Search for Baryon-Number Violating Ξ_b^0 Oscillations

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

(Received 22 August 2017; published 3 November 2017)

A search for baryon-number violating Ξ_b^0 oscillations is performed with a sample of pp collision data recorded by the LHCb experiment, corresponding to an integrated luminosity of 3 fb^{-1}. The baryon number at the moment of production is identified by requiring that the Ξ_b^0 come from the decay of a resonance $\Xi_b^{*-} \to \Xi_b^0\pi^-$ or $\Xi_b^{\prime -} \to \Xi_b^0\pi^-$, and the baryon number at the moment of decay is identified from the final state using the decays $\Xi_b^0 \to \Xi_c^+\pi^-, \Xi_c^+ \to pK^-\pi^+$. No evidence of baryon-number violation is found, and an upper limit at the 95% confidence level is set on the oscillation rate of $\omega < 0.08\ \mathrm{ps}^{-1}$, where ω is the associated angular frequency.

DOI: 10.1103/PhysRevLett.119.181807

Three conditions are necessary for the formation of a matter-dominated universe: C and CP violation, baryon-number violation (BNV), and the absence of thermal equilibrium [1]. The existence of C and CP violation has been established experimentally for decades [2–4], although the amount of CP violation present in the standard model (SM) is known to be insufficient to generate the matter-antimatter asymmetry observed in the Universe today [5,6], prompting numerous searches for sources of CP violation beyond the SM. By contrast, despite baryon-number conservation being an accidental low-temperature symmetry of the SM, BNV has never been observed experimentally, and stringent lower limits have been placed on the mean lifetimes of protons and of bound neutrons [7]. These limits impose constraints on generic models of physics beyond the SM. In particular, in supersymmetric extensions of the SM, a mechanism such as R-parity conservation is required to naturally suppress baryon-number violation [8–11]. An alternative is that the new physics has nongeneric flavor interactions, such that only certain BNV processes are allowed, and the experimental constraints are respected. One possibility would be for new BNV couplings to be entirely flavor diagonal [12,13], such as a six-fermion operator that couples two fermions from each generation. This would couple two from each of $\{u, d, e, \nu_e\}$, $\{c, s, \mu, \nu_\mu\}$, and $\{t, b, \tau, \nu_\tau\}$, with duplication allowed within a generation, e.g., a $usb\overline{usb}$ vertex would be permitted. Such an operator could arise in models with leptoquarks or R-parity-violating supersymmetric extensions of the SM [13,14]. The six-fermion operator could allow BNV while being consistent with the experimental limit on the proton lifetime, since the proton initial state contains only first-generation fermions and, therefore, its coupling to the operator would require two flavor-changing neutral processes and would be heavily suppressed [13].

Most experimental processes involving such an operator are difficult to observe, since they include multiple third-generation fermions. For example, the signatures proposed in Ref. [13] require performing asymmetry measurements of same-sign dilepton pairs produced in association with a top-quark jet. However, there is a process that could give rise to a clean, unambiguous experimental signature: baryon-antibaryon oscillations of hadrons that contain a valence quark from each generation. The only such baryon observed to date that decays weakly is the Ξ_b^0 (bsu). The interest of searching for Ξ_b^0 oscillations was noted in Refs. [15,16], with an oscillation period potentially as short as $\mathcal{O}(0.1\ \mathrm{ps})$ suggested. More recently, heavy baryon oscillations have been proposed as a possible mechanism for baryogenesis [14,17].

The signature for a BNV process is that a Ξ_b^0 baryon is produced and decays weakly as an antibaryon to a final state such as $\bar{\Xi}_c^-\pi^+$ (or, vice versa, that an antibaryon is produced and decays as a baryon). The strong decays (the inclusion of charge-conjugate processes is implied throughout) $\Xi_b^{\prime -} \to \Xi_b^0\pi^-$ and $\Xi_b^{*-} \to \Xi_b^0\pi^-$ (denoted $\Xi_b^{\prime,*-} \to \Xi_b^0\pi^-$), where $\Xi_b^{\prime -}$ and Ξ_b^{*-} are the narrow resonances $\Xi_b^{\prime}(5935)^-$ and $\Xi_b^*(5955)^-$ recently observed by the LHCb Collaboration [18], allow the baryon number at the time of production to be determined from the charge of the pion. Figure 1 shows quark-level diagrams of example non-BNV [Fig. 1(a)] and BNV processes [Fig. 1(b)].

For baryon states propagating in free space, the formalism for oscillations is similar to that of neutral mesons [7,19,20], which has been studied extensively in the context of K^0, D^0, B^0, and B_s^0 mixing [21]. However, a difference arises in the presence of a magnetic field $\vec{B}$ due to the nonzero magnetic moment μ possessed by the baryons,

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

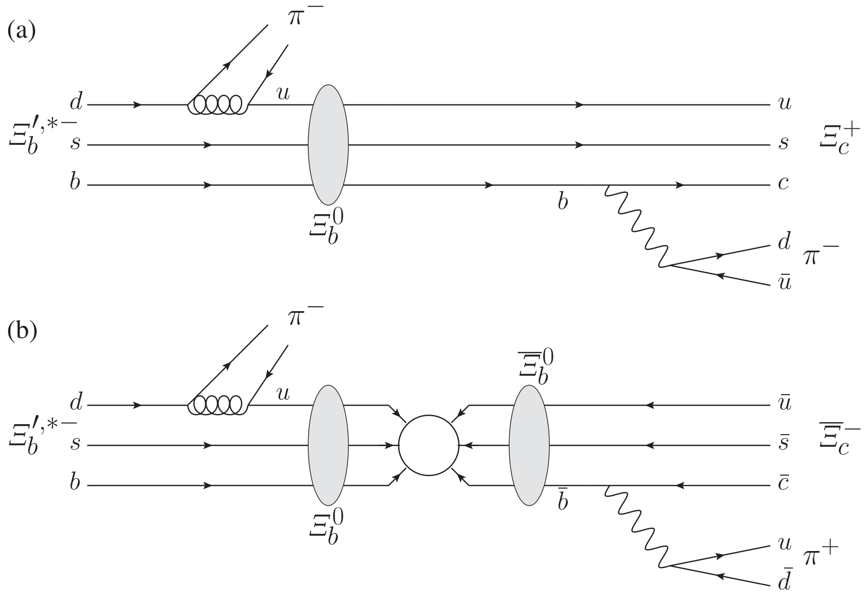

FIG. 1. (a) A non-BNV quark diagram for a $\Xi_b^{\prime,*-} \to \Xi_b^0\pi^-$ strong decay followed by a $\Xi_b^0 \to \Xi_c^+\pi^-$ weak decay. (b) The corresponding BNV diagram with a Ξ_b^0 to $\bar{\Xi}_b^0$ oscillation followed by a decay to the final state $\bar{\Xi}_c^-\pi^+$.

resulting in a splitting of the baryon and antibaryon energy levels of $\Delta E = 2\vec{\mu}\cdot\vec{B}$. This splitting leads to a damping of the oscillations over time. For the case of neutron oscillations, even a modest ambient magnetic field would greatly suppress the oscillation probability on the time scale of the neutron lifetime [22]. The criterion for the effect of the magnetic field to be negligible is $|\Delta E|t/2 \ll 1$, where t is the time of propagation of the baryon. Taking the Ξ_b^0 magnetic moment to be comparable to the nuclear magneton [7], the energy splitting associated with the magnetic field in the interaction region of the LHCb detector, which is $\lesssim$10 mT, may be computed. For a typical time of propagation equal to the known Ξ_b^0 lifetime [23] of 1.477 ± 0.032 ps, $|\Delta E|t/2 \lesssim 10^{-4}$. This effect can, therefore, be neglected and, in the limit of small mixing, the ratio of the rate of oscillated decays $P_{X\to\bar{X}}(t)$ to the rate of nonoscillated decays $P_{X\to X}(t)$ varies over time as

$$R(t) \equiv \frac{P_{X\to\bar{X}}(t)}{P_{X\to X}(t)} = \tan^2(t/\tau_{\rm mix}) \simeq \frac{t^2}{\tau_{\rm mix}^2} \equiv (\omega t)^2, \quad (1)$$

where $2\pi\tau_{\rm mix}$ is the oscillation period, and $\omega = 1/\tau_{\rm mix}$ gives the corresponding angular frequency and is zero in the absence of oscillations. This angular frequency is related to the mass difference ΔM and the width difference $\Delta\Gamma$ between the eigenstates of the Hamiltonian by $\omega^2 = (\Delta M/2)^2 + (\Delta\Gamma/4)^2$, and in the limit that BNV in the decay itself is negligible, $\omega = \Delta M/2$.

This Letter presents a search for baryon-number violating Ξ_b^0 oscillations performed with a sample of pp collision data recorded by the LHCb experiment, corresponding to an integrated luminosity of 3 fb^{-1} collected at center-of-mass energies $\sqrt{s} = 7$ and 8 TeV. This is the first such search for oscillations in heavy baryons. The LHCb detector [24,25] 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 particularly relevant to 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 momentum p of charged particles, and two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons. Samples of simulated events are used to study the detector response and its effect on the measurement. In the simulation, pp collisions are generated using PYTHIA [26] with a specific LHCb configuration [27]. Decays of hadronic particles are described by EVTGEN [28], in which final-state radiation is generated using PHOTOS [29]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [30] as described in Ref. [31].

Two classes of $\Xi_b^{\prime,*-}$ candidates are defined. Baryon-number conserving decays, in which a strong decay $\Xi_b^{\prime,*-} \to \Xi_b^0\pi^-$ is followed by weak decays $\Xi_b^0 \to \Xi_c^+\pi^-$ and $\Xi_c^+ \to pK^-\pi^+$, are referred to as opposite-sign (OS) candidates, since the π^- emitted in the strong decay and the p have charges of opposite sign. Conversely, in same-sign (SS) candidates, the first decay $\Xi_b^{\prime,*-} \to \Xi_b^0\pi^-$ is followed by weak decays to a final state of different baryon number, $\bar{\Xi}_b^0 \to \bar{\Xi}_c^-\pi^+$ and $\bar{\Xi}_c^- \to \bar{p}K^+\pi^-$.

The reconstruction and selection procedures are the same as those described in Ref. [18], except for one additional requirement on the track quality of the pion produced in the

$\Xi_b^{\prime,*-}$ decay. This requirement rejects a source of peaking background that can arise when a genuine $\Xi_b^{\prime,*-} \to \Xi_b^0\pi^-$ decay occurs but the π^- track is misreconstructed such that its charge is incorrect, and the candidate migrates from the OS to the SS class [32]. In studies of simulated events, the fitted SS yield of this contribution is found to be smaller than that of correctly reconstructed OS signal by a factor of $(1.3 \pm 0.3) \times 10^{-3}$, where the uncertainty is statistical. Applying the additional track quality requirement reduces the SS contribution in simulation by an order of magnitude, such that it becomes smaller than the OS yield by a factor of $(1.6 \pm 2.0) \times 10^{-4}$, corresponding to an expected SS peaking background yield of less than 0.1, which is negligible. The track quality requirement also reduces the OS signal yield in the data by approximately 10% and the combinatorial background by approximately 20% compared to Ref. [18]. Figure 2 shows the spectra of the mass difference δm for the selected OS and SS candidates, defining $\delta m \equiv m(\Xi_b^0\pi) - m(\Xi_b^0) - m_\pi$, where m_π is the known $\pi^\pm$ mass [7], and $m(\Xi_b^0\pi)$ and $m(\Xi_b^0)$ are the reconstructed invariant masses of the $\Xi_b^0\pi$ and Ξ_b^0 candidates. The figure also shows an unbinned extended maximum likelihood fit to the OS candidates, performed following the same procedure as described below and in Ref. [18], as a blue curve.

The data are divided into seven bins of decay time (illustrated in Fig. 3) that have approximately equal OS signal yields and cover the range $0 < t < 8$ ps, corresponding to approximately 5.4 times the mean Ξ_b^0 lifetime. The OS resonance yields in the ith bin are determined from a fit to the δm distribution of the OS data in that bin, with the resonance masses and the Ξ_b^{*-} width fixed to values obtained in a fit to the whole OS data sample. In each bin of decay time, the shape and normalization of the SS

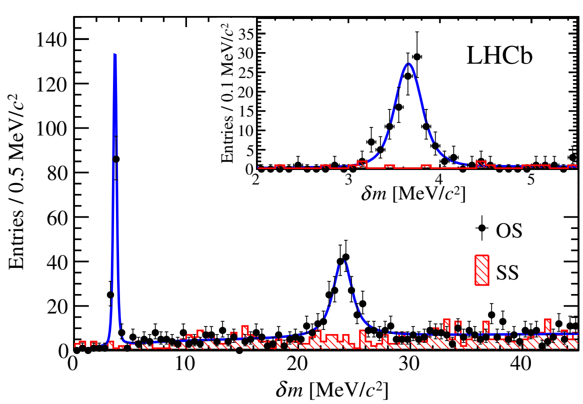

FIG. 2. Spectra of the mass difference $\delta m \equiv m(\Xi_b^0\pi) - m(\Xi_b^0) - m_\pi$ in the data after the full selection, for the OS sample (black points with error bars) and SS decays (red, hatched histogram). The blue curve is a fit to the OS data. The $\Xi_b^{\prime-}$ and Ξ_b^{*-} peaks are at $\delta m \approx 3.7$ and 24 MeV$/c^2$, and the δm resolution at these points is approximately 0.2 and 0.5 MeV$/c^2$, respectively; the Ξ_b^{*-} also has a non-negligible natural width of $\Gamma \approx 1.7$ MeV [23]. Inset: Detail of the region $2.0 < \delta m < 5.5$ MeV$/c^2$.

combinatorial background are obtained from a fit to the δm sideband regions of the SS data in that bin (the sidebands being 0–2, 6–15, and 32–45 MeV$/c^2$). For a given value of the angular frequency ω of the oscillations, the expected ratio of SS to OS decays in the bin may be computed. In combination with the OS yield and the shape and normalization of the SS background obtained as described above, this fully determines the probability density function for the SS data in bin i, and the corresponding likelihood $L_i(\omega)$ is evaluated. The overall likelihood is obtained by combining all bins as $L(\omega) = \prod_i L_i(\omega)$.

A test statistic Δ is defined based on the likelihood ratio approach as $\Delta \equiv 2\ln L(\hat{\omega}) - 2\ln L(0)$, where $\hat{\omega}$ is the best-fit value of ω and is estimated from a likelihood scan. Only the physical domain $\omega \geq 0$ is considered, and, consequently, $\hat{\omega}$ is expected to be zero approximately half of the time under the null hypothesis. The best-fit value for the data is found to be $\hat{\omega} = 0$, and the test statistic is, therefore, $\Delta = 0$.

Since no evidence of BNV oscillations is found, an upper limit at the 95% confidence level is placed on ω following the CL_s method [33,34]. Ensembles of parametrized simulations referred to as pseudoexperiments are generated for a range of different oscillation angular frequencies ω. The pseudoexperiments include variation of efficiency with decay time, decay time and mass resolution, combinatorial background, and misclassification of OS candidates as SS via the misreconstruction described earlier. To incorporate the associated systematic uncertainties, the input parameters used to define the distributions (the masses and yields of the resonances, the natural width of the Ξ_b^{*-}, the background yield and shape parameters, and the signal misclassification rate) are varied randomly within their uncertainties for each pseudoexperiment. Each pseudoexperiment is analyzed in the same way as the data, and its

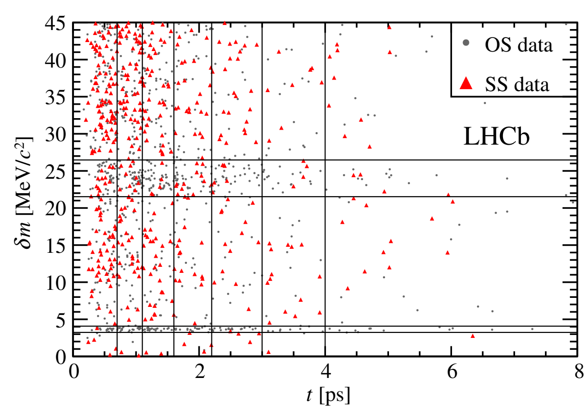

FIG. 3. Distribution of δm vs decay time. The OS data are shown as grey points and the SS data as larger red triangles. The vertical lines indicate the decay time bins. The horizontal lines are intended to guide the eye and indicate the $\Xi_b^{\prime-}$ and Ξ_b^{*-} regions. Because of selection requirements, few candidates are present at short decay times.

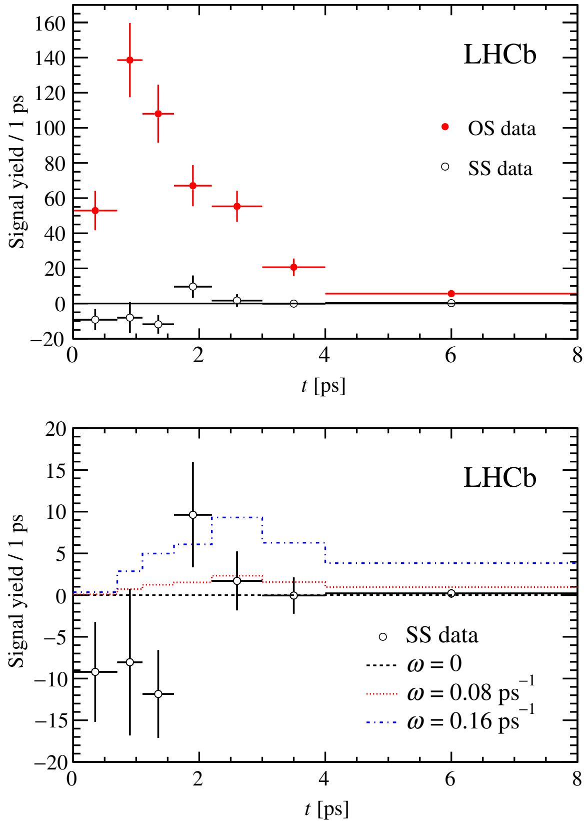

FIG. 4. For illustration, plots of the decay time distribution of signal candidates. In these plots, the two resonance regions are combined, and background is subtracted with a simplified statistical procedure that, unlike the likelihood described in the text, allows negative SS yields. (Upper) The OS and SS data. (Lower) Detail of the SS data, along with the expected SS yields under various hypotheses for the angular frequency ω of the oscillations.

test statistic Δ computed. Coverage tests with pseudoexperiments indicate that the procedure overcovers for small values of ω, with 100% coverage at $\omega = 0$, and that the coverage converges asymptotically to 95% as the true value of ω increases.

An upper limit of $\omega < 0.08\ \mathrm{ps}^{-1}$ at the 95% confidence level is obtained, which corresponds to $\tau_{\mathrm{mix}} > 13$ ps. This result can also be expressed in terms of the time-integrated mixing rate χ defined as the fraction of particles produced as Ξ_b^0 that decay as $\bar{\Xi}_b^0$ or vice versa. Under the assumption of quadratic time dependence for $R(t)$, $\chi = 2\omega^2\tau^2 < 2.7\%$ at the 95% confidence level, where τ is the known Ξ_b^0 lifetime [23]. For the purposes of illustration, the evolution of the expected SS yield with decay time for $\omega = 0.08\ \mathrm{ps}^{-1}$ and $\omega = 0.16\ \mathrm{ps}^{-1}$ is shown in Fig. 4 and compared to the SS yield in the data as obtained with a simplified statistical procedure.

In summary, a search is performed for baryon-antibaryon oscillations in the Ξ_b^0 system. This is the first such search in the heavy-flavor sector and is of particular interest since Ξ_b^0 baryons may couple directly to flavor-diagonal six-fermion operators that violate baryon number [13]. No evidence of baryon-number violating oscillations is found. In the limit of a small oscillation rate, the ratio of same-sign to opposite-sign decays is expected to increase quadratically with decay time. A limit on the oscillation angular frequency $\omega < 0.08\ \mathrm{ps}^{-1}$ at the 95% confidence level is obtained, equivalent to $\tau_{\mathrm{mix}} > 13$ ps. This rules out oscillations with a period comparable to the Ξ_b^0 lifetime, as proposed in Ref. [15].

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 (People's Republic of China); CNRS/IN2P3 (France); BMBF, DFG, and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MinES and FASO (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); 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 OSC (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 AvH Foundation (Germany), EPLANET, Marie Skłodowska-Curie Actions, and ERC (European Union), ANR, Labex P2IO, ENIGMASS and OCEVU, and Région Auvergne-Rhône-Alpes (France), RFBR and Yandex LLC (Russia), GVA, XuntaGal, and GENCAT (Spain), Herchel Smith Fund, the Royal Society, the English-Speaking Union and the Leverhulme Trust (United Kingdom).

[1] A. D. Sakharov, Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the Universe, Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32 (1967); JETP Lett. **5**, 24 (1967); Sov. Phys. Usp. **34**, 392 (1991).
[2] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Evidence for the 2π Decay of the K_2^0 Meson, Phys. Rev. Lett. **13**, 138 (1964).
[3] B. Aubert *et al.* (*BABAR* Collaboration), Observation of *CP* Violation in the B^0 Meson System, Phys. Rev. Lett. **87**, 091801 (2001).
[4] K. Abe *et al.* (Belle Collaboration), Observation of Large *CP* Violation in the Neutral *B* Meson System, Phys. Rev. Lett. **87**, 091802 (2001).
[5] M. B. Gavela, P. Hernández, J. Orloff, and O. Pène, Standard model *CP* violation and baryon asymmetry, Mod. Phys. Lett. A **09**, 795 (1994).

[6] M. B. Gavela, P. Hernandez, J. Orloff, O. Péne, and C. Quimbay, Standard model *CP* violation and baryon asymmetry. Part 2: Finite temperature, Nucl. Phys. **B430**, 382 (1994).
[7] C. Patrignani *et al.* (Particle Data Group Collaboration), Review of particle physics, Chin. Phys. C **40**, 100001 (2016), and 2017 update.
[8] A. Salam and J. A. Strathdee, Supersymmetry and fermion number conservation, Nucl. Phys. **B87**, 85 (1975).
[9] P. Fayet, Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino, Nucl. Phys. **B90**, 104 (1975).
[10] S. Weinberg, Supersymmetry at ordinary energies. Masses and conservation laws, Phys. Rev. D **26**, 287 (1982).
[11] G. R. Farrar and S. Weinberg, Supersymmetry at ordinary energies. II. *R* invariance, Goldstone bosons, and gauge fermion masses, Phys. Rev. D **27**, 2732 (1983).
[12] C. Smith, Proton stability from a fourth family, Phys. Rev. D **85**, 036005 (2012).
[13] G. Durieux, J.-M. Gérard, F. Maltoni, and C. Smith, Three-generation baryon and lepton number violation at the LHC, Phys. Lett. B **721**, 82 (2013).
[14] K. Aitken, D. McKeen, A. E. Nelson, and T. Neder, Baryogenesis from oscillations of charmed or beautiful baryons, Phys. Rev. D **96**, 075009 (2017).
[15] V. A. Kuzmin, Might fast *B*-violating transitions be found soon?, arXiv:hep-ph/9609253.
[16] J. D. Bjorken Report No. SLAC-PUB-5673, 1991.
[17] D. McKeen and A. E. Nelson, *CP* violating baryon oscillations, Phys. Rev. D **94**, 076002 (2016).
[18] R. Aaij *et al.* (LHCb Collaboration), Observation of Two New Ξ_b^- Baryon Resonances, Phys. Rev. Lett. **114**, 062004 (2015).
[19] P. F. Harrison and H. R. Quinn, SLAC Report No. SLAC-R-504, 1998.
[20] A. J. Bevan *et al.* (*BABAR* and Belle Collaborations), The physics of the *B* factories, Eur. Phys. J. C **74**, 3026 (2014).
[21] Y. Amhis *et al.* (Heavy Flavor Averaging Group Collaboration), Averages of *b*-hadron, *c*-hadron, and τ-lepton properties as of summer 2016, arXiv:1612.07233; updated results and plots available at http://www.slac.stanford.edu/xorg/hflav/.
[22] D. G. Phillips II *et al.*, Neutron-antineutron oscillations: Theoretical status and experimental prospects, Phys. Rep. **612**, 1 (2016).
[23] R. Aaij *et al.* (LHCb Collaboration), Precision Measurement of the Mass and Lifetime of the Ξ_b^0 Baryon, Phys. Rev. Lett. **113**, 032001 (2014).
[24] A. A. Alves, Jr. *et al.* (LHCb Collaboration), The LHCb detector at the LHC, J. Instrum. **3**, S08005 (2008).
[25] R. Aaij *et al.* (LHCb Collaboration), LHCb detector performance, Int. J. Mod. Phys. A **30**, 1530022 (2015).
[26] 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.
[27] I. Belyaev *et al.*, Handling of the generation of primary events in Gauss, the LHCb simulation framework, J. Phys. Conf. Ser. **331**, 032047 (2011).
[28] D. J. Lange, The EvtGen particle decay simulation package, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).
[29] P. Golonka and Z. Was, PHOTOS Monte Carlo: A precision tool for QED corrections in *Z* and *W* decays, Eur. Phys. J. C **45**, 97 (2006).
[30] 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).
[31] 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).
[32] R. Aaij *et al.* (LHCb Collaboration), First Observation of $D^0-\bar{D}^0$ Oscillations in $D^0\to K^+\pi^+\pi^-\pi^-$ Decays and a Measurement of the Associated Coherence Parameters, Phys. Rev. Lett. **116**, 241801 (2016).
[33] A. L. Read, Presentation of search results: The CL_s technique, J. Phys. G **28**, 2693 (2002).
[34] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C **71**, 1554 (2011).

R. Aaij,[40] B. Adeva,[39] M. Adinolfi,[48] Z. Ajaltouni,[5] S. Akar,[59] J. Albrecht,[10] F. Alessio,[40] M. Alexander,[53] A. Alfonso Albero,[38] S. Ali,[43] G. Alkhazov,[31] P. Alvarez Cartelle,[55] A. A. Alves Jr.,[59] S. Amato,[2] S. Amerio,[23] Y. Amhis,[7] L. An,[3] L. Anderlini,[18] G. Andreassi,[41] M. Andreotti,[17,a] J. E. Andrews,[60] R. B. Appleby,[56] F. Archilli,[43] P. d'Argent,[12] J. Arnau Romeu,[6] A. Artamonov,[37] M. Artuso,[61] E. Aslanides,[6] G. Auriemma,[26] M. Baalouch,[5] I. Babuschkin,[56] S. Bachmann,[12] J. J. Back,[50] A. Badalov,[38,b] C. Baesso,[62] S. Baker,[55] V. Balagura,[7,c] W. Baldini,[17] A. Baranov,[35] R. J. Barlow,[56] C. Barschel,[40] S. Barsuk,[7] W. Barter,[56] F. Baryshnikov,[32] V. Batozskaya,[29] V. Battista,[41] A. Bay,[41] L. Beaucourt,[4] J. Beddow,[53] F. Bedeschi,[24] I. Bediaga,[1] A. Beiter,[61] L. J. Bel,[43] N. Beliy,[63] V. Bellee,[41] N. Belloli,[21,d] K. Belous,[37] I. Belyaev,[32] E. Ben-Haim,[8] G. Bencivenni,[19] S. Benson,[43] S. Beranek,[9] A. Berezhnoy,[33] R. Bernet,[42] D. Berninghoff,[12] E. Bertholet,[8] A. Bertolin,[23] C. Betancourt,[42] F. Betti,[15] M.-O. Bettler,[40] M. van Beuzekom,[43] Ia. Bezshyiko,[42] S. Bifani,[47] P. Billoir,[8] A. Birnkraut,[10] A. Bitadze,[56] A. Bizzeti,[18,e] M. Bjørn,[57] T. Blake,[50] F. Blanc,[41] J. Blouw,[11] S. Blusk,[61] V. Bocci,[26] T. Boettcher,[58] A. Bondar,[36,f] N. Bondar,[31] W. Bonivento,[16] I. Bordyuzhin,[32]

A. Borgheresi,[21,d] S. Borghi,[56] M. Borisyak,[35] M. Borsato,[39] F. Bossu,[7] M. Boubdir,[9] T. J. V. Bowcock,[54] E. Bowen,[42] C. Bozzi,[17,40] S. Braun,[12] T. Britton,[61] J. Brodzicka,[27] D. Brundu,[16] E. Buchanan,[48] C. Burr,[56] A. Bursche,[16,g] J. Buytaert,[40] W. Byczynski,[40] S. Cadeddu,[16] H. Cai,[64] R. Calabrese,[17,a] R. Calladine,[47] M. Calvi,[21,d] M. Calvo Gomez,[38,b] A. Camboni,[38,b] P. Campana,[19] D. H. Campora Perez,[40] L. Capriotti,[56] A. Carbone,[15,h] G. Carboni,[25,i] R. Cardinale,[20,j] A. Cardini,[16] P. Carniti,[21,d] L. Carson,[52] K. Carvalho Akiba,[2] G. Casse,[54] L. Cassina,[21] L. Castillo Garcia,[41] M. Cattaneo,[40] G. Cavallero,[20,40,j] R. Cenci,[24,k] D. Chamont,[7] M. Charles,[8] Ph. Charpentier,[40] G. Chatzikonstantinidis,[47] M. Chefdeville,[4] S. Chen,[56] S. F. Cheung,[57] S.-G. Chitic,[40] V. Chobanova,[39] M. Chrzaszcz,[42,27] A. Chubykin,[31] P. Ciambrone,[19] X. Cid Vidal,[39] G. Ciezarek,[43] P. E. L. Clarke,[52] M. Clemencic,[40] H. V. Cliff,[49] J. Closier,[40] J. Cogan,[6] E. Cogneras,[5] V. Cogoni,[16,g] L. Cojocariu,[30] P. Collins,[40] T. Colombo,[40] A. Comerma-Montells,[12] A. Contu,[40] A. Cook,[48] G. Coombs,[40] S. Coquereau,[38] G. Corti,[40] M. Corvo,[17,a] C. M. Costa Sobral,[50] B. Couturier,[40] G. A. Cowan,[52] D. C. Craik,[58] A. Crocombe,[50] M. Cruz Torres,[1] R. Currie,[52] C. D'Ambrosio,[40] F. Da Cunha Marinho,[2] E. Dall'Occo,[43] J. Dalseno,[48] A. Davis,[3] O. De Aguiar Francisco,[54] S. De Capua,[56] M. De Cian,[12] J. M. De Miranda,[1] L. De Paula,[2] M. De Serio,[14,l] P. De Simone,[19] C. T. Dean,[53] D. Decamp,[4] L. Del Buono,[8] H.-P. Dembinski,[11] M. Demmer,[10] A. Dendek,[28] D. Derkach,[35] O. Deschamps,[5] F. Dettori,[54] B. Dey,[65] A. Di Canto,[40] P. Di Nezza,[19] H. Dijkstra,[40] F. Dordei,[40] M. Dorigo,[40] A. Dosil Suárez,[39] L. Douglas,[53] A. Dovbnya,[45] K. Dreimanis,[54] L. Dufour,[43] G. Dujany,[8] P. Durante,[40] R. Dzhelyadin,[37] M. Dziewiecki,[12] A. Dziurda,[40] A. Dzyuba,[31] S. Easo,[51] M. Ebert,[52] U. Egede,[55] V. Egorychev,[32] S. Eidelman,[36,f] S. Eisenhardt,[52] U. Eitschberger,[10] R. Ekelhof,[10] L. Eklund,[53] S. Ely,[61] S. Esen,[12] H. M. Evans,[49] T. Evans,[57] A. Falabella,[15] N. Farley,[47] S. Farry,[54] D. Fazzini,[21,d] L. Federici,[25] D. Ferguson,[52] G. Fernandez,[38] P. Fernandez Declara,[40] A. Fernandez Prieto,[39] F. Ferrari,[15] F. Ferreira Rodrigues,[2] M. Ferro-Luzzi,[40] S. Filippov,[34] R. A. Fini,[14] M. Fiore,[17,a] M. Fiorini,[17,a] M. Firlej,[28] C. Fitzpatrick,[41] T. Fiutowski,[28] F. Fleuret,[7,c] K. Fohl,[40] M. Fontana,[16,40] F. Fontanelli,[20,j] D. C. Forshaw,[61] R. Forty,[40] V. Franco Lima,[54] M. Frank,[40] C. Frei,[40] J. Fu,[22,m] W. Funk,[40] E. Furfaro,[25,i] C. Färber,[40] E. Gabriel,[52] A. Gallas Torreira,[39] D. Galli,[15,h] S. Gallorini,[23] S. Gambetta,[52] M. Gandelman,[2] P. Gandini,[57] Y. Gao,[3] L. M. Garcia Martin,[70] J. García Pardiñas,[39] J. Garra Tico,[49] L. Garrido,[38] P. J. Garsed,[49] D. Gascon,[38] C. Gaspar,[40] L. Gavardi,[10] G. Gazzoni,[5] D. Gerick,[12] E. Gersabeck,[12] M. Gersabeck,[56] T. Gershon,[50] Ph. Ghez,[4] S. Gianì,[41] V. Gibson,[49] O. G. Girard,[41] L. Giubega,[30] K. Gizdov,[52] V. V. Gligorov,[8] D. Golubkov,[32] A. Golutvin,[55,40] A. Gomes,[1,n] I. V. Gorelov,[33] C. Gotti,[21,d] E. Govorkova,[43] J. P. Grabowski,[12] R. Graciani Diaz,[38] L. A. Granado Cardoso,[40] E. Graugés,[38] E. Graverini,[42] G. Graziani,[18] A. Grecu,[30] R. Greim,[9] P. Griffith,[16] L. Grillo,[21,40,d] L. Gruber,[40] B. R. Gruberg Cazon,[57] O. Grünberg,[67] E. Gushchin,[34] Yu. Guz,[37] T. Gys,[40] C. Göbel,[62] T. Hadavizadeh,[57] C. Hadjivasiliou,[5] G. Haefeli,[41] C. Haen,[40] S. C. Haines,[49] B. Hamilton,[60] X. Han,[12] T. H. Hancock,[57] S. Hansmann-Menzemer,[12] N. Harnew,[57] S. T. Harnew,[48] J. Harrison,[56] C. Hasse,[40] M. Hatch,[40] J. He,[63] M. Hecker,[55] K. Heinicke,[10] A. Heister,[9] K. Hennessy,[54] P. Henrard,[5] L. Henry,[70] E. van Herwijnen,[40] M. Heß,[67] A. Hicheur,[2] D. Hill,[57] C. Hombach,[56] P. H. Hopchev,[41] Z. C. Huard,[59] W. Hulsbergen,[43] T. Humair,[55] M. Hushchyn,[35] D. Hutchcroft,[54] P. Ibis,[10] M. Idzik,[28] P. Ilten,[58] R. Jacobsson,[40] J. Jalocha,[57] E. Jans,[43] A. Jawahery,[60] F. Jiang,[3] M. John,[57] D. Johnson,[40] C. R. Jones,[49] C. Joram,[40] B. Jost,[40] N. Jurik,[57] S. Kandybei,[45] M. Karacson,[40] J. M. Kariuki,[48] S. Karodia,[53] N. Kazeev,[35] M. Kecke,[12] M. Kelsey,[61] M. Kenzie,[49] T. Ketel,[44] E. Khairullin,[35] B. Khanji,[12] C. Khurewathanakul,[41] T. Kirn,[9] S. Klaver,[56] K. Klimaszewski,[29] T. Klimkovich,[11] S. Koliiev,[46] M. Kolpin,[12] I. Komarov,[41] R. Kopecna,[12] P. Koppenburg,[43] A. Kosmyntseva,[32] S. Kotriakhova,[31] M. Kozeiha,[5] L. Kravchuk,[34] M. Kreps,[50] P. Krokovny,[36,f] F. Kruse,[10] W. Krzemien,[29] W. Kucewicz,[27,o] M. Kucharczyk,[27] V. Kudryavtsev,[36,f] A. K. Kuonen,[41] K. Kurek,[29] T. Kvaratskheliya,[32,40] D. Lacarrere,[40] G. Lafferty,[56] A. Lai,[16] G. Lanfranchi,[19] C. Langenbruch,[9] T. Latham,[50] C. Lazzeroni,[47] R. Le Gac,[6] A. Leflat,[33,40] J. Lefrançois,[7] R. Lefèvre,[5] F. Lemaitre,[40] E. Lemos Cid,[39] O. Leroy,[6] T. Lesiak,[27] B. Leverington,[12] P.-R. Li,[63] T. Li,[3] Y. Li,[7] Z. Li,[61] T. Likhomanenko,[68] R. Lindner,[40] F. Lionetto,[42] V. Lisovskyi,[7] X. Liu,[3] D. Loh,[50] A. Loi,[16] I. Longstaff,[53] J. H. Lopes,[2] D. Lucchesi,[23,p] M. Lucio Martinez,[39] H. Luo,[52] A. Lupato,[23] E. Luppi,[17,a] O. Lupton,[40] A. Lusiani,[24] X. Lyu,[63] F. Machefert,[7] F. Maciuc,[30] V. Macko,[41] P. Mackowiak,[10] S. Maddrell-Mander,[48] O. Maev,[31,40] K. Maguire,[56] D. Maisuzenko,[31] M. W. Majewski,[28] S. Malde,[57] A. Malinin,[68] T. Maltsev,[36,f] G. Manca,[16,g] G. Mancinelli,[6] P. Manning,[61] D. Marangotto,[22,m] J. Maratas,[5,q] J. F. Marchand,[4] U. Marconi,[15] C. Marin Benito,[38] M. Marinangeli,[41] P. Marino,[41] J. Marks,[12] G. Martellotti,[26] M. Martin,[6] M. Martinelli,[41] D. Martinez Santos,[39] F. Martinez Vidal,[70] D. Martins Tostes,[2] L. M. Massacrier,[7] A. Massafferri,[1] R. Matev,[40] A. Mathad,[50] Z. Mathe,[40] C. Matteuzzi,[21] A. Mauri,[42] E. Maurice,[7,c] B. Maurin,[41] A. Mazurov,[47] M. McCann,[55,40] A. McNab,[56] R. McNulty,[13] J. V. Mead,[54] B. Meadows,[59] C. Meaux,[6] F. Meier,[10] N. Meinert,[67] D. Melnychuk,[29] M. Merk,[43] A. Merli,[22,40,m] E. Michielin,[23] D. A. Milanes,[66] E. Millard,[50] M.-N. Minard,[4] L. Minzoni,[17] D. S. Mitzel,[12] A. Mogini,[8] J. Molina Rodriguez,[1] T. Mombacher,[10] I. A. Monroy,[66] S. Monteil,[5] M. Morandin,[23] M. J. Morello,[24,k] O. Morgunova,[68] J. Moron,[28] A. B. Morris,[52] R. Mountain,[61] F. Muheim,[52] M. Mulder,[43] D. Müller,[56] J. Müller,[10] K. Müller,[42] V. Müller,[10] P. Naik,[48] T. Nakada,[41] R. Nandakumar,[51] A. Nandi,[57] I. Nasteva,[2] M. Needham,[52] N. Neri,[22,40] S. Neubert,[12] N. Neufeld,[40] M. Neuner,[12] T. D. Nguyen,[41] C. Nguyen-Mau,[41,r] S. Nieswand,[9] R. Niet,[10] N. Nikitin,[33] T. Nikodem,[12] A. Nogay,[68] D. P. O'Hanlon,[50] A. Oblakowska-Mucha,[28] V. Obraztsov,[37] S. Ogilvy,[19] R. Oldeman,[16,g] C. J. G. Onderwater,[71] A. Ossowska,[27] J. M. Otalora Goicochea,[2] P. Owen,[42] A. Oyanguren,[70] P. R. Pais,[41] A. Palano,[14,l] M. Palutan,[19,40] A. Papanestis,[51] M. Pappagallo,[14,l] L. L. Pappalardo,[17,a] W. Parker,[60] C. Parkes,[56] G. Passaleva,[18] A. Pastore,[14,l] M. Patel,[55] C. Patrignani,[15,h] A. Pearce,[40] A. Pellegrino,[43] G. Penso,[26] M. Pepe Altarelli,[40] S. Perazzini,[40] P. Perret,[5] L. Pescatore,[41] K. Petridis,[48] A. Petrolini,[20,j] A. Petrov,[68] M. Petruzzo,[22,m] E. Picatoste Olloqui,[38] B. Pietrzyk,[4] M. Pikies,[27] D. Pinci,[26] A. Pistone,[20,j] A. Piucci,[12] V. Placinta,[30] S. Playfer,[52] M. Plo Casasus,[39] F. Polci,[8] M. Poli Lener,[19] A. Poluektov,[50,36] I. Polyakov,[61] E. Polycarpo,[2] G. J. Pomery,[48] S. Ponce,[40] A. Popov,[37] D. Popov,[11,40] S. Poslavskii,[37] C. Potterat,[2] E. Price,[48] J. Prisciandaro,[39] C. Prouve,[48] V. Pugatch,[46] A. Puig Navarro,[42] H. Pullen,[57] G. Punzi,[24,s] W. Qian,[50] R. Quagliani,[7,48] B. Quintana,[5] B. Rachwal,[28] J. H. Rademacker,[48] M. Rama,[24] M. Ramos Pernas,[39] M. S. Rangel,[2] I. Raniuk,[45] F. Ratnikov,[35] G. Raven,[44] M. Ravonel Salzgeber,[40] M. Reboud,[4] F. Redi,[55] S. Reichert,[10] A. C. dos Reis,[1] C. Remon Alepuz,[70] V. Renaudin,[7] S. Ricciardi,[51] S. Richards,[48] M. Rihl,[40] K. Rinnert,[54] V. Rives Molina,[38] P. Robbe,[7] A. Robert,[8] A. B. Rodrigues,[1] E. Rodrigues,[59] J. A. Rodriguez Lopez,[66] P. Rodriguez Perez,[56] A. Rogozhnikov,[35] S. Roiser,[40] A. Rollings,[57] V. Romanovskiy,[37] A. Romero Vidal,[39] J. W. Ronayne,[13] M. Rotondo,[19] M. S. Rudolph,[61] T. Ruf,[40] P. Ruiz Valls,[70] J. Ruiz Vidal,[70] J. J. Saborido Silva,[39] E. Sadykhov,[32] N. Sagidova,[31] B. Saitta,[16,g] V. Salustino Guimaraes,[1] C. Sanchez Mayordomo,[70] B. Sanmartin Sedes,[39] R. Santacesaria,[26] C. Santamarina Rios,[39] M. Santimaria,[19] E. Santovetti,[25,i] G. Sarpis,[56] A. Sarti,[26] C. Satriano,[26,t] A. Satta,[25] D. M. Saunders,[48] D. Savrina,[32,33] S. Schael,[9] M. Schellenberg,[10] M. Schiller,[53] H. Schindler,[40] M. Schlupp,[10] M. Schmelling,[11] T. Schmelzer,[10] B. Schmidt,[40] O. Schneider,[41] A. Schopper,[40] H. F. Schreiner,[59] K. Schubert,[10] M. Schubiger,[41] M.-H. Schune,[7] R. Schwemmer,[40] B. Sciascia,[19] A. Sciubba,[26,u] A. Semennikov,[32] E. S. Sepulveda,[8] A. Sergi,[47] N. Serra,[42] J. Serrano,[6] L. Sestini,[23] P. Seyfert,[40] M. Shapkin,[37] I. Shapoval,[45] Y. Shcheglov,[31] T. Shears,[54] L. Shekhtman,[36,f] V. Shevchenko,[68] B. G. Siddi,[17,40] R. Silva Coutinho,[42] L. Silva de Oliveira,[2] G. Simi,[23,p] S. Simone,[14,l] M. Sirendi,[49] N. Skidmore,[48] T. Skwarnicki,[61] E. Smith,[55] I. T. Smith,[52] J. Smith,[49] M. Smith,[55] l. Soares Lavra,[1] M. D. Sokoloff,[59] F. J. P. Soler,[53] B. Souza De Paula,[2] B. Spaan,[10] P. Spradlin,[53] S. Sridharan,[40] F. Stagni,[40] M. Stahl,[12] S. Stahl,[40] P. Stefko,[41] S. Stefkova,[55] O. Steinkamp,[42] S. Stemmle,[12] O. Stenyakin,[37] M. Stepanova,[31] H. Stevens,[10] S. Stone,[61] B. Storaci,[42] S. Stracka,[24,s] M. E. Stramaglia,[41] M. Straticiuc,[30] U. Straumann,[42] J. Sun,[3] L. Sun,[64] W. Sutcliffe,[55] K. Swientek,[28] V. Syropoulos,[44] M. Szczekowski,[29] T. Szumlak,[28] M. Szymanski,[63] S. T'Jampens,[4] A. Tayduganov,[6] T. Tekampe,[10] G. Tellarini,[17,a] F. Teubert,[40] E. Thomas,[40] J. van Tilburg,[43] M. J. Tilley,[55] V. Tisserand,[4] M. Tobin,[41] S. Tolk,[49] L. Tomassetti,[17,a] D. Tonelli,[24] F. Toriello,[61] R. Tourinho Jadallah Aoude,[1] E. Tournefier,[4] M. Traill,[53] M. T. Tran,[41] M. Tresch,[42] A. Trisovic,[40] A. Tsaregorodtsev,[6] P. Tsopelas,[43] A. Tully,[49] N. Tuning,[43,40] A. Ukleja,[29] A. Usachov,[7] A. Ustyuzhanin,[35] U. Uwer,[12] C. Vacca,[16,g] A. Vagner,[69] V. Vagnoni,[15,40] A. Valassi,[40] S. Valat,[40] G. Valenti,[15] R. Vazquez Gomez,[19] P. Vazquez Regueiro,[39] S. Vecchi,[17] M. van Veghel,[43] J. J. Velthuis,[48] M. Veltri,[18,v] G. Veneziano,[57] A. Venkateswaran,[61] T. A. Verlage,[9] M. Vernet,[5] M. Vesterinen,[57] J. V. Viana Barbosa,[40] B. Viaud,[7] D. Vieira,[63] M. Vieites Diaz,[39] H. Viemann,[67] X. Vilasis-Cardona,[38,b] M. Vitti,[49] V. Volkov,[33] A. Vollhardt,[42] B. Voneki,[40] A. Vorobyev,[31] V. Vorobyev,[36,f] C. Voß,[9] J. A. de Vries,[43] C. Vázquez Sierra,[39] R. Waldi,[67] C. Wallace,[50] R. Wallace,[13] J. Walsh,[24] J. Wang,[61] D. R. Ward,[49] H. M. Wark,[54] N. K. Watson,[47] D. Websdale,[55] A. Weiden,[42] M. Whitehead,[40] J. Wicht,[50] G. Wilkinson,[57,40] M. Wilkinson,[61] M. Williams,[56] M. P. Williams,[47] M. Williams,[58] T. Williams,[47] F. F. Wilson,[51] J. Wimberley,[60] M. Winn,[7] J. Wishahi,[10] W. Wislicki,[29] M. Witek,[27] G. Wormser,[7] S. A. Wotton,[49] K. Wraight,[53] K. Wyllie,[40] Y. Xie,[65] Z. Xu,[4] Z. Yang,[3] Z. Yang,[60] Y. Yao,[61] H. Yin,[65] J. Yu,[65] X. Yuan,[61] O. Yushchenko,[37] K. A. Zarebski,[47] M. Zavertyaev,[11,w] L. Zhang,[3] Y. Zhang,[7] A. Zhelezov,[12] Y. Zheng,[63] X. Zhu,[3] V. Zhukov,[33] J. B. Zonneveld,[52] and S. Zucchelli[15]

(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]LAPP, Université Savoie Mont-Blanc, CNRS/IN2P3, Annecy-Le-Vieux, France
[5]Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France
[6]Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
[7]LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
[8]LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France
[9]I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany
[10]Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
[11]Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
[12]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[13]School of Physics, University College Dublin, Dublin, Ireland
[14]Sezione INFN di Bari, Bari, Italy
[15]Sezione INFN di Bologna, Bologna, Italy
[16]Sezione INFN di Cagliari, Cagliari, Italy
[17]Universita e INFN, Ferrara, Ferrara, Italy
[18]Sezione INFN di Firenze, Firenze, Italy
[19]Laboratori Nazionali dell'INFN di Frascati, Frascati, Italy
[20]Sezione INFN di Genova, Genova, Italy
[21]Universita e INFN, Milano-Bicocca, Milano, Italy
[22]Sezione di Milano, Milano, Italy
[23]Sezione INFN di Padova, Padova, Italy
[24]Sezione INFN di Pisa, Pisa, Italy
[25]Sezione INFN di Roma Tor Vergata, Roma, Italy
[26]Sezione INFN di Roma La Sapienza, Roma, Italy
[27]Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
[28]AGH—University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
[29]National Center for Nuclear Research (NCBJ), Warsaw, Poland
[30]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
[31]Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
[32]Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
[33]Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
[34]Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
[35]Yandex School of Data Analysis, Moscow, Russia
[36]Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia
[37]Institute for High Energy Physics (IHEP), Protvino, Russia
[38]ICCUB, Universitat de Barcelona, Barcelona, Spain
[39]Universidad de Santiago de Compostela, Santiago de Compostela, Spain
[40]European Organization for Nuclear Research (CERN), Geneva, Switzerland
[41]Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[42]Physik-Institut, Universität Zürich, Zürich, Switzerland
[43]Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands
[44]Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands
[45]NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
[46]Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
[47]University of Birmingham, Birmingham, United Kingdom
[48]H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
[49]Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[50]Department of Physics, University of Warwick, Coventry, United Kingdom
[51]STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
[52]School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[53]School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[54]Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[55]Imperial College London, London, United Kingdom
[56]School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[57]Department of Physics, University of Oxford, Oxford, United Kingdom
[58]Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[59]University of Cincinnati, Cincinnati, Ohio, USA
[60]University of Maryland, College Park, Maryland, USA
[61]Syracuse University, Syracuse, New York, USA
[62]Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil
(associated with Institution Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil)

[63] *University of Chinese Academy of Sciences, Beijing, China (associated with Institution Center for High Energy Physics, Tsinghua University, Beijing, China)*
[64] *School of Physics and Technology, Wuhan University, Wuhan, China (associated with Institution Center for High Energy Physics, Tsinghua University, Beijing, China)*
[65] *Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China (associated with Institution Center for High Energy Physics, Tsinghua University, Beijing, China)*
[66] *Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia (associated with Institution LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France)*
[67] *Institut für Physik, Universität Rostock, Rostock, Germany (associated with Institution Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)*
[68] *National Research Centre Kurchatov Institute, Moscow, Russia (associated with Institution Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia)*
[69] *National Research Tomsk Polytechnic University, Tomsk, Russia (associated with Institution Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia)*
[70] *Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain (associated with Institution ICCUB, Universitat de Barcelona, Barcelona, Spain)*
[71] *Van Swinderen Institute, University of Groningen, Groningen, Netherlands (associated with Institution Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)*

[a] Also at Università di Ferrara, Ferrara, Italy.
[b] Also at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.
[c] Also at Laboratoire Leprince-Ringuet, Palaiseau, France.
[d] Also at Università di Milano Bicocca, Milano, Italy.
[e] Also at Università di Modena e Reggio Emilia, Modena, Italy.
[f] Also at Novosibirsk State University, Novosibirsk, Russia.
[g] Also at Università di Cagliari, Cagliari, Italy.
[h] Also at Università di Bologna, Bologna, Italy.
[i] Also at Università di Roma Tor Vergata, Roma, Italy.
[j] Also at Università di Genova, Genova, Italy.
[k] Also at Scuola Normale Superiore, Pisa, Italy.
[l] Also at Università di Bari, Bari, Italy.
[m] Also at Università degli Studi di Milano, Milano, Italy.
[n] Also at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil.
[o] Also at AGH—University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland.
[p] Also at Università di Padova, Padova, Italy.
[q] Also at Iligan Institute of Technology (IIT), Iligan, Philippines.
[r] Also at Hanoi University of Science, Hanoi, Viet Nam.
[s] Also at Università di Pisa, Pisa, Italy.
[t] Also at Università della Basilicata, Potenza, Italy.
[u] Also at Università di Roma La Sapienza, Roma, Italy.
[v] Also at Università di Urbino, Urbino, Italy.
[w] Also at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.