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 $2.3 \times 10^6 \ D^0 \rightarrow K_S^0 \pi^+ \pi^-$ 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 $\Delta x = [2.7 \pm 1.6 \text{(stat)} \pm 0.4 \text{(syst)}] \times 10^{-3}$ and the $CP$-violating parameter $\phi = [0.94^{+0.17}_{-0.17}, -0.13^{+0.26}_{-0.17}]$. Improving the knowledge of $\Delta x$, 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 $\sin \phi$.

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 on 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 $\Delta x$ [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 $m^{2}_{\pi\pi}$ is the squared invariant mass $m^2 (K^0_S \pi^\pm)$ for $D^0 \rightarrow K^0_S \pi^+ \pi^-$. 

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decays and \( m^2(K^0_S\pi^\pm) \) for \( \overline{D^0} \to K^0_S\pi^+\pi^- \) 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 \( \overline{D^0} \) amplitudes within each bin [15]. Two sets of eight bins are formed, and they are optimized symmetrically with respect to the principal bisector \( m^2_+ = m^2_- \). Bins are labeled with the indices \( \pm b \), where \( b = 1, \ldots, 8 \). Positive indices refer to the (lower) \( m^2_+ > m^2_- \) region, where unmixed Cabibbo-favored \( D^0 \to K^+(892)^-\pi^+ \) 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 \( R^b_{\tau_j}(R^b_{\tau_{j-j}}) \) between initially produced \( D^0 (\overline{D^0}) \) 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]

\[
R^b_{\tau_j} \approx \frac{r_b + (1/4)r_b(t^2_j)\text{Re}(z^2_{CP} - \Delta z^2) + (1/4)(t^2_j) z_{CP} \pm \Delta z^2 + \sqrt{r_b(t)^2} \text{Re}[X_b(z_{CP} \pm \Delta z)]}{1 + (1/4)(t^2_j) \text{Re}(z^2_{CP} - \Delta z^2) + r_b(1/4)(t^2_j) z_{CP} \pm \Delta z^2 + \sqrt{r_b(t)^2} \text{Re}[X_b(z_{CP} \pm \Delta z)]}.
\]

Specifically, the mass of the \( D^0 \) candidate is required to meet \( 1.84 < m(K^0_L\pi^0\pi^-) < 1.89 \text{ GeV}/c^2 \), and the difference between the \( D^{\pm} \) and \( D^0 \) candidate masses is required to satisfy \( |\Delta m| < 151.1 \text{ MeV}/c^2 \). 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 \( D^{\pm} \) candidate to originate from the primary vertex [19]. In the reconstruction of the Dalitz-plot coordinates, we additionally constrain the \( K^0_L \) 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 \( \overline{B} \to D^0(-K^0_L\pi^+\pi^-)\mu^+\nu_\mu \) 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 \( 2.5 < m(D^0\mu^-) < 6.0 \text{ GeV}/c^2 \) and the corrected mass \( \sqrt{m^2(D^0\mu^-) + p^2_{\parallel}(D^0\mu^-) + p^2_{\perp}(D^0\mu^-)} \), where the momentum component \( p_{\parallel}(D^0\mu^-) \) of the \( D^0\mu^- \) system transverse to the \( \overline{B} \) flight direction partially compensates for the momentum of unconstructed decay products, to be smaller than 5.8 GeV/c^2. The \( \overline{B} \) flight direction is inferred from the measured positions of the primary and \( D^0\mu^- \) vertices. A kinematic fit constrains the \( D^0 \) and \( K^0_L \) masses to their known values.

In both samples, two categories of signal candidates are used: those with \( K^0_S \to \pi^+\pi^- \) 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 \( D^{\pm} (\overline{B}) \) 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
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 $\Delta m$ and $m(K^0_S\pi^-\pi^+)$ distributions of the prompt and semileptonic samples, respectively. The prompt sample contains $1.3 \times 10^6$ signal decays (45% with downstream $K^0_S$ candidates) and a small background dominated by genuine $D^0 \rightarrow K^0_S\pi^+\pi^-$ 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 $1.0 \times 10^6$ signal decays (66% with downstream $K^0_S$ candidates) and a sizable background dominated by unrelated $K^0_S\pi^-\pi^-$ 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 $D^0 \rightarrow K^0_S\pi^-\pi^0$ and $D^0 \rightarrow K^0_S h^{(0)}$ (where $h^{(0)}$ 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 $D^0 \rightarrow K^0_S\pi^+\pi^-$ 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 $K^0_S$ candidates because they feature different correlations. Figure 2 shows the smoothed $(m^2(\pi^+\pi^-), t)$ map for the sample with downstream $K^0_S$ 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 $\overline{B} \rightarrow D^0(\rightarrow K^0_S\pi^+\pi^-)\mu^-X$ decays.

We divide prompt and semileptonic samples according to the $K^0_S$ 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 $D^+ \rightarrow D^0(\rightarrow K^0_S\pi^+\pi^-)$ candidates and the $m(K^0_S\pi^-\pi^+)$ distribution for the $\overline{B} \rightarrow D^0(\rightarrow K^0_S\pi^+\pi^-)\mu^-X$ candidates. All components are modeled empirically. The $\Delta m$ model combines a $D^+$ signal with a smooth

![Figure 1](https://example.com/figure1.png)

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

![Figure 2](https://example.com/figure2.png)

**FIG. 2.** Smoothed efficiency as a function of $m^2(\pi^+\pi^-)$ and $t/\tau$ in $D^+ \rightarrow D^0(\rightarrow K^0_S\pi^+\pi^-)\pi^+$ decays, as determined from the data with downstream $K^0_S$ 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 \((t)_{ij}\) and \((t^2)_{ij}\) 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 \((m_1^2 < m_2^2)\) 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 \(0.1\tau\) and \(0.25\tau\) 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 \((\sigma)\), with the expected values reported in Eq. (1),

\[
\chi^2 = \sum_{pr,sl} \sum_{l,d} \sum_{+,-} \sum_{b,j} \frac{(N^\pm_{+bj} - N_{+bj} R^\pm_{+bj})^2}{\sigma_{\pm bj}^2} + \frac{(\sigma_{\pm bj} R^\pm_{+bj})^2}{(\sigma_{\pm bj} R^\pm_{-bj})^2} + \sum_{b,b'} (X_b^\text{CLEO} - X_b) (V^{-1}_b^\text{CLEO})_{bb'} (X_{b'}^\text{CLEO} - X_{b'}). \tag{2}
\]

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 \(X_{X_b}^\text{CLEO}\) measured by the CLEO collaboration through a Gaussian penalty term that uses the sum \(V^{-1}_b\) of the statistical and systematic covariance matrices [16]. In the fit, the parameters \(r_b\) are determined independently for each subsample \((pr, sl, l, d)\) 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 \(\chi_{CP}\) 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 \(m_{\pi}^2\) resolutions, and the neglected efficiency variations across the decay time and Dalitz plot, constitute the dominant systematic uncertainty on \(\chi_{CP}\) \((0.94 \times 10^{-3})\). 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 x_{CP}=[2.7±1.6(stat)±0.4(syst)]×10^{-3} and the CP-violating parameter Δx=[−0.53±0.70(stat)±0.22(syst)]×10^{-3}. In addition, we report the CP-averaged normalized width difference y_{CP}=[7.4±3.6(stat)±1.1(syst)]×10^{-3}, along with the corresponding CP-violating parameter Δy=[0.6±1.6(stat)±0.3(syst)]×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}) × 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}–D^{0} system are also greatly improved, with precisions on |q/p| and φ more than doubled as compared to previous averages [5].

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