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Flavour physics and CP violation / Physique de la saveur et violation de CP

Future of charm physics

Futur de la physique du charme

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A B S T R A C T

Charm particles provide a unique opportunity to study particle–antiparticle mixing induced by virtual down-type quarks. CP violation in charm physics is still a Terra Incognita which remains to be explored. Charm hadrons are also a laboratory to control hadronic uncertainties in weak transitions of heavy quarks. To do this physics program, large data samples registered close to the production threshold or at higher energies are needed.

R É S U M É

Les particules charmées fournissent l'unique possibilité d'étudier le mélange entre particule et antiparticule induit par des quarks de type « down ». La violation de la symétrie CP dans le charme reste une terre inexplorée. Les hadrons charmés sont aussi un laboratoire pour controler les incertitudes hadroniques dans les transitions faibles des quarks lourds. Pour réaliser ce programme de physique, de grandes quantités de données enregistrées au voisinage du seuil de production du charme et à plus haute énergie sont nécessaires.

1. Role of charm physics – past and future

1.1. Charm at the birth of the Standard Model

Originally one had three quarks – u, d and s – and three leptons – e, μ and ν. This match between three quarks and leptons was upset in 1962 by the discovery of having two neutrinos – until in 1964 daring theorists [1,2] re-established this match by postulating a fourth quark. Equally daring theorists [3] realized in 1970 that the fourth quark can explain the observed suppression of the strangeness changing neutral currents (SCNC) in ΔM_K and $BR(K_L \to \mu^+\mu^-)$, etc. This fourth quark has to couple to charged currents in analogy to u quarks to create a destructive interference with them and its mass has to fall around 2 GeV. The name for 'charm' was coined not in analogy to 'beauty', but from its role as a 'snake charmer' in suppressing the dangerous SCNC. It was one of the crucial features of the Standard Model (SM) based on the concept of 'families' of fundamental fermions of quarks and leptons. These were old-fashioned predictions from theorists, since they were given clearly before experimental discoveries.

S.C.C. Ting and B. Richter were awarded the Nobel prize in Physics in 1976 for their 1974 "pioneering work in the discovery of a heavy elementary particle of a new kind", namely the J/ψ, which was then recognized as bound state of

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Table 1
Typical measurement accuracy on branching fractions and lifetimes for weakly decaying charm hadrons [8].

Charm particle	Reference channel	BR (%)	$\sigma(BR)/BR$ (%)	Lifetime (10^{-15} s)	$\sigma(\tau)/\tau$ (%)
D^0	$K^-\pi^+$	3.87 ± 0.05	1.3	410.1 ± 1.5	0.36
D^+	$K^-\pi^+\pi^+$	9.13 ± 0.19	2.2	1040 ± 7	0.67
D_s^+	$K^-K^+\pi^+$	5.49 ± 0.27	4.9	500 ± 7	1.4
Λ_c^0	$pK^-\pi^+$	$5.0 \pm 1.3(?)$	26	200 ± 6	3
Ξ_c^+	?	?	?	442 ± 26	6
Ξ_c^0	?	?	?	112^{+13}_{-10}	12
Ω_c^0	?	?	?	69 ± 12	17

a charm quark and antiquark. Open charm hadrons, composed by charm and other light quarks, were established only in 1976. This history illustrates how evidence for New Physics (NP) can be inferred from the study of a rare process.

There is another example connected to it. The first evidence for a charm hadron was found by the group of K. Niu in 1971 [4] in cosmic data in Japan. This result was shown the same year at a conference on Cosmic rays held in Australia, but left mostly unnoticed. In Japan, however, this result was well known. It helped M. Kobayashi and T. Maskawa in 1973 [5] to speculate that more than two families with four quarks could exist and that three (or more) families naturally create CP violation. This realization was given after CP violation was observed in $K_L \to \pi^+\pi^-$ in 1964 – but well before the Υ discovery and even more for top quarks.

In the following we consider measurements which are relevant for the study of weak interactions. For this reason we have not detailed recent discoveries of new charmonium states at b-factories nor the spectroscopy of $c\bar{q}$ mesons with $q = u$, d or s where several new states have been identified.

1.2. Status of decay branching fractions and lifetimes of charm hadrons

1.2.1. Decay branching fractions

The exclusive reconstruction of charm meson decays was first done in 1976 at SLAC with the MARKI detector at the SPEAR e^+e^- collider running at around 4 GeV center of mass energy.

Absolute measurements of branching fractions require to reconstruct a given decay channel of a charm hadron and to know how many such hadrons have been produced independently of their decay mode. Usually the second point is the most difficult to achieve in an accurate way. For colliders operating at (or close to) a $D\overline{D}$ production threshold, one of the two D mesons is exclusively reconstructed to prepare a sample of charm mesons with a known flavour. From the counting of the accompanying charm meson decaying into a given channel it is then possible to measure the corresponding decay branching fraction. For D^0 and D^+ mesons one can operate an e^+e^- collider at the production energy of the $\Psi(3770)$ resonance. For D_s mesons the energy of 4.17 GeV, a value close to the $D_s^- D_s^{*+}$ threshold, is chosen by the CLEO-c Collaboration. At present, no dedicated data has been collected at these machines in the region of charm baryon production for corresponding absolute branching fraction measurements.

At b-factories the energy working point is usually close to the $\Upsilon(4S)$ resonance mass, and it corresponds also to a large cross section (~ 1.3 nb) for charm events produced in the continuum. But, as this energy is far from threshold for charm production, the flavour correlation is lost between the two emitted charm hadrons, because additional particles are produced in the event. It is still possible to tag the production of a charm hadron of a given flavour by reconstructing all other particles produced in the event. This approach was pioneered by Belle [6] to measure semileptonic decays of D^0 mesons. It has been used more recently by BaBar to measure absolute leptonic decay branching fractions of D_s mesons [7]. The D_s meson production is tagged by considering events from the reaction $e^+e^- \to c\bar{c} \to H_c K X D_s^- \gamma$; H_c is D^0, D^+, D^* or Λ_c exclusively reconstructed, K a K^+ or K_S^0 and X a system of at most three pions, including at most one π^0 with a total electric charge appropriate to ensure the neutrality of the overall final state. The number of produced D_s mesons is obtained by considering the distribution in the recoil mass $M_{\rm rec}(DKX\gamma)$ which has a peak at the D_s mass for signal events. This analysis has a 100 times lower tagging efficiency than the CLEO-c data collected at threshold. Yet this small efficiency is compensated by the much higher integrated luminosity registered at b-factories. While measurements at CLEO-c are statistically limited, systematic uncertainties related to the background control dominate the methods developed at b-factories. These competitions about absolute charm branching fraction measurements will fade during the coming years from BESIII data, a real charm factory (and future ones). Another important benefit from a charm factory operating at charm threshold production is that the small combinatorial background allows to measure accurately decay channels with one or several neutrals.

1.2.2. Future goals for branching ratios

For D mesons in 2010, the most accurate branching fraction measurements are obtained by CLEO-c. For D_s mesons, a similar statistical accuracy is reached by BaBar on some channels. As already advertised, absolute branching fractions of charm baryons have still to be measured. Present values obtained for some reference decay channels are reminded in Table 1.

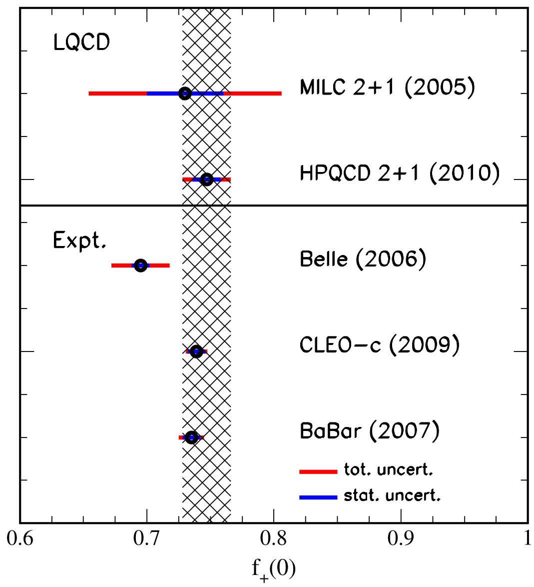

Fig. 1. Comparison between measurements of the hadronic form factor at $q^2 = 0$ in $D^0 \to K^- e^+ \nu_e$ decays and corresponding LQCD evaluations (hatched area).

For D^0 Cabibbo favoured (CA) decays, relative accuracies are close to 1%, but larger for Cabibbo suppressed (CS) and even worse for doubly Cabibbo suppressed (DCS) ones. For D^+ and D_s^+ the errors are increased by a factor of order two and four, respectively, and much larger for charm baryons.

The cleanest transitions where a partial decay width can show the manifestation of NP are $D^+/D_s^+ \to \ell \nu_\ell$ ($\ell = \mu, \tau$). The decay partial widths depend on a single hadronic parameter, namely the decay constants $f_{D_{(s)}}$. Their values have been computed at present in LQCD with an accuracy of 2% and 1.3% for D^+ and D_s^+ respectively. It is anticipated that LQCD computations will reach an accuracy about a few per mill. On the experimental side the absolute lepton identification and background control can be improved likewise to the few per mill level. Extrapolating from CLEO-c's achieved uncertainty of 4% based on 0.8 fb^{-1} one expects BESIII can achieve 1% statistical accuracy on f_{D^+} with an expected 10 fb^{-1} registered integrated luminosity. With an order of magnitude increase in the integrated luminosity at a new charm factory machine, one can attain the goal of the 3 per mil to match experimental and theoretical uncertainties.

The large statistics registered at b-factories and their good detector capabilities can be used to analyze Dalitz plots of non-leptonic decays and obtain detailed information on the different contributing amplitudes and on low mass hadronic resonances parameters. In these analyses there is no need to reconstruct the other charm hadron, nor the accompanying particles and, as a result, distributions with very large statistics are obtained allowing to measure detailed properties of such decays. Those will give new lessons on (semi-)soft QCD – and, as sketched below, on CP asymmetries.

1.3. Charm – a laboratory for validating LQCD

We have good chances to find NP in flavour transitions by measuring differences between SM predictions and observed data. They depend on our control of hadronic parameters in K, B and D descriptions, in particular of non-perturbative QCD. The most universal method to obtain them with controlled uncertainties is from LQCD as referred above. Charm transitions occur in the range between hard and soft QCD effects, where LQCD simulations can be given from first principle; then they can be extrapolated using heavy quark symmetry to B hadrons. Even if progress is anticipated in LQCD decay constants expectations, the situation is quite different from QED and it is unlikely that uncertainties at the per mille level will be obtained. This limitation fixes the goals for measurement accuracies which have to reach few per mille levels. It indicates also that significant deviations from new physics will be observed in this approach only if they are above at least one percent.

As mentioned, the rates for $D_{[s]}^+ \to \mu^+ \nu$ are measured with an experimental uncertainty matched with the theoretical uncertainty from LQCD results for f_D now and better soon with the BESIII measurements.

The next validation comes from exclusive semileptonic D decays. Fig. 1 compares present measurements of $f_+(0)$, the value evaluated at $q^2 = (p_e + p_{\nu_e})^2 = 0$ of the hadronic form factor entering in the decay $D^0 \to K^- e^+ \nu_e$. Measurements of BaBar and CLEO-c have a similar relative uncertainty of 1.2% whereas LQCD reaches 2.5%. To calculate the rates for exclusive non-leptonic $D \to K\pi$, 2π, $K\overline{K}$, LQCD has to face more conceptual and technical challenges, and this will take more time.

1.4. Lifetimes of charm hadrons

To obtain decay rates from branching fractions one needs charm hadrons lifetimes:

$$\Gamma(D \to f) = BR(D \to f) \times \Gamma_{tot} \propto BR(D \to f)/\tau(D) \tag{1}$$

Colliders running at threshold with symmetric beam energies cannot contribute to these measurements. Lifetimes are measured at fixed target experiments, b-factories and high energy hadronic colliders. These measurements (Table 1) are more accurate than present determinations of decay branching fractions. Considering the values given in Table 1, apart for the D^0, all other lifetime measurements need to be improved so that they are not an additional source of accuracy limitation in partial widths determinations.

For the theoretical treatment the Heavy-Mass Expansion has been used in the framework of the OPE (Operator Product Expansion). Expectations agree with the measurements of seven weakly decaying charm hadrons within about 30% – better than one would expect. In the future LQCD can improve accuracies of the values for several static hadronic expectations that enter the OPE.

1.5. D^0–$\overline{D}^0$ oscillations

Only D^0–$\overline{D}^0$ oscillations can occur for mesons from up-type quarks. π^0 or η mesons decay electromagnetically and cannot oscillate whereas top quarks decay weakly before they can form neutral top mesons. One has to keep in mind that the impact from New Physics can be different for up-type quarks than for down-type and the study of D^0–$\overline{D}^0$ oscillations is unique in this respect.

Following Refs. [9] and [10], let us recall the general formalism to describe D^0–$\overline{D}^0$ oscillations. We define p and q as the charm eigenstate components in the mass eigenstates $|D_{1,2}\rangle$:

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D^0}\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D^0}\rangle \end{aligned} \tag{2}$$

with the normalization: $|p|^2 + |q|^2 = 1$. The two physical states ($|D_{(1,2)}\rangle$) evolve according to:

$$\big|D_i(t)\big\rangle = e^{-(iM_i + \frac{\Gamma_i}{2})t}\big|D_i(0)\big\rangle \tag{3}$$

in which M_i and Γ_i are the physical mass and width, respectively.

The observation of oscillation was obtained by measuring the time evolution of states which are pure $|D^0\rangle$ or $|\overline{D^0}\rangle$ when they are created. Using Eqs. (2) and (3) it gives:

$$\big|D_0(t)\big\rangle = f_+(t)|D^0\rangle + \frac{q}{p} f_-(t)|\overline{D^0}\rangle \tag{4}$$

$$\big|\overline{D^0}(t)\big\rangle = f_+(t)|\overline{D^0}\rangle + \frac{p}{q} f_-(t)|D^0\rangle \tag{5}$$

where

$$f_+(t) = e^{-(iM_D + \frac{\Gamma_D}{2})t} \cos\left[\frac{1}{2}\left(\Delta M_D - \frac{i\Delta\Gamma_D}{2}\right)t\right] \tag{6}$$

$$\begin{aligned} f_-(t) &= e^{-(iM_D + \frac{\Gamma_D}{2})t} i \sin\left[\frac{1}{2}\left(\Delta M_D - \frac{i\Delta\Gamma_D}{2}\right)t\right] \\ M_D &= \frac{M_1 + M_2}{2}, \qquad \Delta M_D = M_2 - M_1, \\ \Gamma_D &= \frac{\Gamma_1 + \Gamma_2}{2}, \qquad \Delta\Gamma_D = \Gamma_2 - \Gamma_1 \end{aligned} \tag{7}$$

In the search for D^0–$\overline{D}^0$ oscillations one is primarily interested in DCS decays of these states into a final state $|f\rangle$ and one can define the following decay amplitudes:

$$\begin{aligned} A &= \langle f|H|D^0\rangle, \qquad B = \langle f|H|\overline{D^0}\rangle, \\ \overline{A} &= \langle \overline{f}|H|\overline{D^0}\rangle, \qquad \overline{B} = \langle \overline{f}|H|D^0\rangle \end{aligned} \tag{8}$$

A and $\overline{A}$ denote DCS amplitudes whereas B and $\overline{B}$ are CA. $\langle f|$ and $\langle \overline{f}|$ describe CP conjugate states as $K^+\pi^-$ and $K^-\pi^+$, for example.

The decay amplitudes into DCS states are then:

$$\langle f|H|D^0(t)\rangle = B\frac{q}{p}\left[\lambda f_+(t) + f_-(t)\right] \tag{9}$$

$$\langle \bar{f}|H|\overline{D^0}(t)\rangle = \bar{B}\frac{q}{p}\left[\bar{\lambda} f_+(t) + f_-(t)\right],$$

$$\lambda = \frac{p}{q}\frac{A}{B}, \qquad \bar{\lambda} = \frac{q}{p}\frac{\bar{A}}{\bar{B}} \tag{10}$$

Present experimental results verify $\Delta M_D \ll \Gamma_D$, $\Delta\Gamma_D \ll \Gamma_D$ and $\lambda \ll 1$. Using these approximations, the time dependence of the D^0 decay partial width into the DCS state f can be written:

$$\Gamma\left[D^0(t) \to f\right] = \frac{e^{-\Gamma_D t}}{4}|B|^2\left|\frac{q}{p}\right|^2 \times \left[4|\lambda|^2 + \left(\Delta M_D^2 + \frac{\Delta\Gamma_D^2}{4}\right)t^2 + 2\,\mathrm{Re}(\lambda)\Delta\Gamma_D t + 4\,\mathrm{Im}(\lambda)\Delta M_D t\right] \tag{11}$$

A similar expression is obtained for $\Gamma[\overline{D^0}(t) \to \bar{f}]$ by changing f, B, λ to $\bar{f}$, $\bar{B}$, $\bar{\lambda}$ and $p \leftrightarrow q$. The term proportional to $|\lambda|^2$ describes the contribution from the DCS rate, the term proportional to t^2 describes the lowest order contribution from oscillations, and the term proportional to t represents interference between oscillation and DCS amplitudes.

If CP symmetry is conserved, then:

$$\frac{|A|}{|\bar{A}|} = \frac{|B|}{|\bar{B}|} = 1, \quad \left|\frac{p}{q}\right| = 1 \quad \text{and} \quad \lambda = \bar{\lambda} \tag{12}$$

A hadronic phase (δ_f) remains possibly between the A (DCS) and B (CA) amplitudes and the term which is proportional to t in Eq. (11) depends on a linear combination of ΔM_D and $\Delta\Gamma_D$.

1.5.1. Experimental status

D^0–$\bar{D}^0$ oscillations have been observed by BaBar in 2007 and confirmed by Belle and CDF Collaborations. Combining all measurements, the null oscillation hypothesis is now excluded at more than 10σ [11]. Two main experimental studies have produced results.

(i) One consists in tagging the production of a D^0 meson at the time of the collision using the decay $D^{*+} \to D^0\pi^+$ and in measuring the time dependence of a decay final state which originates totally or partially from a $\bar{D}^0$ meson. A semileptonic decay as $K^+\ell^-\bar{\nu}_\ell$ receives only contribution from the $\bar{D}^0$ ($A = \bar{A} = 0$) whereas the final state $K^+\pi^-$ corresponds also to a DCS decay. Using Eq. (11) and neglecting CP violation, the time dependence of the measured event rate is written as:

$$T_{DCS}(t) \propto e^{-t/\tau}\left[R_{DCS} + \sqrt{R_{DCS}}\,y'_D\left(\frac{t}{\tau}\right) + \frac{x'^2_D + y'^2_D}{4}\left(\frac{t}{\tau}\right)^2\right] \tag{13}$$

where $\tau = 1/\Gamma_D$ is the D^0 lifetime and R_{DCS} the ratio between CA and DCS decay branching fractions; x'_D and y'_D are related to x_D and y_D through the hadronic phase δ_f between CA and DCS amplitudes:

$$x_D = \frac{\Delta M_D}{\Gamma_D}, \qquad y_D = \frac{\Delta\Gamma_D}{2\Gamma_D} \tag{14}$$

$$x'_D = x_D\cos\delta_f + y_D\sin\delta_f, \qquad y'_D = -x_D\sin\delta_f + y_D\cos\delta_f \tag{15}$$

As x_D, $y_D \ll 1$ measurements are mainly sensitive to the linear term in t.

(ii) The other approach consists in measuring the lifetime of decay final states having a different composition in the two mass eigenstates. Assuming CP symmetry the $\pi^+\pi^-$ and K^+K^- final states are produced by the CP even mass eigenstate, while $K^\pm\pi^\mp$ final states give the average of the two mass eigenstates:

$$y_D \simeq y_D^{CP} = \frac{\tau(K^\pm\pi^\mp)}{\tau(K^+K^- \text{ or } \pi^+\pi^-)} - 1 \tag{16}$$

BaBar and Belle get the largest significance by measuring y_D^{CP} giving [11]:

$$y_D^{CP} = (1.11 \pm 0.22)\% \tag{17}$$

Combining data obtained from $D^0/\overline{D^0} \to K^\mp\pi^\pm$, $\pi^+\pi^-$, K^+K^-, $K_S\pi^+\pi^-$ yields [11]:

$$x_D = (0.63 \pm 0.20)\%, \qquad y_D = (0.75 \pm 0.12)\% \tag{18}$$

To relate (x'_D, y'_D) to (x_D, y_D), one needs the strong phase δ_f. It can be measured at threshold using quantum coherence [12]. Analyzing data with 0.8 fb^{-1} CLEO-c finds a value compatible with zero and a non-Gaussian uncertainty of

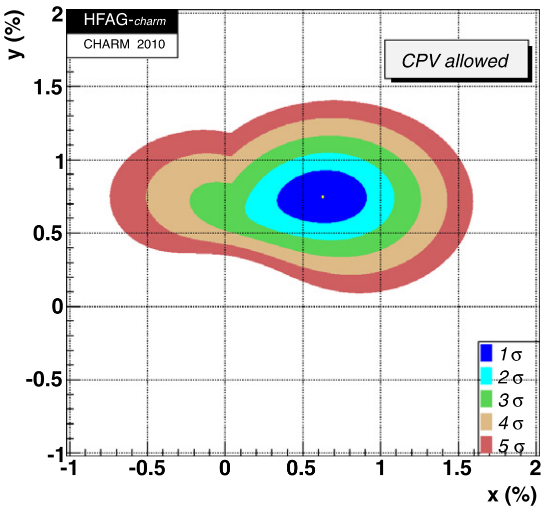

Fig. 2. Region of the (x_D, y_D) plane favoured when combining all measurements sensitive to D^0–$\overline{D}^0$ oscillations [11].

around 22°. The region favoured by present measurements in the (x_D, y_D) plane is given in Fig. 2. While the D^0–$\overline{D^0}$ oscillations have been established, the values of x_D, y_D are not well known, not even their relative size. One needs more accurate values for both as sketched below. They should be provided by LHCb and the Super-Flavour Factory; for the phases δ_f one needs a high luminosity collider operating at charm threshold.

1.6. Theory interpretation

The observed sizes of x_D and y_D are in the range 0.5–1%. The history of SM predictions in this domain does not form one of the glorious pages of theoretical HEP (although there have been a few heretics against the orthodoxy). This is mainly because the charm quark is not really heavy and also because intermediate hadronic states involve light down-type quarks (the coupling to intermediate b-quarks is negligible). Large corrections are thus expected, from strong interactions, to naive estimates based on first order OPE which give: $x_D \sim 10^{-5}$ and $y_D \sim 10^{-7}$. In the Standard Model and in the limit of exact SU(3) flavour symmetry x_D and y_D vanish. It has been demonstrated [13,14] that these two quantities are proportional to the square of SU(3) breaking effects.

$$x_D, \quad y_D \simeq \sin^2(\theta_C) \times \left[\mathrm{SU(3)}\ \mathit{breaking}\right]^2 \tag{19}$$

Meanwhile it is still difficult, at present, to obtain accurate evaluations of these quantities in the SM [13,16]. While the measured values might be accommodated in the SM dynamics, we should understand that:

- x_D and y_D originate from quite different processes, namely x_D and y_D by *off*-shell and *on*-shell exchanges, respectively;
- therefore x_D can be much more affected by New Physics than y_D because off-shell new particles can contribute in the loop;
- Considering phase space differences as sources of SU(3) breaking effects, it is shown in [14] that a value of $y_D \sim 1\%$ is plausible within the SM. Using the same considerations and applying dispersion relations to relate x_D and y_D [15] it is found that $|x_D| \sim (0.1–1)\%$.

Considering the theoretical uncertainties in predictions for x_D and y_D it is quite possible that NP could significantly affect the value of x_D. In Ref. [17] constraints on different scenarios are reviewed and it is shown how a class of NP models that are primarily motivated outside flavour dynamics can produce a large part of x_D and how it can enhance CP asymmetries in D decays greatly, as discussed below. For these reasons one must measure separately the values of x_D and y_D. More accurate measurements of the absolute and relative sizes of these two quantities will help significantly also to encourage more reliable theoretical projects where LQCD and other analyses methods co-operate. To look for NP, x_D is more favourable but, experimentally it is more difficult to measure, as it needs also accurate determinations of y_D and of the strong phases δ_f. In this respect a high luminosity charm factory is unique to obtain δ_f.

The small values of x_D and y_D imply that the study of D^0 oscillations, themselves, at a charm factory is extremely difficult. Let us consider, as an example, the decay $\Psi(3770) \to K^-\pi^+K^-\pi^+$. As the D^0 and $\overline{D}^0$ are produced from the decay of the $\Psi(3770)$, quantum coherence implies that the considered final state comes only from the oscillation of a $\overline{D}^0$ into a D^0. The corresponding production rate is proportional to $x_D^2 + y_D^2$ rendering the measurement almost impossible for x_D, $y_D < 1\%$. Running the machine at a higher energy, the final state $e^+e^- \to D^0\overline{D}^0\gamma \to K^-\pi^+K^-\pi^+\gamma$ has a production rate which is sensitive to the linear term of interference between DCS and oscillation amplitudes (as in Eq. (13)). Neglecting uncertainties from the background control, such a possibility can be envisaged only with a high luminosity collider ($> 10^{34}$ cm^{-2} s^{-1}, because $\sigma(y'_D) \sim 1.5\%$ is expected with an integrated luminosity of 10 fb^{-1} registered at 4.14 GeV).

1.7. CP violation

Rare charm decays might reveal manifestations of physics beyond the SM as for K and B mesons. However the large impact of long distance dynamics here might not be a promising area – unless one probes CP asymmetries!

As with other flavour physics, CP violating contributions in charm can be classified into three categories (see as an example [18] and references therein):

- direct CP violation when the absolute value of a D decay amplitude into a final state f is different from the one for CP conjugated states;
- indirect CP violation or CP violation in D^0–$\overline{D^0}$ oscillations; it corresponds to $|p/q| \neq 1$, see Eq. (2);
- CP violation in the interference of decays with and without oscillations. It is possible for states to which both D^0 and $\overline{D^0}$ can decay. For a given final state, CP violating contributions can be summarized in the parameter λ, see Eq. (10).

As charm decays involve quarks from the first two families, the SM can produce only very small CP asymmetries, and the strong interactions cannot generate them *by themselves*. Since D^0–$\overline{D^0}$ oscillations are somewhat larger than possibly expected in the SM, one has to state more explicitly what 'very small' means for CP violations in the SM. While non-perturbative effects in QCD can enhance x_D and y_D, they cannot significantly increase indirect CP violation beyond what SM can generate. The present world average is $|q/p| = 0.91^{+0.18}_{-0.16}$ [11]. It is compatible with one and large improvements in terms of statistics and in the control of systematic uncertainties are needed to reach the 1% region where effects from NP may appear.

For direct CP asymmetries one needs the interference between two different weak amplitudes with different strong phases. The need for different strong phases in the observed amplitudes is easily satisfied in charm decays. However having different weak phases cannot happen for CA and DCS decays (unless K_S is in the final states). Only CS transitions can show CP violation and at a level of the order of 10^{-3} or less which is still far below the present experimental sensitivity (around 1%). Because of uncertainties from strong interactions, there are no accurate predictions for CP asymmetries in CS decays and New Physics signals could be obtained, in a convincing way, only if several channels are analyzed and if a consistent picture emerge.

A special attention has to be devoted to the transition $D^+ \to K^0_S \pi^+$ which reflects the interference between $D^+ \to \overline{K^0}\pi^+$ (CA) and $D^+ \to K^0\pi^+$ (DCS) amplitudes [19]. The known CP impurity in the K^0_S state induces a difference without any theory uncertainty:

$$\frac{\Gamma(D^+ \to K^0_S\pi^+) - \Gamma(D^- \to K^0_S\pi^-)}{\Gamma(D^+ \to K^0_S\pi^+) + \Gamma(D^- \to K^0_S\pi^-)} = -2\,\mathrm{Re}(\epsilon_K) \simeq -3.3 \times 10^{-3} \tag{20}$$

New Physics can enter most probably in the DCS amplitude, changing the size and possibly the sign of the asymmetry.

Many models for NP have been constructed specially for large deviations from SM predictions in charm transitions, while a few ones are based on more general motivations like the Little Higgs Models [10].

Measuring CP asymmetries between D and $\overline{D}$ decays with the needed accuracy (10^{-3} or better) depends on the control of reconstruction efficiencies for particles and their corresponding antiparticles. This can be best achieved when running at an energy close to the charm production threshold because hadronic decays of the J/Ψ meson can be used to illuminate the detector with particles of known type and energy.

However to distinguish indirect and direct CP violation it is important to track the time dependence of the decays. That can be achieved only well above the charm production threshold (unless one has an asymmetric charm factory). The decay of a charged D^* can be used to tag the production of a D^0 or $\overline{D}^0$ meson at the time of the collision. The $D^0 \to K_S\phi$ transition has several interesting properties [10] and NP can produce indirect, but hardly observable direct CP violation (apart from the known time independent CP violation in the K_S composition no matter about its origin). However one has to distinguish $D^0 \to K_S\phi$ from $D^0 \to K_S f_0$, since the two final states are 'odd' and 'even' CP eigenstates, respectively. In Cabibbo suppressed decays the SM predicts also direct CP violation and also typical NP models do. Such asymmetries will also come from production asymmetries. The overall rates in $D \to 3h$ decays do depend on their productions; while CP asymmetries in corresponding regions in the Dalitz plot do not! Therefore dedicated searches for CP asymmetries have to be applied to $D \to 3h$ [20]. Such analyses need more experimental and theoretical works than for two-body decays, but offer more advantages even beyond their independence from production asymmetries: 'local' asymmetries should be typically larger than 'global' asymmetries; their position in the Dalitz plots will help their interpretation of direct vs. indirect asymmetry and SM versus NP dynamics; for D^0 decays one needs time partially resolved Dalitz plots. To be more specific: one needs Dalitz plots analyses of $D^0/D^+ \to 3\pi$, $K\overline{K}\pi$.

More complex charm meson decays as $D \to 4$ particles, and charm baryons are also source of channels to look for CP violation.

1.8. Conclusion

Precision flavour physics needs an accurate control of hadronic parameters entering in several K, D and B physics measurements when interpreted in terms of physics observables. A charm factory, running at threshold with high luminosity (two orders of magnitude higher than BESIII) is needed in this respect. Oscillations of D^0–$\overline{D}^0$ mesons have been recently measured at b-factories. The study of this process is complementary to analyses of neutral K and B systems because it is the only one to be induced by the transformation of heavy up-type quarks. Because of theoretical uncertainties, this effect is compatible with SM expectations but can be also due to NP. Separating contributions from the mass and the width difference of the two physical D^0 mass eigenstates is mandatory to look for NP in this area. Information from a charm factory running at threshold is needed in this respect. In spite of the limited accuracy of present measurements and of theoretical uncertainties, several valuable constraints are already imposed on several New Physics scenarios. Observing CP violation, in future, may clarify the situation. Such measurements can be envisaged at threshold (direct CP violation) or at high energy colliders (CP violation through oscillations).

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