Theory Overview

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We first review some aspects of the determination of the sides and angles of the unitarity triangle. We pay particular attention to theory shortcomings, and present many alternative proposals for the determination of $|V_{ub}|$ (which at present is problematic). We then turn our attention to the more general question: What have we learned so far about flavor physics and where do we go from here? We argue that the aim of Flavor Physics should be to establish or rule out Minimal Flavor Violating interactions up to a scale of 10 TeV.

1. Introduction and UT Theory

In this first section of this talk I will skim over the determination of sides and angles of the unitarity triangle (UT). I do not pretend to make a complete review or even an overview. I picked topics on the basis of where I thought we should be weary overly cautions of theorists "predictions." In subsequent sections I attempt to get some perspective on the field, and will ask and try to answer the questions of what we have learned in FP and CP physics and where should we go from here.

1.1. $|V_{td}/V_{ts}|$

The magnitudes of V_{td} and V_{ts} are determined from measurements of neutral B_d and B_s oscillations, respectively. The big news last year was the precise measurement of the B_s mixing rate at Tevatron experiments[1, 2]. While $|V_{ts}|$ does not provide direct information on the apex of the unitarity triangle, the ratio $|V_{td}/V_{ts}|$ does. The interest in the ratio stems from the cancellation of hadronic uncertainties:

$$\frac{|V_{td}|}{|V_{ts}|} = \xi \sqrt{\frac{\Delta m_s \, m_{B_s}}{\Delta m_d \, m_{B_d}}}, \quad \text{where} \quad \xi^2 \equiv \frac{B_{B_s} f_{B_s}^2}{B_{B_d} f_{B_d}^2}. \quad (1)$$

The hadronic parameter ξ would be unity in the flavor-$SU(3)$ symmetry limit. Lattice QCD gives[3] $\xi = 1.21\,^{+0.047}_{-0.035}$, and combining with the experimental result

$$\frac{|V_{td}|}{|V_{ts}|} = 0.2060 \pm 0.0007(\exp)\,^{+0.0081}_{-0.0060}(\text{theory})$$

The error, approximately 3%, is dominated by theory, which comes solely from the error in ξ. There aren't many examples of quantities that the lattice has post-dicted (let alone predicted) with this sort of accuracy. So can the rest of us, non-latticists, trust it? On the one hand, because this result is protected by symmetry the required precision is not really 3%. The quantity one must measure is the deviation from the symmetry limit, $\xi^2 - 1$, for which the error is about 25% and perhaps we should be confident that the lattice result is correct at this level. On the other hand,

this also tells us that other methods can be competitive at this level. The leading chiral log calculation[4] gives $\xi \approx 1.15$, and the error in $\xi^2 - 1$ is estimated from naive dimensional analysis as $m_K^2/\Lambda_\chi^2 \sim 24\%$, comparable to the lattice result. Moreover, the lattice determination has been made with only one method (staggered fermions) and it would be reassuring to see the same result from other methods. For the lattice to achieve the 0.35% accuracy in ξ needed to match the experimental error in $|V_{td}/V_{ts}|$ a precision of 2% in the determination of $\xi^2 - 1$ is required. Before we, skeptics, trust any significant improvement in this determination, other independent lattice QCD post-dictions of similar accuracy are necessary.

1.2. $|V_{cb}|$

A. Inclusive

The method of moments gives a very accurate determination of $|V_{cb}|$ from inclusive semileptonic B decays. In QCD, the rate $\mathrm{d}\Gamma(B \to X_c \ell\nu)/\mathrm{d}x\,\mathrm{d}y = |V_{cb}|^2 f(x, y)$, where x and y are the invariant lepton pair mass and energy in units of m_B, is given in terms of four parameters: $|V_{cb}|$, α_s, m_c and m_b. $|V_{cb}|$, which is what we are after, drops out of normalized moments. Since α_s is well known, the idea is to fix m_c and m_b from normalized moments and then use them to compute the normalization, hence determining $|V_{cb}|$. In reality we cannot solve QCD to give the moments in terms of m_c and m_b, but we can use a $1/m_Q$ expansion to write the moments in terms of m_c, m_b and a few constants that parametrize our ignorance[5]. These constants are in fact matrix elements of operators in the $1/m_Q$ expansion. If terms of order $1/m_Q^3$ are retained in the expansion one needs to introduce five such constants; and an additional two are determined by meson masses. All five constants and two quark masses can be over-determined from a few normalized moments that are functions of E_cut, the lowest limit of the lepton energy integration. The error in the determination of $|V_{cb}|$ is a remarkably small 2%[6]. But even most remarkable is that this estimate for the error is truly believable. It is obtained by assigning the last term *retained* in the expansion to the error, as opposed to the less conservative guessing of the next

order *not* kept in the expansion. Since there is also a perturbative expansion, the assigned error is the combination of the last term kept in all expansions, of order $\beta_0 \alpha_s^2$, $\alpha_s \Lambda_{\rm QCD}/m_b$ and $(\Lambda_{\rm QCD}/m_b)^3$.

There is only one assumption in the calculation that is not fully justified from first principles. The moment integrals can be computed perturbatively (in the $1/m_Q$ expansion) only because the integral can be turned into a contour over a complex E away from the physical region[7]. However, the contour is pinned at the minimal energy, $E_{\rm cut}$, on the real axis, right on the physical cut. So there is a small region of integration where quark-hadron duality cannot be justified and has to be invoked. Parametrically this region of integration is small, a fraction of order Λ/m_Q of the total. But this is a disaster because this is parametrically much larger than the claimed error of order $(\Lambda/m_Q)^3$. However, this is believed not to be a problem. For one thing, the fits to moments as functions of $E_{\rm cut}$ are extremely good: the system is overconstrained and these internal checks work. And for another, it has been shown[8] that duality works exactly in the Shifman-Voloshin (small velocity) limit, to order $1/m_Q^2$. It seems unlikely that the violation to local quark-hadron duality mainly changes the normalization and has mild dependence on $E_{\rm cut}$, and that this effect only shows up away from the SV limit.

B. Exclusive

The exclusive determination of $|V_{cb}|$ is in pretty good shape theoretically, but is not competitive with the inclusive one. So it provides a sanity check, but not an improvement. The semileptonic rates into either D or D^* are parametrized by functions $\mathcal{F}$, $\mathcal{F}_*$, of the rapidity of the charmed meson in the B rest-frame, w. Luke's theorem[9] states $\mathcal{F} = \mathcal{F}_* = 1 + \mathcal{O}(\Lambda_{\rm QCD}/m_c)^2$ at $w = 1$. The rate is measured at $w > 1$ and extrapolated to $w = 1$. The extrapolation is made with a first principles calculation to avoid introducing extraneous errors[10]. The result has a 4% error dominated by the uncertainty in the determination of $\mathcal{F}$, $\mathcal{F}_*$ at $w = 1$.

There is some tension between theory and experiment in these exclusive decays that needs attention. The ratios of form factors $R_{1,2}$ are at variance from theory by three and two sigma respectively[11]. Also, in the heavy quark limit the slopes ρ^2 of $\mathcal{F}$ and $\mathcal{F}_*$ should be equal. One can estimate symmetry violations and obtains[12] $\rho_{\mathcal{F}}^2 - \rho_{\mathcal{F}_*}^2 \simeq 0.19$, while experimentally this is -0.22 ± 0.20, a deviation in the opposite direction. This is a good place for the lattice to make post-dictions at the few percent error level that may lend it some credibility in other areas where it is needed to determine a fundamental parameter.

1.3. $|V_{ub}|$

The magnitude $|V_{ub}|$ determines the rate for $B \to X_u \ell \nu$. The well known experimental difficulty is that since $|V_{ub}| \ll |V_{cb}|$ the semileptonic decay rate is dominated by charmed final states. To measure a signal it is necessary to either look at exclusive final states or suppress charm kinematically. The interpretation of the measurement requires, in the exclusive case, knowledge of hadronic matrix elements parametrized in terms of form-factors, and for inclusive decays, understanding of the effect of the kinematic cuts on the the perturbative expansion and quark-hadron duality.

C. Inclusive

This has been the method of choice until recently, since it was thought that the perturbative calculation was reliable and systematic and hence could be made sufficiently accurate. However it has become increasingly clear of late that the calculation cannot be made arbitrarily precise. The method uses effective field theories to expand the amplitude systematically in inverse powers of a large energy, either the heavy mass or the energy of the up-quark (or equivalently, of the hadronic final state). One shows that in the restricted kinematic region needed for experiment (to enhance the up-signal to charm-background) the inclusive amplitude is governed by a non-perturbative "shape function," which is, however, universal: it also determines other processes, like the radiative $B \to X_s \gamma$. So the strategy has been to eliminate this unknown, non-perturbative function from the rates for semileptonic and radiative decays.

Surprisingly, most analysis do not eliminate the shape function dependence between the two processes. Instead, practitioners commonly use parametrized fits that unavoidably introduce uncontrolled errors. It is not surprising that errors quoted in the determination of $|V_{ub}|$ are smaller if by a parametrized fit than by the elimination method of [13]. The problem is that parameterized fits introduce systematic errors that are unaccounted for.

Parametrized fits aside, there is an intrinsic problem with the method. Universality is violated by subleading terms[14] in the large energy expansion ("subleading shape functions"). One can estimate this uncontrolled correction to be of order $\alpha_s \Lambda/m_b$, where Λ is hadronic scale that characterizes the sub-leading effects (in the effective theory language: matrix elements of higher dimension operators). We can try to estimate these effects using models of sub-leading shape functions but then one introduces uncontrolled errors into the determination. At best one should use models to estimate the errors. I think it is fair, albeit unpopular, to say that this method is limited to a precision of about 15%: since there are about 10 sub-leading shape functions, I estimate the precision

as $\sqrt{10}\,\alpha_s \Lambda/m_b$. This is much larger than the error commonly quoted in the determination of $|V_{ub}|$.

This is just as well, since the value of $|V_{ub}|$ from inclusives is in disagreement not only with the value from exclusives but also with the global unitarity triangle fit. You can quantify this if you like, but it is graphically obvious when you see plots of the fit in the ρ-η plane that use only some inputs inputs and contrast those with the remaining inputs of the global fit. At this conference last year, Jerome Charles presented[15] three pairs of fits contrasting measurements: tree vs. loop, CP violating vs. CV conserving, and theory free vs. QCD based (see also slide 25 of Heiko Lacker, this conference). In all these it is evident to the naked eye that $|V_{ub}|$ (the dark green circle's radius) is too large; the input used is dominated by inclusives.

D. Exclusives

The branching fraction $\mathcal{B}(B \to \pi \ell \nu)$ is known[16] to 8%. A comparable determination of $|V_{ub}|$ requires knowledge of the $B \to \pi$ form factor $f_+(q^2)$ to 4%. There are some things we do know about f_+: (i)The shape is constrained by dispersion relations[17]. This means that if we know f_+ at a few well spaced points we can pretty much determine the whole function f_+. (ii)We can get a rough measurement of the form factor at $q^2 = m_\pi^2$ from the rate for $B \to \pi\pi$[18]. This requires a sophisticated effective theory (SCET) analysis which both shows that the leading order contains a term with $f_+(m_\pi^2)$ and systematically characterizes the corrections to the lowest order SCET. It is safe to assume that this determination of $f_+(m_\pi^2)$ will not improve beyond the 10% mark.

Lattice QCD can determine the form factor, at least over a limited region of large q^2. At the moment there is some disagreement between the best two lattice calculations, which however use the same method[19]. A skeptic would require not only agreement between the two existing calculations but also with other methods, not to mention a set of additional independent successful post-dictions, before the result can be trusted for a precision determination of $|V_{ub}|$.

The experimental and lattice measurements can be combined using constraints from dispersion relations and unitarity[20]. Because these constraints follow from fundamentals, they do not introduce additional uncertainties. They improve the determination of $|V_{ub}|$ significantly. The lattice determination is for the q^2-region where the rate is smallest. This is true even if the form factor is largest there, because in that region the rate is phase space suppressed. But a rough shape of the spectrum is experimentally observed, through a binned measurement[16], and the dispersion relation constraints allows one to combine the full experimental spectrum with the restricted-q^2 lattice measurement. The result of this analysis gives

a 13% error in $|V_{ub}|$, completely dominated by the lattice errors.

E. Alternatives

Exclusive and inclusive determinations of $|V_{ub}|$ have comparable precisions. Neither is very good and the prospect for significant improvement is limited. Other methods need be explored, if not to improve on existing $|V_{ub}|$ to lend confidence to the result. A lattice-free method would be preferable. A third method, proposed a while ago[21], uses the idea of double ratios[22] to reduce hadronic uncertainties. Two independent approximate symmetries protect double ratios from deviations from unity, which are therefore of the order of the product of two small symmetry breaking parameters. For example, the double ratio $(f_{B_s}/f_{B_d})/(f_{D_s}/f_{D_d}) = (f_{B_s}/f_{D_s})/(f_{B_d}/f_{D_d}) = 1 + \mathcal{O}(m_s/m_c)$ because $f_{B_s}/f_{B_d} = f_{D_s}/f_{D_d} = 1$ by $SU(3)$ flavor, while $f_{B_s}/f_{D_s} = f_{B_d}/f_{D_d} = \sqrt{m_c/m_b}$ by heavy flavor symmetry. One can extract $|V_{ub}/V_{ts}V_{tb}|$ by measuring the ratio,

$$\frac{\mathrm{d}\Gamma(\bar{B}_d \to \rho\ell\nu)/\mathrm{d}q^2}{\mathrm{d}\Gamma(\bar{B}_d \to K^*\ell^+\ell^-)/\mathrm{d}q^2} = \frac{|V_{ub}|^2}{|V_{ts}V_{tb}|^2} \cdot \frac{8\pi^2}{\alpha^2} \cdot \frac{1}{N(q^2)} \cdot R_B,$$
(2)

where q^2 is the lepton pair invariant mass, and $N(q^2)$ is a known function[23]. When expressed as functions of the rapidity of the vector meson, $y = E_V/m_V$, the ratios of helicity amplitudes

$$R_B = \frac{\sum_\lambda |H_\lambda^{B\to\rho}(y)|^2}{\sum_\lambda |H_\lambda^{B\to K^*}(y)|^2}, \quad R_D = \frac{\sum_\lambda |H_\lambda^{D\to\rho}(y)|^2}{\sum_\lambda |H_\lambda^{D\to K^*}(y)|^2},$$

are related by a double ratio: $R_B(y) = R_D(y)(1 + \mathcal{O}(m_s(m_c^{-1} - m_b^{-1})))$. This measurement could be done today: CLEO has accurately measured the required semileptonic D decays[24, 25].

A fourth method is available if we are willing to use rarer decays. To extract $|V_{ub}|$ from $\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (0.88^{+0.68}_{-0.67} \pm 0.11) \times 10^{-4}$[26] one needs a lattice determination of f_B. Since we want to move away from relying on non-perturbative methods (lattice) to extract $|V_{ub}|$ we propose a cleaner but more difficult measurement, the double ratio

$$\frac{\frac{\Gamma(B_u \to \tau\nu)}{\Gamma(B_s \to \ell^+\ell^-)}}{\frac{\Gamma(D_d \to \ell\nu)}{\Gamma(D_s \to \ell\nu)}} \sim \frac{|V_{ub}|^2}{|V_{ts}V_{tb}|^2} \cdot \frac{\pi^2}{\alpha^2} \cdot \left(\frac{f_B/f_{B_s}}{f_D/f_{D_s}}\right)^2$$
(3)

In the SM $\mathcal{B}(B_s \to \mu^+\mu^-) \approx 3.5 \times 10^{-9} \times (f_{B_s}/210\,\mathrm{MeV})^2 (|V_{ts}|/0.040)^2$ is the only presently unknown quantity in the double ratio and is expected to be well measured at the LHC[27].

The ratio $\Gamma(B^+ \to \tau^+\nu)/\Gamma(B_d \to \mu^+\mu^-)$ gives us a fifth method. It has basically no hadronic uncertainty, since the hadronic factor $f_B/f_{B_d} = 1$, by isospin. It involves $|V_{ub}|^2/|V_{td}V_{tb}|^2$, an unusual combination of

CKMs. In the $\rho - \eta$ plane it forms a circle centered at $\sim (-0.2, 0)$ of radius ~ 0.5. Of course, measuring $\Gamma(B_d \to \mu^+ \mu^-)$ is extremely hard.

In a sixth method one studies wrong charm decays $\bar{B}_{d,s} \to \bar{D}X$ (really $b\bar{q} \to u\bar{c}$). This can be done both in semi-inclusive decays[28] (an experimentally challenging measurement) or in exclusive decays[29] (where an interesting connection to $B_{d,s}$ mixing matrix elements is involved).

1.4. α from $B \to \pi\pi, \pi\rho, \rho\rho$.

In principle the penguin contamination problem[30] requires a full isospin analysis[31] for a theoretically clean determination of the angle α. The angle determination works slightly better than we had a right to expect a priori. The reason lies in two empirical observation in $B \to \rho\rho$. First, the longitudinal polarization dominates, and therefore the final state is to good approximation a CP eigenstate (CP even, in fact). And second, the branching fraction for $B \to \rho^0\rho^0$ is small: relative to $B \to \rho^+\rho^-$ it is 6±3%, to be compared with the neutral to charged decay into pions of $23 \pm 4\%$. This means that the contamination from penguin operators is small and one can get a clean measurement of α. All three decay modes are about equally important in current fits, which give $\alpha = 93^{+11}_{-9}$ degrees.

1.5. γ from $B^\pm \to DK^\pm$.

Three different methods are used. They are all based on the interference between Cabibbo-allowed (*e.g.*, $B^- \to D^0 K^-$) and suppressed decays (*e.g.*, $B^- \to \overline{D^0} K^-$) with D^0, $\overline{D^0}$ decaying to a common state. The GLW[32] method uses decays to a common CP eigenstate. In the ADS method[33] the final state is chosen to be a suppressed D decay mode if the D came from an allowed B decay; for example, the final state in the charm decay can be taken to be $K^+\pi^-$ so it is doubly Cabibbo suppressed for a D^0 decay but allowed for a $\overline{D^0}$ decay. The efficacy of this method depends sensitively on the ratio of amplitudes, which can be measured separately, $r_B = |A(B^- \to \overline{D^0} K^-)/A(B^- \to D^0 K^-)|$. In the GGSZ method[34] the D^0 and $\overline{D^0}$ are reconstructed in a common three body final state. The results to date vary depending on which decay mode is actually used, so the determination of γ from all measurements combined is not very good, $\gamma = 62^{+38}_{-24}$ degrees. More data should improve the determination of γ.

1.6. Are there anomalies?

There seem to be as many papers in the literature claiming there is a "$B \to K\pi$ puzzle" as those that claim it is not a puzzle. It is easy to see why. In order to find a puzzle one must know a priori the hadronic amplitudes. Those who find a puzzle in $B \to K\pi$ make assumptions about hadronic amplitudes that those who find no puzzle think are unwarranted. Moreover, Ref. [35] showed that soft final state interactions do not disappear in the large m_b limit, and Refs. [36] and [37] studied this quantitatively for $B \to K\pi$ and $B \to \pi\pi$, respectively, and concluded the effects should be expected to be large. For example, the CP asymmetry in $B \to K\pi$ could easily be 20% and the bound $\sin^2 \gamma \leq R$, where $R = \Gamma(B_d \to \pi^\mp K^\pm)/\Gamma(B^\pm \to \pi^\pm K)$ could easily be violated at the 20% level.

The case for new physics in CPV in charmless $b \to s$ decays would seem to be stronger. Regardless of decay mode β_{eff} is predicted by SCET, QCD-factorization and pQCD to deviate from $\beta_{J/\psi K_s}$ by a small positive amount. Experimentally the deviations vary from mode to mode but are all non-positive and not necessarily small. However, many things have to be checked before one can begin to believe we are seeing new physics here. First, all of the theoretical schemes need to come to terms with the soft final state interactions issue raised in [35] or show that work is incorrect. Then, also, the fact that all deviations are negative strongly suggests that the measurements have been corrupted by an admixture of the opposite CP final state.

In my view there is at present no case for deviations from the standard CKM model of flavor.

2. Perspective

How precise should we ultimately measure the elements of the CKM matrix? I am not asking what is the ultimate precision afforded by present day methods, but rather, how precisely do we need to know them? A rather common answer is that one should aspire to determine them as well as possible given available methods because the CKM elements are fundamental constants of nature, as fundamental as any other coupling in the Lagrangian of the Standard Model of electroweak and strong interactions (SM). But I find this answer lame and naïve, particularly when the effort is rather expensive both in real money and in human capital. A much better answer is obtained by estimating realistically how large deviation due to new physics could reasonably be.

It is not difficult to find extensions of the standard model that would give deviations from expected measurements just beyond the precision attained to date. For example, one can take the minimal extension to the supersymmetrized SM (the MSSM), and choose parameters appropriately, that is, on the verge of being ruled out (or discovered). But this is contrived, and not a reasonable way to answer our question.

One way of estimating the precision with which we need to determine CKM elements is to verify that the CKM matrix is unitary. Violations to CKM unitarity must come from additional quarks beyond those in the SM. This is already very constrained by electroweak precision measurements and for that reason I will not consider it any further (but creative theorists can get around these constraints; see, *e.g.,* Ref. [38]).

Instead I will concentrate on the question, which I think is more interesting, what precision is needed to exclude new physics at the TeV scale? In the absence of new dynamics radiative corrections would render the mass scale of the electroweak theory comparable to the Planck scale. New physics at the TeV scale is generally invoked to explain this "hierarchy problem." But quark mass terms break the electroweak symmetry group, so the quark mass matrices are necessarily connected to this new physics. New "higgs dynamics" at the TeV scale must incorporate new flavor physics too.

This suggests another criterion for the required precision in the determination of CKMs, namely, enough that we can see clearly the effects of this new flavor physics originating from the new, TeV-scale dynamics. It is easy to describe the effects of new TeV dynamics at below TeV energies in a model independent way. One simply extends the Lagrangian of the SM by operators of dimension higher than four, suppressed by powers of the new physics scale, Λ. The work in [39, 40] lists all operators of dimension five and six and analyzes some of their effects. Ignoring operators mediating flavor changing neutral currents (FCNC), $\Lambda \sim$ a few TeV is consistent with experiment. But if the coefficient of FCNC operators is given by dimensional analysis, then $\Lambda \sim$ a few TeV is strongly excluded. A much larger scale, $\Lambda \sim 10^4$ TeV, is still consistent with experiment, but then a hierarchy problem reappears.

Let $\mathcal{A}$ denote the amplitude for some process which we write as the sum of SM and new physics pieces, $\mathcal{A} = \mathcal{A}_{\mathrm{SM}} + \mathcal{A}_{\mathrm{New}}$. If this proceeds at tree level in the SM we estimate, roughly,

$$\mathcal{A}_{\mathrm{SM}} \sim \frac{g^2}{M_W^2} \times \mathrm{CKM} \quad \text{and} \quad \mathcal{A}_{\mathrm{New}} \sim \frac{1}{\Lambda^2}, \quad (4)$$

where the factor "CKM" stands for some combination of CKM elements. If we want to be sensitive to the the second term the uncertainty in the first one should be no larger than the expected size of new physics effects:

$$\frac{\delta(\mathrm{CKM})}{\mathrm{CKM}} \sim \frac{1}{\mathrm{CKM}} \frac{1/\Lambda^2}{g^2/M_W^2} \sim 1\% \left(\frac{0.03}{\mathrm{CKM}} \right) \left(\frac{10 \text{ TeV}}{\Lambda} \right)^2 \tag{5}$$

Repeat now the power counting leading to (5), but for processes involving FCNC. These require at least one loop in the SM, but not in the new physics. We now estimate

$$\mathcal{A}_{\mathrm{SM}} \sim \frac{\alpha}{4\pi \sin^2 \theta_w} \frac{g^2}{M_W^2} \times \mathrm{CKM}, \tag{6}$$

so that

$$\frac{\delta(\mathrm{CKM})}{\mathrm{CKM}} \sim \frac{1}{\mathrm{CKM}} \frac{1/\Lambda^2}{(\alpha/4\pi \sin^2 \theta_w)(g^2/M_W^2)}$$
$$\sim 400\% \times \left(\frac{0.03}{\mathrm{CKM}} \right) \left(\frac{10 \text{ TeV}}{\Lambda} \right)^2 \tag{7}$$

This is an underestimate since for SM's FCNC the CKM combination is smaller than 0.03. Alternatively one can write this as a limit one places on the scale of new physics, (7) gives

$$\Lambda > v \sqrt{\frac{1}{\frac{\delta(\mathrm{CKM})}{\mathrm{CKM}}} \frac{1}{\mathrm{CKM}} \frac{4\pi \sin^2 \theta_w}{\alpha}}$$
$$\sim 10^3 \text{ TeV} \times \left(\frac{10\%}{\frac{\delta(\mathrm{CKM})}{\mathrm{CKM}}} \right)^{\frac{1}{2}} \left(\frac{0.0002}{\mathrm{CKM}} \right)^{\frac{1}{2}} \tag{8}$$

So 10% precision already makes a strong statement about the scale of new physics, Λ. We argued above that since the solution to the hierarchy problem involves the higgs (or more generally, the breaking of EW symmetry), and since this is responsible for quark/lepton masses, then it is natural that the new physics that solves the hierarchy involves flavor.

What gives? I see three possibilities:

1. Cancellations among several new physics (NP) contributions

2. Large scale ($\Lambda \sim 1000$ TeV) of NP except for a light higgs (or a light flavor blind sector)

3. Automatic alignment of small CKMs in NP with the small CKMs in SM.

Let's examine these generic possibilities a bit more closely. The first one presumes there is new physics at the TeV scale. It explains the absence of FCNCs by happenstance, masses and couplings in the sum of terms contributing to the amplitude conspiring to cancel to good approximation. When stated this way, this seems like a very unappealing possibility. Yet this is what the MSSM does, particularly if one insists on light (~ 100 GeV) partners of "normal" particles. For example, in order to avoid unacceptably large rate for $B \to X_s \gamma$, it needs to cancel the charged higgs mediated contribution (which always adds coherently to the SM contribution and is only suppressed to the extent that the charged higgs mass is made heavy) against some other contribution, like a gaugino mediated graph. In general terms, if we are willing to allow some level of fine tuning to suppress FCNC then we correspondingly loose a clear idea of what is the scale we are probing, or equivalently, what we are aiming at.

The second possibility is that the scale of the flavor dynamics is about 1000 TeV (or larger). FCNCs associated with this scale are not experimentally ruled out.

Yet the scale of EW symmetry breaking is three orders of magnitude smaller, so this is a new, but smaller, hierarchy problem. One expects dynamics that solves the hierarchy problem to show up at the LHC (either the little hierarchy or the big one or both), but, depending on the actual scale of flavor, there may be no sign of FCNCs in B and K physics. Technicolor models in which flavor is generated by an extended sector at the 1000 TeV scale fall in this class, as do many more modern examples of theories designed to solve the little hierarchy problem; see, for example, Refs. [41, 42, 43].

The third and last possibility is that the NP at the TeV scale is aligned in flavor with the SM. The reason FCNCs are suppressed in the SM is that they do not appear at tree level and they are suppressed by a small CKM factor. The NP is not ruled out if it has the same (or similarly suppressed) CKM factors associated with FCNCs. The difference with the first possibility is that no cancellation of graphs is required, other than those cancellations that follow automatically from the unitarity of the CKM matrix. Indeed, we see from Eq. (8) that if we take away the last factor the scale of new physics is only bounded to be greater than about 10 TeV. In fact SUSY theories make use of this automatic suppression, and are free of additional fine tunings if one can take all SUSY masses to be ~ 10 TeV$/4\pi \sim 1$ TeV. The first possibility discussed above applies to SUSY if one insists that SUSY masses are much lighter, say, with masses of a few hundred GeV. This third and last possibility is appealing in the sense that it makes fairly definite predictions and should be accessible experimentally.

This is made even more appealing by realizing that it follows naturally from imposing a simple principle based on symmetry considerations alone. In the absence of quark masses the SM has a large flavor symmetry, $SU(3)^3$ (one factor of $SU(3)$ for each of quark doublets, right handed up-type quarks and right handed down-type quarks). The principle of Minimal Flavor Violation asserts that this symmetry is only violated by the quark mass matrices. Any new interaction that breaks this large flavor symmetry must do so by including the appropriately transforming combination of quark mass matrices. This can be implemented as an effective theory, by adding higher dimension operators to the SM suppressed by powers of the NP scale Λ, as discussed above. The difference is that now the coefficients of these operators are the product of an unknown constant of order one times a factor of the quark mass matrix fixed by these symmetry considerations. In the quark mass eigenstate basis this gives rise to coefficients that include small CKM suppression factors in FCNCs. A complete analysis of the effects of dimensions six operators on FCNCs has been performed[44] and shows that the scale of NP must be of the order of 10 TeV, in accordance with the crude estimates above. The most stringent bound

comes from radiative B decays ($\Lambda \geq 9$ TeV), with other processes giving bounds in the range 1 TeV to 6 TeV. I believe the aim of FPCP should be to exclude $\Lambda \leq 10$ TeV in MFV from all FCNC processes.

There exist other mechanisms, like next-to-minimal Flavor Violation, which also naturally produce small coefficients for NP contributions to FCNCs. Since MFV gives the minimal expected deviations of FCNC from SM predictions it still serves as a template against which one should calibrate experimental reach. For more on these alternatives see Ref. [45].

If $\Lambda < 10$ TeV MFV is excluded then one should expect that $\Lambda > 10$ TeV also for flavor conserving NP. If NP is found at the LHC (say, as anomalous higgs or W couplings), it would be strongly suggestive that the scale of FP is large, $\Lambda_{FP} > 1000$ TeV. Although this would be bad news for this workshop, it would be very interesting as it would suggest that the second possibility above is the correct one. The LHC would then explore the physics of EW symmetry breaking (higgs properties, perhaps techniparticles) and we would have to be creative to figure out how to explore the much higher scale of flavor physics.

Alternatively, if deviations from SM FCNCs are found and are consistent with MFV (or its extensions) with $\Lambda \sim 10$ TeV then for weakly coupled NP the new particles have masses of the order of a few TeV. This could be just beyond the reach of the LHC. I can't help but pointing out that this would have been well within the reach of the SSC! In any case, FPCP would afford the best look at physics beyond the SM.

MFV has many surprising implications. But none is more striking than the following. If leptons and quarks unify, and if the solution to the hierarchy problem introduces flavor physics at the TeV scale then[46] lepton flavor violation should be observed in $\mu \to e$ processes at MEG and PRISM. Exciting flavor physics ahead, indeed!

Acknowledgments

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