

Latest results on mixing and CP violation in the charm decays at the B -factories

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In this report, latest results on mixing and CP violation in the charm decays at the B -factories are presented.

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1. Introduction

Mixing between D^0 and \bar{D}^0 provides crucial information about electroweak interactions and the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Phenomenon of mixing can be described as decaying two-component quantum states.

$$\text{Mass eigenstates}(D_1, D_2) \neq \text{Flavor eigenstates}(D^0, \bar{D}^0). \quad (1.1)$$

The two parameters characterizing $D^0 - \bar{D}^0$ mixing are

$$x \equiv \frac{\Delta M}{\Gamma}, \quad \Delta M \equiv M_1 - M_2, \quad (1.2)$$

$$y \equiv \frac{\Delta\Gamma}{2\Gamma}, \quad \Delta\Gamma \equiv \Gamma_1 - \Gamma_2, \quad (1.3)$$

where $M_{1,2}$ ($\Gamma_{1,2}$) are the masses (decay widths) of $D_{1,2}$, and $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$ is the mean decay width.

Flavor eigenstates can be written as:

$$|D^0(t)\rangle = \frac{1}{2p} [|D_1(t)\rangle + |D_2(t)\rangle] \text{ and } |\bar{D}^0(t)\rangle = \frac{1}{2q} [|D_1(t)\rangle - |D_2(t)\rangle] \quad (1.4)$$

The coefficients p and q are complex coefficients satisfying $|p|^2 + |q|^2 = 1$, and $q/p = |q/p|e^{i\phi}$.

In the Standard Model (SM), D^0 - \bar{D}^0 mixing is well described by box diagram containing down-type (d, s, b) quarks. While both s and d box amplitudes are suppressed by a factor $(m_s^2 - m_d^2)^2 / (m_W^2 m_c^2)$ due to the Glashow-Iliopoulos-Maiani mechanism [1], the contributions from loops involving b quarks is further suppressed by CKM factors $|V_{ub}V_{cb}^*|^2 / |V_{us}V_{cs}^*|^2 = \mathcal{O}(10^{-6})$. The short-distance SM predictions are $x = \mathcal{O}(10^{-5})$ and $y = \mathcal{O}(10^{-7})$ [2, 3, 4]. The long-distance contributions can yield $x, y \leq 10^{-3}$ [4]. Further, $SU(3)_F$ violation in the final-state phase space could provide enough breaking to generate $y \sim 10^{-2}$ [5] and $x \sim 10^{-3} - 10^{-2}$ [3, 4]. New Physics (NP) can enhance the D^0 - \bar{D}^0 mixing rate [6, 7]. Currently, D^0 - \bar{D}^0 mixing has been observed and well established. Due to the uncertainties in both SM and NP, observation at $\mathcal{O}(10^{-2})$ does not indicate presence of NP [4].

CP violation (CPV) can play an important role in search for NP. In D meson decays, it is categorized as:

- CPV in mixing occurs when the mixing probability of D^0 to \bar{D}^0 is different than that of \bar{D}^0 to D^0 . This happens if and only if $|q/p| \neq 1$. Depends only on the mixing parameters and not on the final state of decay.
- Direct CPV appears when the amplitude for a decay and its CP conjugate processes have different magnitudes. It occurs only if the differences between CP-conserving strong phases and the differences between the CP-violating weak phases of the two contributing amplitudes are non-zero.
- CPV in the interference between a direct decay $D^0 \rightarrow f$, and decay involving mixing, $D^0 \rightarrow \bar{D}^0 \rightarrow f$.

The SM predicts CP asymmetries in D meson to be very small, less than $\mathcal{O}(0.01\%)$ [8, 9, 10, 11]. NP scenarios such as supersymmetric gluino-squark loops, yield direct CP asymmetries as large as $\mathcal{O}(1\%)$ [12].

2. Mixing results from B-factories

2.1 Wrong sign decay $D^0 \rightarrow K^+ \pi^-$

In wrong sign (WS) D^0 decay $D^0 \rightarrow K^+ \pi^-$, the final state is reached either through direct doubly Cabibbo suppressed (DCS) decay, or via mixing where $D^0 \rightarrow \bar{D}^0$ and then $\bar{D}^0 \rightarrow K^+ \pi^-$ through Cabibbo favored (CF) right sign (RS) decay. Interference between the two amplitude occurs. One can normalize the WS to the RS rate to obtain

$$R(t) = \frac{N_{\text{WS}}(t)}{N_{\text{RS}}(t)} = R_D + \sqrt{R_D} y' \Gamma t + \frac{x'^2 + y'^2}{4} (\Gamma t)^2, \quad (2.1)$$

where $R_D = \left| \frac{A_{\text{DCS}}}{A_{\text{CF}}} \right|^2$, and the x' and y' are related to the mixing parameters (x and y) through a rotation by the strong phase, $\delta_{K\pi}$:

$$x' \equiv x \cos \delta_{K\pi} + y \sin \delta_{K\pi}, \quad (2.2)$$

$$y' \equiv y \cos \delta_{K\pi} - x \sin \delta_{K\pi}. \quad (2.3)$$

Table 1: Mixing parameters measured by different experiments. The quoted uncertainties include both statistical and systematic.

Experiment	$R_D, \times 10^{-3}$	$y', \times 10^{-3}$	$x'^2, \times 10^{-3}$
Belle [13]	3.53 ± 0.13	4.6 ± 3.4	0.09 ± 0.22
BaBar [14]	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37
CDF [15]	3.51 ± 0.35	4.3 ± 4.3	0.08 ± 0.18
LHCb [16]	3.533 ± 0.054	5.23 ± 0.84	3.6 ± 4.3

The relative WS decay rate at B-factories allows a determination of x'^2 , y' and R_D , but not the strong phase $\delta_{K\pi}$.

B-factories use slow pion π_s^+ of the strong decay $D^{*+} \rightarrow D^0 \pi^+$ to determine ('tag') the charm flavor. The charge of π_s and the charge of kaon from decay products of D is used to identify the WS and RS. The values of x'^2 and y' are extracted by a fit to the time-dependent ratio of WS to RS decay. Belle [13] (BaBar [14]) excluded non-mixing hypothesis at 5.1σ (3.9σ). Table 1 summarizes the mixing parameters by different experiments. Belle observed the mixing using WS D decay.

2.2 Decays to CP eigenstates $D^0 \rightarrow K^+ K^- / \pi^+ \pi^-$

Mixing in D^0 decays to CP eigenstates, gives rise to an effective lifetime τ that differs from that in the decays to flavor eigenstates such as $D^0 \rightarrow K^- \pi^+$. The mixing parameter y can thus

be measured by comparing the rate of D^0 decays to CP eigenstates with decays to non- CP eigenstates. If decays to CP eigenstates have a shorter effective lifetime than those decaying to non- CP eigenstates, then y would be positive [4]. Belle [17] has measure:

$$y_{CP} = [+1.11 \pm 0.22 \pm 0.09]\% \text{ and } A_{\Gamma} = [-0.03 \pm 0.20 \pm 0.07]\% \quad (2.4)$$

using 976 fb^{-1} data, while BaBar [18] used 468 fb^{-1} to measured:

$$y_{CP} = [+0.72 \pm 0.18 \pm 0.12]\% \text{ and } A_{\Gamma} = [-0.18 \pm 0.52 \pm 0.12]\%. \quad (2.5)$$

The first uncertainty is statistical and the second systematic. The y_{CP} results from Belle [17] (BaBar [18]) exclude the null mixing hypothesis at 4.7σ (3.3σ) significance.

2.3 Time-dependent analysis of three-body decay modes

Using amplitude analyses of multi-body D^0 decay modes, one can measure mixing without the ambiguity of an unknown strong phase. Interferences between intermediate resonances provide sensitivity to both magnitude and sign of the mixing parameters. Belle and BaBar have performed mixing studies using D^0 decay to $K_S^0 \pi^+ \pi^-$ and $K_S^0 K^+ K^-$ final states.

The particle-antiparticle mixing phenomenon causes an initially produced (at proper time $t = 0$) pure D^0 or \bar{D}^0 meson state to evolve in time to a linear combination of D^0 and \bar{D}^0 states. One can describe the decay amplitude for D^0 (\bar{D}^0) into the final state, \mathcal{A}_f ($\bar{\mathcal{A}}_f$), as a function of Dalitz plot (DP) variables. Time-dependent decay amplitudes for these decays are:

$$\mathcal{M}(m_-^2, m_+^2, t) = \mathcal{A}(m_-^2, m_+^2) \frac{e_1(t) + e_2(t)}{2} + \frac{q}{p} \bar{\mathcal{A}}(m_-^2, m_+^2) \frac{e_1(t) - e_2(t)}{2} \quad (2.6)$$

$$\bar{\mathcal{M}}(m_-^2, m_+^2, t) = \bar{\mathcal{A}}(m_-^2, m_+^2) \frac{e_1(t) + e_2(t)}{2} + \frac{p}{q} \mathcal{A}(m_-^2, m_+^2) \frac{e_1(t) - e_2(t)}{2} \quad (2.7)$$

where \mathcal{A} ($\bar{\mathcal{A}}$) decay amplitude for D^0 (\bar{D}^0), $m_{\pm}^2 \equiv m^2(K_S^0 \pi^{\pm})$ is parameterized with an amplitude a_r and a phase ϕ_r , $\mathcal{A}(m_-^2, m_+^2) = \sum_r a_r e^{i\phi_r} \mathcal{A}_r(m_-^2, m_+^2) + a_{nr} e^{i\phi_{nr}}$ and $\bar{\mathcal{A}}(m_-^2, m_+^2) = \sum_r \bar{a}_r e^{i\phi_r} \bar{\mathcal{A}}_r(m_-^2, m_+^2) + \bar{a}_{nr} e^{i\phi_{nr}}$. Time dependence is contained in $e_{1,2}(t) = e^{-i(m_{1,2} - i\Gamma_{1,2}/2)t}$.

In order to fit the DP distribution as function of time, one needs to assume an amplitude model. These models include a coherent sum of quasi-two-body intermediate resonances (r) plus a nonresonant (nr) component. P - and D -wave amplitudes are modeled by Breit-Wigner (BW) or Gounaris-Sakurai functional forms, including Blatt-Weisskopf centrifugal barrier factors. For describing $\pi\pi$ S -wave dynamics, the K -matrix formalism with P -vector approximation is used.

Belle [19] obtained 1231731 ± 1633 signal events for $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ with purity of 95.5% by using 921 fb^{-1} . Two observables $M_{K_S^0 \pi^+ \pi^-}$ and $Q \equiv M(K_S^0 \pi^+ \pi^- \pi_S) - M(K_S^0 \pi^+ \pi^-) - m(\pi_S)$ are used to identify the signal. Using CP conserved fit, Belle measured $x = (0.56 \pm 0.19_{-0.09-0.09}^{+0.03+0.06})\%$ and $y = (0.30 \pm 0.15_{-0.05-0.06}^{+0.04+0.03})\%$. No mixing hypothesis is excluded with significance of 2.5σ . Also a search for CPV was carried out measuring $|q/p| = 0.90_{-0.15-0.04-0.05}^{+0.16+0.05+0.06}$ and $\arg(q/p) = (-6 \pm 11 \pm 3_{-4}^3)^\circ$. The x and y values are consistent with CP conserved fit. The last uncertainty is due to the amplitude model.

BaBar [20] used M_D^0 and ΔM to identify the signal and obtained 540800 ± 800 (79900 ± 300) signal events in the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ ($D^0 \rightarrow K_S^0 K^+ K^-$) decay. Mixing hypothesis is favored with

significance of 1.9σ . Results for the nominal mixing fit, in which both D^0 and \bar{D}^0 samples from $K_S^0\pi^+\pi^-$ and $K_S^0K^+K^-$ channels are combined, are $x = (1.6 \pm 2.3 \pm 1.2 \pm 0.8) \times 10^{-3}$ and $y = (5.7 \pm 2.0 \pm 1.3 \pm 0.7) \times 10^{-3}$.

BaBar also performed the first measurement of mixing parameters from a time-dependent amplitude analysis of the singly Cabibbo-suppressed (SCS) decay $D^0 \rightarrow \pi^+\pi^-\pi^0$ [21]. Signal is identified with the ΔM variable. Using an isobar model of relativistic BW line shape, they measured $x = (1.5 \pm 1.2 \pm 0.6)\%$ and $y = (0.2 \pm 0.9 \pm 0.5)\%$. Owing to less statistics, no CP violation was attempted.

3. Direct CP asymmetry measurement

D^0 candidates are selected from the decay $D^{*+} \rightarrow D^0\pi_s^+$, where π_s^+ reveals the flavor content of neutral D meson. The D^{*+} momentum calculated in the e^+e^- center-of-mass frame is used to suppress D^{*+} from B decays as well as to reduce the combinatorial background. D^{*+} mesons mostly originate from $e^+e^- \rightarrow c\bar{c}$ process via hadronization, where the inclusive yield has a large uncertainty of 12.5% [22]. To avoid this uncertainty, we measure the branching fraction of signal decay with respect to the well measured mode as normalization mode

$$\mathcal{B}_{\text{sig}} = \mathcal{B}_{\text{norm}} \times \frac{N_{\text{sig}}}{N_{\text{norm}}} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}}, \quad (3.1)$$

where N is the extracted yield, ϵ the reconstructed efficiency and \mathcal{B} the branching fraction for signal (sig) and normalization (norm) modes. For $\mathcal{B}_{\text{norm}}$, the world average values [22] is used. Assuming the total decay width to be same for particles and antiparticles, the time-integrated A_{CP} is:

$$A_{CP} = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow \bar{f})}, \quad (3.2)$$

where, Γ represents the partial decay width and f is specific final state. The extracted raw asymmetry is given by:

$$A_{\text{raw}} = \frac{N(D^0 \rightarrow f) - N(\bar{D}^0 \rightarrow \bar{f})}{N(D^0 \rightarrow f) + N(\bar{D}^0 \rightarrow \bar{f})} = A_{CP} + A_{FB} + A_{\epsilon}^{\pi_s}. \quad (3.3)$$

Here, A_{FB} is the forward-backward production asymmetry, and $A_{\epsilon}^{\pi_s}$ is asymmetry due to difference in detection efficiencies for positively and negatively charged pions. Both can be eliminated through a relative measurement of A_{CP} if the charged final-state particles are identical. The CP asymmetry of the signal mode can then be expressed as:

$$A_{CP}(\text{sig}) = A_{\text{raw}}(\text{sig}) - A_{\text{raw}}(\text{norm}) + A_{CP}(\text{norm}). \quad (3.4)$$

For the $A_{CP}(\text{norm})$, the world average value [22] is used. This way one can also reduce systematic uncertainties as those are common to both the signal and normalization mode get canceled.

3.1 $D^0 \rightarrow V\gamma$ study

Radiative charm decays are dominated by non-perturbative long range dynamics, so measurements of their branching fractions can be a useful test for the QCD based theoretical calculations.

Further motivation for a study of $D^0 \rightarrow V\gamma$, where V is a vector meson, arises due to the potential sensitivity of these decays to NP via A_{CP} measurement. Some studies predict that A_{CP} can rise to several percent in contrast to $\mathcal{O}(10^{-3})$ SM expectation [23, 24].

Belle [25] performed the first measurement of CP violation in $D^0 \rightarrow V\gamma$ decays using $943 fb^{-1}$ of data. The signal decays are reconstructed in the sub-decay channels of the vector meson: $\phi \rightarrow K^+K^-$, $\bar{K}^{*0} \rightarrow K^-\pi^+$ and $\rho \rightarrow \pi^+\pi^-$. The corresponding normalization modes are $D^0 \rightarrow K^+K^-$ (ϕ mode), $D^0 \rightarrow K^-\pi^+$ (\bar{K}^{*0} mode) and $D^0 \rightarrow \pi^+\pi^-$ (ρ^0 mode).

Signal is extracted via a simultaneous two-dimensional fit to the invariant mass $m(D^0)$ and the cosine of the helicity angle ($\cos\theta_H$), which is the angle between D^0 and one of the charged hadrons in the rest frame of the V meson. We measure:

$$\begin{aligned} \mathcal{B}(D^0 \rightarrow \phi\gamma) &= (2.76 \pm 0.19 \pm 0.10) \times 10^{-5}, & A_{CP}(D^0 \rightarrow \phi\gamma) &= -0.094 \pm 0.066 \pm 0.001, \\ \mathcal{B}(D^0 \rightarrow \bar{K}^{*0}\gamma) &= (4.66 \pm 0.21 \pm 0.21) \times 10^{-4}, & A_{CP}(D^0 \rightarrow \bar{K}^{*0}\gamma) &= -0.003 \pm 0.020 \pm 0.000, \\ \mathcal{B}(D^0 \rightarrow \rho^0\gamma) &= (1.77 \pm 0.30 \pm 0.07) \times 10^{-5}, & A_{CP}(D^0 \rightarrow \rho^0\gamma) &= +0.056 \pm 0.152 \pm 0.006, \end{aligned}$$

where the first uncertainty is statistical and the second is systematic. Results are consistent with no CP asymmetry in any of the $D^0 \rightarrow V\gamma$ decay modes. Further, the $D^0 \rightarrow \rho^0\gamma$ decay is observed for the first time.

3.2 $D^0 \rightarrow K_S^0 K_S^0$ study

SCS decays such as $D^0 \rightarrow K_S^0 K_S^0$ are of special interest as possible interference with NP amplitude could lead to larger non-zero CPV. SM based calculations estimate that direct CP violation in this decay mode can reach upto 1.1% (at 95% confidence level) [26]. Earlier search for CP asymmetry in $D^0 \rightarrow K_S^0 K_S^0$ has been performed by the CLEO Collaboration as $(-23 \pm 19)\%$ [27] and LHCb as $(-2.9 \pm 5.2 \pm 2.2)\%$ [28].

Belle extract signal via a simultaneous fit of the ΔM variable using the normalization mode $D^0 \rightarrow K_S^0 \pi^0$. The signal yield for $D^0 \rightarrow K_S^0 K_S^0$ is $5,399 \pm 87$ and for $D^0 \rightarrow K_S^0 \pi^0$ as $531,807 \pm 796$ events. A simultaneous fit to the ΔM distribution of D^{*+} and D^{*-} is used to estimate the asymmetry. The preliminary time-integrated CP-violating asymmetry A_{CP} obtained using $921 fb^{-1}$ in the $D^0 \rightarrow K_S^0 K_S^0$ decay is $A_{CP} = (-0.02 \pm 1.53 \pm 0.17)\%$ [29]. The dominant systematic uncertainty comes from the A_{CP} error of the normalization channel. The result is consistent with SM expectation and is a significantly improves over the previous measurements.

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