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# Charm physics at BaBar and Belle

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Recent results on charm physics from Belle and BaBar are reported. These include studies of charm mixing, *CP* violation in the charm sector and properties of charmed meson decay. Measurements of the $D_s$ pseudoscalar purely leptonic decay branching fractions are also reported, which allow for experimental comparisons with the lattice calculation of the $f_{D_s}$ decay constant.

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During the last decade the $B$-factories [1], BaBar and Belle, have play a crucial role in the understanding of the heavy flavor sector in the Standard Model (SM). Both detectors use asymmetric energy $e^+e^-$ beams at the c.m. energy of the $\Upsilon(4S)$ resonance, where $\sigma(e^+e^- \to c\overline{c}) \sim 1.3\,\text{nb}$, achieving more than $6\times 10^8$ and $9\times 10^8$ charm events in BaBar and Belle, respectivelly. At $B$-factories, $D^0$ analyses share some aspects: $D^0$ mesons are produced with high-momentum in the c.m. frame, from the $e^+e^- \to D^{*+}(D^0\pi_s^+)X^-$ decay; the flavor of the $D^0$ is identified ("tagged") at production with the charge of the low-momentum $\pi_s^+$; these events are usually characterized using the invariant mass of the exclusively reconstructed $D^0$ meson, $m_{D^0}$, and the mass difference between the reconstructed $D^{*+}$ and $D^0$ mesons, $\Delta m = m_{D^{*+}} - m_{D^0}$.

## 1. Extraction of the $f_{D_s}$ decay constant

The pseudoscalar meson decay constant $f_{D_s}$ contains information on the overlap of the wave functions of the light and heavy quarks inside the $D_s$ meson. The determination of $f_{D_s}$ is very important, since it is an input for the calculation of hadronic matrix elements for several key processes. The leptonic decays of the $D_s$ meson, are CKM favored and mediated by tree level diagrams via $W$ boson exchange, resulting in a precise and clean way to measure $f_{D_s}$, which is used to validate lattice QCD calculations that are also applicable to $B$ meson decays. It may be also a source of New Physics (NP), since several models involving physics beyond the SM can induce a difference between the theoretical prediction and the measured value. The most precise SM theoretical prediction is $f_{D_s} = (241\pm 3)\,\text{MeV}$, obtained from unquenched lattice QCD [2].

In the SM, the total decay width of the $D_s^+$ into the leptonic final state is

$$\Gamma(D_s^+ \to l^+\nu_l) = \frac{G_F^2}{8\pi} M_{D_s^+}^3 \left(\frac{m_l}{M_{D_s^+}}\right)^2 \left(1 - \frac{m_l^2}{M_{D_s^+}^2}\right)^2 |V_{cs}|^2 f_{D_s}^2, \tag{1.1}$$

where $M_{D_s^+}$ and $m_l$ are the $D_s^+$ and lepton masses, respectivelly, $G_F$ is the Fermi constant, $|V_{cs}|$ is the magnitude of the CKM matrix element. The factor $(m_l/M_{D_s^+})^2$ is an helicity effect, while $(1-m_l^2/M_{D_s^+}^2)^2$ is a phase-space factor.

The BaBar collaboration analyzed the decay chain $D_s^+ \to \tau^+\nu_\tau$ with $\tau^+ \to e^+\nu_e\overline{\nu}_\tau$ [3]. Here, the signal branching fraction $\mathscr{B}(D_s^+ \to \tau^+\nu_\tau)$ relative to the well measured branching fraction $\mathscr{B}(D_s^+ \to K_S^0 K^+) = (1.49\pm 0.09)\%$, is determined and used to extract the decay constant $f_{D_s}$. In the process $e^+e^- \to c\overline{c} \to D_s^{*+}\overline{D}_{TAG}\overline{K}X$, the $D_s^{*+}$ is reconstructed as a missing particle, and the subsequent decay $D_s^{*+} \to D_s^+\gamma$ yields an inclusive $D_s^+$ data sample, $\overline{D}_{TAG}$ refers to a fully reconstructed hadronic $\overline{D}$ decay required to suppress large light-quark background, $\overline{K}$ is a $K^-$ or $\overline{K}^0$ meson needed to assure overall stangeness balance, and $X$ stands for any number of charged or neutral pions produced in the fragmentation process. The measured value is $f_{D_s} = (233\pm 13(\text{stat.}) \pm 10(\text{syst.}) \pm 7(\text{th.}))\,\text{MeV}$, where the last uncertainty arises from theoretical inputs. The $f_{D_s}$ world average from the Heavy Flavors Averaging Group (HFAG)[4], including this result, is $f_{D_s} = (254.6\pm 5.9)\,\text{MeV}$, where the discrepancy with the theoretical value is $\sim 2\sigma$.

## 2. Charm mixing and *CP* violation

Mixing of neutral mesons has been observed in the $K^0$ [5], $B_d^0$ [6] and $B_s^0$ [7] systems, and in the last few years strong experimental evidence in the $D^0$ system was also claimed [8, 9, 10, 11, 12, 13]. Neutral $D$ mesons, are created as flavor eigenstates of strong interactions but they may oscillate through weak interactions. The mixing process is described by the 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 corresponding masses and widths of the mass eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$ and $\Gamma = (\Gamma_1 + \Gamma_2)/2$. In the SM, mixing arises from $|\Delta C = 2|$ transitions ($C$ stands for the charm quantum number) from short-distance box diagrams containing only down-type quarks, highly suppressed by either GIM cancellation mechanism or small CKM couplings. Enhancement of mixing may appear introducing models beyond SM [14], or also accounting for $|\Delta C = 1|$ long-distance SM contributions, via hadronic intermediate states accesible from both $D^0$ and $\overline{D}^0$. Theoretical predictions for $x$ and $y$ span a large range ($10^{-5} - 10^{-2}$) showing that $D^0 - \overline{D}^0$ mixing process is very hard to calculate. However, SM predictions converge to the fact that $|x| < |y|$ and therefore $|x| \gg |y|$ can be addressed as a signature of NP.

Regarding $CP$ violation ($CPV$), it can appear due to three different sources: $CPV$ in the decay if $|\overline{A}_{\overline{f}}/A_f| \neq 1$; $CPV$ in the mixing if $|q/p| \neq 1$; and $CPV$ in the interference of the decay and mixing if $\phi = \arg\{q/p \cdot \overline{A}_f/A_f\} \neq 0, \pi$, where the initial state ($t = 0$) amplitudes are $A_f \equiv \langle f|\mathscr{H}|D^0\rangle$ and $\overline{A}_f \equiv \langle f|\mathscr{H}|\overline{D}^0\rangle$. In the SM it is predicted to be very small ($< 10^{-4}$) and any evidence of $CPV$ with current data samples can be addressed as a NP effect.

**Wrong-Sign hadronic decays.** The first strong evidence of mixing in the charm sector was found by the BaBar experiment [8], in the Wrong-Sign (WS) $D^0 \to K^+\pi^-$ decay. This final state can be achieved via a direct doubly-Cabibbo-suppressed (DCS) decay, or by mixing to a $\overline{D}^0$ and a further Cabibbo-favored (CF) decay, $D^0 \to \overline{D}^0 \to K^+\pi^-$. In the small mixing limit and assuming $R_D \equiv A_f/\overline{A}_f \ll 1$, the time-dependent decay width is given by

$$\Gamma_{D^0\to f_{WS}}(t) \sim e^{-\Gamma t}\left\{R_D + y'\sqrt{R_D}(\Gamma t) + \frac{x'^2 + y'^2}{2}(\Gamma t)^2\right\}, \tag{2.1}$$

where, $x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$ and $y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$, with $\delta_{K\pi}$ the relative strong phase among the DCS and CF amplitudes. Time evolution allows to disentangle the different contributions to the process, DCS decay (no time dependence), mixing ($\sim t^2$) and their intereference ($\sim t$). Here, the unknowledge of the phase $\delta_{K\pi}$ avoids the direct extraction of $x$ and $y$. BaBar measurement has been performed on a $384\,\mathrm{fb}^{-1}$ data sample with $4030 \pm 90$ WS signal events. The reconstructed proper time has been modeled with the Eq. 2.1 convolved with a resolution function determined using the Right-Sign (RS) signal events. The fit result for the rotated mixing parameters is $x'^2 = (-0.022 \pm 0.030(\text{stat.}) \pm 0.021(\text{syst.}))\%$ and $y' = (0.97 \pm 0.44(\text{stat.}) \pm 0.31(\text{syst.}))\%$ with a correlation of -0.95%, excluding the no-mixing hypothesis ($x' = y' = 0$) at $3.9\sigma$. Belle [15] and CDF [10] experiments have reported compatible results in this decay mode.

**Decay into *CP* eigenstates.** The presence of mixing is expected to modify the decay proper time distributions of states with different $CP$ content. The study of these differences, between $CP-$even eigenstates $D^0 \to h^+h^-$ ($h = \pi, K$), and the $CP-$mixed CF $D^0 \to K^-\pi^+$ state, has led also to determination of experimental evidence of mixing in the charm sector. In fact, the first evidence of mixing in the Belle experiment [9], was obseved in this kind of analysis. Here, the time-dependent amplitude of the decay into the $CP$ eigenstate in the small mixing limit is

$\Gamma_{D^0\to f_{CP}} \sim e^{-\Gamma(1+y_{CP})t}$, with $y_{CP} = \tau_{K^-\pi^+}/\tau_{h^+h^-} - 1 = y\cos\phi$, where $\phi$ is the *CPV* phase arising from the mixing. Belle experiment, using $540\,\mathrm{fb}^{-1}$ of data corresponding to $1.22\times10^6$, $49\times10^3$ and $111\times10^3$ signal events for $K^-\pi^+$, $\pi^+\pi^-$, $K^+K^-$ final states, respectivelly, has measured $y_{CP} = (1.31\pm0.32(\mathrm{stat.})\pm0.25(\mathrm{syst.}))\%$. This value excludes the no-mixing hypothesis ($y_{CP} = 0$) with a significance of $3.2\sigma$. Compatible results using the same decay modes were found by the BaBar collaboration [11].

A recent BaBar analysis [13], using an "untagged" sample, has measured $y_{CP} = (1.12\pm0.26(\mathrm{stat.})\pm0.22(\mathrm{syst.}))\%$. In this analysis, since the initial flavor of the decaying $D^0$ is not identified, no $D^{*+}$ reconstruction is required, increasing significantly the reconstruction efficiency but increasing also the amount of background. The combination of the statistically independent samples, tagged and untagged, leads to $y_{CP} = (1.16\pm0.22(\mathrm{stat.})\pm0.18(\mathrm{syst.}))\%$ , excluding the no-mixing hypothesis at $4.1\sigma$.

$D^0$ **3-body decays.** The methods described above provide compelling evidence of mixing in the charm sector, however, these methods are not able to give a direct measurement of $x$ and $y$. The Dalitz-plot analysis of the $D^0\to K^0_S h^+h^-$ allows to extract mixing information from the the rich dynamics of the 3-body decay and its evolution in time. For instance, the $D^0\to K^0_S\pi^+\pi^-$ Dalitz-plot contains CF and DCS resonances ($K^*(892)^\pm$), the interference among them, and also contains *CP* eigenstates ($\rho(770)$). This can be understood as the combination of the methods explained above. In this case the initial state amplitudes are function of the Dalitz-plot position, $A_f = A_f(s_+,s_-)$, with $s_\pm = m^2(K^0_S h^\pm)$ the 2-particle squared invariant mass. These amplitudes for $D^0$ and $\overline{D}^0$ fall into the same Dalitz-plot if we assume *CP* conserved in the decay ($A(s_+,s_-) = \overline{A}(s_-,s_+)$). Here, the time-dependent decay in the small mixing limit can be written as

$$\Gamma_{D^0\to f_{K^0_S h^+h^-}}(t) \sim e^{-\Gamma t}\left\{R_D + y'\sqrt{R_D}(\Gamma t) + \frac{x'^2+y'^2+R_D(y'^2-x'^2)}{4}(\Gamma t)^2\right\}. \tag{2.2}$$

Lets recall the expresion $y' = -x\sin\delta_f + y\cos\delta_f$, with $\delta_f$ been now the relative strong phase in each point of the Dalitz-plot. A model for the dependance with the Dalitz-plot will allow us to deconvolve $y'$ and $x'$, and measure $x$ and $y$. Nowadays, this is the only way to access direct and unumbiguosly to the mixing parameters. Using a $468.5\,\mathrm{fb}^{-1}$ data sample, BaBar collaboration performed a combinned $D^0\to K^0_S\pi^+\pi^-$ and $D^0\to K^0_S K^+K^-$ time-dependent Dalitz-plot fit in the $\{m_{D^0},\Delta m\}$ signal box, assuming no *CPV* ($\phi = 0$ and $|q/p| = 1$), to extract the mixing parameters $x$ and $y$ [16]. The Dalitz-plot model uses a $K-$matrix approach to describe the $S-$wave and Breit-Wigner lineshapes for the $P-$ and $D-$ waves, as described in [17]. The purity of the data sample exceeds 98%, and $541\times10^3$ ($80\times10^3$) signal events were found in $D^0\to K^0_S\pi^+\pi^-$ ($D^0\to K^0_S K^+K^-$). The fit results are $x = (0.16\pm0.23(\mathrm{stat.})\pm0.12(\mathrm{syst.})\pm0.08(\mathrm{model.}))\%$, and $y = (0.57\pm0.20(\mathrm{stat.})\pm0.13(\mathrm{syst.})\pm0.07(\mathrm{model.}))\%$, with a correlation of the order of the percent. This result is the most precise single measurement of the mixing parameters and exclude the no-mixing hypothesis at $1.9\sigma$. This measurement favors small values for mixing, and $|x| < |y|$ places the measure within the expected SM ranges. This measure is compatible with previous measurements using the $D^0\to K^0_S\pi^+\pi^-$ decay mode [18].

$D^0-\overline{D}^0$ **mixing world Average.** The combination of all measurements of the mixing parameters (those described in this document and additional 3-body and semileptonic decay modes [19] with less sensitivity to mixing) by the HFAG [4], gives $x = (0.61^{+0.19}_{-0.20})\%$ and $y = (0.79 \pm 0.13)\%$, shown in Fig. 1 (Left), excluding the no-mixing hypothesis at more than $10\sigma$. The effect of the new BaBar Dalitz-plot measurement can be observed comparing with Fig. 1 (Right), which corresponds to the previous HFAG average. It is clear how this measurement drifts the average towards SM values, specially for $x$ where the uncertainty is largerly reduced.

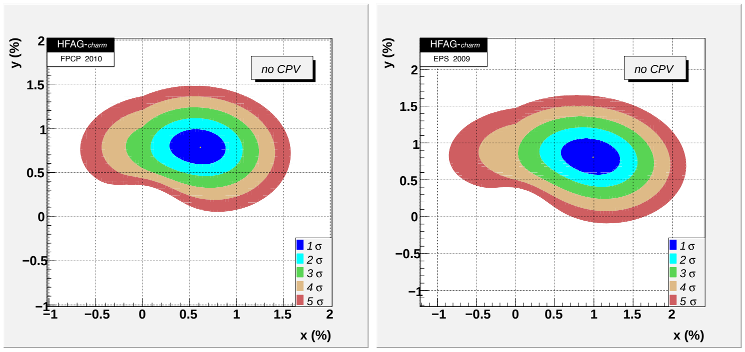

**Figure 1:** (Left) New HFAG [4] world average contour plot for the mixing parameters $x$ and $y$ including the new time-dependent Dalitz-plot analysis from BaBar [16]. (Right) Previous HFAG average.

*CP* **violation in the charm sector.** From the experimental point of view, the construction of *CP* asymmetries including all *CPV* sources, is the simpliest way to study *CPV*. In the $B-$factories, time-integrated searches have been performed in the singly-Cabibbo-suppressed (SCS) final states $D^0 \to h^+h^-$ [20] and $D^0 \to \pi^0 h^+h^-$ [21], where Dalitz-plot integrated asymmetries where also studied. No evidence of *CPV* was found with a statistical resolution of $\sim 0.3\%$.

Recently, BaBar experiment performed an analysis in which a $T-$violating asymmetry is measured [22]. Assuming *CPT* a well conserved symmetry, then a test for $T-$violation will represent also a test for *CPV*. With the momentum in the $D^0$ rest frame of the final state particles in the reaction $D^0 \to K^+K^-\pi^+\pi^-$, a $T-$odd triple product such as $C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$ ($\overline{C}_T$ for the $\overline{D}^0$ decays) is built. Strong interaction dynamics in the decay may produce non-vanishing asymmetries,

$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) - \Gamma(C_T < 0)}, \qquad \overline{A}_T \equiv \frac{\Gamma(-\overline{C}_T > 0) - \Gamma(-\overline{C}_T < 0)}{\Gamma(-\overline{C}_T > 0) - \Gamma(-\overline{C}_T < 0)}, \tag{2.3}$$

and from here, the true $T-$violating asymmetry as $\mathscr{A}_T = (A_T - \overline{A}_T)/2$. In the signal region a fit was performed over $50 \times 10^3$ signal events, obtaining $\mathscr{A}_T = (0.10 \pm 0.51(\mathrm{stat.}) \pm 0.44(\mathrm{syst.}))\%$, where the systematic uncertainty is dominated by the particle identification. This measurement improves the statistical resolution in one order of magnitude with respect to the previous measurement [23], however, no sign of $T-$violation was found.

## 3. Conclusions

New measurements at the $B-$facories have provided a best understanding of the physics in the charm sector. We have shown recent results from the BaBar experiment on the measurement of the $f_{D_s}$ decay constant, as well as crucial results on the $D^0-\overline{D}^0$ mixing using a time-dependent Dalitz-plot analysis and an improvement on the search for $T-$violation in multibody $D^0$ decays.

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