THE VIETRI CODICES

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Abstract

Studying heavy flavour physics is driven by multiple motivations: to probe our theoretical control over QCD; enhance our information on gluon and sea quark structure functions; use heavy flavour production as signal for the onset of the quark-gluon plasma; revisit light flavour spectroscopy through the final states in heavy flavour decays; extract fundamental quantities like CKM and MNS parameters; search for new Physics. The last two years have witnessed tremendous amplification in our knowledge of heavy flavour dynamics. We know the elements of the CKM matrix with significantly improved reliability; a new door has been opened by the observation of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$; with direct CP violation being established in $K_L$ decays and the expected huge CP asymmetry been observed in $B_d(t) \rightarrow \psi K_S$ the CKM description has attained the level of a tested theory of CP violation. Yet more than ever

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the Standard Model is viewed as incomplete: apart from the peculiar pattern in mass related parameters of the fundamental fermions there is more direct evidence in the signals for neutrino oscillations, the strong CP problem and the baryon number of the universe. A worldwide, interrelated and comprehensive program has been developed for heavy quark and lepton physics that will provide essential impetus towards a deeper understanding of nature’s grand design.

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1 Reflections

Fifty-five years ago two events happened that typify the study of fundamental dynamics central to this conference: in 1947 Rochester and Butler published a paper \cite{1} on the observation of kaons decaying into two pions; in the same year Purcell and Ramsey \cite{2} started the journey towards measuring an electric dipole moment for neutrons. While we have learnt everything that can be learnt from $K \rightarrow \pi\pi$, this is far from true for the journey to $d_N$.

There are three reasons why I have chosen the title ”Vietri Codices” for this summary:

- Written information was originally stored on rolls. Yet as Callimachus working at the ancient library of Alexandria in the third century B.C. once remarked: ”A big roll is a big nuisance.” The form of the codex or book was developed as a first form of R(andom)A(ccess)M(emory). A summary talk can provide you with multiple, though not random access.

- Leonardo da Vinci had the habit of writing ‘parity inverted’. A normal mortal therefore has to read his writings – like the Leicester Codex containing his scientific observations – through a mirror \cite{3}. The symbolism for the topics of this conference is obvious.

- The celebrated Dresden Codex with symbols from the Mayas must contain profound elements of their knowledge, presumably about astronomy. Unfortunately one has not found its dictionary. One hopes to infer its contents through uncovering correlations between its symbols and celestial events. We are facing a similar interpretative challenge; we have actually (at least) two Dresden codices in front of us, namely the CKM and MNS matrices. We can be certain they contain profound messages about truly fundamental dynamics – alas it is highly coded with even the synthax mysterious. The analogy is even visual: looking at a page from the Dresden Codex \cite{4} you see groupings of three dots together with symbols similar to matrices and mass spectra of neutrinos.

This conference focusses on heavy quarks and leptons. At first it might seem they have little in common beyond charge quantization: quarks are
subject to the strong interactions and are actually confined. You often hear a lot of moaning that this introduces all kinds of unpleasant hadronization effects. Whenever feeling thus challenged one can remember the following eternal truths: there is no royal way to knowledge; hardship builds character and there is salvation at the very end. You might find little solace in such advice thinking it merely reflects the teachings of my employer. However I insist you should view hadronization as a true blessing even if well disguised. For without hadronization there would be no $K^0 - \bar{K}^0$ oscillations providing such a glorious lab to reveal indirect CP violation, and direct CP violation could not manifest itself through the observables $\eta_{+-} \neq \eta_{00}$. Likewise there could be no $B^0 - \bar{B}^0$ oscillations and no huge CP violation in $\Delta B = 2$ transitions; the latter could not serve as a highly sensitive probe for New Physics. More specifically, the formation of the $K_L$ and $K_S$ mass eigenstates with the former being just above the 3 pion threshold presents us with two powerful tools: it provides a phase space suppression of the CP allowed $K_L \to 3\pi$ modes by a factor of $\sim 500$ relative to the CP forbidden $K_L \to \pi\pi$ channels, and at the same time it allows CP violation to manifest itself through the existence of a transition rather than an asymmetry.

One can understand also on very general grounds that the strong interactions should be viewed as the hero rather than the villain in the story of CP violation: since the latter can arise through a complex phase only due to CPT invariance, one needs two different, yet coherent amplitudes for an asymmetry to emerge; hadronization provides such a second amplitude $K^0 \Rightarrow \bar{K}^0 \Rightarrow f$ in addition to $K^0 \Rightarrow f$ – and ‘cools’ the degrees of freedom to increase considerably the coherence and thus interferability of the two amplitudes. Later I will tell you about an example why we should be very careful in what we wish.

The dynamics of heavy flavour hadrons reflects the interplay of strong and electroweak forces. Despite our problems in establishing computational control over QCD I would characterize the situation as follows: "QCD is the only thing – $SU(2)_L \times U(1)$ not even the greatest thing!" I.e., there is no alternative to QCD among local quantum field theories. Therefore I find it quite inappropriate to state we are testing QCD: for it would imply that a failure would lead to QCD being discarded; this, however, is not going to happen. The correct statement is that we are probing QCD to understand its inner workings. A failure in such a probe only means that we have to learn from our mistakes and adjust our calculational tools.
There are five classes of possible lessons, of which the first three refer to QCD and the remaining two to the electroweak sector:

- Refining theoretical technologies for QCD, namely perturbative QCD, chiral perturbation theory, $1/m_Q$ expansions and lattice QCD;
- extracting gluon and sea structure functions of the nucleon \[5\];
- doing our homework on heavy flavour production to interpret heavy ion collisions \[6\];
- determining fundamental quantities like the CKM and MNS parameters and fermion masses;
- searching for New Physics – the Great Prize \[7, 8\].

The remainder of my talk will be organized as follows: in Sect.2 I will summarize the presentations on heavy flavour production; in Sect.3 I will deal with the weak decays of strange, charm and beauty hadrons; after sketching the CP landscape in Sect.4 I will describe the unreasonable success of the CKM theory in Sect.5 before turning to searches for New Physics in Sect.6; after addressing recent results presented here on the lepton sector in Sect.7 I will offer some concluding remarks.

2 Production of Heavy Flavours

Heavy flavour production can be categorized by the numbers of hadrons in the initial state: zero hadrons for $e^+e^-$ annihilation, one hadron for deep inelastic lepton-nucleon scattering, $(1 + \alpha)$ and two hadrons for photo- and hadro-production, respectively. Obviously the theoretical challenge increases with the number of hadrons.

No excuses would be accepted for hadroproduction of top quarks (top hadrons do not form \[9\]) – and none are needed \[10\].

Hadroproduction of beauty hadrons provides an intriguing tale \[10\]. Both CDF and D0 have reported beauty production rates exceeding predictions by factors of two to three. Most recently CDF has stated an excess factor of $2.9 \pm 0.2 \pm 0.4$ \[11\]. This is hard to swallow considering the large beauty mass and that one is dealing with central production of beauty. Beauty fragmentation
might hold the key to the puzzle. Using a harder fragmentation function than the Peterson et al. implementation the authors of Ref.[12] find a reduced factor of $1.7 \pm 0.5_{\text{th}} \pm 0.5_{\text{exp}}$, i.e. hardly a significant excess. Future data will shed light on it.

We should not declare victory yet. As reported by Gladilin [13], beauty production in $ep$ collisions "typically" exceeds predictions.

A great deal can be learnt from charm production in $\nu$ scattering [14]: $|V(\text{cs})|$ and $|V(\text{cd})|$ can be extracted, the absolute value of $\text{BR}_{\text{SL}}(\Lambda_c)$ be determined without undue reliance on a model etc. I want to state a caveat though concerning the charm quark mass. It represents a much more subtle object than a parameter in a quark-parton model. With quarks being confined, there is no ‘natural’ definition of a quark mass; there is actually an infinity of possible definitions of quark masses in a quantum field theory taken at different scales. I suspect that the charm quark mass receives significant nonperturbative contributions that are specific to the production process. The tools are there to analyze this issue, yet to my knowledge it has not been done. However as long as one uses it pragmatically to parametrize the threshold behaviour in a given reaction without any claim to have determined a fundamental quantity, I would not object to it.

3 Weak Decays of Heavy Flavour Hadrons

3.1 Strange decays

The theoretical tool of choice here is chiral perturbation theory. It is probed for its intrinsic reason, to extract $|V(us)|$ and to gain better theoretical control over various CP asymmetries [15].

$|V(us)|$ is extracted from $K_{e3}$ decays. The ‘classic’ analysis by Leutwyler & Roos from 1984 [16] yields

$$|V(us)|_{K_{e3}} = 0.2196 \pm 0.0023$$  \hspace{1cm} (1)

Weak Universality – one of the fundamental features of the SM we understand – requires

$$|V(ud)|^2 + |V(us)|^2 + |V(ub)|^2 = 1$$  \hspace{1cm} (2)

Using the PDG 2000 value for $|V(ud)|$ one infers from Eq.(2) a higher value


\( (V(ub) \) is numerically insignificant):

\[
|V(us)|_{\text{unit}} = 0.2287 \pm 0.0034 ;
\]

i.e., the value in Eq. (1) does not satisfy the unitarity requirement. The elements of this argument have of course to be re-analyzed:

- Updating the analysis of Leutwyler & Roos Cirigliano et al. found almost no numerical change [17]:

\[
|V(us)|_{K_{e3}} = 0.2201 \pm 0.0013|\Delta \Gamma \pm 0.0008|\Delta \lambda_+ \pm 0.0019|\Delta f_+(0)
\]

- A new measurement by E 865 finds the very preliminary value \( \text{BR}(K_{e3}) = (5.13 \pm 0.02 \pm 0.08 \pm 0.04)\% \) [18] to be compared to the PDG 2000 value of \( (4.82 \pm 0.06)\% \). It would suggest \( |V(us)|_{K_{e3}} = 0.2271 \pm 0.0024 \), in full agreement with Eq. (3).

- PDQ 2002 has adopted the following values as directly determined [19]:

\[
|V(us)|_{K_{e3}} = 0.2196 \pm 0.0026, \quad |V(ud)| = 0.9734 \pm 0.0008
\]

where the latter represents an average over data on mirror nuclei and free neutrons.

- Taking the central values of Eq. (3) one finds a 2.7 \( \sigma \) deficit for Eq. (2); on the other hand an overall fit with weak universality built in yields the ranges

\[
|V(us)|_{\text{unit}} = 0.219 \div 0.226, \quad |V(ud)|_{\text{unit}} = 0.9741 \div 0.9756 ;
\]

\( |V(ud)|_{\text{unit}} \) is a touch high viz. Eq. (3), yet not conclusively so.

I think that clarification of this complex issue both requires and deserves considerable efforts on the experimental and theoretical side based on its intrinsic interest as well as a case study of indirect searches for New Physics. Personally I view it as highly unlikely that Eq. (2) could be violated by as much as 1 \%: for I believe that such a violation of weak universality should lead to observable effects in the electric dipole moment of neutrons.

Both the modulus and imaginary part of \( V(td) \) can be determined in \( K \rightarrow \pi \nu \bar{\nu} \) decays [20, 21]. To be more specific: The SM predicts for \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \)
and $K_L \to \pi^0\nu\bar{\nu}$ branching ratios of $(7.2 \pm 2.1) \cdot 10^{-11}$ and $(2.6 \pm 1.2) \cdot 10^{-11}$, respectively. The large range in the two predictions reflects our ignorance about the value of $V(td)$ and shows why measurements of these two branching ratios will significantly enhance our knowledge; for the intrinsic uncertainty in the latter is estimated to be around 2% and in the former around 7% (mostly due to ignorance concerning the charm quark mass). E787 has seen two events, which corresponds to a branching ratio $(1.57^{+1.75}_{-0.82}) \cdot 10^{-10}$, i.e. about double the SM expectation, yet not significantly different; on the other hand there is a 0.02% probability for the background to generate two events. The successor experiment E949 expects to see $\sim 5 - 10$ SM $K^+ \to \pi^+\nu\bar{\nu}$ events over the next two years or so to be followed by CKM aiming at about 100 SM events after 2008. The neutral mode $K_L \to \pi^0\nu\bar{\nu}$ has not been seen yet; KOPIO hopes to collect $\sim 50$ SM events after 2006. These are certainly challenging experiments, yet central in our quest to determine fundamental quantities and search for New Physics.

Two more points:

- From NA48 data on $K_L \to \pi^0\gamma\gamma$ one can deduce that the CP conserving contribution to $K_L \to \pi^0e^+e^-$ is insignificant [22].

- It seems to me that the prize for the most improved player should go to KLOE which has begun to produce intriguing data [23]. I took note of their measurement of the relative rates for the radiative transitions $\phi \to \eta'\gamma$ vs. $\phi \to \eta\gamma$ where they find no evidence for a $gg$ component in the $\eta'$ state. I remember that at a place long ago and far away MARKIII analyzing the analogous decays $\psi \to \eta'\gamma$ vs. $\psi \to \eta\gamma$ arrived at different conclusions.

## 3.2 Charm decays

The width for $D^* \to D\pi$ has been measured by CLEO [27]; the value extracted for the strong $D^*D\pi$ coupling appears to be significantly higher than what can be accommodated with predictions based on light cone sum rules [28]. Since I feel those predictions cannot be dismissed easily, I advocate further experimental scrutiny.

The $1/m_Q$ expansion provides a decent semi-quantitative description of the lifetime ratios for charm hadrons; this could not be counted upon since
the charm quark mass does not exceed ordinary hadronic scales by a large amount. Yet the \( \Xi_c^+ \) lifetime seems to be quite a bit longer than predicted \([24, 25]\); on the other hand the \( \Xi_c^0 \) lifetime for which there is a new preliminary number from FOCUS \([29]\)

\[
\tau(\Xi_c^0) = 118^{+14}_{-12} \pm 5 \text{ fs} \quad (7)
\]

seems to be in line with expectations.

Buccella described a phenomenological treatment of nonleptonic two-body modes of charm mesons on the Cabibbo allowed and once suppressed level \([26]\). One has to be realistic in one’s expectations concerning the accuracy of this ansatz. It is nontrivial that one gets a decent overall description without having to introduce too many ‘epicycles’ in the form of resonances and other final state interactions. The most important lesson one wants to learn from such an exercise is to find out which channels exhibit the strongest final state interactions that would allow direct CP violation to surface there.

Miranda made a good case \([30]\) that the final state in the decays of charm hadrons represent a novel and promising lab to study light flavour spectroscopy since one is dealing with exclusive states of well-known overall quantum numbers. At the same time some caveats have to be kept in mind like that a Breit-Wigner ansatz is an approximation of varying accuracy; in particular for scalar di-meson resonances a lot of information exists from data that a Breit-Wigner ansatz provides in general a poor description \([31]\). More work is clearly needed there, and theorists should spend some quality time on this new frontier.

Considerable information has been accumulated on the decay constant \( f_{D_s} \) extracted from \( D_s \to \tau \nu \) and \( D_s \to \mu \nu \) \([32]\). Experimental extractions range from about 200 MeV to above 300 MeV. The most recent and partially unquenched lattice results yield \( 240^{+30}_{-25} \) MeV.

In 1993 I had stated at a tau-charm factory workshop in Spain that the "tau-charm factory is the QCD machine for the '90's" \([33]\). I was wrong by just ten years, for it seems very likely now that Cornell can realize CLEO-c taking data in the charm region over the next three or so years.

As I will sketch later, there is a very considerable potential for New Physics to manifest itself in charm hadron transitions as can be studied at \( B \) factories – a point I will return to.
3.3 Beauty decays

The decays of beauty hadrons exhibit a rich and multilayered CKM phenomenology with interplay of all three families. With BABAR already exceeding its design luminosity of $3 \cdot 10^{33} \text{s}^{-1} \text{cm}^{-2}$ and BELLE getting close to its even more ambitious design value of $10^{34} \text{s}^{-1} \text{cm}^{-2}$ data are accumulated in huge streams and will continue to do so [34, 35, 49]. This will allow us to conduct measurements in the foreseeable future that a few years ago we would not have dared to even contemplate.

BELLE has seen the new ‘colour suppressed’ channels $B_d \to D^0 + \pi^0/\eta/\omega$ and also the unconventional mode $B^\pm \to p\bar{p}K^\pm$ with a branching ratio of $(4.3^{+1.1}_{-0.9} \pm 0.5) \cdot 10^{-6}$ [34].

We have a well-stocked chest of theoretical technologies of varying complexity and range of applicability: (i) Heavy quark expansions [37], (ii) HQET, (iii) lattice QCD, (iv) QCD factorization [38] and (v) chiral dynamics [31]. They allow us to make predictions with a reliability, accuracy and breadth that ten years ago would have seemed merely wishful thinking. In semileptonic and radiative $B$ decays one can give detailed error budgets; a well defined kinetic $b$ quark mass can be extracted from $\Upsilon(4S) \to b\bar{b} - m_b^{\text{kin}}(1 \text{ GeV}) = 4.57 \pm 0.08 \text{ GeV}$ [39, 40, 41] – and from the moments in semileptonic $B$ decays $m_b^{\text{kin}}(1 \text{ GeV}) = 4.65 \pm 0.10 \text{ GeV}$ [37]. It provides a highly remarkable test that these two methods, which are so different in both their experimental and theoretical aspects, yield results in such good agreement! This supports the statement that we have extracted $|V(cb)|$ with about 5 % theoretical uncertainty [37]:

$$|V(cb)| = 0.0412 \cdot (1 \pm 0.015_{\text{pert}} \pm 0.01m_c \pm 0.012 \pm 0.012) \cdot \left[ \frac{\text{BR}_{SL}(B)}{0.105} \right]^{1/2}$$

and that the latter can be reduced further already in the near future [37]. This state of maturity and interconnectedness is well characterized by Uraltsev’s statement ”ill-defined parameters lead to observable problems”.

Neubert [38] presented extensive tables with QCD based predictions on two-body modes of $B$ mesons; there appears no longer a ”$\eta/\eta'$ problem”. It was emphasized that these nonleptonic decays favour $\phi_3[\gamma] > 90^\circ$, whereas $\Delta B = 2$ transitions $- \Delta m(B_d)$ and the bound on $B_s - \bar{B}_s$ oscillations $- \text{yield } \phi_3[\gamma] < 90^\circ$. 

10
A promising way to extract $\phi_2(\alpha)$ is from studying the evolution of $B_d(t) \to \rho\pi$ [42]. In the data there will be contributions from $B \to \sigma\pi$ as well; this complication can be dealt with [31], although it presumably increases the level of statistics needed. Yet when aiming at an accuracy of a few %, one has to evaluate very carefully whether the resonance structures are adequately described [31].

4 CP Violation – The Landscape

CP violation was discovered 1964 through the decay $K_L \to \pi^+\pi^- – causing considerable consternation among theorists [43]. Till 1999, i.e. for 35 years, CP violation could be described by a single non-vanishing real number – namely the phase between the quantities $M_{12}$ and $\Gamma_{12}$ in the $K^0 – \bar{K}^0$ mass matrix – in face of a large body of data. Direct CP violation has been unequivocally established in 1999. In the summer of 2001 peaceful coexistence has been achieved between the data of NA48 and KTeV with a new world average [44]:

$$\langle \epsilon'/\epsilon_K \rangle = (1.72 \pm 0.18) \cdot 10^{-3}$$

(9)

Quoting the result in this way does not do justice to the experimental achievement, since $\epsilon_K$ is a very small number itself. The sensitivity achieved and the control over systematic uncertainties established becomes more obvious when quoted in terms of actual widths:

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) – \Gamma(\bar{K}^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\bar{K}^0 \to \pi^+\pi^-)} = (5.7 \pm 0.6) \cdot 10^{-6}$$

(10)

This represents a discovery of the very first rank – no matter what theory does or does not say. We can take pride in this achievement. The two groups deserve our respect; they have certainly earned my admiration.

It had been predicted already 1980 that the CKM description implies large CP asymmetries in several classes of $B$ decays involving $B_d – \bar{B}_d$ oscillations, most notably in $B_d \to \psi K_S$ [45, 46]. The existence of a huge CP asymmetry in $B_d \to \psi K_S$ has been firmly established in 2001 by BELLE and BABAR; this spring they have presented updates that agree very nicely [47]:

$$\sin 2\phi_1(\beta) = \begin{cases} 0.75 \pm 0.09 \pm 0.04 & \text{BABAR} \\ 0.82 \pm 0.12 \pm 0.05 & \text{BELLE} \end{cases}$$

(11)
After the meeting both groups have further updated their results \[48, 49\]:

\[
\sin 2\phi_1[\beta] = \begin{cases} 
0.741 \pm 0.067 \pm 0.033 & \text{BABAR} \\
0.719 \pm 0.074 \pm 0.035 & \text{BELLE} 
\end{cases}
\]  

We can conclude that the CP asymmetry in \(B_d \to \psi K_S\) is there for sure and it is huge – as expected! For intellectual interest one can add that the measurements, which are based on EPR correlations [50], illustrate nicely that CP violation is coupled with T violation [51].

5 The Unreasonable Success of the CKM Description

In 1998, i.e. before \(\epsilon' \neq 0\) and CP violation in \(B_d\) decays were established, the status of the CKM description could be sketched as follows: \(\Delta m_K, \epsilon_K\) and \(\Delta m(B_d)\) could be reproduced; \(\epsilon'/\epsilon_K \leq 10^{-3}\) was widely advocated except for some heretics [52, 53]; concerning the CP asymmetries in \(B\) decays it was stated that some have to be of order unity with no "plausible" deniability; in the early '90's – i.e. before the discovery of top quarks – this was specified to predicting \(\sin 2\phi_1[\beta] \sim 0.6 - 0.7\) if today’s estimates of \(f_B\) are used [54]. In '98 courageous souls gave a prediction of \(\sin 2\phi_1[\beta] \sim 0.72 \pm 0.07\) [56].

It is indeed true that large fractions of \(\Delta m_K, \epsilon_K\) and \(\Delta m_B\) and even most of \(\epsilon'\) could be due to New Physics; constraints from data thus translate into 'broad' bands in plots of the unitarity triangle. Yet such a statement seemingly reflecting facts misses the real point! One has to keep in mind that the dimensional quantities describing the weak observables span several orders of magnitude in energy units, namely the range \(\mathcal{O}(10^{-14}) \div \mathcal{O}(10^{-9})\) MeV. It is highly remarkable that the CKM description can always get to within a factor of two or three – in particular with numerical values in its parameters and the fermion masses that \(a\ priori\) would have seemed to represent frivolous choices, like \(m_t \simeq 180\) GeV. And it appears right on the mark for \(\sin 2\phi_1\)! Hence I conclude that the CKM description is no longer a mere ansatz, but a tested theory; its forces are with us to stay. En passant we have learnt that when complex phases surface they can be large. An aside might be allowed here. A CP odd quantity depends also on the \(\sin\) (and \(\cos\)) of the three CKM angles in addition to the complex phase. While the latter is
large, the former are small or even tiny – something that can be understood in the context of theories with extra dimensions [6] – allowing CP violation a la CKM to be generated perturbatively [55]. A large CP asymmetry can arise when also the decay rate is suppressed by small CKM parameters as it happens in $B$ decays.

Yet this new and spectacular success of the SM does not resolve any of its mysteries – why are there families, why three, what is the origin of the peculiar pattern in the quark mass matrices – they actually deepen them. Consider the structure of the CKM matrix:

$$|V_{CKM}| \sim \begin{pmatrix} 1 & \mathcal{O}(\lambda) & \mathcal{O}(\lambda^3) \\ \mathcal{O}(\lambda) & 1 & \mathcal{O}(\lambda^2) \\ \mathcal{O}(\lambda^3) & \mathcal{O}(\lambda^2) & 1 \end{pmatrix}, \lambda = \sin \theta_C$$

There has to be fundamental information encoded in this hierarchical pattern. The situation can be categorized by saying “we know so much, yet understand so little!” I.e., it re-emphasizes that the SM is incomplete, that New Physics must exist. Theories with extra dimensions might provide an answer [7].

6 Searching for New Physics

6.1 The ‘King Kong’ scenario

$\Delta S = 1, 2$ dynamics have provided several examples of revealing the intervention of features that represented New Physics at that time; it thus has been instrumental in the evolution of the SM. This happened through the observation of ‘qualitative’ discrepancies; i.e., rates that were expected to vanish did not, or rates were found to be smaller than expected by several orders of magnitude. Such an indirect search for New Physics can be characterised as a ‘King Kong’ scenario: ”One might be unlikely to encounter King Kong; yet once it happens there can be no doubt that one has come across something extra-ordinary”. Such a situation can be realized again in different ways:

- Dedicated searches for EDM’s of neutrons, atoms and molecules are a definite must as emphasized by Pospelow [57] – no excuses are acceptable. For one should keep in mind that they are so tiny in the SM for reasons very specific to the CKM implementation of $T$ violation.
• Searching for a transverse polarization of muons in $K^+ \rightarrow \mu^+\nu\pi^0$ is a promising way to uncover the intervention of Higgs based CP violation.

• There exists a large literature on $D^0 - \bar{D}^0$ oscillations with predictions for observables covering several orders of magnitude. That does not mean that they are all equally credible, though. A systematic analysis has been given now based on the operator product expansion expressing $x = \Delta m_D/\Gamma$ and $y = \Delta\Gamma/2\Gamma$ in powers of $1/m_c$, $m_s$ and KM factors. One finds $x, y \sim \mathcal{O}(10^{-3})$ with the prospects for reducing the uncertainties rather slim; one should also note that $y$ is more sensitive to violations of quark-hadron duality than $x$. Recent claims $[59]$ that there is a model independant estimate yielding $x, y$ around 1% are greatly overstated.

After the early indication from FOCUS that $y$ might be around 1%, other data, also from the $B$ factories have not confirmed it $[60]$: $y$ as well as $x$ are consistent with zero on the 1-2 % level. Detailed searches for CP asymmetries in $D$ decays have been and are being undertaken: data are consistent with no asymmetries so far, again on the few percent level $[61]$.

While it is possible to construct New Physics scenarios producing effects as large as 10 % or so, a more reasonable range is the 1% level. Thus one is only now entering territory where there are some realistic prospects for New Physics to emerge.

6.2 The ‘Novel Challenge’

The situation is quite different in $B$ transitions since the CKM dynamics already generate large CP asymmetries. The one significant exception arises in $B_s(t) \rightarrow \psi + \eta/\phi$ where one can reliably predict a small asymmetry not exceeding 2 % for reasons that are very specific to the CKM description $[16]$: anything beyond that is a manifestation of New Physics.

As presented in the talks by Matteuzzi $[62]$ and Yamamoto $[13]$, we can expect that the (Super-)B factories, BTeV and LHC-b will allow to measure a host of CP asymmetries with experimental uncertainties not exceeding a few percent. The question then arises whether we can exploit this level

\[3\text{On the leading level quarks of only the second and third family participate.}\]
of sensitivity \textit{theoretically}, i.e., whether one can interpret data and make predictions with no more than a few percent theoretical uncertainty. I do not consider such a goal for theoretical control a luxury. With the exception of $B_s(t) \rightarrow \psi + \phi/\eta$ noted above CP asymmetries in $B$ decays often are large within the SM (or are severely restricted by the need for strong phase shifts). Therefore New Physics typically cannot change SM predictions by orders of magnitude. Furthermore I had argued above that the success of the CKM theory in describing weak observables characterized by scales ranging over several orders of magnitude is highly non-trivial. Accordingly I do not find it very likely that New Physics will affect transition rates for $B$ hadrons in a \textit{massive} way. For to have escaped detection before it had to ‘know’ about the flavour structure of the SM. While such a feat might be turned by some SUSY implementation of New Physics, one cannot count on it.

Thus one is faced with a novel challenge: can one be confident of having established the presence of New Physics when the difference between the expected and the observed signal is much less than an order of magnitude? To be more specific: assume one predicts an asymmetry of 40 \%, yet observes 60 \% – can one be certain of New Physics? What about if one observes 50\%? Interpreting such \textit{quantitative} discrepancies represents a challenge which we have not faced before.

7 \hspace{1em} \textbf{News from the Lepton Sector}

7.1 \hspace{1em} \textbf{Charged current interactions}

Important lessons can still be learnt from charged current transitions, in particular in $\tau$ decays as discussed by Kühn \cite{Kuhn}. Efforts are under way to extract the strange quark mass $m_s$ and $|V(us)|$ from Cabibbo suppressed $\tau$ decays; one gets very ‘reasonable values’, however at present the theory uncertainties are under poor control. One can also search for CP asymmetries, which would establish the intervention of New Physics, in single $\tau \rightarrow K\pi\nu$ decays \textit{without} $\tau$ polarization.
7.2 Flavour changing neutral currents

Lepton flavour changing neutral current transitions represents the most intriguing aspects of lepton dynamics. They require neutrinos to be mass non-degenerate. Theorists have thought hard and long about a reason for neutrinos being massless. With them never having succeeded I conclude there is no such reason – and therefore neutrinos are not massless after all. The ‘see-saw’ mechanism requiring the existence of right-handed neutrinos and a Majorana mass $M_M$ much larger than Dirac fermion masses $m_D$ provides a very appealing solution since it implies the existence of very heavy mostly right-handed neutrinos and mostly left-handed neutrinos with masses $\sim m_D^2/M_M$. With neutrinos not mass-degenerate lepton-flavour changing transitions can take place.

The present bound on $\mu \rightarrow e\gamma$ reads \[^{[64]}\]

$$\text{BR}(\mu \rightarrow e\gamma) \leq 1.2 \cdot 10^{-11}$$  \hspace{1cm} (14)

The intervention of New Physics is unequivocally needed to create a signal that could ever be observed. An experiment at PSI aims at a sensitivity level of around $10^{-14}$! No miracle is needed for a signal to surface at that level.

Searches for $\mu - e$ conversion are complementary. The best available bound has been obtained in the quasi-elastic reaction

$$\frac{\sigma(\mu^- + Au \rightarrow e^- + Au)}{\sigma(\mu^- + Au \rightarrow \mu^- + Au)} \leq 6.1 \cdot 10^{-11}.$$

\hspace{1cm} (15)

There is the ambitious goal to go even after the $10^{-17}$ level \[^{[64]}\]!

For a long time neutrino oscillations and their consequences have been searched for. Finally it seems they have made their presence felt and it makes even sense to distinguish between different oscillation scenarios \[^{[65]}\].

The solar neutrino deficit and the atmospheric muon anomaly are widely taken to show clear signals of neutrino oscillations \[^{[4]}\]. With respect to the solar $\nu$ deficit the evidence is based mainly and – after SNO – robustly on the total ‘disappearance’ rate with first indications arising now about more unique signals like the energy etc. dependance. As far as the atmospheric anomaly is concerned, the deficit in the muon signal is seen as robust; more

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\[^{4}\text{The LSND signal can be incorporated only at the price of a sterile neutrino or even CPT violation.}\]
intriguing since more specific is the very robust azimuthal dependance of the signal and the evidence for the appropriate energy dependance.

A priori there are several contenders for the correct oscillation scenario. The leading one now is the L(arge)M(ixing)A(ngle) case. It used to be quite different, and the shift came about due to more data, mainly from SNO and K2K. The latter observes 44 fully contained events when $64^{+6.1}_{-6.6}$ are expected without oscillation; the no oscillation hypothesis is presently disfavoured at the $\sim 2\sigma$ level [66]. I just cannot resist to point out a parallel to the soccer world championship going on right now. There was a lot of conviction about who the leading contenders were; yet this clear picture has been scrambled significantly by new data, i.e. the outcome of real soccer matches! 2002 has the potential to provide us with some decisive progress in our knowledge about the neutrino sector, but – unlike soccer – it will not tell us yet who the true champion is.

7.3 ”If the gods want to harm you ...” – CP violation in the lepton sector

Above I have emphasized what the CKM theory can do. However it has a significant deficit as well: it cannot generate the baryon number of the universe. At present it seems likely that baryogenesis actually represents a shadow of leptogenesis. To generate a lepton number for the universe one needs CP violation in the lepton sector. It is clearly desirable to directly study CP violation in leptodynamics. This can be done by

- probing for an electric dipole moment of electrons, atoms and molecules,
- searching for CP asymmetries in $\tau$ decays,
- analyzing the muon transverse polarization in $K_{\mu3}$ decays and
- probing for CP violation in neutrino oscillations.

As far as theoretical control is concerned neutrino physics in general and oscillations in particular are optimal systems. However the situation reminds me of a saying by the ancient Greek:”If the gods want to really harm you, then they fulfill your wishes!” It appears extremely challenging or iffy if CP violation in neutrino oscillations could ever be established because of the
neutrino parameters indicated by the present oscillation phenomenology and due to matter oscillations introducing an environmental bias \[66\]. There is one general lesson to be derived from this: we should be careful in what we wish and be thankful for hadronization as explained in the beginning.

8 Outlook

"The SM is consistent with the data" is a statement most of you experience as a worn-out refrain. However in the last two years it has acquired new dimensions (pun intended) leaving the Higgs sector as the only remaining ‘terra incognita’ of the SM. For an essential test of the CKM description of CP violation has been performed in \(B \rightarrow \psi K_S\); the first CP asymmetry outside the \(K^0 - \bar{K}^0\) complex has been observed, and it is huge – as expected. In my judgement the CKM description of CP violation thus has been promoted from an ansatz to a tested theory that is going to stay with us. Yet this success of the CKM theory does not resolve any of the central mysteries of the SM concerning the heavy flavour sector: why is there family replication, why are there three families, what generates the very peculiar pattern in the quark masses and the CKM parameters? It actually deepens those mysteries and – in my view – makes a convincing case that the SM is incomplete.

This conclusion is further strengthened by three observations:

1. One might argue that neutrino oscillations can be incorporated into a ‘trivial’ extension of the SM by just adding right-handed neutrinos without gauge interactions; one can engineer neutrino Yukawa couplings to Higgs doublets in such a way as to obtain the needed mass matrices. However that would be highly contrived; the only known natural way to understand the tiny neutrino masses is, as already stated, through the see-saw mechanism, which requires Majorana masses. Yet those cannot be obtained from doublet Higgs fields! While the see-saw mechanism suggests a highly hierarchical structure in the neutrino parameters, this is not necessarily so as pointed out by Jezabek, since there are actually two matrices describing \(\nu\) mass-related parameters \[67\].

2. The ‘strong CP problem’ remains unsolved.
3. We know now that CKM dynamics cannot generate the baryon number of the Universe.

It is obvious then that the dedicated study of heavy flavour dynamics can never become marginal, let alone obsolete. Much more can be said about this; here I want to comment only on directions for CP studies. It hardly needs justification to analyze all kinds of CP asymmetries in the decays of beauty hadrons with as much precision as possible. Yet this truth should not make us forget about other important avenues to pursue. For the non-CKM CP violating dynamics needed to generate the Universe’s baryon number could well be buried in $B$ decays under the CKM ‘background’ of huge CP asymmetries. Telegdi’s dictum can be applied here in a modified way: ”yesterday’s sensation” – CP violation in $B_d \to \psi K_S$ – ”is today’s calibration” – for CP violation in $B_d \to \pi\pi$ – ”and tomorrow’s background” – when searching for what is generating the baryon number of the Universe. Their impact on ordinary matter made up from the light flavours would have to deal with hardly a competition from CKM dynamics. At the same time we would benefit tremendously from the expertise accumulated and the opportunities spotted in different areas: atoms, molecules and nuclei can represent promising labs to search for $T$ odd effects like EDM’s etc.

I have mentioned in the beginning that we have two ‘Dresden codices’ to decipher, namely the CKM, Eq.(13, and MNS matrices. Like with the original Dresden codex we can succeed only by examining many correlations with accuracy and dedication. Gaining much more experimental information will be crucial – yet by itself not sufficient. When all the data are ‘in’, we have to do more than just connect and interprete them – we have to understand them. That – in my not quite unbiased view – means that one will need decisive input from theorists!

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