SEARCH FOR $D^0 - \overline{D}^0$ MIXING AT BELLE AND BABAR

M. STARIČ
J. Stefan Institute, Ljubljana, Slovenia
(for the BELLE Collaboration)

We discuss recent measurements of the Belle and BaBar collaborations performed to search for mixing in the neutral D-meson system. The data were obtained in e^+e^- collisions at or near the $\Upsilon(4S)$ resonance. The analyses cover semileptonic decays, wrong-sign hadronic decays, self-conjugate decays and decays to CP eigenstates. In the latter case the Belle collaboration has found the first experimental evidence for the D-mixing.

1 Introduction

The phenomenon of mixing between a particle and its anti-particle has been observed in several systems of neutral mesons [1,2]: neutral kaons, B_d^0, and most recently B_s^0 mesons. This process is also possible in the D-meson system, but has not previously been observed.

The time evolution of a D^0 or $\overline{D}^0$ is governed by the mixing parameters $x = (M_1 - M_2)/\Gamma$ and $y = (\Gamma_1 - \Gamma_2)/2\Gamma$, where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths, respectively, of the mass eigenstates, and $\Gamma = (\Gamma_1 + \Gamma_2)/2$. For no mixing, $x = y = 0$. Within the Standard Model (SM) the rate of D-mixing is expected to be small due to the near degeneracy of the s and d quark masses relative to the W mass, and the small value of the b quark couplings. Predictions for x and y are dominated by non-perturbative processes that are difficult to calculate [3,4]. The largest predictions are $|x|,\ |y| \sim \mathcal{O}(10^{-2})$ [4]. Loop diagrams including new, as-yet-unobserved particles could significantly affect the experimental values [5]. CP-violating effects in D-mixing would be a clear signal of new physics, as CP violation (CPV) is expected to be very small in the SM [6].

Both semileptonic and hadronic D^0 decays have been used to constrain x and y [1]. In order to tag the flavour at the production the D^0 meson is usually reconstructed in the decay[a] $D^{*+} \to D^0\pi_s^+$, where the charge of a characteristic slow pion π_s tags the initial D^0 flavour. Usually also the D^0 proper decay time is measured, since the decay time distribution of mixed

[a] Charge conjugate modes are implied unless explicitly stated otherwise.

events depends on the mixing parameters x and y and differs from that of un-mixed events. The proper decay time of an event is determined from the distance between the production and the decay vertex. The decay vertex is obtained from D^0 daughter tracks, refitted to originate from a common point. The production vertex is found by constraining the D^0 momentum vector to originate from the e^+e^- interaction region. The proper decay time resolution is typically equal to a half of the D^0 lifetime.

The measurements are performed at $\Upsilon(4S)$ resonance. To reject D^{*+} mesons coming from the decays of B mesons a cut on the D^{*+} or D^0 momentum in the e^+e^- center-of-mass frame (CM) is applied at about 2.5 GeV/c. This cut also suppresses the combinatorial background.

2 Semileptonic decays

In semileptonic decays the wrong-sign (WS) process $D^{*+} \to K^+\ell^-\nu\pi_s^+$ can proceed only through D^0 mixing followed by the right-sign (RS) decay: $D^0 \to \overline{D}^0 \to K^+\ell^-\nu$. The mixing rate $R_M = \frac{1}{2}(x^2+y^2)$ can be measured in the time-integrated way. By counting WS and RS events (N_{WS}, N_{RS}) and by applying small efficiency corrections ($\epsilon_{WS}, \epsilon_{RS}$) one can determine the mixing rate with

$$R_M = \frac{N_{WS}}{N_{RS}}\frac{\epsilon_{RS}}{\epsilon_{WS}} \tag{1}$$

The Belle collaboration published their measurement in semileptonic decays with an electron in the final state [7] using 253 fb^{-1} of data. They reconstructed 229×10^3 RS signal events with a purity of 73%. In the WS spectra they found no evidence for a signal. They reported an upper limit for the mixing rate of $R_M < 1.2 \times 10^{-3}$ @ 95% $C.L.$

The new measurement by BaBar collaboration performed on 344 fb^{-1} of data uses a double flavor tagging method for background suppression [8]. With this method the initial flavor is tagged twice: once using the slow pion and once using the flavor of a fully reconstructed D meson in the hemisphere opposite to the semileptonic candidate. Both tags are required to be consistent. After applying their final selection criteria, they found 4780 RS signal events and 3 WS candidates. The expected WS background was 2.85 events. The upper limit for the mixing rate obtained from these numbers is $R_M < 1.2 \times 10^{-3}$ @ 90% $C.L.$

3 Wrong-sign decay $D^0 \to K^+\pi^-$

The WS final state $K^+\pi^-$ can be accessed either directly via doubly Cabibbo-suppressed (DCS) decay or through mixing followed by the Cabibbo-favored (CF) decay $D^0 \to \overline{D}^0 \to K^+\pi^-$. The two decays can be distinguished by the decay-time distribution. For $|x|, |y| \ll 1$, and assuming negligible CP violation, the decay-time distribution for the WS process can be expressed as

$$\frac{dN}{dt} \propto [R_D + y'\sqrt{R_D}(\Gamma t) + \frac{x'^2 + y'^2}{4}(\Gamma t)^2]e^{-\Gamma t} \tag{2}$$

where R_D is the ratio of DCS to CF decay rates, $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$, and δ is the strong phase difference between DCS and CF amplitudes. The first (last) term is due to the DCS (CF) amplitude, and the middle term is due to interference between the two processes.

The Belle collaboration reported the results of a search for D-mixing in this decay mode [9] based on 400 fb^{-1}. They found 1.07×10^6 RS and 4024 WS signal events with a ratio of WS signal to background of 1.1. The RS events were used to establish the resolution function parameters and the D^0 lifetime, which they found to be consistent with the world average. The unbinned maximum likelihood fit of the WS data assuming CP conservation resulted in $R_D = (0.364 \pm 0.017)\%$, while the mixing parameters $x'^2 = (0.18^{+0.21}_{-0.23}) \times 10^{-3}$ and $y' = (0.6^{+4.0}_{-3.9}) \times 10^{-3}$ are consistent with zero. They fitted also with the assumption of CP violation; again the mixing

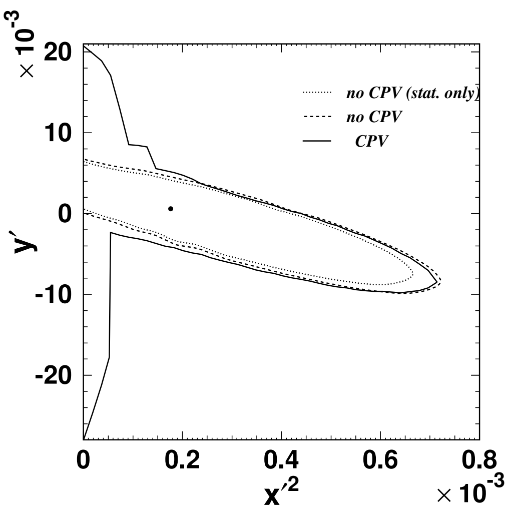

Figure 1: Belle measurement of 95% C.L. regions for (x'^2, y'). The point is the best fit result assuming CP conservation. The dashed line is the contour assuming CP conservation and the solid line is the contour assuming CP violation.

parameters and the CP asymmetries in mixing and in decay are consistent with zero. The upper limit for the mixing rate is $R_M < 0.40 \times 10^{-3}$ @ 95% $C.L.$

Fig. 1 shows the 95% C.L. contours. In the case of CP conservation, the no-mixing point $x'^2 = y' = 0$ lies just outside the 95% C.L. contour; this point corresponds to a C.L. of 3.9%. The BaBar collaboration reported just after this presentation a positive D-mixing result in this decay mode and on a similar-size data set [10]; the no-mixing point in their measurement corresponds to a C.L. of 1×10^{-4}.

4 Wrong-sign decays $D^0 \to K^+\pi^-\pi^0$ and $D^0 \to K^+\pi^-\pi^+\pi^-$

As in the $K^+\pi^-$ final state, the WS decays $D^0 \to K^+\pi^-\pi^0$ and $D^0 \to K^+\pi^-\pi^+\pi^-$ can proceed either through DCS decay or through mixing followed by CF decay. For a nonleptonic multibody WS decay, the decay-time distribution is approximated by [11]

$$\frac{dN}{dt} \propto [\widetilde{R}_D + \alpha \widetilde{y}' \sqrt{\widetilde{R}_D}(\Gamma t) + \frac{\widetilde{x}'^2 + \widetilde{y}'^2}{4}(\Gamma t)^2]e^{-\Gamma t} \;, \qquad 0 \le \alpha \le 1, \tag{3}$$

similar to Eq. 2. The tilde indicates that the corresponding quantities from Eq. 2 have been integrated over a certain region of phase-space. The parameter α is a suppression factor that accounts for strong-phase variation over the phase-space. The time-integrated mixing rate is $R_M = \frac{1}{2}(x^2 + y^2) = \frac{1}{2}(\widetilde{x}'^2 + \widetilde{y}'^2)$ and is independent of the position in the Dalitz plot.

The BaBar collaboration analyzed 230 fb^{-1} of data to search for D-mixing in both decay modes. In the $K\pi\pi^0$ analysis [12] they reduced the ratio of DCS to CF decays by excluding events with two-body invariant masses in the range of the K^{*+} and K^{*0} resonances. Their final selection included 503×10^3 RS and 763 WS signal events. Assuming CP conservation they found that the data were consistent with the no-mixing hypothesis at the 4.5% confidence level, and they set an upper limit $R_M < 0.54 \times 10^{-3}$ @ 95% $C.L.$

In the $K\pi\pi\pi$ analysis [13] no phase-space selection was made. The signal yields were 700×10^3 events for the RS and 2202 events for the WS final states. Assuming CP conservation, the data were consistent with no mixing at the 4.3% confidence level. The upper limit was set to $R_M < 0.48 \times 10^{-3}$ @ 95% $C.L.$ By combining the results of both analyses they determined the upper limit $R_M < 0.42 \times 10^{-3}$ @ 95% $C.L.$ for the time-integrated mixing rate. The no-mixing hypothesis was found to be at the 2.1% C.L.

5 Time-dependent Dalitz analysis of $D^0 \to K_s^0\pi^+\pi^-$

A new measurement in the self-conjugate decays $D^0 \to K_s^0\pi^+\pi^-$ based on 540 fb^{-1} was performed by the Belle collaboration using a time-dependent Dalitz plot analysis [14]. The time dependence of the $K_s^0\pi^+\pi^-$ Dalitz plot distribution allows one to measure x and y directly. This method was developed by CLEO [15] using 9.0 fb^{-1}.

Assuming CP conservation, the decay amplitude at time t of an initially produced D^0 or $\overline{D}^0$ can be expressed as

$$\mathcal{M}(m_-^2, m_+^2, t) = \mathcal{A}(m_-^2, m_+^2)\frac{e_1(t) + e_2(t)}{2} + \mathcal{A}(m_+^2, m_-^2)\frac{e_1(t) - e_2(t)}{2} \tag{4}$$

where $\mathcal{A}$ is the decay amplitude as a function of the invariant masses squared $m_\pm^2$, defined with the D^* tag

$$m_\pm^2 = \begin{cases} m(K_s, \pi^\pm)^2 & D^{*+} \to D^0\pi^+ \\ m(K_s, \pi^\mp)^2 & D^{*-} \to \overline{D}^0\pi^- \end{cases} \tag{5}$$

The time dependence is contained in the terms $e_{1,2}(t) = exp[-i(m_{1,2} - i\Gamma_{1,2}/2)t]$. Upon squaring $\mathcal{M}$, one obtains decay rates containing terms $exp(-\Gamma t)\cos(x\Gamma t)$, $exp(-\Gamma t)\sin(x\Gamma t)$ and $exp[-(1 \pm y)\Gamma t]$.

The overall decay amplitude $\mathcal{A}$ can be expressed as a sum of quasi-two-body amplitudes $\mathcal{A}_r$ and a constant non-resonant term (subscript NR):

$$\mathcal{A}(m_-^2, m_+^2) = \sum_r a_r e^{i\phi_r}\mathcal{A}_r(m_-^2, m_+^2) + a_{NR}e^{i\phi_{NR}} \tag{6}$$

The functions $\mathcal{A}_r$ are products of Blatt-Weiskopf form factors and relativistic Breit-Wigner functions [16].

The D^0 candidates were reconstructed in the decay chain $D^{*+} \to D^0\pi_s^+$, $D^0 \to K_s^0\pi^+\pi^-$ and the charge of π_s was used to tag the D^0 flavor at production. The K_s^0 was reconstructed in the decay to the $\pi^+\pi^-$ final state; an invariant mass within ± 10 MeV of $m_{K_s^0}$ and a common vertex separated from the interaction region were required. The D^0 decay point was constructed from charged pion tracks only and the production point was obtained from the intersection of the D^0 momentum vector with the e^+e^- interaction region.

The signal and background yields were determined from a two-dimensional fit to the variables $M \equiv m_{K_s^0\pi\pi}$ and $Q \equiv m_{K_s^0\pi\pi\pi_s} - m_{K_s^0\pi\pi} - m_\pi$. The background was classified into two types: random π_s background and combinatorial background. In the signal region, defined as 3σ intervals in M and Q, they found 534×10^3 signal events and background fractions of 1% and 4% for the random π_s and combinatorial backgrounds, respectively.

For the events in the signal region they performed a simultaneous unbinned likelihood fit to the Dalitz plot variables m_-^2 and m_+^2, and the decay time t. The likelihood function is:

$$\mathcal{L} = \sum_{i=1}^{N}\sum_j f_j(M_i, Q_i)\mathcal{P}_j(m_{-,i}^2, m_{+,i}^2, t_i) \tag{7}$$

where $j = \{sig, rnd, cmb\}$ denotes the signal or background components, and the index i runs over all events. The event weights f_j are functions of M and Q and were obtained from the $M - Q$ fit mentioned above.

The probability density function (PDF) $\mathcal{P}_{sig}$ equals $|\mathcal{M}|^2$ convolved with the detector response. The resolution in the decay time t is parameterized by a sum of three Gaussians with a common mean and widths $\sigma_k = S_k \cdot \sigma_t$, $(k = 1, 2, 3)$, where σ_t is the decay time uncertainty calculated event-by-event, and the S_k are scale factors, left as free parameters in the fit.

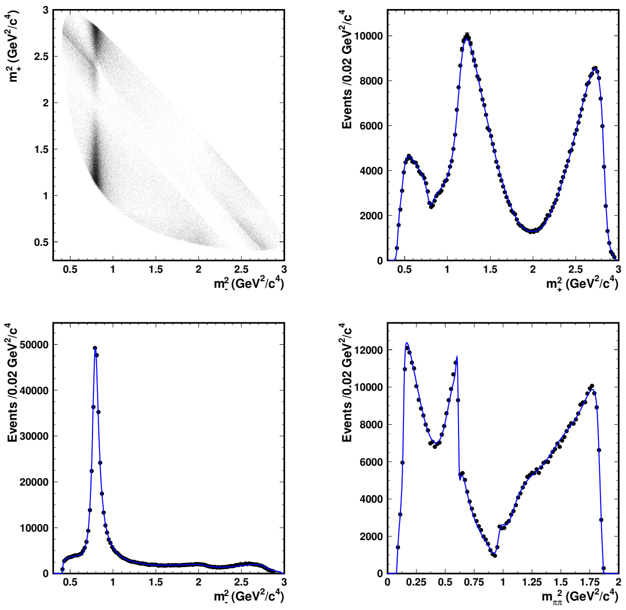

Figure 2: Dalitz plot distribution and its projections with fitted curves superimposed.

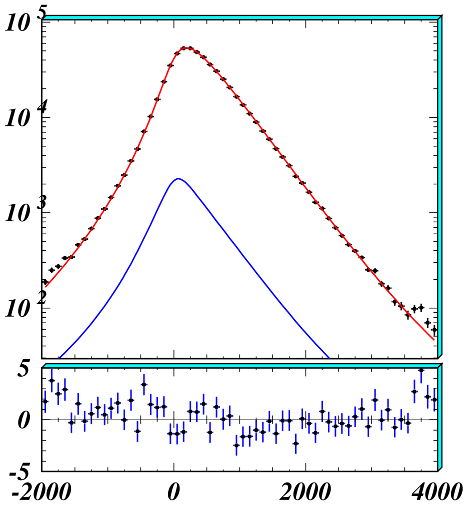

Figure 3: Decay time distribution with the fit superimposed. The curve below the data points is the time distribution of background. The lower plot shows the residuals.

The random π_s background contains real D^0 and $\overline{D}^0$ decays uncorrelated to the charge of a slow pion. The PDF is taken to be $(1 - f_w)|\mathcal{M}(m_-^2, m_+^2, t)|^2 + f_w|\mathcal{M}(m_+^2, m_-^2, t)|^2$, convolved with the same resolution function as the signal PDF. The fraction f_w was determined from fitting events in the Q sideband.

For the combinatorial background, $\mathcal{P}_{cmb}$ is a product of the Dalitz plot and decay time PDFs. The latter is parameterized as the sum of a delta function and an exponential function convolved with a Gaussian resolution function. The resolution function has a σ_t dependent offset. This and other timing parameters, as well as the Dalitz PDF, were obtained from the events in the mass sideband.

The free parameters in the fit were x, y, τ_{D^0}, the timing resolution parameters of the signal, and the Dalitz plot resonance parameters $a_{r(NR)}$ and $\phi_{r(NR)}$. The resonance model assumed 18 quasi-two-body resonances; masses and widths were taken from world averages.

The Dalitz plot and its projections, along with projections of the resulting fit, are shown in Fig. 2. The decay-time distribution and the fit are shown in Fig. 3. The fitted D^0 lifetime $\tau_{D^0} = 409.9 \pm 1.0$ fs is consistent with the world average. The preliminary results for the mixing parameters are $x = (0.80 \pm 0.29 \pm 0.17)\%$ and $y = (0.33 \pm 0.24 \pm 0.15)\%$. The largest contributions to the systematic uncertainty of the result are found to arise from model dependence and from the fit to the decay-time distribution. The result for the mixing parameter x represents the most stringent limit on this parameter obtained up to now.

6 Decays to CP eigenstates $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

Belle collaboration has performed a new measurement in the decays to CP eigenstates $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$; treating the decay time distributions as exponential, they measured the quantity

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1, \tag{8}$$

where $\tau(K^+K^-)$ and $\tau(K^-\pi^+)$ are the lifetimes of $D^0 \to K^+K^-$ (or $\pi^+\pi^-$) and $D^0 \to K^-\pi^+$ decays. It can be shown that $y_{CP} = y\cos\phi - \frac{1}{2}A_M x \sin\phi$ [17], where A_M parameterizes CPV in

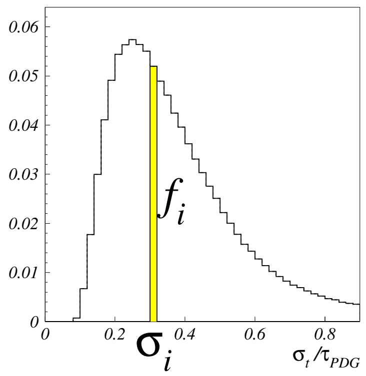

Figure 4: Normalized distribution of errors σ_t on the decay time t for $D^0 \to K^-\pi^+$, showing the construction of the resolution function using the fraction f_i in the bin with $\sigma_t = \sigma_i$.

mixing and ϕ is a weak phase. If CP is conserved, $A_M = \phi = 0$ and $y_{CP} = y$. To date several measurements of y_{CP} have been reported [18]; the average value is $\sim$2 standard deviations (σ) above zero. The new Belle measurement, based on 540 fb^{-1}, yields a nonzero value of y_{CP} with $> 3\sigma$ significance [19]. They also searched for CPV by measuring the quantity

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)}; \tag{9}$$

this observable equals $A_\Gamma = \frac{1}{2}A_M y\cos\phi - x\sin\phi$ [17].

They reconstructed $D^{*+} \to D^0\pi_s^+$ decays, and $D^0 \to K^+K^-$, $K^-\pi^+$, and $\pi^+\pi^-$. D^0 daughter tracks were refitted to a common vertex, and the D^0 production vertex was found by constraining its momentum vector and the π_s track to originate from the e^+e^- interaction region. A D^{*+} momentum greater than $2.5\,\mathrm{GeV}/c$ (in the CM) was required to reject D-mesons produced in B-meson decays and to suppress combinatorial background. The proper decay time of the D^0 candidate was then calculated from the projection of the vector joining the two vertices, $\vec{L}$, onto the D^0 momentum vector, $t = m_{D^0}\vec{L}\cdot\vec{p}/p^2$, where m_{D^0} is the nominal D^0 mass. The decay time uncertainty σ_t was evaluated event-by-event from the covariance matrices of the production and decay vertices.

Candidate D^0 mesons were selected using two kinematic observables: the invariant mass of the D^0 decay products, M, and the energy released in the D^{*+} decay, $q = (M_{D^*} - M - m_\pi)c^2$. M_{D^*} is the invariant mass of the $D^0\pi_s$ combination and m_π is the π^+ mass.

According to Monte Carlo (MC) simulated distributions of t, M, and q, background events fall into four categories: (1) combinatorial, with zero apparent lifetime; (2) true D^0 mesons combined with random slow pions (this has the same apparent lifetime as the signal) (3) D^0 decays to three or more particles, and (4) other charm hadron decays. The apparent lifetime of the latter two categories is 10–30% larger than τ_{D^0}.

The sample of events for the lifetime measurements was selected using $|\Delta M|/\sigma_M$, where $\Delta M \equiv M - m_{D^0}$; $|\Delta q| \equiv q - (m_{D^{*+}} - m_{D^0} - m_\pi)c^2$; and σ_t. The invariant mass resolution σ_M varies from 5.5–6.8 MeV$/c^2$, depending on the decay channel. Selection criteria were chosen to minimize the expected statistical error on y_{CP}, using the MC: they required $|\Delta M|/\sigma_M < 2.3$, $|\Delta q| < 0.80\,\mathrm{MeV}$, and $\sigma_t < 370$ fs. They found 111×10^3 K^+K^-, 1.22×10^6 $K^-\pi^+$, and 49×10^3 $\pi^+\pi^-$ signal events, with purities of 98%, 99%, and 92% respectively.

The relative lifetime difference y_{CP} was determined from $D^0 \to K^+K^-$, $K^-\pi^+$, and $\pi^+\pi^-$ decay time distributions by performing a simultaneous binned maximum likelihood fit to the three samples. Each distribution was assumed to be a sum of signal and background contributions, with the signal contribution being a convolution of an exponential and a detector resolution function,

$$dN/dt = \frac{N_{\mathrm{sig}}}{\tau}\int e^{-t'/\tau}\cdot R(t-t')\,\mathrm{d}t' + B(t). \tag{10}$$

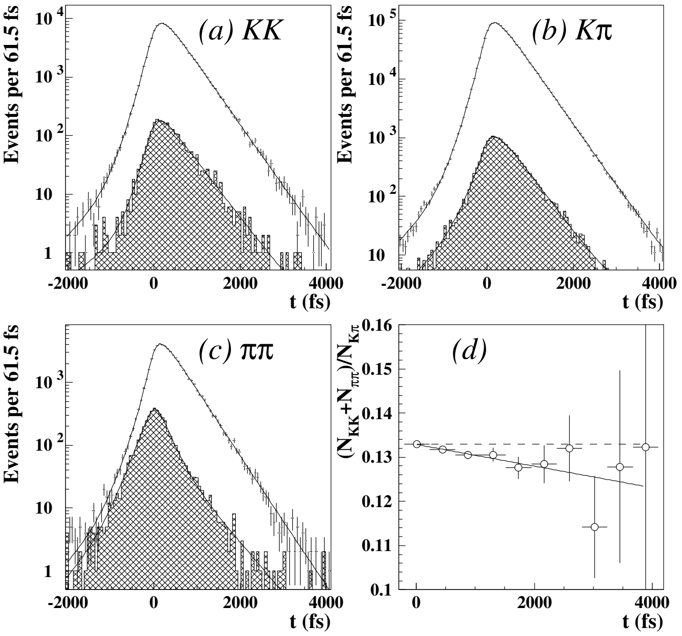

Figure 5: Results of the simultaneous fit to decay time distributions of (a) $D^0 \to K^+K^-$, (b) $D^0 \to K^-\pi^+$ and (c) $D^0 \to \pi^+\pi^-$ decays. The cross-hatched area represents background contributions, the shape of which was fitted using M sideband events. (d) Ratio of decay time distributions between $D^0 \to K^+K^-, \pi^+\pi^-$ and $D^0 \to K^-\pi^+$ decays. The solid line is a fit to the data points.

The resolution function $R(t-t')$ was constructed from the normalized distribution of the decay time uncertainties σ_t (see Fig. 4). The σ_t of a reconstructed event ideally represents an uncertainty with a Gaussian probability density: in this case, bin i in the σ_t distribution is taken to correspond to a Gaussian resolution term of width σ_i, with a weight given by the fraction f_i of events in that bin. However, the distribution of "pulls", i.e. the normalized residuals $(t_{\rm rec} - t_{\rm gen})/\sigma_t$ (where $t_{\rm rec}$ and $t_{\rm gen}$ are reconstructed and generated MC decay times), is not well-described by a Gaussian. They found that this distribution can be fitted with a sum of three Gaussians of different widths $\sigma_k^{\rm pull}$ and fractions w_k, constrained to the same mean. They therefore choose a parameterization

$$R(t-t') = \sum_{i=1}^{n} f_i \sum_{k=1}^{3} w_k G(t-t'; \sigma_{ik}, t_0), \tag{11}$$

with $\sigma_{ik} = s_k \sigma_k^{\rm pull} \sigma_i$, where the s_k are three scale factors introduced to account for differences between the simulated and real $\sigma_k^{\rm pull}$, and t_0 allows for a (common) offset of the Gaussian terms from zero.

The background $B(t)$ was parameterized assuming two lifetime components: an exponential and a δ function, each convolved with corresponding resolution functions as parameterized by Eq. (11). Separate $B(t)$ parameters for each final state were determined by fits to the t distributions of events in M sidebands. The MC was used to select the sideband region that best reproduces the timing distribution of background events in the signal region.

Fits to the $D^0 \to K^+K^-$, $K^-\pi^+$ and $\pi^+\pi^-$ data are shown in Fig. 5(a)-(c). The fitted lifetime of D^0 mesons in the $K^-\pi^+$ final state, $\tau_{D^0} = (408.7 \pm 0.6 \text{ (stat.)})$ fs, is in good agreement with the current world average. The result for the apparent lifetime of D^0 mesons between decays to CP-even eigenstates and the $K^-\pi^+$ final state is

$$y_{CP} = (1.31 \pm 0.32(\text{stat.}) \pm 0.25(\text{syst.}))\%. \tag{12}$$

Combining the errors in quadrature this result is a 3.2 standard deviations from zero and represents the first experimental evidence for the D-mixing, regardless of possible CPV. The effect is presented visually in Fig. 5(d), which shows the ratio of decay time distributions for $D^0 \to K^+K^-, \pi^+\pi^-$ and $D^0 \to K^-\pi^+$ decays. They also searched for CP violation by separately measuring decay times of D^0 and $\overline{D}^0$ mesons in CP-even final states. They find an asymmetry consistent with zero, $A_\Gamma = (0.01 \pm 0.30(\text{stat.}) \pm 0.15(\text{syst.}))\%$.

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