



Measurement of the Charm-Mixing Parameter y_{CP}

Roel Aaij, Carlos Abellán Beteta, Bernardo Adeva, Marco Adinolfi, Christine Angela Aidala, Ziad Ajaltouni, Simon Akar, Pietro Albicocco, Johannes Albrecht, Federico Alessio, et al.

► To cite this version:

Roel Aaij, Carlos Abellán Beteta, Bernardo Adeva, Marco Adinolfi, Christine Angela Aidala, et al.. Measurement of the Charm-Mixing Parameter y_{CP} . Phys.Rev.Lett., 2019, 122 (1), pp.011802. 10.1103/PhysRevLett.122.011802 . hal-01909261

HAL Id: hal-01909261

<https://hal.science/hal-01909261>

Submitted on 23 Nov 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.



CERN-EP-2018-270
LHCb-PAPER-2018-038
October 16, 2018

Measurement of the charm-mixing parameter y_{CP}

LHCb collaboration[†]

Abstract

A measurement of the charm-mixing parameter y_{CP} using $D^0 \rightarrow K^+ K^-$, $D^0 \rightarrow \pi^+ \pi^-$, and $D^0 \rightarrow K^- \pi^+$ decays is reported. The D^0 mesons are required to originate from semimuonic decays of B^- and $\bar{B}^0$ mesons. These decays are partially reconstructed in a data set of proton-proton collisions at center-of-mass energies of 7 and 8 TeV collected with the LHCb experiment and corresponding to an integrated luminosity of 3 fb^{-1} . The y_{CP} parameter is measured to be $(0.57 \pm 0.13 \text{ (stat)} \pm 0.09 \text{ (syst)})\%$, in agreement with, and as precise as, the current world-average value.

Published in Phys. Rev. Lett. 122 (2019) 011802

© 2019 CERN for the benefit of the LHCb collaboration. CC-BY-4.0 licence.

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

Neutral charm mesons can change their flavor and turn into antimesons, and vice versa, before they decay. This phenomenon, known as flavor oscillation or D^0 – $\bar{D}^0$ mixing, occurs because the eigenstates of the Hamiltonian governing the time evolution of the neutral D system are superpositions of the flavor eigenstates, $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$, where p and q are complex parameters satisfying $|p|^2 + |q|^2 = 1$. In the limit of charge-parity (CP) symmetry, q equals p and the oscillations are characterized by only two dimensionless parameters, $x \equiv (m_1 - m_2)/\Gamma$ and $y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$, where $m_{1(2)}$ and $\Gamma_{1(2)}$ are the mass and decay width of the CP -even (odd) eigenstate $D_{1(2)}$, respectively, and $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$ is the average decay width [1]. The values of x and y are of the order of 1% or smaller [2]. In the presence of CP violation, the mixing rates for mesons produced as D^0 and $\bar{D}^0$ differ, further enriching the phenomenology.

Because of D^0 – $\bar{D}^0$ mixing, the *effective* decay width Γ_{CP+} of decays to CP -even final states, such as h^+h^- ($h = K, \pi$), differs from the average width Γ . The latter can be measured in decays that involve an equal mixture of CP -even and CP -odd states, such as $D^0 \rightarrow K^-\pi^+$.¹ The quantity

$$y_{CP} \equiv \frac{\Gamma_{CP+}}{\Gamma} - 1 \quad (1)$$

is equal to the mixing parameter y if CP symmetry is conserved. Otherwise, it is related to x , y , $|q/p|$, and $\phi \equiv \arg(q\bar{\mathcal{A}}/p\mathcal{A})$, as $2y_{CP} \approx (|q/p| + |p/q|)y \cos \phi - (|q/p| - |p/q|)x \sin \phi$, where $\mathcal{A}$ ($\bar{\mathcal{A}}$) is the D^0 ($\bar{D}^0$) decay amplitude [3, 4]. The approximation holds for decays, such as $D^0 \rightarrow h^+h^-$, that can be described by a single amplitude. Neglecting the $\mathcal{O}(10^{-3})$ difference between the phases of the $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decay amplitudes, ϕ is universal and y_{CP} is independent of the h^+h^- final state.

The current world average value of y_{CP} , $(0.84 \pm 0.16)\%$ [2], is dominated by measurements at the B factories [5, 6] and is consistent with the value of y , $(0.62 \pm 0.07)\%$ [2]. The only measurement of y_{CP} at a hadron collider, $(0.55 \pm 0.63 \text{ (stat)} \pm 0.41 \text{ (syst)})\%$, has been made by the LHCb collaboration using a sample of proton-proton collisions corresponding to an integrated luminosity of 29 pb^{-1} [7]. Improving the precision of both y_{CP} and y might lead to evidence of CP violation in D^0 – $\bar{D}^0$ mixing if they differ significantly. This would offer sensitivity to a broad class of non-standard-model processes that could contribute to the mixing amplitude by increasing the oscillation rate and/or introducing CP -violation effects that are highly suppressed in the standard model [8–13]. Searches for CP violation in the up-quark sector are also complementary to those performed with beauty and strange mesons, thus providing a unique opportunity to make progress in the understanding of the mechanisms responsible for the observed asymmetry between matter and antimatter in the Universe [14, 15].

In this Letter, a measurement of y_{CP} using $D^0 \rightarrow K^+K^-$, $D^0 \rightarrow \pi^+\pi^-$, and $D^0 \rightarrow K^-\pi^+$ decays is reported. The D^0 mesons are required to originate from semimuonic decays of B^- or $\bar{B}^0$ mesons, collectively referred to as $\bar{B} \rightarrow D^0 \mu^- \bar{\nu}_\mu X$. The difference between the widths of D^0 decays to CP -even and CP -mixed final states,

$$\Delta_\Gamma \equiv \Gamma_{CP+} - \Gamma, \quad (2)$$

is measured from a fit to the ratio between $D^0 \rightarrow K^+K^-$ (or $D^0 \rightarrow \pi^+\pi^-$) and $D^0 \rightarrow K^-\pi^+$ signal yields as a function of the D^0 decay time. The parameter y_{CP} is then calculated

¹Throughout this Letter, the inclusion of the charge-conjugate decay mode is implied unless otherwise stated.

from the measured value of Δ_Γ and the precisely known value of Γ [1] as $y_{CP} = \Delta_\Gamma/\Gamma$. The D^0 decay time is defined as $t = (m \vec{L} \cdot \vec{p})/|\vec{p}|^2$, where m is the known value of the D^0 mass [1], $\vec{L}$ is the vector connecting the $\bar{B}$ and the D^0 decay vertices, and $\vec{p}$ is the momentum of the D^0 meson. The selection efficiency as a function of the D^0 decay time (decay-time acceptance) is very similar for $D^0 \rightarrow h^+ h^-$ and $D^0 \rightarrow K^- \pi^+$ decays. However, since the average opening angle of a two-body decay in the laboratory frame depends on the masses of its decay products, differences of the order of a few percent are present and are corrected for in the analysis. The correction is evaluated using simulation and validated using control samples of data, which also include $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^+ \rightarrow K^+ K^- \pi^+$ decays with D^+ decays originating from semimuonic $\bar{B}$ decays (referred to as $\bar{B} \rightarrow D^+ \mu^- \bar{\nu}_\mu X$). To avoid potential experimenter's bias, the measured value of y_{CP} remained unknown during the development of the analysis and was examined only after the analysis procedure and the evaluation of the systematic uncertainties were finalized.

Semileptonic decays of $\bar{B}$ mesons are partially reconstructed in a data set collected with the LHCb experiment in pp collisions at center-of-mass energies of 7 and 8 TeV and corresponding to an integrated luminosity of 3 fb^{-1} . The LHCb detector is a single-arm forward spectrometer equipped with precise charged-particle vertexing and tracking detectors, hadron-identification detectors, calorimeters, and muon detectors, optimized for the study of bottom- and charm-hadron decays [16, 17]. Simulation [18–20] is used to model all relevant sources of decays, correct the data for the decay-time acceptance, study the decay-time resolution, and evaluate systematic uncertainties on the measurement.

The online event selection is performed by a trigger that consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a two-level software stage, which applies a full event reconstruction [21]. To select semimuonic $\bar{B}$ decays, the hardware trigger requires a muon candidate with transverse momentum exceeding 1.5 to 1.8 GeV/ c , depending on the data-taking period. In the first level of the software trigger, the selected muon is required to be displaced from any pp interaction point. These requirements do not bias the decay time of the D candidate. In the second level of the software trigger, the muon candidate is associated with one, two, or three charged particles, all displaced from the same pp interaction point. This association can bias the decay time, favoring shorter D flight distances, as the muon and the D decay products satisfying the trigger criteria must be consistent with originating from a common displaced vertex.

In the offline reconstruction, the muon candidate is combined with charged particles, forming the D -meson candidate and identified to be either kaons or pions, according to the topology and kinematics of $\bar{B} \rightarrow D^0 \mu^- \bar{\nu}_\mu X$ and $\bar{B} \rightarrow D^+ \mu^- \bar{\nu}_\mu X$ decays. The requirements to select $\bar{B} \rightarrow D^0 \mu^- \bar{\nu}_\mu X$ decays are inherited from the analysis reported in Ref. [22]; those for $\bar{B} \rightarrow D^+ \mu^- \bar{\nu}_\mu X$ decays are taken from Ref. [23]. In these selections, the D decay products are requested to be displaced from the pp interaction point with respect to which they have the smallest χ_{IP}^2 , by imposing $\chi_{\text{IP}}^2 > 9$. The χ_{IP}^2 is defined as the difference in the vertex-fit χ^2 of a given interaction point reconstructed with and without the particle being considered. These requirements are particularly relevant for the measurement of y_{CP} as they bias the D decay-time distribution, being more efficient for decays with a larger flight distance. The following additional requirements, not used in Refs. [22, 23], are applied. The $D\mu$ invariant mass, $m(D\mu)$, must not exceed $5.2 \text{ GeV}/c^2$, to suppress genuine charm decays accidentally combined with unrelated muon candidates. The mass of the D candidate must be in the range $1.825\text{--}1.920 \text{ GeV}/c^2$. Its decay time

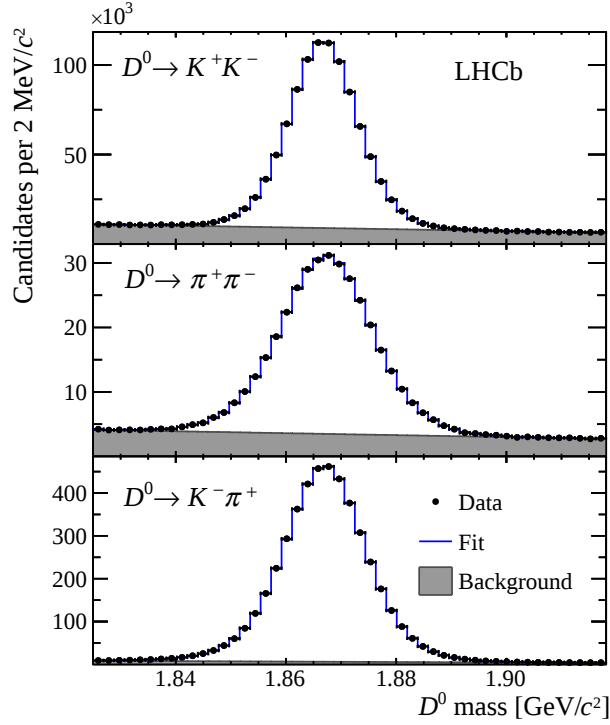


Figure 1: Distribution of D^0 mass for candidates passing the selection with fit projections overlaid: (top) $D^0 \rightarrow K^+ K^-$ decays, (center) $D^0 \rightarrow \pi^+ \pi^-$ decays, and (bottom) $D^0 \rightarrow K^- \pi^+$ decays.

must be larger than 0.15 ps to minimize a bias observed in simulation at $t \approx 0$ due to the reconstruction of the $\bar{B}$ vertex. A requirement on the component of the D momentum transverse to the $\bar{B}$ flight direction is applied as a function of the corrected $\bar{B}$ mass to suppress decays of b hadrons into final states with a pair of charm hadrons, of which one decays semileptonically, and background from semitauonic decays $\bar{B} \rightarrow D\tau^-\bar{\nu}_\tau X$, with $\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau$. The corrected $\bar{B}$ mass is determined from the $D\mu$ invariant mass as $\sqrt{m^2(D\mu) + p_\perp^2(D\mu)} + p_\perp(D\mu)$, using the momentum of the $D\mu$ system transverse to the $\bar{B}$ flight direction, $p_\perp(D\mu)$, to partially compensate for the momentum of the unreconstructed decay products. After the selection, these background contributions total to at most 1.5% of the signal yield. A contamination of about 1% of D decays produced directly in the pp collision (prompt D) is also estimated to be present in the selected sample. All these background decays are checked to have negligible impact on the measurement of y_{CP} .

Figure 1 shows the D^0 mass distributions of the selected candidates. Prominent signal peaks at the known D^0 mass values are visible on top of a smooth background made of random combinations of charged particles faking a D^0 candidate. The small contamination of prompt D^0 decays is included in the signal peak. Binned χ^2 fits to the mass distributions determine the signal yields reported in Table 1, together with the yields of the control samples of D^+ decays. The fits use a probability density function (pdf) consisting of a Johnson S_U distribution [24] (or the sum of a Johnson S_U and a Gaussian distribution in the case of $D^0 \rightarrow K^- \pi^+$ and $D^+ \rightarrow K^- \pi^+ \pi^+$ decays) to describe the asymmetric shape of the signal peak, and a linear distribution to describe the background.

The sample is split into 19 disjoint subsets (bins) of D decay time spanning the range

Table 1: Signal yields of the selected candidates.

Decay	Signal yield [10^3]
$D^0 \rightarrow K^+ K^-$	878.2 ± 1.2
$D^0 \rightarrow \pi^+ \pi^-$	311.6 ± 0.9
$D^0 \rightarrow K^- \pi^+$	4579.5 ± 3.2
$D^+ \rightarrow K^- \pi^+ \pi^+$	2260.2 ± 1.9
$D^+ \rightarrow K^+ K^- \pi^+$	98.0 ± 0.3

0.15–4 ps. The signal yields are determined in each decay-time bin with fits to the D mass distribution using the same pdf as described above. In these fits all signal-shape parameters are fixed to the values from the decay-time-integrated fits, with the exception of the mean and width of the Johnson function. The ratio between $D^0 \rightarrow K^+ K^-$ (or $D^0 \rightarrow \pi^+ \pi^-$) and $D^0 \rightarrow K^- \pi^+$ signal yields as a function of decay time is fitted to determine the value of Δ_Γ . The fit minimizes a χ^2 function where the signal-yield ratio in a decay-time bin is described by the ratio of the integrals of two decreasing exponential functions, one for the numerator with exponent $\Gamma_{CP+} = \Delta_\Gamma + \Gamma$, and the other for the denominator with exponent Γ . The value of Γ is fixed to its world average of 2.4384 ps^{-1} [1], while Δ_Γ and a decay-time-independent normalization factor of the ratio are free to vary in the fit. It should be noted that Γ can be fixed to any arbitrary value, since the distribution of the ratio is only sensitive to Δ_Γ . In the fit, the signal-yield ratio is corrected in each decay-time bin by a factor calculated as the ratio of the decay-time acceptances of the decays in the numerator and the denominator. This correction is determined from simulation and shows up to 6% variations around unity as a function of D^0 decay time (Figure 2). The correction is similar in magnitude, but with an opposite trend as a function of t , for the determination of Δ_Γ with $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ decays.

Several null tests are performed on data to prove that the estimates of the signal yields are unbiased, and that the corrections from simulation are reliable. The tests use samples of (i) $D^+ \rightarrow K^+ K^- \pi^+$ and $D^+ \rightarrow K^- \pi^+ \pi^+$ decays, (ii) $D^+ \rightarrow K^- \pi^+ \pi^+$ decays,

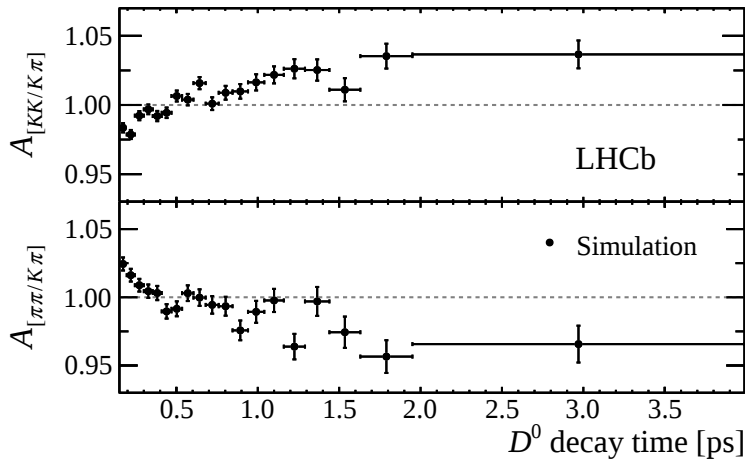


Figure 2: Ratio of decay-time acceptances from simulation for (top) $D^0 \rightarrow K^+ K^-$ over $D^0 \rightarrow K^- \pi^+$ decays and (bottom) $D^0 \rightarrow \pi^+ \pi^-$ over $D^0 \rightarrow K^- \pi^+$ decays.

Table 2: Measured values of Δ_Γ and y_{CP} . The first uncertainty is statistical, the second is systematic.

Decay	Δ_Γ [ps ⁻¹]	y_{CP} [%]
$D^0 \rightarrow K^+ K^-$	$0.0153 \pm 0.0036 \pm 0.0027$	$0.63 \pm 0.15 \pm 0.11$
$D^0 \rightarrow \pi^+ \pi^-$	$0.0093 \pm 0.0067 \pm 0.0038$	$0.38 \pm 0.28 \pm 0.15$

(iii) $D^0 \rightarrow K^- \pi^+$ decays, and (iv) $D^0 \rightarrow K^+ K^-$ decays. In test (i), the width difference is measured by fitting the yield ratio of $D^+ \rightarrow K^+ K^- \pi^+$ to $D^+ \rightarrow K^- \pi^+ \pi^+$ decays. The corrections for the ratio of decay-time acceptances are similar to those in the y_{CP} measurement. In tests (ii)–(iv), the selected data are split randomly into two independent sets: one is used as the denominator sample, and the other, featuring a tighter requirement of $\chi^2_{IP} > 60$ for the D decay products, is used as the numerator sample. The threshold on χ^2_{IP} is chosen such that the ratio of decay-time acceptances deviates from a constant by up to 40%, *i.e.*, almost an order of magnitude larger variation than that present in the y_{CP} measurement. In all tests, the measured decay-width difference is consistent with zero, with fit p values ranging from 8% to 84%. The two most precise tests, (ii) and (iii), correspond to a validation of the measurement of y_{CP} with an uncertainty of 0.14%, which includes the limited knowledge of the decay-time acceptance correction. Another test (v) consists in measuring the decay-width difference of D^+ and D^0 mesons, using the largest-yield samples of $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^0 \rightarrow K^- \pi^+$ decays. In this measurement, the ratio of the decay-time acceptances presents variations up to about 10%. However, the decays considered in the numerator and the denominator have sufficiently different topologies that potential biases on the measurement of the width difference are not suppressed in the ratio at the same level as in the y_{CP} measurement. In addition, the very different lifetimes between D^+ and D^0 mesons lead to a signal-yield ratio spanning over a very broad interval, with a maximum approximately 25 times larger than its minimum. The ratio of D^+ to D^0 lifetimes is determined to be 2.5141 ± 0.0082 , where the uncertainty is only statistical, in agreement with the known value of 2.536 ± 0.019 [1]. Biases that scale with Δ_Γ are excluded by this test within a relative precision of about 1%. In summary, the five tests yield results consistent with the expectations with a χ^2 of 5.5, which corresponds to a p value of 36%. The tests demonstrate that the acceptance effects needed for the measurement of y_{CP} are understood within the precision provided by the limited size of the simulated samples. The tests also confirm that background originating from prompt D decays, from b -hadron decays to double-charm final states, and from semitauonic $\bar{B}$ decays can be neglected. They contaminate all samples considered in the tests with fractions similar to those estimated in the y_{CP} measurement.

Figure 3 shows the acceptance-corrected signal-yield ratio measured for the $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ decays with respect to $D^0 \rightarrow K^- \pi^+$ decays, with fit projections overlaid. The obtained values of Δ_Γ and y_{CP} are reported in Table 2. The use of a common reference sample ($D^0 \rightarrow K^- \pi^+$) does not introduce any significant correlation between the statistical uncertainties of the $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ measurements.

Systematic uncertainties of 0.0027 ps^{-1} (0.0038 ps^{-1}) on Δ_Γ , and therefore 0.11% (0.15%) on y_{CP} , are assigned for the measurement done with $D^0 \rightarrow K^+ K^-$ ($D^0 \rightarrow \pi^+ \pi^-$) decays. The correlation between the systematic uncertainties is 5%. They are dominated

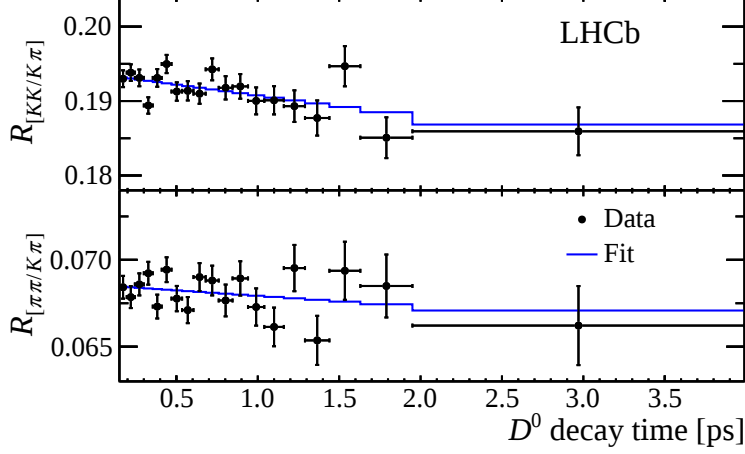


Figure 3: Acceptance-corrected signal-yield ratio of (top) $D^0 \rightarrow K^+K^-$ over $D^0 \rightarrow K^-\pi^+$ decays and (bottom) $D^0 \rightarrow \pi^+\pi^-$ over $D^0 \rightarrow K^-\pi^+$ decays as a function of D^0 decay time, with fit projection overlaid.

by the knowledge of the correction for the ratio of decay-time acceptances, which is limited by the finite size of the simulated samples. This yields systematic uncertainties of 0.0026 ps^{-1} (0.0037 ps^{-1}) on Δ_Γ and 0.11% (0.15%) on y_{CP} , which are uncorrelated between the $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ measurements. Other systematic uncertainties, contributing less, are associated with the assumed decay model and composition of the simulated samples of semileptonic $\bar{B}$ decays (0.0006 ps^{-1} on Δ_Γ , 0.02% on y_{CP}), possible biases introduced by the fit method as determined in large ensembles of pseudoexperiments (0.0004 ps^{-1} on Δ_Γ , 0.02% on y_{CP}), and the neglected 0.12 ps decay-time resolution (0.0003 ps^{-1} on Δ_Γ , 0.01% on y_{CP}). These systematic uncertainties are fully correlated between the measurements with $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays. Asymmetric production of D^0 and $\bar{D}^0$ mesons from semileptonic B^- and $\bar{B}^0$ decays produce biases on y_{CP} that are smaller than 10^{-5} . Uncertainties on the measured decay-length arising from relative misalignments of subdetectors and the uncertainty of the input value of Γ , $2.4384 \pm 0.0089 \text{ ps}^{-1}$ [1], which is used to determine y_{CP} from Δ_Γ , have negligible contributions. Finally, consistency checks based on repeating the y_{CP} measurement on independent subsamples chosen according to data-taking periods, trigger-selection criteria and interaction-point multiplicity all yield compatible results within statistical fluctuations.

In summary, the charm mixing-parameter y_{CP} is measured using $D^0 \rightarrow K^+K^-$, $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^-\pi^+$ decays originating from semileptonic B^- and $\bar{B}^0$ decays produced in pp collision data collected with the LHCb experiment at center-of-mass energies of 7 and 8 TeV, and corresponding to an integrated luminosity of 3 fb^{-1} . The results from $D^0 \rightarrow K^+K^-$, $y_{CP} = (0.63 \pm 0.15 \text{ (stat)} \pm 0.11 \text{ (syst)})\%$, and $D^0 \rightarrow \pi^+\pi^-$ decays, $y_{CP} = (0.38 \pm 0.28 \text{ (stat)} \pm 0.15 \text{ (syst)})\%$, are consistent with each other and with determinations from other experiments [2]. The value of y_{CP} measured in the $D^0 \rightarrow K^+K^-$ mode is the most precise to date from a single experiment. The two measurements are combined and yield $y_{CP} = (0.57 \pm 0.13 \text{ (stat)} \pm 0.09 \text{ (syst)})\%$, which is consistent with and as precise as the current world average value, $(0.84 \pm 0.16)\%$ [2]. The result is also consistent with the known value of the mixing parameter y , $(0.62 \pm 0.07)\%$ [2], showing no evidence for CP violation in D^0 - $\bar{D}^0$ mixing. As larger data samples are accumulated

by LHCb, the dominant systematic uncertainty due to finite simulation samples will also be reduced, giving good prospects for further reduction in the uncertainty of y_{CP} .

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: 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); 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 and OCEVU, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, and the Thousand Talents Program (China); RFBR, RSF and Yandex LLC (Russia); GVA, XuntaGal and GENCAT (Spain); the Royal Society and the Leverhulme Trust (United Kingdom); Laboratory Directed Research and Development program of LANL (USA).

References

- [1] Particle Data Group, M. Tanabashi *et al.*, *Review of particle physics*, Phys. Rev. **D98** (2018) 030001.
- [2] Heavy Flavor Averaging Group, Y. Amhis *et al.*, *Averages of b -hadron, c -hadron, and τ -lepton properties as of summer 2016*, Eur. Phys. J. **C77** (2017) 895, [arXiv:1612.07233](https://arxiv.org/abs/1612.07233), updated results and plots available at <https://hflav.web.cern.ch>.
- [3] D. S. Du, *Searching for possible large CP -violation effects in neutral-charm-meson decays*, Phys. Rev. **D34** (1986) 3428.
- [4] S. Bergmann *et al.*, *Lessons from CLEO and FOCUS measurements of D^0 - $\bar{D}^0$ mixing parameters*, Phys. Lett. **B486** (2000) 418, [arXiv:hep-ph/0005181](https://arxiv.org/abs/hep-ph/0005181).
- [5] BaBar collaboration, J. P. Lees *et al.*, *Measurement of D^0 - $\bar{D}^0$ mixing and CP violation in two-body D^0 decays*, Phys. Rev. **D87** (2013) 012004, [arXiv:1209.3896](https://arxiv.org/abs/1209.3896).
- [6] Belle collaboration, M. Starič *et al.*, *Measurement of D^0 - $\bar{D}^0$ mixing and search for CP violation in $D^0 \rightarrow K^+K^-$, $\pi^+\pi$ decays with the full Belle data set*, Phys. Lett. **B753** (2016) 412, [arXiv:1509.08266](https://arxiv.org/abs/1509.08266).

- [7] LHCb collaboration, R. Aaij *et al.*, *Measurement of mixing and CP violation parameters in two-body charm decays*, JHEP **04** (2012) 129, [arXiv:1112.4698](#).
- [8] G. Blaylock, A. Seiden, and Y. Nir, *The role of CP violation in D^0 - $\bar{D}^0$ mixing*, Phys. Lett. **B355** (1995) 555, [arXiv:hep-ph/9504306](#).
- [9] S. Bianco, F. L. Fabbri, D. Benson, and I. Bigi, *A Cicerone for the physics of charm*, Riv. Nuovo Cim. **26 n. 7-8** (2003) 1, [arXiv:hep-ex/0309021](#).
- [10] Y. Grossman, A. L. Kagan, and Y. Nir, *New physics and CP violation in singly Cabibbo suppressed D decays*, Phys. Rev. **D75** (2007) 036008, [arXiv:hep-ph/0609178](#).
- [11] A. A. Petrov, *Charm mixing in the standard model and beyond*, Int. J. Mod. Phys. **A21** (2006) 5686, [arXiv:hep-ph/0611361](#).
- [12] E. Golowich, J. Hewett, S. Pakvasa, and A. A. Petrov, *Implications of D^0 - $\bar{D}^0$ mixing for new physics*, Phys. Rev. **D76** (2007) 095009, [arXiv:0705.3650](#).
- [13] M. Ciuchini *et al.*, *D^0 - $\bar{D}^0$ mixing and new physics: General considerations and constraints on the MSSM*, Phys. Lett. **B655** (2007) 162, [arXiv:hep-ph/0703204](#).
- [14] A. D. Sakharov, *Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe*, Pisma Zh. Eksp. Teor. Fiz. **5** (1967) 32, Usp. Fiz. Nauk **161** (1991) 61.
- [15] P. Huet and E. Sather, *Electroweak baryogenesis and standard model CP violation*, Phys. Rev. **D51** (1995) 379, [arXiv:hep-ph/9404302](#).
- [16] LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.
- [17] LHCb collaboration, R. Aaij *et al.*, *LHCb detector performance*, Int. J. Mod. Phys. **A30** (2015) 1530022, [arXiv:1412.6352](#).
- [18] I. Belyaev *et al.*, *Handling of the generation of primary events in Gauss, the LHCb simulation framework*, J. Phys. Conf. Ser. **331** (2011) 032047.
- [19] M. Clemencic *et al.*, *The LHCb simulation application, Gauss: Design, evolution and experience*, J. Phys. Conf. Ser. **331** (2011) 032023.
- [20] D. Müller, M. Clemencic, G. Corti, and M. Gersabeck, *ReDecay: A novel approach to speed up the simulation at LHCb*, Eur. Phys. J. **C78** (2018) 1009, [arXiv:1810.10362](#).
- [21] R. Aaij *et al.*, *The LHCb trigger and its performance in 2011*, JINST **8** (2013) P04022, [arXiv:1211.3055](#).
- [22] LHCb collaboration, R. Aaij *et al.*, *Measurement of CP asymmetry in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays*, JHEP **07** (2014) 041, [arXiv:1405.2797](#).
- [23] LHCb collaboration, R. Aaij *et al.*, *Measurement of B_s^0 and D_s^- meson lifetimes*, Phys. Rev. Lett. **119** (2017) 101801, [arXiv:1705.03475](#).
- [24] N. L. Johnson, *Systems of frequency curves generated by methods of translation*, Biometrika **36** (1949) 149.

LHCb Collaboration

R. Aaij²⁹, C. Abellán Beteta⁴⁶, B. Adeva⁴³, M. Adinolfi⁵⁰, C.A. Aidala⁷⁷, Z. Ajaltouni⁷, S. Akar⁶¹, P. Albicocco²⁰, J. Albrecht¹², F. Alessio⁴⁴, M. Alexander⁵⁵, A. Alfonso Alberio⁴², G. Alkhazov³⁵, P. Alvarez Cartelle⁵⁷, A.A. Alves Jr⁴³, S. Amato², S. Amerio²⁵, Y. Amhis⁹, L. An³, L. Anderlini¹⁹, G. Andreassi⁴⁵, M. Andreotti¹⁸, J.E. Andrews⁶², F. Archilli²⁹, J. Arnau Romeu⁸, A. Artamonov⁴¹, M. Artuso⁶³, K. Arzymatov³⁹, E. Aslanides⁸, M. Atzeni⁴⁶, B. Audurier²⁴, S. Bachmann¹⁴, J.J. Back⁵², S. Baker⁵⁷, V. Balagura^{9,b}, W. Baldini¹⁸, A. Baranov³⁹, R.J. Barlow⁵⁸, G.C. Barrand⁹, S. Barsuk⁹, W. Barter⁵⁸, M. Bartolini²¹, F. Baryshnikov⁷³, V. Batzskaya³³, B. Batsukh⁶³, A. Battig¹², V. Battista⁴⁵, A. Bay⁴⁵, J. Beddow⁵⁵, F. Bedeschi²⁶, I. Bediaga¹, A. Beiter⁶³, L.J. Bel²⁹, S. Belin²⁴, N. Bely⁴, V. Belle⁴⁵, N. Belloli^{22,i}, K. Belous⁴¹, I. Belyaev³⁶, G. Bencivenni²⁰, E. Ben-Haim¹⁰, S. Benson²⁹, S. Beranek¹¹, A. Berezhnoy³⁷, R. Bernet⁴⁶, D. Berninghoff¹⁴, E. Bertholet¹⁰, A. Bertolin²⁵, C. Betancourt⁴⁶, F. Betti^{17,44}, M.O. Bettler⁵¹, Ia. Bezshyiko⁴⁶, S. Bhasin⁵⁰, J. Bhom³¹, S. Bifani⁴⁹, P. Billoir¹⁰, A. Birnkraut¹², A. Bizzeti^{19,u}, M. Bjørn⁵⁹, M.P. Blago⁴⁴, T. Blake⁵², F. Blanc⁴⁵, S. Blusk⁶³, D. Bobulska⁵⁵, V. Bocci²⁸, O. Boente Garcia⁴³, T. Boettcher⁶⁰, A. Bondar^{40,x}, N. Bondar³⁵, S. Borghi^{58,44}, M. Borisyak³⁹, M. Borsato⁴³, F. Bossu⁹, M. Boubdir¹¹, T.J.V. Bowcock⁵⁶, C. Bozzi^{18,44}, S. Braun¹⁴, M. Brodski⁴⁴, J. Brodzicka³¹, A. Brossa Gonzalo⁵², D. Brundu^{24,44}, E. Buchanan⁵⁰, A. Buonauro⁴⁶, C. Burr⁵⁸, A. Bursche²⁴, J. Buytaert⁴⁴, W. Byczynski⁴⁴, S. Cadeddu²⁴, H. Cai⁶⁷, R. Calabrese^{18,g}, R. Calladine⁴⁹, M. Calvi^{22,i}, M. Calvo Gomez^{42,m}, A. Camboni^{42,m}, P. Campana²⁰, D.H. Campora Perez⁴⁴, L. Capriotti¹⁷, A. Carbone^{17,e}, G. Carboni²⁷, R. Cardinale²¹, A. Cardini²⁴, P. Carniti^{22,i}, L. Carson⁵⁴, K. Carvalho Akiba², G. Casse⁵⁶, L. Cassina²², M. Cattaneo⁴⁴, G. Cavallero²¹, R. Cenci^{26,p}, D. Chamont⁹, M.G. Chapman⁵⁰, M. Charles¹⁰, Ph. Charpentier⁴⁴, G. Chatzikonstantinidis⁴⁹, M. Chefdeville⁶, V. Chekalina³⁹, C. Chen³, S. Chen²⁴, S.-G. Chitic⁴⁴, V. Chobanova⁴³, M. Chrzasczcz⁴⁴, A. Chubykin³⁵, P. Ciambrone²⁰, X. Cid Vidal⁴³, G. Ciezarek⁴⁴, F. Cindolo¹⁷, P.E.L. Clarke⁵⁴, M. Clemencic⁴⁴, H.V. Cliff⁵¹, J. Closier⁴⁴, V. Coco⁴⁴, J.A.B. Coelho⁹, J. Cogan⁸, E. Cogneras⁷, L. Cojocariu³⁴, P. Collins⁴⁴, T. Colombo⁴⁴, A. Comerma-Montells¹⁴, A. Contu²⁴, G. Coombs⁴⁴, S. Coquereau⁴², G. Corti⁴⁴, M. Corvo^{18,g}, C.M. Costa Sobral⁵², B. Couturier⁴⁴, G.A. Cowan⁵⁴, D.C. Craik⁶⁰, A. Crocombe⁵², M. Cruz Torres¹, R. Currie⁵⁴, F. Da Cunha Marinho², C.L. Da Silva⁷⁸, E. Dall'Occo²⁹, J. Dalseno^{43,v}, C. D'Ambrosio⁴⁴, A. Danilina³⁶, P. d'Argent¹⁴, A. Davis³, O. De Aguiar Francisco⁴⁴, K. De Bruyn⁴⁴, S. De Capua⁵⁸, M. De Cian⁴⁵, J.M. De Miranda¹, L. De Paula², M. De Serio^{16,d}, P. De Simone²⁰, J.A. de Vries²⁹, C.T. Dean⁵⁵, D. Decamp⁶, L. Del Buono¹⁰, B. Delaney⁵¹, H.-P. Dembinski¹³, M. Demmer¹², A. Dendek³², D. Derkach⁷⁴, O. Deschamps⁷, F. Desse⁹, F. Dettori⁵⁶, B. Dey⁶⁸, A. Di Canto⁴⁴, P. Di Nezza²⁰, S. Didenko⁷³, H. Dijkstra⁴⁴, F. Dordei⁴⁴, M. Dorigo^{44,y}, A.C. dos Reis¹, A. Dosil Suárez⁴³, L. Douglas⁵⁵, A. Dovbnya⁴⁷, K. Dreimanis⁵⁶, L. Dufour²⁹, G. Dujany¹⁰, P. Durante⁴⁴, J.M. Durham⁷⁸, D. Dutta⁵⁸, R. Dzhelyadin⁴¹, M. Dziwiecki¹⁴, A. Dziurda³¹, A. Dzyuba³⁵, S. Easo⁵³, U. Egede⁵⁷, V. Egorychev³⁶, S. Eidelman^{40,x}, S. Eisenhardt⁵⁴, U. Eitschberger¹², R. Ekelhof¹², L. Eklund⁵⁵, S. Ely⁶³, A. Ene³⁴, S. Escher¹¹, S. Esen²⁹, T. Evans⁶¹, A. Falabella¹⁷, C. Färber⁴⁴, N. Farley⁴⁹, S. Farry⁵⁶, D. Fazzini^{22,44,i}, L. Federici²⁷, M. Féo²⁹, P. Fernandez Declara⁴⁴, A. Fernandez Prieto⁴³, F. Ferrari¹⁷, L. Ferreira Lopes⁴⁵, F. Ferreira Rodrigues², M. Ferro-Luzzi⁴⁴, S. Filippov³⁸, R.A. Fini¹⁶, M. Fiorini^{18,g}, M. Firlej³², C. Fitzpatrick⁴⁵, T. Fiutowski³², F. Fleuret^{9,b}, M. Fontana⁴⁴, F. Fontanelli^{21,h}, R. Forty⁴⁴, V. Franco Lima⁵⁶, M. Frank⁴⁴, C. Frei⁴⁴, J. Fu^{23,q}, W. Funk⁴⁴, E. Gabriel⁵⁴, A. Gallas Torreira⁴³, D. Galli^{17,e}, S. Gallorini²⁵, S. Gambetta⁵⁴, Y. Gan³, M. Gandelman², P. Gandini²³, Y. Gao³, L.M. Garcia Martin⁷⁶, J. García Pardiñas⁴⁶, B. Garcia Plana⁴³, J. Garra Tico⁵¹, L. Garrido⁴², D. Gascon⁴², C. Gaspar⁴⁴, L. Gavardi¹², G. Gazzoni⁷, D. Gerick¹⁴, E. Gersabeck⁵⁸, M. Gersabeck⁵⁸, T. Gershon⁵², D. Gerstel⁸, Ph. Ghez⁶, V. Gibson⁵¹, O.G. Girard⁴⁵,

P. Gironella Gironell⁴², L. Giubega³⁴, K. Gizdov⁵⁴, V.V. Gligorov¹⁰, C. Göbel⁶⁵, D. Golubkov³⁶,
 A. Golutvin^{57,73}, A. Gomes^{1,a}, I.V. Gorelov³⁷, C. Gotti^{22,i}, E. Govorkova²⁹, J.P. Grabowski¹⁴,
 R. Graciani Diaz⁴², L.A. Granado Cardoso⁴⁴, E. Graugés⁴², E. Graverini⁴⁶, G. Graziani¹⁹,
 A. Grecu³⁴, R. Greim²⁹, P. Griffith²⁴, L. Grillo⁵⁸, L. Gruber⁴⁴, B.R. Gruber Cazon⁵⁹,
 O. Grünberg⁷⁰, C. Gu³, E. Gushchin³⁸, A. Guth¹¹, Yu. Guz^{41,44}, T. Gys⁴⁴, T. Hadavizadeh⁵⁹,
 C. Hadjivasiliou⁷, G. Haefeli⁴⁵, C. Haen⁴⁴, S.C. Haines⁵¹, B. Hamilton⁶², X. Han¹⁴,
 T.H. Hancock⁵⁹, S. Hansmann-Menzemer¹⁴, N. Harnew⁵⁹, S.T. Harnew⁵⁰, T. Harrison⁵⁶,
 C. Hasse⁴⁴, M. Hatch⁴⁴, J. He⁴, M. Hecker⁵⁷, K. Heinicke¹², A. Heister¹², K. Hennessy⁵⁶,
 L. Henry⁷⁶, M. Heß⁷⁰, J. Heuel¹¹, A. Hicheur⁶⁴, R. Hidalgo Charman⁵⁸, D. Hill⁵⁹, M. Hilton⁵⁸,
 P.H. Hopchev⁴⁵, J. Hu¹⁴, W. Hu⁶⁸, W. Huang⁴, Z.C. Huard⁶¹, W. Hulsbergen²⁹, T. Humair⁵⁷,
 M. Hushchyn⁷⁴, D. Hutchcroft⁵⁶, D. Hynds²⁹, P. Ibis¹², M. Idzik³², P. Ilten⁴⁹, A. Inyakin⁴¹,
 K. Ivshin³⁵, R. Jacobsson⁴⁴, J. Jalocha⁵⁹, E. Jans²⁹, B.K. Jashal⁷⁶, A. Jawahery⁶², F. Jiang³,
 M. John⁵⁹, D. Johnson⁴⁴, C.R. Jones⁵¹, C. Joram⁴⁴, B. Jost⁴⁴, N. Jurik⁵⁹, S. Kandybei⁴⁷,
 M. Karacson⁴⁴, J.M. Kariuki⁵⁰, S. Karodia⁵⁵, N. Kazeev⁷⁴, M. Kecke¹⁴, F. Keizer⁵¹,
 M. Kelsey⁶³, M. Kenzie⁵¹, T. Ketel³⁰, E. Khairullin³⁹, B. Khanji⁴⁴, C. Khurewathanakul⁴⁵,
 K.E. Kim⁶³, T. Kirn¹¹, S. Klaver²⁰, K. Klimaszewski³³, T. Klimovich¹³, S. Koliev⁴⁸,
 M. Kolpin¹⁴, R. Kopečna¹⁴, P. Koppenburg²⁹, I. Kostiuik²⁹, S. Kotriakhova³⁵, M. Kozeiha⁷,
 L. Kravchuk³⁸, M. Kreps⁵², F. Kress⁵⁷, P. Krokovny^{40,x}, W. Krupa³², W. Krzemien³³,
 W. Kucewicz^{31,l}, M. Kucharczyk³¹, V. Kudryavtsev^{40,x}, A.K. Kuonen⁴⁵, T. Kvaratskheliya^{36,44},
 D. Lacarrere⁴⁴, G. Lafferty⁵⁸, A. Lai²⁴, D. Lancierini⁴⁶, G. Lanfranchi²⁰, C. Langenbruch¹¹,
 T. Latham⁵², C. Lazzeroni⁴⁹, R. Le Gac⁸, R. Lefèvre⁷, A. Leflat³⁷, J. Lefrançois⁹, F. Lemaitre⁴⁴,
 O. Leroy⁸, T. Lesiak³¹, B. Leverington¹⁴, P.-R. Li^{4,ab}, Y. Li⁵, Z. Li⁶³, X. Liang⁶³,
 T. Likhomanenko⁷², R. Lindner⁴⁴, F. Lionetto⁴⁶, V. Lisovskyi⁹, G. Liu⁶⁶, X. Liu³, D. Loh⁵²,
 A. Loi²⁴, I. Longstaff⁵⁵, J.H. Lopes², G.H. Lovell⁵¹, D. Lucchesi^{25,o}, M. Lucio Martinez⁴³,
 A. Lupato²⁵, E. Luppi^{18,g}, O. Lupton⁴⁴, A. Lusiani²⁶, X. Lyu⁴, F. Machefert⁹, F. Maciuc³⁴,
 V. Macko⁴⁵, P. Mackowiak¹², S. Maddrell-Mander⁵⁰, O. Maev^{35,44}, K. Maguire⁵⁸,
 D. Maisuzenko³⁵, M.W. Majewski³², S. Malde⁵⁹, B. Malecki³¹, A. Malinin⁷², T. Maltsev^{40,x},
 G. Manca^{24,f}, G. Mancinelli⁸, D. Marangotto^{23,q}, J. Maratas^{7,w}, J.F. Marchand⁶, U. Marconi¹⁷,
 C. Marin Benito⁹, M. Marinangeli⁴⁵, P. Marino⁴⁵, J. Marks¹⁴, P.J. Marshall⁵⁶, G. Martellotti²⁸,
 M. Martin⁸, M. Martinelli⁴⁴, D. Martinez Santos⁴³, F. Martinez Vidal⁷⁶, A. Massafferri¹,
 M. Materok¹¹, R. Matev⁴⁴, A. Mathad⁵², Z. Mathe⁴⁴, C. Matteuzzi²², A. Mauri⁴⁶,
 E. Maurice^{9,b}, B. Maurin⁴⁵, A. Mazurov⁴⁹, M. McCann^{57,44}, A. McNab⁵⁸, R. McNulty¹⁵,
 J.V. Mead⁵⁶, B. Meadows⁶¹, C. Meaux⁸, N. Meinert⁷⁰, D. Melnychuk³³, M. Merk²⁹,
 A. Merli^{23,q}, E. Michelin²⁵, D.A. Milanes⁶⁹, E. Millard⁵², M.-N. Minard⁶, L. Minzoni^{18,g},
 D.S. Mitzel¹⁴, A. Mödden¹², A. Mogini¹⁰, R.D. Moise⁵⁷, T. Mombächer¹², I.A. Monroy⁶⁹,
 S. Monteil⁷, M. Morandin²⁵, G. Morello²⁰, M.J. Morello^{26,t}, O. Morgunova⁷², J. Moron³²,
 A.B. Morris⁸, R. Mountain⁶³, F. Muheim⁵⁴, M. Mulder²⁹, D. Müller⁴⁴, J. Müller¹², K. Müller⁴⁶,
 V. Müller¹², C.H. Murphy⁵⁹, D. Murray⁵⁸, P. Naik⁵⁰, T. Nakada⁴⁵, R. Nandakumar⁵³,
 A. Nandi⁵⁹, T. Nanut⁴⁵, I. Nasteva², M. Needham⁵⁴, N. Neri^{23,q}, S. Neubert¹⁴, N. Neufeld⁴⁴,
 M. Neuner¹⁴, R. Newcombe⁵⁷, T.D. Nguyen⁴⁵, C. Nguyen-Mau^{45,n}, S. Nieswand¹¹, R. Niet¹²,
 N. Nikitin³⁷, A. Nogay⁷², N.S. Nolte⁴⁴, A. Oblakowska-Mucha³², V. Obraztsov⁴¹, S. Ogilvy⁵⁵,
 D.P. O'Hanlon¹⁷, R. Oldeman^{24,f}, C.J.G. Onderwater⁷¹, A. Ossowska³¹,
 J.M. Otalora Goicochea², T. Ovsiannikova³⁶, P. Owen⁴⁶, A. Oyanguren⁷⁶, P.R. Pais⁴⁵,
 T. Pajero^{26,t}, A. Palano¹⁶, M. Palutan²⁰, G. Panshin⁷⁵, A. Papanestis⁵³, M. Pappagallo⁵⁴,
 L.L. Pappalardo^{18,g}, W. Parker⁶², C. Parkes^{58,44}, G. Passaleva^{19,44}, A. Pastore¹⁶, M. Patel⁵⁷,
 C. Patrignani^{17,e}, A. Pearce⁴⁴, A. Pellegrino²⁹, G. Penso²⁸, M. Pepe Altarelli⁴⁴, S. Perazzini⁴⁴,
 D. Pereima³⁶, P. Perret⁷, L. Pescatore⁴⁵, K. Petridis⁵⁰, A. Petrolini^{21,h}, A. Petrov⁷²,
 S. Petrucci⁵⁴, M. Petruzzo^{23,q}, B. Pietrzyk⁶, G. Pietrzyk⁴⁵, M. Pikies³¹, M. Pili⁵⁹, D. Pinci²⁸,
 J. Pinzino⁴⁴, F. Pisani⁴⁴, A. Piucci¹⁴, V. Placinta³⁴, S. Playfer⁵⁴, J. Plews⁴⁹, M. Plo Casasus⁴³,
 F. Polci¹⁰, M. Poli Lener²⁰, A. Poluektov⁵², N. Polukhina^{73,c}, I. Polyakov⁶³, E. Polycarpo²,

G.J. Pomery⁵⁰, S. Ponce⁴⁴, A. Popov⁴¹, D. Popov^{49,13}, S. Poslavskii⁴¹, C. Potterat², E. Price⁵⁰, J. Prisciandaro⁴³, C. Prouve⁵⁰, V. Pugatch⁴⁸, A. Puig Navarro⁴⁶, H. Pullen⁵⁹, G. Punzi^{26,p}, W. Qian⁴, J. Qin⁴, R. Quagliani¹⁰, B. Quintana⁷, N.V. Raab¹⁵, B. Rachwal³², J.H. Rademacker⁵⁰, M. Rama²⁶, M. Ramos Pernas⁴³, M.S. Rangel², F. Ratnikov^{39,74}, G. Raven³⁰, M. Ravonel Salzgeber⁴⁴, M. Reboud⁶, F. Redi⁴⁵, S. Reichert¹², F. Reiss¹⁰, C. Remon Alepuz⁷⁶, Z. Ren³, V. Renaudin⁹, S. Ricciardi⁵³, S. Richards⁵⁰, K. Rinnert⁵⁶, P. Robbe⁹, A. Robert¹⁰, A.B. Rodrigues⁴⁵, E. Rodrigues⁶¹, J.A. Rodriguez Lopez⁶⁹, M. Roehrken⁴⁴, S. Roiser⁴⁴, A. Rollings⁵⁹, V. Romanovskiy⁴¹, A. Romero Vidal⁴³, M. Rotondo²⁰, M.S. Rudolph⁶³, T. Ruf⁴⁴, J. Ruiz Vidal⁷⁶, J.J. Saborido Silva⁴³, N. Sagidova³⁵, B. Saitta^{24,f}, V. Salustino Guimaraes⁶⁵, C. Sanchez Gras²⁹, C. Sanchez Mayordomo⁷⁶, B. Sanmartin Sedes⁴³, R. Santacesaria²⁸, C. Santamarina Rios⁴³, M. Santimaria^{20,44}, E. Santovetti^{27,j}, G. Sarpis⁵⁸, A. Sarti^{20,k}, C. Satriano^{28,s}, A. Satta²⁷, M. Saur⁴, D. Savrina^{36,37}, S. Schael¹¹, M. Schellenberg¹², M. Schiller⁵⁵, H. Schindler⁴⁴, M. Schmelling¹³, T. Schmelzer¹², B. Schmidt⁴⁴, O. Schneider⁴⁵, A. Schopper⁴⁴, H.F. Schreiner⁶¹, M. Schubiger⁴⁵, M.H. Schune⁹, R. Schwemmer⁴⁴, B. Sciascia²⁰, A. Sciubba^{28,k}, A. Semennikov³⁶, E.S. Sepulveda¹⁰, A. Sergi⁴⁹, N. Serra⁴⁶, J. Serrano⁸, L. Sestini²⁵, A. Seuthe¹², P. Seyfert⁴⁴, M. Shapkin⁴¹, Y. Shcheglov^{35,†}, T. Shears⁵⁶, L. Shekhtman^{40,x}, V. Shevchenko⁷², E. Shmanin⁷³, B.G. Siddi¹⁸, R. Silva Coutinho⁴⁶, L. Silva de Oliveira², G. Simi^{25,o}, S. Simone^{16,d}, I. Skiba¹⁸, N. Skidmore¹⁴, T. Skwarnicki⁶³, M.W. Slater⁴⁹, J.G. Smeaton⁵¹, E. Smith¹¹, I.T. Smith⁵⁴, M. Smith⁵⁷, M. Soares¹⁷, I. Soares Lavra¹, M.D. Sokoloff⁶¹, F.J.P. Soler⁵⁵, B. Souza De Paula², B. Spaan¹², E. Spadaro Norella^{23,q}, P. Spradlin⁵⁵, F. Stagni⁴⁴, M. Stahl¹⁴, S. Stahl⁴⁴, P. Stefko⁴⁵, S. Stefkova⁵⁷, O. Steinkamp⁴⁶, S. Stemmle¹⁴, O. Stenyakin⁴¹, M. Stepanova³⁵, H. Stevens¹², A. Stocchi⁹, S. Stone⁶³, B. Storaci⁴⁶, S. Stracka²⁶, M.E. Stramaglia⁴⁵, M. Straticiu³⁴, U. Straumann⁴⁶, S. Strov⁷⁵, J. Sun³, L. Sun⁶⁷, K. Swientek³², A. Szabelski³³, T. Szumlak³², M. Szymanski⁴, Z. Tang³, A. Tayduganov⁸, T. Tekampe¹², G. Tellarini¹⁸, F. Teubert⁴⁴, E. Thomas⁴⁴, M.J. Tilley⁵⁷, V. Tisserand⁷, S. T'Jampens⁶, M. Tobin³², S. Tol⁴⁴, L. Tomassetti^{18,g}, D. Tonelli²⁶, D.Y. Tou¹⁰, R. Tourinho Jadallah Aoude¹, E. Tournefier⁶, M. Traill⁵⁵, M.T. Tran⁴⁵, A. Trisovic⁵¹, A. Tsaregorodtsev⁸, G. Tuci^{26,p}, A. Tully⁵¹, N. Tuning^{29,44}, A. Ukleja³³, A. Usachov⁹, A. Ustyuzhanin³⁹, U. Uwer¹⁴, A. Vagner⁷⁵, V. Vagnoni¹⁷, A. Valassi⁴⁴, S. Valat⁴⁴, G. Valenti¹⁷, M. van Beuzekom²⁹, E. van Herwijnen⁴⁴, J. van Tilburg²⁹, M. van Veghel²⁹, R. Vazquez Gomez⁴⁴, P. Vazquez Regueiro⁴³, C. Vázquez Sierra²⁹, S. Vecchi¹⁸, J.J. Velthuis⁵⁰, M. Veltri^{19,r}, G. Veneziano⁵⁹, A. Venkateswaran⁶³, M. Vernet⁷, M. Veronesi²⁹, M. Vesterinen⁵⁹, J.V. Viana Barbosa⁴⁴, D. Vieira⁴, M. Vieites Diaz⁴³, H. Viemann⁷⁰, X. Vilasis-Cardona^{42,m}, A. Vitkovskiy²⁹, M. Vitti⁵¹, V. Volkov³⁷, A. Vollhardt⁴⁶, D. Vom Bruch¹⁰, B. Voneki⁴⁴, A. Vorobyev³⁵, V. Vorobyev^{40,x}, N. Voropaev³⁵, R. Waldi⁷⁰, J. Walsh²⁶, J. Wang⁵, M. Wang³, Y. Wang⁶⁸, Z. Wang⁴⁶, D.R. Ward⁵¹, H.M. Wark⁵⁶, N.K. Watson⁴⁹, D. Websdale⁵⁷, A. Weiden⁴⁶, C. Weisser⁶⁰, M. Whitehead¹¹, J. Wicht⁵², G. Wilkinson⁵⁹, M. Wilkinson⁶³, I. Williams⁵¹, M. Williams⁶⁰, M.R.J. Williams⁵⁸, T. Williams⁴⁹, F.F. Wilson⁵³, M. Winn⁹, W. Wislicki³³, M. Witek³¹, G. Wormser⁹, S.A. Wotton⁵¹, K. Wyllie⁴⁴, D. Xiao⁶⁸, Y. Xie⁶⁸, A. Xu³, M. Xu⁶⁸, Q. Xu⁴, Z. Xu⁶, Z. Xu³, Z. Yang³, Z. Yang⁶², Y. Yao⁶³, L.E. Yeomans⁵⁶, H. Yin⁶⁸, J. Yu^{68,aa}, X. Yuan⁶³, O. Yushchenko⁴¹, K.A. Zarebski⁴⁹, M. Zavertyaev^{13,c}, D. Zhang⁶⁸, L. Zhang³, W.C. Zhang^{3,z}, Y. Zhang⁹, A. Zhelezov¹⁴, Y. Zheng⁴, X. Zhu³, V. Zhukov^{11,37}, J.B. Zonneveld⁵⁴, S. Zucchelli¹⁷.

¹Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil

²Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

³Center for High Energy Physics, Tsinghua University, Beijing, China

⁴University of Chinese Academy of Sciences, Beijing, China

⁵Institute Of High Energy Physics (ihep), Beijing, China

⁶Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France

- ⁷ *Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
- ⁸ *Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*
- ⁹ *LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
- ¹⁰ *LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*
- ¹¹ *I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*
- ¹² *Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
- ¹³ *Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*
- ¹⁴ *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ¹⁵ *School of Physics, University College Dublin, Dublin, Ireland*
- ¹⁶ *INFN Sezione di Bari, Bari, Italy*
- ¹⁷ *INFN Sezione di Bologna, Bologna, Italy*
- ¹⁸ *INFN Sezione di Ferrara, Ferrara, Italy*
- ¹⁹ *INFN Sezione di Firenze, Firenze, Italy*
- ²⁰ *INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ²¹ *INFN Sezione di Genova, Genova, Italy*
- ²² *INFN Sezione di Milano-Bicocca, Milano, Italy*
- ²³ *INFN Sezione di Milano, Milano, Italy*
- ²⁴ *INFN Sezione di Cagliari, Monserrato, Italy*
- ²⁵ *INFN Sezione di Padova, Padova, Italy*
- ²⁶ *INFN Sezione di Pisa, Pisa, Italy*
- ²⁷ *INFN Sezione di Roma Tor Vergata, Roma, Italy*
- ²⁸ *INFN Sezione di Roma La Sapienza, Roma, Italy*
- ²⁹ *Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*
- ³⁰ *Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*
- ³¹ *Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
- ³² *AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*
- ³³ *National Center for Nuclear Research (NCBJ), Warsaw, Poland*
- ³⁴ *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
- ³⁵ *Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia*
- ³⁶ *Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia*
- ³⁷ *Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia*
- ³⁸ *Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia*
- ³⁹ *Yandex School of Data Analysis, Moscow, Russia*
- ⁴⁰ *Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia*
- ⁴¹ *Institute for High Energy Physics (IHEP), Protvino, Russia*
- ⁴² *ICCUB, Universitat de Barcelona, Barcelona, Spain*
- ⁴³ *Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*
- ⁴⁴ *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
- ⁴⁵ *Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
- ⁴⁶ *Physik-Institut, Universität Zürich, Zürich, Switzerland*
- ⁴⁷ *NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
- ⁴⁸ *Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
- ⁴⁹ *University of Birmingham, Birmingham, United Kingdom*
- ⁵⁰ *H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
- ⁵¹ *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ⁵² *Department of Physics, University of Warwick, Coventry, United Kingdom*
- ⁵³ *STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ⁵⁴ *School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵⁵ *School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵⁶ *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁵⁷ *Imperial College London, London, United Kingdom*
- ⁵⁸ *School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁵⁹ *Department of Physics, University of Oxford, Oxford, United Kingdom*

- ⁶⁰ *Massachusetts Institute of Technology, Cambridge, MA, United States*
⁶¹ *University of Cincinnati, Cincinnati, OH, United States*
⁶² *University of Maryland, College Park, MD, United States*
⁶³ *Syracuse University, Syracuse, NY, United States*
⁶⁴ *Laboratory of Mathematical and Subatomic Physics, Constantine, Algeria, associated to ²*
⁶⁵ *Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to ²*
⁶⁶ *South China Normal University, Guangzhou, China, associated to ³*
⁶⁷ *School of Physics and Technology, Wuhan University, Wuhan, China, associated to ³*
⁶⁸ *Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China, associated to ³*
⁶⁹ *Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia, associated to ¹⁰*
⁷⁰ *Institut für Physik, Universität Rostock, Rostock, Germany, associated to ¹⁴*
⁷¹ *Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to ²⁹*
⁷² *National Research Centre Kurchatov Institute, Moscow, Russia, associated to ³⁶*
⁷³ *National University of Science and Technology "MISIS", Moscow, Russia, associated to ³⁶*
⁷⁴ *National Research University Higher School of Economics, Moscow, Russia, associated to ³⁹*
⁷⁵ *National Research Tomsk Polytechnic University, Tomsk, Russia, associated to ³⁶*
⁷⁶ *Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain, associated to ⁴²*
⁷⁷ *University of Michigan, Ann Arbor, United States, associated to ⁶³*
⁷⁸ *Los Alamos National Laboratory (LANL), Los Alamos, United States, associated to ⁶³*

- ^a *Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil*
^b *Laboratoire Leprince-Ringuet, Palaiseau, France*
^c *P.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*
^h *Università di Genova, Genova, Italy*
ⁱ *Università di Milano Bicocca, Milano, Italy*
^j *Università di Roma Tor Vergata, Roma, Italy*
^k *Università di Roma La Sapienza, Roma, Italy*
^l *AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland*
^m *LIFAEELS, La Salle, Universitat Ramon Llull, Barcelona, Spain*
ⁿ *Hanoi University of Science, Hanoi, Vietnam*
^o *Università di Padova, Padova, Italy*
^p *Università di Pisa, Pisa, Italy*
^q *Università degli Studi di Milano, Milano, Italy*
^r *Università di Urbino, Urbino, Italy*
^s *Università della Basilicata, Potenza, Italy*
^t *Scuola Normale Superiore, Pisa, Italy*
^u *Università di Modena e Reggio Emilia, Modena, Italy*
^v *H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
^w *MSU - Iligan Institute of Technology (MSU-IIT), Iligan, Philippines*
^x *Novosibirsk State University, Novosibirsk, Russia*
^y *Sezione INFN di Trieste, Trieste, Italy*
^z *School of Physics and Information Technology, Shaanxi Normal University (SNNU), Xi'an, China*
^{aa} *Physics and Micro Electronic College, Hunan University, Changsha City, China*
^{ab} *Lanzhou University, Lanzhou, China*

[†] *Deceased*