Implications of Standard-Model flavor violation for new physics searches

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Abstract. I discuss far-flung ramifications of light-quark flavor physics for searches for physics beyond the Standard Model and consider, particularly, its role in the interpretation of CP-violating observables in meson decays.

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INTRODUCTION

The differing masses and electroweak couplings of the quarks give rise to appreciably distinct effects and hence to “flavor physics.” The quarks vary widely in mass; indeed, the very large value of the top quark mass drives the hierarchy problem and speaks to a resolution which also involves flavor. In this contribution I set aside consideration of the possible flavor structure of new physics and discuss, rather, how the light-quark flavor dynamics of the Standard Model (SM) can impact the interpretation of low-energy experiments designed to identify departures from the SM.

The decipherment of the flavor and spin structure of the proton and neutron continues to be of intense interest, and at this meeting it has been a central theme: many have discussed the role of strange quarks or that of the up and down quarks, as well as of charge-symmetry breaking (CSB), in nucleon observables. The flavor physics of the light quarks also has broad implications for the search for physics beyond the SM. I will offer an overview of these and then focus on its implications for the study of CP violation.

THE SEARCH FOR NEW PHYSICS

There is much theoretical “evidence” that the Standard Model is incomplete — it leaves many questions unanswered. For example, there is no natural reason for the precise value of the weak mass scale, nor for the observed pattern of the fermions and their masses and mixing. The model does not incorporate gravity by design, and it offers no explanation for either dark matter or dark energy. Most notably, the Standard Model only explains some 5% of the known Universe [1].

Searches for new physics, which may well redress these limitations, can be organized along different themes, as shown in Fig. 1. The figure means to illustrate the possible interconnectedness of these efforts. For example, the origin of “dark matter” may ulti-
FIGURE 1. Themes in the search for new physics. How does flavor enter?

mately be resolved [2, 3], all or in part, by a mechanism related to electroweak symmetry breaking, or by a mechanism related to that which explains the baryon asymmetry of the universe, or by a sterile neutrino, or by a completely unrelated — and perhaps as yet unknown — mechanism. Let us consider how light-quark flavor physics enters in the interpretation of low-energy experiments which probe these possibilities.

THE MANY THREADS OF FLAVOR PHYSICS

At this meeting we have already seen examples of how flavor physics can impact the search for new physics. In regards to the mechanism of electroweak symmetry breaking, both Londergan [4] and Cloët et al. [5] have studied the impact of CSB and medium effects, respectively, on the determination $\sin^2 \theta_W$ from the NuTeV experiment [6]. Moreover, Young has studied the impact of strange quarks in the proton on the determination of the weak couplings of the $u$ and $d$ quarks from parity-violating electron scattering [7]. In each case the flavor-breaking effects required explicit evaluation.

The strange-quark structure of the nucleon also impacts the hunt for dark matter. In particular, it impacts the interpretation of the weakly-interacting massive particle (WIMP) exclusion plots which emerge from direct searches for anomalous nuclear recoils from WIMP-nucleon scattering [8]. A WIMP can be a neutralino, which is the dark-matter candidate of the minimally supersymmetric (SUSY) SM. The neutralino-nucleon cross section is particularly sensitive to the strange scalar density, namely, the value of $y = 2 \langle N | \bar{s}s | N \rangle / \langle N | \bar{u}u + \bar{d}d | N \rangle$ [9]; its value impacts where the allowed region of SUSY cross sections sit with respect to the exclusion curves. Earlier studies relate $y$ to the $\pi N$ sigma term $\Sigma_{\pi N}$ via $y = 1 - \sigma_0 / \Sigma_{\pi N}$ for fixed $\sigma_0 \equiv ((m_u + m_d) / 2) \langle N | \bar{u}u + \bar{d}d - 2 \bar{s}s | N \rangle$ [9, 10]. However, as Young has discussed at this meeting, $y$ can be computed directly using lattice QCD techniques and need not be predicated by the value of $\Sigma_{\pi N}$ [7, 10]. The outcome tends to make the spin-independent WIMP-nucleon cross section smaller than that usually assumed [10], so that it would tend to diminish the new physics reach of a particular WIMP direct detection experiment, note Ref. [11] for comparisons of experimental exclusion plots with theory. It is worth noting that
an exclusion limit itself contains astrophysical assumptions [12], so that the negative implications of flavor violation in this context for new physics searches need not be definitive.

**Flavor and CP Violation**

In studies of weak decays, flavor physics can impact or has impacted the discovery of CP-violating effects, the interpretation of CP-violating observables, and the pattern of new physics itself.

My own work in this subject began with a visit to Adelaide in 1996, and I am here now in appreciation of Tony’s gift of opportunity — and to say a bit about how it has all turned out. In 1996 Tony and I had a common interest in isospin-breaking in the NN force; in the language of meson-exchange currents, $\rho^0 - \omega$ mixing mediates important isospin-breaking effects. We became intrigued by the notion of the role of $\rho^0 - \omega$ mixing in hadronic B-meson decay [14]; at the time the asymmetric B-factories were not yet in operation. Our paper [15], with Heath B. O’Connell, entitled “$\rho$-$\omega$ Mixing and Direct CP Violation in Hadronic B Decays,” proposed that the sign of the large CP-violating asymmetry predicted to exist in $B^{\pm} \rightarrow \rho^{\pm} \rho^0$($\omega$) decay could be used to fix the sign of $\sin \alpha$, where $\alpha = \arg[-(V_{td}V_{tb}^*)(V_{ud}V_{ub}^*)]$. This is possible because $\rho^0 - \omega$ mixing in $B^{\pm} \rightarrow \rho^{\pm} \rho^0$ decay allows direct CP violation to occur, and information on the needed mixing matrix element can be gleaned from $e^+e^- \rightarrow \pi^+\pi^-$ data [15, 16]. Let us now turn to the context in which this work sits, as well as to a broader discussion of the role of flavor.

In the SM all CP-violating, weak-interaction phenomena derive from a single phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [17]. To test the mechanism of CP violation in the SM we must thus test the relationships it entails. CP-violating effects first appear at one-loop order in the weak interaction because all three generations must participate. However, intergenerational mixing is suppressed by factors of $|V_{us}| \equiv \lambda \sim 0.2$ in the SM, so that CP-violating effects can be difficult to detect experimentally. From this perspective B-meson decays offer a particularly auspicious way to study CP violation because the requisite quark mixing effects are all of $\mathcal{O}(\lambda^3)$, and CP violation can appear without suppression from intergenerational mixing. The CKM unitarity test probed by $b$-quark decay reflects this as well; thus enters “the” unitarity triangle formed from the constraint $V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0$. The current empirical status of the determination of the apex of the unitarity triangle is shown in Fig. 2. The height of the apex is of $\mathcal{O}(1)$; thus CP-violating effects can be large in the SM, though they appear in a rather special way.

Different CP-violating effects exist in the B meson system [18, 19]. CP violation in the B system can appear in $B^0\bar{B}^0$ mixing, though this has not yet been observed. If we consider $B^0$ decay to a CP self-conjugate final state $f_{CP}$, it can also appear as the interference between $B^0\bar{B}^0$ mixing and direct decay. A meson which is “tagged” as a $B^0$ meson at proper time $\tau = 0$ has a finite probability of being a $\bar{B}^0$ meson at proper time $\tau$, so that both $B^0 \rightarrow f_{CP}$ and $B^0 \rightarrow \bar{B}^0 \rightarrow f_{CP}$ can occur. If the decay $B^0, \bar{B}^0 \rightarrow f_{CP}$ is controlled by a single weak phase, then all strong-interaction effects cancel in the
time-dependent, CP-violating asymmetry which yields $\sin 2\phi_B$ where $\phi_B$, the phase of $B^0\bar{B}^0$ mixing, is $\beta$ in the SM. Finally, CP violation can also appear in direct decay; this can be probed through a non-zero value of the partial-rate asymmetry, i.e., via $|A(B \to h_1h_2)|^2 - |A(\bar{B} \to \bar{h}_1\bar{h}_2)|^2 \neq 0$.

Figure 2 shows that the CKM mechanism of CP violation works very well; this sets important constraints on the energy scale of possible new physics [20]. We see, moreover, that the determinations of $\beta$ and $\alpha$ are both discretely ambiguous, so that resolving a discrete ambiguity can potentially be an efficient means of identifying new physics. Interestingly, our suggestion [15] of resolving the sign of $\sin \alpha$ is still relevant!

To illustrate the role of flavor in the study of CP violation, we will consider how flavor informed the discovery of direct CP violation in the B system as well as how it can be used to make sharper tests of the SM of CP violation.

On direct CP violation. In the B-meson system direct CP violation was first observed in 2004 via the rate asymmetry in $B \to K^+\pi^-$ [21]. To leading order in $G_F$, the sign of the $K^\pm$ “tags” the flavor of the decaying $B^0$ ($\bar{B}^0$) meson, so that one loses none of the data set to the determination of the flavor of the decaying B-meson.

The measured rate asymmetry is [21] $\mathcal{A}_{K\pi} \equiv (n_{K^-\pi^+} - n_{K^+\pi^-})/(n_{K^-\pi^+} + n_{K^+\pi^-}) = -0.133 \pm 0.030 \text{(stat)} + 0.009 \text{(sys)}$, in good agreement with Ref. [22], where $n_{K^-\pi^+}$ is the measured yield for the $K^-\pi^+$ final state. The size of the asymmetry is uncomfortably large for QCD factorization [23], but the empirical asymmetry can be confronted successfully without physics beyond the SM [24, 25]. The observation of CP violation in the D meson system, however, would signal new physics. Analogous “untagged” studies
of direct CP violation in D decay are possible, such as in $D \rightarrow K_S \pi^+ \pi^-$, e.g., or to any final state of definite CP in particle content. The breaking of the mirror symmetry of the untagged Dalitz plot realized in terms of the ($K_S \pi^\pm$) invariant masses would signal direct CP violation [26, 27].

On the interpretation of CP-violating observables. Flavor-based assumptions can be used to eliminate some sensitivity to Standard Model physics but can induce other uncertainties. Let us first consider the measurement of $\beta$ with $b \rightarrow s$ penguins, to end of determining whether the value of $\sin(2\beta)$ is universal as in the SM [28]. In the case of the “golden” mode $B \rightarrow J/\psi K_S$, the direct decay is characterized by a single weak phase to an excellent approximation, so that the time-dependent CP asymmetry measures $\sin(2\beta)$. For other modes, computation, or estimation, of the SM-induced shift from $\sin(2\beta)$ is crucial. In $B \rightarrow \phi K_S$ [28, 30] and $B \rightarrow f_0(980)K_S$ [31] decays the corrections are small. This emerges in the former case because the $\phi$ is very nearly an ideally mixed ($s\bar{s}$) state, though the corrections to this limit have an appreciable effect [30], and in the latter case because the vacuum-to-scalar matrix element of the strange vector current, which drives the “wrong-phase” tree contribution, vanishes by charge-conjugation symmetry [31, 30].

We can also consider the measurement of $\alpha$ — or $\gamma$, given $\beta$ — with the $b \rightarrow u$ amplitude through the $B \rightarrow \pi\pi$, or generally $B \rightarrow n\pi$, decay modes. Here an assumption of isospin symmetry is essential [32, 33]. Isospin-breaking effects are particularly important in $B \rightarrow \pi\pi$. In this case transition amplitudes can emerge which did not appear in the isospin symmetric limit [34]. It is possible to assess all leading, strong isospin-breaking effects in the $B \rightarrow n\pi$ modes [34, 35, 36, 37]. However, the current limits on $\alpha$ are driven by features of the $B \rightarrow \rho\rho$ data which are insensitive to isospin breaking [13].

And what of the flavor of possible new physics? At current levels of precision, the CKM mechanism dominates flavor violation as well [13, 20].

**SUMMARY**

The pattern of CP violation in Nature can be described by a single parameter in the quark-mixing (CKM) matrix to an accuracy of some 20% [38]. No new sources of CP violation beyond the SM have as yet been established. One can find terrestrial evidence for physics beyond the SM in low-energy experiments by observing either processes which are highly forbidden in the SM, such as CP violation in the D system or a permanent electric dipole moment, and/or by decided failures of unitarity triangle tests. The prospect of the direct detection of dark matter also tantalizes. Flavor physics has played and will continue to play a crucial role in all of these developments.

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