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OPENING TALK FOR HEAVY QUARKS AND LEPTONS 2004

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Abstract

Before preparing this talk I asked our host Angel Lopez what he wanted from an opening talk—his response was that I should set the context for what follows, to get the audience to think about the future of this subfield of physics, and give some of my own opinions on this area of physics. So that is what this talk does. It highlights a biased selection of topics; there is much more in the week of lectures than I can cover in this introductory talk.

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1 What are the deep questions in this field?

A few questions are mentioned often as the deep puzzles of flavor physics, questions such as

- Why are there multiple generations?
- Do the patterns of mass and mixing tell us anything?
- Can we understand the CP asymmetry of the Universe?

Let us begin by talking about these for a while.

My own reaction to the first question is to remark that in our science we never actually answer the question "Why?" in the conventional sense. In everyday situations any answer to that question is a description of a mechanism that occurs at some smaller scale and explains the behavior seen at the scale where the question was asked. Most of us think it is likely that quarks and leptons have no smaller scale structure, because attempts to answer the above questions via substructure for quarks and leptons have failed miserably. Once we are dealing with elementary particles there can be no mechanism at a smaller scale to provide reasons for an observed behavior or pattern. Thus all we can do is find the underlying mathematical theory that describes what we observe and can predict future results. We convert "why?" into questions like the following:

- What underlying symmetry or conservation law that forbids this process?
- What mathematical structures can be predictive about these features of the physics?

The Standard Model describes the physics of flavor, though it must be extended to encompass neutrino masses. The deep questions about flavor are not addressed by its mathematical structures. It allows, but does not require, multiple generations. The Yukawa couplings of the fermions to the Higgs field give all the flavor structure we observe. We have a set of arbitrary parameter choices, not an explanation in even the limited sense discussed above.

One might be tempted to argue that the observed CP violation in the quark sector of the Standard Model requires three quark generations[1]. That is not strictly true, one could equally well have violation with two generations and two complex Higgs-type multiplets[2]. We do not know yet whether nature uses both of these possibilities for CP violation, or only one of them. The success of the CKM picture shows that the weak-coupling phases are non-trivial and dominate the CP violation so far observed. Even if this is the dominant source of CP violation, we cannot call it an "explanation" for the existence of three generations.

Neutrinos have mass, even though they are not "heavy" in the traditional sense of this conference series. Thus they are an important part of the physics of flavor and should be a major part of this meeting's agenda, as indeed they are. (Perhaps the series title should change to "the Physics of Flavor".) Neutrino masses can be accommodated by extending the Standard Model a little, at the price of a larger set of arbitrary Yukawa coupling parameters. In addition we need an arbitrary large Majorana-type mass term to generate the small neutrino masses via a see-saw mechanism.

Even when we extend the Standard Model to a grand unified theory, or add supersymmetry we get no real answer to our questions about flavor structure. Many such extensions do have the benefit of making the additional neutrino states needed for a massive neutrino theory unavoidable, rather than an arbitrary, and somewhat uncomfortable, addition to the theory. We also gain relationships between quark and lepton parameters from the multiplet structure of a Grand Unified theory. However, the predictions with a single multiplet type do not fit the observed mass and mixing patterns, so different in the quark sector and the neutrino sector. Grand unified theories with no B-L violating terms predict similar patterns in the two sectors. I think it is a fair statement of history to say that it was only after the data pointed the way that the focus turned to theories that accommodate two very different patterns. So these patterns were not a prediction, but they can be fit by some choice of representation content and possibly some added U(1) symmetry that distinguishes the generations[3].

Some attempts to explain mass and mixing patterns use an approach known as "textures" where a particular pattern of zeros in the coupling matrix is assumed. If this approach can give an acceptable set of physical parameters, one then needs some deeper reason for the texture, coming from a symmetry or an underlying theory. An added U(1) flavor-distinguishing symmetry such as mentioned above can perhaps provide this. Then the apparently symmetry-breaking mass terms can arise in an effective field theory as higher-dimensional products of fields, with some powers of a gauge-group singlet field that carries one unit of the flavor charge. Such terms are assumed to be suppressed by denominator powers of a large mass.

One of the initial great hopes of string theory was that, in addition to solving the problem of formulating a finite theory of quantum gravity, it would be predictive about the number of generations and the parameters of the flavor sector. This does not seem to be the case. One can find ways to wrap branes on the topological cycles of the extra six dimensional (Calabi-Yau) manifold so that the resulting theory has three chiral generations[4]. Other approaches use different distributions of fermion states in the additional (extended) dimensions to obtain a variety of coupling strengths to a Higgs field that exists on the 3+1 dimensional brane[5]. In these approaches one relates the parameters of the field theory to the way the various flavors of quarks populate the additional dimensions, or to the overlaps of the various branes. Any theory that gives the Standard Model as its low energy realization is one option among many similar possibilities. We choose the parameters of the string theory to get the right parameters for the field theory. This would not "explain" the generation structure or the pattern of masses and mixings. Perhaps my second question gets an answer here, in a strange reversed fashion—what the patterns of masses and mixing may tell us is how we must choose the extra six-dimensional manifold and what branes we need to wrap it up with to give us our observed world of particles.

As for the matter-antimatter asymmetry of the Universe,[6] the Standard Model alone seems to be inadequate to answer this question. However there are many possible extensions of it which give the observed asymmetry starting from CP-violating effects in either from the lepton sector (leptogenesis)[7] or the quark sector (baryogenesis)[8]. No one scenario is, as yet, compelling. Perhaps more data will rule out one or the other possibility; as long as both remain viable it is difficult to choose between them.

The third possible answer to the question of mater-antimatter asymmetry of the Universe is that it arises as an initial condition on the Universe. In this regard, Pauli, writing to Heisenberg in 1933 (after the discovery of positrons), said "I do not believe in the hole theory, since I would like to have the asymmetry between positive and negative electricity in the laws of nature (**it does not satisfy me to shift the empirically established asymmetry to one of the initial state**)"[9]. I have highlighted here Pauli's parenthetical remark, which I find remarkable. As far as I know, until the experimental discovery of CP violation in 1964, Pauli was the only person to object to the fact that the equations of nature appeared to be symmetric between matter and antimatter, while the Universe does not, and to reject the idea that the observed imbalance arises from an initial condition.

I share Pauli's prejudice against a finely-tuned initial condition. If you give me one, why not many? Why not a young universe with initial conditions tuned to create all the data that we interpret as evidence of its evolution and its age? I think we all find that idea absurd. In addition to this philosophical objection, there is a physical reason to doubt this answer. Initial conditions cannot be maintained without a conservation law to protect them. Thermal equilibrium between matter and antimatter would give equal populations, because of their CPT-required equal masses. If no conservation laws protect an imbalance, it would be wiped out by the progression to thermal equilibrium. We do not know that such a conservation law applies in the high-energy environment of the early Universe.

In the Standard Model at high temperature there are processes that violate both lepton number and baryon number, although they preserve B-L. Many extensions of the theory to a grand unified theory do not conserve that quantity; indeed to get the different lepton and quark mass patterns it seems one needs to distinguish quarks from leptons in ways that tend to break this symmetry. It thus seems to me unlikely that the answer to the CP asymmetry of the Universe lies in a conserved initial condition of matter-antimatter imbalance.

2 Turning to the detailed questions

It seems we have no good answers to any of my “big” questions, nor much hope of answering any of them soon. However the current Standard Model is almost surely incomplete, even when we extend it to include neutrino masses. It gives us no candidate particles to be the dark matter that we know pervades the Universe; CP conservation of the strong interactions appears to be an accident (or a fine-tuning); and the theory as it stands does not give a good scenario for the generation of the matter-antimatter asymmetry of the Universe. Beyond these obvious problems there are the problems of unification with gravity and the existence of either dark energy or a cosmological constant. These are total mysteries, problems that are not even addressable, in the Standard Model.

One might add the hierarchy problem, namely the fine-tuning required to have the scale of physics where electroweak symmetry breaking occurs so small compared to the scale of grand unified symmetry breaking. Solutions to this issue via supersymmetry suggest new particles and also new interactions of the Standard Model particles. At least some evidence of these should appear around the TeV scale. Very possibly there is more than one “new physics” scale. No one new mechanism fixes all the problems listed above.

If there is physics beyond the Standard Model, perhaps we cannot answer the big questions because we do not know enough as yet to be asking them. Einstein failed in his quest for a Unified theory of matter and gravity. At least in part, his failure was surely because he did not know enough about the fundamental structure of matter. He was trying to unify gravity with the wrong ideas about matter. He may have been asking the right question, but so far ahead of its time that it was the wrong question. Perhaps we too are making this mistake when we ask the above “deep” questions. Perhaps when we know more about the physics beyond the Standard Model we will see why these are simply the wrong questions.

The path to knowledge is thus the usual path of science, via experiment. We need to test the predictions of our current theory in further detail, to hunt for clues about physics beyond the Standard Model. One way to do this is to search directly for new particles with new higher energy machines. A second way, the way of flavor physics, is to search for those places where new physics effects cause inconsistencies with precision predictions of the Standard Model.

Weak interactions can yield precision physics. Perturbative calculations of weak decays in the Standard Model quark sector are governed by the the masses of the W and Z mesons, the electromagnetic coupling constant, the Weinberg angle, and the four parameters of the flavor sector, those that determine the CKM matrix of weak decays[10], and the quark masses. The first four of these are by now well measured. We can obtain multiple independent measurements of the four CKM quantities (one of which is CP violating) and the heavy quark masses, by exploring many different weak decay processes. New physics effects may impact these measurements differently and thereby cause us to get inconsistent results for the Standard Model parameters.

New physics can enter these decays through new heavy particles in intermediate states. Tree diagrams with such particles are typically very suppressed by the large mass of the new intermediate particles. The chief impact of such particles thus comes from loop diagrams; with high momentum in the loop the large mass is less of a suppressing factor. Even so loop diagrams do not give large effects. Thus the places where we are most likely to be sensitive to these effects are those places where the Standard Model predicts a null result, or where the Standards Model process is itself rare, either because it is a loop process or because it is suppressed by Standard Model approximate symmetries.

The challenge in testing the Standard Model is not just for the experiments to obtain precision data. In most cases there is also a theoretical challenge to obtain precision predictions. The relationships between measurements and Standard Model parameters are seldom free of corrections to the quark-level weak decay because what we observe are not quarks but hadrons. Hence strong interaction physics plays a role. This complicates the situation. The challenge to theorists is to determine the impact of strong interaction effects and the residual uncertainties in the extraction of weak interaction parameters that arise because of uncertainties in these effects. Before turning to my own special interest of B physics, I want to make a few comments on how these issues play out in some of the other areas of physics that will be discussed in this meeting.

3 Rare Processes

One way that new physics could be obvious even in the face of order 1 uncertainties from hadronic physics, is if a decay that is very rare in the Standard Model is found at a level orders of magnitude above its prediction. Then we do not need a precision calculation to see that new physics is playing a role. This was the hope in, for example, the search for rare K decays, or for $D^0 - \bar{D}^0$ mixing. Once these searches are close to the Standard Model level then the question of Standard Model precision again becomes a challenge for the search for new physics. Some particular channels such as $K^0 \nu \bar{\nu}$ are cleanly predicted, but very difficult to measure. Other channels have experimental limits still well above Standard Model estimates and in these cases a detection that would signal new physics is still a possibility.

Sometimes early optimism about a test for new physics is tempered by more careful examination of the uncertainties in the Standard Model prediction. In the case of $D^0 - \bar{D}^0$ mixing there is at present a very large theory uncertainty in the Standard Model prediction. In the Standard Model, in the SU(3) limit, the effect is expected to be tiny, partly because of an SU(3) cancellation (or GIM suppression) of the leading graphs. However the actual s and d quark masses are quite different. Thus SU(3) breaking terms can significantly enhance the effect. It has been argued that significant differences in the phase space for multiparticle states which differ only in K and π content can give a substantial the imaginary part of the D mixing amplitude (and by analyticity, this also enhances the real part)[11, 12, 13]. This gives an uncertainty in the Standard Model prediction comparable to the magnitude of the current limits on the effect, so it ceases to be a good place to search for new physics. One possible exception is if the real part is found to be large compared to the imaginary part. Thus the challenge to experiment is not just to measure this effect but to untangle the real and imaginary parts.

In the case of neutrinos the challenges are still chiefly on the experimental side, although there too theoretical uncertainties can plague certain measurements. Since the next talk will cover this area I will not dwell on it further[14]. Neutrino masses also induce tiny Standard Model flavor violations in charged lepton decays. Searches for these rare processes are another way to search for new physics, which could possibly amplify these effects to an observable level.

4 Heavy Quark Spectroscopy

In the past year or so considerable excitement has been generated by observations of some states that, while not entirely unexpected, were not a good match to predictions. Two classes of states have emerged, new charm-strange mesons[15] and the so-called "pentaquarks"[16]. The first are probably more solid experimentally; their interest stems from the fact that the potential models for heavy-light bound states did not predict the masses and widths that are found[17]. Since the charm quark is not so very heavy and the strange quark is not so very light, perhaps this discrepancy should not be so surprising. Furthermore, any potential model is at best an approximation to the full QCD theory. We learn from these states something about what was missing in those approximations.

The case of pentaquarks is even muddier, here there are apparently discrepant experiments as well as a wealth of ideas as to how to describe the inner working of the claimed states. Given the current mixed-bag of the data, we can only wait and see what survives with higher statistics. We will hear some reports on the current status at this meeting[16]. From the theory side, my own attitude to these things is that none of them can tell us anything about physics beyond the Standard Model. While weak decays have uncertainties due to strong interaction corrections, spectroscopy is strong interactions from the start. We calculate none of it from first principles. Hence when results and calculations do not match we do not have to suspect our underlying QCD theory, we only have to modify our approximations to it. We can learn how to model the physics better, but I think it is very unlikely that the study of these states can reveal any fundamental flaws in the underlying theory.

One thing further that puzzles me is the very classical "either it is this or it is that" discussion which often occurs here. These states are quantum states, there is no reason why a single static substructure configuration dominates. Configurations of the constituents for a pentaquark state, such as two di-quarks and an antiquark, rather than a state that is effectively (spatially) a baryon plus a meson in a bound configuration, are suggested. The true states are likely to be quantum superpositions of both these "pictures" and more. Perhaps the various configurations can give us some insight as to why the state is narrow (if indeed it is), but, in all probability, no one of them a full description of the interacting quantum system of four quarks plus one antiquark of a distinct flavor[18].

5 B Physics—Generalities

In B decays too, the search for new physics is most likely to succeed in cases where the Standard Model contribution is suppressed or null. Alternatively we look for multiple measurements of the same set of CKM parameters to see if new physics effects give inconsistent values from the Standard Model interpretation. There are now many papers in the literature about which modes are of interest and why. The collection of analyzed data is now also growing at a formidable rate.

To test the Standard Model in B physics one must first determine the magnitudes of the CKM matrix elements V_{cb}, V_{ub} and V_{td} which enter the predictions (along with the better known V_{ud}, V_{cd} and V_{tb}) as the scales for sides of the unitarity triangle that follows from the relationship

$$\Sigma_j V_{jb} V^*_{jd} = 0 \ . \tag{1}$$

This relationship is one of several given by the requirement that the CKM matrix is unitary. It is perhaps the most interesting one because all three terms in the sum are of comparable magnitude, so phase differences (weak phases) between the sides of the triangle can be large, leading to large CP violating effects.

I will not dwell here on the challenges of measuring the sides, later talks in this conference will discuss that in detail. We now have numbers for all three sides, and uncertainties in these numbers are gradually shrinking. In addition the magnitude of the CP violation seen via the decay $K_L \to \pi\pi$ gives a constraint on a combination of parameters. In all cases, except for the ratio of B_s mixing to B_d mixing as a measure of V_{td}, the uncertainties are now dominated by theory uncertainties. We will hear about recent work, both theory and experiment, later in the week[19].

I now turn to measurement of the angles of the Unitarity triangle via CP violation studies. The basics of the subject of B decays and the study of CP violation is well described in some excellent text books[20]. Here I will give only a lightening review to define a bit of the jargon of this field. B decays to two-body or quasi-two-body final states where these states are CP eigenstates (or can be separated into CP odd and CP even fractions by angular analysis of the decay) are of particular interest[21]. The first situation occurs when the final four valence quarks are CP self conjugate and at least one of the final particles has zero spin. The second occurs when the quarks are self-conjugate but both particles have non-zero spin. In that case the two particles can have either odd or even relative angular momentum, and the angular analysis sorts these two cases.

For general multiparticle decays, even if the quark content is CP-self-conjugate, the final states are generally an unknown admixture of CP-odd and CP-even states. Since the sign of the most readily interpreted asymmetry effect depends on this CP quantum number, information about underlying CKM parameters comes best from two body channels.

In the electron-positron B factories the B^0 and $\bar{B}^0$ are produced in a coherent state that contains one of each particle until such time as one of them decays. Then the other evolves, because it is a superposition of mass eigenstates, until it too decays. We search for events where one B decays to the final state under study and the other to a state that tells us its flavor. This latter is called the tag decay. Any asymmetry between the rate for a B^0 tag and that for a $\bar{B}^0$ tag is a CP violation. In the B factories, because of the coherent initial state, the most interesting CP violation effects vanish when integrated over the time difference between the decay of interest and the tag decay, so one must study the differences as a function of time.

In general there are three types of CP violation. The first, which can occur for any decay, is a difference in rate between any process and its CP conjugate process, $|\bar{A}/A| \neq 1$. This is known as direct CP violation, though a better name is CP violation in the decay amplitudes. (It has been observed for the kaon system in the result $\epsilon' \neq 0$.)

The two other types of CP violation occur only in the case of decays of the neutral but flavored pairs of mesons $P = K, D, B$ to final states that are common to both members of the pair, and can be resolved into CP eigenstates. We denote the mass eigenstates of these mesons by $P_{H,L} = pP^0 \pm q\bar{P}^0$, where the subscripts H and L refer to the heavier and lighter mass states. The second type of CP violation is that which shows that these mass eigenstates cannot be CP eigenstates, namely $|q/p| \neq 1$. This is called CP violation in the mixing. It is seen in the decay of the long-lived neutral kaon states (which would be the CP-odd state if CP were a good quantum number) to the CP-even final states of two pions.

The third type of CP violation can occur even if both of the first two do not. The CP asymmetries in decays to CP-eigenstate final states f are all governed by the ratios

$$\lambda_f = \frac{qA(\bar{B} \to f)}{pA(B \to f)} \ . \tag{2}$$

The amplitude in the numerator is $\eta_f = \pm 1$ times the CP conjugate of the amplitude in the denominator, where η_f is the CP quantum number of the state f. The third type of CP violation, which arises from interference between decays with with and without mixing transitions, is signaled by $\mathrm{Im}\lambda_f \neq 0$, namely by a difference between the weak phase of the decay amplitude ratio and the weak phase of the mixing parameter q/p. When both ratios are of unit magnitude the quantity $\mathrm{Im}\lambda_f$ can be directly related to the phases of a product of CKM matrix elements, that is to weak-coupling phase differences.

There is now a copious literature suggesting many channels for analysis. First among these is the "golden mode" $B_d \to J/\psi K_S$. This and the related final states with other $c\bar{c}$ states (or a K_L) have both $|\bar{A}/A| = 1$ and $|q/p| = 1$ to high accuracy. The SLAC and the KEK B factories now have collected large samples and analyzed these modes in detail.

The CP-violating asymmetry that is measured is given by

$$\begin{aligned} a_f &= \frac{\Gamma(B^0(t) \to f)) - \Gamma(\bar{B}^0(t) \to f)}{\Gamma(B^0(t) \to f)) + \Gamma(\bar{B}^0(t) \to f)} \\ &= \cos(\Delta M t)\frac{1-|\lambda_f|^2}{1+|\lambda_f^2|} + \sin(\Delta M t)\frac{2Im\lambda_f}{1+|\lambda_f|^2} \\ \text{for } |\lambda_f| = 1 &\to \sin(\Delta M t) Im\lambda_f \end{aligned} \tag{3}$$

Here $B^0(t)$ is time-dependent state that was (or will be) pure B^0 at time $t = 0$. The time dependence is obvious if one recognizes that it is a superposition of the two mass eigenstates, B_{heavy} and B_{light}. The t in Eq.(3) is the time between the decay of one B to a state that labels its flavor and the decay of the other to the state f under study. (This can be either positive or negative as either decay may be the first that occurs.) The term with the cosine in time contributes if either of the first two types of CP violation are present, while the sine term contributes only if the third type occurs, whether or not the first two types are present. For the B_d system, $|q/p| = 1$ to a good approximation.(When we study B_s decays in hadronic B production facilities we will not have this simple situation.)

One can write a generic B decay amplitude as a sum of two terms with different CKM structure. For the quark level decay, $b \to q_1\bar{q}_2q_3$ two classes of diagrams can contribute, weak-interaction tree diagrams and weak-loop diagrams, (commonly called penguin diagrams). The loop diagrams give a contribution of the form

$$\delta_{12}\Sigma_j V_{jb}V^*_{jq_3}F(m_j) = 0 \tag{4}$$

where the sum over j runs over up-type quarks. The delta function denotes the fact that such diagrams contribute only when a matching $q\bar{q}$ pair is produced. The function $F(m_j)$ arises from the loop integral and depends on the mass of the up-type quark in the loop. One of the three products of CKM coefficients that appears here is the same as that for any tree-type diagram that contributes to the same final state. (Indeed there is no meaningful distinction between a tree diagram plus some final state rescattering and the long range part of a penguin loop amplitude). One can use the unitarity relationship of Eq. (1) to remove any one of the three CKM coefficients by rewriting it as the negative of the remaining two (thereby obtaining the two terms mentioned at the beginning of this paragraph).

Amplitudes with significant contributions for two different weak phases can lead to the first type of CP violation (if they also have two different strong phases). To extract Standard Model parameters from such channels we would need to calculate the relative size and relative strong phase of the two terms. This brings in strong interaction physics, and in general leads to large uncertainties.

6 B Physics –the "simple" modes

Cases where a single product of CKM matrix elements dominates are thus of particular interest. Then $|\frac{\bar{A}_f}{A_f}| = 1$. Remember that for B_d decays the approximation $|q/p| = 1$ is also very accurate, so in these cases $|\lambda_f| = 1$ to a good approximation. Then the quantity Imλ_f directly measures a CKM phase difference.

A single term dominates the decay amplitude for the "golden mode" cases of ψK_S and ψK_L channels, where ψ denotes any $c\bar{c}$ resonance. More generally, we get a single dominant term proportional to $V_{cb}V_{cs}^*$ for any $b \to c\bar{c}s$ decay. There are penguin graph terms with this coefficient as well as the dominant tree graph. One can use unitarity to remove the term proportional to $V_{tb}V_{ts}^*$. Then the remaining penguin term is proportional to $V_{ub}V_{us}^*$, which is suppressed by two additional powers of $\lambda = V_{us}$. The dominant term is also enhanced because it has the larger tree contribution as well as a penguin part, thus corrections to $|\bar{A}_f/A_f| = 1$ are expected to be at most a few percent. †

The measured results from combining all such channels are[23]

$$\begin{aligned} Im\lambda_f &= \sin(2\beta) = 0.741 \pm 0.067 \pm 0.033 \quad \text{BaBar} \\ Im\lambda_f &= \sin(2\beta) = 0.733 \pm 0.057 \pm 0.028 \quad \text{Belle} \\ Im\lambda_f &= \sin(2\beta) = 0.736 \pm 0.048 \quad \text{World average .} \end{aligned} \tag{5}$$

These results give clear evidence for the third type of CP violation, furthermore they give a relative phase, here called β, of $V_{cb}^*V_{cd}$ and $V_{tb}^*V_{td}$ that agrees well with that expected from the best-fit values of the lengths of the sides of the Unitarity triangle, and the constraint from $K_L \to \pi\pi$ decays, as can be seen in Fig. 1. This is a spectacular success for the CKM picture of CP violation.

For channels dominated by $b \to s\bar{s}s$ the same two CKM coefficients as in the $c\bar{c}s$ case occur, although here there is no tree graph contribution to further enhance the dominant term. Thus, in the Standard Model, up to small and relatively well-estimated corrections, these channels should have the same CP-violating asymmetry as the golden mode channels. The experimental results here are, at present, a puzzle. The numbers are

†A paper I wrote with Grossman, Ligeti and Nir[22] defined rigorous bounds on this deviation from data on SU(3)-related channels. These bounds are much larger that the few percent quoted above. This should not be interpreted as an indication that the deviation is large, it merely shows that, at present and in this case, the data-driven bound is not a strong one.

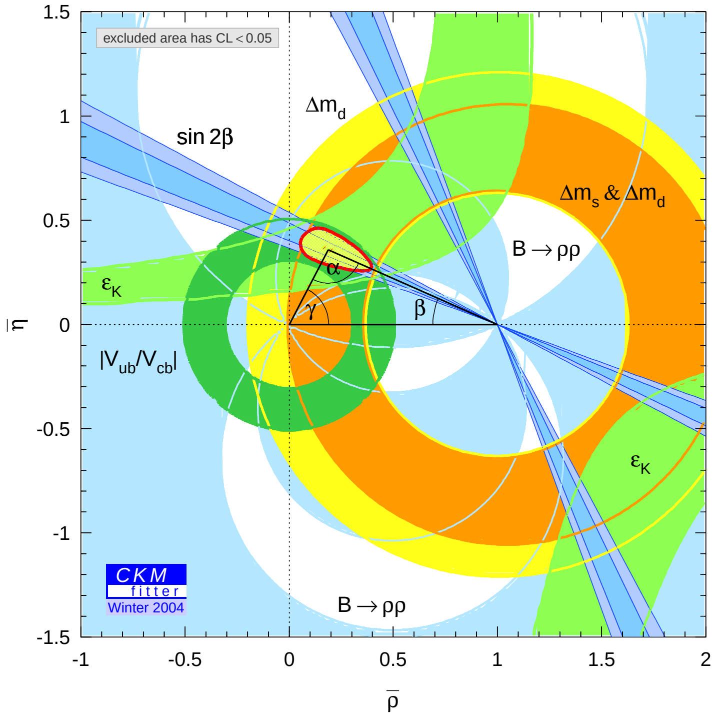

Figure 1: *Concordance of all measurements of Standard Model flavor parameters as shown by the unitarity triangle for B decays. This figure is taken from the CKM Fitter website which also provides the details of the input data used[24].*

$$
\begin{aligned}
\mathrm{Im}\lambda_{\psi K_S} &= 0.736 \pm 0.049 \\
\mathrm{Im}\lambda_{\phi K_S} &= -0.96 \pm 0.50^{+0.09}_{-0.11} \quad \text{Belle} \\
\mathrm{Im}\lambda_{\phi K_S} &= 0.47 \pm 0.34^{+0.08}_{-.06} \quad \text{BaBar} .
\end{aligned} \tag{6}
$$

Clearly, unless someone is making a mistake in their analysis, this situation can be expected to be resolved with more data. We will just have to wait a few years to see if the tantalizing hint that there may be a new physics contribution here survives.

Any channel with three distinct quark types produced in the b-decay has only a tree-diagram contribution. For example $b \to c\bar{u}s$ (or $c\bar{u}d$) give modes such as D^0K_S or $D^0\pi^0$, where the D^0 decays to a CP eigenstate . These modes give ways to extract the CKM parameter γ (modulo the complication of doubly CKM suppressed corrections from $b \to u\bar{c}s$ (or $c\bar{u}d$))[25]. We do not yet have enough data for these rare modes to make the asymmetry analysis accurate, so I will not talk further about them. Eventually they will be very interesting to study.

For $b \to u\bar{u}s$ (and $b \to d\bar{d}s$ channels, which cannot be experimentally separated in B_d decays), the uncertainty in the Standard Model correction is larger, because the CKM-suppressed term is enhanced by having the larger tree graph contribution, so these $K\pi$ channels do not provide a sensitive test for new physics.

7 B Physics—modes with two competing terms in the amplitude

In the case of $b \to q\bar{q}d$ decays, such as $B \to \pi^+\pi^-$, there are always two comparable magnitude CKM terms in the amplitude, however one of them is somewhat enhanced by having the larger tree graph contribution in addition to the penguin terms. Early papers used this argument to suggest that these channels too could give clean extraction of CKM phases, but experience has taught us that this argument is not reliable; the penguin contribution is larger than early estimates suggested. Hence one needs to use additional theoretical input to relate the measured CP asymmetries to CKM phases. In the rest of this talk I discuss some ways in which this can be done.

In these cases the quantity $\mathrm{Im}\lambda_f$ depends on the relative magnitudes and the strong phases of the two terms in the amplitude. These are hadronic physics effects. Uncertainties in the interpretation of the measurement arise because we cannot readily calculate them. The theory effort is thus to find ways to reduce our ignorance to a few quantities that enter into more than one measurement, so that we can use multiple measurements to determine both the uninteresting (for our purposes) hadronic physics quantities and the weak interaction parameters that we are trying to measure.

There are two general directions to go. The first is to use strong interaction symmetries, isospin or SU(3), to determine the necessary quantities using other measurable rates. In a few cases this is all one needs. Theory uncertainties then arise from the impact of symmetry breaking effects, since these are not exact symmetries. However these uncertainties are typically smaller, and better understood, than the uncertainties that would arise from using models of hadrons to calculate the hadronic physics effects.

For example let us look at the decays $B \to \pi\pi$. If we can measure all such decays, including those for charged B's, we can use isospin symmetry to remove the unwanted complications and get a clean determination of the angle $\alpha = \pi - \beta - \gamma$ at the apex of the unitarity triangle[26]. We need the rates for $B^0 \to \pi^0\pi^0$ and $\bar{B}^0 \to \pi^0\pi^0$ separately; as yet only their average is measured. It will take over ten times the present data to get sufficiently accurate numbers to give a well-constrained answer by this method.

The same method can be applied, together with angular analysis, for $B \to \rho\rho$. Here the two-neutrals channel is smaller (but easier to detect); thus a method for using the combined B^0 and $\bar{B}^0$ decays to bound the correction to the value of α[27] gives the best determination of α at present. This analysis too will be presented later in this conference[28].

The second method uses all the tools. In addition to symmetries the main theory tools are the Operator Product Expansion which allows us to expand the effects of hard gluons in powers of $\alpha_s(m_b)$, plus the heavy quark expansion, which organizes the calculation in powers of Λ_{QCD}/M_b. A more recent addition to the toolkit is a technique for grouping the effects of soft gluons and those collinear to a hard quark

(Soft Collinear Effective Theory). This gives an expansion in $\sqrt{(\Lambda_{QCD}/E)}$ where E is the energy of some final state particle, and thus is typically something of order $M_B/2$. The coefficients of the expansion contain a set of hadronic quantities, both operator matrix elements and quark distribution functions for mesons. These functions are particle dependent, but process independent. The symmetries further reduce the number of unknown quantities. They can relate one matrix element or quark distribution function to others, up to some uncertainty due to symmetry breaking effects.

To make all these words a bit more concrete let me give you a couple of examples of the application of these ideas. To extract the magnitude of V_{ub} from the rate of semileptonic B decays to any final state with no charm particles we need to know the spectrum of such decays. Any method to remove backgrounds from charm decays of b-quark will also remove some fraction of the desired decays. We need the spectrum to determine what that fraction is. The theory relates the spectrum in this decay to that seen in $B \to X_s\gamma$ where X_s is any state with non-zero strangeness. So we can use the measurement in the one case to reduce the uncertainty coming from the cut on the spectrum in the other. This methodology, together with improvement in statistics of the data, have considerably reduced the uncertainty on V_{ub}. You will hear more about this later in this conference[19].

The same matrix elements that determine this spectrum, also enter in decays of a B meson to two light pseudoscalars. Furthermore the matrix elements and distribution functions that enter for decay to two pions and that to a kaon plus a pion have SU(3) symmetry relationships. The calculation of the impact of penguins in the two pion decay can be accomplished using all these tools. Note that the CKM factors do not respect SU(3) symmetry, that applies only to the hadronic part of the amplitude. The upshot is that the penguin contribution that dominates the $B \to K\pi$ decay can be used to determine the similar penguin contribution in $B \to \pi\pi$, up to SU(3) corrections. The residual uncertainties are still significant, but they are smaller and better controlled than was the case before all the tools were brought to bear[29].

Lattice QCD calculations are another important tool, used to determine one-particle to one particle (or one to zero) matrix elements. Here too there has been a steady advance in precision, with the biggest recent steps being the move to "unquenched" calculations (including light quark loops), and better extrapolations to the physical light-quark mass values using chiral calculations to guide the functional form of the extrapolation[30]. An example where this work plays a role is the extraction of V_{td} from the measurement of the B_d mixing parameters.

All this theory discussion makes it clear that we need more than improved statistics to mine the physics out of the data. We also need ongoing reductions of theoretical uncertainties. Theorists tend to tackle these hard problems when theory uncertainties dominate over those from experiment in extracting a parameter that they care about. The challenge is to keep everyone honest about these uncertainties, which are often very difficult to quantify. Experience shows that theorists often underestimate them.

The temptation for an experimental analysis is to use the particular theoretical input that gives the smallest quoted uncertainty. This may be overly optimistic if other similar theoretical approaches give different values for the result, or for its uncertainty.

8 Concluding remarks

I began this talk with some generalities, and I will end there too. We know that Standard Model extensions are needed before we can begin to address any of the deeper questions that remain. Heavy quark physics provides probes that are sensitive to many of these extensions, and can possibly distinguish between classes of ideas. The neutrino sector likewise may exhibit CP violation and lepton flavor violation, and provides another possible answer the question about the matter antimatter asymmetry of the Universe. Here there are more parameters that are as yet undetermined, some of them perhaps reachable in the next round of experiments some much harder to get at (perhaps even beyond our wildest accelerator dreams). Of course direct searches for new particles target some of same extensions of the theory. We need more data on all three fronts to make further progress. I am sure that this conference will present some interesting steps forward in this ongoing quest.

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