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Flavor Physics and the TeV Scale

Springer

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To the memories of
Prof. Chia-Chu Hou and Mr. Chiao-Shen Lu,
beloved father and father in-law.

Preface

The flavor sector carries the largest number of parameters in the Standard Model of particle physics. With no evident symmetry principle behind its existence, it is not as well understood as the SU(3)×SU(2)×U(1) gauge interactions. Yet it tends to be underrated, sometimes even ignored, by the erudite. This is especially so on the verge of the LHC era, where the exploration of the physics of electroweak symmetry breaking at the high energy frontier would soon be the main thrust of the field.

Yet, the question of "Who ordered the muon?" by I.I. Rabi lingers.

We do not understand why there is "family" (or generation) replication. That three generations are needed to have *CP* violation is a partial answer. We do not understand why there are only three generations, but Nature insists on (just about) only three active neutrinos. But then the *CP* violation with three generations fall far short of what is needed to generate the baryon asymmetry of the Universe. We do not understand why most fermions are so light on the weak symmetry breaking scale (v.e.v.), yet the third-generation top quark is a v.e.v. scale particle. We do not understand why quarks and leptons look so different, in particular, why neutrinos are rather close to being massless, but then have (at least two) near maximal mixing angles. We shall not, however, concern ourselves with the neutrino sector. It has a life of its own.

This monograph is on the usefulness of flavor physics as probes of the TeV scale to provide a timely interface for the emerging LHC era. Historically, the kaon system has been a major wellspring for the emergence of the Standard Model. It gave us the Cabibbo angle, hence quark mixings, K^0–$\bar{K}^0$ oscillations, *CP* violation, absence of FCNC and, the GIM mechanism, prediction of charm (mass), and ultimately the Kobayashi–Maskawa model and the prediction of the third generation. The torch, however, has largely passed on to the *B* meson system, the elucidation of which forms the bulk of this book. Following, and expanding on, the successful paths of the CLEO and ARGUS experiments, the B factories have dominated the scene for the past decade.

The B factories have produced a vast amount of knowledge. Fortunately, by concerning ourselves only with the TeV scale connection, a large part of the B factory output can be bypassed. We do not concern ourselves with rather indirect links to physics beyond the Standard Model, such as the measurement of CKM sides or the consistency of the unitary phases with three generations. The advantage is that we do not need to go into the details of "precision measurement" studies, as they are now rather involved. Our emphasis is on loop-induced processes, which allow us to probe virtual TeV scale physics through quantum processes, in the good traditions of muon $g - 2$ and rare kaon processes. In this sense, flavor physics is quite complementary to the LHC collider physics that would soon unfold before us. If New Physics is discovered by the LHC, flavor probes would provide extra information to help pin down parameters. If no New Physics emerges from the LHC, then flavor physics still provides multiple probes to physics above the TeV scale. Either way, the construction of the so-called Super B factories, to go far beyond the successful B factories in luminosity, is called for.

A glance at the Table of Contents shows that two thirds of the book is concerned with $b \to s$ or $b\bar{s} \leftrightarrow s\bar{b}$ transitions. The B factories have not uncovered strong hints for New Physics in $b\bar{d} \leftrightarrow d\bar{b}$ or $b \to d$ transitions. It is remarkable that all evidence supports the three generation Kobayashi–Maskawa model in the so-called $b \to d$ CKM triangle, $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ (and the Nobel prize has been awarded). Further probes in $b \to d$ transitions tend to be marred by hadronic or Standard Model effects and at best are part of the long road of three generation Standard Model consistency tests that we have decided to sidestep. In contrast, $b \to s$ transitions are not only the current frontier of flavor physics, it actually offers good hope that New Physics may soon be uncovered, maybe even before the first physics is repeated at the LHC. On the one hand, this is because the $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$ CKM triangle is so squashed and hardly a triangle in the Standard Model, so the expected CP violation in loop-dominated $b \to s$ transitions is tiny. This means that any clear observation could indicate New Physics. On the other hand, $b \to s$ transitions offer multiple probes into physics beyond the Standard Model that have come of age only recently. As we advocate, the measurement of $\sin 2\Phi_{B_s}$ in $B_s \to J/\psi\phi$, analogous to $\sin 2\phi_1/\beta$ measurement in $B_d \to J/\psi K_S$ at the B factories, holds the best promise for an unequivocal discovery of New Physics, if its measured value at the Tevatron or LHC turn out to be sizable. It is exciting that we seem to be heading that way.

A common thread that links the several hints of New Physics in $b \to s$ transitions, to our prediction of large and negative $\sin 2\Phi_{B_s}$, is the existence of a fourth generation. Of course, there are strong arguments against the existence of a fourth generation, by the aforementioned "neutrino counting" and by electroweak precision tests. However, these objections arise from outside of flavor physics. While these should be taken seriously, one should not throw the fourth generation away when considering flavor physics, since the richness of flavor physics rests on the existence of three generations and extending to four generations provide considerable enrichment, particularly in $b \to s$ transitions. It also provides multiple links between different flavor processes, through the unitarity of the 4×4 CKM matrix. As emphasized in this book, a fourth generation could most easily enter box and electroweak penguin diagrams. Accounts of these are scattered throughout the book, as we touch upon different processes. These are effects due to large Yukawa couplings, which link flavor physics to the Higgs, or electroweak symmetry breaking sector.

While writing this book, we observed that *adding a fourth quark generation could enhance the so-called Jarlskog invariant for* CP *violation by a factor of* 10^{+13} *or more*, and the (fourth generation) KM model could provide the source of *CP* violation for the baryon asymmetry of the Universe. A sketch of this insight is given in the final discussion chapter, which also serves as justification for our frequent mentioning of the fourth generation throughout the book. *Flavor physics could provide* CP *violation for the Heaven and the Earth.*

Two other chapters, on D^0 mixing and $K \to \pi\nu\nu$ and on lepton number violating τ decays, are loop-induced probes of New Physics that are analogous to the emphasis of our main text on B physics. Interestingly, there are still tree-level processes that can probe New Physics, such as the probe of charged Higgs boson H^+ through $B^+ \to \tau^+\nu_\tau$, or light dark matter or pseudoscalar Higgs boson search in $\Upsilon(nS)$ decays.

We have taken an experimental perspective in writing this book. This means selecting *processes*, rather than the theories or models, as the basis to explore flavor physics as probe of the TeV scale. In the first few chapters, emphasis is on *CP* violation measurables in $b \to s$ transitions. We then switch to using a particular process to illustrate the probe of a special kind of physics. We therefore also spend some time in elucidating what it takes to measure these processes. However, this is not a worker's manual for experimental analysis, but on bringing out the physics. For the same reason, we do not go into any detail on theoretical models. Our guiding principle has been: unless it can be identified as the smoking gun, it is better to stick to the simplest (rather than elaborate) explanation of an effect that requires New Physics.

The origins of this monograph is the plenary talk I gave at the SUSY 2007 conference held in Karlsruhe, Germany. It was interesting to attend the SUSY conference for the first time, while giving an *experimental* plenary talk. I thank the Belle spokespersons, Masa Yamauchi in particular, for nominating me as "that special physicist" to give this talk. I also thank my old friend and former colleague, Hans Kühn, for encouraging and inviting me to expand the talk into a monograph for Springer Tracts of Modern Physics. It is impossible to thank the numerous colleagues in the field of flavor physics for benefits of discussion and insight. I thank Yeong-jyi Lei for help on figures. Last, and above all, I thank my family for the understanding and support throughout the period of writing this book.

Les Houches, Geneva, and Taipei *George W.S. Hou*
September 2008

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