Hadronization – the Unsung Hero
rather than the Alleged Villain in the Tale of CP Violation

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Abstract
The novel successes scored by the Standard Model of High Energy Physics in the last few years concerning heavy flavour dynamics do not weaken the case for ‘New Physics’ around the TeV scale. They do suggest however that one cannot count on that New Physics impacting heavy flavour decays in a numerically massive way. Yet studying this impact will be essential in diagnosing the features of the New Physics. In particular the decays of beauty hadrons have to be analyzed with considerable precision on the experimental as well as theoretical side. While hadronization effects often represent the main bottleneck in our understanding in the short run, they will provide powerful and discriminating tools in the long run, when applied comprehensively and judiciously. The expertise required to exhaust the discovery potential in $B$ decays does exist in the hadron physics community or can be developed without needing a new breakthrough – yet a greater effort has to be made to communicate it to the heavy flavour community.

1 Prologue
There are three reasons why I am grateful for the invitation to participate in this conference and speak to you. Terry Goldman expressed the third reason the other day: Rio de Janeiro gives a new and very pleasant meaning to the word ‘winter conference’. The second reason will be explained in my talk. My first reason is of a general nature. I am experiencing high energy physics as a truly noble human activity and view it as the most global one, where I cannot see any drawback to globalization – contrary to other manifestations of globalization. However as far as its geographic distribution is concerned, I am exaggerating: marking on a globe where high energy physics research is done, you will

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find it happens almost exclusively in the northern hemisphere. This lack of balance concerns me, and I hope for a wider distribution in the future. We owe a lot of gratitude to our colleagues, who maintain and further build high energy physics in the southern hemisphere. I view CBPF here in Rio as the flagship of fundamental physics in the southern hemisphere, appreciate the work Alberto Reis and his colleagues are doing in ‘spreading the gospel’ and promise my support to them.

2 Introduction

Around the turn of the millenium – in the years 1998 – 2001 – a ‘quantum jump’ in our knowledge (though not our understanding) of fundamental physics has occurred:

- "the completion of an era": the establishment of direct CP violation in $K_L$ decays;
- "the beginning of a new journey": the first observation of CP violation in a system other than the $K^0 - \bar{K}^0$ complex, namely in $B_d \rightarrow \psi K_S$;
- "messages from the heavens": the discovery of neutrino oscillations;
- "the birth of a Standard Model of Cosmology": a consistent picture concerning the composition of our Universe \(^2\) in terms of visible and dark matter and ‘dark energy’ and the distribution of the cosmic microwave radiation and its fluctuations has emerged. The evidence for ‘dark energy’ can best be commented by repeating Rabi’s famous quote about the muon: “Who ordered that?”

The first three items certainly and the fourth one probably impact our views of microscopic dynamics profoundly, although it is still too early to say how. Concerning the first two items I would like to emphasize without an explanation (that can be found in my Varenna lectures \(^1\)) that the SM has scored not ‘merely’ more or even new successes, but actually novel ones, i.e. of a qualitatively new kind: the predicted ‘Paradigm of large CP violation in $B$ decays’ \(^2\) has been verified through the discovery of indirect and direct CP violation in $B_d \rightarrow \psi K_S$, $B \rightarrow K \pi$ and presumably also in $B_d \rightarrow \pi^+ \pi^-$ \(^3\) \(^4\); these large CP asymmetries are commensurate with T violation without assuming the full power of CPT invariance \(^5\).

Yet none of these novel successes of the SM weaken the case for it being incomplete and for New Physics being even ‘nearby’, i.e. around the TeV scale. We have ‘heavenly’ data showing the incompleteness of the SM: baryogenesis, neutrino oscillations, ‘dark matter’ and the most puzzling feature of all, ‘dark energy’. On the theoretical side we still have not solved the Strong CP Problem \(^6\).

\(^2\)If indeed there exist other ‘universes’ besides ours, the term universe is no longer appropriate. With our ‘universe’ being just one among countless others, also the name ‘cosmos’ is misplaced. For this Greek word refers to an order that derives its beauty from careful arrangement.
More generally these successes do not shed light on any of the mysterious features of
the SM.

(i) What are the dynamics driving the electroweak symmetry breaking of $SU(2)_L \times\ U(1) \rightarrow U(1)_{QED}$. How can we tame the instability of Higgs dynamics with its quadratic
mass divergence? I find the arguments compelling that point to New Physics at the
$\sim 1$ TeV scale – like low-energy SUSY; therefore I call it the ‘confidently predicted’ New
Physics or $cpNP$.

(ii) The family structure with the quantization of the electric charges of quarks and
leptons as expressed for example through

$$Q_e = 3Q_d$$

This would be naturally explained through Grand Unification at very high energy scales
implemented through, e.g., $SO(10)$ gauge dynamics. I call this the ‘guaranteed New
Physics’ or $gNP$.

(iii) $Finite family replication$: we infer from the observed width of $Z^0$ decays that there
are three (light) neutrino species. The hierarchical pattern of CKM parameters as revealed
by the data is so peculiar as to suggest that some other dynamical layer has to underlie
it. I refer to it as ‘strongly suspected New Physics’ or $ssNP$. Saying we pin our hopes for
explaining the family replication on Super-String or M theory is a scholarly way of saying
we have hardly a clue what that $ssNP$ is.

Comprehensive studies of heavy flavour dynamics might provide insights into the $gNP$
and $ssNP$, items (ii) and (iii), but I would not count on it. However – and this is the
central element of my message – they will be crucial in identifying the $cpNP$.

In a nutshell my message reads as follows: We expect confidently that New Physics
surfaces at the TeV scale. Yet we have to aim beyond ‘merely’ establishing the existence
of New Physics – our goal has to be to identify its salient features. TeV scale dynamics is
likely to have some nontrivial impact on $B$ decays, and the discovery potential in $B$ decays
is essential for figuring out the $cpNP$, not a luxury. Yet due to the past ‘unlikely’ success of
the CKM description one cannot count on massive manifestations of New Physics, at least
not in $B$ decays typically. Therefore we need high accuracy both on the experimental and
theoretical side in heavy flavour studies. This requires a better quantitative understanding
of hadronization to exhaust the discovery potential in $B$ decays. The necessary expertise
exists or can be acquired without a new theoretical breakthrough.

By the past ‘unlikely’ success of the CKM description I mean the following. As far as
we know large fractions of the observables $\Delta M_K$, $\epsilon_K$ and $\Delta M_B$ could be due to physics
beyond the SM and even most of $\epsilon'$. Likewise the constraints from the data on the CKM
parameters translate into seemingly broad bands in plots of the CKM unitarity triangle
$[6]$. The problem with this statement is that it is not even wrong – it just misses the
main point: it is already very remarkable and highly nontrivial that all these constraints
can be incorporated in a meaningful way in such plots. This becomes more obvious when
plotting these and other observables from the strange, charm and beauty transitions on
a commensurate energy scale. They cover several orders of magnitude between $10^{-8}$ and $10^{-16}$ MeV. That the CKM expectations are always within 50% or so of the data over this range is most remarkable and could not be expected a priori – in particular when coupled with the fact that these predictions are based on values for the CKM and other mass parameters that would seem frivolous at best – if they were not forced upon us by independent measurements. The huge top quark mass of about 175 GeV (which is the only quark mass not only to approach the vector boson masses, but even to exceed them considerably) provides a case in point. There could easily have been inconsistencies. In other words: for CKM theory to provide a satisfactory description of the data, its parameters had to reside in a very peculiar corner of the general parameter space – yet nature has put them exactly into that ‘neighbourhood’\footnote{7}. Therefore some of us had been rather confident that the CP asymmetry measured in $B_d \to \psi K_S$ would be close to the CKM prediction, whatever the latter would be – as indeed was the case.

The observation of this asymmetry in 2001 by both BABAR and BELLE\footnote{4} has established the CKM paradigm as a tested theory that no longer deserves the patronizing label of an ‘ansatz’. Furthermore a ‘demystification’ of CP violation has occurred: we have seen that if the dynamics are sufficiently rich as to be able to support CP violation, the latter can be large (although we still do not know how to give meaning to the notion of ‘maximal’ CP violation). This process of demystification will have been completed, if CP violation is found anywhere in the lepton sector – a point I will return to later. We also know that the standard CKM theory is utterly irrelevant for baryogenesis, that the observed baryon number of the Universe shows the need for New Physics\footnote{8}.

In summary: we have to conduct dedicated and comprehensive searches for New Physics. You have heard that before, have you not? And it reminds you of a quote by Samuel Beckett:

”Ever tried? Ever failed? No matter. Try again. Fail again. Fail better.”

Only an Irishman can express profound skepticism concerning the world in such a poetic way. Beckett actually spent most of his life in Paris, since Parisians like to listen to someone expressing such a world view, even while they do not share it. Being in the service of Notre Dame du Lac, the home of the ‘Fighting Irish’, I cannot just ignore such advice. Yet my response is: "Cheer up – we know there is New Physics (see above) – we will not fail forever!"

My friend Antonio Masiero likes to say: "You have to be lucky to find New Physics.” True enough – yet let me quote someone who just missed by one year being a fellow countryman of Masiero, namely Napoleon, who said: "Being lucky is part of the job description for generals.” Quite seriously I think that if you as an high energy physicist do not believe that someday somewhere you will be a general – maybe not in a major encounter, but at least in a skirmish – then you are in the wrong line of business.
In the following I will focus on CP violation for rather pragmatic reasons; they are one of the most sensitive probes for New Dynamics, since CP asymmetries can be linear in a New Physics amplitude rather than quadratic and thus exhibit an enhanced sensitivity to New Physics.

The remainder of my talk will be organized as follows: after singing the praise of hadronization in Sect. 3 I will sketch ‘King Kong’ scenarios for New Physics searches in Sect. 4; then I will return to the need for precision and illustrate it with lessons from the extraction of \( V(cb) \) in Sect. 5 and case studies concerning hadronization in Sect. 6. Sect. 7 contains an outlook and a personal appeal.

### 3 Prelude: Singing the Praise of Hadronization

Hadronization and nonperturbative dynamics in general are usually viewed as unwelcome complication, if not outright nuisances. A case in point was already mentioned: while I view the CKM predictions for \( \Delta M_K, \Delta M_B, \epsilon_K \) to be in remarkable agreement with the data, significant contributions from New Physics could be hiding there behind the theoretical uncertainties. While this is factually correct, it misses a deeper truth. Without hadronization bound states of quarks and antiquarks will not form; without the existence of kaons \( K^0 - \bar{K}^0 \) oscillations obviously cannot occur. It is hadronization that provides the ‘cooling’ of the (anti)quark degrees of freedom, which allows subtle quantum mechanical effects to add up coherently over macroscopic distances. Otherwise one would not have access to a super-tiny energy difference \( \text{Im} M_{12} \sim 10^{-8} \text{ eV} \), which is very sensitive to different layers of dynamics, and indirect CP violation could not manifest itself. The same would hold for \( B \) mesons and \( B^0 - \bar{B}^0 \) oscillations.

To express it in a more down to earth way:

- Hadronization leads to the formation of kaons and pions with masses exceeding greatly (current) quark masses. It is the hadronic phase space that suppresses the CP conserving rate for \( K_L \to 3\pi \) by a factor \( \sim 500 \), since the \( K_L \) barely resides above the three pion threshold.

- It awards ‘patience’; i.e. one can ‘wait’ for a pure \( K_L \) beam to emerge after starting out with a beam consisting of \( K^0 \) and \( \bar{K}^0 \).

- It enables CP violation to emerge in the existence of a reaction, namely \( K_L \to 2\pi \) rather than an asymmetry; this greatly facilitates its observation.

For these reasons alone we should praise hadronization as the hero in the tale of CP violation rather than the villain it is all too often portrayed.
4 ‘King Kong Scenarios’ for New Physics Searches

This scenario can be portrayed as follows: "It is unlikely that one will encounter King Kong; yet once it happens there will be no doubt that one has come across something wildly out of the ordinary.” The point of analogy is the following. When, say, a certain transition has been observed to proceed although it is predicted not to – like \( K_L \rightarrow 2\pi \) in 1964 – or when predicted and observed rates differ by orders of magnitude, we can speak of a ‘qualitative’ discrepancy, which establishes the existence of New Physics right away, though not its nature. This has happened with the decays of strange hadron – and it might happen again.

4.1 CP Violation in Charm Decays

I can be very brief here, since a detailed exposition has been given in the ‘Cicerone’ \([9]\) and we have heard a nice talk by D. Asner \([10]\).

The relative dullness of the weak SM phenomenology for charm can be harnessed as a laboratory for studying hadronization. Yet charm decays still have the potential to reveal New Physics as well. One should note that New Physics in general and flavour changing neutral currents in particular can affect down-type – \( d, s \) and \( b \) – and up-type quarks – \( u, c \) and \( t \) – quite differently; charm is the only up-type quark allowing the full range of probes for New Physics:

- top quarks do not hadronize;
- \( \pi^0 - \pi^0 \) oscillations are not possible, since neutral pions are their own antiparticle;

with so few decay modes for pions CP asymmetries are basically ruled out by CPT symmetry.

My basic contention is: charm transitions provide unique portals for obtaining novel access to New Physics with the experimental situation being a priori favourable (apart from the fact that its leading decays are Cabibbo allowed). Searches for CP violation constitute the most powerful and promising tool in the long run for several reasons: (i) Baryogenesis requires new sources of CP violation. (ii) Within the SM the weak phase is highly diluted in once Cabibbo suppressed modes, namely \( \mathcal{O}(\sin^4\theta_C) \sim 10^{-3} \), and zero in Cabibbo favoured and doubly suppressed modes (except for \( D^\pm \rightarrow K_S\pi^\pm \) \([14]\)). (iii) A CP asymmetry can be linear in the New Physics amplitude and thus is more sensitive to it. (iv) Final state interactions are very active in the charm region. (v) The branching ratios for CP eigenstates are large. (vi) There is one fly in the ointment, though: \( D^0 - \bar{D}^0 \) oscillations are slow at best \([9]\).

\( B \)-factories clearly can make a tremendous contributions to CP studies in the charm sector. The challenge in particular to LHCb is: ”Can you?” To which degree can LHCb search for an asymmetry in \( D^{*+} \rightarrow D^0(t) + \pi^+ \rightarrow [K^+\pi^-]_D + \pi^+ \) vs. \( D^{*-} \rightarrow \bar{D}^0(t) + \pi^- \rightarrow [K^-\pi^+]_D + \pi^- \) as a function of the time of decay \( t \)?
4.2 CP Violation in Leptodynamics

There is a compelling impetus for searching for CP violation in leptodynamics, namely to complete the aforementioned ‘demystification’ of CP violation and to get a firmer handle on baryogenesis as driven by primary leptogenesis [11].

4.2.1 Neutrino Oscillations

When searching for a CP asymmetry in neutrino oscillations, you do not have to worry about hadronization. Yet one has to disentangle genuine CP violation from enhancements due to the environment being made up of matter rather than antimatter. This will likely turn out to be a challenging task. I would not be surprised if our colleagues engaged in this enterprise will rue previous requests to be free of hadronization. This reminds me of an ancient Greek saying: ”When the gods really want to harm you, they fulfill your wishes.”

4.2.2 Electric Dipole Moments

Truly impressive experimental sensitivity has been achieved concerning the electric dipole moments of electrons and neutrons:

\[ d_e = (0.07 \pm 0.07) \cdot 10^{-26} \text{ ecm} , \quad d_N < 0.63 \cdot 10^{-25} \text{ ecm} \] (2)

Even so they are still many orders of magnitude above CKM predictions

\[ d_e^{CKM} < 10^{-36} \text{ ecm} , \quad d_N^{CKM} < 10^{-30} \text{ ecm} \] (3)

On the other hand typical benchmarks for New Physics scenarios are

\[ d_e^{NP} , \quad d_N^{NP} \sim (10^{-28} - 10^{-26}) \text{ ecm} \] (4)

a range that should be reached in the foreseeable future.

4.2.3 CP Violation in \( \tau \) Decays – the Next Hero Candidate

The most promising channels for exhibiting CP asymmetries are \( \tau \rightarrow \nu K \pi \), since due to the heaviness of the lepton and quark flavours they are most sensitive to nonminimal Higgs dynamics, and they can show asymmetries also in the final state distributions rather than integrated rates [12].

There is also a unique opportunity in \( e^+e^- \rightarrow \tau^+\tau^- \): since the \( \tau \) pair is produced with its spins aligned, the decay of one \( \tau \) can ‘tag’ the spin of the other \( \tau \). I.e., one can probe spin-dependent CP asymmetries with unpolarized beams. This provides higher sensitivity and more control over systematic uncertainties.
I feel these features are not sufficiently appreciated even by proponents of Super-B factories. It has been recently pointed \cite{13} out that based on known physics one can actually predict a CP asymmetry:

\[
\frac{\Gamma(\tau^+ \to K_S\pi^+\nu) - \Gamma(\tau^- \to K_S\pi^-\nu)}{\Gamma(\tau^+ \to K_S\pi^+\nu) + \Gamma(\tau^- \to K_S\pi^-\nu)} = (3.27 \pm 0.12) \times 10^{-3}
\]

due to $K_S$'s preference for antimatter.

5 The Need for Precision – Extracting $V(cb)$ as a Lesson

New Physics scenarios typically will not create massive deviations from the SM predictions in $B$ decays. Thus precision is essential on the experimental as well as theoretical side. This is not a noble, yet unreachable goal. It can be achieved when one combines a robust theoretical framework with comprehensive and detailed data. I will briefly illustrate it with a mature example, namely the extraction of $V(cb)$ from inclusive semileptonic $B$ decays.

The robust theoretical framework there was provided by heavy quark expansions, which treat nonperturbative effects through an expansion in inverse powers of the heavy quark $m_Q$. It provides an analytical algorithm genuinely based on QCD and receiving support from various sum rules; in the future it can incorporate findings from lattice QCD as well \cite{15}.

The total semileptonic width of $B$ mesons as well as the lepton spectra encoded through lepton energy and hadronic mass moments can be expressed through heavy quark parameters $V(cb)$, beauty and charm quark masses $m_{c,b}$, and $B$ meson expectation values of local heavy quark operators \cite{16, 17}. With a mere handful of such parameters one can describe a host of observables. Those provide a large number of overconstraints. Obtaining a consistent fit is thus far from assured a priori. Achieving it provides an impressive demonstration that even systematic uncertainties are under control \cite{18, 19}. As an extra bonus one has found that the fitted values of these heavy quark parameters obey certain theoretical constraints although those were not imposed on the fit; furthermore they even agree with other determinations of these parameters. For example the (kinetic) $b$ quark mass can be determined in $B$ production just above threshold – $\Upsilon(4S) \to b\bar{b}$ – which is determined by the strong and electromagnetic forces, and in the weak decays of $B$ hadrons:

\[
m_b^{\text{kin}}(1 \text{ GeV})|_{\Upsilon(4S)\to b\bar{b}} = 4.57 \pm 0.08 \text{ GeV} \quad \text{vs.} \quad m_b^{\text{kin}}(1 \text{ GeV})|_{B \to l\nu X_c} = 4.61 \pm 0.068 \text{ GeV} \quad (6)
\]

With them being fully consistent, it makes sense to average them. A comprehensive analysis \cite{20} yields (with the relative error given in parenthesis)

\[
m_b^{\text{kin}}(1 \text{ GeV}) = (4.59 \pm 0.04) \text{ GeV} \quad (\sim 1\%)
\]
\[ m_c^{\text{kin}}(1 \text{ GeV}) = (1.14 \pm 0.06) \text{ GeV} \ (\sim 5\%) \]
\[ |V(cb)| = (41.58 \pm 0.67) \cdot 10^{-3} \ (\sim 1.6\%) \]  

(7)

One should note here that the present uncertainty on |V(us)| is about 1.1 %. The numbers in Eq.(7) show that percent level precision is not utopian even when nonperturbative dynamics is involved.

6 Case Studies for Hadronization as a Difficult Ally

\( \Delta M_K, \epsilon_K \) and \( \epsilon' \) – weak observables of central importance – are affected by hadronization effects like \( \pi \pi \) phase shifts, the \( \eta - \eta' \) wave functions, the role of the \( \sigma \) resonance etc., yet in a way that has never been reliably quantified. Here I will list four case studies of a more recent provenance, which concern \( B \) decays and where hadronization can actually be employed as a powerful tool – if applied judiciously.

First I would like to remind you that spectroscopy has been the subject of philosophical reflections over the centuries, the fruits of which can be distilled into the ‘three Razors of Spectroscopy’:

Ockham’s Razor:

"Entities should not be multiplied unnecessarily!"

Peter Minkowski’s Razor:

"No experiment can make two discoveries in the same data set!"

Stefano Bianco’s Razor:

"You can learn a lot by cutting judiciously!"

These rules are not necessarily binding; however you can ignore them only at your own peril. The first Razor is almost self-evident, although open to interpretation, in particular a posteriori. The second Razor can be based on many examples from history. For the third one, which is the only one with a positive content, I will give an example below.

6.1 Case I: The ‘1/2 > 3/2 Puzzle’

Beyond what charm spectroscopy can teach us about QCD there are (at least) three more motivations for understanding it: (i) To determine the total width for \( B \to l\nu X_c \) and keep the error on it small, one needs accurate and realistic modeling of the hadronic system in the final state. (ii) One needs it to gauge the errors on the measurements of the exclusive modes \( B \to l\nu D/D^* \) due to a feed down from higher resonances. (iii) With heavy quark symmetry decoupling the spin of the heavy quark, one can label heavy flavour hadrons by their total spin and the angular momentum \( s_q \) carried by the light degrees of freedom [21]. To the degree that charm can be treated as a heavy flavour,
one has two meson groundstates – $D \& D^*$ – and four excited states formed by P wave $c\bar{q}$ configurations, two of which carry $s_q = 3/2$ and are predicted to be narrow with the other two carrying $s_q = 1/2$ and being broad. With heavy quark theory one can derive sum rules from QCD that relate heavy quark parameters – quark masses, $B$ expectation values of heavy quark operators – with subclasses of semileptonic $B$ decays, in particular $B \to l\nu D(s_q = 1/2 \text{ or } 3/2)$. If the P wave states saturate those sum rules – a very natural, albeit not proven assumption – then the production of the narrow $s_q = 3/2$ charm meson states should dominate over that of the broad $s_q = 1/2$ ones in semileptonic $B$ decays. This prediction is in apparent conflict with DELPHI studies. They show that the final states not being just $D$ or $D^*$ are made up more by broad than narrow charm states. One possible conjecture for resolving this discrepancy is that a significant fraction of the broad component is made up by radial excitations rather than P wave $D(s_q = 1/2)$.

This is not an academic problem and actually goes beyond even precise determinations of $|V(cb)|$ and $|V(ub)|$: the SM predicts $b \to l\nu q$ to proceed by pure $(V - A)_q \times (V - A)_l$ currents. A $(V - A)_q \times (V + A)_l$ coupling is most unlikely even with New Physics, since the required right-handed neutrino is unlikely to be sufficiently light due to Majorana masses; yet New Physics could conceivably induce a $(V + A)_q \times (V - A)_l$ current. Its main impact would be on the shape of the lepton spectrum making it softer and thus changing its moments. However such an impact had to be disentangled from hadronization effects. Modeling incorrectly the charm final state could then either fake a signal for $(V + A)_q \times (V - A)_l$ currents or hide one.

6.2 Case II: $\phi_1$ from $B_d \to 3$ Kaons

Analysing CP violation in $B_d \to \phi K_S$ decays is a most promising way to search for New Physics. For the underlying quark-level transition $b \to s\bar{s}s$ represents a pure loop-effect in the SM, it is described by a single $\Delta B = 1 \& \Delta I = 0$ operator (a ‘Penguin’), a reliable SM prediction exists for it [24] – $\sin^2 \phi_1(B_d \to \psi K_S) \simeq \sin^2 \phi_1(B_d \to \phi K_S)$ – and the $\phi$ meson represents a narrow resonance.

Great excitement was created when BELLE reported a large discrepancy between the predicted and observed CP asymmetry in $B_d \to \phi K_S$. Based on more data taken, this discrepancy has shrunk considerably: the BABAR/BELLE average for 2005 yields [4]

$$\sin^2 \phi_1(B_d \to \psi K_S) = 0.685 \pm 0.032$$

(8)

compared to

$$\begin{align*}
\sin^2 \phi_1(B_d \to \phi K_S) & \begin{cases} 
0.50 \pm 0.25^{+0.07}_{-0.04} & \text{BABAR} \\
0.44 \pm 0.27 \pm 0.05 & \text{BELLE} \end{cases} 
\end{align*}$$

(9)

BABAR’s as well as BELLE’s numbers are below the prediction, albeit by one sigma only. It is ironic that such a smaller deviation, although not significant, is actually more believable than the large one originally reported by BELLE.
This issue has to be pursued with vigour, since this reaction provides such a natural portal to New Physics. One complication has to be studied, though, in particular if the observed value of $\sin^2 \phi_1(B_d \to \phi K_S)$ falls below the predicted one by a moderate amount only. For one is actually observing $B_d \to K^+ K^- K_S$. If there is a single weak phase like in the SM one finds

$$\sin^2 \phi_1(B_d \to \phi K_S) = -\sin^2 \phi_1(B_d \to 'f_0(980)' K_S),$$

where '$f_0(980)' denotes any *scalar* $K^+ K^-$ configuration with a mass close to that of the $\phi$, be it a resonance or not. A smallish pollution by such a '$f_0(980)' K_S – by, say, 10% in amplitude – can thus reduce the asymmetry assigned to $B_d \to \phi K_S$ significantly – by 20% in this example.

In the end it is therefore mandatory to perform a *full time dependent Dalitz plot analysis* for $B_d \to K^+ K^- K_S$ and compare it with that for $B_d \to 3 K_S$ and $B^+ \to K^+ K^- K^+, K^+ K_S K_S$ and also with $D \to 3 K$. This is a very challenging task, but in my view essential. There is no ‘royal’ way to fundamental insights. 

An important intermediate step in this direction is given by one application of Bianco’s Razor, namely to analyze the $\mathbf{C P}$ asymmetry in $B_d \to [K^+ K^-] M K_S$ as a function of the cut $M$ on the $K^+ K^-$ mass.

### 6.3 Case III: $\phi_2$ from $B_d \to \text{Pions}$

Unlike the preceding case two different operators drive $B \to \text{pions}$, namely one obtained from a tree and one from the Penguin diagram. With only the first one depending on the weak phase $\phi_2$ it is highly nontrivial to extract its size from these decays, since the $\mathbf{C P}$ asymmetry depends on the relative weight of those two operators, which is shaped by strong dynamics over which we have less than full theoretical control.

A theoretically clean way to disentangle the impact from the Penguin operator is to measure the isospin two final state $B \to [\pi \pi]_{I=2}$ [25]. By measuring all rates $B_d \to \pi^+ \pi^-, \pi^0 \pi^0, B^\pm \to \pi^\pm \pi^0$ this can be achieved in principle, but maybe not in practice with sufficient accuracy; $B_d \to \pi^0 \pi^0$ provides the bottle neck. Less challenging experimentally are the modes $B \to \rho \pi$, but one pays a theoretical price there: the actual final state state consists of three pions, where the $\rho$ cannot be seen as a narrow resonance. Furthermore there are other contributions to the three-pion final state like $\sigma \pi$. It hardly matters actually whether the $\sigma$ is a bona fide resonance or some other dynamical enhancement. What matters is that merely cutting on the di-pion mass will not produce a $\rho \pi$ final state with sufficient purity; furthermore the $\sigma$ structure cannot be described adequately by a Breit-Wigner shape. As analyzed first in [26] and then in more detail in [27] ignoring such complications can induce a systematic uncertainty in the extracted value of $\phi_2$. The

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3The ruler of a Greek city in southern Italy once approached the resident sage with the request to be educated in mathematics, but in a ‘royal way’, since he was very busy with many obligations. Whereupon the sage replied with admirable candor: There is no royal way to mathematics.
case of $B \rightarrow \rho \rho$, which experimentally is even better than the previous one, is even worse theoretically. We have to aim at a total uncertainty – experimental plus theoretical – of not exceeding 5%. To achieve this ambitious goal in $B \rightarrow 3\pi$ we have to bring the full machinery of a time dependent Dalitz plot analysis to bear augmented by our understanding of chiral dynamics.

6.4 Case IV: $\phi_3$ from $B^\pm \rightarrow D^{\text{neut}}K^\pm$

As first mentioned in 1980 [28], then explained in more detail in 1985 [29] and further developed in [30], the modes $B^\pm \rightarrow D_{\text{neut}}K^\pm$ should exhibit direct CP violation driven by the angle $\phi_3$, if the neutral $D$ mesons decay to final states that are common to $D^0$ and $\bar{D}^0$. Based on simplicity the original idea was to rely on two-body modes like $K_S\pi^0$, $K^+K^-$, $\pi^+\pi^-$, $K^\pm\pi^{\mp}$. One drawback of that method are the small branching ratios and low efficiencies.

A new method was pioneered by BELLE and then implemented also by BABAR, namely to employ $D_{\text{neut}} \rightarrow K_S\pi^+\pi^-$ and perform a full Dalitz plot analysis. This requires a very considerable analysis effort – yet once this initial investment has been made, it will pay handsome profit in the long run. For obtaining at least a decent description of the full Dalitz plot population provides considerable cross checks concerning systematic uncertainties and thus a high degree of confidence in the results. BELLE and BABAR find [4]:

\[
\phi_3 = \begin{cases} 
68^\circ \pm 15^\circ (\text{stat}) \pm 13^\circ (\text{syst}) \pm 11^\circ (\text{model}) & \text{BELLE} \\
70^\circ \pm 31^\circ (\text{stat}) \pm 12^\circ (\text{syst}) \pm 14^\circ (\text{model}) & \text{BABAR}
\end{cases}
\]  

I view it still a pilot study, yet a most promising one. It exemplifies how the complexities of hadronization can be harnessed to establish confidence in the accuracy of our results. I consider this to be the way of the future.

7 On HEP’s Future Landscape – a Call to Action & an Appeal

To me there is persuasive evidence of a theoretical as well as experimental nature that the SM is incomplete pointing to New Physics driving the electroweak phase transition: the confidently predicted New Physics $cpNP$ at the TeV scale. This is the justification – an excellent one in my view – for the LHC. The goal has to go beyond establishing the presence of some New Physics – we have to identify its salient features as well. One should keep in mind that SUSY – for me the most likely candidate for the $cpNP$ – is not a true theory yet or even a class of theories: it is largely an organizing principle given our current lack of understanding its breaking.

It has been recognized that the LHC is primarily a discovery machine sweeping out huge regions of ‘terra incognita’; this lead to the proposal of a linear collider as a more
surgical and focussed probe for the \( cpNP \) – yet the same justification applies to flavour factories! While comprehensive studies of heavy flavour transitions are not very likely to shed light on the \( ssNP \) behind the flavour puzzle of the SM (although they might), they will be essential in elucidating salient features of the \( cpNP \). For New Physics at the TeV scale can affect flavour transitions significantly, and analyzing them is thus complementary to the program of the LHC and Linear Collider. It is actually essential to obtain all the information experimental research can give us on Nature’s Grand Design. *Dedicated and comprehensive studies of heavy flavour dynamics are thus a necessity, not a luxury.*

New Physics having a significant impact on \( B, \tau \) and charm decays does not mean it will be numerically massive and thus obvious. We must succeed in adding the element of ‘high accuracy’ to that of ‘high sensitivity’.

I view a Super-B factory as crucial for us achieving that high accuracy and decoding the \( cpNP \). It requires close collaboration between experiment and theory. A central message of my talk is to treat hadronization and nonperturbative dynamics in general as our ally – albeit a complex and sometimes quirky one – rather than as a nuissance. I would like to combine this with a personal appeal: The expertise required to attain an essential goal, namely to exhaust the discovery potential in heavy flavour transitions by harnessing low-energy hadronization does exist or can be acquired with no need for a breakthrough. However it tends to reside in a community all too often disjoint from the heavy flavour community – *this has to change!* We need input from studies of \( \pi\pi, K\bar{K}, K\pi \) etc. final state interactions at low energies, in nonleptonic as well as semileptonic charm decays and in \( B \to \) multineutrals, and we have to refine and extend our understanding of chiral dynamics. These are very complex tasks; when tackling them we should remember the example of Swiss watches for guidance: those became famous by being reliable and sturdy, not necessarily elegant.

One final remark: The pion has been discovered in 1947. Its dynamics have been studied intensely for the last sixty years. This conference here in magnificent Rio has shown that it is not a closed chapter; a great deal still has to be learnt. This demonstrates much better than many words, how momentous the discovery of the pion was, how profound a paradigm shift it created. We thus owe a great deal of gratitude to our late colleague Cesar Lattes for his work, as summarized in the following Memorial.

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