0.56\,(0.44)\ \text{at}\ 90\%\,(95\%)\ \text{C.L.},$$
$$\alpha_\gamma^+ = -0.56^{+0.36}_{-0.33}\,(\text{stat.})^{+0.16}_{-0.09}\,(\text{syst.}),$$

consistent with CP symmetry.

To summarize, the photon polarization in $b \to s\gamma$ transitions has been measured for the first time in b-baryon decays exploiting the decay chain $\Lambda_b^0 \to \Lambda\gamma$, $\Lambda \to p\pi^-$, which enables the determination of this observable from the angular distribution of the Λ decay products. The α_γ result is compatible with the SM prediction at the level of one standard deviation and provides new constraints that are compatible with previous measurements of the photon polarization in b-meson decays [7,8]. Additionally, CP -breaking effects on this observable are studied for the first time and the results are compatible with CP-symmetry. These results can be used to place constraints on the real and imaginary contributions of right-handed currents in BSM models. The precision of the results is dominated by the statistical uncertainty; furthermore, the dominant systematic uncertainty, due to the angular shape of the background, can be reduced with more data. Consequently, future data that will be collected by the LHCb experiment during the next decade will enable significant improvements of these results.

ACKNOWLEDGMENTS

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb Institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ, and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MSHE (Russia); MICINN (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and NERSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from ARC and ARDC (Australia); AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union); A*MIDEX, ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central Universities, and the Science and Technology Program of Guangzhou (China); RFBR, RSF, and Yandex LLC (Russia); GVA, XuntaGal and GENCAT (Spain); the Leverhulme Trust, the Royal Society and UKRI (United Kingdom).

[1] D. Atwood, M. Gronau, and A. Soni, Mixing Induced CP Asymmetries in Radiative B Decays in and Beyond the Standard Model, Phys. Rev. Lett. **79**, 185 (1997).

[2] G. Hiller and A. Kagan, Probing for new physics in polarized Λ_b decays at the Z pole, Phys. Rev. D **65**, 074038 (2002).

[3] F. Legger and T. Schietinger, Photon helicity in $\Lambda_b \to pK\gamma$ decays, Phys. Lett. B **645**, 204 (2007); Erratum, Phys. Lett. B **647**, 527 (2007).

[4] E. Kou, C.-D. Lü, and F.-S. Yu, Photon polarization in the $b \to s\gamma$ processes in the left-right symmetric model, J. High Energy Phys. 12 (2013) 102.

[5] B. Aubert *et al.* (*BABAR* Collaboration), Measurement of time-dependent CP asymmetry in $B^0 \to K_S^0\pi^0\gamma$ decays, Phys. Rev. D **78**, 071102 (2008).

[6] Y. Ushiroda *et al.* (Belle Collaboration), Time-Dependent CP Asymmetries in $B^0 \to K_S^0\pi^0\gamma$ transitions, Phys. Rev. D **74**, 111104 (2006).

[7] R. Aaij *et al.* (LHCb Collaboration), Measurement of CP -Violating and Mixing-Induced Observables in $B_s^0 \to \phi\gamma$ Decays, Phys. Rev. Lett. **123**, 081802 (2019).

[8] R. Aaij *et al.* (LHCb Collaboration), Strong constraints on the $b \to s\gamma$ photon polarisation from $B^0 \to K^{*0}e^+e^-$ decays, J. High Energy Phys. 12 (2020) 081.

[9] M. Gremm, F. Krüger, and L. M. Sehgal, Angular distribution and polarization of photons in the inclusive decay $\Lambda_b^0 \to X_s\gamma$, Phys. Lett. B **355**, 579 (1995).

[10] T. Mannel and S. Recksiegel, Flavor changing neutral current decays of heavy baryons: The Case $\Lambda_b^0 \to \Lambda\gamma$, J. Phys. G **24**, 979 (1998).

[11] R. Aaij *et al.* (LHCb Collaboration), First Observation of the Radiative Decay $\Lambda_b^0 \to \Lambda\gamma$, Phys. Rev. Lett. **123**, 031801 (2019).

[12] L. M. García Martín, B. Jashal, F. Martínez Vidal, A. Oyanguren, S. Roy, R. Sain, and R. Sinha, Radiative

b -baryon decays to measure the photon and b-baryon polarization, Eur. Phys. J. C **79**, 634 (2019).

[13] T. D. Lee and C.-N. Yang, General partial wave analysis of the decay of a hyperon of spin $1/2$, Phys. Rev. **108**, 1645 (1957).

[14] A. M. Sirunyan *et al.* (CMS Collaboration), Measurement of the Λ_b polarization and angular parameters in $\Lambda_b \to J/\psi\Lambda$ decays from pp collisions at $\sqrt{s} = 7$ and 8 TeV, Phys. Rev. D **97**, 072010 (2018).

[15] R. Aaij *et al.* (LHCb Collaboration), Measurement of the $\Lambda_b^0 \to J/\psi\Lambda$ angular distribution and the Λ_b^0 polarisation in pp collisions, J. High Energy Phys. 06 (2020) 110.

[16] R. Aaij *et al.* (LHCb Collaboration), Measurement of the ratio of branching fractions $\mathcal{B}(B^0 \to K^{*0}\gamma)/\mathcal{B}(B_s^0 \to \phi\gamma)$ and the direct CP asymmetry in $B^0 \to K^{*0}\gamma$, Nucl. Phys. **B867**, 1 (2013).

[17] A. A. Alves Jr. *et al.* (LHCb Collaboration), The LHCb detector at the LHC, J. Instrum. **3**, S08005 (2008).

[18] R. Aaij *et al.* (LHCb Collaboration), LHCb detector performance, Int. J. Mod. Phys. A **30**, 1530022 (2015).

[19] R. Aaij *et al.* (LHCb Collaboration), First Experimental Study of Photon Polarization in Radiative B_s^0 Decays, Phys. Rev. Lett. **118**, 021801 (2017).

[20] R. Aaij *et al.* (LHCb Collaboration), Measurement of the ratio of branching fractions $\mathcal{B}(B^0 \to K^{*0}\gamma)/\mathcal{B}(B_s^0 \to \phi\gamma)$, Phys. Rev. D **85**, 112013 (2012).

[21] R. Aaij *et al.*, The LHCb trigger and its performance in 2011, J. Instrum. **8**, P04022 (2013).

[22] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. **178**, 852 (2008); PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026.

[23] I. Belyaev *et al.*, Handling of the generation of primary events in Gauss, the LHCb simulation framework, J. Phys. Conf. Ser. **331**, 032047 (2011).

[24] D. J. Lange, The EvtGen particle decay simulation package, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).

[25] N. Davidson, T. Przedzinski, and Z. Was, PHOTOS interface in C++: Technical and physics documentation, Comput. Phys. Commun. **199**, 86 (2016).

[26] J. Allison *et al.* (Geant4 Collaboration), GEANT4 developments and applications, IEEE Trans. Nucl. Sci. **53**, 270 (2006); S. Agostinelli *et al.* (Geant4 Collaboration), GEANT4: A simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).

[27] M. Clemencic, G. Corti, S. Easo, C. R. Jones, S. Miglioranzi, M. Pappagallo, and P. Robbe, The LHCb simulation application, Gauss: Design, evolution and experience, J. Phys. Conf. Ser. **331**, 032023 (2011).

[28] R. Aaij *et al.* (LHCb Collaboration), Observation of the suppressed decay $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$, J. High Energy Phys. 04 (2017) 029.

[29] P. A. Zyla *et al.* (Particle Data Group), Review of particle physics, Prog. Theor. Exp. Phys. **2020**, 083C01 (2020).

[30] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification and Regression Trees* (Wadsworth international group, Belmont, California, USA, 1984).

[31] T. Chen and C. Guestrin, XGBOOST: A scalable tree boosting system, in *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, KDD '16*, 2016 (ACM, New York, NY, USA, 2016), pp. 785–794.

[32] F. Pedregosa *et al.*, Scikit-learn: Machine learning in PYTHON, J. Mach. Learn. Res. **12**, 2825 (2011), and online at http://scikit-learn.org/stable/.

[33] T. Skwarnicki, A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances, Ph.D. thesis, Institute of Nuclear Physics, Krakow, 1986 [Report No. DESY-F31-86-02].

[34] G. J. Feldman and R. D. Cousins, Unified approach to the classical statistical analysis of small signals, Phys. Rev. D **57**, 3873 (1998).

[35] M. Ablikim *et al.* (BESIII Collaboration), Polarization and entanglement in Baryon-Antibaryon pair production in electron-positron annihilation, Nat. Phys. **15**, 631 (2019).

[36] R. Aaij *et al.* (LHCb Collaboration), Observation of a $\Lambda_b^0 - \bar{\Lambda}_b^0$ production asymmetry in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV, J. High Energy Phys. 10 (2021) 060.

[37] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevD.105.L051104 for further details.

R. Aaij,[32] A. S. W. Abdelmotteleb,[56] C. Abellán Beteta,[50] F. Abudinén,[56] T. Ackernley,[60] B. Adeva,[46] M. Adinolfi,[54] H. Afsharnia,[9] C. Agapopoulou,[13] C. A. Aidala,[87] S. Aiola,[25] Z. Ajaltouni,[9] S. Akar,[65] J. Albrecht,[15] F. Alessio,[48] M. Alexander,[59] A. Alfonso Albero,[45] Z. Aliouche,[62] G. Alkhazov,[38] P. Alvarez Cartelle,[55] S. Amato,[2] J. L. Amey,[54] Y. Amhis,[11] L. An,[48] L. Anderlini,[22] A. Andreianov,[38] M. Andreotti,[21] F. Archilli,[17] A. Artamonov,[44] M. Artuso,[68] K. Arzymatov,[42] E. Aslanides,[10] M. Atzeni,[50] B. Audurier,[12] S. Bachmann,[17] M. Bachmayer,[49] J. J. Back,[56] P. Baladron Rodriguez,[46] V. Balagura,[12] W. Baldini,[21] J. Baptista Leite,[1] M. Barbetti,[22] R. J. Barlow,[62] S. Barsuk,[11] W. Barter,[61] M. Bartolini,[24,b] F. Baryshnikov,[83] J. M. Basels,[14] S. Bashir,[34] G. Bassi,[29] B. Batsukh,[68] A. Battig,[15] A. Bay,[49] A. Beck,[56] M. Becker,[15] F. Bedeschi,[29] I. Bediaga,[1] A. Beiter,[68] V. Belavin,[42] S. Belin,[27] V. Bellee,[50] K. Belous,[44] I. Belov,[40] I. Belyaev,[41] G. Bencivenni,[23] E. Ben-Haim,[13] A. Berezhnoy,[40] R. Bernet,[50] D. Berninghoff,[17] H. C. Bernstein,[68] C. Bertella,[62] A. Bertolin,[28] C. Betancourt,[50] F. Betti,[48] Ia. Bezshyiko,[50] S. Bhasin,[54] J. Bhom,[35] L. Bian,[73] M. S. Bieker,[15] S. Bifani,[53] P. Billoir,[13] M. Birch,[61] F. C. R. Bishop,[55] A. Bitadze,[62] A. Bizzeti,[22,c] M. Bjørn,[63] M. P. Blago,[48] T. Blake,[56] F. Blanc,[49] S. Blusk,[68] D. Bobulska,[59] J. A. Boelhauve,[15] O. Boente Garcia,[46] T. Boettcher,[65] A. Boldyrev,[82] A. Bondar,[43]

N. Bondar,[38,48] S. Borghi,[62] M. Borisyak,[42] M. Borsato,[17] J. T. Borsuk,[35] S. A. Bouchiba,[49] T. J. V. Bowcock,[60] A. Boyer,[48] C. Bozzi,[21] M. J. Bradley,[61] S. Braun,[66] A. Brea Rodriguez,[46] J. Brodzicka,[35] A. Brossa Gonzalo,[56] D. Brundu,[27] A. Buonaura,[50] L. Buonincontri,[28] A. T. Burke,[62] C. Burr,[48] A. Bursche,[72] A. Butkevich,[39] J. S. Butter,[32] J. Buytaert,[48] W. Byczynski,[48] S. Cadeddu,[27] H. Cai,[73] R. Calabrese,[21,d] L. Calefice,[15,13] L. Calero Diaz,[23] S. Cali,[23] R. Calladine,[53] M. Calvi,[26,e] M. Calvo Gomez,[85] P. Camargo Magalhaes,[54] P. Campana,[23] A. F. Campoverde Quezada,[6] S. Capelli,[26,e] L. Capriotti,[20,f] A. Carbone,[20,f] G. Carboni,[31] R. Cardinale,[24,b] A. Cardini,[27] I. Carli,[4] P. Carniti,[26,e] L. Carus,[14] K. Carvalho Akiba,[32] A. Casais Vidal,[46] G. Casse,[60] M. Cattaneo,[48] G. Cavallero,[48] S. Celani,[49] J. Cerasoli,[10] D. Cervenkov,[63] A. J. Chadwick,[60] M. G. Chapman,[54] M. Charles,[13] Ph. Charpentier,[48] G. Chatzikonstantinidis,[53] C. A. Chavez Barajas,[60] M. Chefdeville,[8] C. Chen,[3] S. Chen,[4] A. Chernov,[35] V. Chobanova,[46] S. Cholak,[49] M. Chrzaszcz,[35] A. Chubykin,[38] V. Chulikov,[38] P. Ciambrone,[23] M. F. Cicala,[56] X. Cid Vidal,[46] G. Ciezarek,[48] P. E. L. Clarke,[58] M. Clemencic,[48] H. V. Cliff,[55] J. Closier,[48] J. L. Cobbledick,[62] V. Coco,[48] J. A. B. Coelho,[11] J. Cogan,[10] E. Cogneras,[9] L. Cojocariu,[37] P. Collins,[48] T. Colombo,[48] L. Congedo,[19,g] A. Contu,[27] N. Cooke,[53] G. Coombs,[59] I. Corredoira,[46] G. Corti,[48] C. M. Costa Sobral,[56] B. Couturier,[48] D. C. Craik,[64] J. Crkovská,[67] M. Cruz Torres,[1] R. Currie,[58] C. L. Da Silva,[67] S. Dadabaev,[83] L. Dai,[71] E. Dall'Occo,[15] J. Dalseno,[46] C. D'Ambrosio,[48] A. Danilina,[41] P. d'Argent,[48] J. E. Davies,[62] A. Davis,[62] O. De Aguiar Francisco,[62] K. De Bruyn,[79] S. De Capua,[62] M. De Cian,[49] J. M. De Miranda,[1] L. De Paula,[2] M. De Serio,[19,g] D. De Simone,[50] P. De Simone,[23] F. De Vellis,[15] J. A. de Vries,[80] C. T. Dean,[67] F. Debernardis,[19,g] D. Decamp,[8] V. Dedu,[10] L. Del Buono,[13] B. Delaney,[55] H.-P. Dembinski,[15] A. Dendek,[34] V. Denysenko,[50] D. Derkach,[82] O. Deschamps,[9] F. Desse,[11] F. Dettori,[27,h] B. Dey,[77] A. Di Cicco,[23] P. Di Nezza,[23] S. Didenko,[83] L. Dieste Maronas,[46] H. Dijkstra,[48] V. Dobishuk,[52] C. Dong,[3] A. M. Donohoe,[18] F. Dordei,[27] A. C. dos Reis,[1] L. Douglas,[59] A. Dovbnya,[51] A. G. Downes,[8] M. W. Dudek,[35] L. Dufour,[48] V. Duk,[78] P. Durante,[48] J. M. Durham,[67] D. Dutta,[62] A. Dziurda,[35] A. Dzyuba,[38] S. Easo,[57] U. Egede,[69] V. Egorychev,[41] S. Eidelman,[43,a,i] S. Eisenhardt,[58] S. Ek-In,[49] L. Eklund,[59,86] S. Ely,[68] A. Ene,[37] E. Epple,[67] S. Escher,[14] J. Eschle,[50] S. Esen,[13] T. Evans,[48] A. Falabella,[20] J. Fan,[3] Y. Fan,[6] B. Fang,[73] S. Farry,[60] D. Fazzini,[26,e] M. Féo,[48] A. Fernandez Prieto,[46] A. D. Fernez,[66] F. Ferrari,[20,f] L. Ferreira Lopes,[49] F. Ferreira Rodrigues,[2] S. Ferreres Sole,[32] M. Ferrillo,[50] M. Ferro-Luzzi,[48] S. Filippov,[39] R. A. Fini,[19] M. Fiorini,[21,d] M. Firlej,[34] K. M. Fischer,[63] D. S. Fitzgerald,[87] C. Fitzpatrick,[62] T. Fiutowski,[34] A. Fkiaras,[48] F. Fleuret,[12] M. Fontana,[13] F. Fontanelli,[24,b] R. Forty,[48] D. Foulds-Holt,[55] V. Franco Lima,[60] M. Franco Sevilla,[66] M. Frank,[48] E. Franzoso,[21] G. Frau,[17] C. Frei,[48] D. A. Friday,[59] J. Fu,[6] Q. Fuehring,[15] E. Gabriel,[32] G. Galati,[19,g] A. Gallas Torreira,[46] D. Galli,[20,f] S. Gambetta,[58,48] Y. Gan,[3] M. Gandelman,[2] P. Gandini,[25] Y. Gao,[5] M. Garau,[27] L. M. Garcia Martin,[56] P. Garcia Moreno,[45] J. García Pardiñas,[26,e] B. Garcia Plana,[46] F. A. Garcia Rosales,[12] L. Garrido,[45] C. Gaspar,[48] R. E. Geertsema,[32] D. Gerick,[17] L. L. Gerken,[15] E. Gersabeck,[62] M. Gersabeck,[62] T. Gershon,[56] D. Gerstel,[10] L. Giambastiani,[28] V. Gibson,[55] H. K. Giemza,[36] A. L. Gilman,[63] M. Giovannetti,[23,j] A. Gioventù,[46] P. Gironella Gironell,[45] L. Giubega,[37] C. Giugliano,[21,48,d] K. Gizdov,[58] E. L. Gkougkousis,[48] V. V. Gligorov,[13] C. Göbel,[70] E. Golobardes,[85] D. Golubkov,[41] A. Golutvin,[61,83] A. Gomes,[1,k] S. Gomez Fernandez,[45] F. Goncalves Abrantes,[63] M. Goncerz,[35] G. Gong,[3] P. Gorbounov,[41] I. V. Gorelov,[40] C. Gotti,[26] E. Govorkova,[48] J. P. Grabowski,[17] T. Grammatico,[13] L. A. Granado Cardoso,[48] E. Graugés,[45] E. Graverini,[49] G. Graziani,[22] A. Grecu,[37] L. M. Greeven,[32] N. A. Grieser,[4] L. Grillo,[62] S. Gromov,[83] B. R. Gruberg Cazon,[63] C. Gu,[3] M. Guarise,[21] M. Guittiere,[11] P. A. Günther,[17] E. Gushchin,[39] A. Guth,[14] Y. Guz,[44] T. Gys,[48] T. Hadavizadeh,[69] G. Haefeli,[49] C. Haen,[48] J. Haimberger,[48] T. Halewood-leagas,[60] P. M. Hamilton,[66] J. P. Hammerich,[60] Q. Han,[7] X. Han,[17] T. H. Hancock,[63] E. B. Hansen,[62] S. Hansmann-Menzemer,[17] N. Harnew,[63] T. Harrison,[60] C. Hasse,[48] M. Hatch,[48] J. He,[6,l] M. Hecker,[61] K. Heijhoff,[32] K. Heinicke,[15] A. M. Hennequin,[48] K. Hennessy,[60] L. Henry,[48] J. Heuel,[14] A. Hicheur,[2] D. Hill,[49] M. Hilton,[62] S. E. Hollitt,[15] R. Hou,[7] Y. Hou,[8] J. Hu,[17] J. Hu,[72] W. Hu,[7] X. Hu,[3] W. Huang,[6] X. Huang,[73] W. Hulsbergen,[32] R. J. Hunter,[56] M. Hushchyn,[82] D. Hutchcroft,[60] D. Hynds,[32] P. Ibis,[15] M. Idzik,[34] D. Ilin,[38] P. Ilten,[65] A. Inglessi,[38] A. Ishteev,[83] K. Ivshin,[38] R. Jacobsson,[48] H. Jage,[14] S. Jakobsen,[48] E. Jans,[32] B. K. Jashal,[47] A. Jawahery,[66] V. Jevtic,[15] F. Jiang,[3] M. John,[63] D. Johnson,[48] C. R. Jones,[55] T. P. Jones,[56] B. Jost,[48] N. Jurik,[48] S. H. Kalavan Kadavath,[34] S. Kandybei,[51] Y. Kang,[3] M. Karacson,[48] M. Karpov,[82] F. Keizer,[48] D. M. Keller,[68] M. Kenzie,[56] T. Ketel,[33] B. Khanji,[15] A. Kharisova,[84] S. Kholodenko,[44] T. Kirn,[14] V. S. Kirsebom,[49] O. Kitouni,[64] S. Klaver,[32] N. Kleijne,[29] K. Klimaszewski,[36] M. R. Kmiec,[36] S. Koliiev,[52] A. Kondybayeva,[83] A. Konoplyannikov,[41] P. Kopciewicz,[34] R. Kopecna,[17] P. Koppenburg,[32] M. Korolev,[40] I. Kostiuk,[32,52] O. Kot,[52] S. Kotriakhova,[21,38] P. Kravchenko,[38] L. Kravchuk,[39] R. D. Krawczyk,[48] M. Kreps,[56] F. Kress,[61] S. Kretzschmar,[14] P. Krokovny,[43,i] W. Krupa,[34] W. Krzemien,[36] M. Kucharczyk,[35] V. Kudryavtsev,[43,i] H. S. Kuindersma,[32,33] G. J. Kunde,[67] T. Kvaratskheliya,[41] D. Lacarrere,[48] G. Lafferty,[62] A. Lai,[27] A. Lampis,[27] D. Lancierini,[50] J. J. Lane,[62]

R. Lane,[54] G. Lanfranchi,[23] C. Langenbruch,[14] J. Langer,[15] O. Lantwin,[83] T. Latham,[56] F. Lazzari,[29,m] R. Le Gac,[10] S. H. Lee,[87] R. Lefèvre,[9] A. Leflat,[40] S. Legotin,[83] O. Leroy,[10] T. Lesiak,[35] B. Leverington,[17] H. Li,[72] P. Li,[17] S. Li,[7] Y. Li,[4] Y. Li,[4] Z. Li,[68] X. Liang,[68] T. Lin,[61] R. Lindner,[48] V. Lisovskyi,[15] R. Litvinov,[27] G. Liu,[72] H. Liu,[6] Q. Liu,[6] S. Liu,[4] A. Lobo Salvia,[45] A. Loi,[27] J. Lomba Castro,[46] I. Longstaff,[59] J. H. Lopes,[2] S. López Soliño,[46] G. H. Lovell,[55] Y. Lu,[4] C. Lucarelli,[22] D. Lucchesi,[28,n] S. Luchuk,[39] M. Lucio Martinez,[32] V. Lukashenko,[32,52] Y. Luo,[3] A. Lupato,[62] E. Luppi,[21,d] O. Lupton,[56] A. Lusiani,[29,o] X. Lyu,[6] L. Ma,[4] R. Ma,[6] S. Maccolini,[20,f] F. Machefert,[11] F. Maciuc,[37] V. Macko,[49] P. Mackowiak,[15] S. Maddrell-Mander,[54] O. Madejczyk,[34] L. R. Madhan Mohan,[54] O. Maev,[38] A. Maevskiy,[82] D. Maisuzenko,[38] M. W. Majewski,[34] J. J. Malczewski,[35] S. Malde,[63] B. Malecki,[48] A. Malinin,[81] T. Maltsev,[43,i] H. Malygina,[17] G. Manca,[27,h] G. Mancinelli,[10] D. Manuzzi,[20,f] D. Marangotto,[25,p] J. Maratas,[9,q] J. F. Marchand,[8] U. Marconi,[20] S. Mariani,[22,r] C. Marin Benito,[48] M. Marinangeli,[49] J. Marks,[17] A. M. Marshall,[54] P. J. Marshall,[60] G. Martelli,[78] G. Martellotti,[30] L. Martinazzoli,[48,e] M. Martinelli,[26,e] D. Martinez Santos,[46] F. Martinez Vidal,[47] A. Massafferri,[1] M. Materok,[14] R. Matev,[48] A. Mathad,[50] V. Matiunin,[41] C. Matteuzzi,[26] K. R. Mattioli,[87] A. Mauri,[32] E. Maurice,[12] J. Mauricio,[45] M. Mazurek,[48] M. McCann,[61] L. Mcconnell,[18] T. H. Mcgrath,[62] N. T. Mchugh,[59] A. McNab,[62] R. McNulty,[18] J. V. Mead,[60] B. Meadows,[65] G. Meier,[15] N. Meinert,[76] D. Melnychuk,[36] S. Meloni,[26,e] M. Merk,[32,80] A. Merli,[25,p] L. Meyer Garcia,[2] M. Mikhasenko,[48] D. A. Milanes,[74] E. Millard,[56] M. Milovanovic,[48] M.-N. Minard,[8] A. Minotti,[26,e] L. Minzoni,[21,d] S. E. Mitchell,[58] B. Mitreska,[62] D. S. Mitzel,[15] A. Mödden,[15] R. A. Mohammed,[63] R. D. Moise,[61] S. Mokhnenko,[82] T. Mombächer,[46] I. A. Monroy,[74] S. Monteil,[9] M. Morandin,[28] G. Morello,[23] M. J. Morello,[29,o] J. Moron,[34] A. B. Morris,[75] A. G. Morris,[56] R. Mountain,[68] H. Mu,[3] F. Muheim,[58,48] M. Mulder,[48] D. Müller,[48] K. Müller,[50] C. H. Murphy,[63] D. Murray,[62] P. Muzzetto,[27,48] P. Naik,[54] T. Nakada,[49] R. Nandakumar,[57] T. Nanut,[49] I. Nasteva,[2] M. Needham,[58] I. Neri,[21] N. Neri,[25,p] S. Neubert,[75] N. Neufeld,[48] R. Newcombe,[61] E. M. Niel,[11] S. Nieswand,[14] N. Nikitin,[40] N. S. Nolte,[64] C. Normand,[8] C. Nunez,[87] A. Oblakowska-Mucha,[34] V. Obraztsov,[44] T. Oeser,[14] D. P. O'Hanlon,[54] S. Okamura,[21] R. Oldeman,[27,h] F. Oliva,[58] M. E. Olivares,[68] C. J. G. Onderwater,[79] R. H. O'Neil,[58] J. M. Otalora Goicochea,[2] T. Ovsiannikova,[41] P. Owen,[50] A. Oyanguren,[47] K. O. Padeken,[75] B. Pagare,[56] P. R. Pais,[48] T. Pajero,[63] A. Palano,[19] M. Palutan,[23] Y. Pan,[62] G. Panshin,[84] A. Papanestis,[57] M. Pappagallo,[19,g] L. L. Pappalardo,[21,d] C. Pappenheimer,[65] W. Parker,[66] C. Parkes,[62] B. Passalacqua,[21] G. Passaleva,[22] A. Pastore,[19] M. Patel,[61] C. Patrignani,[20,f] C. J. Pawley,[80] A. Pearce,[48] A. Pellegrino,[32] M. Pepe Altarelli,[48] S. Perazzini,[20] D. Pereima,[41] A. Pereiro Castro,[46] P. Perret,[9] M. Petric,[59,48] K. Petridis,[54] A. Petrolini,[24,b] A. Petrov,[81] S. Petrucci,[58] M. Petruzzo,[25] T. T. H. Pham,[68] A. Philippov,[42] L. Pica,[29,o] M. Piccini,[78] B. Pietrzyk,[8] G. Pietrzyk,[49] M. Pili,[63] D. Pinci,[30] F. Pisani,[48] M. Pizzichemi,[26,48,e] Resmi P. K,[10] V. Placinta,[37] J. Plews,[53] M. Plo Casasus,[46] F. Polci,[13] M. Poli Lener,[23] M. Poliakova,[68] A. Poluektov,[10] N. Polukhina,[83,s] I. Polyakov,[68] E. Polycarpo,[2] S. Ponce,[48] D. Popov,[6,48] S. Popov,[42] S. Poslavskii,[44] K. Prasanth,[35] L. Promberger,[48] C. Prouve,[46] V. Pugatch,[52] V. Puill,[11] H. Pullen,[63] G. Punzi,[29,t] H. Qi,[3] W. Qian,[6] J. Qin,[6] N. Qin,[3] R. Quagliani,[49] B. Quintana,[8] N. V. Raab,[18] R. I. Rabadan Trejo,[6] B. Rachwal,[34] J. H. Rademacker,[54] M. Rama,[29] M. Ramos Pernas,[56] M. S. Rangel,[2] F. Ratnikov,[42,82] G. Raven,[33] M. Reboud,[8] F. Redi,[49] F. Reiss,[62] C. Remon Alepuz,[47] Z. Ren,[3] V. Renaudin,[63] R. Ribatti,[29] S. Ricciardi,[57] K. Rinnert,[60] P. Robbe,[11] G. Robertson,[58] A. B. Rodrigues,[49] E. Rodrigues,[60] J. A. Rodriguez Lopez,[74] E. R. R. Rodriguez Rodriguez,[46] A. Rollings,[63] P. Roloff,[48] V. Romanovskiy,[44] M. Romero Lamas,[46] A. Romero Vidal,[46] J. D. Roth,[87] M. Rotondo,[23] M. S. Rudolph,[68] T. Ruf,[48] R. A. Ruiz Fernandez,[46] J. Ruiz Vidal,[47] A. Ryzhikov,[82] J. Ryzka,[34] J. J. Saborido Silva,[46] N. Sagidova,[38] N. Sahoo,[56] B. Saitta,[27,h] M. Salomoni,[48] C. Sanchez Gras,[32] R. Santacesaria,[30] C. Santamarina Rios,[46] M. Santimaria,[23] E. Santovetti,[31,j] D. Saranin,[83] G. Sarpis,[14] M. Sarpis,[75] A. Sarti,[30] C. Satriano,[30,u] A. Satta,[31] M. Saur,[15] D. Savrina,[41,40] H. Sazak,[9] L. G. Scantlebury Smead,[63] A. Scarabotto,[13] S. Schael,[14] S. Scherl,[60] M. Schiller,[59] H. Schindler,[48] M. Schmelling,[16] B. Schmidt,[48] S. Schmitt,[14] O. Schneider,[49] A. Schopper,[48] M. Schubiger,[32] S. Schulte,[49] M. H. Schune,[11] R. Schwemmer,[48] B. Sciascia,[23,48] S. Sellam,[46] A. Semennikov,[41] M. Senghi Soares,[33] A. Sergi,[24,b] N. Serra,[50] L. Sestini,[28] A. Seuthe,[15] Y. Shang,[5] D. M. Shangase,[87] M. Shapkin,[44] I. Shchemerov,[83] L. Shchutska,[49] T. Shears,[60] L. Shekhtman,[43,i] Z. Shen,[5] V. Shevchenko,[81] E. B. Shields,[26,e] Y. Shimizu,[11] E. Shmanin,[83] J. D. Shupperd,[68] B. G. Siddi,[21] R. Silva Coutinho,[50] G. Simi,[28] S. Simone,[19,g] N. Skidmore,[62] T. Skwarnicki,[68] M. W. Slater,[53] I. Slazyk,[21,d] J. C. Smallwood,[63] J. G. Smeaton,[55] A. Smetkina,[41] E. Smith,[50] M. Smith,[61] A. Snoch,[32] M. Soares,[20] L. Soares Lavra,[9] M. D. Sokoloff,[65] F. J. P. Soler,[59] A. Solovev,[38] I. Solovyev,[38] F. L. Souza De Almeida,[2] B. Souza De Paula,[2] B. Spaan,[15] E. Spadaro Norella,[25,p] P. Spradlin,[59] F. Stagni,[48] M. Stahl,[65] S. Stahl,[48] S. Stanislaus,[63] O. Steinkamp,[50,83] O. Stenyakin,[44] H. Stevens,[15] S. Stone,[68,48] M. Straticiuc,[37] D. Strekalina,[83] F. Suljik,[63] J. Sun,[27] L. Sun,[73] Y. Sun,[66] P. Svihra,[62] P. N. Swallow,[53] K. Swientek,[34]

A. Szabelski,[36] T. Szumlak,[34] M. Szymanski,[48] S. Taneja,[62] A. R. Tanner,[54] M. D. Tat,[63] A. Terentev,[83] F. Teubert,[48] E. Thomas,[48] D. J. D. Thompson,[53] K. A. Thomson,[60] V. Tisserand,[9] S. T'Jampens,[8] M. Tobin,[4] L. Tomassetti,[21,d] X. Tong,[5] D. Torres Machado,[1] D. Y. Tou,[13] E. Trifonova,[83] C. Trippl,[49] G. Tuci,[6] A. Tully,[49] N. Tuning,[32,48] A. Ukleja,[36] D. J. Unverzagt,[17] E. Ursov,[83] A. Usachov,[32] A. Ustyuzhanin,[42,82] U. Uwer,[17] A. Vagner,[84] V. Vagnoni,[20] A. Valassi,[48] G. Valenti,[20] N. Valls Canudas,[85] M. van Beuzekom,[32] M. Van Dijk,[49] H. Van Hecke,[67] E. van Herwijnen,[83] C. B. Van Hulse,[18] M. van Veghel,[79] R. Vazquez Gomez,[45] P. Vazquez Regueiro,[46] C. Vázquez Sierra,[48] S. Vecchi,[21] J. J. Velthuis,[54] M. Veltri,[22,v] A. Venkateswaran,[68] M. Veronesi,[32] M. Vesterinen,[56] D. Vieira,[65] M. Vieites Diaz,[49] H. Viemann,[76] X. Vilasis-Cardona,[85] E. Vilella Figueras,[60] A. Villa,[20] P. Vincent,[13] F. C. Volle,[11] D. Vom Bruch,[10] A. Vorobyev,[38] V. Vorobyev,[43,i] N. Voropaev,[38] K. Vos,[80] R. Waldi,[17] J. Walsh,[29] C. Wang,[17] J. Wang,[5] J. Wang,[4] J. Wang,[3] J. Wang,[73] M. Wang,[3] R. Wang,[54] Y. Wang,[7] Z. Wang,[50] Z. Wang,[3] Z. Wang,[6] J. A. Ward,[56,69] N. K. Watson,[53] S. G. Weber,[13] D. Websdale,[61] C. Weisser,[64] B. D. C. Westhenry,[54] D. J. White,[62] M. Whitehead,[54] A. R. Wiederhold,[56] D. Wiedner,[15] G. Wilkinson,[63] M. Wilkinson,[68] I. Williams,[55] M. Williams,[64] M. R. J. Williams,[58] F. F. Wilson,[57] W. Wislicki,[36] M. Witek,[35] L. Witola,[17] G. Wormser,[11] S. A. Wotton,[55] H. Wu,[68] K. Wyllie,[48] Z. Xiang,[6] D. Xiao,[7] Y. Xie,[7] A. Xu,[5] J. Xu,[6] L. Xu,[3] M. Xu,[7] Q. Xu,[6] Z. Xu,[5] Z. Xu,[6] D. Yang,[3] S. Yang,[6] Y. Yang,[6] Z. Yang,[5] Z. Yang,[66] Y. Yao,[68] L. E. Yeomans,[60] H. Yin,[7] J. Yu,[71] X. Yuan,[68] O. Yushchenko,[44] E. Zaffaroni,[49] M. Zavertyaev,[16,s] M. Zdybal,[35] O. Zenaiev,[48] M. Zeng,[3] D. Zhang,[7] L. Zhang,[3] S. Zhang,[71] S. Zhang,[5] Y. Zhang,[5] Y. Zhang,[63] A. Zharkova,[83] A. Zhelezov,[17] Y. Zheng,[6] T. Zhou,[5] X. Zhou,[6] Y. Zhou,[6] V. Zhovkovska,[11] X. Zhu,[3] X. Zhu,[7] Z. Zhu,[6] V. Zhukov,[14,40] J. B. Zonneveld,[58] Q. Zou,[4] S. Zucchelli,[20,f] D. Zuliani,[28] and G. Zunica[62]

(LHCb Collaboration)

[1]*Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil*
[2]*Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*
[3]*Center for High Energy Physics, Tsinghua University, Beijing, China*
[4]*Institute Of High Energy Physics (IHEP), Beijing, China*
[5]*School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[6]*University of Chinese Academy of Sciences, Beijing, China*
[7]*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*
[8]*Univ. Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France*
[9]*Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
[10]*Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*
[11]*Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France*
[12]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
[13]*LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*
[14]*I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*
[15]*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[16]*Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*
[17]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[18]*School of Physics, University College Dublin, Dublin, Ireland*
[19]*INFN Sezione di Bari, Bari, Italy*
[20]*INFN Sezione di Bologna, Bologna, Italy*
[21]*INFN Sezione di Ferrara, Ferrara, Italy*
[22]*INFN Sezione di Firenze, Firenze, Italy*
[23]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[24]*INFN Sezione di Genova, Genova, Italy*
[25]*INFN Sezione di Milano, Milano, Italy*
[26]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[27]*INFN Sezione di Cagliari, Monserrato, Italy*
[28]*Universita degli Studi di Padova, Universita e INFN, Padova, Padova, Italy*
[29]*INFN Sezione di Pisa, Pisa, Italy*
[30]*INFN Sezione di Roma La Sapienza, Roma, Italy*
[31]*INFN Sezione di Roma Tor Vergata, Roma, Italy*
[32]*Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*

[33]Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands
[34]AGH—University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
[35]Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
[36]National Center for Nuclear Research (NCBJ), Warsaw, Poland
[37]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
[38]Petersburg Nuclear Physics Institute NRC Kurchatov Institute (PNPI NRC KI), Gatchina, Russia
[39]Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia
[40]Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
[41]Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia
[42]Yandex School of Data Analysis, Moscow, Russia
[43]Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia
[44]Institute for High Energy Physics NRC Kurchatov Institute (IHEP NRC KI), Protvino, Russia, Protvino, Russia
[45]ICCUB, Universitat de Barcelona, Barcelona, Spain
[46]Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
[47]Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain
[48]European Organization for Nuclear Research (CERN), Geneva, Switzerland
[49]Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[50]Physik-Institut, Universität Zürich, Zürich, Switzerland
[51]NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
[52]Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
[53]University of Birmingham, Birmingham, United Kingdom
[54]H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
[55]Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[56]Department of Physics, University of Warwick, Coventry, United Kingdom
[57]STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
[58]School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[59]School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[60]Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[61]Imperial College London, London, United Kingdom
[62]Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[63]Department of Physics, University of Oxford, Oxford, United Kingdom
[64]Massachusetts Institute of Technology, Cambridge, MA, United States
[65]University of Cincinnati, Cincinnati, OH, United States
[66]University of Maryland, College Park, MD, United States
[67]Los Alamos National Laboratory (LANL), Los Alamos, United States
[68]Syracuse University, Syracuse, NY, United States
[69]School of Physics and Astronomy, Monash University, Melbourne, Australia (associated with Department of Physics, University of Warwick, Coventry, United Kingdom)
[70]Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil (associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil)
[71]Physics and Micro Electronic College, Hunan University, Changsha City, China (associated with Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China)
[72]Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Institute of Quantum Matter, South China Normal University, Guangzhou, China (associated with Center for High Energy Physics, Tsinghua University, Beijing, China)
[73]School of Physics and Technology, Wuhan University, Wuhan, China (associated with Center for High Energy Physics, Tsinghua University, Beijing, China)
[74]Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia (associated with LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France)
[75]Universität Bonn—Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany (associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)
[76]Institut für Physik, Universität Rostock, Rostock, Germany (associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)
[77]Eotvos Lorand University, Budapest, Hungary (associated with European Organization for Nuclear Research (CERN), Geneva, Switzerland)

[78]INFN Sezione di Perugia, Perugia, Italy (associated with INFN Sezione di Ferrara, Ferrara, Italy)
[79]Van Swinderen Institute, University of Groningen, Groningen, Netherlands
(associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)
[80]Universiteit Maastricht, Maastricht, Netherlands
(associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)
[81]National Research Centre Kurchatov Institute, Moscow, Russia
(associated with Institute of Theoretical and Experimental Physics NRC Kurchatov Institute
(ITEP NRC KI), Moscow, Russia)
[82]National Research University Higher School of Economics, Moscow, Russia
(associated with Yandex School of Data Analysis, Moscow, Russia)
[83]National University of Science and Technology "MISIS", Moscow, Russia
(associated with Institute of Theoretical and Experimental Physics NRC Kurchatov Institute
(ITEP NRC KI), Moscow, Russia)
[84]National Research Tomsk Polytechnic University, Tomsk, Russia
(associated with Institute of Theoretical and Experimental Physics NRC Kurchatov Institute
(ITEP NRC KI), Moscow, Russia)
[85]DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain
(associated with ICCUB, Universitat de Barcelona, Barcelona, Spain)
[86]Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden
(associated with School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom)
[87]University of Michigan, Ann Arbor, United States
(associated with Syracuse University, Syracuse, NY, United States)

[a]Deceased.
[b]Also at Università di Genova, Genova, Italy.
[c]Also at Università di Modena e Reggio Emilia, Modena, Italy.
[d]Also at Università di Ferrara, Ferrara, Italy.
[e]Also at Università di Milano Bicocca, Milano, Italy.
[f]Also at Università di Bologna, Bologna, Italy.
[g]Also at Università di Bari, Bari, Italy.
[h]Also at Università di Cagliari, Cagliari, Italy.
[i]Also at Novosibirsk State University, Novosibirsk, Russia.
[j]Also at Università di Roma Tor Vergata, Roma, Italy.
[k]Also at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil.
[l]Also at Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China.
[m]Also at Università di Siena, Siena, Italy.
[n]Also at Università di Padova, Padova, Italy.
[o]Also at Scuola Normale Superiore, Pisa, Italy.
[p]Also at Università degli Studi di Milano, Milano, Italy.
[q]Also at MSU—Iligan Institute of Technology (MSU-IIT), Iligan, Philippines.
[r]Also at Università di Firenze, Firenze, Italy.
[s]Also at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.
[t]Also at Università di Pisa, Pisa, Italy.
[u]Also at Università della Basilicata, Potenza, Italy.
[v]Also at Università di Urbino, Urbino, Italy.