

Measurement of the Mass Difference Between Neutral Charm-Meson Eigenstates

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

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We report a measurement of the mass difference between neutral charm-meson eigenstates using a novel approach that enhances sensitivity to this parameter. We use 2.3×10^6 $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays reconstructed in proton-proton collisions collected by the LHCb experiment in 2011 and 2012. Allowing for CP violation in mixing and in the interference between mixing and decay, we measure the CP -averaged normalized mass difference $x_{CP} = [2.7 \pm 1.6(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-3}$ and the CP -violating parameter $\Delta x = [-0.53 \pm 0.70(\text{stat}) \pm 0.22(\text{syst})] \times 10^{-3}$. The results are consistent with CP symmetry. These determinations are the most precise from a single experiment and, combined with current world-average results, yield the first evidence that the masses of the neutral charm-meson eigenstates differ.

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Flavor oscillations are transitions between neutral flavored mesons and their corresponding antimesons that follow an oscillating pattern as a function of decay time. In the standard model, these transitions are mediated by weak-interaction amplitudes involving exchanges of virtual $W^\pm$ bosons and heavy quarks. Unknown particles of arbitrarily high mass can contribute as virtual particles in the amplitude, possibly enhancing the average oscillation rate or the difference between the rates of mesons and antimesons. This makes flavor oscillations sensitive to non-standard-model dynamics at large energy scales [1].

Oscillations occur because the mass eigenstates of neutral flavored mesons are linear combinations of the flavor eigenstates. In particular, for charm mesons, one writes $|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\bar{D}^0\rangle$, where p and q are complex parameters. In the limit of charge-parity (CP) symmetry, and by defining $D_{1(2)}$ as the CP -even (odd) state, the oscillation rate depends only on the dimensionless mixing parameters $x \equiv (m_1 - m_2)c^2/\Gamma$ 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 $D_{1(2)}$ state, respectively, and Γ equals $(\Gamma_1 + \Gamma_2)/2$ [2]. If CP symmetry is violated, the oscillation rates for mesons produced as D^0 and $\bar{D}^0$ differ. The difference is generated in the mixing amplitude if $|q/p| \neq 1$ or in the interference between mixing and decay if $\phi_f \equiv \arg(q\bar{A}_f/pA_f) \neq 0$. The amplitude A_f ($\bar{A}_f$) refers to the decay $D^0 \rightarrow f$ ($\bar{D}^0 \rightarrow f$), where f is a common final state. If CP is conserved in the

decay amplitude ($|A_f|^2 = |\bar{A}_f|^2$), the CP -violating phase is independent of the final state $\phi_f \approx \phi = \arg(q/p)$ [3,4].

Current global averages of charm-mixing parameters have large uncertainties and are consistent with CP symmetry, yielding $x = (3.6^{+2.1}_{-1.6}) \times 10^{-3}$, $y = (6.7^{+0.6}_{-1.3}) \times 10^{-3}$, $|q/p| = 0.94^{+0.17}_{-0.07}$, and $\phi = -0.13^{+0.26}_{-0.17}$ [5]. Improving the knowledge of x , which has not been shown to differ significantly from zero, is especially critical because the sensitivity to the small phase ϕ relies predominantly on observables proportional to $x \sin \phi$.

Direct experimental access to charm-mixing parameters is offered by self-conjugate multibody decays, such as $D^0 \rightarrow K_S^0 \pi^+ \pi^-$. Inclusion of charge-conjugate processes is implied unless stated otherwise. A joint fit of the Dalitz-plot and decay-time distributions of these decays allows the identification of a D^0 component that increases as a function of decay time in a sample of candidates produced as $\bar{D}^0$ mesons, and vice versa. This approach is challenging because it requires analyzing the decay-time evolution of signal decays across the Dalitz plot with a detailed amplitude model while accounting for efficiencies, resolutions, and background [6–8]. Model-independent approaches that obviate the need for an amplitude analysis exist [9–11], but they rely on an accurate description of the efficiencies.

This Letter reports on a measurement of charm oscillations in $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays based on a novel model-independent approach, called the bin-flip method, which is optimized for the measurement of the parameter x [12]. The method relies on ratios between charm decays reconstructed in similar kinematic and decay-time conditions, thus avoiding the need for an accurate modeling of the efficiency variation across phase space and decay time. We express the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ dynamics with two invariant masses following the Dalitz formalism [13,14], where $m_\pm^2$ is the squared invariant mass $m^2(K_S^0 \pi^\pm)$ for $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

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decays and $m^2(K_S^0\pi^\mp)$ for $\bar{D}^0 \rightarrow K_S^0\pi^+\pi^-$ decays. We partition the Dalitz plot into disjoint regions (“bins”) that preserve nearly constant strong-phase differences $\Delta\delta(m_-^2, m_+^2)$ between the D^0 and $\bar{D}^0$ amplitudes within each bin [15]. Two sets of eight bins are formed, and they are organized symmetrically about the principal bisector $m_+^2 = m_-^2$. Bins are labeled with the indices $\pm b$, where $b = 1, \dots, 8$. Positive indices refer to the (lower) $m_+^2 > m_-^2$ region, where unmixed Cabibbo-favored

$D^0 \rightarrow K^*(892)^-\pi^+$ decays dominate; negative indices refer to the symmetric (upper) $m_+^2 < m_-^2$ region, which receives a larger contribution from decays following oscillation. The data are further split into bins of decay time, which are indexed with j . For each, we measure the ratio R_{bj}^+ (R_{bj}^-) between initially produced D^0 ($\bar{D}^0$) mesons in Dalitz bin $-b$ and Dalitz bin b . For small mixing parameters and CP -conserving decay amplitudes, which are good approximations here, the ratios are [12]

$$R_{bj}^\pm \approx \frac{r_b + (1/4)r_b\langle t^2 \rangle_j \text{Re}(z_{CP}^2 - \Delta z^2) + (1/4)\langle t^2 \rangle_j |z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t \rangle_j \text{Re}[X_b^*(z_{CP} \pm \Delta z)]}{1 + (1/4)\langle t^2 \rangle_j \text{Re}(z_{CP}^2 - \Delta z^2) + r_b(1/4)\langle t^2 \rangle_j |z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t \rangle_j \text{Re}[X_b(z_{CP} \pm \Delta z)]}. \quad (1)$$

Here, $\langle t \rangle_j$ ($\langle t^2 \rangle_j$) is the average (squared) decay time of unmixed decays in bin j , in units of the D^0 lifetime $\tau = \hbar/\Gamma$ [2]. The parameter r_b is the ratio of signal yields in symmetric Dalitz-plot bins $\mp b$ at $t = 0$, and X_b quantifies the average strong-phase difference in these bins [12]. The z_{CP} and Δz parameters, defined by $z_{CP} \pm \Delta z \equiv -(q/p)^{\pm 1}(y + ix)$, are obtained, along with r_b , from a joint fit of the observed $R_{bj}^\pm$ ratios in which external information on $c_b \equiv \text{Re}(X_b)$ and $s_b \equiv -\text{Im}(X_b)$ [16] is used as a constraint. The results are expressed in terms of the CP -averaged mixing parameters $x_{CP} \equiv -\text{Im}(z_{CP})$ and $y_{CP} \equiv -\text{Re}(z_{CP})$, and of the CP -violating differences $\Delta x \equiv -\text{Im}(\Delta z)$ and $\Delta y \equiv -\text{Re}(\Delta z)$. Conservation of CP symmetry in mixing, or in the interference between mixing and decay, implies $x_{CP} = x$, $y_{CP} = y$, and $\Delta x = \Delta y = 0$.

Samples of $D^0 \rightarrow K_S^0\pi^+\pi^-$ decays are reconstructed from proton-proton collisions collected by the LHCb experiment in 2011 and 2012, corresponding to integrated luminosities of 1 and 2 fb⁻¹, respectively. In the 2012 data, both the strong-interaction decay $D^{*+} \rightarrow D^0\pi^+$ and the semileptonic b -hadron decay $\bar{B} \rightarrow D^0\mu^-X$, where X generically indicates unreconstructed particles, are used to determine whether a D^0 or a $\bar{D}^0$ is produced. In the 2011 data, only the $\bar{B} \rightarrow D^0\mu^-X$ decays were used because the online-selection efficiency for $D^{*+} \rightarrow D^0\pi^+$ decays was low. Throughout this Letter, D^{*+} indicates the $D^*(2010)^+$ meson and a soft pion indicates the pion from its decay.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$ equipped with charged-hadron identification detectors, calorimeters, and muon detectors; and it is designed for the study of particles containing b or c quarks [17,18].

The online selection of $D^{*+} \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\pi^+$ decays (prompt sample) uses criteria on momenta and final-state charged-particle displacements from any proton-proton primary interaction. Offline, we apply criteria consistent with the decay topology on momenta, vertex and track displacements, particle-identification information, and invariant masses of the D^{*+} decay products.

Specifically, the mass of the D^0 candidate is required to meet $1.84 < m(K_S^0\pi^+\pi^-) < 1.89$ GeV/ c^2 , and the difference between the D^{*+} and D^0 candidate masses is required to satisfy $\Delta m < 151.1$ MeV/ c^2 . The D^0 and soft pion candidates are required to point back to one of the proton-proton interactions (the primary vertex) to suppress signal candidates originating from decays of b hadrons (secondary decays). A kinematic fit constrains the tracks according to the decay topology and the D^{*+} candidate to originate from the primary vertex [19]. In the reconstruction of the Dalitz-plot coordinates, we additionally constrain the K_S^0 and D^0 meson masses to the known values [2] to ensure that all candidates populate the kinematically allowed phase space.

The online selection of $\bar{B} \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\mu^-X$ decays (semileptonic sample) requires at least one displaced high-transverse-momentum muon and a vertex consistent with the decay of a b hadron. Offline, we apply criteria consistent with the decay topology on momenta, vertex and track displacements, particle identifications, and invariant masses of the D^0 decay products. In addition, candidate $D^0\mu^-$ pairs are formed by requiring $2.5 < m(D^0\mu^-) < 6.0$ GeV/ c^2 and the corrected mass $\sqrt{m^2(D^0\mu^-) + p_\perp^2(D^0\mu^-) + p_\perp^2(D^0\mu^-)}$, where the momentum component $p_\perp(D^0\mu^-)$ of the $D^0\mu^-$ system transverse to the $\bar{B}$ flight direction partially compensates for the momentum of unreconstructed decay products, to be smaller than 5.8 GeV/ c^2 . The $\bar{B}$ flight direction is inferred from the measured positions of the primary and $D^0\mu^-$ vertices. A kinematic fit constrains the D^0 and K_S^0 masses to their known values.

In both samples, two categories of signal candidates are used: those with $K_S^0 \rightarrow \pi^+\pi^-$ candidates reconstructed in the vertex detector (long K_S^0), and those with K_S^0 candidates reconstructed after the vertex detector (downstream K_S^0).

About 2% (3%) of the selected D^{*+} ($\bar{B}$) candidates belong to events in which multiple candidates are reconstructed by pairing the same D^0 candidate with different soft pions (muons). For these events, we randomly choose a

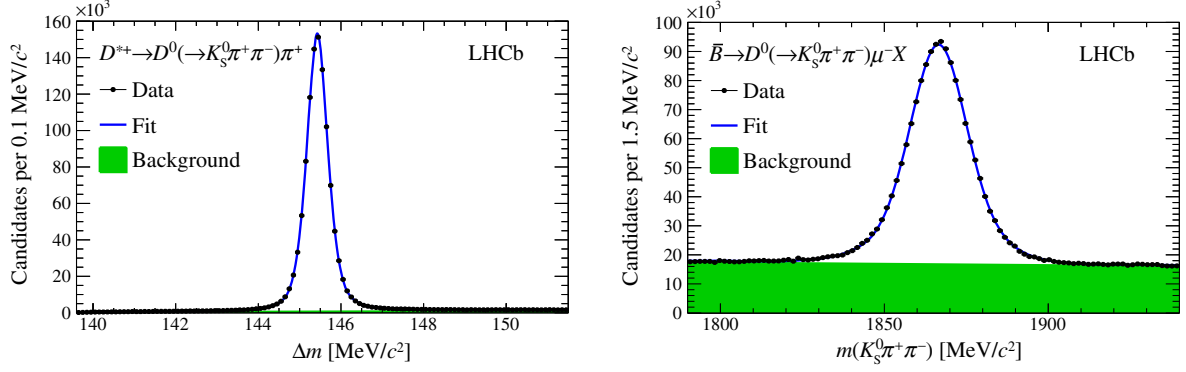


FIG. 1. Distribution of (left) the difference between D^{*+} and D^0 masses for $D^{*+} \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\pi^+$ candidates and (right) D^0 mass for $\bar{B} \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\mu^-X$ candidates.

single candidate. We consider the prompt and semileptonic samples independent because their overlap amounts to less than 0.1% of the semileptonic sample size.

Figure 1 shows the Δm and $m(K_S^0\pi^+\pi^-)$ distributions of the prompt and semileptonic samples, respectively. The prompt sample contains 1.3×10^6 signal decays (45% with downstream K_S^0 candidates) and a small background dominated by genuine $D^0 \rightarrow K_S^0\pi^+\pi^-$ decays associated to random soft pions. Secondary D^{*+} decays contribute approximately 3% to the signal yield, as determined using D^0 candidates not pointing to the primary vertex. The semileptonic sample contains 1.0×10^6 signal decays (66% with downstream K_S^0 candidates) and a sizable background dominated by unrelated $K_S^0\pi^+\pi^-$ combinations. Genuine D^0 decays associated with random muons contribute less than 1% to the D^0 yield, as determined from the yield of false $\bar{B}$ candidates formed by associating $D^{*+} \rightarrow D^0\pi^+$ with same-sign μ^+ candidates. Contributions from backgrounds due to misreconstructed D^0 decays, such as $D^0 \rightarrow K_S^0\pi^+\pi^-\pi^0$ and $D^0 \rightarrow K_S^0h^+h^{(\prime)-}$ (where $h^+h^{(\prime)-}$ indicates a pair of light hadrons other than $\pi^+\pi^-$), are negligible.

Simulated [20,21] prompt decays show that the online requirements on displacement and momenta of the D^0 decay products introduce efficiency variations that are correlated between the squared mass of the two final-state pions, $m^2(\pi^+\pi^-)$, and the D^0 decay time. Because $(m^2(\pi^+\pi^-), t)$ correlations can bias the results, we correct for them using data. The smallness of the mixing parameters [5], along with the known $D^0 \rightarrow K_S^0\pi^+\pi^-$ decay amplitudes [6–8], rules out any measurable $(m^2(\pi^+\pi^-), t)$ correlation introduced by D^0 – $\bar{D}^0$ mixing with current sample sizes. Hence, we ascribe any observed dependence between $m^2(\pi^+\pi^-)$ and t to instrumental effects. We use the background-subtracted $(m^2(\pi^+\pi^-), t)$ distribution to determine the decay-time efficiency, normalized to the average decay-time distribution, as a function of $m^2(\pi^+\pi^-)$. This two-dimensional map is smoothed and used to assign per-candidate weights proportional to the inverse of the relative efficiency at each candidate's $(m^2(\pi^+\pi^-), t)$ coordinates,

effectively removing the correlated nonuniformities. The corrections are determined separately for long and downstream K_S^0 candidates because they feature different correlations. Figure 2 shows the smoothed $(m^2(\pi^+\pi^-), t)$ map for the sample with downstream K_S^0 candidates, where the correlations are more prominent. The 6% of candidates reconstructed with $t < 0.9\tau$ are discarded because the corresponding weights cannot be determined precisely. No $(m^2(\pi^+\pi^-), t)$ correlations are observed in $\bar{B} \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\mu^-X$ decays.

We divide prompt and semileptonic samples according to the K_S^0 category, D^0 meson flavor, Dalitz-plot position, and decay time. In each subsample, we determine the signal yield and—for each decay-time bin—the average decay time and average squared decay time of the signal candidates. Finally, we fit the decay-time dependence of the ratio of the signal yields symmetric with respect to the Dalitz-plot bisector.

We determine the signal yields by fitting the Δm distribution, weighted to correct for the $(m^2(\pi^+\pi^-), t)$ correlations, for the $D^{*+} \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\pi^+$ candidates and the $m(K_S^0\pi^+\pi^-)$ distribution for the $\bar{B} \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\mu^-X$ candidates. All components are modeled empirically. The Δm model combines a D^{*+} signal with a smooth

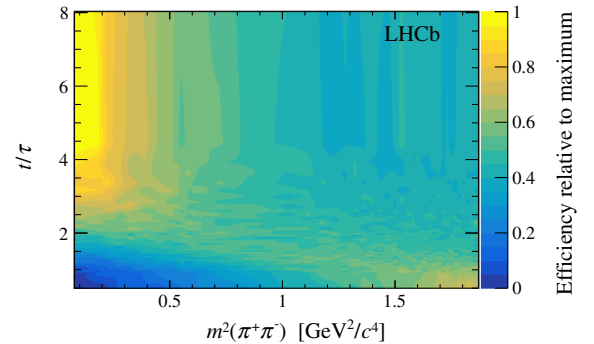


FIG. 2. Smoothed efficiency as a function of $m^2(\pi^+\pi^-)$ and t/τ in $D^{*+} \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\pi^+$ decays, as determined from the data with downstream K_S^0 candidates.

phase-space-like background. The $m(K_S^0\pi^+\pi^-)$ model combines a D^0 signal with a linear background. Signal and background shape parameters are determined independently for long and downstream K_S^0 candidates, for D^0 and $\bar{D}^0$ mesons, and in each decay-time and Dalitz-plot bin. The signal model assumes the same parameters for each pair of positive and negative Dalitz-plot bins.

We estimate $\langle t \rangle_j$ and $\langle t^2 \rangle_j$ from the background-subtracted t distribution in each decay-time bin j separately for prompt and semileptonic samples, as well as for long and downstream K_S^0 candidates. Background is subtracted using weights derived from the mass fits [22] of candidates restricted to the lower half ($m_-^2 < m_+^2$) of the Dalitz plot, which is enriched in D^0 mesons that did not undergo oscillations. We neglect the decay-time resolutions, which are typically 0.1τ and 0.25τ for the $D^{*+} \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\pi^+$ and $\bar{B} \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\mu^-X$ samples, respectively; and we account for this approximation in the systematic uncertainties.

The mixing parameters are determined by minimizing a least-squares function that compares the decay-time evolution of signal yields (N) observed in Dalitz bins $-b$ and $+b$, along with their uncertainties (σ), with the expected values reported in Eq. (1),

$$\chi^2 \equiv \sum_{\text{pr,sl}} \sum_{l,d} \sum_{+,-} \sum_{b,j} \frac{(N_{-bj}^\pm - N_{+bj}^\pm R_{+bj}^\pm)^2}{(\sigma_{-bj}^\pm)^2 + (\sigma_{+bj}^\pm R_{+bj}^\pm)^2} + \sum_{b,b'} (X_b^{\text{CLEO}} - X_b)(V_{\text{CLEO}}^{-1})_{bb'}(X_{b'}^{\text{CLEO}} - X_{b'}). \quad (2)$$

We fit simultaneously the prompt (pr) and semileptonic (sl) samples, separated between long (l) and downstream (d) K_S^0 candidates, as well as between D^0 (+) and $\bar{D}^0$ (−) flavors, across all decay-time bins j and Dalitz-plot bins b . We constrain the parameters X_b to the values X_b^{CLEO} measured by the CLEO collaboration through a Gaussian penalty term that uses the sum V_{CLEO} of the statistical and systematic covariance matrices [16]. In the fit, the parameters r_b are determined independently for each subsample (pr, sl, l , and d) because they are affected by the sample-specific variation of the efficiency over the Dalitz plot [12]. The values of x_{CP} , Δx , and Δy were kept blind until the analysis was finalized.

Figure 3 shows the yield ratios with fit projections overlaid for prompt and semileptonic data. The offsets between semileptonic and prompt data are due to sample-specific efficiency variations across the Dalitz plot; their slopes, due to charm oscillations, are consistent across samples. Table I lists the results. The data are consistent with CP symmetry ($\Delta x = \Delta y = 0$). The precision is dominated by the statistical contribution, which incorporates a subleading component due to the precision of the CLEO measurements.

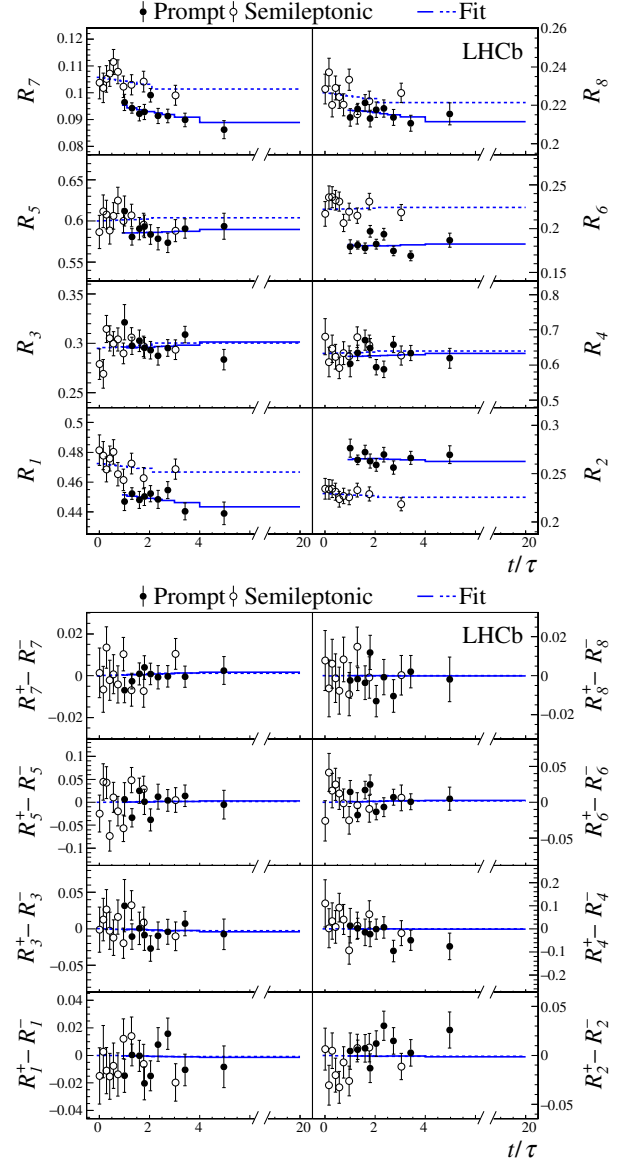


FIG. 3. (Top) CP -averaged yield ratios and (bottom) differences of D^0 and $\bar{D}^0$ yield ratios as functions of t/τ for each Dalitz bin. Prompt (closed points) and semileptonic (open points) data are shown separately. Fit projections over the prompt (solid line) and semileptonic (dashed line) data are overlaid.

The dominant systematic uncertainties on x_{CP} are associated with the 3% contamination from secondary D^{*+} decays in the prompt sample (0.24×10^{-3}) and from the 1% contamination of genuine D^0 mesons associated with random muons in the semileptonic sample (0.34×10^{-3}). Biases due to the neglected decay-time and $m_\pm^2$ resolutions, and the neglected efficiency variations across the decay time and Dalitz plot, constitute the dominant systematic uncertainty on y_{CP} (0.94×10^{-3}). Possible asymmetric nonuniformities with respect to the bisector in the Dalitz plot induced by reconstruction inefficiencies dominate the systematic uncertainty on Δx

TABLE I. Fit results. The first contribution to the uncertainty is statistical, and the second is systematic.

Parameter	Value [10^{-3}]	Statistical correlations			Systematic correlations		
		y_{CP}	Δx	Δy	y_{CP}	Δx	Δy
x_{CP}	$2.7 \pm 1.6 \pm 0.4$	−0.17	0.04	−0.02	0.15	0.01	−0.02
y_{CP}	$7.4 \pm 3.6 \pm 1.1$		−0.03	0.01		−0.05	−0.03
Δx	$−0.53 \pm 0.70 \pm 0.22$			−0.13			0.14
Δy	$0.6 \pm 1.6 \pm 0.3$						

(0.22×10^{-3}) and Δy (0.25×10^{-3}). Other minor effects, such as mismodeling in the signal-yield fits or in the determination of the bin-averaged decay times, are also considered. The consistency between results on the prompt and semileptonic sample [15], and on various partitions of the data, supports the robustness of the analysis, including the correction of the $(m^2(\pi^+\pi^-), t)$ correlations.

In summary, we report a measurement of the normalized mass difference between neutral charm-meson eigenstates using the recently proposed bin-flip method. Allowing for CP violation in charm mixing, or in the interference between mixing and decay, we measure the CP -averaged normalized mass difference $x_{CP} = [2.7 \pm 1.6(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-3}$ and the CP -violating parameter $\Delta x = [-0.53 \pm 0.70(\text{stat}) \pm 0.22(\text{syst})] \times 10^{-3}$. In addition, we report the CP -averaged normalized width difference $y_{CP} = [7.4 \pm 3.6(\text{stat}) \pm 1.1(\text{syst})] \times 10^{-3}$, along with the corresponding CP -violating parameter $\Delta y = [0.6 \pm 1.6(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-3}$. We use the results to form a likelihood function of x , y , $|q/p|$, and ϕ ; and we derive confidence intervals (Table II) using a likelihood-ratio ordering that assumes the observed correlations to be independent of the true parameter values [23]. The resulting determination of the mass difference is the most precise from a single experiment, as are the determinations of the CP -violation parameters. Although our result is consistent with $x = 0$ within two standard deviations, combined with the current global knowledge, it yields $x = (3.9_{-1.2}^{+1.1}) \times 10^{-3}$ [5], strongly contributing to the emerging evidence for a nonzero (positive) mass difference between the neutral charm-meson eigenstates. The global constraints on CP violation in the D^0 - $\bar{D}^0$ system are also greatly improved, with precisions on $|q/p|$ and ϕ more than doubled as compared to previous averages [5].

TABLE II. Point estimates and 95.5% confidence-level (C.L.) intervals for the derived parameters. Uncertainties include statistical and systematic contributions.

Parameter	Value	95.5% C.L. interval
x [10^{-2}]	$0.27_{-0.15}^{+0.17}$	[−0.05, 0.60]
y [10^{-2}]	0.74 ± 0.37	[0.00, 1.50]
$ q/p $	$1.05_{-0.17}^{+0.22}$	[0.55, 2.15]
ϕ	$−0.09_{-0.16}^{+0.11}$	[−0.73, 0.29]

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S. Coquereau,⁴² G. Corti,⁴⁴ C. M. Costa Sobral,⁵² B. Couturier,⁴⁴ G. A. Cowan,⁵⁴ D. C. Craik,⁶⁰ A. Crocombe,⁵²
 M. Cruz Torres,¹ R. Currie,⁵⁴ C. L. Da Silva,⁷⁸ E. Dall’Occo,²⁹ J. Dalseno,^{43,j} C. D’Ambrosio,⁴⁴ A. Danilina,³⁵ P. d’Argent,¹⁴
 A. Davis,⁵⁸ O. De Aguiar Francisco,⁴⁴ K. De Bruyn,⁴⁴ S. De Capua,⁵⁸ M. De Cian,⁴⁵ J. M. De Miranda,¹ L. De Paula,²
 M. De Serio,^{16,k} P. De Simone,²⁰ J. A. de Vries,²⁹ C. T. Dean,⁵⁵ W. Dean,⁷⁷ D. Decamp,⁶ L. Del Buono,¹⁰ B. Delaney,⁵¹
 H.-P. Dembinski,¹³ M. Demmer,¹² A. Dendek,³² D. Derkach,⁷⁴ O. Deschamps,⁷ F. Desse,⁹ F. Dettori,²⁴ B. Dey,⁶⁸
 A. Di Canto,⁴⁴ P. Di Nezza,²⁰ S. Didenko,⁷³ H. Dijkstra,⁴⁴ F. Dordei,²⁴ M. Dorigo,^{44,l} A. C. dos Reis,¹ A. Dosil Suárez,⁴³
 L. Douglas,⁵⁵ A. Dovbnya,⁴⁷ K. Dreimanis,⁵⁶ L. Dufour,⁴⁴ G. Dujany,¹⁰ P. Durante,⁴⁴ J. M. Durham,⁷⁸ D. Dutta,⁵⁸
 R. Dzhelyadin,^{40,a} M. Dziewiecki,¹⁴ A. Dziurda,³¹ A. Dzyuba,⁴¹ S. Easo,⁵³ U. Egede,⁵⁷ V. Egorychev,³⁵ S. Eidelman,^{39,f}
 S. Eisenhardt,⁵⁴ U. Eitschberger,¹² R. Ekelhof,¹² L. Eklund,⁵⁵ S. Ely,⁶³ A. Ene,³⁴ S. Escher,¹¹ S. Esen,²⁹ T. Evans,⁶¹
 A. Falabella,¹⁷ C. Färber,⁴⁴ N. Farley,⁴⁹ S. Farry,⁵⁶ D. Fazzini,^{22,c} M. Féo,⁴⁴ P. Fernandez Declara,⁴⁴ A. Fernandez Prieto,⁴³
 F. Ferrari,^{17,d} L. Ferreira Lopes,⁴⁵ F. Ferreira Rodrigues,² S. Ferreres Sole,²⁹ M. Ferro-Luzzi,⁴⁴ S. Filippov,³⁷ R. A. Fini,¹⁶
 M. Fiorini,^{18,g} M. Firlej,³² C. Fitzpatrick,⁴⁵ T. Fiutowski,³² F. Fleuret,^{9,b} M. Fontana,⁴⁴ F. Fontanelli,^{21,m} R. Forty,⁴⁴
 V. Franco Lima,⁵⁶ M. Frank,⁴⁴ C. Frei,⁴⁴ J. Fu,^{23,n} W. Funk,⁴⁴ E. Gabriel,⁵⁴ A. Gallas Torreira,⁴³ D. Galli,^{17,d} S. Gallorini,²⁵
 S. Gambetta,⁵⁴ Y. Gan,³ M. Gandelman,² P. Gandini,²³ Y. Gao,³ L. M. Garcia Martin,⁷⁶ J. García Pardiñas,⁴⁶
 B. Garcia Plana,⁴³ J. Garra Tico,⁵¹ L. Garrido,⁴² D. Gascon,⁴² C. Gaspar,⁴⁴ G. Gazzoni,⁷ D. Gerick,¹⁴ E. Gersabeck,⁵⁸
 M. Gersabeck,⁵⁸ T. Gershon,⁵² D. Gerstel,⁸ Ph. Ghez,⁶ V. Gibson,⁵¹ O. G. Girard,⁴⁵ P. Gironella Gironell,⁴² L. Giubega,³⁴
 K. Gizdov,⁵⁴ V. V. Gligorov,¹⁰ C. Göbel,⁶⁵ D. Golubkov,³⁵ A. Golutvin,^{57,73} A. Gomes,^{1,o} I. V. Gorelov,³⁶ C. Gotti,^{22,c}
 E. Govorkova,²⁹ J. P. Grabowski,¹⁴ R. Graciani Diaz,⁴² L. A. Granado Cardoso,⁴⁴ E. Graugés,⁴² E. Graverini,⁴⁶
 G. Graziani,¹⁹ A. Grecu,³⁴ R. Greim,²⁹ P. Griffith,²⁴ L. Grillo,⁵⁸ L. Gruber,⁴⁴ B. R. Gruber Cazon,⁵⁹ C. Gu,³ E. Gushchin,³⁷
 A. Guth,¹¹ Yu. Guz,^{40,44} T. Gys,⁴⁴ T. Hadavizadeh,⁵⁹ C. Hadjivasiliou,⁷ G. Haefeli,⁴⁵ C. Haen,⁴⁴ S. C. Haines,⁵¹
 B. Hamilton,⁶² X. Han,¹⁴ T. H. Hancock,⁵⁹ S. Hansmann-Menzemer,¹⁴ N. Harnew,⁵⁹ T. Harrison,⁵⁶ C. Hasse,⁴⁴ M. Hatch,⁴⁴
 J. He,⁴ M. Hecker,⁵⁷ K. Heinicke,¹² A. Heister,¹² K. Hennessy,⁵⁶ L. Henry,⁷⁶ M. Heß,⁷⁰ J. Heuel,¹¹ A. Hicheur,⁶⁴
 R. Hidalgo Charman,⁵⁸ D. Hill,⁵⁹ M. Hilton,⁵⁸ P. H. Hopchev,⁴⁵ J. Hu,¹⁴ W. Hu,⁶⁸ W. Huang,⁴ Z. C. Huard,⁶¹
 W. Hulsbergen,²⁹ T. Humair,⁵⁷ M. Hushchyn,⁷⁴ D. Hutchcroft,⁵⁶ D. Hynds,²⁹ P. Ibis,¹² M. Idzik,³² P. Ilten,⁴⁹ A. Inglessi,⁴¹
 A. Inyakin,⁴⁰ K. Ivshin,⁴¹ R. Jacobsson,⁴⁴ S. Jakobsen,⁴⁴ J. Jalocha,⁵⁹ E. Jans,²⁹ B. K. Jashal,⁷⁶ A. Jawahery,⁶² F. Jiang,³
 M. John,⁵⁹ D. Johnson,⁴⁴ C. R. Jones,⁵¹ C. Joram,⁴⁴ B. Jost,⁴⁴ N. Jurik,⁵⁹ S. Kandybei,⁴⁷ M. Karacson,⁴⁴ J. M. Kariuki,⁵⁰
 S. Karodia,⁵⁵ N. Kazeev,⁷⁴ M. Kecke,¹⁴ F. Keizer,⁵¹ M. Kelsey,⁶³ M. Kenzie,⁵¹ T. Ketel,³⁰ B. Khanji,⁴⁴ A. Kharisova,⁷⁵
 C. Khurewathanakul,⁴⁵ K. E. Kim,⁶³ T. Kim,¹¹ V. S. Kirsebom,⁴⁵ S. Klaver,²⁰ K. Klimaszewski,³³ S. Koliiev,⁴⁸ M. Kolpin,¹⁴
 R. Kopečna,¹⁴ P. Koppenburg,²⁹ I. Kostiuik,^{29,48} S. Kotriakhova,⁴¹ M. Kozeiha,⁷ L. Kravchuk,³⁷ M. Kreps,⁵² F. Kress,⁵⁷
 S. Kretzschmar,¹¹ P. Krokovny,^{39,f} W. Krupa,³² W. Krzemien,³³ W. Kucewicz,^{31,p} M. Kucharczyk,³¹ V. Kudryavtsev,^{39,f}
 A. K. Kuonen,⁴⁵ T. Kvaratskheliya,³⁵ D. Lacarrere,⁴⁴ G. Lafferty,⁵⁸ A. Lai,²⁴ D. Lancieri,⁴⁶ G. Lanfranchi,²⁰
 C. Langenbruch,¹¹ T. Latham,⁵² C. Lazzeroni,⁴⁹ R. Le Gac,⁸ R. Lefèvre,⁷ A. Leflat,³⁶ F. Lemaitre,⁴⁴ O. Leroy,⁸ T. Lesiak,³¹
 B. Leverington,¹⁴ H. Li,⁶⁶ P.-R. Li,^{4,q} Y. Li,⁵ Z. Li,⁶³ X. Liang,⁶³ T. Likhomanenko,⁷² R. Lindner,⁴⁴ F. Lionetto,⁴⁶
 V. Lisovskyi,⁹ G. Liu,⁶⁶ X. Liu,³ D. Loh,⁵² A. Loi,²⁴ I. Longstaff,⁵⁵ J. H. Lopes,² G. Loustau,⁴⁶ G. H. Lovell,⁵¹
 D. Lucchesi,^{25,r} M. Lucio Martinez,⁴³ Y. Luo,³ A. Lupato,²⁵ E. Luppi,^{18,g} O. Lupton,⁵² A. Lusiani,²⁶ X. Lyu,⁴ F. Machefert,⁹
 F. Maciuc,³⁴ V. Macko,⁴⁵ P. Mackowiak,¹² S. Maddrell-Mander,⁵⁰ O. Maev,^{41,44} K. Maguire,⁵⁸ D. Maisuzenko,⁴¹
 M. W. Majewski,³² S. Malde,⁵⁹ B. Malecki,⁴⁴ A. Malinin,⁷² T. Maltsev,^{39,f} H. Malygina,¹⁴ G. Manca,^{24,s} G. Mancinelli,⁸
 D. Marangotto,^{23,n} J. Maratas,^{7,t} J. F. Marchand,⁶ U. Marconi,¹⁷ C. Marin Benito,⁹ M. Marinangeli,⁴⁵ P. Marino,⁴⁵
 J. Marks,¹⁴ P. J. Marshall,⁵⁶ G. Martellotti,²⁸ M. Martinelli,⁴⁴ D. Martinez Santos,⁴³ F. Martinez Vidal,⁷⁶ A. Massafferri,¹
 M. Materok,¹¹ R. Matev,⁴⁴ A. Mathad,⁴⁶ Z. Mathe,⁴⁴ V. Matiunin,³⁵ C. Matteuzzi,²² K. R. Mattioli,⁷⁷ A. Mauri,⁴⁶
 E. Maurice,^{9,b} B. Maurin,⁴⁵ M. McCann,^{57,44} A. McNab,⁵⁸ R. McNulty,¹⁵ J. V. Mead,⁵⁶ B. Meadows,⁶¹ C. Meaux,⁸
 N. Meinert,⁷⁰ D. Melnychuk,³³ M. Merk,²⁹ A. Merli,^{23,n} E. Michielin,²⁵ D. A. Milanes,⁶⁹ E. Millard,⁵² M.-N. Minard,⁶
 L. Minzoni,^{18,g} D. S. Mitzel,¹⁴ A. Mödden,¹² A. Mogini,¹⁰ R. D. Moise,⁵⁷ T. Mombächer,¹² I. A. Monroy,⁶⁹ S. Monteil,⁷
 M. Morandin,²⁵ G. Morello,²⁰ M. J. Morello,^{26,u} J. Moron,³² A. B. Morris,⁸ R. Mountain,⁶³ F. Muheim,⁵⁴ M. Mukherjee,⁶⁸
 M. Mulder,²⁹ D. Müller,⁴⁴ J. Müller,¹² K. Müller,⁴⁶ V. Müller,¹² C. H. Murphy,⁵⁹ D. Murray,⁵⁸ P. Naik,⁵⁰ T. Nakada,⁴⁵
 R. Nandakumar,⁵³ A. Nandi,⁵⁹ T. Nanut,⁴⁵ I. Nasteva,² M. Needham,⁵⁴ N. Neri,^{23,n} S. Neubert,¹⁴ N. Neufeld,⁴⁴
 R. Newcombe,⁵⁷ T. D. Nguyen,⁴⁵ C. Nguyen-Mau,^{45,v} S. Nieswand,¹¹ R. Niet,¹² N. Nikitin,³⁶ N. S. Nolte,⁴⁴
 A. Oblakowska-Mucha,³² V. Obraztsov,⁴⁰ S. Ogilvy,⁵⁵ D. P. O’Hanlon,¹⁷ R. Oldeman,^{24,s} C. J. G. Onderwater,⁷¹
 J. D. Osborn,⁷⁷ A. Ossowska,³¹ J. M. Otalora Goicochea,² T. Ovsiannikova,³⁵ P. Owen,⁴⁶ A. Oyanguren,⁷⁶ P. R. Pais,⁴⁵

T. Pajero,^{26,u} A. Palano,¹⁶ M. Palutan,²⁰ G. Panshin,⁷⁵ A. Papanestis,⁵³ M. Pappagallo,⁵⁴ L. L. Pappalardo,^{18,g} W. Parker,⁶²
 C. Parkes,^{58,44} G. Passaleva,^{19,44} A. Pastore,¹⁶ M. Patel,⁵⁷ C. Patrignani,^{17,d} A. Pearce,⁴⁴ A. Pellegrino,²⁹ G. Penso,²⁸
 M. Pepe Altarelli,⁴⁴ S. Perazzini,⁴⁴ D. Pereima,³⁵ P. Perret,⁷ L. Pescatore,⁴⁵ K. Petridis,⁵⁰ A. Petrolini,^{21,m} A. Petrov,⁷²
 S. Petrucci,⁵⁴ M. Petruzzo,^{23,n} B. Pietrzyk,⁶ G. Pietrzyk,⁴⁵ M. Pikies,³¹ M. Pili,⁵⁹ D. Pinci,²⁸ J. Pinzino,⁴⁴ F. Pisani,⁴⁴
 A. Piucci,¹⁴ V. Placinta,³⁴ S. Playfer,⁵⁴ J. Plews,⁴⁹ M. Plo Casasus,⁴³ F. Polci,¹⁰ M. Poli Lener,²⁰ M. Poliakov,⁶³
 A. Poluektov,⁸ N. Polukhina,^{73,w} I. Polyakov,⁶³ E. Polycarpo,² G. J. Pomery,⁵⁰ S. Ponce,⁴⁴ A. Popov,⁴⁰ D. Popov,^{49,13}
 S. Poslavskii,⁴⁰ E. Price,⁵⁰ C. Prouve,⁴³ V. Pugatch,⁴⁸ A. Puig Navarro,⁴⁶ H. Pullen,⁵⁹ G. Punzi,^{26,i} W. Qian,⁴ J. Qin,⁴
 R. Quagliani,¹⁰ B. Quintana,⁷ N. V. Raab,¹⁵ B. Rachwal,³² J. H. Rademacker,⁵⁰ M. Rama,²⁶ M. Ramos Pernas,⁴³
 M. S. Rangel,² F. Ratnikov,^{38,74} G. Raven,³⁰ M. Ravonel Salzgeber,⁴⁴ M. Reboud,⁶ F. Redi,⁴⁵ S. Reichert,¹² F. Reiss,¹⁰
 C. Remon Alepuz,⁷⁶ Z. Ren,³ V. Renaudin,⁵⁹ S. Ricciardi,⁵³ S. Richards,⁵⁰ K. Rinnert,⁵⁶ P. Robbe,⁹ A. Robert,¹⁰
 A. B. Rodrigues,⁴⁵ E. Rodrigues,⁶¹ J. A. Rodriguez Lopez,⁶⁹ M. Roehrken,⁴⁴ S. Roiser,⁴⁴ A. Rollings,⁵⁹ V. Romanovskiy,⁴⁰
 A. Romero Vidal,⁴³ J. D. Roth,⁷⁷ M. Rotondo,²⁰ M. S. Rudolph,⁶³ T. Ruf,⁴⁴ J. Ruiz Vidal,⁷⁶ J. J. Saborido Silva,⁴³
 N. Sagidova,⁴¹ B. Saitta,^{24,s} V. Salustino Guimaraes,⁶⁵ C. Sanchez Gras,²⁹ C. Sanchez Mayordomo,⁷⁶ B. Sanmartin Sedes,⁴³
 R. Santacesaria,²⁸ C. Santamarina Rios,⁴³ M. Santimaria,^{20,44} E. Santovetti,^{27,x} G. Sarpis,⁵⁸ A. Sarti,^{20,y} C. Satriano,^{28,z}
 A. Satta,²⁷ M. Saur,⁴ D. Savrina,^{35,36} S. Schael,¹¹ M. Schellenberg,¹² M. Schiller,⁵⁵ H. Schindler,⁴⁴ M. Schmelling,¹³
 T. Schmelzer,¹² B. Schmidt,⁴⁴ O. Schneider,⁴⁵ A. Schopper,⁴⁴ H. F. Schreiner,⁶¹ M. Schubiger,⁴⁵ S. Schulte,⁴⁵
 M. H. Schune,⁹ R. Schwemmer,⁴⁴ B. Sciascia,²⁰ A. Sciubba,^{28,y} A. Semennikov,³⁵ E. S. Sepulveda,¹⁰ A. Sergi,^{49,44}
 N. Serra,⁴⁶ J. Serrano,⁸ L. Sestini,²⁵ A. Seuthe,¹² P. Seyfert,⁴⁴ M. Shapkin,⁴⁰ T. Shears,⁵⁶ L. Shekhtman,^{39,f} V. Shevchenko,⁷²
 E. Shmanin,⁷³ B. G. Siddi,¹⁸ R. Silva Coutinho,⁴⁶ L. Silva de Oliveira,² G. Simi,^{25,r} S. Simone,^{16,k} I. Skiba,¹⁸ N. Skidmore,¹⁴
 T. Skwarnicki,⁶³ M. W. Slater,⁴⁹ J. G. Smeaton,⁵¹ E. Smith,¹¹ I. T. Smith,⁵⁴ M. Smith,⁵⁷ M. Soares,¹⁷ I. Soares Lavra,¹
 M. D. Sokoloff,⁶¹ F. J. P. Soler,⁵⁵ B. Souza De Paula,² B. Spaan,¹² E. Spadaro Norella,^{23,n} P. Spradlin,⁵⁵ F. Stagni,⁴⁴
 M. Stahl,¹⁴ S. Stahl,⁴⁴ P. Steffko,⁴⁵ S. Stefkova,⁵⁷ O. Steinkamp,⁴⁶ S. Stemmler,¹⁴ O. Stenyakin,⁴⁰ M. Stepanova,⁴¹
 H. Stevens,¹² A. Stocchi,⁹ S. Stone,⁶³ S. Stracka,²⁶ M. E. Stramaglia,⁴⁵ M. Straticiuc,³⁴ U. Straumann,⁴⁶ S. Strokov,⁷⁵
 J. Sun,³ L. Sun,⁶⁷ Y. Sun,⁶² K. Swientek,³² A. Szabelski,³³ T. Szumlak,³² M. Szymanski,⁴ Z. Tang,³ T. Tekampe,¹²
 G. Tellarini,¹⁸ F. Teubert,⁴⁴ E. Thomas,⁴⁴ M. J. Tilley,⁵⁷ V. Tisserand,⁷ S. T'Jampens,⁶ M. Tobin,⁵ S. Tolk,⁴⁴
 L. Tomassetti,^{18,g} D. Tonelli,²⁶ D. Y. Tou,¹⁰ R. Tourinho Jadallah Aoude,¹ E. Tourniefier,⁶ M. Traill,⁵⁵ M. T. Tran,⁴⁵
 A. Trisovic,⁵¹ A. Tsaregorodtsev,⁸ G. Tuci,^{26,44,i} A. Tully,⁵¹ N. Tuning,²⁹ A. Ukleja,³³ A. Usachov,⁹ A. Ustyuzhanin,^{38,74}
 U. Uwer,¹⁴ A. Vagner,⁷⁵ V. Vagnoni,¹⁷ A. Valassi,⁴⁴ S. Valat,⁴⁴ G. Valenti,¹⁷ M. van Beuzekom,²⁹ E. van Herwijnen,⁴⁴
 C. B. Van Hulse,¹⁵ J. van Tilburg,²⁹ M. van Veghel,²⁹ R. Vazquez Gomez,⁴⁴ P. Vazquez Regueiro,⁴³ C. Vázquez Sierra,²⁹
 S. Vecchi,¹⁸ J. J. Velthuis,⁵⁰ M. Veltri,^{19,aa} A. Venkateswaran,⁶³ M. Vernet,⁷ M. Veronesi,²⁹ M. Vesterinen,⁵²
 J. V. Viana Barbosa,⁴⁴ D. Vieira,⁴ M. Vieites Diaz,⁴³ H. Viemann,⁷⁰ X. Vilasis-Cardona,^{42,h} A. Vitkovskiy,²⁹ M. Vitti,⁵¹
 V. Volkov,³⁶ A. Vollhardt,⁴⁶ D. Vom Bruch,¹⁰ B. Voneki,⁴⁴ A. Vorobyev,⁴¹ V. Vorobyev,^{39,f} N. Voropaev,⁴¹ R. Waldi,⁷⁰
 J. Walsh,²⁶ J. Wang,⁵ M. Wang,³ Y. Wang,⁶⁸ Z. Wang,⁴⁶ D. R. Ward,⁵¹ H. M. Wark,⁵⁶ N. K. Watson,⁴⁹ D. Websdale,⁵⁷
 A. Weiden,⁴⁶ C. Weissner,⁶⁰ M. Whitehead,¹¹ G. Wilkinson,⁵⁹ M. Wilkinson,⁶³ I. Williams,⁵¹ M. Williams,⁶⁰
 M. R. J. Williams,⁵⁸ T. Williams,⁴⁹ F. F. Wilson,⁵³ M. Winn,⁹ W. Wislicki,³³ M. Witek,³¹ G. Wormser,⁹ S. A. Wotton,⁵¹
 K. Wyllie,⁴⁴ D. Xiao,⁶⁸ Y. Xie,⁶⁸ H. Xing,⁶⁶ A. Xu,³ M. Xu,⁶⁸ Q. Xu,⁴ Z. Xu,⁶ Z. Xu,³ Z. Yang,³ Z. Yang,⁶² Y. Yao,⁶³
 L. E. Yeomans,⁵⁶ H. Yin,⁶⁸ J. Yu,^{68,bb} X. Yuan,⁶³ O. Yushchenko,⁴⁰ K. A. Zarebski,⁴⁹ M. Zavertyaev,^{13,w} M. Zeng,³
 D. Zhang,⁶⁸ L. Zhang,³ W. C. Zhang,^{3,cc} Y. Zhang,⁴⁴ A. Zhelezov,¹⁴ Y. Zheng,⁴ X. Zhu,³ V. Zhukov,^{11,36}
 J. B. Zonneveld,⁵⁴ and S. Zucchelli^{17,d}

(LHCb Collaboration)

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

⁷Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France

⁸Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

- ⁹LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- ¹⁰LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
- ¹¹I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany
- ¹²Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
- ¹³Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
- ¹⁴Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ¹⁵School of Physics, University College Dublin, Dublin, Ireland
- ¹⁶INFN Sezione di Bari, Bari, Italy
- ¹⁷INFN Sezione di Bologna, Bologna, Italy
- ¹⁸INFN Sezione di Ferrara, Ferrara, Italy
- ¹⁹INFN Sezione di Firenze, Firenze, Italy
- ²⁰INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ²¹INFN Sezione di Genova, Genova, Italy
- ²²INFN Sezione di Milano-Bicocca, Milano, Italy
- ²³INFN Sezione di Milano, Milano, Italy
- ²⁴INFN Sezione di Cagliari, Monserrato, Italy
- ²⁵INFN Sezione di Padova, Padova, Italy
- ²⁶INFN Sezione di Pisa, Pisa, Italy
- ²⁷INFN Sezione di Roma Tor Vergata, Roma, Italy
- ²⁸INFN Sezione di Roma La Sapienza, Roma, Italy
- ²⁹Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands
- ³⁰Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands
- ³¹Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
- ³²AGH—University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
- ³³National Center for Nuclear Research (NCBJ), Warsaw, Poland
- ³⁴Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
- ³⁵Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ³⁶Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
- ³⁷Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia
- ³⁸Yandex School of Data Analysis, Moscow, Russia
- ³⁹Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia
- ⁴⁰Institute for High Energy Physics (IHEP), Protvino, Russia
- ⁴¹Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St.Petersburg, Russia
- ⁴²ICCUB, Universitat de Barcelona, Barcelona, Spain
- ⁴³Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
- ⁴⁴European Organization for Nuclear Research (CERN), Geneva, Switzerland
- ⁴⁵Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
- ⁴⁶Physik-Institut, Universität Zürich, Zürich, Switzerland
- ⁴⁷NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
- ⁴⁸Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
- ⁴⁹University of Birmingham, Birmingham, United Kingdom
- ⁵⁰H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
- ⁵¹Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ⁵²Department of Physics, University of Warwick, Coventry, United Kingdom
- ⁵³STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
- ⁵⁴School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁵⁵School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁶Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁵⁷Imperial College London, London, United Kingdom
- ⁵⁸School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁵⁹Department of Physics, University of Oxford, Oxford, United Kingdom
- ⁶⁰Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
- ⁶¹University of Cincinnati, Cincinnati, Ohio, USA
- ⁶²University of Maryland, College Park, Maryland, USA
- ⁶³Syracuse University, Syracuse, New York, USA
- ⁶⁴Laboratory of Mathematical and Subatomic Physics, Constantine, Algeria
[associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil]
- ⁶⁵Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil
[associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil]

- ⁶⁶*South China Normal University, Guangzhou, China (associated with Center for High Energy Physics, Tsinghua University, Beijing, China)*
- ⁶⁷*School of Physics and Technology, Wuhan University, Wuhan, China (associated with Center for High Energy Physics, Tsinghua University, Beijing, China)*
- ⁶⁸*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China (associated with Center for High Energy Physics, Tsinghua University, Beijing, China)*
- ⁶⁹*Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia (associated with LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France)*
- ⁷⁰*Institut für Physik, Universität Rostock, Rostock, Germany (associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)*
- ⁷¹*Van Swinderen Institute, University of Groningen, Groningen, Netherlands (associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)*
- ⁷²*National Research Centre Kurchatov Institute, Moscow, Russia [associated with Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia]*
- ⁷³*National University of Science and Technology “MISIS”, Moscow, Russia [associated with Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia]*
- ⁷⁴*National Research University Higher School of Economics, Moscow, Russia (associated with Yandex School of Data Analysis, Moscow, Russia)*
- ⁷⁵*National Research Tomsk Polytechnic University, Tomsk, Russia [associated with Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia]*
- ⁷⁶*Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain (associated with ICCUB, Universitat de Barcelona, Barcelona, Spain)*
- ⁷⁷*University of Michigan, Ann Arbor, USA (associated with Syracuse University, Syracuse, New York, USA)*
- ⁷⁸*Los Alamos National Laboratory (LANL), Los Alamos, USA (associated with Syracuse University, Syracuse, New York, USA)*

^aDeceased.

^bAlso at Laboratoire Leprince-Ringuet, Palaiseau, France.

^cAlso at Università di Milano Bicocca, Milano, Italy.

^dAlso at Università di Bologna, Bologna, Italy.

^eAlso at Università di Modena e Reggio Emilia, Modena, Italy.

^fAlso at Novosibirsk State University, Novosibirsk, Russia.

^gAlso at Università di Ferrara, Ferrara, Italy.

^hAlso at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.

ⁱAlso at Università di Pisa, Pisa, Italy.

^jAlso at H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom.

^kAlso at Università di Bari, Bari, Italy.

^lAlso at Sezione INFN di Trieste, Trieste, Italy.

^mAlso at Università di Genova, Genova, Italy.

ⁿAlso at Università degli Studi di Milano, Milano, Italy.

^oAlso at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil.

^pAlso at AGH—University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland.

^qAlso at Lanzhou University, Lanzhou, China.

^rAlso at Università di Padova, Padova, Italy.

^sAlso at Università di Cagliari, Cagliari, Italy.

^tAlso at MSU—Iligan Institute of Technology (MSU-IIT), Iligan, Philippines.

^uAlso at Scuola Normale Superiore, Pisa, Italy.

^vAlso at Hanoi University of Science, Hanoi, Vietnam.

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

^xAlso at Università di Roma Tor Vergata, Roma, Italy.

^yAlso at Università di Roma La Sapienza, Roma, Italy.

^zAlso at Università della Basilicata, Potenza, Italy.

^{aa}Also at Università di Urbino, Urbino, Italy.

^{bb}Also at Physics and Micro Electronic College, Hunan University, Changsha City, China.

^{cc}Also at School of Physics and Information Technology, Shaanxi Normal University (SNNU), Xi'an, China.