THE SYBILS’ ADVICE ON CHARM
(AND \(\tau\) LEPTONS)

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Abstract

The importance of future studies of charm and \(\tau\) decays is emphasized as probes of New Physics: the most powerful tools are CP asymmetries in charm and \(\tau\) decays both in partial widths and final state distributions. While these searches for CP violation are instrumentalized in the search for and hopefully future analysis of New Physics, they might also shed light on the CP breaking dynamics required to implement baryogenesis. \(e^+e^-\) Super-Flavour Factories are optimally suited for the challenge, in many aspects even uniquely so.

1 Executive Summary

Talking about charm near Rome is particularly pleasant to me: For many of the allegories I have used over the years concerning charm have an obvious connection to Rome.

- My intention: ”I have come to praise C., not bury it.”
- My judgment:”Charm – Come Botticelli nella Sistina”
- My IAC: The Sybils – ”La Delfica” aka ”Pythia” and the local one from Tivoli, ”La Tiburtina”, see Fig. 1.

While the meaning of the first item is obvious, the other two need some elucidation. While Botticelli – charm physics – can match neither Michelangelo – beauty physics – nor Raffaello – kaon physics – and therefore is often overlooked vis-a-vie the masterworks
by Michelangelo in the Sistine chapel and by Raffaello nearby through an adverse ‘genius loci’, he is still Botticelli, i.e. a world class artist. My visionary advisors emphasize four items:

• After having found that CP violating phases in the quark sector can be truly large, we need to uncover CP violation in leptodynamics. The three most promising (or should I say least discouraging) areas are:

  – neutrino oscillations;
  – electron electric dipole moments (EDM’s);
  – τ decays.

• Baryogenesis implies the need for a ‘New Paradigm of CP Violation’ – possibly or even probably in leptodynamics.

• New Physics most likely induces flavour changing neutral currents: those could be (much) less suppressed for up- than down-type quarks.

• Charm is the only up-type quark allowing a full range of probes for New Physics:

  – Since top quarks do not hadronize [1], 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.
  – 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.

In my view the justification for a Super-B factory can be and has to be based on three goals:
1. A comprehensive and detailed analysis of $B$ (and $B_s$) transitions must be the first and foremost goal.

2. Analyzing $\tau$ decays represent a superb second goal, since their most profound lessons might still be waiting to be learnt, and no other machine can be competitive.

3. Probing charm processes constitute a still excellent third goal when one considers the envisioned luminosity $L \sim 10^{36}$ cm$^{-2}$ s$^{-1}$ [2] and energy flexibility coupled with the ability to study final state distributions with neutrals that is unmatched by any other set-up.

Thus I find it most appropriate to speak of a Super-Flavour factory.

I would like to emphasize the following design considerations for the detector.

- A very hermetic detector coupled with low backgrounds will be most helpful or even essential to control systematics in $B$, $\tau$ and charm studies, like $B \to \tau\tau/\tau\nu/\tau\nu X_c/\tau\nu D$, $\tau \to l\nu\bar{\nu}$.

- The resolution of the microvertex detector should be driven by the presumably more demanding requirements of charm physics, in particular concerning $D^0 - \bar{D}^0$ oscillations and CP violation there. This should benefit also searches for CP violation in $\tau$ decays and in $B_s$ transitions on the $\Upsilon(5S)$ with the latter driven by $\Delta\Gamma$ effects.

- A polarized electron beam would be most helpful for CP studies in $\tau$ and $\Lambda_c$ decays to enhance sensitivity and control systematics.

There are several excellent reviews that the committed reader can consult to find out about details and further support for the statements on charm decays in this overview [3].

Future studies of $\tau$ and charm transitions constitutes 'hypothesis generating' rather than 'hypothesis driven' research. Antiquity’s paradigm of ‘hypothesis generating’ analysis is represented by Delphi and its Pythia – and by the nearby Tivoli with La Tiburtina.

2 $\tau$ Decays – the Next Hero Candidate

The study of $\tau$ decays, which has taught us valuable lessons on QCD, can still reveal the intervention of New Physics through lepton flavour violating (LFV) transitions [4–6] and CP asymmetries.

With respect to LFV there are three classes of modes, namely (i) $\tau \to l\gamma$, (ii) $\tau \to l_1l_2l_3$ and (iii) $\tau \to l\nu_1\nu_2$. While typically rates for type (i) channels exceed those for type (ii), there are notable exceptions. Furthermore type (iii) can be probed through careful checks of lepton universality in $\tau$ decays [7]. Since all these types are forbidden in the SM, the observable rate is quadratic in the New Physics amplitude.
2.1 CP Violation

As already mentioned to implement baryogenesis we need a new source of CP violation, and that might well be in leptodynamics driving leptogenesis as the primary effect. $\tau$ leptons provide one of the more promising areas to search for such effects:

- The $\tau$ spin provides an important tool to enhance the experimental sensitivity.
- CPT constraints are less restrictive than in $\mu$ decays.
- Non-minimal Higgs dynamics, which can provide a source of CP violation, enjoy enhanced couplings in $\tau$ decays, in particular for $\tau \rightarrow \nu K\pi$, which is Cabibbo suppressed in the SM.

Two general remarks might be of use here: (a) The sought-after CP asymmetry is linear in the New Physics amplitude, since the SM provides the other amplitude. (b) One can search for CP violation in the production of $\tau$ leptons through their EDM. Yet there one is competing against electromagnetic forces, in marked contrast to the situation with weak decays. Therefore the chances for an observable effect are better in the latter case.

In principle one can perform a comprehensive ‘Fetscher-type’ analysis of $\tau \rightarrow l\nu\bar{\nu}$ as for $\mu \rightarrow e\nu\bar{\nu}$ [8]. Yet I view the channels $\tau^\pm \rightarrow \nu K^{\mp}\pi^0/K^0\pi^\pm$ as more promising also for the observable features of its final state: such a three-body final state can exhibit CP violation also through asymmetries in the final state as discussed in general terms in Refs. [9], namely Dalitz plot asymmetries and/or $T$ odd distributions. It is quite possible – actually likely – that asymmetries in differential distributions are significantly larger than in integrated rates. Furthermore they would yield more information on the underlying transition operator and allow consistency checks to control systematics.

$T$ odd moments – correlations that change sign under time reversal $T$ – allow to make efficient use of limited statistics. A $T$ odd and CP violating correlation has been found in $K_L \rightarrow \pi^+\pi^- e^+e^-$ between the di-pion and di-lepton planes. It has been searched for in $K^+ \rightarrow \mu^+\nu\pi^0$: $\langle \vec{s}_\mu \cdot (\vec{p}_\mu \times \vec{p}_\pi) \rangle$. In close analogy to the latter one can form a $T$ odd moment in $\tau \rightarrow \nu K\pi$, if the $\tau$ spin can be exploited:

$$O_T \equiv \langle \vec{s}_\tau \cdot (\vec{p}_K \times \vec{p}_\pi) \rangle \overset{T}{\rightarrow} -O_T$$

This would be possible most efficiently if one had the $e^-$ beam longitudinally polarized, since it would lead to the $\tau$ being produced polarized. Alternatively one can rely on a special property of $e^+e^- \rightarrow \gamma^* \rightarrow \tau^+\tau^-$, namely that the $\tau$ pair is ‘spin-aligned’: the polarization of one $\tau$ can be tagged by the decay of the other [10]. Final state interactions can induce a non-zero $T$ odd correlation even with the dynamics $T$ conserving. Yet in $e^+e^- \rightarrow \tau^+\tau^-$ one can compare CP conjugate moments and thus isolate genuine CP violation.

The aim should be to probe the $10^{-3}$ level; the question is whether systematic uncertainties can be pushed below the 1% level without polarized beams.

The often heard statement that practically no CP violation in $\tau$ decays is expected within the SM is not quite correct in a subtle way. As pointed out recently the ‘known’
\textbf{CP} impurity in the $K_L$ wave function, which implies a corresponding impurity for $K_S$ based on \textbf{CPT} symmetry induces a reliably predicted asymmetry in the absence of New Physics [11]:

$$\frac{\Gamma(\tau^+ \to \bar{\nu}K_S\pi^+) - \Gamma(\tau^- \to \nu K_S\pi^-)}{\Gamma(\tau^+ \to \bar{\nu}K_S\pi^+) + \Gamma(\tau^- \to \nu K_S\pi^-)} \simeq 2\text{Re}\epsilon_K \simeq (3.27 \pm 0.12) \cdot 10^{-3} \quad (2)$$

The intervention of New Physics in $\tau$ decay would then modify this value. Such an effect does of course not exist for the similar mode $\tau^+ \to \bar{\nu}K^+\pi^0$. Comparing the findings in those two modes would thus provide a useful cross check on possible detector biases.

\section{Inconclusive $D^0 - \bar{D}^0$ oscillations}

$D^0 - \bar{D}^0$ oscillations are a fascinating quantum mechanical phenomenon, and they form an important ingredient when searching for manifestations of New Physics, yet by themselves they represent only an ambiguous probe of New Physics.

Oscillations can be characterized by two quantities, namely $x_D = \frac{\Delta M_D}{\Gamma_D}$ and $y_D = \frac{\Delta \Gamma_D}{2\Gamma_D}$. Oscillations are slowed down in the SM due to GIM suppression and $SU(3)_f$ symmetry. Comparing a \textit{conservative} SM bound with the present data

$$x_D(SM), y_D(SM) < \mathcal{O}(0.01) \ \text{vs.} \ \ x_D|_{\text{exp}} < 0.03, \ \ y_D|_{\text{exp}} = 0.01 \pm 0.005 \quad (3)$$

we conclude that the search has just now begun. There exists a considerable literature – yet typically with several ad-hoc assumptions concerning the nonperturbative dynamics. 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 in Ref. [12] 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

$$x_D(SM)|_{\text{OPE}}, \ y_D(SM)|_{\text{OPE}} \sim \mathcal{O}(10^{-3}) \quad (4)$$

Ref. [13] finds very similar numbers, albeit in a quite different approach. When evaluating the predictions in Eq.4 one has to distinguish carefully between two similar sounding questions:

- "What are the \textit{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 $y_D$ \textit{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 keep further in mind that they arise in very different dynamical environments. $\Delta M_D$ is generated from
off-shell intermediate states and thus 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 much more vulnerable to violations of quark-hadron duality. A similar concern applies to $\Delta \Gamma(B_s)$. Observing $y_D \sim 10^{-3}$ together 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. A superb resolution for the $\mu$ vertex detector is presumably essential here.

4 CP Violation with & without Oscillations

Most – though not all – 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 $\sim \mathcal{O}(\lambda^4)$, and it can arise only in singly Cabibbo suppressed transitions, where one expects asymmetries to reach the $\mathcal{O}(0.1\%)$ 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 $D^\pm \rightarrow K_S \pi^\pm$ [14], 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:

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

⊕ 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, it enhances the observability of a signal.

⊕ 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 can 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 \( \text{CP} \) conjugate modes:

\[
O_T(D \rightarrow f) \neq -O_T(\bar{D} \rightarrow \bar{f}) \implies \text{CP violation}
\]

(6)

I view this as a very promising avenue, where we still have to develop the most effective analysis tools for small asymmetries.

⊕ The distinctive channel \( D^{\pm*} \rightarrow D\pi^{\pm} \) provides a powerful tag on the flavour identity of the neutral \( D \) meson.

⊕ The ‘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 \( \text{CP} \) violation involving \( D^0 - \bar{D}^0 \) oscillations is a reliable probe of New Physics: the asymmetry is controlled by \( \sin\Delta m_D t \cdot \text{Im}(q/p)\rho(D \rightarrow f) \). Within the SM both factors are small, namely \( \sim \mathcal{O}(10^{-3}) \), making such an asymmetry unobservably tiny – unless there is New Physics; for a recent New Physics model see Ref. [15]. One should note that this observable is linear in \( x_D \) rather than quadratic as for \( \text{CP} \) insensitive quantities like \( D^0(t) \rightarrow l^-X \). \( D^0 - \bar{D}^0 \) oscillations, \( \text{CP} \) 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 \( \text{CP} \) eigenstates \( D^0 \rightarrow K_S\phi, K^+K^-, \pi^+\pi^- \) – or doubly Cabibbo suppressed modes \( D^0 \rightarrow K^+\pi^- \). In the end it might turn out that the corresponding three-body final states \( D^0 \rightarrow K_S\pi^+\pi^-, D^0 \rightarrow K^+K^-\pi^0/\pi^+\pi^-\pi^0 \) and \( D^0 \rightarrow K^+\pi^-\pi^0 \) – allow searches with higher sensitivity. Undertaking time-dependent Dalitz plot studies requires a higher initial overhead, yet in the long run this should pay handy dividends exactly since Dalitz analyses can invoke many internal correlations that in turn serve to control systematic uncertainties. ¹

⊕ It is all too often overlooked that CPT invariance can provide nontrivial constraints on \( \text{CP} \) 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 \( \text{CP} \) asymmetry in one channel one can then infer in which other channels the ‘compensating’ asymmetries have to arise.

4.1 A Potential New Star: \( \Lambda_c \) (\& \( \Xi_c \)) Decays

With the electron beam longitudinally polarized charm quarks and antiquarks would be produced polarized. At least some of this polarization should emerge, when those charm quarks hadronize into charm baryons, and it can be revealed through their weak decays. This would provide a powerful probe of \( \text{CP} \) violation and \( T \) odd moments similar to what can happen in \( \tau \) decays as described above.

¹Pythagoras’ dictum "There is no royal way to mathematics" applies to fundamental physics as well.
4.2 Experimental Status & Future Benchmarks

So far only 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 [16]. Time dependent CP asymmetries (i.e. those involving $D^0 - \bar{D}^0$ oscillations) still form completely ‘terra incognita’. Considering the charm production rates achieved at the $B$ factories in particular and at FNAL I suspect the main limitation has been a lack of manpower rather than statistics.

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 width 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 it along 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 $O(10^{-4})$ and $O(10^{-3})$ levels, respectively.

Statisticswise 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 [17].

When going after asymmetries below the 1% or so one has to struggle against systematic uncertainties, in particular since detectors are made from matter. I can see three powerful weapons in this struggle:

- Resolving the time evolution of asymmetries that are controlled by $x_D$ and $y_D$, which requires excellent microvertex detectors;
- Dalitz plot consistency checks;
- quantum statistics constraints on distributions, T odd moments etc.

5 Conclusions

Two aspects of $\tau$ decays deserve, actually require even more determined scrutiny than has been brought to bear up to now: lepton flavour violation (LFV) and CP violation.

The observation of neutrino oscillations tells us that LFV does exist in nature. There are intriguing (SUSY) GUT scenarios connecting the observed $b \rightarrow s\gamma$ with $\tau \rightarrow \mu\gamma$ transitions and suggesting the latter to occur possibly at levels close to existing bounds and in any case probably within one or two orders of magnitude of them. The phenomenology of LFV in $\tau$ decays is complementary to that in muon decays and actually richer. While most models predict higher rates for $\tau \rightarrow l\gamma$ than for decays into three leptons [4, 7] one should search also for the latter with vigour. The more experimental sensitivity can be achieved, the better. Finally $\tau$ production in $e^+e^-$ annihilation has no practical competition from any other production process.
We should keep in mind that we need a new CP paradigm to realize baryogenesis and that quite possibly leptogenesis might be the primary effect. This provides a more specific motivation to the general goal to probe CP violation in leptodynamics. Again \( \tau \) decays constitute a much richer and more fertile laboratory than muon decays. Having polarized electron beams leading to the production of polarized \( \tau \) pairs would provide a very powerful though presumably not mandatory tool. It appears unlikely at present that one could have too much experimental sensitivity. No other setup can realistically compete with \( e^+ e^- \to \tau^+ \tau^- \) concerning CP studies.

Charm is often viewed as a ‘has-been’ quantum number: after a few absolute branching ratios have been measured accurately to provide validation opportunities to lattice QCD, there is nothing of substance to be learnt from them. This view overlooks that charm hadrons keep amazing us with features that had not been anticipated as demonstrated recently by the discovery of the \( D^{**}_s \), \( X(3872) \), \( X(3940) \) and \( Y(4260) \) resonances [16]. Those findings have led to a re-analysis of our understanding – or lack thereof – of hadronic spectroscopy [18–20].

Yet even beyond that weak charm decays might teach us important, possibly even unique lessons on New Physics. While it is possible to construct New Physics models that lead to CP asymmetries not far below present bounds and well above SM predictions, they are neither compelling nor particularly intriguing. Yet it behooves us to be aware of our ignorance: “We know so much about the flavour structure, yet understand so little.” It is quite conceivable that flavour changing neutral currents are considerably stronger for up-type than for down-type quarks. Charm is the only up-type quark allowing for a full range of probes of New Physics through CP studies with and without oscillations. Charm thus might, just might provide essential support for the emerging New SM.

Charm studies can benefit from many experimental and phenomenological advantages. They suffer from the drawback that charm decays in contrast to \( K \) and \( B \) decays are not KM suppressed and that oscillations proceed at best at slow speed. Yet even on the theoretical side there are some advantages, namely the ‘dullness’ of the SM electroweak phenomenology and the reasonable expectation that hadronization effects of charm can be brought mostly under theoretical control due to the comprehensive data sets accumulated by the CLEO-c and BESIII collaborations.

We should also keep in mind that we have only recently entered a territory in charm studies, where one could reasonably hope to uncover New Physics – and there are still two to three orders of magnitude in sensitivity waiting for the enterprising ‘treasure hunter’.

One last brief comment on experimental considerations: Doing truly superb studies of \( B \) decays has to be the paramount objective of a Super-Flavour factory. Yet it can also do superb and even unique \( \tau \) and charm studies. One should seriously study how one can maximize the latter without in any way jeopardizing the former. One item might be to ‘overdesign’ the \( \mu \) vertex detector beyond the needs of \( B_{u,d} \) studies to enhance its usefulness for charm and probably also \( \tau \) physics as well as for \( \Delta \Gamma \) effects in \( \Upsilon(5S) \to B^{(*)}_s \bar{B}^{(*)}_s \).
6 Epilogue

Finding any signal of New Physics in high $p_\perp$ studies at the LHC will provide a great boost substantially as well as morally. Among other things it would make it mandatory to analyze the impact of that New Physics in heavy flavour studies. The first working hypothesis though would have to be that $B$ and $K$ decays being CKM suppressed provide the highest sensitivity to the New Physics – unless one finds something rather exotic like a neutral boson decaying into, say, two jets of which only one contains charm.

My message has been as specific as could be expected when coming from the Pythia on the right in Fig.2 rather the one on the left, with whom high energy physicists are more familiar, and when communicated by a mere mortal like me, who is not even a priest.

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