"I Know She Invented Fire, But What Has She Done Recently?" – On The Future Of Charm Physics

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Abstract

Detailed studies of weak charm decays fill an important future role in high energy physics. Chief among them are: (i) validating the theoretical control achieved over hadronization as a worthwhile goal in its own right; (ii) calibrating our tools to saturate the discovery potential for New Physics in $B$ decays; (iii) searching for New Physics in charm decays through hypothesis-generating research. The most promising area for the last item is a comprehensive study of CP violation. Since we need a new CP paradigm to implement baryogenesis, this is not an idle goal. Charm decays provide opportunities unique among up-type quarks. While items (i) and (ii) will be addressed in a meaningful way and hopefully completed in the next few years, item (iii) will presumably require statistics that can be accumulated only by LHCb and a Super-B factory.

1 Prologue

There is a common feeling charm physics had a great past – it provided essential support for the paradigm shift to viewing quarks as physical degrees of freedom rather than objects of mathematical convenience – yet it has no future. For the SM electroweak phenomenology of charm changing transitions appears on the decidedly dull side with the CKM parameters well-known due to three-family unitarity constraints, $D^0 - \bar{D}^0$ oscillations being slow, CP asymmetries small at best and loop driven decays extremely rare with huge backgrounds due to long distance dynamics.

I do not view charm as a closed chapter. Instead: "I have come to praise Ch., not to bury it!" To state it in more prosaic terms: there is a triple motivation for further dedicated studies of charm dynamics:

1Invited Lecture given at CHARM 2006, Beijing, June 2006
Figure 1: CKM unitarity triangle from $|V_{ub}/V_{cb}|$ and $\Delta M(B_d)/\Delta M(B_s)$ on the left and compared to constraints from $\epsilon_K$ and $\sin 2\phi_1/\beta$ on the right (courtesy of M. Pierini)

- to gain new insights into nonperturbative dynamics and make progress in establishing theoretical control over them;
- to calibrate our theoretical tools for $B$ studies;
- to use charm transitions as a novel window onto New Physics.

Lessons from the first item will have an obvious impact on the tasks listed under the second and third items. They might actually be of great value even beyond QCD, if the New Physics anticipated for the TeV scale is of the strongly interacting variety.

The accuracy of the theoretical description is of essential importance in this program. For we cannot count on numerically massive interventions of New Physics in the decays of beauty mesons. This point is brought home again by the recently reported signal for $B_s - \bar{B}_s$ oscillations [1, 2]:

$$\Delta M(B_s) = \begin{cases} 
(19 \pm 2) \text{ ps}^{-1} & \text{D0} \\
(17.3^{+0.42}_{-0.21} \pm 0.07) \text{ ps}^{-1} & \text{CDF} \\
(18.3^{+0.6}_{-1.5}) \text{ ps}^{-1} & \text{CKM fit}
\end{cases} \quad (1)$$

While the strength of the signal has not yet achieved $5 \sigma$ significance, it looks most intriguing. If true, it represents another impressive triumph of CKM theory: the CP insensitive observables $|V_{ub}/V_{cb}|$ and $\Delta M(B_d)/\Delta M(B_s)$ – i.e. observables that do not require CP violation for acquiring a non-zero value – imply

- a non-flat CKM triangle and thus CP violation, see the left of Fig. 1
- that is fully consistent with the observed CP sensitive observables $\epsilon_K$ and $\sin 2\phi_1$, see the right of Fig. 1.

My message is centered on three basic tenets:

(i): None of the new SM successes from the last few years weakens the case for New Physics even ‘nearby’, namely around the TeV scale.
(ii): To learn about all the salient features of this anticipated New Physics we must study its impact on heavy flavour transitions – even if it turns out in the end that none is observable. CP studies are thus ‘instrumentalized’ to probe for and analyze the New Physics, once it has emerged.

(iii): We need precise, reliable and comprehensive studies of flavour dynamics; this means we have to look also at unusual places.

For most details I refer the committed reader to several recent reviews [3, 4, 5].

2 The ‘Guaranteed’ Profit

2.1 Lessons on QCD

The issue at stake here is not whether QCD is the theory of the strong forces – there is no alternative – but our ability to perform calculations. Charm hadrons can act here as a bridge between the worlds of light flavours – as carried by $u$, $d$ and $s$ quarks with masses lighter or at most comparable to $\Lambda_{QCD}$ and described by chiral perturbation theory – and that of the bona fide heavy $b$ quark with $\Lambda_{QCD} \ll m_b$ treatable by heavy quark theory [7].

The verdict so far has been that charm acts ‘mostly somewhat’ as a heavy quark: expansions in powers of $1/m_c$ basically work as far as charm lifetimes are concerned, yet fail for light cone sum rules used to obtain the form factors for $D \rightarrow l\nu\pi/\rho$. The ‘a posteriori’ explanation is that the latter contain corrections of order $1/m_c$ whereas the former start only at order $1/m_c^2$ [4].

Quark models can serve as a most useful tool for training one’s intuition and as a diagnostic of results from sum rules and lattice QCD; however, I do not view them as reliable enough for conclusive answers.

Only lattice QCD carries the promise for a truly quantitative treatment of charm hadrons that can be improved systematically. Furthermore lattice QCD is the only framework available that allows to approach charm from lower as well as higher mass scales, which involves different aspects of nonperturbative dynamics and thus – if successful – would provide impressive validation.

Indulging myself in a short moment of bragging I would like to repeat what I had said in my talk at the 1993 Marbella Tau-Charm Workshop [8]: ”The $\tau$-charm factory is the QCD machine for the 90’s!” Ten years later the value of a such a factory was more widely appreciated, which led to the on-going CLEO-c and the future BESIII programs. At the same time we have to understand that the threshold for significance is much higher now than it was in the 1990’s. This is due to a combination of several factors, chief among them the ability of the $B$ factories to perform high statistics as well as high quality charm studies and the need for precision studies in $B$ decays.

\footnote{Top quarks have to be listed separately as ‘super-heavy’, since due to $\Lambda_{QCD} \ll \Gamma_t$, they decay before they can hadronize [17].}
The required validation of lattice QCD has to go beyond a few ‘gold-plated’ tests: even if it turns out that the measured value for the decay constant $f_D$ and the one inferred from lattice QCD were to agree within, say, a percent – an impressive success for sure – we cannot conclude that there is a universal bound of a percent or two on the theoretical uncertainties even in semileptonic $D$ decays. Validation of lattice QCD requires accurate comparisons of the measured and predicted form factors in Cabibbo allowed as well as forbidden modes of $D^0$, $D^+$ and $D_s$ mesons.

Charmonium studies provide yet another essential test ground; those are covered by other talks at this conference.

2.1.1 Is Charm Heavy?

Let me list three pieces of evidence that charm is marginally heavy:

(i): The value of the charm quark $\overline{MS}$ mass can be inferred from data also using methods other than lattice QCD [9]:

\[
\overline{m}_c = \begin{cases} 
1.19 \pm 0.11 \text{ GeV} & \text{charmonium sum rules} \\
1.18 \pm 0.08 \text{ GeV} & \text{moments of } B \to l\nu X
\end{cases}
\]  

The fact that two quite different theoretical treatments yield very consistent values supports that charm is somewhat heavy, i.e. significantly larger than $\Lambda_{QCD}$.

(ii): More qualitative evidence is provided by the fact that the two channels $B \to l\nu D/D^*$ constitute about two thirds of the inclusive width for $B \to l\nu X_c$. For $D$ and $D^*$ form the ground states in heavy quark symmetry and have to saturate the inclusive semileptonic width for $m_c, m_b \to \infty$.

(iii): As explained in detail in [4] the lifetime ratios for the seven single charm hadrons that decay weakly are surprisingly well described by the heavy quark expansion; in some cases they were even predicted before data of the required accuracy existed. This fact appears quite nontrivial considering that these lifetime ratios span a factor of fourteen between the longest and the shortest lifetimes, namely $\tau(D^*)$ and $\tau(\Omega_c)$.

The SELEX collaboration has reported candidates for weakly decaying double-charm baryons. My judgment as a theorist is as follows: The reported lifetimes are way too short and do not exhibit the expected hierarchy [4]. If SELEX’s interpretation is correct, then I had to conclude – with obvious regret – that the apparently successful description of single charm lifetimes was hardly more than a coincidence.

2.2 ‘Tooling up’ for $B$ Studies

Validating lattice QCD’s result for $f_D$ and $f_{D_s}$ [10] would allow a rather trustworthy prediction for $f_B$ and $f_{B_s}$ by extrapolating $m_c \to m_b$. Yet there are many other applications for lessons learnt in charm decays. Some are obvious like extrapolating results on the form factors for $D_{(s)} \to l\nu\pi/K$ to $B_{(s)} \to l\nu\pi/K$, while others are not. I will give three examples of the latter.
Spectroscopy of open charm hadrons: To extract \(|V(cb)|\) and \(|V(ub)|\) from inclusive semileptonic \(B\) widths one needs to know the values of \(m_b\), \(m_c\) and other heavy quark parameters. Those are inferred from the shape of the lepton energy and hadronic mass moments [9, 11]. In particular the latter are sensitive to the composition of the hadronic final state, the masses, widths and quantum numbers of the charm hadrons produced, i.e. their spectroscopy. The limitations in our understanding of it [12] at present represent one of the main systematic uncertainties. Assuming the wrong spectroscopy in the analysis could create a bias in the results inferred. The fact that a handful of heavy quark parameters describe so well a host of moments [9] with its many over constraints shows that the SM \(V - A\) currents dominate \(B \rightarrow l\nu X\) [13]; yet the aforementioned bias due to a wrong charm spectroscopy could hide the presence of non-SM chiralities or fake one in future studies.

Semileptonic \(D\) decays: In many models of New Physics there is a relatively clear connection between the CP violation observable in \(B_d \rightarrow \phi K_S\) dominated by a strong Penguin operator and the rate for \(B \rightarrow \gamma X_s\) given by the electroweak Penguin. Since the strength of the latter has been found to be close to the SM prediction, one finds rather tight bounds on the asymmetry in \(B_d \rightarrow \phi K_S\). Yet there is an implicit assumption, namely that the emerging photon is mostly left-handed as predicted by the SM. A non-SM contribution from a right-handed photon could not interfere with that from a left-handed one; thus it could contribute only quadratically to \(\Gamma(B \rightarrow \gamma X_s)\). On the other hand the corresponding strong Penguin amplitude would interfere with the SM amplitude in the CP asymmetry in \(B_d \rightarrow \phi K_S\) thus contributing linearly and be of greater weight there. Measuring the photon polarization in radiative \(B\) decays directly is a formidable task. It is more feasible to infer it indirectly from the exclusive mode \(B \rightarrow \gamma K\pi\pi\) [14]. Most helpful or even essential information on the dynamical structure of the relevant \(K\pi\pi\) system can be obtained by analyzing the semileptonic charm channel \(D \rightarrow l\nu K\pi\pi\).

(Time dependent) Dalitz plot studies: The most intriguing indication for New Physics in heavy flavour decays has emerged in the time-dependent CP asymmetries for \(B_d \rightarrow \phi K_S\) (and related channels). A reliable SM prediction tells us that it should closely mirror the situation of \(B_d \rightarrow \psi K_S\) with the same coefficients for the sin & cos\(\Delta M_d t\) terms: \(S \simeq 0.68\) & \(C \simeq 0\). The values of the \(S\) term measured by BELLE and BABAR [15] – while not inconsistent with the SM expectations – are on the low side by an amount that would be natural for New Physics. Future analyzes might turn this into a significant discrepancy.

Yet one has to be aware of the following complication: One has to extract \(B_d \rightarrow \phi K_S\) from \(B_d \rightarrow K^+K^-K_S\). While the \(\phi\) (in contrast to the \(\rho\)) represents a rather narrow resonance, it still has a finite width. Making merely a mass cut on the kaon pair will let other contributions ‘slip through’, non-resonant ones or other resonances like the scalar \(f(980)\). If \(K^+K^-\) form a scalar pair, then the final state in \(B_d \rightarrow [K^+K^-] J=0 K_S\) has the opposite CP parity than \(B_d \rightarrow \phi K_S\), and it will have a CP asymmetry equal in magnitude, yet opposite in sign to that of \(B_d \rightarrow \phi K_S\) (if driven by the same quark level operator). To give an example for illustration: a \(B_d \rightarrow [K^+K^-] J=0 K_S\) amplitude 10% the size of the dominant \(B_d \rightarrow \phi K_S\) amplitude in the sample would reduce the CP asymmetry.
by 20% – i.e. significantly. A detailed analysis of time-dependent Dalitz plots will allow to disentangle such effects. This comes with a hefty price of course, namely that of requiring huge statistics. Yet, adapting a quote from Greek antiquity: ”There is no royal way to fundamental insights.”

Finally and most importantly for this talk, one can learn many lessons about hadronization and final state interactions relevant for $B$ decays by studying the corresponding Dalitz plots for charm decays like $D \rightarrow 3K$. For most of the clear resonance structures lies below 1.5 GeV; also to first approximation the excitation curve for a resonance $R$ produced in $D$ or $B \rightarrow RM$ with $M$ denoting a light flavour meson should be very similar. I would like to add, however, that BELLE data on $B \rightarrow K\pi \pi$ indicate that these are not absolute rules [16].

3 ‘The Best might still be ahead’

There are two kinds of research, namely ‘hypothesis-driven’ and ‘hypothesis-generating’ research. The first kind is essential – and favoured by funding agencies. Yet also the second kind – ‘thinking outside the box’ – must be pursued, although it is much harder to plan; we owe many of the fundamental paradigm shifts to such an approach. The program of the $B$ factories has been largely of the ‘hypothesis-driven’ variety, and a most successful one at that.

The situation is quite different with charm dynamics. Charm spectroscopy has led to the recent renaissance in ‘hypothesis-generating’ studies of QCD. The best long-term motivation for a future charm program is a ‘hypothesis-generating’ search for New Physics. To use an analogy from real life: ”If baseball teams from Boston and Chicago can win the World Series in two successive years – overcoming curses having lasted more than 80 years – then charm can surely reveal New Physics.”

New Physics scenarios in general induce flavour changing neutral currents that a priori have little reason to be as much suppressed as in the SM. More specifically they could be substantially stronger for up-type than for down-type quarks; this can happen in particular in models which have to reduce strangeness changing neutral currents below phenomenologically acceptable levels by some alignment mechanism.

In such scenarios charm plays a unique role among the up-type quarks $u$, $c$ and $t$; for only charm allows the full range of probes for New Physics in general and flavour-changing neutral currents in particular: (i) Since top quarks do not hadronize [17], there can be no $T^0 - \bar{T}^0$ oscillations. More generally, hadronization, while hard to bring under theoretical control, enhances the observability of CP violation. (ii) As far as $u$ quarks are concerned, $\pi^0$, $\eta$ and $\eta'$ decays electromagnetically, not weakly. They are their own antiparticles and thus cannot oscillate. CP asymmetries are mostly ruled out by CPT invariance.

My basic contention can then be formulated as follows: Charm transitions provide a unique portal for a novel access to flavour dynamics with the experimental situation being a priori quite favourable (apart from the absence of Cabibbo suppression). Yet even that handicap can be overcome by statistics.
3.1 ‘Inconclusive’ $D^0 - \bar{D}^0$ Oscillations

$D^0 - \bar{D}^0$ oscillations can be characterized as follows:

⊕ They represent a fascinating quantum mechanical problem;
⊕ while they provide only an ambiguous probe for New Physics,
⊕ they are an important ingredient in CP asymmetries that, if observed, would establish
the intervention of New Physics.

Oscillations are characterized by two dimensionless ratios:

\[ x_D \equiv \frac{\Delta M_D}{\Gamma_D}, \quad y_D \equiv \frac{\Delta \Gamma_D}{2\Gamma_D} \tag{3} \]

A conservative rather model independent bound reads $x_D, y_D \leq \mathcal{O}(0.01)$ [4]. With present data reading [18]

\[ x_D|_{\text{exp}} < 0.03, \quad y_D|_{\text{exp}} \sim 0.01 \pm 0.005 \tag{4} \]

one can conclude that a meaningful search for $D^0$ oscillations has ‘only just’ begun.

At this point allow me a personal comment: the (in)famous ‘Nelson plot’ [19] on
theoretical predictions concerning $x_D$ was witty and an appropriate reminder for theorists
to use some common sense. Yet now it should be retired with honour, since we have a
considerably better understanding of the dynamical issues involved.

It is widely understood that the usual quark box diagram is utterly irrelevant due
to its untypically severe GIM suppression $(m_s/m_c)^4$. A systematic analysis based on
an OPE has been given [20] in terms of powers of $1/m_c$ and $m_s$. Contributions from
higher-dimensional operators with a much softer GIM reduction of $(m_s/\mu_{had})^2$ due to
‘condensate’ terms in the OPE yield

\[ x_D(SM)|_{\text{OPE}}, \quad y_D(SM)|_{\text{OPE}} \sim \mathcal{O}(10^{-3}) \tag{5} \]

The authors of [21] find very similar numbers, albeit in a quite different approach. When
evaluating the predictions in Eq.5 one has to distinguish carefully between two similar
sounding questions:

- “What are the most likely values for $x_D$ and $y_D$ within the SM?”
  My answer as given above: For both $\sim \mathcal{O}(10^{-3}).$
- “How large could $x_D$ and $y_D$ conceivably be within the SM?”
  My answer: One cannot rule out $10^{-2}$.

While one predicts similar numbers for $x_D(SM)$ and $y_D(SM)$, one should note that
they arise in very different dynamical environments. $\Delta M_D$ being generated from off-shell
intermediate states is sensitive to New Physics, which could produce $x_D \sim \mathcal{O}(10^{-2})$. $\Delta \Gamma_D$
on the other hand is shaped by on-shell intermediate states; while it is hardly sensitive
to New Physics, it involves much less averaging or ‘smearing’ than $\Delta M_D$ making it thus
more vulnerable to violations of quark-hadron duality. ³ Observing $y_D \sim 10^{-3}$ together

³A similar concern applies to $\Delta \Gamma(B_s)$. 7
with $x_D \sim 0.01$ would provide intriguing, though not conclusive evidence for New Physics, while $y_D \sim 0.01 \sim x_D$ would pose a true conundrum for its interpretation.

This skepticism does not mean one should not make the utmost efforts to probe $D^0 - \bar{D}^0$ oscillations down to the $x_D, y_D \sim 10^{-3}$ level. For one we might be only one theory breakthrough away from making a precise prediction. Yet more importantly this challenge provides an important experimental validation check when searching for a CP asymmetry involving oscillations.

### 3.2 CP Violation with & without Oscillations

Most factors favour dedicated searches for CP violation in charm transitions:

- Since baryogenesis implies the existence of New Physics in CP violating dynamics, it would be unwise not to undertake dedicated searches for CP asymmetries in charm decays, where the ‘background’ from known physics is between absent and small: for within the SM the effective weak phase is highly diluted, namely $\sim O(\lambda^4)$, and it can arise only in singly Cabibbo suppressed transitions, where one expects asymmetries to reach the $O(0.1\%)$ level; significantly larger values would signal New Physics. Any asymmetry in Cabibbo allowed or doubly suppressed channels requires the intervention of New Physics – except for $D^\pm \to K_S\pi^\pm [4]$, where the CP impurity in $K_S$ induces an asymmetry of $3.3 \cdot 10^{-3}$. One should keep in mind that in going from Cabibbo allowed to Cabibbo singly and doubly suppressed channels, the SM rate is suppressed by factors of about twenty and four hundred, respectively:

$$\Gamma_{SM}(H_c \to [S = -1]) : \Gamma_{SM}(H_c \to [S = 0]) : \Gamma_{SM}(H_c \to [S = +1]) \simeq 1 : 1/20 : 1/400$$

One would expect that this suppression will enhance the visibility of New Physics.

- Strong phase shifts required for direct CP violation to emerge in partial widths are in general large as are the branching ratios into relevant modes; while large final state interactions complicate the interpretation of an observed signal in terms of the microscopic parameters of the underlying dynamics, they enhance its observability.

- CP asymmetries can be linear in New Physics amplitudes thus increasing sensitivity to the latter.

- Decays to final states of more than two pseudoscalar or one pseudoscalar and one vector meson contain more dynamical information than given by their widths; their distributions as described by Dalitz plots or T odd moments can exhibit CP asymmetries that might be considerably larger than those for the width. Final state interactions while not necessary for the emergence of such effects, can fake a signal; yet that can be disentangled by comparing T odd moments for CP conjugate modes [23]:

$$O_T(D \to f) \neq -O_T(\bar{D} \to \bar{f}) \implies \text{CP violation}$$

I view this as a very promising avenue, where we still have to develop the most effective analysis tools for small asymmetries. Below I will briefly illustrate the general method by one explicit example.
⊕ The distinctive channel $D^{\pm*} \to D\pi^{\pm}$ provides a powerful tag on the flavour identity of the neutral $D$ meson.
⊕ 'fly in the ointment' is that $D^0 - \bar{D}^0$ oscillations are on the slow side.
⊕ Nevertheless one should take on this challenge. For $CP$ violation involving $D^0 - \bar{D}^0$ oscillations is a reliable probe of New Physics: the asymmetry is controlled by $\sin\Delta m_D t \cdot \text{Im}(q/p)\bar{\rho}(D \to f)$. Within the SM both factors are small, namely $\sim O(10^{-3})$, making such an asymmetry unobservably tiny – unless there is New Physics; for a recent New Physics model see [22]. One should note that this observable is linear in $x_D$ rather than quadratic as for $CP$ insensitive quantities like $D^0(t) \to l^- X$. $D^0 - \bar{D}^0$ oscillations, $CP$ violation and New Physics might thus be discovered simultaneously in a transition. Such effects can be searched for in final states common to $D^0$ and $\bar{D}^0$ decays like $CP$ eigenstates – $D^0 \to K^0\phi$, $K^+K^-$, $\pi^+\pi^-$ – or doubly Cabibbo suppressed modes – $D^0 \to K^+\pi^-$. In the end it might turn out that the corresponding three-body final states – $D^0 \to K_S\pi^+\pi^-$, $D^0 \to K^+K^-\pi^0/\pi^+\pi^-\pi^0$ and $D^0 \to K^+\pi^-\pi^0$ – allow searches with higher sensitivity. Undertaking time-dependent Dalitz plot studies requires a higher initial overhead, yet in the long run this should pay handsome dividends exactly since Dalitz analyses can invoke many internal correlations that in turn serve to control systematic uncertainties.
⊕ It is all too often overlooked that $CPT$ invariance can provide nontrivial constraints on $CP$ asymmetries. For it imposes equality not only on the masses and total widths of particles and antiparticles, but also on the widths for ‘disjoint’ subsets of channels. ‘Disjoint’ subsets are the decays to final states that cannot rescatter into each other. Examples are semileptonic vs. nonleptonic modes with the latter subdivided further into those with strangeness $S = -1, 0, +1$. Observing a $CP$ asymmetry in one channel one can then infer in which other channels the ‘compensating’ asymmetries have to arise [4].

3.2.1 Theoretical Engineering

$CP$ asymmetries in integrated partial widths depend on hadronic matrix elements and (strong) phase shifts, neither of which can be predicted accurately. However the craft of theoretical engineering can be practiced with profit here. One makes an ansatz for the general form of the matrix elements and phase shifts that are included in the description of $D \to PP, PV, VV$ etc. channels, where $P$ and $V$ denote pseudoscalar and vector mesons, and fits them to the measured branching ratios on the Cabibbo allowed, once and twice forbidden level. If one has sufficiently accurate and comprehensive data, one can use these fitted values of the hadronic parameters to predict $CP$ asymmetries. Such analyses have been undertaken in the past [24], but the data base was not as broad and precise as one would like. CLEOc and BESIII measurements will certainly lift such studies to a new level of reliability.

3.2.2 An Example for a $T$ odd Correlation

$CP$ asymmetries in final state distributions can be substantially larger than in integrated partial widths. A dramatic example for that has been found in $K_L$ decays. Consider
the rare mode \(K_L \to \pi^+\pi^- e^+ e^-\) and define by \(\phi\) the angle between the \(\pi^+\pi^-\) and \(e^+e^-\) planes. The differential width has the general form

\[
\frac{d\Gamma}{d\phi}(K_L \to \pi^+\pi^- e^+ e^-) = \Gamma_1 \cos^2 \phi + \Gamma_2 \sin^2 \phi + \Gamma_3 \cos \phi \sin \phi
\]

Upon integrating over \(\phi\) the \(\Gamma_3\) term drops out from the total width, which thus is given in terms of \(\Gamma_{1,2}\) with \(\Gamma_3\) representing a forward-backward asymmetry.

\[
\langle A \rangle \equiv \frac{\int_0^{\pi/2} \frac{d\Gamma}{d\phi} - \int_{\pi/2}^\pi \frac{d\Gamma}{d\phi}}{\int_0^\pi \frac{d\Gamma}{d\phi}} = \frac{2\Gamma_3}{\pi(\Gamma_1 + \Gamma_2)}
\]

Under \(P\) and \(T\) one has \(\cos \phi \sin \phi \rightarrow -\cos \phi \sin \phi\). Accordingly \(A\) and \(\Gamma_3\) constitute a \(T\) odd correlation, while \(\Gamma_{1,2}\) are \(T\) even. \(\Gamma_3\) is driven by the \(CP\) impurity \(\epsilon_K\) in the kaon wave function. \(\langle A \rangle\) has been measured to be large in full agreement with theoretical predictions [25]:

\[
\langle A \rangle = 0.138 \pm 0.022.
\]

One should note this observable is driven by \(|\epsilon_K| \simeq 0.0023\).

\(D\) decays can be treated in an analogous way. Consider the Cabibbo suppressed channel

\[
D \rightarrow K\bar{K}\pi^+\pi^-
\]

and define by \(\phi\) now the angle between the \(K\bar{K}\) and \(\pi^+\pi^-\) planes. Then one has

\[
\frac{d\Gamma}{d\phi}(D \rightarrow K\bar{K}\pi^+\pi^-) = \Gamma_1 \cos^2 \phi + \Gamma_2 \sin^2 \phi + \Gamma_3 \cos \phi \sin \phi \quad (12)
\]

\[
\frac{d\Gamma}{d\phi}(\bar{D} \rightarrow K\bar{K}\pi^+\pi^-) = \bar{\Gamma}_1 \cos^2 \phi + \bar{\Gamma}_2 \sin^2 \phi + \bar{\Gamma}_3 \cos \phi \sin \phi \quad (13)
\]

As before the partial width for \(D[\bar{D}] \rightarrow K\bar{K}\pi^+\pi^-\) is given by \(\Gamma_{1,2}[\bar{\Gamma}_{1,2}]; \Gamma_1 \neq \bar{\Gamma}_1\) or \(\Gamma_2 \neq \bar{\Gamma}_2\) represents direct \(CP\) violation in the partial width. \(\Gamma_3\&\bar{\Gamma}_3\) constitute \(T\) odd correlations. By themselves they do not necessarily indicate \(CP\) violation, since they can be induced by strong final state interactions. However

\[
\Gamma_3 \neq \bar{\Gamma}_3 \implies CP\ violation!
\]

It is quite possible or even likely that a difference in \(\Gamma_3\) vs. \(\bar{\Gamma}_3\) is significantly larger than in \(\Gamma_1\) vs. \(\bar{\Gamma}_1\) or \(\Gamma_2\) vs. \(\bar{\Gamma}_2\). Furthermore one can expect that differences in detection efficiencies can be handled by comparing \(\Gamma_3\) with \(\Gamma_{1,2}\) and \(\bar{\Gamma}_3\) with \(\bar{\Gamma}_{1,2}\).

\[\text{This mode can exhibit direct } CP\ \text{violation even within the SM.}\]
3.2.3 Experimental Status & Future Benchmarks

Time integrated CP asymmetries have been analyzed where sensitivities of order 1% [several %] have been achieved for Cabibbo allowed and once suppressed modes with two [three] body final states \[10\]. Time dependent CP asymmetries (i.e. those involving \(D^0 - \bar{D}^0\) oscillations) still form largely ‘terra incognita’.

Since the primary goal is to establish the intervention of New Physics, one ‘merely’ needs a sensitivity level above the reach of the SM; ‘merely’ does not mean it can easily be achieved. As far as direct CP violation is concerned – in partial widths as well as in final state distributions – this means asymmetries down to the \(10^{-3}\) or even \(10^{-4}\) level in Cabibbo allowed channels and 1% level or better in twice Cabibbo suppressed modes; in Cabibbo once suppressed decays one wants to reach the \(10^{-3}\) range although CKM dynamics can produce effects of that order because future advances might sharpen the SM predictions – and one will get them along with the other channels. For time dependent asymmetries in \(D^0 \rightarrow K_S \pi^+ \pi^-, K^+ K^-, \pi^+ \pi^-\) etc. and in \(D^0 \rightarrow K^+ \pi^-\) one should strive for the \(\mathcal{O}(10^{-4})\) and \(\mathcal{O}(10^{-3})\) levels, respectively.

Statistics wise these are not utopian goals considering that LHCb expects to record about \(5 \cdot 10^7\) tagged \(D^* \rightarrow D + \pi \rightarrow K^+ K^- + \pi\) events in a nominal year of \(10^7\) s \[26\].

When going after asymmetries below the 1% or so level one has to struggle against systematic uncertainties, in particular since detectors are made from matter. I can see three powerful weapons in this struggle: (i) Resolving the time evolution of asymmetries that are controlled by \(x_D\) and \(y_D\), which requires excellent microvertex detectors; (ii) Dalitz plot consistency checks; (iii) quantum statistics constraints on distributions, \(T\) odd moments etc. \[27\]

4 Outlook – not an Epilogue

We still have two truly central tasks to address in charm studies.

- To validate the quantitative theoretical control one has or soon will achieve over hadronization: (a) it is valuable in its own right (and extending such studies to charm baryons would provide us with novel perspectives onto nonperturbative QCD), and (b) it will sharpen our tools for \(B\) decay studies to saturate the discovery potential for New Physics there.

- Unique searches for New Physics with \(up\)-type quarks: (a) While probing \(D^0 - \bar{D}^0\) oscillations represents an important intermediate stage, searches for CP violation are the essential goal. We should not forget that a new CP paradigm is needed for baryogenesis. (b) The experimental situation is mostly favourable in the charm sector, yet even so we need as much statistics as possible; it will be most desirable that LHCb can contribute to detailed charm studies and that a Super-\(B\) factory will be realized. (c) BESIII will make important contributions, yet not provide final answers.

While no evidence for New Physics has so far been found in charm decays, we should not get discouraged: for only recently have we entered a domain where one could realistically hope for an effect.
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