

Search for Baryon-Number Violating Ξ_b^0 Oscillations

Roel Aaij, Bernardo Adeva, Marco Adinolfi, Ziad Ajaltouni, Simon Akar, Johannes Albrecht, Federico Alessio, Michael Alexander, Alejandro Alfonso Albero, Suvayu Ali, et al.

► To cite this version:

Roel Aaij, Bernardo Adeva, Marco Adinolfi, Ziad Ajaltouni, Simon Akar, et al.. Search for Baryon-Number Violating Ξ_b^0 Oscillations. Physical Review Letters, 2017, 119 (18), pp.181807. 10.1103/PhysRevLett.119.181807. hal-01645918

HAL Id: hal-01645918 https://hal.science/hal-01645918

Submitted on 7 Sep 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)



CERN-EP-2017-189 LHCb-PAPER-2017-023 November 4, 2017

Search for baryon-number-violating Ξ_b^0 oscillations

LHCb collaboration[†]

Abstract

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 $\omega < 0.08 \text{ ps}^{-1}$, where ω is the associated angular frequency.

Published as Phys. Rev. Lett. 119, 181807 (2017)

© CERN on behalf of the LHCb collaboration, licence CC-BY-4.0.

[†]Authors are listed at the end of this Letter.

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 flavour 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 flavour diagonal [12, 13], such as a six-fermion operator that couples two fermions from each generation. This would couple two from each of $\{u, d, e, \nu_e\}, \{c, s, \mu, \nu_\mu\}, \text{ and } \{t, b, \tau, \nu_\tau\}, \text{ with duplication allowed within a generation,}$ e.g. a usbusb 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 flavour-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 $\mathcal{O}(0.1 \text{ ps})$ 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 $\overline{\Xi}_c^-\pi^+$ (or, vice versa, that an antibaryon is produced and decays as a baryon). The strong decays¹ $\Xi_b^{\prime-} \to \Xi_b^0\pi^-$ 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 (a) non-BNV and (b) BNV processes.

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, resulting in a splitting of the baryon and antibaryon energy levels of $\Delta E = 2\vec{\mu} \cdot \vec{B}$. This splitting leads

¹ The inclusion of charge-conjugate processes is implied throughout.



Figure 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 $\overline{\Xi}_b^0$ oscillation followed by a decay to the final state $\overline{\Xi}_c^- \pi^+$.

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 timescale 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 $\leq 10 \text{ mT}$, may be computed. For a typical time of propagation equal to the known Ξ_b^0 lifetime [23] of $1.477 \pm 0.032 \text{ ps}$, $|\Delta E|t/2 \leq 10^{-4}$. This effect can therefore be neglected and, in the limit of small mixing, the ratio of the rate of oscillated decays, $P_{X\to \overline{X}}(t)$, to the rate of nonoscillated decays, $P_{X\to \overline{X}}(t)$, varies over time as

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

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 centre-of-mass energies $\sqrt{s} = 7$ TeV 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 ppinteraction 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 $\Xi_c^+ \to p K^- \pi^+$, 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, $\overline{\Xi}_b^0 \to \overline{\Xi}_c^- \pi^+$ and $\overline{\Xi}_c^- \to \overline{p} K^+ \pi^-$.

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 $\varXi_b^{\prime,*-}$ 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 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 π^{\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 *i*th 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 normalisation of the SS 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 normalisation of the SS background obtained as described above, this fully determines the probability density



Figure 2: Spectra of the mass difference $\delta m \equiv m(\Xi_b^0 \pi) - m(\Xi_b^0) - m_{\pi}$ in data after the full selection, for the opposite-sign (OS) sample (black points with error bars) and same-sign (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 $24 \,\text{MeV}/c^2$, and the δm resolution at these points is approximately 0.2 and $0.5 \,\text{MeV}/c^2$, respectively; the Ξ_b^{*-} also has a non-negligible natural width of $\Gamma \approx 1.7 \,\text{MeV}$ [23]. Inset: detail of the region $2.0 < \delta m < 5.5 \,\text{MeV}/c^2$.

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 parameterised 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 analysed in the same way as data, and its 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.



Figure 3: Distribution of δm vs decay time. The opposite-sign (OS) data are shown as grey points, and the same-sign (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. Due to selection requirements, few candidates are present at short decay times.

An upper limit of $\omega < 0.08 \text{ ps}^{-1}$ at the 95% confidence level is obtained, which corresponds to $\tau_{\text{mix}} > 13 \text{ ps}$. This result can also be expressed in terms of the timeintegrated mixing rate χ , defined as the fraction of particles produced as Ξ_b^0 that decay as $\overline{\Xi}_b^0$, 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 $\omega = 0.08 \text{ ps}^{-1}$ and $\omega = 0.16 \text{ ps}^{-1}$ is shown in Fig. 4, and compared to the SS yield in 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-flavour sector, and is of particular interest since Ξ_b^0 baryons may couple directly to flavour-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 $\omega < 0.08 \text{ ps}^{-1}$ at the 95% confidence level is obtained, equivalent to $\tau_{\text{mix}} > 13 \text{ ps}$. This rules out oscillations with a period comparable to the Ξ_b^0 lifetime, as proposed in Ref. [15].

Acknowledgements

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:



Figure 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.

CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (The 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 (The 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).

References

- [1] A. D. Sakharov, Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe, Pisma Zh. Eksp. Teor. Fiz. 5 (1967) 32, [JETP Lett. 5 (1967) 24].
- [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** (1964) 138.
- BaBar collaboration, B. Aubert et al., Observation of CP violation in the B⁰ meson system, Phys. Rev. Lett. 87 (2001) 091801, arXiv:hep-ex/0107013.
- Belle collaboration, K. Abe et al., Observation of large CP violation in the neutral B meson system, Phys. Rev. Lett. 87 (2001) 091802, arXiv:hep-ex/0107061.
- [5] M. B. Gavela, P. Hernández, J. Orloff, and O. Pène, Standard model CP violation and baryon asymmetry, Mod. Phys. Lett. A9 (1994) 795, arXiv:hep-ph/9312215.
- [6] M. B. Gavela et al., Standard model CP violation and baryon asymmetry. Part 2: Finite temperature, Nucl. Phys. B430 (1994) 382, arXiv:hep-ph/9406289.
- [7] Particle Data Group, C. Patrignani *et al.*, *Review of particle physics*, Chin. Phys. C40 (2016) 100001, and 2017 update.
- [8] A. Salam and J. A. Strathdee, Supersymmetry and fermion number conservation, Nucl. Phys. B87 (1975) 85.
- [9] P. Fayet, Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino, Nucl. Phys. **B90** (1975) 104.
- [10] S. Weinberg, Supersymmetry at ordinary energies. Masses and conservation laws, Phys. Rev. D26 (1982) 287.
- [11] G. R. Farrar and S. Weinberg, Supersymmetry at ordinary energies. II. R invariance, Goldstone bosons, and gauge fermion masses, Phys. Rev. D27 (1983) 2732.
- [12] C. Smith, Proton stability from a fourth family, Phys. Rev. D85 (2012) 036005, arXiv:1105.1723.
- [13] G. Durieux, J.-M. Gérard, F. Maltoni, and C. Smith, Three-generation baryon and lepton number violation at the LHC, Phys. Lett. B721 (2013) 82, arXiv:1210.6598.

- [14] K. Aitken, D. McKeen, A. E. Nelson, and T. Neder, Baryogenesis from oscillations of charmed or beautiful baryons, Phys. Rev. D96 (2017) 075009, arXiv:1708.01259.
- [15] V. A. Kuzmin, Might fast B-violating transitions be found soon?, in Future prospects of baryon instability search in p decay and n → n oscillation experiments: Proceedings, international workshop, Oak Ridge, US, 28-30 Mar, 1996, p. 89, 1996. arXiv:hep-ph/9609253.
- [16] J. D. Bjorken, What lies ahead?, in The project, the progress, the physics: Proceedings of the 1991 symposium on the Superconducting Supercollider Laboratory 13-17 Oct. 1991 Corpus Christi, Texas, p. 651, 1991. SLAC-PUB-5673.
- [17] D. McKeen and A. E. Nelson, CP violating baryon oscillations, Phys. Rev. D94 (2016) 076002, arXiv:1512.05359.
- [18] LHCb collaboration, R. Aaij *et al.*, Observation of two new Ξ_b^- baryon resonances, Phys. Rev. Lett. **114** (2015) 062004, arXiv:1411.4849.
- [19] P. F. Harrison and H. R. Quinn, The BABAR physics book: Physics at an asymmetric B factory, SLAC-R-504, 1998.
- [20] BaBar and Belle collaborations, A. J. Bevan et al., The physics of the B factories, Eur. Phys. J. C74 (2014) 3026, arXiv:1406.6311.
- [21] Heavy Flavor Averaging Group, Y. Amhis et al., 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. Rept. 612 (2016) 1, arXiv:1410.1100.
- [23] LHCb collaboration, R. Aaij et al., Precision measurement of the mass and lifetime of the Ξ⁰_b baryon, Phys. Rev. Lett. **113** (2014) 032001, arXiv:1405.7223.
- [24] LHCb collaboration, A. A. Alves Jr. et al., The LHCb detector at the LHC, JINST 3 (2008) S08005.
- [25] LHCb collaboration, R. Aaij et al., LHCb detector performance, Int. J. Mod. Phys. A30 (2015) 1530022, arXiv:1412.6352.
- [26] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. 178 (2008) 852, arXiv:0710.3820; T. Sjöstrand, S. Mrenna, and P. Skands, PYTHIA 6.4 physics and manual, JHEP 05 (2006) 026, arXiv:hep-ph/0603175.
- [27] I. Belyaev et al., Handling of the generation of primary events in Gauss, the LHCb simulation framework, J. Phys. Conf. Ser. 331 (2011) 032047.
- [28] D. J. Lange, The EvtGen particle decay simulation package, Nucl. Instrum. Meth. A462 (2001) 152.

- [29] P. Golonka and Z. Was, PHOTOS Monte Carlo: A precision tool for QED corrections in Z and W decays, Eur. Phys. J. C45 (2006) 97, arXiv:hep-ph/0506026.
- [30] Geant4 collaboration, J. Allison et al., Geant4 developments and applications, IEEE Trans. Nucl. Sci. 53 (2006) 270; Geant4 collaboration, S. Agostinelli et al., Geant4: A simulation toolkit, Nucl. Instrum. Meth. A506 (2003) 250.
- [31] M. Clemencic et al., The LHCb simulation application, Gauss: Design, evolution and experience, J. Phys. Conf. Ser. 331 (2011) 032023.
- [32] LHCb collaboration, R. Aaij et al., First observation of $D^0 \overline{D}{}^0$ oscillations in $D^0 \to K^+ \pi^+ \pi^- \pi^-$ decays and a measurement of the associated coherence parameters, Phys. Rev. Lett. **116** (2016) 241801, arXiv:1602.07224.
- [33] A. L. Read, Presentation of search results: The CL_s technique, J. Phys. **G28** (2002) 2693.
- [34] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihoodbased tests of new physics, Eur. Phys. J. C71 (2011) 1554, arXiv:1007.1727.

LHCb collaboration

R. Aaij⁴⁰, B. Adeva³⁹, M. Adinolfi⁴⁸, Z. Ajaltouni⁵, S. Akar⁵⁹, J. Albrecht¹⁰, F. Alessio⁴⁰, M. Alexander⁵³, A. Alfonso Albero³⁸, S. Ali⁴³, G. Alkhazov³¹, P. Alvarez Cartelle⁵⁵, A.A. Alves Jr⁵⁹, S. Amato², S. Amerio²³, Y. Amhis⁷, L. An³, L. Anderlini¹⁸, G. Andreassi⁴¹, M. Andreotti^{17,g}, J.E. Andrews⁶⁰, R.B. Appleby⁵⁶, F. Archilli⁴³, P. d'Argent¹², J. Arnau Romeu⁶, A. Artamonov³⁷, M. Artuso⁶¹, E. Aslanides⁶, G. Auriemma²⁶, M. Baalouch⁵, I. Babuschkin⁵⁶, S. Bachmann¹², J.J. Back⁵⁰, A. Badalov^{38,m}, C. Baesso⁶², S. Baker⁵⁵, V. Balagura^{7,b}, W. Baldini¹⁷, A. Baranov³⁵, R.J. Barlow⁵⁶, C. Barschel⁴⁰, S. Barsuk⁷, W. Barter⁵⁶, F. Baryshnikov³², V. Batozskaya²⁹, V. Battista⁴¹, A. Bay⁴¹, L. Beaucourt⁴, J. Beddow⁵³, F. Bedeschi²⁴, I. Bediaga¹, A. Beiter⁶¹, L.J. Bel⁴³, N. Beliy⁶³, V. Bellee⁴¹, N. Belloli^{21,i}, K. Belous³⁷, I. Belyaev³², E. Ben-Haim⁸, G. Bencivenni¹⁹, S. Benson⁴³, S. Beranek⁹, A. Berezhnoy³³, R. Bernet⁴², D. Berninghoff¹², E. Bertholet⁸, A. Bertolin²³, C. Betancourt⁴², F. Betti¹⁵, M.-O. Bettler⁴⁰, M. van Beuzekom⁴³, Ia. Bezshyiko⁴², S. Bifani⁴⁷, P. Billoir⁸, A. Birnkraut¹⁰, A. Bitadze⁵⁶, A. Bizzeti^{18,u}, M. Bjørn⁵⁷, T. Blake⁵⁰, F. Blanc⁴¹, J. Blouw^{11,†}, S. Blusk⁶¹, V. Bocci²⁶, T. Boettcher⁵⁸, A. Bondar^{36,w}, N. Bondar³¹, W. Bonivento¹⁶, I. Bordyuzhin³², A. Borgheresi^{21,i}, S. Borghi⁵⁶, M. Borisyak³⁵, M. Borsato³⁹, F. Bossu⁷, M. Boubdir⁹, T.J.V. Bowcock⁵⁴, E. Bowen⁴², C. Bozzi^{17,40}, S. Braun¹², T. Britton⁶¹, J. Brodzicka²⁷, D. Brundu¹⁶, E. Buchanan⁴⁸, C. Burr⁵⁶, A. Bursche^{16,f}, J. Buytaert⁴⁰, W. Byczynski⁴⁰, S. Cadeddu¹⁶, H. Cai⁶⁴, R. Calabrese^{17,g}, R. Calladine⁴⁷, M. Calvi^{21,i}, M. Calvo Gomez^{38,m}, A. Camboni^{38,m}, P. Campana¹⁹, D.H. Campora Perez⁴⁰, L. Capriotti⁵⁶, A. Carbone^{15,e}, G. Carboni^{25,j}, R. Cardinale^{20,h}, A. Cardini¹⁶, P. Carniti^{21,i}, L. Carson⁵², K. Carvalho Akiba², G. Casse⁵⁴, L. Cassina²¹, L. Castillo Garcia⁴¹, M. Cattaneo⁴⁰, G. Cavallero^{20,40,h}, R. Cenci^{24,t}, D. Chamont⁷, M. Charles⁸, Ph. Charpentier⁴⁰, G. Chatzikonstantinidis⁴⁷, M. Chefdeville⁴, S. Chen⁵⁶, S.F. Cheung⁵⁷, S.-G. Chitic⁴⁰, V. Chobanova³⁹, M. Chrzaszcz^{42,27}, A. Chubykin³¹, P. Ciambrone¹⁹, X. Cid Vidal³⁹, G. Ciezarek⁴³, P.E.L. Clarke⁵², M. Clemencic⁴⁰, H.V. Cliff⁴⁹, J. Closier⁴⁰, J. Cogan⁶, E. Cogneras⁵, V. Cogoni^{16, f}, L. Cojocariu³⁰, P. Collins⁴⁰, T. Colombo⁴⁰, A. Comerma-Montells¹², A. Contu⁴⁰, A. Cook⁴⁸, G. Coombs⁴⁰, S. Coquereau³⁸, G. Corti⁴⁰, M. Corvo^{17,g}, C.M. Costa Sobral⁵⁰, B. Couturier⁴⁰, G.A. Cowan⁵², D.C. Craik⁵⁸, A. Crocombe⁵⁰, M. Cruz Torres¹, R. Currie⁵², C. D'Ambrosio⁴⁰, F. Da Cunha Marinho², E. Dall'Occo⁴³, J. Dalseno⁴⁸, A. Davis³, O. De Aguiar Francisco⁵⁴, S. De Capua⁵⁶, M. De Cian¹², J.M. De Miranda¹, L. De Paula², M. De Serio^{14,d}, P. De Simone¹⁹, C.T. Dean⁵³, D. Decamp⁴, L. Del Buono⁸, H.-P. Dembinski¹¹, M. Demmer¹⁰, A. Dendek²⁸, D. Derkach³⁵, O. Deschamps⁵, F. Dettori⁵⁴, B. Dey⁶⁵, A. Di Canto⁴⁰, P. Di Nezza¹⁹, H. Dijkstra⁴⁰, F. Dordei⁴⁰, M. Dorigo⁴⁰, A. Dosil Suárez³⁹, L. Douglas⁵³, A. Dovbnya⁴⁵, K. Dreimanis⁵⁴, L. Dufour⁴³, G. Dujany⁸, P. Durante⁴⁰, R. Dzhelyadin³⁷, M. Dziewiecki¹², A. Dziurda⁴⁰, A. Dzyuba³¹, S. Easo⁵¹, M. Ebert⁵², U. Egede⁵⁵, V. Egorychev³², S. Eidelman^{36,w}, S. Eisenhardt⁵², U. Eitschberger¹⁰, R. Ekelhof¹⁰, L. Eklund⁵³, S. Ely⁶¹, S. Esen¹², H.M. Evans⁴⁹, T. Evans⁵⁷, A. Falabella¹⁵, N. Farley⁴⁷, S. Farry⁵⁴, D. Fazzini^{21,i}, L. Federici²⁵, D. Ferguson⁵², G. Fernandez³⁸, P. Fernandez Declara⁴⁰, A. Fernandez Prieto³⁹, F. Ferrari¹⁵, F. Ferreira Rodrigues², M. Ferro-Luzzi⁴⁰, S. Filippov³⁴, R.A. Fini¹⁴, M. Fiore^{17,g}, M. Fiorini^{17,g}, M. Firlej²⁸, C. Fitzpatrick⁴¹, T. Fiutowski²⁸, F. Fleuret^{7,b}, K. Fohl⁴⁰, M. Fontana^{16,40}, F. Fontanelli^{20,h}, D.C. Forshaw⁶¹, R. Forty⁴⁰, V. Franco Lima⁵⁴, M. Frank⁴⁰, C. Frei⁴⁰, J. Fu^{22,q}, W. Funk⁴⁰, E. Furfaro^{25,j}, C. Färber⁴⁰, E. Gabriel⁵², A. Gallas Torreira³⁹, D. Galli^{15,e}, S. Gallorini²³, S. Gambetta⁵², M. Gandelman², P. Gandini⁵⁷, Y. Gao³, L.M. Garcia Martin⁷⁰, J. García Pardiñas³⁹, J. Garra Tico⁴⁹, L. Garrido³⁸, P.J. Garsed⁴⁹, D. Gascon³⁸, C. Gaspar⁴⁰, L. Gavardi¹⁰, G. Gazzoni⁵, D. Gerick¹², E. Gersabeck¹², M. Gersabeck⁵⁶, T. Gershon⁵⁰, Ph. Ghez⁴, S. Giani⁴¹, V. Gibson⁴⁹, O.G. Girard⁴¹, L. Giubega³⁰, K. Gizdov⁵², V.V. Gligorov⁸, D. Golubkov³², A. Golutvin^{55,40}, A. Gomes^{1,a}, I.V. Gorelov³³, C. Gotti^{21,i}, E. Govorkova⁴³,

J.P. Grabowski¹², R. Graciani Diaz³⁸, L.A. Granado Cardoso⁴⁰, E. Graugés³⁸, E. Graverini⁴², G. Graziani¹⁸, A. Grecu³⁰, R. Greim⁹, P. Griffith¹⁶, L. Grillo^{21,40,i}, L. Gruber⁴⁰, B.R. Gruberg Cazon⁵⁷, O. Grünberg⁶⁷, E. Gushchin³⁴, Yu. Guz³⁷, T. Gys⁴⁰, C. Göbel⁶², T. Hadavizadeh⁵⁷, C. Hadjivasiliou⁵, G. Haefeli⁴¹, C. Haen⁴⁰, S.C. Haines⁴⁹, B. Hamilton⁶⁰, X. Han¹², T.H. Hancock⁵⁷, S. Hansmann-Menzemer¹², N. Harnew⁵⁷, S.T. Harnew⁴⁸, J. Harrison⁵⁶, C. Hasse⁴⁰, M. Hatch⁴⁰, J. He⁶³, M. Hecker⁵⁵, K. Heinicke¹⁰, A. Heister⁹, K. Hennessy⁵⁴, P. Henrard⁵, L. Henry⁷⁰, E. van Herwijnen⁴⁰, M. Heß⁶⁷, A. Hicheur², D. Hill⁵⁷, C. Hombach⁵⁶, P.H. Hopchev⁴¹, Z.C. Huard⁵⁹, W. Hulsbergen⁴³, T. Humair⁵⁵, M. Hushchyn³⁵, D. Hutchcroft⁵⁴, P. Ibis¹⁰, M. Idzik²⁸, P. Ilten⁵⁸, R. Jacobsson⁴⁰, J. Jalocha⁵⁷, E. Jans⁴³, A. Jawahery⁶⁰, F. Jiang³, M. John⁵⁷, D. Johnson⁴⁰, C.R. Jones⁴⁹, C. Joram⁴⁰, B. Jost⁴⁰, N. Jurik⁵⁷, S. Kandybei⁴⁵, M. Karacson⁴⁰, J.M. Kariuki⁴⁸, S. Karodia⁵³, N. Kazeev³⁵, M. Kecke¹², M. Kelsey⁶¹, M. Kenzie⁴⁹, T. Ketel⁴⁴, E. Khairullin³⁵, B. Khanji¹², C. Khurewathanakul⁴¹, T. Kirn⁹, S. Klaver⁵⁶, K. Klimaszewski²⁹, T. Klimkovich¹¹, S. Koliiev⁴⁶, M. Kolpin¹², I. Komarov⁴¹, R. Kopecna¹², P. Koppenburg⁴³, A. Kosmyntseva³², S. Kotriakhova³¹, M. Kozeiha⁵, L. Kravchuk³⁴, M. Kreps⁵⁰, P. Krokovny^{36,w}, F. Kruse¹⁰, W. Krzemien²⁹, W. Kucewicz^{27,l}, M. Kucharczyk²⁷, V. Kudryavtsev^{36,w}, A.K. Kuonen⁴¹, K. Kurek²⁹, T. Kvaratskheliya^{32,40}, D. Lacarrere⁴⁰, G. Lafferty⁵⁶, A. Lai¹⁶, G. Lanfranchi¹⁹, C. Langenbruch⁹, T. Latham⁵⁰, C. Lazzeroni⁴⁷, R. Le Gac⁶, A. Leflat^{33,40}, J. Lefrançois⁷, R. Lefèvre⁵, F. Lemaitre⁴⁰, E. Lemos Cid³⁹, O. Leroy⁶, T. Lesiak²⁷, B. Leverington¹², P.-R. Li⁶³, T. Li³, Y. Li⁷, Z. Li⁶¹, T. Likhomanenko⁶⁸, R. Lindner⁴⁰, F. Lionetto⁴², V. Lisovskyi⁷, X. Liu³, D. Loh⁵⁰, A. Loi¹⁶, I. Longstaff⁵³, J.H. Lopes², D. Lucchesi^{23,o}, M. Lucio Martinez³⁹, H. Luo⁵², A. Lupato²³, E. Luppi^{17,g}, O. Lupton⁴⁰, A. Lusiani²⁴, X. Lyu⁶³ F. Machefert⁷, F. Maciuc³⁰, V. Macko⁴¹, P. Mackowiak¹⁰, S. Maddrell-Mander⁴⁸, O. Maev^{31,40}, K. Maguire⁵⁶, D. Maisuzenko³¹, M.W. Majewski²⁸, S. Malde⁵⁷, A. Malinin⁶⁸, T. Maltsev^{36,w}, G. Manca^{16,f}, G. Mancinelli⁶, P. Manning⁶¹, D. Marangotto^{22,q}, J. Maratas^{5,v}, J.F. Marchand⁴, U. Marconi¹⁵, C. Marin Benito³⁸, M. Marinangeli⁴¹, P. Marino⁴¹, J. Marks¹², G. Martellotti²⁶, M. Martin⁶, M. Martinelli⁴¹, D. Martinez Santos³⁹, F. Martinez Vidal⁷⁰, D. Martins Tostes², L.M. Massacrier⁷, A. Massafferri¹, R. Matev⁴⁰, A. Mathad⁵⁰, Z. Mathe⁴⁰, C. Matteuzzi²¹, A. Mauri⁴², E. Maurice^{7,b}, B. Maurin⁴¹, A. Mazurov⁴⁷, M. McCann^{55,40}, A. McNab⁵⁶, R. McNulty¹³, J.V. Mead⁵⁴, B. Meadows⁵⁹, C. Meaux⁶, F. Meier¹⁰, N. Meinert⁶⁷, D. Melnychuk²⁹, M. Merk⁴³, A. Merli^{22,40,q}, E. Michielin²³, D.A. Milanes⁶⁶, E. Millard⁵⁰, M.-N. Minard⁴, L. Minzoni¹⁷, D.S. Mitzel¹², A. Mogini⁸, J. Molina Rodriguez¹, T. Mombacher¹⁰, I.A. Monroy⁶⁶, S. Monteil⁵, M. Morandin²³, M.J. Morello^{24,t}, O. Morgunova⁶⁸, J. Moron²⁸, A.B. Morris⁵², R. Mountain⁶¹, F. Muheim⁵², M. Mulder⁴³, D. Müller⁵⁶, J. Müller¹⁰, K. Müller⁴², V. Müller¹⁰, P. Naik⁴⁸, T. Nakada⁴¹, R. Nandakumar⁵¹, A. Nandi⁵⁷, I. Nasteva², M. Needham⁵², N. Neri^{22,40}, S. Neubert¹², N. Neufeld⁴⁰, M. Neuner¹², T.D. Nguyen⁴¹, C. Nguyen-Mau^{41,n}, S. Nieswand⁹, R. Niet¹⁰, N. Nikitin³³, T. Nikodem¹², A. Nogay⁶⁸, D.P. O'Hanlon⁵⁰, A. Oblakowska-Mucha²⁸, V. Obraztsov³⁷, S. Ogilvy¹⁹, R. Oldeman^{16,f}, C.J.G. Onderwater⁷¹, A. Ossowska²⁷, J.M. Otalora Goicochea², P. Owen⁴², A. Oyanguren⁷⁰, P.R. Pais⁴¹, A. Palano^{14,d}, M. Palutan^{19,40}, A. Papanestis⁵¹, M. Pappagallo^{14,d}, L.L. Pappalardo^{17,g}, W. Parker⁶⁰, C. Parkes⁵⁶, G. Passaleva¹⁸, A. Pastore^{14,d}, M. Patel⁵⁵, C. Patrignani^{15,e}, A. Pearce⁴⁰, A. Pellegrino⁴³, G. Penso²⁶, M. Pepe Altarelli⁴⁰, S. Perazzini⁴⁰, P. Perret⁵, L. Pescatore⁴¹, K. Petridis⁴⁸, A. Petrolini^{20,h}, A. Petrov⁶⁸, M. Petruzzo^{22,q}, E. Picatoste Olloqui³⁸, B. Pietrzyk⁴, M. Pikies²⁷, D. Pinci²⁶, A. Pistone^{20,h}, A. Piucci¹², V. Placinta³⁰, S. Playfer⁵², M. Plo Casasus³⁹, F. Polci⁸, M. Poli Lener¹⁹, A. Poluektov^{50,36}, I. Polyakov⁶¹, E. Polycarpo², G.J. Pomery⁴⁸, S. Ponce⁴⁰, A. Popov³⁷, D. Popov^{11,40}, S. Poslavskii³⁷, C. Potterat², E. Price⁴⁸, J. Prisciandaro³⁹, C. Prouve⁴⁸, V. Pugatch⁴⁶, A. Puig Navarro⁴², H. Pullen⁵⁷, G. Punzi^{24,p}, W. Qian⁵⁰, R. Quagliani^{7,48}, B. Quintana⁵, B. Rachwal²⁸, J.H. Rademacker⁴⁸, M. Rama²⁴, M. Ramos Pernas³⁹, M.S. Rangel², I. Raniuk^{45,†},

F. Ratnikov³⁵, G. Raven⁴⁴, M. Ravonel Salzgeber⁴⁰, M. Reboud⁴, F. Redi⁵⁵, S. Reichert¹⁰,

A.C. dos Reis¹, C. Remon Alepuz⁷⁰, V. Renaudin⁷, S. Ricciardi⁵¹, S. Richards⁴⁸, M. Rihl⁴⁰, K. Rinnert⁵⁴, V. Rives Molina³⁸, P. Robbe⁷, A. Robert⁸, A.B. Rodrigues¹, E. Rodrigues⁵⁹, J.A. Rodriguez Lopez⁶⁶, P. Rodriguez Perez^{56,†}, A. Rogozhnikov³⁵, S. Roiser⁴⁰, A. Rollings⁵⁷, V. Romanovskiy³⁷, A. Romero Vidal³⁹, J.W. Ronayne¹³, M. Rotondo¹⁹, M.S. Rudolph⁶¹, T. Ruf⁴⁰, P. Ruiz Valls⁷⁰, J. Ruiz Vidal⁷⁰, J.J. Saborido Silva³⁹, E. Sadykhov³², N. Sagidova³¹, B. Saitta^{16,f}, V. Salustino Guimaraes¹, C. Sanchez Mayordomo⁷⁰, B. Sanmartin Sedes³⁹ R. Santacesaria²⁶, C. Santamarina Rios³⁹, M. Santimaria¹⁹, E. Santovetti^{25,j}, G. Sarpis⁵⁶, A. Sarti²⁶, C. Satriano^{26,s}, A. Satta²⁵, D.M. Saunders⁴⁸, D. Savrina^{32,33}, S. Schael⁹, M. Schellenberg¹⁰, M. Schiller⁵³, H. Schindler⁴⁰, M. Schlupp¹⁰, M. Schmelling¹¹, T. Schmelzer¹⁰, B. Schmidt⁴⁰, O. Schneider⁴¹, A. Schopper⁴⁰, H.F. Schreiner⁵⁹, K. Schubert¹⁰, M. Schubiger⁴¹, M.-H. Schune⁷, R. Schwemmer⁴⁰, B. Sciascia¹⁹, A. Sciubba^{26,k}, A. Semennikov³², E.S. Sepulveda⁸, A. Sergi⁴⁷, N. Serra⁴², J. Serrano⁶, L. Sestini²³, P. Seyfert⁴⁰, M. Shapkin³⁷, I. Shapoval⁴⁵, Y. Shcheglov³¹, T. Shears⁵⁴, L. Shekhtman^{36,w}, V. Shevchenko⁶⁸, B.G. Siddi^{17,40}, R. Silva Coutinho⁴², L. Silva de Oliveira², G. Simi^{23,o}, S. Simone^{14,d}, M. Sirendi⁴⁹, N. Skidmore⁴⁸, T. Skwarnicki⁶¹, E. Smith⁵⁵, I.T. Smith⁵², J. Smith⁴⁹, M. Smith⁵⁵, l. Soares Lavra¹, M.D. Sokoloff⁵⁹, F.J.P. Soler⁵³, B. Souza De Paula², B. Spaan¹⁰, P. Spradlin⁵³, S. Sridharan⁴⁰, F. Stagni⁴⁰, M. Stahl¹², S. Stahl⁴⁰, P. Stefko⁴¹, S. Stefkova⁵⁵, O. Steinkamp⁴², S. Stemmle¹², O. Stenyakin³⁷, M. Stepanova³¹, H. Stevens¹⁰, S. Stone⁶¹, B. Storaci⁴², S. Stracka^{24,p}, M.E. Stramaglia⁴¹, M. Straticiuc³⁰, U. Straumann⁴², J. Sun³, L. Sun⁶⁴, W. Sutcliffe⁵⁵, K. Swientek²⁸, V. Syropoulos⁴⁴, M. Szczekowski²⁹, T. Szumlak²⁸, M. Szymanski⁶³, S. T'Jampens⁴, A. Tayduganov⁶, T. Tekampe¹⁰, G. Tellarini^{17,g}, F. Teubert⁴⁰, E. Thomas⁴⁰, J. van Tilburg⁴³, M.J. Tilley⁵⁵, V. Tisserand⁴, M. Tobin⁴¹, S. Tolk⁴⁹, L. Tomassetti^{17,g}, D. Tonelli²⁴, F. Toriello⁶¹, R. Tourinho Jadallah Aoude¹, E. Tournefier⁴, M. Traill⁵³, M.T. Tran⁴¹, M. Tresch⁴², A. Trisovic⁴⁰, A. Tsaregorodtsev⁶, P. Tsopelas⁴³, A. Tully⁴⁹, N. Tuning^{43,40}, A. Ukleja²⁹, A. Usachov⁷, A. Ustyuzhanin³⁵, U. Uwer¹², C. Vacca^{16,f}, A. Vagner⁶⁹, V. Vagnoni^{15,40}, A. Valassi⁴⁰, S. Valat⁴⁰, G. Valenti¹⁵, R. Vazquez Gomez¹⁹, P. Vazquez Regueiro³⁹, S. Vecchi¹⁷, M. van Veghel⁴³, J.J. Velthuis⁴⁸, M. Veltri^{18,r}, G. Veneziano⁵⁷, A. Venkateswaran⁶¹, T.A. Verlage⁹, M. Vernet⁵, M. Vesterinen⁵⁷, J.V. Viana Barbosa⁴⁰, B. Viaud⁷, D. Vieira⁶³, M. Vieites Diaz³⁹, H. Viemann⁶⁷, X. Vilasis-Cardona^{38,m}, M. Vitti⁴⁹, V. Volkov³³, A. Vollhardt⁴², B. Voneki⁴⁰, A. Vorobyev³¹, V. Vorobyev^{36,w}, C. Voß⁹, J.A. de Vries⁴³, C. Vázquez Sierra³⁹, R. Waldi⁶⁷, C. Wallace⁵⁰, R. Wallace¹³, J. Walsh²⁴, J. Wang⁶¹, D.R. Ward⁴⁹, H.M. Wark⁵⁴, N.K. Watson⁴⁷, D. Websdale⁵⁵, A. Weiden⁴², M. Whitehead⁴⁰, J. Wicht⁵⁰, G. Wilkinson^{57,40}, M. Wilkinson⁶¹. M. Williams⁵⁶, M.P. Williams⁴⁷, M. Williams⁵⁸, T. Williams⁴⁷, F.F. Wilson⁵¹, J. Wimberley⁶⁰, M. Winn⁷, J. Wishahi¹⁰, W. Wislicki²⁹, M. Witek²⁷, G. Wormser⁷, S.A. Wotton⁴⁹, K. Wraight⁵³, K. Wyllie⁴⁰, Y. Xie⁶⁵, Z. Xu⁴, Z. Yang³, Z. Yang⁶⁰, Y. Yao⁶¹, H. Yin⁶⁵, J. Yu⁶⁵, X. Yuan⁶¹, O. Yushchenko³⁷, K.A. Zarebski⁴⁷, M. Zavertyaev^{11,c}, L. Zhang³, Y. Zhang⁷, A. Zhelezov¹², Y. Zheng⁶³, X. Zhu³, V. Zhukov³³, J.B. Zonneveld⁵², S. Zucchelli¹⁵.

- ¹Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil
- ² Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
- ³Center for High Energy Physics, Tsinghua University, Beijing, China
- ⁴LAPP, Université Savoie Mont-Blanc, CNRS/IN2P3, Annecy-Le-Vieux, France
- ⁵Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France
- ⁶Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
- ⁷LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
- ⁸LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France
- ⁹I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany
- ¹⁰ Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
- ¹¹Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
- ¹²Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ¹³School of Physics, University College Dublin, Dublin, Ireland

¹⁴Sezione INFN di Bari, Bari, Italy

¹⁵Sezione INFN di Bologna, Bologna, Italy

¹⁶Sezione INFN di Cagliari, Cagliari, Italy

¹⁷ Universita e INFN, Ferrara, Ferrara, Italy

¹⁸Sezione INFN di Firenze, Firenze, Italy

¹⁹Laboratori Nazionali dell'INFN di Frascati, Frascati, Italy

²⁰Sezione INFN di Genova, Genova, Italy

²¹ Universita & INFN, Milano-Bicocca, Milano, Italy

²²Sezione di Milano, Milano, Italy

²³Sezione INFN di Padova, Padova, Italy

²⁴Sezione INFN di Pisa, Pisa, Italy

²⁵Sezione INFN di Roma Tor Vergata, Roma, Italy

²⁶Sezione INFN di Roma La Sapienza, Roma, Italy

²⁷Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
²⁸AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science,

Kraków, Poland

²⁹National Center for Nuclear Research (NCBJ), Warsaw, Poland

³⁰Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania

³¹Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia

³²Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia

³³Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia

³⁴Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia

³⁵ Yandex School of Data Analysis, Moscow, Russia

³⁶Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia

³⁷Institute for High Energy Physics (IHEP), Protvino, Russia

³⁸ICCUB, Universitat de Barcelona, Barcelona, Spain

³⁹Universidad de Santiago de Compostela, Santiago de Compostela, Spain

⁴⁰European Organization for Nuclear Research (CERN), Geneva, Switzerland

⁴¹Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

⁴²Physik-Institut, Universität Zürich, Zürich, Switzerland

⁴³Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands

⁴⁴Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands

⁴⁵NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine

⁴⁶Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine

⁴⁷ University of Birmingham, Birmingham, United Kingdom

⁴⁸H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom

⁴⁹Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

⁵⁰Department of Physics, University of Warwick, Coventry, United Kingdom

⁵¹STFC Rutherford Appleton Laboratory, Didcot, United Kingdom

⁵²School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

⁵³School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

⁵⁴Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

⁵⁵Imperial College London, London, United Kingdom

⁵⁶School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

⁵⁷Department of Physics, University of Oxford, Oxford, United Kingdom

⁵⁸ Massachusetts Institute of Technology, Cambridge, MA, United States

⁵⁹ University of Cincinnati, Cincinnati, OH, United States

⁶⁰ University of Maryland, College Park, MD, United States

⁶¹Syracuse University, Syracuse, NY, United States

⁶²Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to ²

⁶³University of Chinese Academy of Sciences, Beijing, China, associated to ³

⁶⁴School of Physics and Technology, Wuhan University, Wuhan, China, associated to ³

⁶⁵Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China, associated to ³

⁶⁶Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia, associated to ⁸

⁶⁷Institut für Physik, Universität Rostock, Rostock, Germany, associated to ¹²

⁶⁸National Research Centre Kurchatov Institute, Moscow, Russia, associated to ³²

⁶⁹National Research Tomsk Polytechnic University, Tomsk, Russia, associated to ³²

⁷⁰Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain, associated to ³⁸

⁷¹ Van Swinderen Institute, University of Groningen, Groningen, The Netherlands, associated to ⁴³

^a Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil

^bLaboratoire Leprince-Ringuet, Palaiseau, France

^cP.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia

^d Università di Bari, Bari, Italy

^e Università di Bologna, Bologna, Italy

^f Università di Cagliari, Cagliari, Italy

^g Università di Ferrara, Ferrara, Italy

^hUniversità di Genova, Genova, Italy

ⁱUniversità di Milano Bicocca, Milano, Italy

^j Università di Roma Tor Vergata, Roma, Italy

^k Università di Roma La Sapienza, Roma, Italy

¹AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland

^mLIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain

ⁿHanoi University of Science, Hanoi, Viet Nam

^o Università di Padova, Padova, Italy

^pUniversità di Pisa, Pisa, Italy

^q Università degli Studi di Milano, Milano, Italy

^r Università di Urbino, Urbino, Italy

^s Università della Basilicata, Potenza, Italy

^tScuola Normale Superiore, Pisa, Italy

^u Università di Modena e Reggio Emilia, Modena, Italy

 $^{v}\mathit{Iligan}$ Institute of Technology (IIT), Iligan, Philippines

 $^w Novosibirsk \ State \ University, \ Novosibirsk, \ Russia$

 $^{\dagger}Deceased$