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Measurements of charm mixing and \( CP \) violation using \( D^0 \to K^{\pm}\pi^{\mp} \) decays

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Measurements of charm mixing and \( CP \) violation parameters from the decay-time-dependent ratio of \( D^0 \to K^+\pi^- \) to \( D^0 \to K^-\pi^+ \) decay rates and the charge-conjugate ratio are reported. The analysis uses \( \bar{B} \to D^{*+}\mu^-X \), and charge-conjugate decays, where \( D^{*+} \to D^0\pi^+_c \), and \( D^0 \to K^{\pm}\pi^{\mp} \). The \( pp \) collision data are recorded by the LHCb experiment at center-of-mass energies \( \sqrt{s} = 7 \) and 8 TeV, corresponding to an integrated luminosity of 3 fb\(^{-1}\). The data are analyzed under three hypotheses: (i) mixing assuming \( CP \) symmetry, (ii) mixing assuming no direct \( CP \) violation in the Cabibbo-favored or doubly Cabibbo-suppressed decay amplitudes, and (iii) mixing allowing either direct \( CP \) violation and/or \( CP \) violation in the superpositions of flavor eigenstates defining the mass eigenstates. The data are also combined with those from a previous LHCb study of \( D^0 \to K\pi \) decays from a disjoint set of \( D^{*+} \) candidates produced directly in \( pp \) collisions. In all cases, the data are consistent with the hypothesis of \( CP \) symmetry.

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I. INTRODUCTION

The oscillation of \( D^0 \) mesons into \( \bar{D}^0 \) mesons, and vice versa, is a manifestation of the fact that the flavor and mass eigenstates of the neutral charm meson system differ. Such oscillations are also referred to as mixing. Charge-parity violation (\( CPV \)) in the superpositions of flavor eigenstates defining the mass eigenstates can lead to different mixing rates for \( D^0 \) into \( \bar{D}^0 \) and \( D^0 \) into \( \bar{D}^0 \). The LHCb experiment has previously reported measurements of mixing and \( CP \) violation parameters from studies of \( D^{*+} \to D^0\pi^+_c \), \( D^0 \to K^{\pm}\pi^{\mp} \), where the \( D^{*+} \) meson is produced directly in \( pp \) collisions [1]. In this sample, referred to as “prompt,” the flavor of the \( D^0 \) mesons at the production is determined by the charge of the slow pion \( \pi^+_c \) from the strong decay of the \( D^{*+} \) meson. In this paper we extend the study using \( D^0 \) mesons produced in \( \bar{B} \to D^{*+}\mu^-X \), \( D^{*+} \to D^0\pi^+_c \), \( D^0 \to K^{\pm}\pi^{\mp} \) and charge-conjugate decays [2], using \( pp \) collision data recorded by the LHCb experiment at center-of-mass energies \( \sqrt{s} = 7 \) and 8 TeV, corresponding to an integrated luminosity of 3 fb\(^{-1}\). In this case, the flavor of the \( D^0 \) at production is tagged twice, once by the charge of the muon and once by the opposite charge of the slow pion \( \pi^+_c \) produced in the \( D^{*+} \) decay, leading to very pure samples. The doubly tagged (DT) \( \bar{B} \to D^{*+}\mu^-X \) candidates selected by the trigger are essentially unbiased with respect to the \( D^0 \) decay time, while those in the prompt sample are selected by the trigger with a bias towards higher decay times. As a result, the DT analysis allows for better measurements at lower decay times. In this paper, we first report the results of a mixing and \( CPV \) analysis using the DT sample, and then report the results of simultaneous fits to the DT and prompt samples.

II. THEORETICAL FRAMEWORK

The physical eigenstates of the neutral \( D \) system, which have well-defined masses and lifetimes, can be written as linear combinations of the flavor eigenstates, which have well-defined quark content: \( |D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \). We follow the convention \( (CP)|D^0\rangle = -|\bar{D}^0\rangle \) [3]. The coefficients \( p \) and \( q \) are complex numbers, and satisfy the normalization condition \( |p|^2 + |q|^2 = 1 \). The dimensionless quantities which characterize mixing are \( x = 2(m_3 - m_1)/\langle \Gamma_1 + \Gamma_2 \rangle \) and \( y = (\Gamma_2 - \Gamma_1)/\langle \Gamma_1 + \Gamma_2 \rangle \), where \( m_{1,2} \) and \( \Gamma_{1,2} \) are the masses and widths of the mass eigenstates. In the limit of \( CP \) symmetry, \( p \) and \( q \) are equal. To the extent that \( CPV \) results only from \( p \neq q \), and not from direct \( CPV \) in the \( D \) decay amplitudes themselves, and in the limit \( |1 - |q/p|| \ll 1 \), Wolfenstein’s superweak constraint relates the mixing and \( CPV \) parameters [4,5]:

\[
\tan \varphi = \left( 1 - \frac{q}{p} \right) \frac{x}{y},
\]

where \( \varphi = \arg(q/p) \). Allowing for both direct and indirect \( CPV \), existing measurements give \( x = (0.37 \pm 0.16)\% \) and \( y = (0.66_{-0.10}^{+0.09})\% \) [3]. These values are consistent with Standard Model (SM) expectations for long-distance contributions [6,7]. No evidence for \( CPV \) in mixing rates has been reported, and SM expectations are \( \lesssim 10^{-3} \) [6–10].

We use \( D^0 \to K^{\pm}\pi^{\mp} \) decays to study mixing and \( CPV \). The decays \( D^0 \to K^-\pi^+ \) are called “right sign” (RS) and

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their decay rate is dominated by Cabibbo-favored (CF) amplitudes where no direct CPV is expected in the SM or most of its extensions. Decays of $D^0 \to K^+\pi^-$ are called “wrong sign” (WS). Such decays do not have such a simple description. In the limit $(x, y) \ll 1$, an approximation of the WS decay rates of the $D^0$ and $\bar{D}^0$ mesons is

$$\frac{|\langle K^+\pi^-|H|D^0(t)\rangle|^2}{C_2}\approx\frac{e^{-\Gamma t}}{2}[A_f]^2\left\{R_D^{K\pi^-}\frac{q}{p}\sqrt{R_D^{K\pi^-}[y\cos(\delta-\varphi)-x\sin(\delta-\varphi)]}(\Gamma t)\right.\
\left. +\frac{q}{p}[x^2+y^2-4\Gamma t]^2\right\}.$$  \hspace{1cm} (2)

and

$$\frac{|\langle K^-\pi^+|H|\bar{D}^0(t)\rangle|^2}{C_2}\approx\frac{e^{-\Gamma t}}{2}[\bar{A}_f]^2\left\{R_D^{K\pi^-}\frac{p}{q}\sqrt{R_D^{K\pi^-}[y\cos(\delta+\varphi)-x\sin(\delta+\varphi)]}(\Gamma t)\right.\
\left. +\frac{p}{q}[x^2+y^2-4\Gamma t]^2\right\}. \hspace{1cm} (3)$$

In Eqs. (2) and (3), $A_f$ denotes the CF transition amplitude for $D^0 \to K^-\pi^+$ and $\bar{A}_f$ denotes the CF transition amplitude for $\bar{D}^0 \to K^+\pi^-$. The term $\Gamma$ is the average decay width of the two mass eigenstates. Denoting the corresponding doubly Cabibbo-suppressed (DCS) amplitudes $A_f$ for $D^0 \to K^-\pi^+$ and $\bar{A}_f$ for $\bar{D}^0 \to K^+\pi^+$, the ratios of DCS to CF amplitudes are defined to be $R_D = |A_f/A_f|^2$ and $\bar{R}_D = |\bar{A}_f/\bar{A}_f|^2$. The relative strong phase between the DCS and CF amplitudes $\bar{A}_f$ and $A_f$ is denoted by $\delta$. We explicitly ignore direct CPV in the phases of the CF and DCS amplitudes. As the decay time $t$ approaches zero, the WS rate is dominated by DCS amplitudes, where no direct CPV is expected. At longer decay times, CF amplitudes associated with the corresponding antiparticle produce oscillations; by themselves, they produce a pure mixing rate proportional to $(\Gamma t)^2$, and in combination with the DCS amplitudes they produce an interference rate proportional to $(\Gamma t)$. Allowing for all possible types of CPV, the time-dependent ratio of WS to RS decay rates, assuming $|x|, |y| \ll 1$, can be written as [5]

$$R(t)^\pm = R_D^\pm + \sqrt{R_D^\pm y^\pm}(\frac{t}{7})^2 + \frac{(x^\mp)^2 + (y^\pm)^2}{4}(\frac{t}{7})^2,$$  \hspace{1cm} (4)

where the sign of the exponent in each term denotes whether the decay is tagged at production as $D^0$ (+) or as $\bar{D}^0$ (−). The terms $x'$ and $y'$ are $x$ and $y$ rotated by the strong phase difference $\delta$, and $\tau = 1/\Gamma$.

The measured ratios of WS to RS decays differ from those of an ideal experiment due to detector response and experimental misidentifications. We use the formal approach of Ref. [1] to relate the signal ratios of Eq. (4) to a prediction of the experimentally observed ratios:

$$R(t)^\pm_{\text{pred}} = R(t)^\pm(1 - \Delta^{\pm}_p)(\epsilon_f)^{\pm+1} + p_{\text{other}},$$  \hspace{1cm} (5)

where the term $\epsilon_f = \epsilon(K^+\pi^-)/\epsilon(K^-\pi^+)$ is the ratio of $K^+\pi^-$ detection efficiencies. The efficiencies related to the $K^+$ and $\mu^\pm$ candidates explicitly cancel in this ratio. The term $p_{\text{other}}$ describes peaking backgrounds that contribute differentially to RS and WS decays. All three of these terms are considered to be potentially time dependent.

III. DETECTOR AND TRIGGER

The LHCb detector [11,12] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, and is designed for the study of particles containing $b$ or $c$ quarks. The detector includes a high-precision tracking device consisting of a silicon-strip vertex detector surrounding the $pp$ interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The tracking system provides a measurement of momentum, $p$, of charged particles with a fractional uncertainty that varies from 0.5% at 5 GeV/c to 1.0% at 200 GeV/c. The minimum distance of a track to a primary vertex (PV), the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T) \mu m$, where $p_T$ is the component of the momentum transverse to the beam, in GeV/c. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov (RICH) detectors.

The on-line candidate selection is performed by a trigger [13] which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage. At the hardware stage, candidates are required to have a muon with $p_T > 1.64$ GeV/c (1.76 GeV/c) in the 2011 (2012) data sets. The software trigger, in which all charged particles with $p_T > 500$ (300) MeV/c are reconstructed for 2011 (2012) data, first requires a muon with $p_T > 1.0$ GeV/c, and a large $\chi^2_0$.
with respect to any PV, where $\chi^2_{IP}$ is defined as the difference in vertex fit $\chi^2$ of a given PV reconstructed with and without the muon. Following this selection, the muon and at least one other final-state particle are required to be consistent with the topological signature of the decay of a $b$-hadron [13]. To mitigate detector-related asymmetries, the magnet polarity is reversed periodically.

IV. OFF-LINE SELECTION

In the off-line selection, candidates must have a muon with $p > 3 \text{ GeV}/c$, $p_T > 1.2 \text{ GeV}/c$ and a track fit $\chi^2/\text{ndf} < 4$, where $\text{ndf}$ is the number of degrees of freedom in the fit. Each of the $D^0$ decay products and muon candidates must have $\chi^2_{IP} > 9$, consistent with originating from a secondary vertex. The slow pion candidate must have $p > 2 \text{ GeV}/c$ and $p_T > 300 \text{ MeV}/c$, and have no associated hits in the muon stations. The combination of the $K$ and $\pi$ into a $D^0$ candidate must form a vertex that is well separated from the PV and have a $\chi^2$ per degree of freedom less than 6. The $D^0$ candidate must also have $p_T > 1.4 \text{ GeV}/c$ and its reconstructed invariant mass must lie within $24 \text{ MeV}/c^2$ of its measured mass [14]. The $D^{*+}\mu^-$ invariant mass must lie in the range 3.1–5.1 $\text{ GeV}/c^2$. Candidates must satisfy a vertex fit which constrains the kaon and pion to come from the same vertex, and the muon, the slow pion and the $D^0$ candidate to come from a common vertex with a good $\chi^2/\text{ndf}$. All final-state particles must pass stringent particle identification criteria from the RICH detectors, calorimeters and muon stations to improve the separation between signal and backgrounds produced by misidentified final-state particles. Candidates with reconstructed decay time $t/\tau < -0.5$ are vetoed, where $\tau$ is the measured $D^0$ lifetime [14] and $t$ is calculated as $t = m_{D^0}L/p$, where $L$ is the distance between the $D^0$ production and decay vertices, $m_{D^0}$ is the observed candidate $D^0$ mass, and $p$ is the $D^0$ momentum. The decay-time resolution is roughly 120 fs for the DT sample. Candidates which appear in both this data set and that of the earlier prompt analysis [1] are vetoed.

The same $D^0$ may appear in multiple candidate decay chains. In about 0.5% of cases, a single $D^0\mu^-$ combination has multiple slow pion candidates whose laboratory momentum vector directions lie within 0.6 mrad of each other. In such cases, we randomly accept one of the candidates and discard the others. When two slow pion candidates associated with a single $D^0\mu^-$ candidate are not collinear, the distributions of the $D^0\pi^+_s$ masses are consistent with the hypothesis that they (typically) result from candidates with a real $D^{*+}$ decay plus an additional pion nearby in phase space. In such cases, we retain the multiple candidates; the fit described below correctly determines the signal and background rates as functions of $m(D^0\pi_s^+)$. Real $D^{*+}$ decays, produced either promptly or as decay products of $b$-hadron decays, can be mistakenly associated with muons not truly originating from $b$-hadron decays. In these cases, the production vertex of the $D^0$ may be wrongly determined. We remove these from the $D^0\pi^+_s$ distributions statistically by subtracting the corresponding $D^0\pi^+_s$ distributions of candidates where the $D^{*+}$ and $\mu$ candidates have the same charge, the so-called same-sign samples. Signal candidates are referred to as the opposite-sign sample. The $m(D^0\pi^+_s)$ shapes to be subtracted are taken directly from the same-sign candidates, while otherwise satisfying all DT selection criteria. The absolute numbers of candidates are determined, in each bin of the $D^0$ decay time, by normalizing the same-sign rate to that of the opposite-sign DT sample in the $m(D^{*+}\mu^-)$ range 5.6–6 $\text{ GeV}/c^2$, a region well above the masses of the $B^0_s$ and $B^0$ mesons and dominated by combinatorial backgrounds produced by false muon candidates. The ratio of same-sign to DT candidates in the signal region is roughly 1% and the ratio in the normalization region is 71%. A systematic uncertainty on the same-sign background subtraction is determined by setting the normalization factor to unity.

V. YIELD EXTRACTION AND FIT STRATEGY

Five bins of decay time are defined containing approximately equal numbers of RS decays. We determine $D^{*+}$ signal yields using binned maximum likelihood fits to the $D^0\pi^+_s$ invariant mass distributions. The signal probability density function (PDF) consists of a sum of three Gaussian functions plus a Johnson $S_U$ distribution [15] to model the asymmetric tails; the background PDFs are parametrized using empirical shapes of the form

$$m(D^0\pi^+_s)/m_0 - 1\) e^{-\left(\frac{m(D^0\pi^+_s)}{m_0}\right)^2}.$$ (6)

The parameter $m_0$ represents the kinematic limit of the distribution and is fixed to the sum of the measured mass of the pion and the $D^0$ [14]. The shapes of the RS and WS $D^{*\pm}$ are assumed to be the same and to be independent of the decay time. We first fit the time-integrated RS distribution to determine signal shape parameters. These are fixed for all subsequent fits. The background parameters vary independently in each fit. Systematic uncertainties related to this choice are assessed and discussed in Sec. VII. Figures 1(a) and 1(b) show the fits to the $D^0\pi^+_s$ time-integrated invariant mass distributions for RS and WS samples. They contain $1.73 \times 10^6$ and $6.68 \times 10^3$ $D^{*+}$ decays, respectively.

The numbers of RS and WS signal candidates in each decay time bin are determined from fits, from which the observed WS to RS ratios are calculated. The term $p_{\text{other}}$ is the ratio of the number of peaking events in the $m(D^0\pi^+_s)$
Finally, we fit the data allowing all the parameters to
Second, we fit the data requiring
and DCS amplitudes (i.e. Eq. (4) [i.e. $\chi^2 = \sum (r_i^+ - \bar{R}(t_i)^+)^2 + (r_i^- - \bar{R}(t_i)^-)^2]
\chi^2_e + \chi^2_{\text{peaking}} + \chi^2_{\text{other}}$. (7)
Here, $r_i^\pm$ is the measured WS$^\pm$/RS$^\pm$ ratio for either the
time bin $t_i$ and $R(t_i)$ is the value of $R(t)^{\pm}$ averaged over
The fit accounts for uncertainties in the relative
tracking and reconstruction efficiencies and rates of peaking backgrounds using Gaussian constraints
($\chi^2_e$ + $\chi^2_{\text{peaking}} + \chi^2_{\text{other}}$). The term $\chi^2_{\text{other}}$ relating to the
feedthrough of the prompt sample into the DT sample is explicitly zero in the DT analysis, but is needed for the
simultaneous fit to the DT and prompt data sets. The statistical uncertainties reported by the fit therefore include
the uncertainties associated with how precisely these factors are determined.

Three fits are performed using this framework. First,
we fit the data assuming $CP$ symmetry in the formalism
of Eq. (4) [i.e. $R^+ = R^-$, $(x^+)^2 = (x^-)^2$ and $y^+ = y^-$. Second, we fit the data requiring $CP$ symmetry in the CF
and DCS amplitudes (i.e. $R^+ = R^-$), but allow $CPV$ in
the mixing parameters themselves [($(x^\pm)^2$ and $y^\pm$]. Finally, we fit the data allowing all the parameters to
distribute from the $D^0$ sidebands of the WS sample
projected into the signal region relative to the RS yield. We
measure $p_{\text{other}}$ to be $(7.4 \pm 1.8) \times 10^{-5}$. To measure the
mixing and $CPV$ parameters, the time dependence of these
ratios is fit by minimizing
$\chi^2 = \sum_i \left[ \left( r_i^+ - \bar{R}(t_i)^+ \right)^2 + \left( r_i^- - \bar{R}(t_i)^- \right)^2 \right]$
$\chi^2_e + \chi^2_{\text{peaking}} + \chi^2_{\text{other}}$. (7)
Here, $r_i^\pm$ is the measured WS$^\pm$/RS$^\pm$ ratio for either the
$D^{+}(D^0)$ or the $D^{-}(\overline{D}^0)$ sample with error $\sigma_i$ in a decay
time bin $t_i$ and $R(t_i)$ is the value of $R(t)^{\pm}$ averaged over
the bin. The fit accounts for uncertainties in the relative
$K^\pm\pi^\mp$ tracking and reconstruction efficiencies and rates of peaking backgrounds using Gaussian constraints
($\chi^2_e$ + $\chi^2_{\text{peaking}} + \chi^2_{\text{other}}$). The term $\chi^2_{\text{other}}$ relating to the
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the mixing parameters themselves [($(x^\pm)^2$ and $y^\pm$]. Finally, we fit the data allowing all the parameters to

VI. RELATIVE EFFICIENCIES

The relative efficiency $\epsilon_{\text{r}}$, used in Eq. (5), accounts for
instrumental asymmetries in the $K^\mp\pi^\pm$ reconstruction efficiencies. The largest source of these is the difference
between the inelastic cross sections of $K^-$ and $\pi^-$ mesons
with matter, and those of their antiparticles. We measure $\epsilon_{\text{r}}$
accounting for all detector effects as well as cross-section differences in a similar manner to the prompt analysis [1].
The efficiency is determined using the product of $D^{+} \rightarrow K^\mp\pi^\pm$ and $D^{+} \rightarrow K^0_S(\rightarrow \pi^+\pi^-)\pi^\pm$ decay yields divided
by the product of the corresponding charge-conjugate decay yields. The expected $CPV$ associated with differ\g$\epsilon_{\text{r}}$
and pion candidates such that the kaon
production rates [17] cancels in this ratio,
provided that the kinematic distributions are consistent
across samples. To ensure this cancellation, we weight the
$D^{+} \rightarrow K^\mp\pi^\pm$ candidates such that the kaon
and pion $p_T$ distributions match those in the DT $K\pi$ sample.
Similarly, $D^{+} \rightarrow K^0_S\pi^\pm$ candidates are weighted by $D^+ p_T$ and $\eta$ and pion $p_T$ distributions to match those of the
$D^{+} \rightarrow K^\mp\pi^\pm$. The weighting is performed using a
gradient boosted decision tree implemented in scikit-learn [18] accessed using the HEP_ML framework [19].
We measure the $K\pi$ detection asymmetry to be $A(K\pi) = (\epsilon_- - 1)/(\epsilon_+ + 1) = (0.90 \pm 0.18 \pm 0.10)\%$ for the sample
of this analysis, and find it to be independent of decay time.

FIG. 1. The time-integrated $D^0\pi^\pm$ invariant mass distributions, after same-sign subtraction, for (a) RS decays and (b) WS decays. Fit
projections are overlaid. Below each plot are the normalized residual distributions.
### VII. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties of the DT analysis are summarized in Table I. To avoid bias, offsets to each WS/RS ratio were randomly chosen to blind both direct and indirect CPV, as well as the central values of the mixing parameters. Cross-checks of the blinded data were performed by splitting the data into disjoint subsamples according to criteria that might be sensitive to systematic variations in detector response. We considered two subsamples of magnet polarity, integrated over the entire data taking period, and four subsamples splitting according to criteria that might be sensitive to systematic variations in detector response. The fits are shown in Fig. 2. The fits are shown in a binned projection. The top two plots show the WS/RS ratio as a function of decay time for the candidates tagged at decay time for the candidates tagged at tagging time. The bottom two plots show the WS/RS ratio as a function of decay time for the candidates tagged at tagging time. The ratio of RS $D^{+}\rightarrow K^{+}\pi^{+}\pi^{0}$ to RS $D^{+}$ decays as a function of decay time is consistent with the hypothesis of decay-time independence with a $p$ value of 0.06. We conservatively estimate a systematic uncertainty by modifying $c_{s}$ to allow for a linear time dependence that gives the best description of the RS data. As seen in Table I, this has essentially no effect on the results of the mixing fit where CP symmetry is assumed to be exact. It is the dominant systematic uncertainty in the fit requiring $R_{D}^{+}=R_{D}$, and it produces a systematic uncertainty much smaller than the statistical error in the fit that allows all forms of CPV. Uncertainties are not symmetrized.

### VIII. RESULTS

We determine systematic uncertainties related to variations of the fit procedure by considering alternative choices. To determine uncertainties related to subtraction of the same-sign background $m(D^{0}\pi^{+})$ distributions from the opposite-sign ones, we subtract the raw same-sign distributions rather than the scaled distributions. To determine uncertainties related to excluding candidates considered in the prompt analysis [1] from the DT analysis, we repeat the DT analysis including those candidates. As an alternative to using a single signal shape at all decay times, we determine signal shapes using the RS signal in each decay time bin. We evaluate potential biases in fitting procedure by generating and fitting 11,000 simulated DT samples with values of $x$ and $y$ spanning the 2σ contour about the average values reported by HFAG [3]. The biases we observe are nonzero, and appear to be independent of the generated values. We assign a systematic uncertainty equal to the full observed bias. Table I summarizes the results of these studies. All systematic uncertainties are propagated to the final results using their full covariance matrices.

### TABLE I. Summary of systematic uncertainties for the DT analysis for each of the three fits described in the text.

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</table>

[052004-5]
points appear to lie on straight lines that intersect the vertical axis near $3.5 \times 10^{-3}$ at $t/\tau = 0$ and rise approximately linearly to $4.3 \times 10^{-3}$ near $t/\tau = 2.5$. The difference between the two ratios is shown in the bottom plot. The fit values for the parameters and their uncertainties are collected in Table II. The data are clearly consistent with the hypothesis of CP symmetry, i.e. that the two samples share exactly the same mixing parameters. If direct CPV is assumed to be zero ($R^+ = R^-$ at $t/\tau = 0$), as expected if tree-level amplitudes dominate the CF and DCS amplitudes, the difference in mixing rates (the slope) is observed to be very small. For this data set, the statistical uncertainties are all much greater than the corresponding systematic uncertainties, which include the uncertainties from $e_r$ and peaking backgrounds. Correlation matrices between the fitted parameters are included in Appendix A, Tables V–VII.

The data of the prompt analysis [1], those of the DT analysis and the results of fitting the two (disjoint) samples simultaneously are shown in Fig. 3. The combined sets of data points in the top and middle plots lie on slightly curved lines that intersect the vertical axis near $3.4 \times 10^{-3}$ at $t/\tau = 0$ and rise to approximately $5.9 \times 10^{-3}$ just above $t/\tau = 6.0$. The samples are consistent with CP symmetry. The results of the simultaneous fit are reported in Table III. The corresponding results from the prompt analysis [1] are also reported in Table III for comparison. In Table III, the statistical and systematic uncertainties have been added in quadrature to allow direct comparison of the two sets of results. As all the systematic uncertainties for the prompt analysis were evaluated using $\chi^2$ constraints as in Eq. (7), we determine systematic uncertainties for the simultaneous fits by repeating the fit variations as for the DT fit. These systematics are reported in Table IV. In general, the uncertainties from the combined fits are 10%–20% lower than those from the previous measurement [1].
The combined fit of the DT and prompt sample is consistent with CP symmetry. The WS $D^0$ and $\bar{D}^0$ rates at $t/\tau = 0$ are equal within experimental uncertainties, indicating no direct CP violation. Similarly, the mixing rates are consistent within experimental uncertainties, as seen in the bottom plot of Fig. 3. In the combined fit of this analysis, assuming no direct CP violation, the difference between the projected WS/RS rates at $t/\tau = 6.0$ is only $0.15 \times 10^{-3}$ (see the dashed-dotted line in the bottom plot of Fig. 3), where the WS/RS rates themselves have increased by about $2.5 \times 10^{-3}$ (see the top and middle plots).

The determination of the CPV parameters $|q/p|$ and $\varphi$ from the difference in rates of WS $D^0$ and $\bar{D}^0$ requires the use of independent measurements, as these variables appear in the WS/RS ratios only in combination with the strong phase difference $\delta$ and with $x$ and $y$, as seen in Eqs. (2) and (3). When the results are combined with independent measurements, as done by the Heavy Flavor Averaging Group [3], the precision of the constraints on $|q/p| - 1$ approximately scale with the precision of the difference in WS/RS ratios at high decay time divided by the average increase. Utilizing theoretical constraints such as Eq. (1), in addition to the experimental data, the precision on $|q/p|$ improves by about a factor of 4 [3].

**IX. SUMMARY**

In summary, the analysis of mixing and CPV parameters using the DT $D^0 \to K\pi\pi$ samples provides results consistent with those of our earlier prompt analysis. Simultaneously fitting the disjoint data sets of the two analyses improves the precision of the measured parameters by 10%–20%, even though the DT analysis is based on...
almost 40 times fewer candidates than the prompt analysis. In part, this results from much cleaner signals in the DT analysis, and, in part, it results from the complementary higher acceptance of the DT trigger at low $D$ decay times. The current results supersede those of our earlier publication [1].

Acknowledgments

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Appendix A: Correlation Matrices of the DT Fit

Below are included the correlation matrices for each of the fits to the DT sample. Table V shows the correlation matrices for the no CPV fit, Table VI shows the correlation matrix for the no direct CPV fit, and Table VII shows the correlation matrix for the all CPV allowed fit.

Table V. Correlation matrix for the no CPV fit to the DT data.

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>$R_D [10^{-3}]$</th>
<th>$y^+ [10^{-3}]$</th>
<th>$(x^+)^2 [10^{-4}]$</th>
<th>$x^2 [10^{-4}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ \mu^+$ scaling</td>
<td>0.00</td>
<td>0.05</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>$\Lambda(K\pi)$ time dependence</td>
<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>RS fit model time variation</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>No prompt veto</td>
<td>0.00</td>
<td>0.04</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.01</td>
<td>0.07</td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>

Table VI. Systematic uncertainties for the simultaneous fits of the DT and prompt data sets.

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>Uncertainty on parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_D [10^{-3}]$</td>
</tr>
<tr>
<td>$D^+ \mu^+$ scaling</td>
<td>0.00</td>
</tr>
<tr>
<td>$\Lambda(K\pi)$ time dependence</td>
<td>0.00</td>
</tr>
<tr>
<td>RS fit model time variation</td>
<td>0.00</td>
</tr>
<tr>
<td>No prompt veto</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table VII. Systematic uncertainties for the simultaneous fits of the DT and prompt data sets.

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>Uncertainty on parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_D [10^{-3}]$</td>
</tr>
<tr>
<td>$D^+ \mu^+$ scaling</td>
<td>0.00</td>
</tr>
<tr>
<td>$\Lambda(K\pi)$ time dependence</td>
<td>0.03</td>
</tr>
<tr>
<td>RS fit model time variation</td>
<td>0.00</td>
</tr>
<tr>
<td>No prompt veto</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>0.03</td>
</tr>
</tbody>
</table>
In this appendix, we include the correlation matrices for each of the simultaneous fits to the prompt + DT datasets. Table VIII shows the correlation matrix for the no CPV fit, Table IX shows the correlation matrix for the no direct CPV fit, and Table X shows the correlation matrix for the all CPV allowed fit.

### APPENDIX B: CORRELATION MATRICES OF THE DT + PROMPT FIT

Table VI. Correlation matrix for the no direct CPV fit to the DT data.

<table>
<thead>
<tr>
<th></th>
<th>$R_D$</th>
<th>$y^+$</th>
<th>$(x^+)^2$</th>
<th>$y^-$</th>
<th>$(x^-)^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D$</td>
<td>1</td>
<td>-0.369</td>
<td>0.261</td>
<td>-0.374</td>
<td>0.309</td>
</tr>
<tr>
<td>$y^+$</td>
<td>1</td>
<td>-0.944</td>
<td>0.448</td>
<td>-0.370</td>
<td></td>
</tr>
<tr>
<td>$(x^+)^2$</td>
<td>1</td>
<td>-0.352</td>
<td>0.290</td>
<td>-0.967</td>
<td></td>
</tr>
<tr>
<td>$y^-$</td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$(x^-)^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Table VII. Correlation matrix for the all CPV allowed fit to the DT data.

<table>
<thead>
<tr>
<th></th>
<th>$R_D^+$</th>
<th>$y^+$</th>
<th>$(x^+)^2$</th>
<th>$R_D^-$</th>
<th>$y^-$</th>
<th>$(x^-)^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D^+$</td>
<td>1</td>
<td>-0.658</td>
<td>0.043</td>
<td>-0.005</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>$y^+$</td>
<td>1</td>
<td>0.438</td>
<td>-0.001</td>
<td>-0.000</td>
<td>-0.001</td>
<td></td>
</tr>
<tr>
<td>$(x^+)^2$</td>
<td>1</td>
<td>-0.000</td>
<td></td>
<td>-0.002</td>
<td>0.074</td>
<td></td>
</tr>
<tr>
<td>$R_D^-$</td>
<td>1</td>
<td>-0.621</td>
<td>0.050</td>
<td>-0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$y^-$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>$(x^-)^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table VIII. Correlation matrix for the no CPV simultaneous fit to the prompt + DT data sets.

<table>
<thead>
<tr>
<th></th>
<th>$R_D$</th>
<th>$y'$</th>
<th>$x^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D$</td>
<td>1</td>
<td>-0.932</td>
<td>0.826</td>
</tr>
<tr>
<td>$y'$</td>
<td>-0.932</td>
<td>1</td>
<td>-0.959</td>
</tr>
<tr>
<td>$x^2$</td>
<td></td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Table IX. Correlation matrix for the no direct CPV simultaneous fit to the prompt + DT data sets.

<table>
<thead>
<tr>
<th></th>
<th>$R_D$</th>
<th>$y^+$</th>
<th>$(x^+)^2$</th>
<th>$y^-$</th>
<th>$(x^-)^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D$</td>
<td>1</td>
<td>-0.854</td>
<td>0.686</td>
<td>-0.751</td>
<td>0.586</td>
</tr>
<tr>
<td>$y^+$</td>
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<td>-0.925</td>
<td>-0.631</td>
<td>0.501</td>
<td></td>
</tr>
<tr>
<td>$(x^+)^2$</td>
<td>1</td>
<td>-0.563</td>
<td></td>
<td>0.458</td>
<td></td>
</tr>
<tr>
<td>$y^-$</td>
<td>1</td>
<td></td>
<td></td>
<td>-0.937</td>
<td></td>
</tr>
<tr>
<td>$(x^-)^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Table X. Correlation matrix for the all CPV allowed simultaneous fit to the prompt + DT data sets.

<table>
<thead>
<tr>
<th></th>
<th>$R_D^+$</th>
<th>$y^+$</th>
<th>$(x^+)^2$</th>
<th>$R_D^-$</th>
<th>$y^-$</th>
<th>$(x^-)^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D^+$</td>
<td>1</td>
<td>-0.920</td>
<td>0.823</td>
<td>-0.007</td>
<td>-0.010</td>
<td>0.008</td>
</tr>
<tr>
<td>$y^+$</td>
<td>1</td>
<td>-0.962</td>
<td>-0.011</td>
<td>0.000</td>
<td>-0.002</td>
<td>0.004</td>
</tr>
<tr>
<td>$(x^+)^2$</td>
<td>1</td>
<td>0.009</td>
<td></td>
<td>-0.002</td>
<td>0.004</td>
<td>0.812</td>
</tr>
<tr>
<td>$R_D^-$</td>
<td>1</td>
<td>-0.918</td>
<td></td>
<td></td>
<td></td>
<td>0.956</td>
</tr>
<tr>
<td>$y^-$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>$(x^-)^2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
[2] Except when otherwise explicitly stated, charge-conjugate processes are implied.


PHYSICAL REVIEW D 95, 052004 (2017)
MEASUREMENTS OF CHARM MIXING AND CP …

PHYSICAL REVIEW D 95, 052004 (2017)
MEASUREMENTS OF CHARM MIXING AND CP ...

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