

Search for  $CP$  violation in neutral  $D$  meson Cabibbo-suppressed three-body decays

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Using  $385 \text{ fb}^{-1}$  of  $e^+e^-$  collision data collected at center-of-mass energies around 10.6 GeV, we search for time-integrated  $CP$  violation in the Cabibbo-suppressed decays  $D^0/\bar{D}^0 \rightarrow \pi^- \pi^+ \pi^0$  and  $D^0/\bar{D}^0 \rightarrow K^- K^+ \pi^0$  with both model-independent and model-dependent methods. Measurements of the asymmetries in amplitudes of flavor states and  $CP$  eigenstates provide constraints on theories beyond the standard

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model, some of which predict  $CP$  violation in amplitudes at the 1% level or higher. We find no evidence of  $CP$  violation and hence no conflict with the standard model.

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Charge-parity violation ( $CPV$ ) [1], manifested as an asymmetry between the decay rates of a particle and its  $CP$ -conjugate antiparticle, requires at least two interfering complex quantum mechanical amplitudes with different phases. The strong phase of each amplitude respects  $CP$  symmetry, while the weak phase changes sign under charge-conjugation. In the standard model (SM), direct  $CPV$  is due to relative weak phases that typically enter as a difference in phase between “tree level” and “penguin” [2] SM amplitudes. The penguin amplitudes in charm decays are, however, too small ( $\mathcal{O}(0.1\%)$  [3]) to provide significant  $CPV$ . Extensions of the SM introduce additional amplitudes of  $\mathcal{O}(1\%)$  [3–5] with relative weak phases that can produce  $CPV$  in charmed particle decays [6]. Current experimental searches [7–12] are approaching this level of sensitivity. Observation of  $CPV$  with current experimental sensitivities would provide strong evidence of new physics.

A recent theory paper [3] argues that singly Cabibbo-suppressed (SCS)  $D$  (meaning either  $D^0$  or  $\bar{D}^0$ ) decays are uniquely sensitive to  $CPV$  in  $c \rightarrow u\bar{d}d$ ,  $u\bar{s}s$  transitions and probe contributions from supersymmetric gluonic penguins. Such transitions do not affect the Cabibbo-favored ( $c \rightarrow s\bar{d}u$ ) or doubly Cabibbo-suppressed ( $c \rightarrow d\bar{s}u$ ) decays. Time-integrated  $CP$  asymmetries in  $D$  decays can have three components: direct  $CPV$  in decays to specific states, indirect  $CPV$  in  $D^0 - \bar{D}^0$  mixing, and indirect  $CPV$  in interference of decays with and without mixing. Indirect  $CPV$  is predicted to be universal for amplitudes with final  $CP$  eigenstates, but direct  $CPV$  can be nonuniversal depending on the specifics of the new physics.

We search for time-integrated  $CPV$  in the three-body SCS decays  $D \rightarrow \pi^- \pi^+ \pi^0$ ,  $K^- K^+ \pi^0$ . These decays proceed via  $CP$  eigenstates (e.g.,  $\rho^0 \pi^0$ ,  $\phi \pi^0$ ) and also via flavor states (e.g.,  $\rho^\pm \pi^\mp$ ,  $K^{*\pm} K^\mp$ ), thus making it possible to probe  $CPV$  in both types of amplitudes and in the interference between them. Measuring interference effects in a Dalitz plot (DP) probes asymmetries in both the magnitudes and phases of the amplitudes, not simply in the overall decay rates. We adopt four approaches in our search for evidence of  $CPV$ , three of which are model independent. First, we quantify differences between the  $D^0$  and  $\bar{D}^0$  DPs in two dimensions. Second, we look for differences in the angular moments of the  $D^0$  and  $\bar{D}^0$  intensity distributions. Third, in a model-dependent approach, we look for  $CPV$  in the amplitudes describing intermediate states in the  $D^0$  and  $\bar{D}^0$  decays. Finally, we look for a phase-space-integrated asymmetry. The first two methods are sensitive to differences in the shapes of the  $D^0$  and  $\bar{D}^0$  DPs, allowing regions of phase space with  $CPV$  to

be identified. The third method associates any  $CPV$  observed using the first two methods with specific intermediate amplitudes. The last method is insensitive to differences in the DP shapes, so complements the other methods. To minimize bias, we finalize the analysis procedure without looking at the data.

We perform the present analysis using  $385 \text{ fb}^{-1}$  of  $e^+e^-$  collision data collected at 10.58 GeV and 10.54 GeV center-of-mass (CM) energies with the BABAR detector [13] at the PEP-II storage rings. The event selection criteria are those used in our measurement of the branching ratios of the decays  $D \rightarrow \pi^- \pi^+ \pi^0$  and  $D \rightarrow K^- K^+ \pi^0$  [14]. In particular, we study  $D$  mesons produced in  $D^{*+} \rightarrow D^0 \pi^+$  and  $D^{*-} \rightarrow \bar{D}^0 \pi^-$  decays that distinguish between  $D^0$  and  $\bar{D}^0$ . We require the  $D$  candidate CM momentum  $> 2.77 \text{ GeV}/c$  and  $|m_{D^{*+}} - m_D - 145.4 \text{ MeV}/c^2| < 0.6 \text{ MeV}/c^2$ . Here,  $m$  refers to a reconstructed invariant mass. Around  $\pm 1$  standard deviation of the nominal  $D$  mass, we find  $82468 \pm 321 \pi^- \pi^+ \pi^0$  and  $11278 \pm 110 K^- K^+ \pi^0$  signal events with purities of about 98%. We determine the signal reconstruction efficiency as a function of the position in the DP using simulated  $D^0$  and  $\bar{D}^0$  decays [14] from  $e^+e^- \rightarrow c\bar{c}$  events, subjected to the same selection procedure that is applied to the data.

A direct comparison of the efficiency-corrected and background-subtracted DPs for  $D^0$  and  $\bar{D}^0$  events is the simplest way to look for  $CPV$ . Figure 1 shows the normalized residuals  $\Delta$  in DP area elements, where

$$\Delta = (n_{\bar{D}^0} - R \cdot n_{D^0}) / \sqrt{\sigma_{n_{\bar{D}^0}}^2 + R^2 \cdot \sigma_{n_{D^0}}^2}, \quad (1)$$

and  $n$  denotes the number of events in a DP element and  $\sigma$  its uncertainty. The factor  $R$ , equal to  $0.983 \pm 0.006$  for  $\pi^- \pi^+ \pi^0$  and  $1.020 \pm 0.016$  for  $K^- K^+ \pi^0$ , is the ratio of the number of efficiency-corrected  $\bar{D}^0$  to  $D^0$  events. This is introduced to allow for any asymmetry in the production cross section due to higher order QED corrections or in the branching fractions for  $D^0$  and  $\bar{D}^0$  decay to the same final state.

We calculate  $\chi^2/\nu = (\sum_{i=1}^{\nu} \Delta_i^2)/\nu$ , where  $\nu$  is the number of DP elements: 1429 for  $\pi^- \pi^+ \pi^0$  and 726 for  $K^- K^+ \pi^0$ . In an ensemble of simulated experiments with no  $CPV$ , we find the distribution of  $\chi^2/\nu$  values to have a mean of  $1.012 \pm 0.001$  ( $1.021 \pm 0.002$ ) and a root mean square deviation of 0.018 (0.036) for  $\pi^- \pi^+ \pi^0$  ( $K^- K^+ \pi^0$ ). The measured value in the data is 1.020 for  $\pi^- \pi^+ \pi^0$  and 1.056 for  $K^- K^+ \pi^0$ , so we obtain a one-sided Gaussian confidence level (CL) for consistency with no  $CPV$  of 32.8% for  $\pi^- \pi^+ \pi^0$  and 16.6% for  $K^- K^+ \pi^0$ . The same analysis procedure, when applied to simulated samples with either 1% fractional change in magnitude or  $1^\circ$

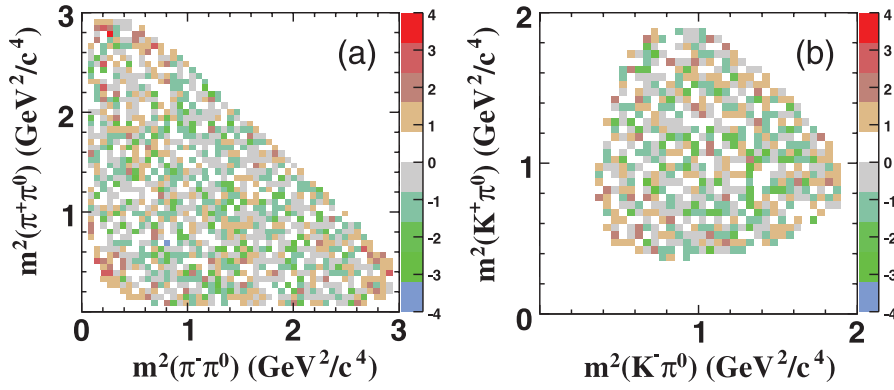


FIG. 1 (color). Normalized residuals in Dalitz plot elements, defined in Eq. (1), for (a)  $D \rightarrow \pi^- \pi^+ \pi^0$  and (b)  $D \rightarrow K^- K^+ \pi^0$ .

change in phase between the  $D^0$  and  $\bar{D}^0$  amplitudes for decay to any of the main resonant states, gives a  $\chi^2/\nu$  that is about  $2\sigma$  away from the no  $CPV$  hypothesis. Systematic uncertainties are small (as will be clear from the model-dependent results of Tables I and II) and have not been included in the CL calculation.

The angular moments of the cosine of the helicity angle of the  $D$  decay products reflect the spin and mass structure of intermediate resonant and nonresonant amplitudes [16]. We define the helicity angle  $\theta_H$  for decays of the type  $D \rightarrow r(AB)C$  as the angle between the momentum of  $A$  in the  $AB$  rest frame and the direction opposite to the  $D$  momentum in that same frame. The angular moments [17] of order  $l$  are defined as the efficiency-corrected invariant mass distributions of events weighted by spherical harmonics  $Y_l^0(\theta_H) = \sqrt{1/2\pi} P_l(\cos\theta_H)$ . Here,  $P_l$  are the Legendre polynomials of order  $l$ . To study differences between the  $D^0$  and  $\bar{D}^0$  amplitudes, we calculate the quantities  $X_l$  for

$l = 0-7$ , where

$$X_l = \frac{(\bar{P}_l - R \cdot P_l)}{\sqrt{\sigma_{\bar{P}_l}^2 + R^2 \cdot \sigma_{P_l}^2}}, \quad (2)$$

and  $P_l$  ( $\bar{P}_l$ ) are obtained from  $D^0$  ( $\bar{D}^0$ ) events. Higher moments are zero within errors in both data and simulation. For illustration, we show the  $X_l$  distributions for  $l = 0-2$ , in Fig. 2.

We then define  $\chi^2/\nu$  of the angular moment distributions of a two-body channel summed over all intervals in invariant mass as

$$\chi^2/\nu = \left( \sum_0^k \sum_{i=0}^7 \sum_{j=0}^7 X_i \rho_{ij} X_j \right) / \nu, \quad (3)$$

where  $\nu = 8k$ ,  $k$  is the number of intervals, and  $\rho_{ij}$  is the correlation coefficient between  $X_i$ ,  $X_j$

TABLE I. Model-dependent  $CP$  asymmetry in the  $D \rightarrow \pi^- \pi^+ \pi^0$  Dalitz plots. The first and second errors are statistical and systematic, respectively. For details on the Dalitz plot parametrization and the  $a_r$ ,  $\phi_r$ , and  $f_r$  values, see Ref. [15]. As explained in the text,  $\Delta f_r$  is closely related to  $\Delta a_r$  and  $\Delta \phi_r$ .

State	$f_r(\%)$	$\Delta a_r(\%)$	$\Delta \phi_r(^{\circ})$	$\Delta f_r(\%)$
$\rho^+(770)$	68	$-3.2 \pm 1.7 \pm 0.8$	$-0.8 \pm 1.0 \pm 1.0$	$-1.6 \pm 1.1 \pm 0.4$
$\rho^0(770)$	26	$2.1 \pm 0.9 \pm 0.5$	$0.8 \pm 1.0 \pm 0.4$	$1.6 \pm 1.4 \pm 0.6$
$\rho^-(770)$	35	$2.0 \pm 1.1 \pm 0.8$	$-0.6 \pm 0.9 \pm 0.4$	$0.7 \pm 1.1 \pm 0.5$
$\rho^+(1450)$	0.1	$2 \pm 11 \pm 8$	$-30 \pm 25 \pm 9$	$0.0 \pm 0.1 \pm 0.1$
$\rho^0(1450)$	0.3	$13 \pm 8 \pm 6$	$-1 \pm 14 \pm 3$	$0.1 \pm 0.2 \pm 0.1$
$\rho^-(1450)$	1.8	$-3 \pm 6 \pm 5$	$8 \pm 7 \pm 3$	$-0.2 \pm 0.3 \pm 0.1$
$\rho^+(1700)$	4	$19 \pm 27 \pm 9$	$9 \pm 7 \pm 3$	$0.4 \pm 1.0 \pm 0.4$
$\rho^0(1700)$	5	$-31 \pm 20 \pm 12$	$-7 \pm 6 \pm 2$	$-1.3 \pm 0.8 \pm 0.3$
$\rho^-(1700)$	3	$-3 \pm 14 \pm 11$	$-3 \pm 8 \pm 3$	$-0.5 \pm 0.6 \pm 0.3$
$f_0(980)$	0.2	$0.0 \pm 0.1 \pm 0.2$	$-3 \pm 7 \pm 4$	$0.0 \pm 0.1 \pm 0.1$
$f_0(1370)$	0.4	$-0.3 \pm 1.3 \pm 1.2$	$7 \pm 14 \pm 5$	$-0.2 \pm 0.1 \pm 0.1$
$f_0(1500)$	0.4	$0.4 \pm 1.1 \pm 0.7$	$-1 \pm 12 \pm 1$	$0.0 \pm 0.1 \pm 0.1$
$f_0(1710)$	0.3	$-3 \pm 3 \pm 2$	$-25 \pm 13 \pm 11$	$0.0 \pm 0.1 \pm 0.1$
$f_2(1270)$	1.3	$8 \pm 4 \pm 5$	$2 \pm 5 \pm 2$	$0.1 \pm 0.1 \pm 0.1$
$\sigma(400)$	0.8	$-0.3 \pm 0.7 \pm 2.0$	$-4 \pm 7 \pm 3$	$-0.1 \pm 0.1 \pm 0.1$
Nonres	0.8	$12 \pm 7 \pm 8$	$11 \pm 9 \pm 4$	$0.2 \pm 0.3 \pm 0.2$



TABLE II. Model-dependent  $CP$  asymmetry in the  $D \rightarrow K^- K^+ \pi^0$  Dalitz plots. The errors are statistical and systematic, respectively. We show the  $a_0(980)$  contribution, when it is included in place of the  $f_0(980)$ , in square brackets. For details on the Dalitz plot parametrization and the  $a_r$ ,  $\phi_r$ , and  $f_r$  values, see Ref. [16]. We use Model I of Ref. [16] to obtain central values and Model II for the study of systematic errors.

State	$f_r(\%)$	$\Delta a_r(\%)$	$\Delta \phi_r(^{\circ})$	$\Delta f_r(\%)$
$K^*(892)^+$	45	$2 \pm 3 \pm 2$	$10 \pm 12 \pm 3$	$0.8 \pm 1.1 \pm 0.4$
$K^*(1410)^+$	4	$101 \pm 65 \pm 37$	$1 \pm 21 \pm 6$	$1.7 \pm 1.8 \pm 0.6$
$K^+ \pi^0(S)$	16	$-130 \pm 64 \pm 51$	$-9 \pm 10 \pm 6$	$-2.3 \pm 4.7 \pm 1.0$
$\phi(1020)$	19	$-1 \pm 2 \pm 1$	$-10 \pm 20 \pm 5$	$-0.4 \pm 0.8 \pm 0.2$
$f_0(980)$	7	$14 \pm 16 \pm 6$	$-12 \pm 25 \pm 8$	$0.4 \pm 2.6 \pm 0.2$
$[a_0(980)^0]$	[6]	[ $19 \pm 16 \pm 6$ ]	[ $-7 \pm 16 \pm 8$ ]	[ $0.6 \pm 1.9 \pm 0.2$ ]
$f_2'(1525)$	0.1	$-38 \pm 74 \pm 8$	$6 \pm 36 \pm 12$	$0.0 \pm 0.1 \pm 0.3$
$K^*(892)^-$	16	$1 \pm 3 \pm 1$	$-7 \pm 4 \pm 2$	$1.7 \pm 1.3 \pm 0.4$
$K^*(1410)^-$	5	$133 \pm 93 \pm 68$	$-23 \pm 13 \pm 9$	$1.7 \pm 2.8 \pm 0.7$
$K^- \pi^0(S)$	3	$8 \pm 68 \pm 36$	$32 \pm 39 \pm 14$	$0.4 \pm 2.4 \pm 0.5$

$$\rho_{ij} = \frac{\langle X_i X_j \rangle - \langle X_i \rangle \langle X_j \rangle}{\sqrt{\langle X_i^2 \rangle - \langle X_i \rangle^2} \cdot \sqrt{\langle X_j^2 \rangle - \langle X_j \rangle^2}}. \quad (4)$$

We determine the  $\rho_{ij}$  in each mass interval by simulating experiments with no  $CPV$ . We test the method on real data by randomly assigning events as  $D^0$  or  $\bar{D}^0$ , and then calculating  $\chi^2/\nu$  for the difference in their angular moments. We repeat this experiment 500 times and find the resulting  $\chi^2/\nu$  distribution to be consistent with no  $CPV$ , validating our calculation of  $\rho_{ij}$ . We then look at the  $D$  flavor in the data and calculate the  $\chi^2/\nu$  values for the two-body channels with charge combinations  $+$ ,  $-$  and  $+$ ,  $0$ . Finally, we obtain a one-sided Gaussian CL for consistency with no  $CPV$  using the reference value and root mean square deviation from simulation. We find the CL for no  $CPV$  to be 28.2% for the  $\pi^+ \pi^-$ , 28.4% for the  $\pi^+ \pi^0$ , 63.1% for the  $K^+ K^-$ , and 23.8% for the  $K^+ \pi^0$  subsystems. Again, a 1% fractional change in magnitude or  $1^{\circ}$  change in phase of any of the main resonant amplitudes gives a  $\chi^2/\nu$  that is about  $2\sigma$  away from the no  $CPV$  hypothesis.

The Dalitz plot amplitude  $\mathcal{A}$  can be parametrized as a sum of amplitudes  $A_r(s_+, s_-)$  for all relevant intermediate states  $r$ , each with a complex coefficient, i.e.,  $\mathcal{A} = \sum_r a_r e^{i\phi_r} A_r(s_+, s_-)$ , where  $a_r$  and  $\phi_r$  are real. Here,  $s_+$  and  $s_-$  are the squared invariant masses of the pair of final state particles with charge combinations  $+$ ,  $0$  and  $-$ ,  $0$ . The fit fraction for each process  $r$  is defined as  $f_r \equiv \int |a_r A_r|^2 ds_+ ds_- / \int |\mathcal{A}|^2 ds_+ ds_-$ . We model incoherent,  $CP$ -symmetric background empirically [15,16]. In the absence of  $CPV$ , we expect the values of  $a_r$  and  $\phi_r$  (and hence  $f_r$ ) to be identical for  $D^0$  and  $\bar{D}^0$  decay. The results obtained with this assumption are listed in Ref. [15] for  $D \rightarrow \pi^- \pi^+ \pi^0$  and in Ref. [16] for  $D \rightarrow K^- K^+ \pi^0$ . To allow the possibility of  $CPV$  in the present analysis, we let a second process—not necessarily of SM origin—contribute to each of the amplitudes  $A_r$ , thus permitting the  $a_r$ ,  $\phi_r$ ,  $f_r$  for  $D^0$  and  $\bar{D}^0$  to differ. We summarize the results of the fit to the data in terms of the differences  $\Delta a_r = a_r^{\bar{D}^0} - a_r^{D^0}$ ,  $\Delta \phi_r = \phi_r^{\bar{D}^0} - \phi_r^{D^0}$ , and  $\Delta f_r = f_r^{\bar{D}^0} - f_r^{D^0}$  in Table I for  $\pi^- \pi^+ \pi^0$  and in Table II for  $K^- K^+ \pi^0$ . The  $CP$  asym-

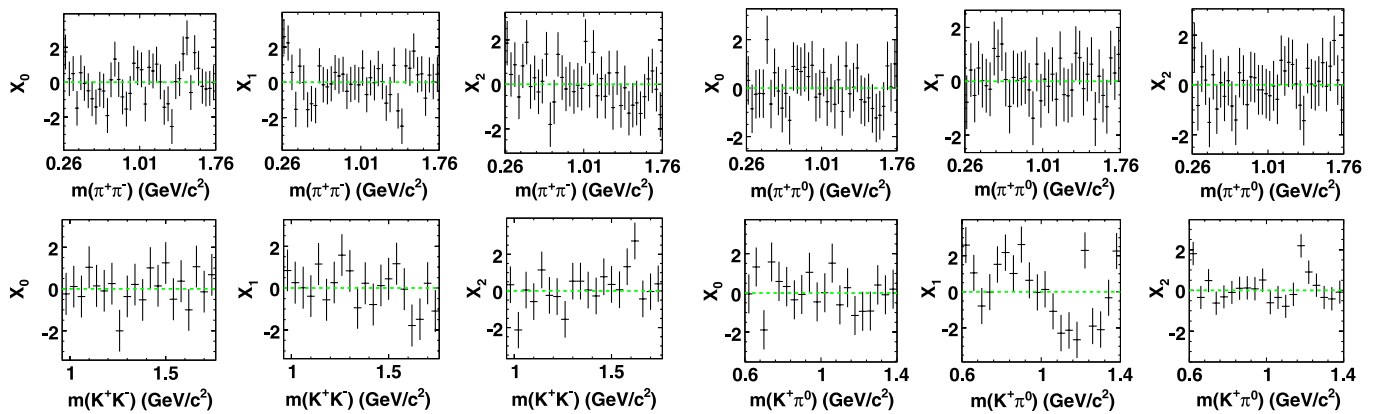


FIG. 2 (color online). Normalized residuals for the first three Legendre polynomial moments of the  $\pi^- \pi^+$  (row 1),  $\pi^+ \pi^0$  (row 2),  $K^- K^+$  (row 3), and  $K^+ \pi^0$  (row 4) subsystems. The confidence level for no  $CP$  violation (dashed line) is obtained from the first eight moments. The error bars represent  $\pm 1\sigma$ .

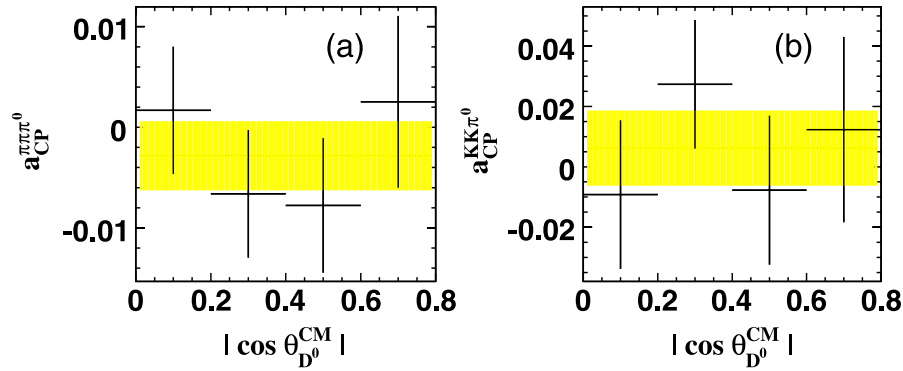


FIG. 3 (color online). Phase-space-integrated  $CP$  asymmetry as a function of the cosine of the polar angle of the reconstructed  $D$  candidate CM momentum for (a)  $D \rightarrow \pi^- \pi^+ \pi^0$  and (b)  $D \rightarrow K^- K^+ \pi^0$  decays. The dashed lines represent the central values, and the shaded regions the  $1\sigma$  intervals.

metry in any amplitude, relative to that of the whole decay, is no larger than a few percent.

Systematic uncertainties in the quantities describing  $CP$  asymmetries, reported in Tables I and II, arise from experimental effects, and also from uncertainties in the models used to describe the data. We determine these separately, as described in Refs. [15,16], and add them in quadrature. For all variations described below, we assign the maximum deviation from the central value as a systematic uncertainty, accounting for correlations among parameters. For resonance lineshapes and form factors, we vary the parameters [18] by  $\pm 1\sigma$ . Similarly, we vary the signal efficiency parameters for separately for  $D^0$  and  $\bar{D}^0$  events by  $\pm 1\sigma$ , the ratios of particle-identification rates in data and simulation by  $\pm 1\sigma$ , and the background shapes by using simulation rather than data sidebands. We include uncertainties from  $D^0 - \bar{D}^0$  misidentification, estimated from simulation, in the experimental systematic uncertainty.

To this point, we have described the investigation of time-integrated  $CP$  asymmetry in neutral  $D$  meson decays using information from the DP distributions. Differences in the overall branching fractions for the  $D^0$  and  $\bar{D}^0$  decays to  $\pi^- \pi^+ \pi^0$ ,  $K^- K^+ \pi^0$  would also indicate time-integrated  $CPV$ . This information is not captured by the differential comparisons of the DP structures already described, and is complementary to them. To correct for any production asymmetry in  $D$ -flavor assignment, we weight each event by the relative efficiency for flavor assignment, as described in Ref. [7]. Since there is an asymmetry [7] between the number of events reconstructed at forward and backward polar angles ( $\theta_{D^0}^{\text{CM}}$ ) of the  $D$  candidate CM momentum, we extract the  $CP$  asymmetry value,  $a_{CP} \equiv \frac{N_{\bar{D}^0} - N_{D^0}}{N_{\bar{D}^0} + N_{D^0}}$ , in intervals of  $|\cos \theta_{D^0}^{\text{CM}}|$ . Here,  $N$  denotes the number of signal events. Any forward-backward asymmetry is canceled by averaging over symmetric intervals in  $\cos \theta_{D^0}^{\text{CM}}$ , as shown in Eqs. 3–5 of Ref. [7]. In Fig. 3, we

show the  $a_{CP}$  for events in the  $D$  mass window used in the DP analysis. We perform  $\chi^2$  minimization to obtain the central values:  $[-0.31 \pm 0.41(\text{stat}) \pm 0.17(\text{syst})]\%$  for  $\pi^- \pi^+ \pi^0$  and  $[1.00 \pm 1.67(\text{stat}) \pm 0.25(\text{syst})]\%$  for  $K^- K^+ \pi^0$  final states. The systematic uncertainties result from signal efficiency, particle-identification, background treatment, and  $D^0 - \bar{D}^0$  misidentification. As a consistency check, we repeat the analysis with a larger  $D$  mass window ( $\pm 2.5\sigma$ ) and find consistent results  $[-0.28 \pm 0.34(\text{stat}) \pm 0.19(\text{syst})]\%$  for  $\pi^- \pi^+ \pi^0$  and  $[0.62 \pm 1.24(\text{stat}) \pm 0.28(\text{syst})]\%$  for  $K^- K^+ \pi^0$ .

In summary, our model-independent and model-dependent analyses show no evidence of  $CPV$  in the SCS decays  $D \rightarrow \pi^- \pi^+ \pi^0$  and  $D \rightarrow K^- K^+ \pi^0$ . The intermediate amplitudes include well-defined flavor states (e.g.,  $\rho^\pm \pi^\mp$ ,  $K^{*\pm} K^\mp$ ) and  $CP$ -odd eigenstates (e.g.,  $\rho^0 \pi^0$ ,  $\phi \pi^0$ ). With the null results of Refs. [7–10] for  $CP$ -even eigenstates  $D \rightarrow K^+ K^-$  and  $D \rightarrow \pi^+ \pi^-$ , we conclude that any  $CPV$  in the SCS charm decays occurs at a rate which is not larger than a few percent. These results are in accord with the SM predictions, and provide constraints on some models beyond the SM [3].

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