D^0 Mixing

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An overview of selected experimental results in the field of D^0-$\bar{D}^0$ oscillations is presented. The average results for the mixing parameters, $x = (0.89 \pm {}^{0.26}_{0.27})\%$ and $y = (0.75 \pm {}^{0.17}_{0.18})\%$, exclude the no-mixing hypothesis at the level of 6.7 standard deviations. No sign of CP violation in the D^0 system is observed. The measurements impose constraints on the parameter space of many New Physics models.

I. INTRODUCTION

Last year, 31 years after the discovery of D^0 mesons, the first evidence of a mixing phenomena in the system of neutral charm mesons has been obtained [1, 2]. Following this breakthrough were several additional measurements enabling - through an averaging procedure - a quite precise determination of the parameters governing the mixing. The results presented in the paper follow from the data collected by the two B-factories experiments, Belle and BaBar, from the charm-factory experiment Cleo-c, as well as from the proton collider experiment CDF. At the B-factories the cross-section for the continuum production of $c\bar{c}$ pairs is around 1.3 nb, which with the integrated luminosity of KEKB amounts to 10^9 produced charmed hadron pairs. At CESR, the ~800 pb^{-1} data sample corresponds to 2.8×10^6 $D^0\bar{D}^0$ pairs produced in a coherent $C = -1$ state. And while at the Tevatron the experimental environment for the presented measurements is more difficult, the cross-section for neutral charm meson production with a transverse momentum larger than 5.5 GeV/c yields a starting data sample of 50×10^9 D^0's. The experiments thus provide a really diverse experimental environment for successful studies in charmed hadron physics.

The mixing, that is the transition of a neutral D^0 meson into its antiparticle and vice-versa, appears as a consequence of states of definite flavour (D^0, $\bar{D}^0$) being a linear superposition of the mass eigenstates (states of simple exponential time evolution, $D_{1,2}$):

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \quad . \qquad (1)$$

It is governed by the lifetime of D mesons, $\tau = 1/\Gamma$, and by the mixing parameters $x = (m_1 - m_2)/\Gamma$ and $y = (\Gamma_1 - \Gamma_2)/2\Gamma$. $m_{1,2}$ and $\Gamma_{1,2}$ denote the masses and widths of the mass eigenstates D_1 and D_2, respectively. $\Gamma = (\Gamma_1 + \Gamma_2)/2$ is the average decay width. The mixing rate is small. The contribution of loop diagrams, successfully describing the oscillations in other neutral meson systems, is suppressed since the D^0 system is the only neutral meson system with down-like quarks exchanged in the loop. In this short distance calculation x is negligibly small due to the small SU(3) flavor symmetry breaking ($m_s^2 \approx m_{u,d}^2$) and elements of Cabibbo-Kobayashi-Maskawa (CKM) matrix ($|V_{ub}| \approx 4 \times 10^-3$) [3]. Long distance contributions to the D^0-$\bar{D}^0$ transition are difficult to calculate. Current theoretical estimates predict the mixing parameters $|x|, |y| \leq 10^{-2}$ [4, 5].

Violation of the CP asymmetry (CPV) in the charm sector is expected to be small. Since the processes with D^0 mesons involve mainly the first two generations of quarks, for which the CKM elements are almost real, the expected level of CPV is $\mathcal{O}(10^{-3})$ which is below the current experimental sensitivity.

II. MEASUREMENTS

Several methods and selection criteria are common to the presented measurements. Tagging of the flavour of an initially produced D^0 meson is achieved by reconstruction of decays $D^{*+} \to D^0\pi_s^+$ or $D^{*-} \to \overline{D}^0\pi_s^-$. The charge of the characteristic low momentum pion π_s determines the tag. The energy released in the D^* decay,

$$q = M(D^*) - M(D^0) - m_\pi \quad , \qquad (2)$$

has a narrow peak for the signal events and thus helps in rejecting the combinatorial background. Here, $M(X)$ is used to denote the invariant mass of the X decay products, and m_X stands for the nominal mass of X. D^0 mesons produced in B decays have different decay time distribution and kinematic properties than the mesons produced in fragmentation. In order to obtain a sample of neutral mesons with uniform properties one selects D^* mesons with momentum above the kinematic limit for B meson decays (B-factories) or uses impact parameter distribution to isolate primary charm mesons (CDF).

A. Decays to CP eigenstates

In the limit of negligible CPV the mass eigenstates $D_{1,2}$ are also CP eigenstates. In decays $D^0 \to f_{CP}$ only the mass eigenstate component of D^0 with the CP eigenvalue equal to the one of f_{CP} contributes. By measuring the lifetime of D^0 in decays to f_{CP} one thus determines the corresponding $1/\Gamma_1$ or $1/\Gamma_2$. On the other hand, flavour specific final states like $K^-\pi^+$

have a mixed CP symmetry. The measured value of the effective lifetime in these decays corresponds to a mixture of $1/\Gamma_1$ and $1/\Gamma_2$. The relation between the two lifetimes can be written as [6]

$$\tau(f_{CP}) = \frac{\tau(D^0)}{1+\eta_f y_{CP}} \quad , \tag{3}$$

where $\tau(f_{CP})$ and $\tau(D^0)$ are the lifetimes measured in $D^0 \to f_{CP}$ and $D^0 \to K^-\pi^+$, respectively. $\eta_f = \pm 1$ denotes the CP eigenvalue of f_{CP}. The relative difference of the lifetimes is described by the parameter y_{CP}.

CP-even final states $f_{CP} = K^+K^-, \pi^+\pi^-$ were used to measure y_{CP} [1]. Expressed in terms of the mixing parameters, y_{CP} reads [6]

$$y_{CP} = y\cos\phi - \frac{1}{2}A_M \sin\phi \quad , \tag{4}$$

with A_M and ϕ describing the CPV in mixing and interference between mixing and decays, respectively. In case of no CPV $(A_M, \phi = 0)$ and $y_{CP} = y$.

Simultaneous fits to decay time distributions of selected $D^0 \to K^+K^-, K^-\pi^+$ and $\pi^+\pi^-$ candidates were performed with y_{CP} as a common free parameter. The fit is presented in Fig. 1(a)-(c). The agreement of the fit function with the data is excellent, $\chi^2/n.d.f = 312/289$. The final value obtained is

$$y_{CP} = (1.31 \pm 0.32 \pm 0.25)\% \quad . \tag{5}$$

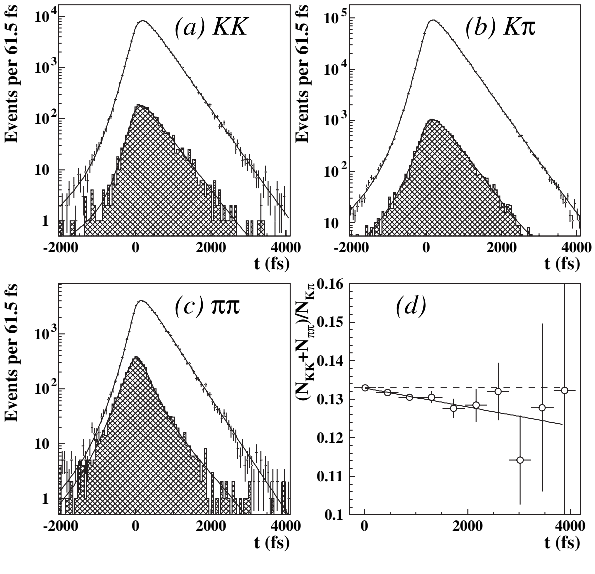

FIG. 1: (a)-(c): Result of the simultaneous fit to decay time distributions in D^0 decays to KK, $K\pi$ and $\pi\pi$ final states. The hatched areas represent the contribution of backgrounds. (d): Ratio of $D^0 \to f_{CP}$ and $D^0 \to K^-\pi^+$ decay time distributions. The slope visualizes the difference of effective lifetimes.

The largest systematic uncertainties arise from the assumed resolution function (common offset in individual decay modes), possible deviations of acceptance dependence on decay time from a constant (estimated by a fit to the generated t distribution of reconstructed MC events) and variation of selection criteria (effect estimated using high statistics MC samples).

The resulting y_{CP} is more than 3 standard deviations above zero and hence represents a clear evidence of $D^0 - \overline{D}^0$ mixing, regardless of possible CPV. The difference of lifetimes is made visually observable by ploting the ratio of decay time distributions for decays to f_{CP} and $K^-\pi^+$ in Fig. 1(d).

Recently the BaBar collaboration performed a similar measurement [7], with results for individual lifetimes shown in Fig. 2. The obtained value of the mixing parameter is

$$y_{CP} = (1.24 \pm 0.39 \pm 0.13)\% \quad . \tag{6}$$

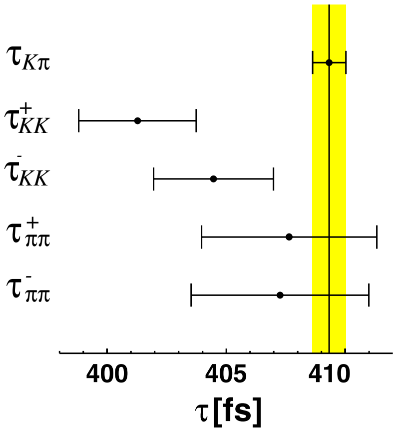

FIG. 2: Lifetimes of D^0 mesons measured in decays to $K\pi$, KK and $\pi\pi$ (separately for D^0 and $\bar{D}^0$ for the latter two modes) [7]. The average value of the lifetime as measured in decays to CP eigenstates is lower than the one measured in flavour specific final state.

The two measurements make y_{CP} the most precisely measured individual mixing parameter in the D^0 system.

Final states of definite CP allow also a search for possible CPV. Two methods, decay time dependent and time integrated, have been exploited. For the former, the lifetime in $D^0 \to f_{CP}$ is measured separately for D^0 and $\bar{D}^0$ tagged events. The asymmetry is [6]

$$\begin{aligned} A_\Gamma &= \frac{\tau(\overline{D}^0 \to f_{CP}) - \tau(D^0 \to f_{CP})}{\tau(\overline{D}^0 \to f_{CP}) + \tau(D^0 \to f_{CP})} = \\ &= \frac{1}{2}A_M y\cos\phi - x\sin\phi \quad . \end{aligned} \tag{7}$$

The values of A_Γ measured by Belle and BaBar are

$$A_\Gamma = (0.01 \pm 0.30 \pm 0.15)\% \ \ [1]$$

$$A_\Gamma \;=\; (0.26 \pm 0.36 \pm 0.08)\% \;\; [7] \;, \qquad (8)$$

and show no sign of CPV at the level of around 0.3%.

With the time integrated method one measures the asymmetry

$$A_{CP} \;=\; \frac{\Gamma(D^0 \to f_{CP}) - \Gamma(\bar{D}^0 \to f_{CP})}{\Gamma(D^0 \to f_{CP}) + \Gamma(\bar{D}^0 \to f_{CP})} = \\ = a^f_{dec} + a_{mix} + a_{int} \;\; . \qquad (9)$$

A_{CP} receives contribution from all three types of CPV, direct, CPV in mixing and in the interference between decays with and without the mixing. The latter two are independent of the final state. Experimentaly the measured asymmetry must be corrected for possible charge asymmetries in detection of the slow pion as well as the forward-backward asymmetry (A_{FB}) in the production of fermion pairs in e^+e^- collisions. The method of determination of π_s correction factors was developed in [8] using the untagged $D^0 \to K^-\pi^+$ decays. The forward-backward asymmetry is separated on the basis of its symmetry properties as a function of the D meson polar angle in the center-of-mass system. Figure 3 shows the measured A_{CP} ((a),(b)) and A_{FB} ((c),(d)) as a function of the D meson polar angle [8]. Averaging over the polar angle yields the value

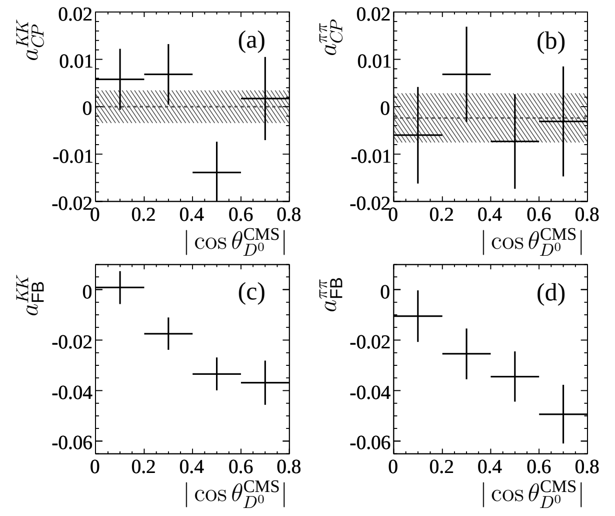

FIG. 3: Time integrated CP asymmetry ((a),(b)) and forward-backward asymmetry ((c),(d)) as a function of the D meson polar angle [8].

$$A^{KK}_{CP} = (0.00 \pm 0.34 \pm 0.13)\% \quad . \qquad (10)$$

Measurement of the Belle collaboration [9]

$$A^{KK}_{CP} = (-0.43 \pm 0.30 \pm 0.11)\% \quad . \qquad (11)$$

is also consistent with no CPV.

B. Wrong-sign decays to hadronic final states

Decays of D mesons to two-body hadronic final states accessible to both, D^0 and $\bar{D}^0$, have traditionally been used to search for the mixing. Final state $K^+\pi^-$ can be reached through a doubly Cabibbo supressed (DCS) D^0 decays as well as through the $D^0 \to \bar{D}^0$ mixing followed by a Cabibbo favoured (CF) decay. The time evolution for these decays has three terms:

$$|\langle K^+\pi^-|D^0(t)\rangle|^2 \propto \big[R_D + \sqrt{R_D}y't + \frac{x'^2 + y'^2}{4}t^2\big]e^{-t} \;\; . \qquad (12)$$

The first one is due to DCS decays, the third one due to the mixing, and the middle term represents the interference of the two contributions. R_D is the Cabibbo suppression factor relative to CF decays. x' and y' are the mixing parameters, rotated by a strong phase difference between DCS and CF decays, $x' = x\cos\delta + y\sin\delta$ and $y' = y\cos\delta - x\sin\delta$. The dimensionless time t is measured in units of $\tau(D^0)$.

BaBar collaboration obtained the first evidence for D^0 mixing by performing the decay time study of wrong-charge decays $D^{*+} \to D^0\pi^+_s$, $D^0 \to K^+\pi^-$ to separate the DCS and the mixing contribution. The parameters obtained from the fit are presented in terms of likelihood contours in Fig. 4 (top). The central value lies slightly in the non-physical region ($x'^2 < 0$) and the no-mixing point ($x'^2 = 0, y' = 0$) is excluded at the level corresponding to 3.9 standard deviations. Recently CDF collaboration obtained the result of similar significance [10] shown in Fig. 4 (bottom left). Result form the Belle collaboration [11] takes into account the presence of a physical boundary and is presented in Fig. 4 (bottom right) as a 95% C.L. contour calculated using the Feldman-Cousins method.

C. Time dependent Dalitz analyses

Several intermediate resonances can contribute to a hadronic multi-body final state. In a specific decay channel $D^0 \to K_S\pi^+\pi^-$, recently analyzed by Belle [12], contributions from CF decays (e.g. $D^0 \to K^{*-}\pi^+$), DCS decays (e.g. $D^0 \to K^{*+}\pi^-$) and decays to CP eigenstates (e.g. $D^0 \to \rho^0 K_S$) are present. Individual contributions can be identified by analyzing the Dalitz distribution of the decay. Moreover, for a self-conjugated final state these different types of decays interfere and it is possible to determine their relative phases (unlike in the case of $D^0 \to K^+\pi^-$ decays). Since these types of intermediate states also exhibit a specific time evolution one can determine directly the mixing parameters x and y by studying the time evolution of the Dalitz distribution.

The signal p.d.f. for a simultaneous fit to the Dalitz

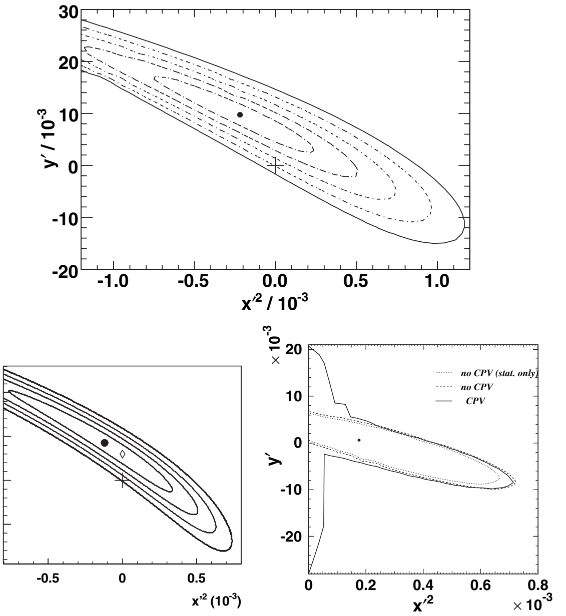

FIG. 4: Top: 1 - 5 σ likelihood contours for parameters x'^2 and y' obtained from a fit to the decay time distribution of $D^0 \to K^+\pi^-$ decays [2]. Bottom left: Bayesian probability contours in x'^2, y' plane corresponding to 1 - 4 σ as obtained in [10]. Bottom right: 95% C.L. contours of x'^2, y' using Feldman-Cousins approach from [11].

and decay-time distribution is

$$\begin{aligned}
&\mathcal{M}(m_-^2, m_+^2, t) = \langle K_S\pi^+\pi^-|D^0(t)\rangle = \\
&= \frac{1}{2}\mathcal{A}(m_-^2, m_+^2)\big[e^{-i\lambda_1 t} + e^{-i\lambda_2 t}\big] + \\
&+ \frac{1}{2}\overline{\mathcal{A}}(m_-^2, m_+^2)\big[e^{-i\lambda_1 t} - e^{-i\lambda_2 t}\big] \quad . \qquad (13)
\end{aligned}$$

The matrix element is composed of an instantaneous amplitude for D^0 decay, $\mathcal{A}(m_-^2, m_+^2)$, and an amplitude for the $\bar{D}^0$ decay, $\bar{\mathcal{A}}(m_-^2, m_+^2)$, arising due to a possibility of mixing. They both depend on the Dalitz variables $m_-^2 = M^2(K_S\pi^-)$ and $m_+^2 = M^2(K_S\pi^+)$. The dependence on the mixing parameters is hidden in $\lambda_{1,2} = m_{1,2} - i\Gamma_{1,2}/2$. If CPV is neglected the amplitude for $\bar{D}^0$ tagged decays is $\bar{\mathcal{M}}(m_+^2, m_-^2, t) = \mathcal{M}(m_-^2, m_+^2, t)$. Amplitudes for D decays are parametrized in the isobar model as a sum of 18 Breit-Wigner resonances and a constant nonresonant term. The result of the fit in terms of mixing parameters is presented in Fig. 5.

Numerically, the fit which allows for the CPV results in

$$\begin{aligned}
x &= (0.80 \pm 0.29 \pm \genfrac{}{}{0pt}{}{0.13}{0.16})\% \\
y &= (0.33 \pm 0.24 \pm \genfrac{}{}{0pt}{}{0.10}{0.14})\% \\
|q/p| &= 0.86 \pm \genfrac{}{}{0pt}{}{0.30}{0.29} \pm \genfrac{}{}{0pt}{}{0.10}{0.09})\%
\end{aligned}$$

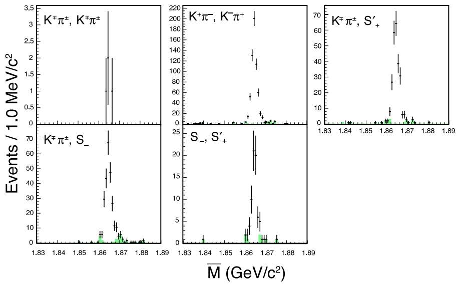

FIG. 5: 95% C.L. region for parameters x and y as obtained in $D^0 \to K_S\pi^+\pi^-$ decays [12].

$$\phi = (-0.24 \pm \genfrac{}{}{0pt}{}{0.28}{0.30} \pm 0.09) \text{ rad} \quad . \qquad (14)$$

The measurement represents the most accurate determination of x. The CP violating parameters $|q/p|$ and $\phi = arg(q/p)$ are consistent with no CP violation.

BaBar has performed the time dependent Dalitz analysis of $D^0 \to K^+\pi^-\pi^0$ decays [13]. The final state is flavour specific and hence the wrong-sign decays again receive contribution from mixing and DCS process. The combined Dalitz-decay-time signal distribution has the form

$$\begin{aligned}
&|\langle K^+\pi^+\pi^-|D^0(t)\rangle|^2 \propto \big[|A_{\bar{f}}|^2 + \\
&+ |\bar{A}_{\bar{f}}||A_{\bar{f}}|(y''\cos\delta_f - x''\sin\delta_f)t + \\
&+ |\bar{A}_{\bar{f}}|^2\frac{x''^2 + y''^2}{4}t^2\big]e^{-t} \quad . \qquad (15)
\end{aligned}$$

$A_{\bar{f}}$ (depending on the Dalitz variables $M^2(K^+\pi^-)$ and $M^2(K^+\pi^0)$) is the amplitude for $D^0 \to K^+\pi^-\pi^0$ decays determined from the fit to the Dalitz distribution of wrong-sign decays. The amplitude for $\bar{D}^0$ decays, $\bar{A}_{\bar{f}}$, is fixed to the values obtained in the fit to the time integrated Dalitz distribution of right-sign $D^0 \to K^-\pi^+\pi^0$ decays. Relative phase δ_f also depends on $M^2(K^+\pi^-)$, $M^2(K^+\pi^0)$, and is determined from the fit to the wrong- and right-sign Dalitz distributions. Parameters x'' and y'' are, similar as in the case of $D^0 \to K^+\pi^-$ decays, a rotated mixing parameters x and y, now by an unknown strong phase shift $\delta_{K\pi\pi^0}$ between two points in phase spaces of DCS and CF decays to $K^-\pi^+\pi^0$.

A fit to the time evolution of the wrong-sign Dalitz distribution results in

$$\begin{aligned}
x'' &= (2.61 \pm \genfrac{}{}{0pt}{}{0.57}{0.67} \pm 0.39)\% \\
y'' &= (-0.06 \pm \genfrac{}{}{0pt}{}{0.55}{0.64} \pm 0.34)\% \quad . \qquad (16)
\end{aligned}$$

D. $\psi(3770) \to D^0\bar{D}^0$

Pairs of neutral D mesons are produced at the threshold in a coherent $C = -1$ state. With the Cleo-c