No Pain, No Gain – On the Challenges and Promises of Charm Studies

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Abstract: The observation of $D^0 - \bar{D}^0$ oscillations has left us in a tantalizing quandary concerning the theoretical interpretation: are they still compatible with the SM or might they require new dynamics (NP)? A comprehensive search for CP violation in D decays should resolve the issue. Finding it should provide compelling evidence for the intervention of New Physics. While the absolute size of CP asymmetries will presumably be modest at best, the ratio of 'signal' to 'noise' – i.e. NP over SM contributions – might well be larger for D than B transitions. A list of promising channels is provided, most of which should be observable in a hadronic environment. Yet to saturate the discovery potential for NP, we need a Superflavour Factory. Valuable lessons can be obtained by analyzing three- and four-body final states.

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Prologue on Charm and its Uniqueness

New Physics (NP) will in general induce flavour changing neutral currents (FCNC). The SM had to be crafted judiciously to have them greatly suppressed for strangeness; the weight of FCNC is then even more reduced for the up-type quarks u, c and t. Yet NP scenarios could exhibit a very different pattern with FCNC being significantly more relevant for up-type quarks. Among those it is only the charm quark that allows the full range of probes for FCNC in general and for CP violation in particular. For top quarks do not hadronize [1] thus eliminating the occurrence of $T^0 - \bar{T}^0$ oscillations. Neutral pions etc. cannot oscillate, since they are their own antiparticles; furthermore CPT constraints are such that they rule out most CP asymmetries. Yet neutral charm mesons have been observed to oscillate: the world averages [2] based on data from BaBar [3], Belle [4] and CDF [5] read

$$x_D = 0.0100^{+0.0024}_{-0.0026} \quad , \quad y_D = 0.0076^{+0.0017}_{-0.0018} \quad (1)$$

$$\frac{x_D^2 + y_D^2}{2} \leq (1.3 \pm 2.7) \cdot 10^{-4} \qquad (2)$$

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).

While $D^0 - \bar{D}^0$ oscillations appear to have been established — $(x_D, y_D) \neq (0, 0)$ — considerable uncertainty exists concerning both the absolute and relative sizes of x_D and y_D; I will return to this point.

I view the theoretical interpretation as unclear [6]: while the SM can 'naturally' generate $x_D \sim y_D \sim \mathcal{O}(10^{-3})$ [7, 8], one cannot rule out values as 'large' as 0.01 [9, 8]. Despite the similar numerical estimates for x_D and y_D the underlying dynamics is of a very different nature: while ΔM_D is generated with *off*-shell intermediate states, $\Delta \Gamma_D$ is obtained from *on*-shell ones; ΔM_D can thus naturally be sensitive to New Physics, which is unlikely for $\Delta \Gamma_D$.

Finding $x_D \gg y_D \sim \mathcal{O}(10^{-3})$ would have represented strong prima facie evidence for the presence of NP. Such a scenario appears to have been ruled out. The present situation can instead be interpreted in two ways: (i) It is beyond our computational abilities to evaluate ΔM_D and $\Delta \Gamma_D$ accurately. (ii) It represents one example of nature being mischievous: $\Delta \Gamma_D$ is anomalously enhanced due to a violation of *local* quark-hadron duality caused by the proximity of hadronic thresholds [8, 10]; ΔM_D on the other hand is enhanced by NP over the value expected in the SM.

My central point here is the following: while x_D, $y_D \sim$ 0.01 might be produced by SM dynamics alone, *the observed size of x_D might also contain a significant NP contribution*. I see no realistic way how this issue could be de-

cided by theoretical means alone in the next few years. Yet there is a course of action to clarify and hopefully decide the issue, namely to conduct a comprehensive and dedicated study of CP invariance in charm decays. One can*not count* on NP creating large CP asymmetries in D transitions, but its manifestations might be clearer here than in B decays; for the SM creates much smaller "backgrounds"; i.e., it induces still much smaller effects:

$$\left[\frac{\text{exp. NP signal}}{\text{SM CP "backgr."}}\right]_{\mathbf{D}} > \left[\frac{\text{exp. NP signal}}{\text{SM CP "backgr."}}\right]_{\mathbf{B}} \quad (3)$$

In summary: while the observed signal for $D^0 - \bar{D}^0$ oscillations represents a tactical draw in our struggle to reach beyond the SM, there is new promise for a strategic victory on the battleground of CP studies. It is the relative 'dullness' of the SM vis-a-vis CP asymmetries in charm transitions that makes such searches promising. The observation of oscillations has widened the stage for NP to reveal itself.

There is a *qualitative* analogy with the case of $B_s - \bar{B}_s$ oscillations: the observed rate as expressed through ΔM_{B_s} is fully consistent with SM predictions [2] – within sizable theoretical uncertainties. The next challenge is to search for a time dependent CP asymmetry in $B_s \to \psi\phi$. For KM dynamics predicts [11] a Cabibbo suppressed asymmetry ~ 3 %. NP whose non-leading contribution to ΔM_{B_s} might be hiding behind the theoretical uncertainty in the SM prediction could enhance the CP asymmetry even by an order of magnitude thus becoming the *leading* effect *there*.

NP Scenarios and their Footprints

Fundamentals of CP Searches in Charm Decays

SM predictions for x_D and y_D are unlikely to be refined significantly anytime soon. Even so determining x_D and y_D with good accuracy is motivated by pragmatic rather than quixotically noble reasons: a measurement of a presumably small time dependent CP asymmetry would be validated by reproducing values for x_D and y_D consistent with *independent* data. Those accurate values are also needed to identify the source(s) of an asymmetry, whether it is due to $\left|\frac{q}{p}\right| \neq 1$ or $\arg \frac{q}{p}\bar{\rho}_f \neq 0$, as discussed later.

Searching for manifestations of NP through CP studies is not a 'wild goose' chase: Baryogenesis requires the intervention of NP *with* CP violation; it is not an unreasonable hope that such CP odd NP would leave its mark also somewhere else – maybe even in charm transitions. One should note that a CP asymmetry is *linear* rather than quadratic in a NP amplitude, which enhances the sensitivity to small amplitudes.

One drawback in searching for NP in charm decays is the fact that the latter occur already on the Cabibbo allowed level unlike for kaons and B mesons, whose modes are Cabibbo and KM suppressed, respectively. Since it is unlikely that NP in Cabibbo favoured channels would have escaped discovery, one has to search for it in significantly suppressed modes. Acquiring huge data sets is thus one essential requirement for our quest.

Otherwise most *experimental* features favour the observability of CP asymmetries in charm decays: (i) The effective branching ratios into pions, kaons and leptons for many relevant modes are relatively sizable. (ii) Final state interactions (FSI) needed to make direct CP violation observable in two-body final states are generally large [1]. (iii) Flavour tagging can conveniently be done by the soft pions in $D^{*\pm} \to D/\bar{D}\pi^{\pm}$. (iv) Many nonleptonic final states contain more than two pseudoscalar or one pseudoscalar and one vector meson. Final state *distributions* are then *non*trivial and can exhibit CP asymmetries, which can be studied through Dalitz plots and T odd moments. (v) The observation of $D^0 - \bar{D}^0$ oscillations greatly widens the stage for CP asymmetries, since it provides a second coherent, yet different amplitude, the weight of which changes with the time of decay.

On the *phenomenological* side there are promising features as well. Since $D^0 \to \bar{D}^0$ transitions are so suppressed within the SM, they open a promising portal for NP to enter. $\Delta C = 1$ nonleptonic modes occur on three Cabibbo levels – allowed (CA), singly (SCS) and doubly Cabibbo suppressed (DCS) – whose typical rates differ by $\text{tg}^2\theta_C$ and $\text{tg}^4\theta_C$, i.e. by one or two to three orders of magnitude, respectively. It is not unreasonable that NP could affect the decay amplitude for DCS and possibly even for SCS modes. Furthermore the SM provides not merely a classification – it makes highly nontrivial, even if not precise predictions concerning CP asymmetries: no *direct* CP violation can occur in CA and DCS channels (except for final states containing K_S [or K_L] mesons [12]); it can for SCS modes, but only on a tiny level, since the required weak phase is highly diluted to the tune of $\mathcal{O}(\text{tg}^4\theta_C) \leq 0.001$. In the SM model the oscillation amplitude is expected to carry a minute weak phase $\sim \mathcal{O}(\text{tg}^4\theta_C) \leq 0.001$ as a benchmark figure [7]. Even a NP contribution that is non-leading in ΔM_D can thus easily provide not only the leading source for CP violation, but even a sizable one.

No CP asymmetry has been found in charm transitions. Let me specify that statement for indirect CP violation:

- CP violation *in* oscillations is expressed by $|q/p| \neq 1$. The world average [2] reads:

$$\left|\frac{q_D}{p_D}\right| = 0.86^{+0.17}_{-0.15} . \quad (4)$$

- No CP asymmetry has been observed in $D^0 \to K^+K^-, \pi^+\pi^-$ [14]:

$$A_{\text{CP}}(K^+K^-) = (0.1 \pm 0.5)\%$$
$$A_{\text{CP}}(\pi^+\pi^-) = (0.0 \pm 0.5)\% \quad (5)$$

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[1]Our lack of theoretical control over final state interactions becomes a problem only when *interpreting* observations in terms of the *microscopic* parameters of the underlying dynamics.

As explained later I view these bounds as hardly telling: for the experimental sensitivity has only recently entered a domain, where one could 'realistically hope' for an effect.

NP Models for Charm Dynamics

The observation of $D^0 - \bar{D}^0$ oscillations has – after some incubation period – motivated theorists to analyze NP models that could have an observable impact on $\Delta C = 2$ transitions. Three complementary approaches have been tried:

• One can review the 'usual list of suspects' [13]; i.e., one analyzes different classes of NP models existing in the literature to analyze how large their impact can be [15]: it could be quite significant.

• One relies on an effective theory approach that reflects NP through an operator product expansion (OPE) containing higher dimensional operators construct from SM fields. One then infers a numerical value or bound for the coefficients of such operators from some observable. In principle this represents a model independent approach; in practice, however, one has to severely limit the number of operators included in the analysis: typically one considers just a single such operator with a specific Lorentz structure – i.e., one does not allow for cancellations among different NP operators. Even so one can infer rough bounds for the scale characterizing NP; by invoking some global symmetry one can also obtain correlations among the impact of NP on different flavour sectors. A recent example is given in [16], where connections between indirect CP violation in the strange and charm sectors are derived from assuming that the effective $\Delta S = 2$ and $\Delta C = 2$ four-quark operators induced by NP involve only quark doublets. As usual these connections are particularly significant for 1 TeV scale NP. SUSY can provide a straightforward dynamical implementation of such a scenario [16].

• One can analyze models that are motivated by considerations quite *un*related to flavour dynamics. One such class of models is formed by little Higgs models with T parity. They are constructed to reconcile the *non*-observation of NP effects even in the quantum corrections to the electroweak parameters with the chance to find NP quanta at the LHC. This class of models is in general *not* of the Minimal Flavour Violation (MFV) variety.

Littlest Higgs Model with T Parity

Basic Features Little Higgs models [17] are constructed to 'delay the day of reckoning' for the gauge hierarchy problem. The Higgs boson appears as a Pseudo-Goldstone boson of a spontaneously broken global symmetry. This allows to keep the Higgs mass at most logarithmically divergent at the one-loop level, when its quadratic renormalization is arranged to vanish due to *bosonic* contributions from a set of new heavy gauge bosons, a super-heavy cousin of the top quark etc. To accommodate the non-observation so far of NP contributions to the electroweak parameters even on the quantum level, a discrete symmetry called T parity is introduced [18, 19]. To implement it, one has to introduce also mirror fermions — one for each quark and lepton species – that are odd under T parity. Flavour mixing in the mirror sector is described by two unitary matrices V_{Hu} and V_{Hd}, parameterising the mirror quark couplings to the SM up- and down-type quarks, respectively. Those matrices are related to each other by the CKM matrix:

$$V_{Hu} = V_{Hd} V_{\text{CKM}}^\dagger . \qquad (6)$$

With $V_{\text{CKM}}^\dagger$ found to be close to the identity matrix, one expects several close connections between K and D decays, including with respect to CP violation. LHT thus provides a dynamical realization of the general ansatz made in [16]. One can express V_{Hd} in terms of three mixing angles and three complex phases as suggested in [20]; V_{Hu}, which shapes the LHT contributions to charm transitions, is then obtained from Eq.(6).

The charm analysis is undertaken assuming for the masses for the extra heavy gauge bosons

$$M_{W_H, Z_H} = gf \sim 650\,\text{GeV}, \; M_{A_H} = \frac{g' f}{\sqrt{5}} \sim 160\,\text{GeV} \qquad (7)$$

and the following range for the mirror fermions masses

$$300\,\text{GeV} \leq m_H^i \leq 1000\,\text{GeV}. \qquad (8)$$

Such mass values are comfortably inside the reach for a direct detection at the LHC.

$D^0 - \bar{D}^0$ **Oscillations** Having found sets of LHT parameters consistent with the data *out*side charm dynamics (including those on K and B decays) we compute M_{12}^D from them. As described in detail in [21] we found that the LHT contributions can yield a significant (or even leading) fraction of the observed value of $x_D = \Delta M_D / \Gamma_D$. More importantly for our discussion LHT can – quite unlike the SM – introduce sizable weak phases into $\Delta C = 2$ amplitudes. This feature can be expressed through the observables $\left| \frac{q}{p} \right| \neq 1$ describing CP violation in $D^0 - \bar{D}^0$ oscillations and $\text{Im} \frac{q}{p} \bar{\rho}(f) \neq 0$ reflecting the interference between oscillations and (non-leptonic) decays [22]. While $\left| \frac{q}{p} \right| \neq 1$ can be probed most cleanly in neutral D decays to 'wrong-sign' leptons

$$
\begin{aligned}
a_{\text{SL}}(D^0) &\equiv \frac{\Gamma(D^0(t) \to \ell^- \bar{\nu} K^+) - \Gamma(\bar{D}^0 \to \ell^+ \nu K^-)}{\Gamma(D^0(t) \to \ell^- \bar{\nu} K^+) + \Gamma(\bar{D}^0 \to \ell^+ \nu K^-)} \\
&= \frac{|q_D|^4 - |p_D|^4}{|q_D|^4 + |p_D|^4} ,
\end{aligned} \qquad (9)
$$

it also affects non-leptonic modes in a prominent way together with $\text{Im} \frac{q}{p} \bar{\rho}(f) \neq 0$. The time dependent CP asymmetry generated by the latter can conveniently be expressed by

$$\frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \equiv S_f \frac{t}{2\bar{\tau}} \qquad (10)$$

for a CP eigenstate f. In the *absence of direct* CP violation these two quantities are necessarily related [21, 23]:

$$S_f = -\eta_f \frac{x_D^2 + y_D^2}{y_D} a_{\text{SL}}(D^0) \qquad (11)$$

For the only source of CP violation is the relative phase between Γ_{12}^D and M_{12}^D. LHT can certainly generate a much larger value for this weak phase than the SM; it can actually be quite sizable in particular when LHT contributes less than half the observed value for ΔM_D.

To be more specific: an extensive sweep over the allowed LHT parameter space shows [21]

$$0.6 \lesssim \left| \frac{q_D}{p_D} \right|^{\text{SM+LHT}} \lesssim 1.3 \qquad (12)$$

to hold and thus

$$-0.8 \lesssim a_{SL}^{\text{SM+LHT}}(D^0) \lesssim +0.3 \,. \qquad (13)$$

While the experimental information of Eq.(4) is fully consistent with CP invariance, it also allows for a large violation. Its two sigma band is similar to what LHT dynamics can typically produce. While we know already that the production of 'wrong-sign' leptons is very low, see Eq.(2), their CP asymmetry could be very large – unlike what we have in K^0, B_d and B_s decays.

Furthermore we find that S_f – the time dependent CP asymmetry in nonleptonic D^0 decays – can hardly exceed the about 1% level, once we impose the experimental constraints on x_D, y_D and $|q/p|$ [21]. This is the basis of my statement above that the present absence of an asymmetry – Eq.(5) – is not very telling. The good news are that any improvement in experimental sensitivity can reveal a signal, and that CKM dynamics cannot produce more than $\mathcal{O}(10^{-5})$ effects.

Intriguing connections emerge with other flavours [21]:

- LHT can generate large deviations from CKM predictions for $|q/p|_D$ and for the time-dependent CP asymmetry $S_{B_s \to \psi\phi}$ [11] – yet most likely *not for both*.

- On the other hand large deviations can arise *simultaneously* for $|q/p|_D$ and for $\text{BR}(K_L \to \pi^0 \nu\bar{\nu})$ – even if $S_{B_s \to \psi\phi} < 0.05$ were found, i.e. a value practically indistinguishable from the CKM prediction. This is one example for the complementarity of the studies of D and K decays on one hand and of B decays on the other in the search for NP.

LHT dynamics provides a new source for *direct* CP violation in Cabibbo suppressed D channels through Penguin operators; their quantitative weight is being analyzed now.

Cast of Candidate Channels

Here I give a list of relevant channels, most of which – but not all – should be observable in hadronic collisions; in any case they deserve nontrivial attention and work:

$$D^0(t) \to K_S K^+ K^-, \ K_S \pi^+\pi^-, \ K_S \eta^{(')}$$
$$D^0(t) \to l^- \bar{\nu} K^+$$
$$D^0(t) \to K^+ K^-, \ \pi^+\pi^-, \ K^+\pi^-$$
$$D^\pm \to K_S \pi^\pm, \ K_S K^\pm$$
$$D \to 3\pi, \ K\bar{K}\pi, \ K^+\pi\pi$$
$$D^0 \to K^+ K^- \pi^+\pi^-, K^+ K^- \mu^+\mu^-, K^+\pi^-\pi^+\pi^-$$
$$D^0 \to \mu^+\mu^-, \ \gamma\gamma \qquad (14)$$

It should be noted that this is at best a representative list, not an exhaustive one. The dedicated reader is invited to come up with her/his personal favourite; in particular she/he can identify the corresponding D_s modes.

List of Relevant Observables in Two-Body Modes

There are two a priori distinct portals for CP violation: it can enter via $\Delta C = 1$ or $\Delta C = 2$ dynamics referred to as direct and indirect CP violation, respectively.

- *Direct* CP violation can reveal itself through a difference in the moduli of the $\Delta C = 1$ decay amplitudes describing CP conjugate transitions:

$$|T(D \to f)| \neq |T(\bar{D} \to \bar{f})| \,. \qquad (15)$$

It requires the presence of two coherent amplitudes differing in both their weak as well as strong phases.

- The effects of $D^0 - \bar{D}^0$ oscillations on CP asymmetries can be expressed through

$$\frac{q_D}{p_D} = \sqrt{\frac{(M_{12}^D)^* - \frac{i}{2}(\Gamma_{12}^D)^*}{M_{12}^D - \frac{i}{2}\Gamma_{12}^D}} \qquad (16)$$

Since M_{12}^D and Γ_{12}^D depend on the phase convention chosen for $\bar{D}^0$, neither of them nor q_D/p_D can be observables by themselves. Yet $|q/p|_D$ is as already stated: $|q_D/p_D| \neq 1$ unequivocally describes *indirect* CP violation in $D^0 - \bar{D}^0$ oscillations, and it affects semileptonic and nonleptonic channels.

- *Tertium datur:* When a nonleptonic final state is common to D^0 and $\bar{D}^0$ decays – in the simplest such cases it will be a CP eigenstate with parity η_f – it can exhibit a time-dependent asymmetry due to the interference between $D^0 - \bar{D}^0$ oscillations and D decay. It can be expressed by S_f, see Eq.(10); ignoring direct CP violation and with $x_D, y_D \ll 1$ we can write down:

$$S_f = -\eta_f \left[y_D \left(\left| \frac{q_D}{p_D} \right| - \left| \frac{p_D}{q_D} \right| \right) \cos 2\varphi \right.$$
$$\left. + x_D \left(\left| \frac{q_D}{p_D} \right| + \left| \frac{p_D}{q_D} \right| \right) \sin 2\varphi \right] \qquad (17)$$

This expression shows why it is important to measure x_D and y_D as accurately as possible in an independent way: for one wants to determine whether an observed CP asymmetry is due to $|q| \neq |p|$ or $\varphi \neq 0$ or both.

- Oscillations can provide access to *direct* CP violation that might otherwise remain unobservable. Consider two different final states f_1 and f_2 that are CP eigenstates and thus common to D^0 and $\bar{D}^0$ decays; for example $f_1 = \phi K_S$ and $f_2 = K^+ K^-$. In the absence of direct CP violation one has

$$S_{f_1} = \eta_{f_1 f_2} S_{f_2} \qquad (18)$$

with $\eta_{f_1 f_2}$ denoting the relative CP parity of f_1 vs. f_2; it is -1 in the example given above. Any difference from this relation shows CP violation in at least one of the $\Delta C = 1$ amplitudes. It should be noted that in the absence of oscillations this source of CP violation would be unobservable if the $D \to f_1$ and/or $D \to f_2$ amplitudes did not each contain two weak and two strong phases.

I will list here channels that appear to be most promising for revealing such effects on various Cabibbo levels. Again no claim is made for this being a complete list – the reader is invited to come up with her/his favourite modes.

Two-Body Channels Searching for asymmetries in CA final states of neutral D mesons represents a clean search for indirect CP violation, since NP affecting CA $\Delta C = 1$ amplitudes should have been noticed by now. The theoretically simplest channels would be

$$D^0 \to K_S \pi^0, \ K_S \eta, \ K_S \eta' \qquad (19)$$

– alas experimentally they are anything but simple. In a hadronic environment they seem to be close to impossible. The next best mode is

$$D^0 \to K_S \phi \to K_S [K^+ K^-]_\phi , \qquad (20)$$

which is given by a single isospin amplitude. The *strong* phase thus drops out from the ratio $\bar{\rho}_{K_S \phi} \equiv \frac{T(\bar{D}^0 \to K_S \phi)}{T(D^0 \to K_S \phi)}$, while their tiny SM weak phase can be ignored for the time being. We have here a *qualitative* analogy to $B_d \to \psi K_S$. The effect will be much smaller of course with much slower oscillations, and a priori one cannot ignore the impact of $y_D \neq 0$ and $\left| \frac{q_D}{p_D} \right| \neq 1$.

Extracting $D^0 \to K_S \phi$ from $D^0 \to K_S K^+ K^-$ is not trivial. Among other challenges one has to distinguish it from $D^0 \to K_S f^0$. For the CP parities of $K_S f^0$ and $K_S \phi$ are opposite. Therefore these final states would have to exhibit CP asymmetries of equal size, yet opposite sign. Ultimately one will perform a CP analysis of the full Dalitz plot for $K_S K^+ K^-$ – a topic I will address below.

The mode

$$D^\pm \to K_S \pi^\pm \qquad (21)$$

at first sight appears to be a CA mode. However that final state can be reached also through a DCS amplitude – $D^\pm \to \overline{K}^0 \pi^\pm / K^0 \pi^\pm \to K_S \pi^\pm$ – and its interference with the CA amplitude provides a non-negligible contribution. With*out* NP there are already two sources for a

direct CP asymmetry [12]: (i) The interference between $D^\pm \to \overline{K}^0 \pi^\pm \to K_S \pi^\pm$ and $D^\pm \to K^0 \pi^\pm \to K_S \pi^\pm$ generates an asymmetry $\sim \mathcal{O}(\mathrm{tg}^6 \theta_C) \sim 10^{-4}$. (ii) The CP impurity in the K_S wave function induces a larger asymmetry:

$$\frac{\Gamma(D^+ \to K_S \pi^+) - \Gamma(D^- \to K_S \pi^-)}{\Gamma(D^+ \to K_S \pi^+) + \Gamma(D^- \to K_S \pi^-)} \simeq \frac{|q_K|^2 - |p_K|^2}{|q_K|^2 + |p_K|^2}$$

$$\simeq -(3.32 \pm 0.06) \cdot 10^{-3} \qquad (22)$$

Any deviation from this accurate prediction would be due to an intervention by NP, presumably entering through the DCS amplitude.

The situation becomes more complex for Cabibbo suppressed channels. For CKM dynamics can already induce CP asymmetries – albeit highly diluted ones to the tune of 10^{-3} or less – since two different isospin amplitudes contribute. That opens the door wider for NP to enhance an asymmetry over its tiny SM expectation, even when it yields no more than a non-leading contribution to the rate.

Prime examples for promising channels are

$$D^0 \to K^+ K^-, \ \pi^+ \pi^- \qquad (23)$$

where now direct as well as indirect CP violation can arise. In the absence of the former the time dependent asymmetry has to be the same for both channels, since it is driven by the oscillations common to both modes. While no asymmetry has been observed there yet – see Eq.(5) – a signal could hardly have emerged on that level, but any improvement in the experimental sensitivity for $D^0(t) \to K^+ K^-, \ \pi^+ \pi^-$ constrains NP scenarios – or could reveal them [30].

Since $D^\pm \to \pi^\pm \pi^0$ leads to a pure isospin-two final state, CPT and isospin symmetries combine to severely limit its CP asymmetry. The situation is more promising for

$$D^\pm \to K^\pm K_S \qquad (24)$$

with $D^\pm \to \pi^\pm \eta^{(\prime)}$ providing the compensating asymmetry to satisfy CPT constraints.

Some DCS contributions have already been considered, when they enter through the 'backdoor' of final states containing a K_S (or K_L). A promising pure DCS channel is [24, 25]:

$$D^0 \to K^+ \pi^- \qquad (25)$$

- For it allows to track both direct and indirect CP violation and separate it through analyzing how the asymmetries evolve with the time of decay.

- The SM amplitude being DCS is significantly reduced by $\mathrm{tg}^2 \theta_C \sim 1/20$.

It should be noted that sources of indirect and direct CP violation could be quite unrelated to each other [26].

Final State Distributions

Dalitz Plot Studies

Final states with three pseudoscalar mesons can be treated in a 'Catholic' style: the Dalitz plot provides a single path to 'heaven'. The challenge we face here can be summarized as follows: we look for probably small-ish asymmetries in subdomains of the Dalitz plot, which is shaped by nonperturbative dynamics. While a proper Dalitz analysis requires a considerable 'overhead' in setting it up, it offers – like T *odd* correlations addressed next – valuable 'pay-offs':

- Local asymmetries are bound to be larger than integrated ones.

- There are correlations in a Dalitz plot that a proper analysis has to exhibit. Such correlations provide us with powerful validation tools in particular for small-ish effects.

- CP asymmetries in a Dalitz plot can provide us with information about the underlying operators – whether the Lagrangian is built from the products of spin-zero or spin-one operators, whether it contains mixed-chirality quark fields – that are not revealed in two-body modes.

Constructing and tuning a model for a full Dalitz plot description requires very large statistics – and even then one can *not* count on a *unique* model. Let me list just two reasons for ambiguities: (i) The non-resonant contributions are usually assumed to be flat across the Dalitz plot; yet it is merely mathematical simplicity rather than a dynamical insight that suggests such an ansatz. Assuming a non-uniform distribution – reflecting, say, a threshold enhancement – can have a considerable impact on what a fit yields for the resonant contributions. (ii) While pseudoscalar and vector resonances can adequately be described by Breit-Wigner excitation curves, chiral dynamics tell us this is not the case for scalar resonances like the sigma or κ. It is a rather subtle dynamical question how those are to be described, and it will vary from channel to channel.

Thus I see a two-fold challenge in front of us:

- Some dedicated theoretical effort has to be made to refine our tools for Dalitz plot descriptions [27].

- Even when maintaining that a description in terms of specific resonant and nonresonant amplitudes is the ultimate method for extracting all dynamical information from the data, it makes sense to develop alternative methods of analysis that are more robust and less model dependent, even if they cannot provide us with the full dynamical information. Such methods might enable us to draw firm, although less complete conclusions from more limited data sets. They could reveal more quickly the existence of a CP asymmetry, which in the case of charm decays might be tantamount to

establish the intervention of NP, and maybe even localize the sub-domain of the Dalitz plot, where the main source of the asymmetry resides. At the very least it would provide us with diagnostics concerning the critical domains for the Dalitz plot models.

Such alternative methods likely revolve issues of pattern recognition. There we can learn a lot from astronomers. They regularly face the problem of searching for something they do not quite know what it is at a priori unknown locations and having to deal with background sources that are all too often not really understood. While this sounds like a hopeless proposition, astronomers have actually been quite successful in overcoming these odds. Inspired by astronomers an intriguing suggestion has been made [28]: rather than search for the customary asymmetry $(N - \bar{N})/(N + \bar{N})$ in particle vs. anti-particle populations N and $\bar{N}$, respectively, analyze

$$\Sigma \equiv \frac{N - \bar{N}}{\sqrt{N + \bar{N}}} \qquad (26)$$

It corresponds to standard procedure in astronomy – suggested in 1983 for gamma ray astronomy [29] and now adopted also by the Auger collaboration – when comparing on- vs. off-source intensity. For a Poissonian distribution the standard deviation can be written as $\sigma = \frac{N_{\mathrm{on}} - \alpha N_{\mathrm{off}}}{\sqrt{N_{\mathrm{on}} + \alpha N_{\mathrm{off}}}}$. In the pilot study of [28] we have analyzed a few scenarios for Monte Carlo generated $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $D^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays, where we had seeded just a single source for CP violation. Using the variable Σ of Eq.(26) we could extract robust signals for the existence of a CP asymmetry and identify correctly the approximate location of the seeded asymmetry. More case studies are under consideration, including those involving time dependent Dalitz plots due to oscillations. It would be most desirable to test this method with real data to get a fuller evaluation of its potential.

This is just one possible example for how we can learn from our astronomer colleagues – I am sure there will be more under the motto: "Copying is the highest form of flattery".

T Odd *Correlations*

Going beyond three-body final states one has to deal with a 'Calvinist' situation. *A priori* there are several paths to heaven, and heaven's blessing is revealed *a posteriori* by the success of one's efforts; i.e. which distribution will provide the clearest CP asymmetry depends on the specifics of the underlying dynamics. This is good and bad in a complementary way: 'bad' in the sense that in a general search for NP one has to analyze several distributions; 'good', because once one has found a distribution – or a moment of such – that reveals an asymmetry, then its form can tell us something important about the underlying NP; or one can design the optimal observable if one searches for a very specific form of NP.

Since under T both momenta $\vec{p}$ and spin vectors $\vec{s}$ change sign, the most elementary T odd moments are given by expectation values of triple correlations like

$$\langle \vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3) \rangle \quad \text{and/or} \quad \langle \vec{s} \cdot (\vec{p}_1 \times \vec{p}_2) \rangle \quad (27)$$

Unless one has access to spin vectors one obviously needs at least a four-body final state for a T odd moment.

There is a subtle, yet important distinction between T odd and, say, P odd moments. Observing a P odd moment unequivocally establishes P violation unlike for the case of a T odd moment. For the latter can be generated also with T invariant dynamics if one goes beyond lowest order; i.e. FSI can *fake* a T violation [22]. This complication is due to time reversal being described by *anti*linear transformations. While FSI are a necessary evil for CP asymmetries to emerge in partial rates, they can be a nuisance for T odd effects: while they are not needed, they can fake an effect.

There are two ways to deal with this interpretative challenge: (i) One can attempt to estimate the order of magnitude of such FSI effects. (ii) One can compare T odd moments in CP conjugate decays of particles and antiparticles: If they are not equal in magnitude, yet opposite in sign, T invariance is broken, since CP transformations are linear.

The simplest cases are provided by [31, 8]

$$D^0 \to K^+ K^- \pi^+ \pi^- \quad vs. \quad \bar{D}^0 \to K^+ K^- \pi^+ \pi^- \quad (28)$$
$$D^0 \to K^+ K^- \mu^+ \mu^- \quad vs. \quad \bar{D}^0 \to K^+ K^- \mu^+ \mu^- \quad (29)$$
$$D^+ \to K^+ K_S \pi^+ \pi^- \quad vs. \quad D^- \to K^- K_S \pi^+ \pi^- \quad (30)$$

since all particles in the final state are distinct. It should be emphasized again that these are merely the most straightforward channels. A pioneering analysis of such correlations has been undertaken by the FOCUS Collab. [32] and is now under study by BaBar [33].

One can also analyze, say, $D^0 \to \pi^+ \pi^- \pi^+ \pi^-$ and use selection criteria like the energies of the pions. It makes sense to analyze T odd moments for neutral D decays as a function of the (proper) time of decay, since oscillations affect the relative weight of different contributions.

Likewise one can use different kinematic variables to form T odd moments. One can measure the azimuthal angle between the $K\bar{K}$ and the $\pi^+ \pi^-$ or $\mu^+ \mu^-$ planes and search for a forward-backward asymmetry in it – in analogy to what has been done for $K_L \to \pi^+ \pi^- e^+ e^-$ [34]. Without a specific model for the underlying CP odd dynamics one cannot decide a priori which correlations are most sensitive to NP dynamics.

Benchmark Goals

Viable NP scenarios could produce CP asymmetries close to the present experimental bounds, but not much higher. To have a 'fighting' chance to find an effect, one should strive to reach

• the $\mathcal{O}(10^{-4})$ [$\mathcal{O}(10^{-3})$] level for time-dependent CP rate asymmetries in $D^0 \to K^+ K^-$, $\pi^+ \pi^-$, $K_S \rho^0$, $K_S \phi$ [$D^0 \to K^+ \pi^-$];

• direct CP asymmetries in partial widths down to $\mathcal{O}(10^{-3})$ in $D \to K_S \pi$ and in singly Cabibbo suppressed modes and down to $\mathcal{O}(10^{-2})$ in doubly Cabibbo suppressed modes;

• the $\mathcal{O}(10^{-3})$ level in Dalitz asymmetries and T odd moments.

On Rare Charm Decays

There seems to be general agreement that studying $D \to \gamma X$ etc. is very unlikely to allow establishing the presence of NP because of uncertainties due to long distance dynamics [36]. I am concerned that the same strong caveat applies also to $D \to l^+ l^- X$.

The story is more promising for $D^0 \to \mu^+ \mu^-$. While its rate suffers greatly from helicity suppression and the need for weak annihilation – even the first factor is almost model independent – it is easier to interpret. In the SM the rate is estimated to be greatly dominated by long-distance dynamics – yet on a very tiny level [35, 36]:

$$\text{BR}(D^0 \to \mu^+ \mu^-)_{\text{SM}} \simeq \text{BR}(D^0 \to \mu^+ \mu^-)_{\text{LD}} \quad (31)$$
$$\simeq 3 \cdot 10^{-5} \times \text{BR}(D^0 \to \gamma\gamma)_{\text{SM}} \quad (32)$$

With the SM contribution to $D^0 \to \gamma\gamma$ again being dominated by long-distance forces [36]

$$\text{BR}(D^0 \to \gamma\gamma)_{\text{SM}} \simeq \text{BR}(D^0 \to \gamma\gamma)_{\text{LD}} \sim (1\pm0.5)\cdot10^{-8} , \quad (33)$$

one infers

$$\text{BR}(D^0 \to \mu^+ \mu^-)_{\text{SM}} \sim 3 \cdot 10^{-13} \quad (34)$$

to be compared with the present bounds

$$\text{BR}(D^0 \to \mu^+ \mu^-) \leq 5.3 \cdot 10^{-7} \quad (35)$$
$$\text{BR}(D^0 \to \gamma\gamma) \leq 2.7 \cdot 10^{-5}. \quad (36)$$

The bound of Eq.(36) implies a bound of 10^{-9} in Eq.(35) – i.e., a much tighter one. In either case there is a rather wide window of opportunity for discovering NP in $D^0 \to \mu^+ \mu^-$. As pointed out in [37] in several NP models there is actually a relatively tight connection between the NP contributions to $\text{BR}(D^0 \to \mu^+ \mu^-)$ and $\Delta M_D / \Gamma_D$.

Specifically LHT makes short-distance contributions to $D^0 \to \mu^+ \mu^-$ and $D^0 \to \gamma\gamma$ that can be calculated in a straightforward way as a function of viable LHT parameters. Their size is under active study now. No matter what drives $D^0 \to \gamma\gamma$ - whether it is from short or long distance dynamics – it provides a long distance contribution to $D^0 \to \mu^+ \mu^-$. For a proper interpretation of these rare D decays it is thus important to search for $D^0 \to \gamma\gamma$ with as high a sensitivity as possible.

On Theoretical Guidance

To say that theoretical predictions have not always been on the mark, in particular when nonperturbative forces are

involved, is putting it delicately. Yet this does not justify immediate rejection of theoretical advice – it merely points to the need for some healthy skepticism.

It is my considered judgment that the 'hadronic community' has acquired a great deal of expertise and accumulated a wealth of information on low energy hadronic interactions. Yet this knowledge has hardly migrated to the heavy flavour community; it could be put to excellent and urgently needed use in studies of charm and beauty decays with unprecedented statistics. It is high time that a broader bridge is built between the two communities – and we intend to do just that [27].

'Theoretical Engineering'

When describing (quasi) two-body channels of the $D \to PP$, PV type we can make an intelligent use of measured partial rates to get to a reasonably reliable theoretical description of CP asymmetries there. On each Cabibbo level one expresses the total transition operator in terms of 'elementary' $\Delta C = 1$ operators whose coefficients are computed from the known CKM factors and QCD radiative corrections. One makes a judicious choice of which such $\Delta C = 1$ operators to include – corresponding to internal and external W emission with or without interference, weak annihilation and Penguin contributions if possible. When evaluating the corresponding amplitudes one leaves the magnitude of the appropriate strong matrix elements and the values of their FSI phases open. From fitting such expressions to a comprehensive set of high statistics data one infers values for these a priori unknowns. The reliability of such extractions rests on the degree of over-constraints one has achieved including cross referencing those numbers against each other using $SU(3)_{fl}$ relations etc. The ability to include also channels with (multi-)neutrals is obviously of essential value here; such measurements belong to the domain of e^+e^- τ-charm factories like BESIII [38].

On CPT Constraints

CPT symmetry provides more constraints than just equality of masses and lifetimes of particles and antiparticles [22]. For it tells us that the widths for *sub*classes of transitions have to be the same. For simplicity consider a toy model where the D meson can decay only into two classes of final states $E = \{e_i, i = 1, ..., n\}$ and $F = \{f_j, j = 1, ..., m\}$ with the strong interactions allowing members of the class E to rescatter into each other and likewise for class F, but *no* rescattering possible *between* classes E and F. Then CPT symmetry tells us partial width asymmetries *summed* over class E already have to vanish and likewise for class F. This CPT 'filter' can hardly be of any practical use for B decays with their multitude of channels on vastly different CKM levels. Yet it might provide nontrivial validation checks for D decays with their considerably fewer channels, where quasi-*elastic* unitarity could conceivably hold in a semiquantitative way.

Penguins despite their poor reputation in flavour dynamics – as expressed through the all too often heard "penguin pollution" – are rather smart beings. When Penguin diagrams are invoked to generate the FSI required for a direct CP asymmetry, examining the light quarks in their loops will tell you in which class of channels the compensating asymmetries have to arise. To cite a simple example: such considerations suggest that a direct CP asymmetry in $D^0 \to K^+K^-$ is compensated mainly by an asymmetry in $D^0 \to \pi^+\pi^-$. Finding these balancing effects would validate the observation of a presumably small asymmetry.

On Relating Direct and Indirect Searches for New Physics

Looking for NP inducing CP violation in charm decays represents 'hypothesis-generating' research – similar to the *present* situation in B physics. Once, say, SUSY is found in high $p_\perp$ collisions at the LHC, future studies of B decays would be of the 'hypothesis-probing' variety; this would be analogous to the situation about fifteen years ago, when the e^+e^- B factories were approved. Finding direct evidence for LHT models might turn the same trick for the detailed study of D decays.

Summary and Outlook

There is general conviction that $D^0 - \bar{D}^0$ oscillations have been observed: $(x_D, y_D) \neq (0, 0)$. However their theoretical interpretation is rather ambiguous: SM dynamics might generate the whole effect or the major part of it or only a minor part. Deciding this issue on theoretical grounds would require a breakthrough in our computational abilities. A comprehensive and detailed program of CP studies in charm transitions can presumably decide the issue: It might establish the intervention of NP; for even if it provided only a non-leading contribution to ΔM_D, it would quite possibly represent the leading source of CP asymmetries due to the 'dullness' of SM CP phenomenology. The present absence of a signal CP violation is not very telling. For future studies we need to know the relative size of x_D and y_D as best as possible.

'Realistically' one cannot hope for much more than $\mathcal{O}(10^{-3})$ effects. Thus we have to learn to exploit the statistical 'muscle' of LHCb and control systematics. Asymmetries in final state distributions as analyzed through Dalitz studies and T odd correlations offer several advantages: differential asymmetries could be considerably larger than integrated ones; internal cross checks provide powerful tools to deal with systematics; they can provide us with novel clues about the nature of the intervening New Physics. On the theory side we can expect a positive learning curve for theorists, yet should not expect miracles. What we can count on is that precise data will prompt some theorists to take on the challenge of developing an adequate description.

My plea for more dedicated charm studies is not merely

a repetition of a "Ceterum censeo fascinum esse studian-dum" ("Moreover I advise that charm has to be studied"). The field of charm studies has achieved a qualitatively new level of maturity and promise through the observation of $D^0 - \bar{D}^0$ oscillations and the 'awakening' this discovery has prompted in the theory community concerning the possibility of NP scenarios leaving their clearest footprint in charm decays.

Andrzej Buras has authorized me to make the following statement: He is willing to bet his beard that LHT models would lead to observable CP violation in D decays! Your studies of charm decays will thus have significant impact irrespective of their outcome: *If* you find CP violation, you have most likely discovered the intervention of NP. *If not*, you will create an even more visible impact as you can imagine from Fig. 1!

Figure 1: A Polish Gentleman boasting now (and forever ?) a superbly-groomed beard.

Epilogue: Bismarck's Dictum

Bismarck – a statesman with firm goals, yet not given to moral qualms about how to achieve those – once declared:

"... the role of the statesman is to grab the mantle of history when he feels it passing by ...". Likewise it is the task of the physicist to make the greatest use of a special gift from Nature. $D^0 - \bar{D}^0$ oscillations are such a gift. Therefore it is your duty to make the best use of it – and there is fame within your grasp!

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