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Measurement of the Mass Difference Between Neutral Charm-Meson Eigenstates

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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 $2.3 \times 10^6 \ D^0 \rightarrow K^0_S \pi^+ \pi^-$ 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 $\Delta x = [2.7 \pm 1.6 \text{(stat)} \pm 0.4 \text{(syst)}] \times 10^{-3}$ and the CP-violating parameter $D$ decay amplitude $|A_f|^2 = |\bar{A}_f|^2)$, the CP-violating phase is independent of the final state $\phi_f \approx \phi = \arg (q/p)$.

Current global averages of charm-mixing parameters have large uncertainties and are consistent with CP symmetry, yielding $x = (3.6^{+1.5}_{-1.9}) \times 10^{-3}$, $y = (6.7^{+0.6}_{-0.3}) \times 10^{-3}$, $|q/p| = 0.94^{+0.17}_{-0.07}$, 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 $\phi$ 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 $D^0 \rightarrow K^0_S \pi^+ \pi^-$. 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 $D^0$ 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 a measurement of charm oscillations in $D^0 \rightarrow K^0_S \pi^+ \pi^-$ 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 $D^0 \rightarrow K^0_S \pi^+ \pi^-$ dynamics with two invariant masses following the Dalitz formalism [13,14], where $m^2_{\pi^\pm}$ is the squared invariant mass $m^2 (K^0_S \pi^\pm)$ for $D^0 \rightarrow K^0_S \pi^+ \pi^-$. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI. Funded by SCOAP3.

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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 \(\tau = h/\Gamma\) [2]. The parameter \(r_b\) is the ratio of signal yields in symmetric Dalitz-plot bins \(\pm b\) at \(t = 0\), and \(X_b\) quantifies the average strong-phase difference in these bins [12]. The \(z_{CP}\) and \(\Delta z\) parameters, defined by \(z_{CP} = \sqrt{\Delta z^2} \equiv -(q/p) \pm 1(y + ix)\), are obtained, along with \(r_b\), from a joint fit of the observed \(R_{bij}^{D^0}\) ratios in which external information on \(c_b \equiv \Re(X_b)\) and \(s_b \equiv -\Im(X_b)\) [16] is used as a constraint. The results are expressed in terms of the \(CP\)-averaged mixing parameters \(x_{CP} \equiv -\Im(z_{CP})\) and \(y_{CP} \equiv -\Re(z_{CP})\), and of the \(CP\)-violating differences \(\Delta x \equiv -\Im(\Delta z)\) and \(\Delta y \equiv -\Re(\Delta z)\). 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 \(D^0 \rightarrow K^0_S\pi^+\pi^-\) 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 unconstructed particles, are used to determine whether a \(D^0\) or a \(D^0\) is produced. In the 2011 data, only the \(\bar{B} \rightarrow D^0\mu^-X\) decays were used because the on-line-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 \(D^{+}\rightarrow D^0(-K^0_S\pi^+\pi^-)\pi^+\) 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 \(1.84 < m(K^0_S\pi^+\pi^-) < 1.89\) 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 \(K^0_S\) 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 \(\bar{B}\rightarrow D^0(-K^0_S\pi^+\pi^-)\mu^-X\) 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 \(m^2(D^0\mu^-) + p_T^2(D^0\mu^-) + p_T^2(D^0\mu^-)\), where the momentum component \(p_T(D^0\mu^-)\) of the \(D^0\mu^-\) system transverse to the \(\bar{B}\) flight direction partially compensates for the momentum of unconstructed 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 \(K^0_S\) masses to their known values.

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

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
shows the smoothed correlation introduced by $D$ for them using data. The smallness of the mixing downstream $K$ ($\pi$) correlated between the squared mass of the two final-state $D$ dominated by genuine $D$ samples independent because their overlap amounts to less than 0.1% of the semileptonic sample size.

Figure 1 shows the $\Delta m$ and $m(K^0_S\pi^+\pi^-)$ 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 $B$ candidates formed by associating $D^{+*} \rightarrow D^0\pi^+$ with same-sign $\mu^+$ candidates. Contributions from backgrounds due to misreconstructed $D^0$ decays, such as $D^0 \rightarrow K_S^0\pi^+\pi^-\pi^0$ and $D^0 \rightarrow K_S^0h^0(\rightarrow l^+l^-)$ (where $h^0\rightarrow l^+l^-$ 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 $D^0\rightarrow \overline{D}^0$ 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 $B \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\mu^+X$ 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 $\Delta m$ distribution, weighted to correct for the $(m^2(\pi^+\pi^-), t)$ correlations, for the $D^{+*} \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)$ candidates and the $m(K^0_S\pi^+\pi^-)$ distribution for the $B \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\mu^+X$ candidates. All components are modeled empirically. The $\Delta m$ model combines a $D^{+*}$ signal with a smooth

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 $B \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\mu^+X$ candidates.

FIG. 2. Smoothed efficiency as a function of $m^2(\pi^+\pi^-)$ and $t/\tau$ 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 ($m_{\pi\pi}^2 < m_{\pi\pi}^2$) 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 0.1$t$ and 0.25$t$ for the $D^{*+} \to D^0(K_S^0\pi^+\pi^-)\pi^+$ and $B \to D^0(K_S^0\pi^+\pi^-)\mu^+\nu X$ 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 ($\sigma$), with the expected values reported in Eq. (1).

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

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 $X_{b}^\text{CLEO}$ measured by the CLEO collaboration through a Gaussian penalty term that uses the sum $V_{b}^{-1}$ 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 $\chi_{CP}$, $\Delta x$, and $\Delta y$ 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.

The dominant systematic uncertainties on $x_{CP}$ are associated with the 3% contamination from secondary $D^{*+}$ decays in the prompt sample ($0.24 \times 10^{-3}$) and from the 1% contamination of genuine $D^0$ mesons associated with random muons in the semileptonic sample ($0.34 \times 10^{-3}$). Biases due to the neglected decay-time and $m_{\pi\pi}^2$ resolutions, and the neglected efficiency variations across the decay time and Dalitz plot, constitute the dominant systematic uncertainty on $x_{CP}$ ($0.94 \times 10^{-3}$). Possible asymmetric nonuniformities with respect to the bisector in the Dalitz plot induced by reconstruction inefficiencies dominate the systematic uncertainty on $\Delta x.$
(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 \( (m^2(π^+π^-), t) \) 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 mass difference \( \Delta m_{CP} = [2.7 \pm 1.6 \text{ (stat)} \pm 0.4 \text{ (syst)}] \times 10^{-3} \) 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 \( \gamma_{CP} = [7.4 \pm 3.6 \text{ (stat)} \pm 1.1 \text{ (syst)}] \times 10^{-3} \), 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 \( \varphi \); and we derive confidence intervals (Table II) using a likelihood-ratio ordering that assumes the observed correlations are 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 \( x = (3.9^{+1.1}_{-1.2}) \times 10^{-3} \) [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 \( \varphi \) more than doubled as compared to previous averages [5].

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