11 Charm Flavor Physics

11.1 Preliminaries

Charm flavor physics plays certainly an important role in the tests of the SM but presently cannot compete with K-meson and B-meson physics as far as tests of the SM are concerned and the search for NP. This is due to the hadronic uncertainties, which are much larger than in the case of the other meson systems that dominate this book. But there is another reason as far as the SM is concerned: FCNC processes in the charm system are much stronger suppressed by GIM mechanism than in the K-meson and B-meson systems because down-quarks and not up-quarks are exchanged in the loops, so that the enhancements through top-Yukawa coupling are absent. As a result hadronic effects and not short-distance effects dominate many processes in the SM. But as the latter are very small, in processes in which hadronic effects can be somehow reduced by taking ratios, NP can show up provided it is larger than hadronic contributions. This might be the case of CP-violating observables.

The chapter about charm flavor physics must be present in this book, but it will be rather short as I basically never worked in this field, the exception being the application of large N ideas to two-body charm decays [225], a short paper on $D^0 - \bar{D}^0$ mixing [675] and in particular [676], where fortunately some fundamentals have been presented. For this reason this chapter will be based dominantly on the latter paper, signed also by the master of charm flavor physics, Ikaros Bigi. However, I will also include several findings from a number of excellent papers that I would like to recommend to anybody who would like to know more about this field beyond the material presented here. These useful papers are in particular [677–691].

11.2 $D^0 - \bar{D}^0$ Mixing

11.2.1 Theoretical Framework

Theoretical framework for $D^0 - \bar{D}^0$ mixing is the same as the one used already for $K^0 - \bar{K}^0$ and $B^0_{s,d} - \bar{B}^0_{s,d}$ mixings, but there are few differences relative to the latter ones, and it is useful to apply directly this formalism to $D^0 - \bar{D}^0$ system so that these differences can be explicitly seen. We follow here [676] and add several insights from the papers listed earlier.

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The time evolution of neutral D mesons is again described by

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix} = \begin{pmatrix} M_{11}^D - \frac{i}{2}\Gamma_{11}^D & M_{12}^D - \frac{i}{2}\Gamma_{12}^D \\ M_{12}^{D^*} - \frac{i}{2}\Gamma_{12}^{D^*} & M_{11}^D - \frac{i}{2}\Gamma_{11}^D \end{pmatrix}\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix}. \tag{11.1}$$

In the presence of flavor violation

$$M_{12}^D \neq 0, \qquad \Gamma_{12}^D \neq 0, \tag{11.2}$$

and the mass eigenstates can be written as

$$|D_1\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}}\left(p|D^0\rangle + q|\bar{D}^0\rangle\right), \tag{11.3}$$

$$|D_2\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}}\left(p|D^0\rangle - q|\bar{D}^0\rangle\right), \tag{11.4}$$

where

$$\boxed{\frac{q}{p} \equiv \sqrt{\frac{M_{12}^{D^*} - \frac{i}{2}\Gamma_{12}^{D^*}}{M_{12}^D - \frac{i}{2}\Gamma_{12}^D}}.} \tag{11.5}$$

We choose the CP phase convention

$$C\mathcal{P}|D^0\rangle = +|\bar{D}^0\rangle, \tag{11.6}$$

which differs from the one used for $K^0 - \bar{K}^0$ and $B_{s,d}^0 - \bar{B}_{s,d}^0$ mixings to follow [676], but this difference is immaterial for physical quantities.

$D^0 - \bar{D}^0$ mixing can then be characterized by the normalized mass and width differences

$$\boxed{x_D \equiv \frac{\Delta M_D}{\overline{\Gamma}}, \qquad y_D \equiv \frac{\Delta\Gamma_D}{2\overline{\Gamma}}, \qquad \overline{\Gamma} = \frac{1}{2}(\Gamma_1 + \Gamma_2),} \tag{11.7}$$

with

$$\begin{aligned}\Delta M_D &= M_1 - M_2 = 2\mathrm{Re}\left[\frac{q}{p}\left(M_{12}^D - \frac{i}{2}\Gamma_{12}^D\right)\right] \\ &= 2\mathrm{Re}\sqrt{|M_{12}^D|^2 - \frac{1}{4}|\Gamma_{12}^D|^2 - i\mathrm{Re}(\Gamma_{12}^D M_{12}^{D^*})},\end{aligned} \tag{11.8}$$

$$\begin{aligned}\Delta\Gamma_D &= \Gamma_1 - \Gamma_2 = -4\mathrm{Im}\left[\frac{q}{p}\left(M_{12}^D - \frac{i}{2}\Gamma_{12}^D\right)\right] \\ &= -4\mathrm{Im}\sqrt{|M_{12}^D|^2 - \frac{1}{4}|\Gamma_{12}^D|^2 - i\mathrm{Re}(\Gamma_{12}^D M_{12}^{D^*})}.\end{aligned} \tag{11.9}$$

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Our definitions in (11.8) and (11.9) follow the PDG conventions, also adopted by the HFAG collaboration; for neutral kaons they lead to $\Delta M_K \cdot \Delta\Gamma_K < 0$. Note that if $|\Gamma_{12}^D| \ll |M_{12}^D|$, as appropriate for B^0 mesons, one would recover the familiar expressions $\Delta M \simeq 2|M_{12}^D|$ and $\Delta\Gamma \ll \Delta M$ presented in previous chapters.

We recall that while ΔM_D and $\Delta\Gamma_D$ tell us nothing about the CP symmetry, the ratio q/p and the relative phase between M_{12}^D and Γ_{12}^D,

$$\boxed{\varphi_{12} = \frac{1}{2}\arg\left(\frac{M_{12}^D}{\Gamma_{12}^D}\right),} \tag{11.10}$$

express the CP impurity in the two mass eigenstates through $|q/p| \neq 1$ and/or $2\varphi_{12} \neq \{0, \pm\pi\}$. While the phases of M_{12}^D and Γ_{12}^D depend on the phase conventions chosen, φ_{12} is phase convention independent and consequently an observable.

The experimental world averages as presented in HFAG read [150]

$$x_D = 0.0046 \pm 0.0013, \qquad y_D = 0.0062 \pm 0.0007, \qquad \frac{x_D^2 + y_D^2}{2} \leq (1.3 \pm 2.7) \cdot 10^{-4}. \tag{11.11}$$

It appears then that in the D system $x \sim y$ or $\Gamma_{12} \sim M_{12}$, whereas in the B system $|\Gamma_{12}/M_{12}| \ll 1$. For future prospects see [305, 692]. For recent measurements of x_D and y_D by the LHCb see [693].

In the limit of (approximate) CP symmetry x_D, $y_D > 0$ implies the CP *even* state to be slightly heavier and shorter lived than the CP *odd* one (unlike for neutral kaons).

As the $D^0 - \bar{D}^0$ mixing itself is subject to large theoretical uncertainties, we refer to section 3 of [305] for the summary of the present situation and move directly to CP violation, which is cleaner and moreover a good place to search for NP.

11.3 CP Asymmetries in *D* Decays

11.3.1 General Formalism

For convenience let us apply the technology of Section 8.1.5 to CP asymmetries in the D-meson system with notation properly adjusted to the literature on the D-meson system.

The time evolution of initially pure D^0 and $\bar{D}^0$ states, respectively, can be obtained from solving (11.1) and is given by

$$|D^0(t)\rangle = f_+(t)|D^0\rangle - \frac{q}{p} f_-(t)|\bar{D}^0\rangle, \tag{11.12}$$

$$|\bar{D}^0(t)\rangle = -\frac{p}{q} f_-(t)|D^0\rangle + f_+(t)|\bar{D}^0\rangle, \tag{11.13}$$

where

$$f_+(t) = e^{-i\bar{M}t} e^{-\bar{\Gamma}t/2} \cos Qt, \qquad f_-(t) = i e^{-i\bar{M}t} e^{-\bar{\Gamma}t/2} \sin Qt, \tag{11.14}$$

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with q/p given in (11.5), $\bar{M} = (M_1 + M_2)/2$ and

$$Q = \sqrt{(M_{12}^D - \frac{i}{2}\Gamma_{12}^D)(M_{12}^{D*} - \frac{i}{2}\Gamma_{12}^D)^*} = \frac{1}{2}(\Delta M_D - \frac{i}{2}\Delta\Gamma_D). \tag{11.15}$$

From (11.12) and (11.13) we find for the time-dependent decay rates of $D^0(t)$ and $\bar{D}^0(t)$ to a final state f:

$$\Gamma(D^0(t) \to f) = \left|T(D^0 \to f)\right|^2 e^{-\bar{\Gamma}t}\left[\frac{1}{2}\left(1 + |\lambda_f|^2\right)\cosh\frac{\Delta\Gamma_D t}{2}\right. \tag{11.16}$$
$$\left. + \frac{1}{2}\left(1 - |\lambda_f|^2\right)\cos\Delta M_D t - \sinh\frac{\Delta\Gamma_D t}{2}\mathrm{Re}\lambda_f + \sin\Delta M_D t\,\mathrm{Im}\lambda_f\right],$$

$$\Gamma(\bar{D}^0(t) \to f) = \left|T(\bar{D}^0 \to f)\right|^2 e^{-\bar{\Gamma}t}\left[\frac{1}{2}\left(1 + \left|\frac{1}{\lambda_f}\right|^2\right)\cosh\frac{\Delta\Gamma_D t}{2}\right. \tag{11.17}$$
$$\left. + \frac{1}{2}\left(1 - \left|\frac{1}{\lambda_f}\right|^2\right)\cos\Delta M_D t - \sinh\frac{\Delta\Gamma_D t}{2}\mathrm{Re}\frac{1}{\lambda_f} + \sin\Delta M_D t\,\mathrm{Im}\frac{1}{\lambda_f}\right],$$

where we dropped the overall phase space factors and defined

$$\lambda_f = \frac{q}{p}\frac{T(\bar{D}^0 \to f)}{T(D^0 \to f)}. \tag{11.18}$$

These general formulas agree with those of Dunietz and Rosner [694] after their definitions of ΔM and $\Delta\Gamma$ are adjusted to ours in (11.8) and (11.9).

From these results, one can easily obtain the CP asymmetries

$$\frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)}, \tag{11.19}$$

where f is a CP eigenstate

$$C\mathcal{P}|f\rangle = \eta_f|f\rangle, \qquad \eta_f = \pm 1. \tag{11.20}$$

We find

$$\frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} = \frac{F_-}{F_+ + \cosh\frac{\Delta\Gamma_D t}{2} + \cos\Delta M_D t}, \tag{11.21}$$

where we have introduced the functions

$$F_\pm = \frac{1}{2}\left(\left|\frac{q}{p}\right|^2 \pm \left|\frac{p}{q}\right|^2\right)\left(\cosh\frac{\Delta\Gamma_D t}{2} - \cos\Delta M_D t\right)$$
$$- \left[\left(\left|\lambda_f\right| \pm \left|\frac{1}{\lambda_f}\right|\right)\cos 2\varphi_f \sinh\frac{\Delta\Gamma_D t}{2} - \left(\left|\lambda_f\right| \mp \left|\frac{1}{\lambda_f}\right|\right)\sin 2\varphi_f \sin\Delta M_D t\right], \tag{11.22}$$

and

$$\varphi_f = \frac{1}{2}\arg\left(\lambda_f\right). \tag{11.23}$$

We emphasize that the phase φ_f is phase convention independent as it depends only on the relative phase between q/p and $T(\bar{D}^0 \to f)/T(D^0 \to f)$ in (11.18).

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For practical purposes, as $x_D, y_D \ll 1$, it is sufficient to consider the CP asymmetry in the limit of a small t. Then (11.21) reduces to

$$\frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} = -\left[y_D \left(|\lambda_f| - \left|\frac{1}{\lambda_f}\right| \right) \cos 2\varphi_f - x_D \left(|\lambda_f| + \left|\frac{1}{\lambda_f}\right| \right) \sin 2\varphi_f \right] \frac{t}{2\bar{\tau}_D}, \tag{11.24}$$

where $\bar{\tau}_D = 1/\bar{\Gamma}$.

In the case of a nonnegligible CP phase ξ_f in the decay amplitude $T(D^0 \to f)$, but $|T(D^0 \to f)| = |T(\bar{D}^0 \to f)|$, λ_f simplifies to

$$\lambda_f = \eta_f \frac{q}{p} e^{-i2\xi_f}, \qquad |\lambda_f| = \left|\frac{q}{p}\right|. \tag{11.25}$$

Moreover, if in the adopted phase convention (like CKM convention) the phase ξ_f is negligible as assumed in what follows, we have

$$\lambda_f = \eta_f \frac{q}{p} = \eta_f \left|\frac{q}{p}\right| e^{i2\tilde{\varphi}}, \qquad \tilde{\varphi} = \frac{1}{2} \arg \frac{q}{p}. \tag{11.26}$$

We then find

$$\frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \equiv S_f \frac{t}{2\bar{\tau}_D}, \tag{11.27}$$

where we defined in analogy with the B system

$$S_f \simeq -\eta_f \left[y_D \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right| \right) \cos 2\tilde{\varphi} - x_D \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right| \right) \sin 2\tilde{\varphi} \right]. \tag{11.28}$$

Note that in the B system $y \ll x$ and $|q/p| \simeq 1$, so that the preceding result simplifies considerably in the case of the CP asymmetries $S_{\psi K_S}$ and $S_{\psi\phi}$ in the B_d and B_s system, respectively.

Finally, we introduce the semileptonic asymmetry

$$a_{\rm SL}(D^0) \equiv \frac{\Gamma(D^0(t) \to \ell^- \bar{\nu} K^{+(*)}) - \Gamma(\bar{D}^0 \to \ell^+ \nu K^{-(*)})}{\Gamma(D^0(t) \to \ell^- \bar{\nu} K^{+(*)}) + \Gamma(\bar{D}^0 \to \ell^+ \nu K^{-(*)})} = \frac{|q|^4 - |p|^4}{|q|^4 + |p|^4} \approx 2\left(\left|\frac{q}{p}\right| - 1 \right), \tag{11.29}$$

which represents CP violation in $\Delta C = 1$ transitions. In writing the last expression, we assumed that $|q/p| - 1$ is much smaller than unity.

11.3.2 Useful Relations

We next list a number of useful relations that have been derived in [685].

We define

$$\boxed{x_{12} \equiv \frac{2|M_{12}|}{\Gamma}, \qquad y_{12} \equiv \frac{2|\Gamma_{12}|}{\Gamma}, \qquad \varphi_{12} = \frac{1}{2} \arg\left(\frac{M_{12}^D}{\Gamma_{12}^D} \right).} \tag{11.30}$$

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Then one finds for x_D and y_D in (11.7)

$$x_D = \text{sign}(\cos\varphi_{12}) \left(x_{12}^2 - y_{12}^2 + \sqrt{(x_{12}^2 - y_{12}^2)^2 - 4x_{12}^2 y_{12}^2 \sin^2\varphi_{12}} \right)^{1/2} \tag{11.31}$$

$$y_D = \left(y_{12}^2 - x_{12}^2 + \sqrt{(x_{12}^2 - y_{12}^2)^2 - 4x_{12}^2 y_{12}^2 \sin^2\varphi_{12}} \right)^{1/2}. \tag{11.32}$$

These equations relate the neutral meson mass and width differences to mixing parameters x_{12}, y_{12} and φ_{12}.

Next

$$\tan\varphi = -\frac{\sin 2\varphi_{12}}{\cos 2\varphi_{12} + y_{12}^2/x_{12}^2}, \tag{11.33}$$

$$\tan\varphi = \left(1 - \left|\frac{q}{p}\right|\right) \frac{x_D}{y_D} = -\frac{a_{\rm SL}}{2} \frac{x_D}{y_D}. \tag{11.34}$$

11.3.3 Correlations

Having all these formulas at hand we can derive two interesting correlations. Following the presentation in [695], we find

$$\sin^2 2\tilde{\varphi} = \frac{x_D^2 (1 - |q/p|^2)^2}{x_D^2 (1 - |q/p|^2)^2 + y_D^2 (1 + |q/p|^2)^2}, \tag{11.35}$$

where in the phase conventions adopted in (11.6) $\tilde{\varphi} = 1/2 \arg(q/p)$. In the limit $||q/p|-1| \ll 1$, $x_D \sim y_D$ (11.35) reduces to [695]

$$\sin 2\tilde{\varphi} = \frac{x_D}{y_D} \left(1 - \left|\frac{q}{p}\right|\right), \tag{11.36}$$

where the sign ambiguity in taking the square root of (11.35) can be resolved numerically. Using then (11.28) and (11.29) we find for $\xi_f = 0$

$$S_f = -\eta_f \frac{x_D^2 + y_D^2}{y_D} a_{\rm SL}(D^0). \tag{11.37}$$

The violation of the relation (11.37) in future experiments would imply the presence of direct CP violation at work [695]. In the presence of a significant phase ξ_f we find

$$S_f = -\eta_f \left[\cos 2\xi_f \frac{x_D^2 + y_D^2}{y_D} a_{\rm SL}(D^0) + 2x_D \sin 2\xi_f \right]. \tag{11.38}$$

Similar correlation is familiar from the B_s system [695–697], and we recall it using the formulation just presented.

Indeed formulas for CP asymmetries just discussed can be applied to the B_s meson system as well. We recall that in the latter system $|q/p| = 1$ with good accuracy, and in addition $y \ll x$. Using (11.35), we find

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$$a_{\rm SL}^s = -2\left|\frac{y_s}{x_s}\right| \frac{S_{\psi\phi}}{\sqrt{1-S_{\psi\phi}^2}}, \tag{11.39}$$

which agrees with [695] and represents an alternative derivation of the correlation found in [696, 697]. Note that we used the definition

$$a_{\rm SL}^s = \frac{\Gamma(\bar{B}_s(t) \to \ell^+ X) - \Gamma(B_s(t) \to \ell^- X)}{\Gamma(\bar{B}_s(t) \to \ell^+ X) + \Gamma(B_s(t) \to \ell^- X)}, \tag{11.40}$$

and $S_{\psi\phi}$ is the coefficient of $\sin \Delta M_s t$ in

$$\frac{\Gamma(\bar{B}_s(t) \to \psi\phi) - \Gamma(B_s(t) \to \psi\phi)}{\Gamma(\bar{B}_s(t) \to \psi\phi) + \Gamma(B_s(t) \to \psi\phi)}. \tag{11.41}$$

Further

$$x_s = \frac{m_H - m_L}{\bar{\Gamma}_s}, \qquad y_s = \frac{\Gamma_H - \Gamma_L}{2\bar{\Gamma}_s}, \tag{11.42}$$

where we stress that our definition of y_s differs by sign from the HFAG one. Finally, in determining the overall sign of (11.39) we assumed $(y_s)_{\rm SM} < 0$.

11.4 Connection between *D* and *K* Physics

In [683] the connection between $D^0 - \bar{D}^0$ and $K^0 - \bar{K}^0$ mixing has been discussed within the framework of approximately $\mathrm{SU}(2)_L$-invariant NP. Due to the connection between up- and down-type quarks in the SM through the CKM matrix, in this scenario the NP contributions to $D^0 - \bar{D}^0$ and $K^0 - \bar{K}^0$ mixing are not independent of each other. This observation has been used in [683] to derive lower bounds on the NP scale in various NP scenarios, emerging if the experimental constraints on $D^0 - \bar{D}^0$ and $K^0 - \bar{K}^0$ mixing are applied to only the $(V - A) \otimes (V - A)$ contribution. One should keep in mind, however, that in models in which new operators contribute to $\Delta F = 2$ processes the power of this approach is limited, as the various contributions interplay with each other and dilute the correlation in question.

On the other hand, the situation is promising in NP models with only SM operators, such as the littlest Higgs model with T-parity (LHT).[1] In fact, this model provides possibly the best example of the physics discussed in [683]. While the following discussion has been triggered by the analysis of $\Delta C = 2$ processes in the LHT model and uses the notations and conventions of [675, 699, 700], it applies as well to all other NP scenarios with only SM operators. Similar to the LHT model, the flavor mixing matrices V_{Hu} and V_{Hd} parameterize the misalignment between the NP and the SM up- and down-type quarks, respectively, and are related via

$$V_{Hu} = V_{Hd} V_{\rm CKM}^\dagger. \tag{11.43}$$

$D^0 - \bar{D}^0$ oscillations are then governed by the combinations ($i = 1, 2, 3$)

$$\xi_i^{(D)} = V_{Hu}^{iu\,*} V_{Hu}^{ic}, \tag{11.44}$$

[1] Readers not familiar with this model should have a brief look at [698].

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while for K, B_d, and B_s physics

$$\xi_i^{(K)} = V_{Hd}^{is\ *} V_{Hd}^{id}, \qquad \xi_i^{(d)} = V_{Hd}^{ib\ *} V_{Hd}^{id}, \qquad \xi_i^{(s)} = V_{Hd}^{ib\ *} V_{Hd}^{is}, \tag{11.45}$$

respectively, are relevant. By making use of (11.43) we can now express $\xi_i^{(D)}$ through combinations of V_{Hd} and CKM elements. Using the Wolfenstein parameterization for $V_{\rm CKM}$ and expanding in powers of λ, we find

$$\begin{aligned}\xi_i^{(D)} = \xi_i^{(K)*} &+ \lambda\left(|V_{Hd}^{is}|^2 - |V_{Hd}^{id}|^2\right) + \lambda^2\left(A\xi_i^{(d)*} - 2\mathrm{Re}(\xi_i^{(K)})\right) \\ &+ \lambda^3\left(\frac{1}{2}(|V_{Hd}^{id}|^2 - |V_{Hd}^{is}|^2) + A\xi_i^{(s)*} + A\xi_i^{(s)}(\rho - i\eta)\right) + O(\lambda^4).\end{aligned} \tag{11.46}$$

The following comments are in order:

- At leading order $\xi_i^{(D)} = \xi_i^{(K)*}$, i. e., D and K physics are governed by the *same* NP flavor structure. We note that the complex conjugation arises, as $|D^0\rangle = |\bar{u}c\rangle$ while $|K^0\rangle = |\bar{s}d\rangle$, and it will give rise to a sign difference in CP violating effects in the D and K systems.
- The correction to linear order in λ is real, irrespective of the precise structure of V_{Hd}. However, as $\Delta C = 2$ CP violation is governed by

$$\mathrm{Im}(\xi_i^{(D)})^2 = 2\mathrm{Re}\xi_i^{(D)}\mathrm{Im}\xi_i^{(D)}, \tag{11.47}$$

  corrections to the one-to-one correspondence between $D^0 - \bar{D}^0$ and $K^0 - \bar{K}^0$ mixings will appear already at $O(\lambda)$ in both CP conserving and violating observables. On the other hand, the $\Delta C = 1$ effective Hamiltonian is governed by a single power of $\xi_i^{(D)}$, so that direct CP violation in rare D and K decays will be much more strongly correlated, and deviations from the one-to-one correspondence will arise only at $O(\lambda^2)$.
- The order $O(\lambda^2)$ correction can be complex, provided that $\mathrm{Im}\xi_i^{(d)} \neq 0$, i. e., that there are new CP-violating effects in the B_d system.
- At $O(\lambda^3)$ a complex correction arises due to the CP violation in the CKM matrix, given by $i\eta$. This correction is nonvanishing also in the limit of a real, i. e., CP conserving V_{Hd}, and vanishes only if $\xi_i^{(s)} = 0$.

This discussion shows that when doing NP phenomenology in the K-meson system one should check whether experimental bounds in charm systems are satisfied. For a recent analysis of this issue in the context of the ratio ε'/ε, see [701].

There is no question that charm will play a significant role in the tests of the SM and the search for NP in the coming years.

These expectations have been confirmed at Moriond 2019. LHCb presented the first observation of CP violation in the decays of charm hadrons. For the difference between the CP asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, they find [702]

$$\boxed{\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}.} \tag{11.48}$$

In this difference the CP violation in mixing cancels out so that this difference measures within excellent approximation direct CP violation. It remains to be seen whether some NP could be responsible for this result [703–705, 1331]. Among these papers I can recommened in particular [705, 1331] and an older paper [706]. A short summary of the LHCb data and the prospects for the future can be found in [707].

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