Footprints of New Physics in the B System

Yuval Grossman

Department of Physics, Technion–Israel Institute of Technology, Technion City, 32000 Haifa, Israel ¹ and Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

and

Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064

Abstract. In the first part of the talk the flavor physics input to models beyond the Standard Model is described. In the second part of the talk we discuss several observables that are sensitive to new physics. We explain what type of new physics can produce deviations from the Standard Model predictions in each of these observables.

INTRODUCTION

The success of the Standard Model (SM) can be seen as a proof that it is an effective low energy description of Nature. Yet, there are many reasons to believe that the SM has to be extended. A partial list includes the hierarchy problem, the strong CP problem, baryogenesis, gauge coupling unification, the flavor puzzle, neutrino masses, and gravity. We are therefore interested in probing the more fundamental theory. One way to go is to search for new particles that can be produced in yet unreached energies. Another way to look for new physics is to search for indirect effects of heavy unknown particles. In this talk we explain how flavor physics is used to probe such indirect signals of physics beyond the SM.

NEW PHYSICS AND FLAVOR

In general, flavor bounds provide strong constraints on new physics models. This fact is called "the new physics flavor problem". The problem is actually the mismatch between the new physics scale that is required in order to solve the hierarchy problem and the one that is needed in order to satisfy the experimental bounds from flavor physics [1]. Here we explain what is the new physics flavor problem and discuss ways to solve it.

In order to understand what is the new physics flavor problem let us first recall the hierarchy problem [2]. In order to prevent the Higgs mass from getting a large radiative correction, new physics must appear at a scale that is a loop factor above the weak scale

$$\Lambda \lesssim 4\pi m_W \sim 1 \text{ TeV.} \tag{1}$$

Here, and in what follows, Λ represents the new physics scale. Note that such TeV new physics can be directly probed in collider searches.

While the SM scalar sector is unnatural, its flavor sector is impressively successful.² This success is linked to the fact that the SM flavor structure is special. First, the charged current interactions are universal. (In the mass basis, this is manifest through the unitarity of the CKM matrix.) Second, Flavor-Changing-Neutral-Currents (FCNCs) are highly suppressed: they are absent at the tree level and at the one loop level they are further suppressed by the GIM mechanism. These special features are important in order to explain the observed pattern of weak decays. Thus, any extension of the SM must conserve these successful features.

Consider a generic new physics model, that is, a model where the only suppression of FCNCs processes is due to the large masses of the particles that mediate them. Naturally, these masses are of the order of the new physics scale, Λ . Flavor physics, in particular measurements of meson mixing and CP-violation, put severe constraints on Λ .

Footprints of New Physics in the B System

December 16, 2003

Work supported in part by the Department of Energy Contract DE-AC02-76SF00515 Presented at the 9th International Conference on B Physics at Hadron Machines (Beauty 2003), 10/14/2002 10/18/2002 Bittshungh, BA

10/14/2003 - 10/18/2003, Pittsburgh, PA

¹ Permanent address.

 $^{^2}$ The flavor structure of the SM is interesting since the quark masses and mixing angles exhibit hierarchy. These hierarchies are not explained within the SM, and this fact is usually called "the SM flavor puzzle". This puzzle is different from the new physics flavor problem that we are discussing here.

In order to find these bounds we take an effective field theory approach. At the weak scale we write all the non-renormalizable operators that are consistent with the gauge symmetry of the SM. In particular, flavorchanging four Fermi operators of the form (the Dirac structure is suppressed)

$$\frac{q_1 \bar{q} q_3 \bar{q}}{\Lambda^2},\tag{2}$$

are allowed. Here q_i can be any quark flavor as long as the electric charges of the four fields in Eq. (2) sum up to zero.³ The strongest bounds are obtained from meson mixing and CP-violation measurements:

• *K* physics: $K - \overline{K}$ mixing and CP-violation in *K* decays imply

$$\frac{s\overline{d}s\overline{d}}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4 \text{ TeV}.$$
 (3)

• *D* physics: $D - \overline{D}$ mixing implies

$$\frac{\overline{vucu}}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^3 \text{ TeV}.$$
 (4)

• *B* physics: $B - \overline{B}$ mixing and CP-violation in *B* decays imply

$$\frac{b\overline{d}b\overline{d}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^3 \text{ TeV.} \tag{5}$$

Note that the bound from kaon data is the strongest.

There is tension between the new physics scale that is required in order to solve the hierarchy problem, Eq. (1), and the one that is needed in order not to contradict the flavor bounds, Eqs. (3)–(5). The hierarchy problem can be solved with new physics at a scale $\Lambda \sim 1$ TeV. Flavor bounds, on the other hand, require $\Lambda > 10^4$ TeV. This tension implies that any TeV scale new physics cannot have a generic flavor structure. This is the new physics flavor problem.

Flavor physics has been mainly an input to model building, not an output. The flavor predictions of any new physics model are not a consequence of its generic structure but rather of the special structure that is imposed to satisfy the severe existing flavor bounds.

Any viable TeV new physics model has to solve the new physics flavor problem. We now describe several ways to do so that have been used in various models.

(*i*) Minimal Flavor Violation (MFV) models [3]. In such models the new physics is flavor blind. That is, the

Footprints of New Physics in the B System

only source of flavor violation are the Yukawa couplings. This is not to say that flavor violation arises only from *W* exchange diagrams via the CKM matrix elements. Other flavor contributions exist, but they are related to the Yukawa interactions. Examples of such models are gauge mediated Supersymmetry breaking models [4] and models with universal extra dimensions [5]. In general, MFV models predict small effects in flavor physics.

(*ii*) Models with flavor suppression mainly in the first two generations. The hierarchy problem is connected mainly to the third generation since its couplings to the Higgs field are the largest. Flavor bounds, however, are most severe in processes that involve only the first two generations. Therefore, one way to ameliorate the new physics flavor problem is to keep the effective scale of the new physics in the third generation low, while having the effective new physics of the first two generations at a higher scale. Examples of such models include Supersymmetric models with the first two generations of quarks heavy [6] and Randall-Sundrum models with bulk quarks [7]. In general, such models predict large effects in the *B* and B_s systems, and smaller effects in *K* and *D* mixings and decays.

(*iii*) Flavor suppression mainly in the up sector. Since the flavor bounds are stronger in the down sector, one way to go in order to avoid them is to have new flavor physics mainly in the up sector. Examples of such models are Supersymmetric models with alignment [8] and models with discrete symmetries [9]. In general such models predict large effects in charm physics and small effects in *B*, B_s and *K* mixings and decays.

(iv) Generic flavor suppression. In many models some mechanism that suppresses flavor violation for all the quarks is implemented. Examples of such models are Supersymmetric models with spontaneously broken flavor symmetry [10] and models of split fermions in flat extra dimension [11]. In general, such models can be tested with flavor physics.

PROBING NEW PHYSICS WITH FLAVOR

Any TeV new physics model has to deal with the flavor bounds. Depending on the mechanism that is used to deal with flavor, the prediction of where deviation from the SM can be expected varies. It is important, however, that in many cases large effects are expected. Thus, we hope that we will be able to find such signals.

Generally, it is easier to search for new physics effects where they are relatively large. Namely, in processes that are suppressed in the SM, in particular in Meson mixing, Loop mediated decays, and CKM suppressed amplitudes. It is indeed a major part in the B factories

³ We emphasize that there is no exact symmetry that can forbid such operators. This is in contrast to operators that violate baryon or lepton number that can be eliminated by imposing symmetries like $U(1)_{B-L}$ or R-parity.

program to study such processes. Below we give several examples for ways to search for new physics.

Before proceeding we emphasize the following point: At present there is no significant deviation from the SM predictions in the flavor sector. In the following we give examples of deviations from the SM predictions that are below the 3σ level. In particular, we choose the following possible tests of the SM: Global fit, $a_{CP}(B \rightarrow \psi K_S)$ vs $a_{CP}(B \rightarrow \phi K_S)$, $B \rightarrow K\pi$ decays, and Polarization in $B \rightarrow VV$ decays. There are many more possible tests. Our choice of examples here is partially biased toward cases where the present experimental ranges deviate by more than one standard deviation from the SM predictions. While, as emphasized above, one should not consider these as significant indications for new physics, it should be interesting to follow future improvements in these measurements. Furthermore, it is an instructive exercise to think what one would learn if the central value of these measurements turn out to be correct. As we will see, this would not only indicate new physics, but actually probe the nature of the new physics.

Global fit

One way to test the SM is to make many measurements that determine the sides and angles of the unitarity triangle, namely, to over-constrain it [12]. Another way to put it is that one tries to measure ρ and η in many possible ways. (λ , A, ρ and η are the Wolfenstein parameters.) We emphasize that this is not the only way to look for new physics. It is just one among many possible ways to look for new physics.

The global fit is done using measurements of (or bounds on) $|V_{cb}|$, $|V_{ub}/V_{cb}|$, ε_K , $B-\overline{B}$ mixing, B_s mixing, and $a_{CP}(B \rightarrow \psi K_S)$. The fit is very good, as can be seen in Fig. 1. Clearly, there is no indication for new physics from the global fit. There are many more measurements that at present have very little impact on the fit. In the future, such measurements can be included, and then discrepancies may show up.

CP-asymmetries in $b \rightarrow s \bar{q}q$ **modes**

The time dependent CP-asymmetry in *B* decays into a CP eigenstate, f_{CP} , is given by [13]

$$\begin{split} &a_{\rm CP}(B\to f_{CP})\equiv\\ &\frac{\Gamma(\overline{B}(t)\to f_{CP})-\Gamma(B(t)\to f_{CP})}{\Gamma(\overline{B}(t)\to f_{CP})+\Gamma(B(t)\to f_{CP})}=\\ &-\frac{(1-|\lambda|^2)\cos(\Delta m_B t)-2Im\lambda\sin(\Delta m_B t)}{1+|\lambda|^2}\equiv \end{split}$$

Footprints of New Physics in the B System



FIGURE 1. Global fit to the unitarity triangle [12]. The fit is based on the measurements of $|V_{cb}|$, $|V_{ub}/V_{cb}|$, ε_K , $B - \overline{B}$ mixing, and $a_{CP}(B \to \psi K_S)$ and the bound on B_s mixing.

$$S\sin(\Delta m_R t) - C\cos(\Delta m_R t). \tag{6}$$

Here $\Delta m_B \equiv m_H - m_L$ and the last line defines S and C. Furthermore,

$$\lambda \equiv \left(\frac{q}{p}\right) \left(\frac{\bar{A}}{A}\right),\tag{7}$$

where $\overline{A} \equiv A(\overline{B} \rightarrow f_{CP})$ and $A \equiv A(B \rightarrow f_{CP})$. The neutral *B* meson mass eigenstates are defined in terms of flavor eigenstates as

$$|B_{L,H}\rangle = p|B\rangle \pm q|\overline{B}\rangle. \tag{8}$$

In the $|\lambda| = 1$ limit, which is a very good approximation in many cases, Eq. (6) reduces to the simple form

$$a_{\rm CP}(B \to f_{CP}) = Im\lambda \,\sin(\Delta m_B t)$$
. (9)

In that case $Im\lambda$ is just the sine of the phase between the mixing amplitude and twice the decay amplitude.

In the SM the mixing amplitude is⁴

$$\arg(A_{mix}) = 2\beta. \tag{10}$$

The phase of the decay amplitude depends on the decay mode. $B \rightarrow \psi K_S$ is mediated by the tree level quark decay $b \rightarrow c \ cs$ which has a real amplitude, namely,

$$\arg(A_{b\to c\bar{c}c}) = 0, \tag{11}$$

⁴ Here, and in what follows, we use the standard parameterization of the CKM matrix. The results, of course, do not depend on the parameterization we choose.

and therefore $Im\lambda = \sin 2\beta$. The penguin $b \rightarrow s \bar{q}q$ (q = u, d, s) decay amplitude is also real to a good approximation, namely,

$$\arg(A_{b \to s \bar{a} a}) = 0. \tag{12}$$

We learn that also in that case $Im\lambda = \sin 2\beta$. In particular, the $B \to \phi K_S$, $B \to \eta' K_S$, $B \to \pi^0 K_S$, and $B \to K^+ K^- K_S$ are examples of decays that are dominated by the $b \to s \bar{q}q$ transition. They are of particular interest since their CP-asymmetries have been measured. We conclude that to first approximation the SM predicts

$$S_{\psi K_S} = -S_{K^+K^-K_S} = S_{\phi K_S} = S_{\eta'K_S} = S_{\pi^0 K_S}$$
(13)

Furthermore, for all these modes the SM predicts $|S| = \sin 2\beta$. Note that in order to violate the predictions of Eq. (13), new physics has to affect the decay amplitudes. New physics in the mixing amplitude shifts all the modes by the same amount, leaving Eq. (13) unaffected.

SU(3) analysis

In order to probe new physics we need to know the theoretical uncertainties in the predictions of (13). Theoretical estimates are that they are less than $\mathcal{O}(1\%)$ for $S_{\psi K_S}$, of $\mathcal{O}(5\%)$ for $S_{\phi K_S}$ and $S_{\eta' K_S}$, $\mathcal{O}(10\%)$ for $S_{\pi^0 K_S}$ and O(20%) for $S_{K^+K^-K_S}$ [17, 14, 18, 19]. Here we like to show one way to bound these theoretical uncertainties.

The SM amplitude for $b \rightarrow sq \bar{q}$ (q = u, d, s) penguin dominant decay modes can be written as follows:

$$A_f \equiv A(B^0 \to f) = V_{cb}^* V_{cs} \, a_f^c + V_{ub}^* V_{us} \, a_f^u \,. \tag{14}$$

The second term is CKM-suppressed compared to the first one since

$$\mathscr{I}m\left(\frac{V_{ub}^*V_{us}}{V_{cb}^*V_{cs}}\right) = \left|\frac{V_{ub}^*V_{us}}{V_{cb}^*V_{cs}}\right|\sin\gamma = \mathscr{O}(\lambda^2), \quad (15)$$

where $\lambda = 0.22$ is the Wolfenstein parameter. For final states with zero strangeness, f', we write the amplitudes as

$$A_{f'} \equiv A(B^0 \to f') = V_{cb}^* V_{cd} \ b_{f'}^c + V_{ub}^* V_{ud} \ b_{f'}^u \,. \tag{16}$$

Here neither term is CKM suppressed compared to the other. We use SU(3) flavor symmetry to relate the $a_f^{u,c}$ amplitudes to sums of $b_{c'}^{u,c}$.

It is convenient to define

$$\xi_{f} \equiv \frac{V_{ub}^{*} V_{us} \, a_{f}^{u}}{V_{cb}^{*} V_{cs} \, a_{f}^{c}},\tag{17}$$

such that we expect $|\xi_f| \ll 1$. Then we rewrite the amplitude of Eq. (14) as

$$A_{f} = V_{cb}^{*} V_{cs} a_{f}^{c} \left(1 + \xi_{f}\right).$$
(18)

Footprints of New Physics in the B System

Finite ξ_f result in deviations from the leading order result, which, to first order in $|\xi_f|$ read

$$-\eta_f S_f - \sin 2\beta = 2\cos 2\beta \sin \gamma \cos \delta_f |\xi_f|, \quad (19)$$
$$C_f = -2\sin \gamma \sin \delta_f |\xi_f|. \quad (20)$$

where η_f is the CP of the final state and $\delta_f = \arg(a_f^u/a_f^c)$.

We discuss here a way to estimate ξ_f using SU(3) (or equivalently U-spin) [15, 17, 18, 19]. The basic idea is to relate $b \rightarrow s$ to $b \rightarrow d$ penguin amplitudes. In the later the tree amplitude is enhanced and thus there is larger sensitivity to it. Then, using SU(3), the tree amplitude in the $b \rightarrow d$ decay is related to the one in $b \rightarrow s$ decay.

The crucial question, when thinking of the deviation of $-\eta_f S_f$ from $\sin 2\beta$, is the size of a_f^u/a_f^c . While a_f^c is dominated by the contribution of $b \to s \bar{q}q$ gluonic penguin diagrams, a_f^u gets contributions from both penguin diagrams and $b \to u \bar{u}s$ tree diagrams. For the penguin contributions, it is clear that $|a_f^u/a_f^c| \sim 1$. (The a_f^c term comes from the charm penguin minus the top penguin, while the up penguin minus the top penguin contributes to a_f^u .) Thus our main concern is the possibility that the tree contributions might yield $|a_f^u/a_f^c|$ significantly larger than one.

We first provide a simple explanation of the method. Let us assume that the decays to final strange states, f, are dominated by the a_f^c terms and that those to final states with zero strangeness, f', are dominated by the $b_{f'}^u$ terms. Thus we can estimate $|a_f^c|$ and $|b_{f'}^u|$ from the measured branching ratios (or the upper bounds on them). Then the SU(3) relations give upper bounds on certain sums of the $b_{f'}^c$ and a_f^u amplitudes from the extracted values of a_f^c and $b_{f'}^u$, respectively. This then gives a bound on $|a_f^u/a_f^c|$, and consequently on $|\xi_f|$.

Actually, the assumptions made in the previous paragraph can be avoided entirely [18, 19]. The SU(3) relations actually provide an upper bound on

$$\widehat{\xi}_{f} \equiv \left| \frac{V_{us}}{V_{ud}} \times \frac{V_{cb}^{*}V_{cd} a_{f}^{c} + V_{ub}^{*}V_{ud} a_{f}^{u}}{V_{cb}^{*}V_{cs} a_{f}^{c} + V_{ub}^{*}V_{us} a_{f}^{u}} \right| \\
= \left| \frac{\xi_{f} + (V_{us}V_{cd})/(V_{ud}V_{cs})}{1 + \xi_{f}} \right|.$$
(21)

If the bound on $\hat{\xi}_f$ is less than unity, then it gives a bound on $|\xi_f|$.

In general we can write

$$a_{f}^{q} = \sum_{f'} x_{f'} b_{f'}^{q}, \qquad (22)$$

where q = u, c and $x_{f'}$ are Clebsch-Gordon coefficients, which are calculated using group theory properties of



FIGURE 2. Points in the $S_{\pi K} - |C_{\pi K}|$ plane allowed by the SU(3) relations. The small plotted point denotes the purepenguin value $S_{\pi K} = \sin 2\beta$, $C_{\pi K} = 0$. The point with large error bars denotes the current experimental value. The dashed arc denotes the boundary of allowed values: $S_{\pi K}^2 + C_{\pi K}^2 \leq 1$.

SU(3). Then, using the relevant measured rates, we get

$$\widehat{\xi}_{f} \leq \lambda \sum_{f'} |x_{f'}| \sqrt{\frac{\mathscr{B}(f')}{\mathscr{B}(f)}}.$$
(23)

These bounds are exact in the SU(3) limit.

The SU(3) relations have worked out in details for several modes [18, 19]. Using the tables in [18] relations for many other modes can be found. Such relation will be important once the asymmetries in those modes will be measured. Here we present only the simplest bound, that is for $\pi^0 K_{\rm S}$. The SU(3) relation reads

$$a(\pi^0 K^0) = b(\pi^0 \pi^0) + b(K^+ K^-)/\sqrt{2}.$$
 (24)

The available experimental data is

$$\begin{aligned} \mathscr{B}(B^0 \to \pi^0 K^0) &= (11.92 \pm 1.44) \times 10^{-6}, \\ \mathscr{B}(B^0 \to \pi^0 \pi^0) &= (1.89 \pm 0.46) \times 10^{-6}, \\ \mathscr{B}(B^0 \to K^+ K^-) &< 0.6 \times 10^{-6}. \end{aligned} \tag{25}$$

which lead to

$$\hat{\xi}_{\pi K} < 0.13, \quad |S_{\pi K} - \sin 2\beta| < 0.19, \quad |C_{\pi K}| < 0.26$$
(26)

We expect $\mathscr{B}(B^0 \to K^+K^-)$ to be much smaller than the present bound. If this is indeed the case we will be able to neglect it and we will get not only a bound on $\hat{\xi}_{\pi K}$, but an actual estimate. Note also that the bounds in (26) are correlated. This can be seen in fig. (2) where the allowed value for $S_{\pi K}$ and $C_{\pi K}$ are plotted.

Footprints of New Physics in the B System

The data do not show a clear picture yet. Using the most recent results [20], the world averages of the asymmetries are⁵

$$S_{\psi K_{S}} = +0.73 \pm 0.05,$$

$$S_{\eta' K_{S}} = +0.27 \pm 0.21,$$

$$S_{\phi K_{S}} = -0.15 \pm 0.70,$$

$$S_{\pi K_{S}} = 0.48^{+0.38}_{-0.47} \pm 0.11,$$

$$-S_{K^{+}K^{-}K_{S}} = +0.51 \pm 0.26^{+0.18}_{-0.00}.$$
(27)

In particular, both $S_{\phi K_S}$ and $S_{\eta' K_S}$ are more then one standard deviation away from $S_{\psi K_S}$. (Since the theoretical errors on $S_{K^+K^-K_S}$ are large and due to the brief nature of this talk, we do not discuss this mode any further.)

Assuming that these anomalies are confirmed in the future, we ask what can explain them. We have to look for new physics that can generate a situation where all the asymmetries above are different. The one loop processes in the SM are expected to receive large new physics effects. Moreover, we expect the shift from $\sin 2\beta$ to be different in the those modes since the ratio of the SM and new physics hadronic matrix elements is in general different. On the contrary, $B \rightarrow \psi K_S$ is a CKM favored tree level decay in the SM and thus we do not expect new physics to have significant effects. We conclude that new physics in the $b \rightarrow s \bar{q}q$ decay amplitude generally gives different asymmetries in all the modes [22].

It is interesting to ask what we would learn if it turns out that $S_{\psi K_S} \neq S_{\phi K_S}$ but $S_{\eta' K_S}$ and $S_{\pi^0 K_S}$ are consistent with $S_{\psi K_S}$. Such a situation can be the result of new parity conserving penguin diagrams [23, 24]. To understand this point note that $B \rightarrow \phi K_S$ is parity conserving while $B \rightarrow \eta' K_S$ is parity violating. Thus, parity conserving new physics in $b \rightarrow s$ penguins only affects $B \rightarrow \phi K_S$. While generically new physics models are not parity conserving, there are models that are approximately parity conserving. Supersymmetric $SU(2)_L \times SU(R) \times Parity$ models provide an example of such an approximate parity conserving new physics framework [23, 24].

December 16, 2003

⁵ We use the PDG prescription of inflating the errors when combining measurements that are in disagreement [21]. Simply combining the errors there is one change in (27), $S_{\phi K_c} = -0.15 \pm 0.33$.

$$B \rightarrow K \pi$$

Consider the four $B \rightarrow K\pi$ decays and the underlying quark transitions that mediate them:

$$B^{+} \to K^{0}\pi^{+} \qquad b \to d\bar{ds},$$

$$B^{+} \to K^{+}\pi^{0} \qquad b \to d\bar{ds} \text{ or } b \to u^{-}us,$$

$$B^{0} \to K^{+}\pi^{-} \qquad b \to u^{-}us, \qquad (28)$$

$$B^{0} \to K^{0}\pi^{0} \qquad b \to d\bar{ds} \text{ or } b \to u^{-}us.$$

In the SM these modes can be used to measure γ . Moreover, there are many SM relations between these modes that can be used to look for new physics [25].

There are three main types of diagrams that contribute to these decays. The strong penguin diagram (P), the tree diagram (T) and the Electro-Weak (EW) penguin diagram (P_{EW}) . It is important to understand the relative magnitudes of these amplitudes. Due to the ratio between the strong and electroweak coupling constants, $P \gg P_{EW}$. The relation between P and T is not as simple. On the one hand, P is a loop amplitude while T is a tree amplitude. On the other hand, the CKM factors in Tare $O(\lambda^2) \sim 0.05$ smaller than in P. Thus, it is not clear which amplitude is dominant. Experimentally, it turns out that $P \gg T$. Thus, to first approximation all the four decay rates in Eq. (28) are mediated by the strong penguin amplitude and therefore have the same rate (up to Clebsch-Gordon coefficients). Yet, there are corrections to this expectation due to the sub-leading Tand P_{FW} amplitudes.

Due to the hierarchy of amplitudes, there are many approximate relations between the four $B \rightarrow K\pi$ decay modes. Let us consider one particular relation, called the Lipkin sum rule [26]. As we explain below the Lipkin sum rule is interesting since the correction to the pure *P* limit is only second order in the small amplitudes.

The crucial ingredient that is used in order to get useful relations is isospin. Penguin diagrams are pure $\Delta I = 0$ amplitudes, while *T* and P_{EW} have both $\Delta I = 0$ and $\Delta I = 1$ parts. The Lipkin sum rule, which is based only on isospin, reads [26]

$$R_L \equiv \frac{2\Gamma(B^+ \to K^+ \pi^0) + 2\Gamma(B^0 \to K^0 \pi^0)}{\Gamma(B^+ \to K^0 \pi^+) + \Gamma(B^0 \to K^+ \pi^-)}$$
$$= 1 + O\left(\frac{P_{EW} + T}{P}\right)^2. \tag{29}$$

Experimentally the ratio was found to be [27]

$$R_L = 1.24 \pm 0.10. \tag{30}$$

Using theoretical estimates [28] that

$$\frac{P_{EW}}{P} \sim \frac{T}{P} \sim 0.1,\tag{31}$$

Footprints of New Physics in the B System

we expect

$$R_L = 1 + O(10^{-2}). \tag{32}$$

We learn that the observed deviation of R_L from 1 is an $O(2\sigma)$ effect.

What can explain $R_L - 1 \gg 10^{-2}$? First, note that any new $\Delta I = 0$ amplitude cannot significantly modify the Lipkin sum rule since it modifies only *P*. From the measurement of the four $B \to K\pi$ decay rates we roughly know the value of *P*. This tells us that new physics cannot modify *P* in a significant way. What is needed in order to explain $R_L - 1 \gg 10^{-2}$ are new "Trojan penguins", P_{NP} , which are isospin breaking ($\Delta I = 1$) amplitudes. They modify the Lipkin sum rule as follows

$$R_{\rm L} = 1 + O\left(\frac{P_{NP}}{P}\right)^2.$$
 (33)

In order to reproduce the observed central value a large effect is needed, $P_{NP} \approx P/2$ [29]. In many models there are strong bounds on P_{NP} from $b \rightarrow s\ell^+\ell^-$. Leptophobic Z' is an example of a viable model that can accommodate significant Trojan penguins amplitude [30].

Polarization in $B \rightarrow VV$ decays

Consider B decays into light vectors, in particular,

$$B \to \rho \rho, \qquad B \to \phi K^*, \qquad B \to \rho K^*.$$
 (34)

Due to the left handed nature of the weak interaction, in the $m_B \rightarrow \infty$ limit we expect [24, 31]

$$\frac{R_T}{R_0} = O\left(\frac{1}{m_B^2}\right), \qquad \frac{R_\perp}{R_\parallel} = 1 + O\left(\frac{1}{m_B}\right), \qquad (35)$$

where R_0 (R_T , R_{\perp} , R_{\parallel}) is the longitudinal (transverse, perpendicular, parallel) polarization fraction. Recall that $R_T = R_{\perp} + R_{\parallel}$ and $R_0 + R_T = 1$.

To understand the above power counting consider for simplicity the pure penguin $B \rightarrow \phi K^*$ decays. It is convenient to work in the helicity basis (\mathscr{A}_- , \mathscr{A}_+ and \mathscr{A}_0), which is related to the transversity basis via

$$\mathscr{A}_{\parallel,\perp} = \frac{\mathscr{A}_{+} \pm \mathscr{A}_{-}}{\sqrt{2}},\tag{36}$$

and the longitudinal amplitude is the same in the two bases. We consider the factorizable helicity amplitudes, namely, those contributions which can be written in terms of products of decay constants and form factors. In the SM they are proportional to

$$\mathscr{A}_{0} \propto \frac{f_{\phi} m_{B}^{3}}{m_{K^{*}}} \left[\left(1 + \frac{m_{K^{*}}}{m_{B}} \right) A_{1} - \left(1 - \frac{m_{K^{*}}}{m_{B}} \right) A_{2} \right] \quad (37)$$
$$\mathscr{A}_{\pm} \propto f_{\phi} m_{\phi} m_{B} \left[\left(1 + \frac{m_{K^{*}}}{m_{B}} \right) A_{1} \pm \left(1 - \frac{m_{K^{*}}}{m_{B}} \right) V \right],$$

December 16, 2003

6

where terms of order $1/m_B^2$ were neglected. The $A_{1,2}$ and V are the $B \rightarrow K^*$ form factors, which are all equal in the $m_B \rightarrow \infty$ limit [32]. Thus, to leading order in α_s [33]

$$\frac{A_2}{A_1} \sim \frac{V}{A_1} = 1 + \mathscr{O}\left(\frac{1}{m_B}\right). \tag{38}$$

Using Eqs. (37) and (38) we see that the helicity amplitudes exhibit the following hierarchy [24, 31]

$$\frac{\mathscr{A}_{+}}{\mathscr{A}_{0}} \sim \mathscr{O}\left(\frac{1}{m_{B}}\right), \qquad \frac{\mathscr{A}_{-}}{\mathscr{A}_{0}} \sim \mathscr{O}\left(\frac{1}{m_{B}^{2}}\right). \tag{39}$$

Using Eq. (36) the relations in Eq. (35) immediately follow.

An intuitive understanding of these relations can be obtained by considering the helicities of the $q^{-}q$ pair that make the vector meson. In the valence quark approximation, when they are both right-handed (left-handed) the vector meson has positive (negative) helicity. When they have opposite helicities the vector meson is longitudinally polarized. In the $m_B \rightarrow \infty$ limit the light quarks are ultra relativistic and their helicities are determined by the chiralities of the weak decay operators. Since the weak interaction involves only left-handed *b* decays, the three outgoing light fermions do not have the same helicities. For example, the leading operator generates decays of the form

$$b \to \bar{s}_{R} s_{L} \bar{s}_{R}.$$
 (40)

(The spectator quark does not have preferred helicity.) Since the ϕ is made from an *s* quark and an \bar{s} antiquark, in this limit it has longitudinal helicity. For finite m_B each helicity flip reduces the amplitude by a factor of $1/m_B$. To get positive helicities one spin flip, that of the *s* quark, is required. To get negative helicities, spin flips of the two antiquarks are needed.

The relations in (35) receive factorizable as well as non-factorizable corrections. Some of these corrections have been calculated, with the result that they do not significantly modify the leading-order results [31]. Still, in order to get a clearer picture, more accurate determinations of the corrections are needed.

Observation of $R_{\perp} \gg R_{\parallel}$ would signal the presence of right-handed chirality effective operators in *B* decays [23, 24]. The hierarchy between \mathscr{A}_+ and \mathscr{A}_- generated by the opposite chirality operator, \tilde{Q}_i , (obtained from Q_i via a parity transformation) is flipped compared to the hierarchy generated by the SM operator. Such righthanded chirality operators lead to an enhancement of R_T and therefore can also upset the first relation in (35).

The polarization data are as follows [27]. The longitudinal fraction has been measured in several modes

$$\begin{split} R_0(B^0 \to \phi K^{*0}) &= 0.58 \pm 0.10, \\ R_0(B^+ \to \phi K^{*+}) &= 0.46 \pm 0.12, \end{split}$$

Footprints of New Physics in the B System

$$\begin{split} R_0(B^+ &\to \rho^0 K^{*+}) = 0.96 \pm 0.16, \\ R_0(B^+ &\to \rho^+ \rho^0) = 0.96 \pm 0.07, \\ R_0(B^0 &\to \rho^+ \rho^-) = 0.99 \pm 0.08. \end{split} \tag{41}$$

There is only one measurement of the perpendicular polarization [34]

$$R_{\perp}(B^0 \to \phi K^{*0}) = 0.41 \pm 0.11.$$
 (42)

(43)

Using $R_0 + R_{\perp} + R_{\parallel} = 1$ we extract $R_{\parallel}(B^0 \rightarrow \phi K^{*0}) = 0.01 \pm 0.15.$

We see that in $B \to \rho\rho$ and $B \to K^*\rho$ the SM prediction $R_T/R_0 \ll 1$ is confirmed, although $R_T/R_0 \gg 1/m_B^2$ remains a possibility. Since in these modes R_T is very small, the second SM prediction, $R_\perp \approx R_\parallel$, cannot be tested yet.

The situation is different in $B \rightarrow \phi K^*$. First, the data favor $R_T/R_0 = O(1)$, which is not a small number. Second, one also finds that $R_{\perp}/R_{\parallel} \gg 1$. Both of these results are in disagreement with the SM predictions (35).

It is interesting that the preliminary data indicate that the SM predictions do not hold in $B \rightarrow \phi K^*$. This is a pure penguin $b \rightarrow s \bar{ss}$ decay. The decays where the SM predictions appear to hold, $B \rightarrow K^*\rho$ and particularly $B \rightarrow \rho\rho$, on the other hand, have significant tree contributions. It is thus important to obtain polarization measurements in other modes, especially the pure penguin $b \rightarrow sd\bar{d} \operatorname{decay} B^+ \rightarrow K^{*0}\rho^+$.

With more precise polarization data it may therefore be possible to determine whether or not there are new right-handed currents, and if so whether or not they are only present in $b \rightarrow s \bar{s}s$ decays.

CONCLUSIONS

The main goal of high energy physics is to find the theory that extends the SM into shorter distances. Flavor physics is a very good tool for such a mission. Depending on the mechanism for suppressing flavor changing processes, different patterns of deviation from the SM are expected to be found. In some cases almost no deviations are expected, while in other we expect deviations in specific classes of processes. While there is no signal for such new physics yet, there are intriguing results. More data is needed in order to look further for fundamental physics using low energy flavor changing processes.

ACKNOWLEDGMENTS

The work of YG is supported by the Department of Energy, contract DE-AC03-76SF00515 and by the Department of Energy under grant No. DE-FG03-92ER40689.

December 16, 2003

REFERENCES

- For a discussion for supersymmetric models see, for example, Z. Ligeti and Y. Nir, Nucl. Phys. Proc. Suppl. 111, 82 (2002) [hep-ph/0202117]; Y. Grossman, Y. Nir and R. Rattazzi, Adv. Ser. Direct. High Energy Phys. 15, 755 (1998) [hep-ph/9701231].
- See, for example, M. Schmaltz, Nucl. Phys. Proc. Suppl. 117, 40 (2003) [hep-ph/0210415]; G. F. Giudice, hep-ph/0311344.
- 3. For a review see, for example, A. J. Buras, hepph/0307203.
- 4. For a review see, Y. Shadmi and Y. Shirman, Rev. Mod. Phys. **72**, 25 (2000) [hep-th/9907225].
- Flavor aspects of universal extra dimensions are discussed in A. J. Buras, M. Spranger and A. Weiler, Nucl. Phys. B 660, 225 (2003) [hep-ph/0212143].
- M. Dine, R. G. Leigh and A. Kagan, Phys. Rev. D 48, 4269 (1993) [hep-ph/9304299]; A. Pomarol and D. Tommasini, Nucl. Phys. B 466, 3 (1996) [hepph/9507462]; G. R. Dvali and A. Pomarol, Phys. Rev. Lett. 77, 3728 (1996) [hep-ph/9607383]; A. G. Cohen, D. B. Kaplan and A. E. Nelson, Phys. Lett. B 388, 588 (1996) [hep-ph/9607394].
- T. Gherghetta and A. Pomarol, Nucl. Phys. B 586, 141 (2000) [hep-ph/0003129]; S. J. Huber and Q. Shafi, Phys. Lett. B 498, 256 (2001) [hep-ph/0010195]; S. J. Huber, Nucl. Phys. B 666, 269 (2003) [hep-ph/0303183]; K. Agashe, A. Delgado, M. J. May and R. Sundrum, hep-ph/0308036; G. Burdman, hep-ph/0310144.
- Y. Nir and N. Seiberg, Phys. Lett. B **309**, 337 (1993) [hep-ph/9304307]; M. Leurer, Y. Nir and N. Seiberg, Nucl. Phys. B **420**, 468 (1994) [hep-ph/9310320].
- 9. For one of the early models see S. Pakvasa and H. Sugawara, Phys. Lett. B **73**, 61 (1978).
- M. Leurer, Y. Nir and N. Seiberg, Nucl. Phys. B 398, 319 (1993) [hep-ph/9212278].
- N. Arkani-Hamed and M. Schmaltz, Phys. Rev. D 61, 033005 (2000) [hep-ph/9903417]; Y. Grossman and G. Perez, Phys. Rev. D 67, 015011 (2003) [hepph/0210053].
- A. Hocker, H. Lacker, S. Laplace and F. Le Diberder, Eur. Phys. J. C 21, 225 (2001) [hep-ph/0104062]. Recent fits can be found in the CKMfitter home page at ckmfitter.in2p3.fr.
- For a review, notation and formalism, see Y. Nir, *Lectures at XXVII SLAC Summer Institute on Particle Physics*, hep-ph/9911321; G.C. Branco, L. Lavoura and J.P. Silva, 'CP violation," *Oxford, UK: Clarendon (1999)*; K. Anikeev *et al.*, hep-ph/0201071.
- D. London and A. Soni, Phys. Lett. B 407, 61 (1997) [hep-ph/9704277]; M. Beneke and M. Neubert, Nucl. Phys. B 651, 225 (2003) [hep-ph/0210085];
- M. J. Savage and M. B. Wise, Phys. Rev. D 39, 3346 (1989) [Erratum-ibid. D 40, 3127 (1989)]; A. S. Dighe, Phys. Rev. D 54, 2067 (1996) [arXiv:hep-ph/9509287];
- B. Grinstein and R. F. Lebed, Phys. Rev. D 53, 6344 (1996) [arXiv:hep-ph/9602218]; A. S. Dighe, M. Gronau and J. L. Rosner, Phys. Rev. D 57, 1783 (1998) [arXiv:hepph/9709223]; N. G. Deshpande, X. G. He and J. Q. Shi, Phys. Rev. D 62, 034018 (2000) [arXiv:hep-ph/0002260].
- Y. Grossman, G. Isidori and M. P. Worah, Phys. Rev. D 58, 057504 (1998) [arXiv:hep-ph/9708305].

- Y. Grossman, Z. Ligeti, Y. Nir and H. Quinn, Phys. Rev. D 68, 015004 (2003) [arXiv:hep-ph/0303171].
- M. Gronau, Y. Grossman and J. L. Rosner, arXiv:hepph/0310020.
- 20. T. E. Browder, arXiv:hep-ex/0312024.
- 21. K. Hagiwara *et al.*, Particle Data Group, Phys. Rev. D **66**, 010001 (2002).
- 22. See, for example, Y. Grossman and M. P. Worah, Phys. Lett. B 395, 241 (1997) [hep-ph/9612269]; A. Kagan, in proceedings of the 7th International Symposium on Heavy Flavor Physics, Santa Barbara, CA July 1997, hepph/9806266; R. Fleischer and T. Mannel, Phys. Lett. B 511, 240 (2001) [hep-ph/0103121]; G. Hiller, Phys. Rev. D 66, 071502 (2002) [hep-ph/0207356]; A. Datta, Phys. Rev. D 66, 071702 (2002) [hep-ph/0208016]; M. Raidal, Phys. Rev. Lett. 89, 231803 (2002) [hep-ph/0208091]; R. Harnik, D. T. Larson, H. Murayama and A. Pierce, hep-ph/0212180; C. W. Chiang and J. L. Rosner, Phys. Rev. D 68, 014007 (2003) [hep-ph/0302094]; G. L. Kane, P. Ko, H. b. Wang, C. Kolda, J. h. Park and L. T. Wang, Phys. Rev. Lett. 90, 141803 (2003) [hep-ph/0304239]; A. K. Giri and R. Mohanta, Phys. Rev. D 68, 014020 (2003) [hep-ph/0306041]; J. F. Cheng, C. S. Huang and X. h. Wu, hep-ph/0306086; R. Arnowitt, B. Dutta and B. Hu, hep-ph/0307152.
- A. L. Kagan, lecture at SLAC Summer Institute, August 2002, www.slac.stanford.edu/gen/meeting/ ssi/2002/kagan1.html#lecture2.
- 24. A. L. Kagan, talk at first workshop on the discovery potential of an asymmetric *B* factory at 10³⁶ luminosity, May 2003, www.slac.stanford.edu/ BFROOT/www/Organization/1036_Study_Group/ 0303Workshop/index.html
- For recent reviews, see: R. Fleischer, Phys. Rept. **370**, 537 (2002) [hep-ph/0207108]; J. L. Rosner, hep-ph/0304200; M. Gronau, hep-ph/0306308.
- H. J. Lipkin, hep-ph/9809347; Phys. Lett. B 445, 403 (1999) [hep-ph/9810351]; M. Gronau and J. L. Rosner, Phys. Rev. D 59, 113002 (1999) [hep-ph/9809384].
- J. Fry, talk presented at the 21st International Symposium On Lepton And Photon Interactions At High Energies (LP03) 11-16 Aug 2003, Batavia, Illinois, conferences.fnal.gov/lp2003/program/papers/fry.ps
- M. Beneke, G. Buchalla, M. Neubert and C. T. Sachrajda, Nucl. Phys. B 606, 245 (2001) [hep-ph/0104110].
- M. Gronau and J. L. Rosner, hep-ph/0307095; A. J. Buras, R. Fleischer, S. Recksiegel and F. Schwab, hepph/0309012.
- Y. Grossman, M. Neubert and A. L. Kagan, JHEP **9910**, 029 (1999) [hep-ph/9909297]; K. Leroux and D. London, Phys. Lett. B **526**, 97 (2002) [hep-ph/0111246].
- 31. A. L. Kagan, in preparation.
- J. Charles, A. Le Yaouanc, L. Oliver, O. Pene and J. C. Raynal, Phys. Rev. D 60, 014001 (1999) [hepph/9812358]; C. W. Bauer, S. Fleming, D. Pirjol and I. W. Stewart, Phys. Rev. D 63, 114020 (2001) [hep-ph/0011336].
- M. Beneke and T. Feldmann, Nucl. Phys. B **592**, 3 (2001) [hep-ph/0008255]; G. Burdman and G. Hiller, Phys. Rev. D **63**, 113008 (2001) [hep-ph/0011266].
- 34. [Belle Collaboration], hep-ex/0307014.

Footprints of New Physics in the B System