We review basic phenomenology on $D^0$ mixing/CPV violation and recent experimental results on them. $D^0$ mixing is established by combining results from multiple experiments but no CP violation in the charm sector has been seen. $D^0$ mixing from a single experiment will clarify the size of the mixing, and observation of CP violation in charm decays at the present level of experimental sensitivity would be clear signal of new physics beyond the standard model.

1. Introduction

Mixing of the strangeness flavor in the kaon system has been observed more than 50 years ago [1] and CP violation in the kaon system has also been well studied indicating, that there is no new physics (NP) beyond the standard model (SM) in the kaon system [2]. Also, the oscillation of the $b$-quark flavor, in both $B_d$ and $B_s$ meson systems, has been established firmly by B-factories and by Tevatron and has been a leading topic in the flavor community of high energy physics [3]. CP violation effects in the $B$ meson system are expected to be as small as $O(10^{-4})$ and universal between CP eigenstates [4]. On the other hand, the direct CP violation can be larger in SM, depending on the final state of the $D$ decay of interest. In the following sections, we briefly discuss basic phenomenology of $D$ meson mixing and CP violation and the corresponding experimental results.

2. $D^0$ Meson Mixing

2.1. Mixing Parameters

In order to describe the time development of neutral $D$-meson system, one starts with writing Schrödinger equation for a column vector that is composed of $D^0$ and $\bar{D}^0$ states:

$$i \frac{d}{dt} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \begin{pmatrix} M - i \Gamma/2 \\ \bar{M} + i \Gamma/2 \end{pmatrix} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix},$$

where $M$ and $\Gamma$ are $2\times2$ matrices that are associated with $\langle D^0, \bar{D}^0 \rangle \leftrightarrow \langle D^0, \bar{D}^0 \rangle$ transitions via off-shell (dispersive), and on-shell (absorptivve) intermediate states, respectively [1]. Diagonal elements of the effective Hamiltonian $H \equiv M - \frac{i}{2} \Gamma$ are associated with the flavor-conserving transitions, while off-diagonal elements are associated with flavor-changing transitions such as $D^0 \leftrightarrow \bar{D}^0$. The eigenstates of the above Schrödinger equation are parameterized as

$$|D_1\rangle \propto p\sqrt{1 - z}|D^0\rangle + q\sqrt{1 + z}|\bar{D}^0\rangle$$

$$|D_2\rangle \propto r\sqrt{1 + z}|D^0\rangle - s\sqrt{1 - z}|\bar{D}^0\rangle$$

using the notation introduced in Ref. [4]. Parameters $p, q$ and $z$ are complex-valued ones that relate flavor to mass eigenstates for the $D$-meson system. The normalized mass difference and the width difference are parameterized as $x$ and $y$: $x \equiv (m_1 - m_2)/\Gamma$, $y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$,

where $m_i$ and $\Gamma_i$ are mass and decay rate values of the eigenstate $|D_i\rangle$ ($i = 1, 2$). $\Gamma$ is the average of two $\Gamma_i$s. The parameters $x$ and $y$ are commonly called mixing parameters in $D$-meson decays and are experimentally measurable. SM calculations based on box diagrams alone give $x \sim 10^{-5}$ and $y \sim 10^{-7}$ [6], but are increased due to the long-distance effects. The parameter $y$ is dominated by long-distance effects and is generally considered to be insensitive to new physics. Therefore, $x \gg y$ would point to NP phenomena [8].

In the case when $D^0$ decays to non-CP eigenstates, for example $D^0 \rightarrow K^\mp \pi^\pm$, one can form four different combinations of amplitudes as $A_f = \langle K^+ \pi^- | H | D^0 \rangle$, $A_f = \langle K^- \pi^+ | H | D^0 \rangle$, $A_f = \langle K^+ \pi^- | H | \bar{D}^0 \rangle$, $A_f = \langle K^- \pi^+ | H | \bar{D}^0 \rangle$, where the first two are called “right-sign” decay amplitudes as they are Cabibbo favored...
events/0.2 ps
200
400
600
800
1000
1200
1400
1600 Data
Mixing fit
Random
Combinatorial
No mixing fit

Figure 1: Projections of the proper-time distribution of combined \(D^0\) and \(\bar{D}^0\) wrong-sign candidates (points) and fit result of \(D^0 \to K^+\pi^-\) in (a). Fit results with and without mixing hypotheses are included as solid and dashed curves, respectively. (b) The points represent the difference between the data and the no-mixing fit. The solid curve shows the difference between fits with and without mixing. BaBar collaboration, Ref. [10].

(CF), and latter two are “wrong-sign” decay amplitudes as they are doubly Cabibbo-suppressed decays (DCSD) or proceed through mixing. Conventionally one normalizes the wrong-sign decay distributions to the integrated rate of right-sign decays to define \(r(t)\) and \(\tau(t)\):

\[
\begin{align*}
\tau(t) & = \frac{\langle f | H | D^0(t) \rangle^2}{|A_f|^2} = \left| \frac{p}{q} \right|^2 \left| g_+(t) \lambda_f^{-1} + g_-(t) \right|^2, \\
r(t) & = \frac{\langle f | H | D^0(t) \rangle^2}{|A_f|^2} = \left| \frac{p}{q} \right|^2 \left| g_+(t) \lambda_T + g_-(t) \right|^2
\end{align*}
\]

where \(\lambda_f = q \bar{A}_f/p A_f\), \(\lambda_T = q \bar{A}_T/p A_T\), and \(g_{\pm}(t) = \frac{1}{2} \left( e^{-i\omega z_1 t} \pm e^{-i\omega z_2 t} \right)\) with \(z_{1,2} = \omega_{1,2}/\Gamma\), \(\omega_{1,2}\) are the eigenvalues of Eq. (1).

2.2. Semi-leptonic Decays

Let us consider the final state \(f = K^+\ell^-\pi\). In this case, \(A_f = A_T = 0\) within the SM. The final state \(f\) is only accessible through mixing and one can obtain

\[
\begin{align*}
\tau(t) & = \left| g_+(t) \right|^2 \left| \frac{p}{q} \right|^2 \approx \frac{e^{-t}}{4} (x^2 + y^2)^2 \left| \frac{p}{q} \right|^2, \\
r(t) & = \left| g_-(t) \right|^2 \left| \frac{p}{q} \right|^2 \approx \frac{e^{-t}}{4} (x^2 + y^2)^2 \left| \frac{p}{q} \right|^2.
\end{align*}
\]

Note that in the SM, \(CP\) violation in charm mixing is small and \(|q/p| \approx 1\) is satisfied. Also, in the limit of \(CP\) conservation, \(r(t) = \tau(t)\). From Eq. (2), one can compute the time-integrated mixing rate relative to the time-integrated right-sign rate for semi-leptonic decays, \(R_M\), as

\[
R_M = \int_0^\infty r(t) \, dt = \frac{1}{2} (x^2 + y^2),
\]

which is a circle in \(x - y\) plane. The present world-average value of \(R_M\) found by the heavy flavor averaging group [5] is \(R_M = (1.30 \pm 2.69) \times 10^{-4}\). The most sensitive estimation of \(R_M\) is carried out by the Belle collaboration [9]. Using the decay mode of \(D^{*+} \to D^0 \pi^+\) when \(D^0 \to K^+\ell^-\nu\) (right-sign) or \(D^0 \to \bar{D}^0 \to K^{(*)+}\ell^-\nu\) (wrong-sign), one can infer the flavor of the \(D\) meson at the production by identifying the charge of the slow pion \(\pi^+\). By counting the yields of right-sign and wrong-sign decays one extract \(R_M = (1.3 \pm 2.2 \pm 2.0) \times 10^{-4}\) or \(R_M < 6.1 \times 10^{-4}\) at 90% confidence level (C.L.) [9].

2.3. Wrong-Sign Decays

For the final state \(f = K^+\pi^-\), one parameterizes the ratio of decay amplitude as

\[
\frac{A_f}{A_f} = -\sqrt{R_D} e^{-i\delta_f}, \quad \text{with} \quad \left| \frac{A_f}{A_f} \right| \sim O(\tan^2\theta_c) \tag{7}
\]

where \(R_D\) is the decay rate ratio of DCSD to CF modes, and \(\delta_f\) is the strong phase difference between them. If we introduce three \(CP\) violating, real-valued parameters \(A_M, A_D,\) and \(\phi,\) in this wrong-sign decays, to leading order \((A_D, A_M \ll 1)\), one can write

\[
\begin{align*}
\tau(t) & = e^{-t} \left[ R_D (1 + A_D) + \sqrt{R_D (1 + A_M)}(1 + A_D) \right] \\
r(t) & = e^{-t} \left[ R_D (1 - A_D) + \sqrt{R_D (1 - A_M)}(1 - A_D) \right]
\end{align*}
\]

\[
\begin{align*}
\tau(t) & = y' t + \frac{1}{2} \left( 1 + A_M \right) R_M t^2 \\
r(t) & = y' t + \frac{1}{2} \left( 1 - A_M \right) R_M t^2 \tag{8}
\end{align*}
\]

where \(y'_\pm \equiv y' \cos \theta \pm x' \sin \phi,\) \(x' = x \cos \delta_{K\pi} + y' \sin \delta_{K\pi},\) and \(y' = y \cos \delta_{K\pi} - x \sin \delta_{K\pi}.\) Note that \(\delta_{K\pi}\) is the relative strong phase between final state \(K\) and \(\pi,\) and therefore extraction of a different set of mixing parameters \(x'\) and \(y'\) in this final state requires the value of \(\delta_{K\pi}.\) An interference effect in the decay chain provides useful sensitivity to \(\delta_{K\pi}\) and is discussed later. The BaBar collaboration looks at the wrong-sign decay \(D^0 \to K^+\pi^-\) and fits the proper time distribution as shown in Fig. [1]. From this, one extract the mixing parameters as \(x' = (0.22 \pm 0.33 \pm 0.21) \times 10^{-3}\) and \(y' = (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}\) [10], clearly the data prefer the mixing hypothesis.
2.4. Determination of Strong Phase

The decay of the quantum-coherent $C = -1$ state, $\psi(3770) \to D^0\bar{D}^0$ provides time-integrated sensitivity to the strong phase. The neutral charm meson in the CLEO-c program does not travel far enough for time-dependent studies. Using the relations

$$\cos \delta_{K\pi} = \frac{|A(D_+ \to K^-\pi^+)|^2 - |A(D_- \to K^+\pi^-)|^2}{2\sqrt{R_D}|A(D^0 \to K^-\pi^+)|^2}$$

where $D_\pm$ denotes a $CP$-even or -odd eigenstate, one can have experimental access to $\delta_{K\pi}$. CLEO-c uses $CP$-tagged decays to obtain $\cos \delta_{K\pi} = 1.10 \pm 0.35 \pm 0.07$ or $\delta_{K\pi} = \left(22^{+11}_{-12}-9\right)^\circ$ [11].

2.5. Decays to $CP$ Eigenstates

When $D^0$ mesons decay to $CP$ eigenstates, for example $f = K^+K^-$, there is no distinction between $f$ and $\bar{f}$, and therefore $A_f = A_{\bar{f}}$ and $\bar{A}_f = \bar{A}_{\bar{f}}$. In this case, we define $y_{CP}$ and $A_{\Gamma}$ in order to probe the amount of indirect $CP$ violation as

$$y_{CP} \equiv \frac{\Gamma_{D^0 \to K^+K^-} + \Gamma_{D^0 \to K^-K^+}}{2\Gamma} - 1 = \cos \theta - \frac{1}{2} A_M x \sin \theta,$$

$$A_{\Gamma} \equiv \frac{\Gamma_{D^0 \to K^+K^-} - \Gamma_{D^0 \to K^-K^+}}{2\Gamma} = \frac{1}{2} A_M y \cos \theta - x \sin \theta.$$

Note that in the limit of $CP$ conservation, we expect that $y_{CP} = 1$ and $A_{\Gamma} = 0$ and therefore they are parameters that probe $CP$ violation phenomena in $D^0$-meson decays. Substantial work on the time-integrated $CP$ asymmetries in decays to $CP$ eigenstates are carried out and so far all are consistent with no $CP$-violation at $\sim O(1\%)$ level. The BaBar collaboration has studied $D^0 \to K^+K^-/\pi^+\pi^-$ decays to extract a value for $y_{CP}$ and extracted $y_{CP}$ value. Experimentally, $y_{CP} = \langle\tau_{hh}\rangle/\langle\tau_{hh}\rangle - 1$, where $\langle\tau_{hh}\rangle = (\tau_{hh}^0 + \tau_{hh}^{-})/2$ and is measured to be $y_{CP} = (1.16 \pm 0.22 \pm 0.18\%)$ [12] consistent with no $CP$ violation hypothesis. The Belle collaboration has measured the decay-rate asymmetry for the $CP$-even final states $A_{\Gamma}$ by separately determining the apparent lifetimes of $D^0$ and $D^0$ in decays to the $CP$ eigenstates as $A_{\Gamma} = (0.01 \pm 0.30 \pm 0.15\%)$ [13]. Again, the result is consistent with the assumption of no $CP$ violation in the charm sector.

2.6. Dalitz Analysis

Dalitz analysis is an invaluable technique exploited in many charm analyses. In general, for a three-body decay $D \to A + B + C$, one can fully describe the kinematics of such decay using two parameters $m_{AB}^2 \equiv (p_A + p_B)^2$ and $m^2_{BC} \equiv (p_B + p_C)^2$. They are extremely useful since they are Lorentz invariant, the phase space of the decay is flat, and because of that, possible two-body resonances can be clearly seen. This technique has been used in light meson spectroscopy, CKM angle $\phi_3(\gamma)$ measurements, and mixing/$CP$ violation studies. Note that this technique can easily be extended to four and higher number body decays. In the decay of $D^0 \to K^0_S\pi^+\pi^-$, there are many quasi two-body intermediate states such as $D^0 \to K^{*-}\pi^+$ $(\text{CF})$, $D^0 \to K^{*+}\pi^-$ $(\text{DCSD})$, and $D^0 \to p^0K_S^0$ $(CP$ eigenstate). Therefore, one form a total amplitude as

$$A(m_2^2, m_4^2) = \sum_{r} \alpha_r e^{i\phi_r} A_r(m_2^2, m_4^2) + a_{\text{NR}} e^{i\phi_{\text{NR}}}$$

$$\bar{A}(m_2^2, m_4^2) = \sum_{r} \bar{\alpha}_r e^{i\phi_{\bar{r}}} \bar{A}_r(m_2^2, m_4^2) + \bar{a}_{\text{NR}} e^{i\phi_{\text{NR}}}$$

where all resonant amplitudes $(A_r)$ are summed up with relative phase information as well as non-resonant $(\text{NR})$ terms. From above, time-dependent decay rate parameters such as $e^{-t\Gamma} \cos(x\Gamma t)$, $e^{-t\Gamma} \sin(x\Gamma t)$, and $e^{-[(x\pm y)\Gamma]t}$ can be extracted from the measurements. This is a fairly complicated analysis since it contains 18 quasi two-body Dalitz-plot parameters with time-dependent unBinsned maximum likelihood analysis. Both Belle and BaBar collaborations analyze their data. BaBar has measured [14] $x = (0.16 \pm 0.23 \pm 0.14\%)$, and $y = (0.57 \pm 0.20 \pm 0.15\%)$. On the other hand, Belle has measured $|q/p|$ and $\phi$.
in addition to $x$ and $y$: $x = (0.80 \pm 0.29 \pm 0.13)\%$, $y = (0.33 \pm 0.24 \pm 0.10)\%$, $|q/p| = 0.86 \pm 0.30 \pm 0.09$, and $\phi = -0.24 \pm 0.30 \pm 0.09$. Figure 2 shows the allowed region measured by the Belle collaboration.  

2.7. World Average of Mixing Parameters

The heavy flavor averaging group average of $D^0$ mixing/$CP$ violation underlying physics parameters from existing observables are summarized in Fig. 3 and Fig. 4. Even if the impact is not significant, the recent results from the LHCb experiment are included here. The world average values are $x = (0.63^{+0.19}_{-0.20})\%$, $y = (0.75^{+0.12}_{-0.11})\%$, $|q/p| = 0.89^{+0.17}_{-0.15}$, and $\phi(\circ) = -10.0^{+9.4}_{-8.8}$. These indicate that no mixing scenario is excluded at $1\sigma$ level but there is no indication of $CP$ violation in the $D^0$ mixing. From this, one can test various NP models. For example, from the present bound of $x$, one can constrain the 4th generation quark doublet coupling as $|V_{u'\nu}V_{\nu'}| < 10^{-3}$ for $m_\nu = 500$ GeV.

3. CP Violation in D Meson Decays

For the time-integrated search for $CP$ violation, one has to extract the $CP$ asymmetry from detector effect and production asymmetry in the observed asymmetry. To a good approximation,

$$A_{\text{rec}} = \frac{N_D^{\text{rec}} - N_{\bar{D}}^{\text{rec}}}{N_D^{\text{rec}} + N_{\bar{D}}^{\text{rec}}} = A_{CP} + A_{FB} + A_e$$

where $N_D$ and $N_{\bar{D}}$ are reconstructed yields for $D$ and $\bar{D}$ mesons, respectively. $A_{\text{rec}}$ is the reconstructed asymmetry, $A_{CP}$ is the $CP$ asymmetry, $A_{FB}$ is the forward-backward asymmetry in the production, and $A_e$ is the one due to the charged particle reconstruction efficiency asymmetry. To remove asymmetries that do not originate from $CP$ violation, various techniques have been developed depending on availability of control samples of particular decay mode of interest. The important point here is that to control systematics, one really has to use real data.

3.1. Time-integrated Search for CP Violation

The CDF collaboration analyzes the data of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$. The formulation of various asymmetries in this case is as follows:

$$A_{\text{rec}}(hh^*) = A_{CP}(hh) + A_e(\pi)_{hh^*}$$

$$A_{\text{rec}}(K\pi^*) = A_{CP}(K\pi) + A_e(\pi)_{K\pi^*} + A_e(K)_{K\pi^*}$$

$$A_{\text{rec}}(K\pi) = A_{CP}(K\pi) + A_e(K)_{K\pi}$$

$$A_{CP}(hh) = A_{\text{rec}}(hh^*) - A_{\text{rec}}(K\pi^*) + A_{\text{rec}}(K\pi)$$

where (*) indicates that the $D^0$ meson flavor is tagged with slow pions. Note that the last equation is obtained by computing a linear combination of above three. Using the relation above, $A_{CP}(\pi\pi) = (0.22 \pm 0.24 \pm 0.11)\%$ and $A_{CP}(KK) = (-0.24 \pm 0.22 \pm 0.10)\%$ are obtained. Both direct ($a_{\text{dir}}^{CP}$) and mixing-induced $CP$ violation ($a_{\text{ind}}^{CP}$) contribute to the asymmetry as

$$A_{CP} = a_{\text{dir}}^{CP} + \frac{\tau}{T} a_{\text{ind}}^{CP}$$

where $\tau$ is the mean lifetime.
of $D^0$ meson and $(t)$ is the mean value of decay time distribution from the measurement. Note that the measurement errors are smaller than those from $B$-factories.

Time-integrated $CP$ violation search in $D^+ \to K^+_S \pi^+$ is carried out by both the Belle and the BaBar collaborations [19, 20]. In both experiments, one has to remove the forward-backward asymmetry from the production and the asymmetry from the charged particle reconstruction. To correct for them, Belle uses $D^+_s \to \phi \pi^+$ and $D^0 \to K^- \pi^+$ decay modes. The measured asymmetry is $A_{CP}(D^+ \to K^+_S \pi^+) = (-0.71 \pm 0.19 \pm 0.20\%)$ where the major systematic uncertainty is from the statistics of $D^+_s \to \phi \pi^+$ sample (0.18%). On the other hand, BaBar uses inclusive data of on- and off-resonance data for the correction and this enables one to reduce the systematic uncertainty due to the correction down to 0.08%. The corrected asymmetry value from BaBar is $A_{CP}(D^+ \to K^+_S \pi^+) = (-0.44 \pm 0.13 \pm 0.10\%)$. The $CP$ asymmetry from BaBar is shown in Fig. 5 as a function of $|\cos \theta_D|$ indicating a weak deviation from zero. If results from two experiments are combined, one gets $A_{CP}(D^+ \to K^+_S \pi^+) = (-0.51 \pm 0.14\%)$ and this may be the first hint of $CP$ violation in the charm sector. On the other hand, this is consistent with $CP$ violation from neutral kaon mixing $(-0.332 \pm 0.006\%)$ [11].

$A_{CP}(D^0 \to K^0_S P^0)$, where $P^0$ is $\pi^0$ or $\eta(\text{in})$ is measured by the Belle experiment [21]. The decay $D^{*+} \to D^{0} \pi^{*+}$ is used in order to identify the flavor of the $D^0$ meson, and in correct for $A_{\pi^+}^\text{(untagged)}$, $D^0 \to K^- \pi^+$ and $D^{*+} \to D^0 \pi^{*+} \to K^- \pi^+ \pi^{*+}$ (tagged) are used. The results are $A_{CP}(D^0 \to K^0_S \pi^0) = (-0.28 \pm 0.19 \pm 0.10\%)$, $A_{CP}(D^0 \to K^0_S \eta) = (+0.54 \pm 0.51 \pm 0.16\%)$, and $A_{CP}(D^0 \to K^0_S \eta') = (+0.98 \pm 0.67 \pm 0.14\%)$. One can assume $A_{CP}(D^0 \to K^0_S \pi^0) = A_{CP}^{\text{K}^0} + a_{\text{ind}}$ and therefore can extract $a_{\text{ind}}$. They extract $a_{\text{ind}}(D^0 \to K^0_S \pi^0) = (+0.05 \pm 0.19 \pm 0.10\%)$ and this is the first experimental test of the universality of $a_{\text{ind}}$ in $D^0$ decays.

The first observations of DCSD modes $D^+ \to K^+ \eta(\text{in})$ is made by the Belle experiment [22]. When standard criteria are imposed, there is little indication of the signal as shown in Fig. 6. In order to extract such small signals from the backgrounds, extremely tight selection criteria are imposed based on a grid search technique [23]. Based on our grid search, a tight set of selections is imposed to the data and clear signals are first observed as shown in Fig. 7. These, relative branching fractions are extracted to be $B(D^+ \to K^+ \eta)/B(D^+ \to \pi^+ \pi^-) = (3.06 \pm 0.43 \pm 0.14\%)$ and $B(D^+ \to K^+ \eta')/B(D^+ \to \pi^+ \pi^-) = (3.77 \pm 0.39 \pm 0.10\%)$. Using the relations in Ref. [24], which give

$$ |T|^2 = 3|A(K^+ \eta)|^2 $$

$$ |A|^2 = \frac{1}{2} \left[ |A(K^+ \pi^0)|^2 + |A(K^+ \eta')|^2 \right] $$

$$ \cos \delta_{T,A} = \frac{1}{2|T||A|} \left[ 2|A(K^+ \eta)|^2 + \frac{1}{2}|A(K^+ \eta')|^2 \right] - \frac{3}{2} |A(K^+ \pi^0)|^2 $$

(11)

where $T$ $(A)$ is the tree (annihilation) amplitude and $A$ is the specified decay amplitude, and from the
recent branching fraction measurement of $\mathcal{B}(D^+ \rightarrow K^+\pi^0) = (1.72 \pm 0.20) \times 10^{-4}$ [23], they find that the relative final-state phase difference between the tree and annihilation in $D^+$ decays, $\delta_{TA}$, is $(72 \pm 9)\,^\circ$ or $(288 \pm 9)^\circ$. This is the first experimental access to the phase difference between the tree and annihilation amplitudes in these decay modes.

### 3.2. Time Reversal Violation

Under the assumption of $CPT$ invariance, $T$-violation is a signal for $CP$ violation and therefore it can be studied via $T$-violation search. For a multi-particle ($>3$) final state, one can form a kinematic product that is odd under time reversal as

$$C_T = p_1 \cdot (p_2 \times p_3)$$

(12)

where $p_i$ is the momentum vector of a daughter particle $i$. Note that at least four different particles are required in the final state so that three of them are independent. The strong interaction dynamics can produce a non-zero value of the asymmetries:

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}$$

$$\bar{A}_T = \frac{\Gamma(-C_T > 0) - \Gamma(-C_T < 0)}{\Gamma(-C_T > 0) + \Gamma(-C_T < 0)}$$

(13)

where the second equation is the asymmetry for the $CP$-conjugate decay process. However, the difference characterizes $T$-violation in the weak decay process as

$$A_T = \frac{1}{2}(A_T - \bar{A}_T).$$

(14)

This $T$-violation observable is measured by the BaBar experiment in decays of $D^0 \rightarrow K^+K^−\pi^+\pi^−$ and $D^+_s \rightarrow K^+K^0_S\pi^+\pi^−$ [26]. No evidence of $T$-violation is seen and results are $A_T(D^0 \rightarrow K^+K^-\pi^+\pi^-) = (1.0 \pm 5.1 \pm 4.4) \times 10^{-3}$, $A_T(D^+ \rightarrow K^+K^0_S\pi^+\pi^-) = (-12.0 \pm 10.1 \pm 4.6) \times 10^{-3}$, and $A_T(D^+_s \rightarrow K^+K^0_S\pi^+\pi^-) = (-13.6 \pm 7.7 \pm 3.4) \times 10^{-3}$.

### Table I Expected sensitivity with 5 ab$^{-1}$ and with 50 ab$^{-1}$ in future Belle-II experiment.

| Parameters | Present uncertainty | $5 \text{ ab}^{-1}$ | $50 \text{ ab}^{-1}$ |
|------------|---------------------|---------------------|---------------------|
| $y_{CP}$   | $\pm 0.39$          | $\pm 0.12$          | $\pm 0.05$          |
| $A_T$      | $\pm 0.33$          | $\pm 0.10$          | $\pm 0.04$          |
| $x(\%)$    | $\pm 0.31$          | $\pm 0.10$          | $\pm 0.03$          |
| $y(\%)$    | $\pm 0.26$          | $\pm 0.08$          | $\pm 0.03$          |
| $|q/p|$     | $\pm 0.30$          | $\pm 0.10$          | $\pm 0.03$          |
| $\phi(\text{rad})$ | $\pm 0.30$          | $\pm 0.10$          | $\pm 0.03$          |

### 4. Summary and Outlook

We reviewed present status of $D^0$ mixing/$CPV$ and $D$ decays. The mixing, the oscillation of $D^0$ meson flavor, has been firmly established [5], but not from a single experiment yet. The search for $CP$ violation in $D$ meson decays are carried out and show no $CP$ violation effect down to $O(10^{-3})$. There may be a hint of $CP$ violation in $D^+ \rightarrow K^0_S\pi^+\pi^−$ decay mode but it is consistent with $CP$ violation from the kaon mixing.

However, we are entering a new era of flavor physics, in particular for the charmed meson physics. The remaining yet to be analyzed data from present $B$-factories will produce even higher-sensitive results in near future. The LHCb is starting to demonstrate great ability to reconstruct charmed mesons with extremely low background [18]. Also, planned super $B$-factories are expected to reach highest amount of data sample ever achieved, to 50 ab$^{-1}$ [27]. Table I lists expected sensitivity for various mixing and $CP$ violation parameters for the Belle-II experiment, expecting to explore physics beyond SM, mostly through quantum loops in the reaction.

### Acknowledgments

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group and the NI for valuable computing and SINET4 network support. We acknowledge support from MEXT, JSPS and Nagoya’s TLPRC (Japan); ARC and DIISR (Australia); NSFC (China); MSMT (Czechia); DST (India); MEST, NRF, NSDC of KISTI, and WCU (Korea); MNiSW (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA). E. Won acknowledges support by NRF Grant No. 2011-0027652 and B. R. Ko acknowledges support by NRF Grant No. 2011-0025750.
References

[1] K. Lande et al., Phys. Rev. D **103**, 1901 (1956).
[2] I. I. Bigi and A. I. Sanda, *CP Violation*, Cambridge University Press, 2009.
[3] A. Abashian et al. (Belle Collaboration), Phys. Rev. Lett. **86**, 2509 (2001); B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. **86**, 2515 (2001); A. Abulencia et al. (CDF Collaboration), Phys. Rev. Lett. **97**, 242003 (2006).
[4] K. Nakamura et al. (Particle Data Group), J. Phys. G **37**, 075021 (2010).
[5] Heavy flavor averaging group, [http://www.slac.stanford.edu/xorg/hfag/](http://www.slac.stanford.edu/xorg/hfag/).
[6] A. F. Falk et al., Phys. Rev. D **65**, 054034 (2002); A. F. Falk et al., Phys. Rev. D **69**, 114021 (2002).
[7] Y. Grossman et al., Phys. Rev. D **75**, 036008 (2007); F. Buccella et al., Phys. Rev. D **51**, 3478 (1995).
[8] G. Wilkinson, XXVIII PHYSICS IN COLLISION - Perugia, Italy, June, 25-28, 2008.
[9] U. Bitenc et al. (Belle Collaboration), Phys. Rev. D **77**, 112003 (2008).
[10] B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. **98**, 211802 (2007).
[11] J. L. Rosner et al. (CLEO-c Collaboration), Phys. Rev. Lett. **100**, 211801 (2008).
[12] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D **80**, 071103 (2009).
[13] M. Starić et al. (Belle Collaboration), Phys. Rev. Lett. **98**, 211803 (2007).
[14] B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. **105**, 081803 (2010).
[15] L. M. Zhang et al. (Belle Collaboration), Phys. Rev. Lett. **99**, 131803 (2007).
[16] P. Koppenburg, *Heavy Flavour Results at the LHC*, in this proceeding.
[17] E. Golowich et al., Phys. Rev. D **76**, 095009 (2007).
[18] The CDF Collaboration, CDF Note 10296 (2011).
[19] B. R. Ko et al. (Belle Collaboration), Phys. Rev. Lett. **104**, 181602 (2010).
[20] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D **83**, 071103 (2011).
[21] B. R. Ko et al. (Belle Collaboration), Phys. Rev. Lett. **106**, 211801 (2011).
[22] E. Won et al. (Belle Collaboration), Phys. Rev. Lett. **107**, 221801 (2011).
[23] E. Won, Ph. D. thesis, University of Rochester, 2000; H. Prosper et al., in Proceedings of the 1995 Computing in High Energy Physics Conference, Rio de Janeiro, 1995 (World Scientific Publishing Co., River Edge, 1995).
[24] C.-W. Chiang, and J. L. Rosner, Phys. Rev. D **65**, 054007 (2002).
[25] H. Mendez et al. (CLEO Collaboration), Phys. Rev. D **81**, 052013 (2010).
[26] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D **81**, 111103 (2010); B. Aubert et al. (BaBar Collaboration), Phys. Rev. D **84**, 031103 (2011).
[27] T. Aushev et al., [arXiv:1002.5012](http://arxiv.org/abs/1002.5012) (2010).