

Theoretical issues in b physics

J.L. Rosner

Enrico Fermi Institute and Department of Physics, University of Chicago, 5640 S. Ellis Avenue, Chicago, IL 60637 USA,
e-mail: rosner@hep.uchicago.edu

Received: 8 August 2003 / Accepted: 3 February 2003 /
Published Online: 13 July 2004 – © Springer-Verlag / Società Italiana di Fisica 2004

Abstract. Examples are given of some current questions in b physics to which LHC experiments may provide answers. These include (i) the precise determination of parameters of the Cabibbo-Kobayashi-Maskawa (CKM) matrix; (ii) measurements of CKM phases using B decays to CP eigenstates; (iii) the search for direct CP asymmetries in B decays; (iv) rare radiative B decays; (v) the study of B_s properties and decays, (vi) excited states of B and B_s mesons, and (vii) the search for heavier quarks which could mix with the b quark.

PACS. 1 1.30.Er – 11.30.Hv – 13.25.Hw – 14.40.Nd

1 Introduction

The Large Hadron Collider (LHC) will permit the exploration of physics at unprecedented energy scales toward the end of this decade, but it will also produce b quarks more copiously than any other accelerator. If the hadrons containing these quarks can be identified, many questions we now face can be addressed, while undoubtedly others will arise. In this talk I would like to give some examples of *current* questions in b physics to which we would like answers. Others may well be more timely in the LHC era.

In Sect. 2 we review information on weak quark transitions as encoded in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. We then discuss CP asymmetries in B decays to CP eigenstates (Sect. 3) and to self-tagging modes (“direct asymmetries,” Sect. 4). Rare radiative B decays, mentioned briefly in Sect. 5, provide useful information on possible new physics. Hadron colliders such as the LHC are the tool of choice for the study of strange B (B_s) properties and decays (Sect. 6). Excited states of B and B_s mesons, for which there have been interesting parallel developments in the charm sector, are discussed in Sect. 7. The search for heavier quarks which could mix with the b quark is noted in Sect. 8, while Sect. 9 concludes.

2 Weak quark transitions

The relative strengths of charge-changing weak quark transitions are illustrated in Fig. 1. This pattern is one of the central mysteries of particle physics, along with the values of the quark masses. We shall not address its deeper origin here, but will seek better knowledge of strengths and phases of the transitions, to see whether all weak phe-

nomena including CP violation can be described satisfactorily via this pattern.

2.1 The CKM matrix

The interactions in Fig. 1 may be parametrized by a unitary 3×3 matrix, the Cabibbo-Kobayashi-Maskawa (CKM) matrix. A convenient form [1, 2], unitary to sufficiently high order in a small quantity λ , is

$$V_{\text{CKM}} = \begin{bmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 & 1 \end{bmatrix}, \quad (1)$$

where $\bar{\rho} \equiv \rho(1 - \frac{\lambda^2}{2})$ and $\bar{\eta} \equiv \eta(1 - \frac{\lambda^2}{2})$. The columns refer to d, s, b and the rows to u, c, t . The parameter $\lambda = 0.224$ [2] is $\sin \theta_c$, where θ_c is the Cabibbo angle. The value $|V_{cb}| \simeq 0.041$, obtained from $b \rightarrow c$ decays, indicates $A \simeq 0.82$, while $|V_{ub}/V_{cb}| \simeq 0.09$, obtained from $b \rightarrow u$ decays, implies $(\rho^2 + \eta^2)^{1/2} \simeq 0.4$. We shall generally use the CKM parameters quoted in [3].

2.2 The unitarity triangle

The unitarity of the CKM matrix implies that the scalar product of any column with the complex conjugate of any other column is zero; for example, $V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0$. If one divides by $-V_{cb}^*V_{cd}$, this relation becomes equivalent to a triangle in the complex $\bar{\rho} + i\bar{\eta}$ plane, with vertices at $(0,0)$ (angle $\phi_3 = \gamma$), $(1,0)$ (angle $\phi_1 = \beta$), and $(\bar{\rho}, \bar{\eta})$ (angle $\phi_2 = \alpha$). The triangle has unit base and

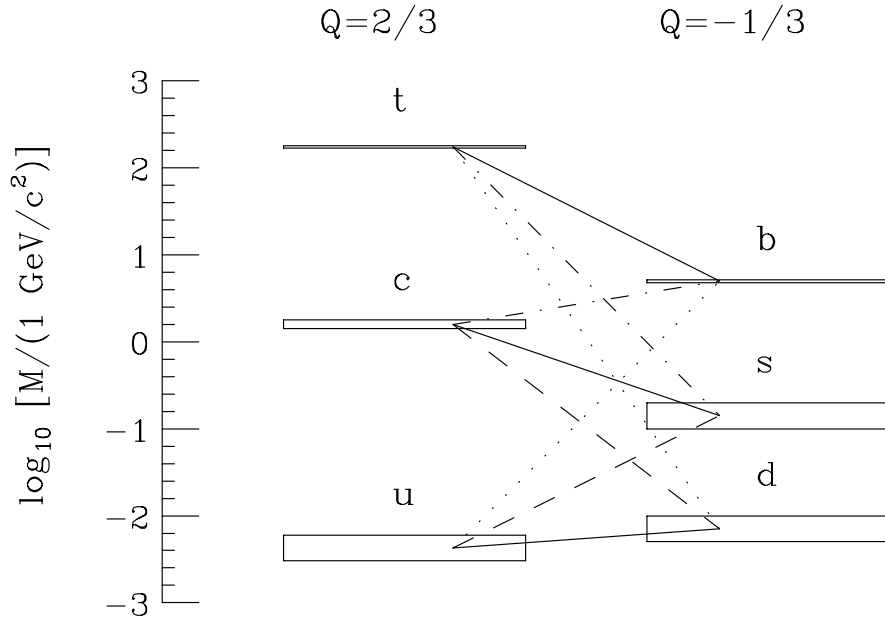


Fig. 1. Pattern of charge-changing weak transitions among quarks. *Solid lines:* relative strength 1; *dashed lines:* relative strength 0.22; *dot-dashed lines:* relative strength 0.04; *dotted lines:* relative strength ≤ 0.01 . Breadths of horizontal lines denote estimated errors for masses

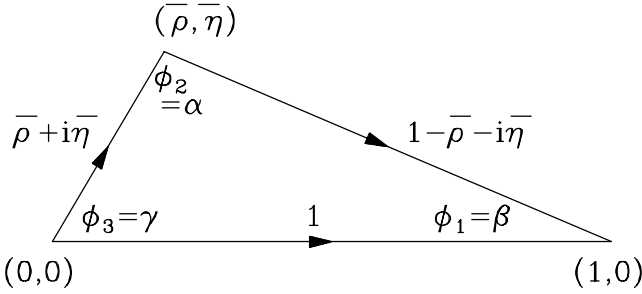


Fig. 2. The unitarity triangle

its other two sides are $\bar{\rho} + i\bar{\eta} = -(V_{ub}^*V_{ud}/V_{cb}^*V_{cd})$ (opposite $\phi_1 = \beta$) and $1 - \bar{\rho} - i\bar{\eta} = -(V_{tb}^*V_{td}/V_{cb}^*V_{cd})$ (opposite $\phi_3 = \gamma$). The result is shown in Fig. 2.

In addition to the direct measurements of CKM parameters mentioned above, flavor-changing loop diagrams provide a number of indirect constraints. CP-violating $K^0-\bar{K}^0$ mixing is dominated by the second-order-weak virtual transition $\bar{s}d \rightarrow \bar{d}s$ with virtual $t\bar{t}$ and W^+W^- intermediate states, and thus constrains $\text{Im}(V_{td}^2) \sim \bar{\eta}(1-\bar{\rho})$, leading to a hyperbola in the $(\bar{\rho}, \bar{\eta})$ plane. $B^0-\bar{B}^0$ mixing is similarly dominated by $t\bar{t}$ and W^+W^- in the loop diagram for $\bar{b}d \rightarrow \bar{d}b$, and thus constrains $|V_{td}|$ and hence $|1 - \bar{\rho} - i\bar{\eta}|$. By comparing $B_s-\bar{B}_s$ and $B^0-\bar{B}^0$ mixing, one can reduce dependence on unknown matrix elements and learn a lower limit on $|V_{ts}/V_{td}|$ or an upper limit on $|1 - \bar{\rho} - i\bar{\eta}|$. The range of parameters allowed at 95% c.l. [3] is $0.08 \leq \bar{\rho} \leq 0.34$, $0.25 \leq \bar{\eta} \leq 0.43$ (but see, e.g., [4] for more a more optimistic view of our present knowledge).

3 B decays to CP eigenstates

One can learn CKM phases from decays of neutral B mesons to CP eigenstates f , where $CP|f\rangle = \xi_f|f\rangle$, $\xi_f = \pm 1$. As a result of $B^0-\bar{B}^0$ mixing, a state which is B^0 at proper time $t = 0$ will evolve into one, denoted $B^0(t)$, which is a mixture of B^0 and \bar{B}^0 . Thus there will be one pathway to the final state f from B^0 through the amplitude A and another from \bar{B}^0 through the amplitude \bar{A} , which acquires an additional phase $2\phi_1 = 2\beta$ through the mixing. The interference of these two amplitudes can differ in the decays $B^0(t) \rightarrow f$ and $\bar{B}^0(t) \rightarrow f$, leading to a time-integrated rate asymmetry

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\bar{B}^0 \rightarrow f) - \Gamma(B^0 \rightarrow f)}{\Gamma(\bar{B}^0 \rightarrow f) + \Gamma(B^0 \rightarrow f)} \quad (2)$$

as well as to time-dependent rates

$$\left\{ \begin{array}{l} \Gamma[B^0(t) \rightarrow f] \\ \Gamma[\bar{B}^0(t) \rightarrow f] \end{array} \right\} \sim e^{-\Gamma t} [1 \mp \mathcal{A}_f \cos \Delta m t \mp \mathcal{S}_f \sin \Delta m t] \quad (3)$$

where

$$\mathcal{A}_f \equiv \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}, \quad \mathcal{S}_f \equiv \frac{2\text{Im}\lambda}{|\lambda|^2 + 1}, \quad \lambda \equiv e^{-2i\beta} \frac{\bar{A}}{A} \quad (4)$$

where $\mathcal{S}_f^2 + \mathcal{A}_f^2 \leq 1$. More details may be found in [5, 6]. I now note some specific cases.

3.1 $B^0 \rightarrow J/\psi K_S$ and $\phi_1 = \beta$

For this decay one has $\bar{A}/A \simeq \xi_{J/\psi K_S} = -1$. One finds that the time-integrated asymmetry \mathcal{A}_{CP} is proportional to $\sin(2\phi_1) = \sin(2\beta)$. Using this and related decays involving the same $\bar{b} \rightarrow \bar{s}c\bar{c}$ subprocess, BaBar [7] finds $\sin(2\beta) = 0.741 \pm 0.067 \pm 0.033$ while Belle [8] finds $0.719 \pm 0.074 \pm 0.035$. The two values agree with each other; the world average [9] is $\sin(2\beta) = 0.734 \pm 0.054$, consistent with other determinations [3, 4, 10].

3.2 $B^0 \rightarrow \pi^+\pi^-$ and $\phi_2 = \alpha$

Here two amplitudes contribute to the decay: a ‘‘tree’’ T and a ‘‘penguin’’ P . The decay amplitudes are

$$A = -(|T|e^{i\gamma} + |P|e^{i\delta}) \quad , \quad \bar{A} = -(|T|e^{-i\gamma} + |P|e^{i\delta}) \quad , \quad (5)$$

where δ is the relative P/T strong phase. The asymmetry \mathcal{A}_{CP} would be proportional to $\sin(2\alpha)$ if the penguin amplitude could be neglected. However, one must account for its contribution.

An isospin analysis [11] of B decays to $\pi^+\pi^-$, $\pi^\pm\pi^0$, and $\pi^0\pi^0$ separates the contributions of decays involving $I = 0$ and $I = 2$ final states. Information can then be obtained on both strong and weak phases. Since the branching ratio of B^0 to $\pi^0\pi^0$ may be very small, of order 10^{-6} , I shall discuss instead methods [12, 13] in which flavor SU(3) symmetry is used to estimate the penguin contribution [14, 15, 16].

The tree amplitude for $B^0(= \bar{b}d) \rightarrow \pi^+\pi^-$ involves $\bar{b} \rightarrow \pi^+\bar{u}$, with the spectator d quark combining with \bar{u} to form a π^- . Its magnitude is $|T|$; its weak phase is $\text{Arg}(V_{ub}^*) = \gamma$; by convention its strong phase is 0. The penguin amplitude involves the flavor structure $\bar{b} \rightarrow \bar{d}$, with the final $\bar{d}d$ pair fragmenting into $\pi^+\pi^-$. Its magnitude is $|P|$. The dominant t contribution in the loop diagram for $\bar{b} \rightarrow \bar{d}$ can be integrated out and the unitarity relation $V_{td}V_{tb}^* = -V_{cd}V_{cb}^* - V_{ud}V_{ub}^*$ used. The $V_{ud}V_{ub}^*$ contribution can be absorbed into a redefinition of the tree amplitude, after which the weak phase of the penguin amplitude is 0 (mod π). By definition, its strong phase is δ .

The time-dependent asymmetries $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ specify both γ (or $\alpha = \pi - \beta - \gamma$) and δ , if one has an independent estimate of $|P/T|$. One may obtain $|P|$ from $B^+ \rightarrow K^0\pi^+$ using flavor SU(3) [14, 15, 17] and $|T|$ from $B \rightarrow \pi l\nu$ using factorization [18]. An alternative method [13, 16] uses the measured ratio of the $B^+ \rightarrow K^0\pi^+$ and $B^0 \rightarrow \pi^+\pi^-$ branching ratios to constrain $|P/T|$. I shall discuss the first method.

In addition to $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$, a useful quantity is the ratio of the $B^0 \rightarrow \pi^+\pi^-$ branching ratio $\bar{\mathcal{B}}(\pi^+\pi^-)$ (averaged over B^0 and \bar{B}^0) to that due to the tree amplitude alone:

$$R_{\pi\pi} \equiv \frac{\bar{\mathcal{B}}(\pi^+\pi^-)}{\bar{\mathcal{B}}(\pi^+\pi^-)|_{\text{tree}}} = 1 + 2 \left| \frac{P}{T} \right| \cos \delta \cos \gamma + \left| \frac{P}{T} \right|^2 \quad . \quad (6)$$

Table 1. Values of $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ quoted by BaBar and Belle and their averages. Here we have applied scale factors $S \equiv \sqrt{\chi^2} = (2.31, 1.24)$ to the errors for $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$, respectively

Quantity	BaBar [19]	Belle [20]	Average
$\mathcal{S}_{\pi\pi}$	$0.02 \pm 0.34 \pm 0.05$	$-1.23 \pm 0.41_{-0.07}^{+0.08}$	-0.49 ± 0.61
$\mathcal{A}_{\pi\pi}$	$0.30 \pm 0.25 \pm 0.04$	$0.77 \pm 0.27 \pm 0.08$	0.51 ± 0.23

One also has

$$R_{\pi\pi}\mathcal{S}_{\pi\pi} = \sin 2\alpha + 2 \left| \frac{P}{T} \right| \cos \delta \sin(\beta - \alpha) - \left| \frac{P}{T} \right|^2 \sin 2\beta \quad , \quad (7)$$

$$R_{\pi\pi}\mathcal{A}_{\pi\pi} = -2|P/T| \sin \delta \sin \gamma \quad . \quad (8)$$

The value of β is specified to within a few degrees; we shall take it to have its central value of 23.6° . The value of $|P/T|$ (updating [12, 13]) is 0.28 ± 0.06 . Taking the central value, one can plot trajectories in the $(\mathcal{S}_{\pi\pi}, \mathcal{A}_{\pi\pi})$ plane as δ is allowed to vary from $-\pi$ to π .

The experimental situation regarding the time-dependent asymmetries is not yet settled. As shown in Table 1, BaBar [19] and Belle [20] obtain very different values, especially for $\mathcal{S}_{\pi\pi}$. Even if this conflict were to be resolved, however, there is a possibility of a discrete ambiguity, since curves for different values of α intersect one another. The discrete ambiguity may be resolved with the help of $R_{\pi\pi} = 0.62 \pm 0.28$, but the error is still too large to be helpful. At present values of $\phi_2 = \alpha > 90^\circ$ are favored, but with large uncertainty. It is not yet settled whether $\mathcal{A}_{\pi\pi} \neq 0$, corresponding to ‘‘direct’’ CP violation.

3.3 $B^0 \rightarrow \phi K_S$ vs. $B^0 \rightarrow J/\psi K_S$

In $B^0 \rightarrow \phi K_S$, governed by the $\bar{b} \rightarrow \bar{s}$ penguin amplitude, the standard model predicts the same CP asymmetries as in those processes (like $B^0 \rightarrow J/\psi K_S$) governed by $\bar{b} \rightarrow \bar{s}c\bar{c}$. In both cases the weak phase is expected to be 0 (mod π), so the indirect CP asymmetry should be governed by $B^0\text{--}\bar{B}^0$ mixing and thus should be proportional to $\sin 2\beta$. There should be no direct CP asymmetries (i.e., $\mathcal{A} \simeq 0$) in either case. This is true for $B \rightarrow J/\psi K$; \mathcal{A} is consistent with zero in the neutral mode, while the direct CP asymmetry is consistent with zero in the charged mode [7]. However, a different result for $B^0 \rightarrow \phi K_S$ could point to new physics in the $\bar{b} \rightarrow \bar{s}$ penguin amplitude [21].

The experimental asymmetries in $B^0 \rightarrow \phi K_S$ [22, 23] are shown in Table 2. For $\mathcal{A}_{\phi K_S}$ there is a substantial discrepancy between BaBar and Belle. The value of $\mathcal{S}_{\phi K_S}$, which should equal $\sin 2\beta = 0.734 \pm 0.054$ in the standard model, is about 2.7σ away from it. If the amplitudes for $B^0 \rightarrow \phi K^0$ and $B^+ \rightarrow \phi K^+$ are equal (true in many approaches), the time-integrated CP asymmetry \mathcal{A}_{CP} in the charged mode should equal $\mathcal{A}_{\phi K_S}$. The BaBar Collaboration [24] has recently reported $\mathcal{A}_{CP} = 0.039 \pm 0.086 \pm 0.011$.

Many proposals for new physics can account for the departure of $\mathcal{S}_{\phi K_S}$ from its expected value of $\sin 2\beta$ [25]. A method similar to that [12, 13] used in analyzing $B^0 \rightarrow \pi\pi$

Table 2. Values of $\mathcal{S}_{\phi K_S}$ and $\mathcal{A}_{\phi K_S}$ quoted by BaBar and Belle and their averages. Here we have applied a scale factor of $\sqrt{\chi^2} = 2.29$ to the error on $\mathcal{A}_{\phi K_S}$

Quantity	BaBar [22]	Belle [23]	Average
$\mathcal{S}_{\phi K_S}$	$-0.18 \pm 0.51 \pm 0.07$	$-0.73 \pm 0.64 \pm 0.22$	-0.38 ± 0.41
$\mathcal{A}_{\phi K_S}$	$0.80 \pm 0.38 \pm 0.12$	$-0.56 \pm 0.41 \pm 0.16$	0.19 ± 0.68

for extracting a new physics amplitude has been developed in collaboration with Cheng-Wei Chiang [26]. One uses the measured values of $\mathcal{S}_{\phi K_S}$ and $\mathcal{A}_{\phi K_S}$ and the ratio

$$R_{\phi K_S} \equiv \frac{\overline{\mathcal{B}}(B^0 \rightarrow \phi K_S)}{\overline{\mathcal{B}}(B^0 \rightarrow \phi K_S)|_{\text{std}}} = 1 + 2r \cos \phi \cos \delta + r^2, \quad (9)$$

where r is the ratio of the magnitude of the new amplitude to the one in the standard model, and ϕ and δ are their relative weak and strong phases. For any values of $R_{\phi K_S}$, ϕ , and δ , (9) can be solved for the amplitude ratio r and one then calculates

$$R_{\phi K_S} \mathcal{S}_{\phi K_S} = \sin 2\beta + 2r \cos \delta \sin(2\beta - \phi) + r^2 \sin 2(\beta - \phi) \quad (10)$$

$$R_{\phi K_S} \mathcal{A}_{\phi K_S} = 2r \sin \phi \sin \delta. \quad (11)$$

The ϕK_S branching ratio in the standard model is calculated using the penguin amplitude from $B^+ \rightarrow K^{*0} \pi^+$ and an estimate of electroweak penguin corrections. It was found [26] that $R_{\phi K_S} = 1.0 \pm 0.2$.

Various regions of (ϕ, δ) can reproduce the observed values of $\mathcal{S}_{\phi K_S}$ and $\mathcal{A}_{\phi K_S}$. As errors on the observables shrink, so will the allowed regions. However, there will always be a solution for *some* ϕ and δ as long as R remains compatible with 1. (The allowed regions of ϕ and δ are restricted if $R \neq 1$ [26].) Typical values of r are of order 1; one generally needs to invoke new-physics amplitudes comparable to those in the standard model.

The above scenario envisions new physics entirely in $B^0 \rightarrow \phi K^0$ and not in $B^+ \rightarrow K^{*0} \pi^+$. An alternative is that new physics contributes to the $\bar{b} \rightarrow \bar{s}$ penguin amplitude and thus appears in *both* decays. Here it is convenient to define a ratio

$$R' \equiv \frac{\overline{\Gamma}(B^0 \rightarrow \phi K^0)}{\overline{\Gamma}(B^+ \rightarrow K^{*0} \pi^+)} \quad (12)$$

where $\overline{\Gamma}$ denotes a partial width averaged over a process and its CP conjugate. Present data indicate $R' = 0.78 \pm 0.17$. The $B^0 \rightarrow \phi K^0$ amplitude contains a contribution from both the gluonic and electroweak penguin terms, while $B^+ \rightarrow K^{*0} \pi^+$ contains only the former. Any departure from the expected ratio of the electroweak to gluonic penguin amplitudes would signify new physics. Again, the central value of \mathcal{S} would suggest this to be the case [26], but one must wait until the discrepancy with the standard model becomes more significant. At present both the decays $B^0 \rightarrow K_S(K^+ K^-)_{CP=+}$ and $B^0 \rightarrow \eta' K_S$ display CP asymmetries consistent with standard expectations.

3.4 $B^0 \rightarrow K_S(K^+ K^-)_{CP=+}$

The Belle Collaboration [23] finds that for $K^+ K^-$ not in the ϕ peak, most of the decay $B^0 \rightarrow K_S K^+ K^-$ involves even CP for the $K^+ K^-$ system ($\xi_{K^+ K^-} = +1$). It is found that

$$-\xi_{K^+ K^-} \mathcal{S}_{K^+ K^-} = 0.49 \pm 0.43 \pm 0.11_{-0.00}^{+0.33}, \quad (13)$$

$$\mathcal{A}_{K^+ K^-} = -0.40 \pm 0.33 \pm 0.10_{-0.26}^{+0.00}, \quad (14)$$

where the third set of errors arise from uncertainty in the fraction of the CP-odd component. Independent estimates of this fraction have been performed in [27] and [28]. The quantity $-\xi_{K^+ K^-} \mathcal{S}_{K^+ K^-}$ should equal $\sin 2\beta$ in the standard model, but additional non-penguin contributions can lead this quantity to range between 0.2 and 1.0 [28].

3.5 $B \rightarrow \eta' K$ (charged and neutral modes)

At present neither the rate nor the CP asymmetry in $B \rightarrow \eta' K$ present a significant challenge to the standard model. The rate can be reproduced with the help of a modest contribution from a “flavor-singlet penguin” amplitude, the need for which was pointed out [29] prior to the observation of this decay. One only needs to boost the standard penguin amplitude’s contribution by about 50% via the flavor-singlet term in order to explain the observed rate [30,31,32,33]. (An alternative treatment [34] finds an enhanced standard-penguin contribution to $B \rightarrow \eta' K$.) The CP asymmetry is not a problem; the ordinary and singlet penguin amplitudes are expected to have the same weak phase $\text{Arg}(V_{ts}^* V_{tb}) \simeq \pi$ and hence one expects $\mathcal{S}_{\eta' K_S} \simeq \sin 2\beta$, $\mathcal{A}_{\eta' K_S} \simeq 0$. The experimental situation is shown in Table 3. The value of $\mathcal{S}_{\eta' K_S}$ is consistent with the standard model expectation at the 1σ level, while $\mathcal{A}_{\eta' K_S}$ is consistent with zero.

The singlet penguin amplitude may contribute elsewhere in B decays. It is a possible source of a low-effective-mass $\bar{p}p$ enhancement [35] in $B^+ \rightarrow \bar{p}p K^+$ [36].

4 Direct CP asymmetries

Decays such as $B \rightarrow K\pi$ (with the exception of $B^0 \rightarrow K^0 \pi^0$) are *self-tagging*, i.e., their final states indicate the flavor of the decaying state. For example, the $K^+ \pi^-$ final state is expected to originate purely from a B^0 and not from a \bar{B}^0 . Since such self-tagging decays do not involve a CP eigenstate, they involve both weak and strong phases. Several methods permit one to separate these from one another. We give some examples.

Table 3. Values of \mathcal{S}_{η'/K_S} and \mathcal{A}_{η'/K_S} quoted by BaBar and Belle and their averages. Here we have applied scale factors $S \equiv \sqrt{\chi^2} = (1.48, 1.15)$ to the errors for \mathcal{S}_{η'/K_S} and \mathcal{A}_{η'/K_S} , respectively

Quantity	BaBar [22]	Belle [23]	Average
\mathcal{S}_{η'/K_S}	$0.02 \pm 0.34 \pm 0.03$	$0.76 \pm 0.36^{+0.05}_{-0.06}$	0.37 ± 0.37
\mathcal{A}_{η'/K_S}	$-0.10 \pm 0.22 \pm 0.03$	$0.26 \pm 0.22 \pm 0.03$	0.08 ± 0.18

4.1 $B^0 \rightarrow K^+\pi^-$ vs. $B^+ \rightarrow K^0\pi^+$

The decay $B^+ \rightarrow K^0\pi^+$ is a pure penguin (P) process, while the amplitude for $B^0 \rightarrow K^+\pi^-$ is proportional to $P+T$, where T is a (strangeness-changing) tree amplitude. The ratio T/P has magnitude r , weak phase $\gamma \pm \pi$, and strong phase δ . The ratio R_0 of these two rates (averaged over a process and its CP conjugate) is

$$R_0 \equiv \frac{\overline{\Gamma}(B^0 \rightarrow K^+\pi^-)}{\overline{\Gamma}(B^+ \rightarrow K^0\pi^+)} = 1 - 2r \cos \gamma \cos \delta + r^2 \geq \sin^2 \gamma \quad , \quad (15)$$

where the inequality holds for any r and δ . For $R_0 < 1$ this inequality can be used to impose a useful constraint on γ [37]. On the basis of branching ratios [38, 39, 40] summarized in [41] and using the B^+/B^0 lifetime ratio from [42], one finds $R_0 = 0.99 \pm 0.09$, which is consistent with 1 and does not permit application of the bound. However, using additional information on r and the CP asymmetry in $B^0 \rightarrow K^+\pi^-$, one can obtain a constraint on γ [12, 43].

The CP asymmetry \mathcal{A}_{CP} (2) can be written for $B^0 \rightarrow K^+\pi^-$ as

$$\mathcal{A}_{CP}(K^+\pi^-) \equiv \frac{\Gamma(\overline{B}^0 \rightarrow K^-\pi^+) - \Gamma(B^0 \rightarrow K^+\pi^-)}{2\overline{\Gamma}(B^0 \rightarrow K^+\pi^-)} = -\frac{2r \sin \gamma \sin \delta}{R_0} \quad . \quad (16)$$

One may eliminate δ between this equation and (15) and plot R_0 as a function of γ for the allowed range of $\mathcal{A}_{CP}(K^+\pi^-)$. The value of r , based on present branching and arguments given in [12, 41, 43]), is $r = 0.17 \pm 0.04$. The latest BaBar and Belle data imply $\mathcal{A}_{CP}(K^+\pi^-) = -0.09 \pm 0.04$ [33], leading us to take $|\mathcal{A}_{CP}(K^+\pi^-)| \leq 0.13$ at the 1σ level. Curves for $\mathcal{A}_{CP} = 0$ and $|\mathcal{A}_{CP}| = 0.13$ (the $K^+\pi^-$ final state is to be understood) are shown in Fig. 3. The lower limit $r = 0.13$ is used to generate these curves since the limit on γ will be the most conservative.

At the 1σ level, using the constraints that R_0 must lie between 0.90 and 1.08 and $|\mathcal{A}_{CP}|$ must lie between zero and 0.13, one can establish that $\gamma \gtrsim 60^\circ$. No bound can be obtained at the 95% confidence level, however. Despite the impressive improvement in experimental precision (a factor of 2 decrease in errors since the analysis of [12]), further data are needed in order for a useful constraint to be obtained.

4.2 $B^+ \rightarrow K^+\pi^0$ vs. $B^+ \rightarrow K^0\pi^+$

The comparison of rates for $B^+ \rightarrow K^+\pi^0$ and $B^+ \rightarrow K^0\pi^+$ also can give information on γ . The amplitude for

$B^+ \rightarrow K^+\pi^0$ is proportional to $P + T + C$, where C is a color-suppressed amplitude. Originally it was suggested that this amplitude be compared with P from $B^+ \rightarrow K^0\pi^+$ and $T+C$ taken from $B^+ \rightarrow \pi^+\pi^0$ using flavor SU(3) [44] using a triangle construction to determine γ . However, electroweak penguin amplitudes contribute significantly in the $T + C$ term [45]. It was noted subsequently [46] that since the $T + C$ amplitude corresponds to isospin $I(K\pi) = 3/2$ for the final state, the strong-interaction phase of its EWP contribution is the same as that of the rest of the $T + C$ amplitude, permitting the calculation of the EWP correction.

New data on branching ratios and CP asymmetries permit an update of previous analyses [12, 46]. One makes use of the quantities (see [33] for values)

$$R_c \equiv \frac{2\overline{\Gamma}(B^+ \rightarrow K^+\pi^0)}{\overline{\Gamma}(B^+ \rightarrow K^0\pi^+)} = 1 - 2r_c \cos \delta_c (\cos \gamma - \delta_{EW}) + r_c^2(1 - 2\delta_{EW} \cos \gamma + \delta_{EW}^2) = 1.30 \pm 0.15 \quad , \quad (17)$$

$$\mathcal{A}_{CP}(K^+\pi^0) = -\frac{2r_c \sin \delta_c \sin \gamma}{R_c} = 0.035 \pm 0.071 \quad , \quad (18)$$

where $r_c \equiv |(T + C)/P| = 0.20 \pm 0.02$, and δ_c is a strong phase, eliminated by combining (17) and (18). One must also use an estimate [46] of the electroweak penguin parameter $\delta_{EW} = 0.65 \pm 0.15$. One obtains the most conservative (i.e., weakest) bound on γ for the maximum values of r_c and δ_{EW} [12]. The resulting plot is shown in Fig. 4. One obtains a bound at the 1σ level very similar to that in the previous case: $\gamma \gtrsim 58^\circ$. The bound is actually set by the curve for *zero* CP asymmetry, as emphasized in [46].

4.3 $B^+ \rightarrow \pi^+\eta$

The possibility that several different amplitudes could contribute to $B^+ \rightarrow \pi^+\eta$, thereby leading to the possibility of a large direct CP asymmetry, has been recognized for some time [17, 29, 30, 47, 48]. Contributions can arise from a tree amplitude (color-favored plus color-suppressed) $T + C$, whose magnitude is estimated to be $\sqrt{2/3}$ that occurring in $B^+ \rightarrow \pi^+\pi^0$, a penguin amplitude P , obtained via flavor SU(3) from $B^+ \rightarrow K^0\pi^+$, and a singlet penguin amplitude S , obtained from $B \rightarrow \eta'K$.

In Table 4 we summarize branching ratios and CP asymmetries obtained for the decay $B^+ \rightarrow \pi^+\eta$ by CLEO [49], BaBar [50], and Belle [39]. We assume that the S and P amplitudes have the same weak and strong phases. The equality of their weak phases is quite likely, while tests exist for the latter assumption [33].

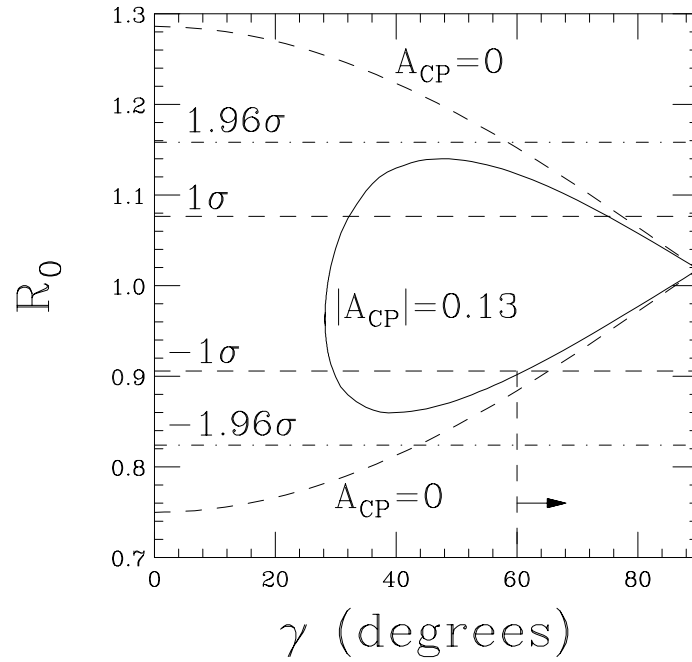


Fig. 3. Behavior of R_0 for $r = 0.13$ and $\mathcal{A}_{CP}(K^+\pi^-) = 0$ (dashed curves) or $|\mathcal{A}_{CP}(K^+\pi^-)| = 0.13$ (solid curve) as a function of the weak phase γ . Horizontal *dashed lines* denote $\pm 1\sigma$ experimental limits on R_0 , while *dot-dashed lines* denote 95% c.l. ($\pm 1.96\sigma$) limits. The upper branches of the curves correspond to the case $\cos\gamma\cos\delta < 0$, while the lower branches correspond to $\cos\gamma\cos\delta > 0$

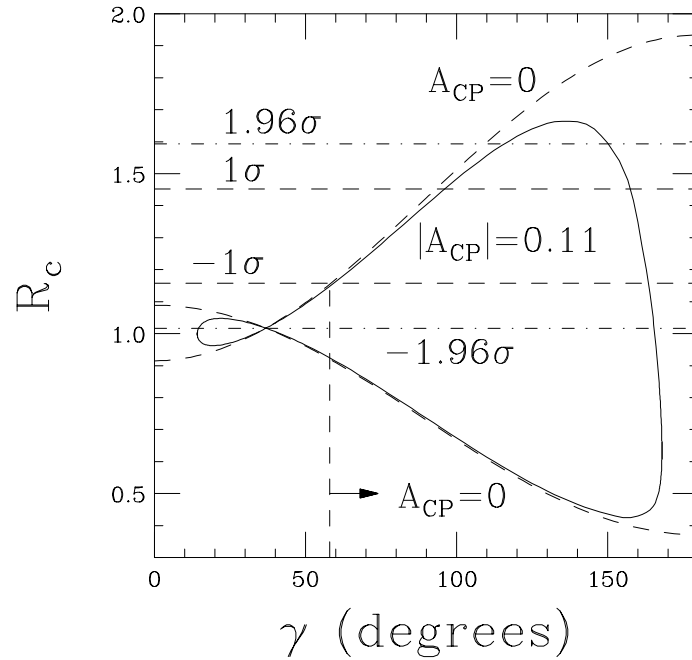


Fig. 4. Behavior of R_c for $r_c = 0.22$ (1σ upper limit) and $\mathcal{A}_{CP}(K^+\pi^0) = 0$ (dashed curves) or $|\mathcal{A}_{CP}(K^+\pi^0)| = 0.11$ (solid curve) as a function of the weak phase γ . Horizontal *dashed lines* denote $\pm 1\sigma$ experimental limits on R_c , while *dot-dashed lines* denote 95% c.l. ($\pm 1.96\sigma$) limits. Upper branches of curves correspond to $\cos\delta_c(\cos\gamma - \delta_{EW}) < 0$, while lower branches correspond to $\cos\delta_c(\cos\gamma - \delta_{EW}) > 0$. Here we have taken $\delta_{EW} = 0.80$ (its 1σ upper limit), which leads to the most conservative bound on γ

If the amplitude A for a process receives two contributions with differing strong and weak phases, one can write

$$A = a_1 + a_2 e^{i\phi} e^{i\delta} \quad , \quad \bar{A} = a_1 + a_2 e^{-i\phi} e^{i\delta} \quad . \quad (19)$$

The CP-averaged decay rate is proportional to $a_1^2 + a_2^2 + 2a_1 a_2 \cos\phi \cos\delta$, while the CP asymmetry is

$$A_{CP} = - \frac{2a_1 a_2 \sin\phi \sin\delta}{a_1^2 + a_2^2 + 2a_1 a_2 \cos\phi \cos\delta} \quad . \quad (20)$$

Table 4. Branching ratios and CP asymmetries for $B \rightarrow \pi^+ \eta$

	$\overline{\mathcal{B}} (10^{-6})$	A_{CP}
CLEO [49]	$1.2_{-1.2}^{+2.8} (< 5.7)$	–
BaBar [50]	$4.2_{-0.9}^{+1.0} \pm 0.3$	$-0.51_{-0.18}^{+0.20}$
Belle [39]	$5.2_{-1.7}^{+2.0} \pm 0.6$	–
Average	4.1 ± 0.9	$-0.51_{-0.18}^{+0.20}$
$ T + C ^2$ alone	3.5	0
$ P + S ^2$ alone	1.9	0

In the case of $B^+ \rightarrow \pi^+ \eta$ the rates and CP asymmetry suggest that $|\sin \phi \sin \delta| > |\cos \phi \cos \delta|$. Details of this pattern and its implications for other processes are described in [33]. It is predicted there that $\overline{\mathcal{B}}(B^+ \rightarrow \pi^+ \eta') = (2.7 \pm 0.7) \times 10^{-6}$ (below current upper bounds) and that $A_{CP}(\pi^+ \eta') = -0.57 \pm 0.23$.

5 Rare radiative B decays

A number of processes in which a B or B_s decays to final states with photons or lepton pairs are particularly sensitive to non-standard physics. An example is $B_s \rightarrow \mu^+ \mu^-$, for which the standard model predicts $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) = (3.1 \pm 1.4) \times 10^{-9}$ [51]. Charged Higgs boson exchanges or other effects could enhance this branching ratio significantly while respecting the constraint associated with the branching ratio for $b \rightarrow s \gamma$, which appears compatible with standard model predictions. For a good discussion of this process and of $B \rightarrow X_s \ell^+ \ell^-$ see [52], as well as several presentations at the present conference [53]. In the latter decay the forward-backward asymmetries exhibit interesting behavior as a function of $m(\ell^+ \ell^-)$, with signs and a characteristic zero in the standard model which can be different in variant theories.

6 B_s properties and decays

6.1 B_s - \overline{B}_s mixing

The ratio of the B_s - \overline{B}_s mixing amplitude Δm_s to the B^0 - \overline{B}^0 mixing amplitude Δm_d ($B_d \equiv B^0$) is given by

$$\frac{\Delta m_s}{\Delta m_d} = \frac{f_{B_s}^2 B_{B_s} m_{B_s}}{f_{B_d}^2 B_{B_d} m_{B_d}} \left| \frac{V_{ts}}{V_{td}} \right|^2 \simeq 48 \times 2^{\pm 1} \quad (21)$$

Here $f_{B_{d,s}}$ are meson decay constants, while $B_{B_{d,s}}$ are numbers of order 1 expressing the degree to which the mixing amplitude can be calculated by saturating with vacuum intermediate states. The latest lattice estimate of the ratio $\xi \equiv (f_{B_s}/f_{B_d})\sqrt{B_{B_s}/B_{B_d}}$ is $1.21 \pm 0.04 \pm 0.05$ [54]. We have taken a generous range

$$|V_{td}| = A\lambda^3 |1 - \bar{\rho} - i\bar{\eta}| = (0.8 \pm 0.2)A\lambda^3 \quad (22)$$

with $|V_{ts}| = A\lambda^2$ and $\lambda = 0.22$. With [42] $\Delta m_d = 0.503 \pm 0.007 \text{ ps}^{-1}$ one then predicts

$$\Delta m_s = 24 \text{ ps}^{-1} \times 2^{\pm 1} \quad (23)$$

The lower portion of this range is already excluded by the bound [42]

$$\Delta m_s > 14.4 \text{ ps}^{-1} \text{ (95\% c.l.)} \quad (24)$$

When Δm_s is measured it is likely to be known fairly well immediately, and will constrain $\bar{\rho}$ significantly.

6.2 Decays to CP eigenstates

6.2.1 $B_s \rightarrow J/\psi \phi, J/\psi \eta, \dots$

Since the weak phase in $\bar{b} \rightarrow \bar{c} \bar{c} s$ is expected to be zero while that of B_s - \overline{B}_s mixing is expected to be very small [in the parametrization of (1) an imaginary part $\text{Im}(V_{ts}) = -A\lambda^4 \eta$ was not written explicitly], one expects CP asymmetries to be only a few percent in the standard model for those B_s decays dominated by this quark subprocess. The $B_s \rightarrow J/\psi \phi$ final state is not a CP eigenstate but the even and odd CP components can be separated using an angular analysis. The final states of $B_s \rightarrow J/\psi \eta$ and $B_s \rightarrow J/\psi \eta'$ are CP-even so no such analysis is needed.

6.2.2 $B_s \rightarrow K^+ K^-$ vs. $B^0 \rightarrow \pi^+ \pi^-$

A comparison of time-dependent asymmetries in $B_s \rightarrow K^+ K^-$ and $B^0 \rightarrow \pi^+ \pi^-$ [55] allows one to separate out strong and weak phases and relative tree and penguin contributions. In $B_s \rightarrow K^+ K^-$ the $\bar{b} \rightarrow \bar{s}$ penguin amplitude is dominant, while the strangeness-changing tree amplitude $\bar{b} \rightarrow \bar{u} u s$ is subsidiary. In $B^0 \rightarrow \pi^+ \pi^-$ it is the other way around: The $\bar{b} \rightarrow \bar{u} u d$ tree amplitude dominates, while the $\bar{b} \rightarrow \bar{d}$ penguin is Cabibbo-suppressed. The U-spin subgroup of SU(3), which interchanges s and d quarks, relates each amplitude in one process to that in the other aside from the CKM factors.

6.2.3 $\overline{B}_s, B^0 \rightarrow K^+ \pi^-$

A potential problem with $B_s \rightarrow K^+ K^-$ and $B^0 \rightarrow \pi^+ \pi^-$ is that the mass peaks will overlap with one another if analyzed in terms of the same final state (e.g., $\pi^+ \pi^-$) [56]. Thus, in the absence of good particle identification, a variant on this scheme employing the decays $B^0 \rightarrow K^+ \pi^-$ and $B_s \rightarrow K^- \pi^+$ (also related to one another by U-spin) may be useful [57]. For these final states, kinematic separation may be easier. A further variant is to study the time-dependence of $B_s \rightarrow K^+ K^-$ while normalizing the penguin amplitude using $B_s \rightarrow K^0 \overline{K}^0$ [58].

6.3 Other SU(3) relations

The U-spin subgroup of SU(3) allows one to relate many other B_s decays besides those mentioned above to corresponding B_d decays [59]. Particularly useful are relations between CP-violating rate *differences*. One thus will have the opportunity to perform many tests of flavor SU(3) and to learn a great deal more about final-state phase patterns when a variety of B_s decays can be studied.

7 Excited states

7.1 Flavor tagging for neutral B mesons

One promising method for tagging the flavor of a neutral B meson is to study the charge of the leading light hadron accompanying the fragmentation of the heavy quark. This method was initially proposed by Ali and Barreiro [60] to identify the flavor of a B_s via the charge of the accompanying kaon. It was utilized in [61,62] to distinguish B^0 's from \bar{B}^0 's. An initial b will fragment into a \bar{B}^0 by “dressing” itself with a \bar{d} . The accompanying d , if incorporated into a charged pion, will end up in a π^- . Thus a π^- is more likely to be “near” a \bar{B}^0 than to a B^0 in phase space. This correlation between π^- and \bar{B}^0 (and the corresponding correlation between π^+ and B^0) is also what one would expect on the basis of non-exotic resonance formation. Thus the study of the resonance spectrum of the excited B mesons which can decay to $B + \pi$ or $B^* + \pi$ is of special interest [63]. The lowest such mesons are the P-wave levels of a \bar{b} antiquark and a light (u or d) quark.

7.2 Surprise: Excited D_s state below DK threshold

A new sensation has been reported by the BaBar Collaboration [64] and confirmed by CLEO [65]. Partial information on the P-wave levels of a charmed quark c and an antistrange \bar{s} consists of candidates for $J = 1$ and $J = 2$ states at 2535 and 2572 MeV [66]. These levels have narrow widths and are behaving as would be expected if the spin of the \bar{s} and the orbital angular momentum were coupled up to $j = 3/2$. (One expects j - j rather than L - S coupling in a light-heavy system [67,68,69].) If the $j = 1/2$ states were fairly close to these in mass one would then expect another $J = 1$ state and a $J = 0$ state somewhere above 2500 MeV. Instead, a candidate for a $J = 0$ $c\bar{s}$ state has been found around 2317 MeV, with the second $J = 1$ level around 2463 MeV. Both are narrow, since they are too light to decay respectively to DK or D^*K . They decay instead via the isospin-violating transitions $D_{s0}(2317) \rightarrow D_s\pi^0$ and $D_{s1}(2463) \rightarrow D_s^*\pi^0$. They are either candidates for $D^{(*)}K$ molecules [70], or indications of a broken chiral symmetry which places them as positive-parity partners of the D_s and D_s^* negative-parity $c\bar{s}$ ground states [71]. Indeed, the mass splittings between the parity partners appear to be exactly as predicted ten years ago [72]. Potential-based quarkonium models have a hard time accommodating such low masses [73,74,75],

There should exist *non-strange* $j = 1/2$ 0^+ and 1^+ states, lower in mass than the $j = 3/2$ states at 2422 and 2459 MeV [66] but quite broad since their respective $\bar{B}\pi$ and $\bar{B}^*\pi$ channels will be open. The study of such states will be of great interest since the properties of the corresponding B -flavored states will be useful in tagging the flavor of neutral B mesons, as noted in the previous subsection.

7.3 Narrow positive-parity states below $\bar{B}^{(*)}K$ threshold?

If a strange antiquark can bind to a charmed quark in both negative- and positive-parity states, the same must be true for a strange antiquark and a b quark. One should then expect to see narrow $J^P = 0^+$ and 1^+ states with the quantum numbers of $\bar{B}K$ and \bar{B}^*K but below those respective thresholds. They should decay to $\bar{B}_s\pi^0$ and $\bar{B}_s^*\pi^0$, respectively. To see such decays one will need a multi-purpose detector with good charged particle and π^0 identification! Such detectors are envisioned for both the Tevatron [76] and the LHC [77].

8 Exotic $Q = -1/3$ quarks

Might there be heavier quarks visible at hadron colliders? At present we have evidence for three families of quarks and leptons belonging to 16-dimensional multiplets of the grand unified group SO(10) (counting right-handed neutrinos as a reasonable explanation of the observed oscillations between different flavors of neutrinos). Now, just as SO(10) was pieced together from multiplets of SU(5) with dimensions 1, 5, and 10, we can imagine a still larger grand unified group whose smallest representation contains the 16-dimensional SO(10) spinor. Such a group is the exceptional group E_6 [78]. Its smallest representation, of dimension 27, contains a 16-dimensional spinor, a 10-dimensional vector, and a singlet of SO(10). The 10-dimensional vector contains vector-like isosinglet quarks “ h ” and antiquarks \bar{h} of charge $Q = \pm 1/3$ and isodoublet leptons. The SO(10) singlets are candidates for sterile neutrinos, one for each family.

The new exotic h quarks can mix with the b quark and push its mass down with respect to the top quark [79]. Troy Andre and I are currently looking at signatures of $h\bar{h}$ production in hadron colliders, with an eye to either setting lower mass limits or seeing such quarks through their decays to $Z + b$, $W + t$, and possibly Higgs + b . The Z , for example, would be identified by its decays to $\nu\bar{\nu}$, $\ell^+\ell^-$, or jet + jet, while the Higgs boson would show up through its $b\bar{b}$ decay if it were far enough below W^+W^- threshold.

9 Summary

The process $B^0 \rightarrow J/\psi K_S$ has provided spectacular confirmation of the Kobayashi-Maskawa theory of CP violation, measuring β to a few degrees. Now one is entering the territory of more difficult measurements.

The decay $B^0 \rightarrow \pi^+\pi^-$ has great potential for giving useful information on α . One needs either a measurement of $\mathcal{B}(B^0 \rightarrow \pi^0\pi^0)$ [11], probably at the 10^{-6} level (present limits [38,39,40] are several times that), or a better estimate of the tree amplitude from $B \rightarrow \pi l\nu$ [18]. Indeed, such an estimate has been presented recently [80]. The BaBar and Belle experimental CP asymmetries [19,20] will eventually converge to one another, as did the initial measurements of $\sin 2\beta$ using $B^0 \rightarrow J/\psi K_S$.

The $B \rightarrow \phi K_S$ decay can display new physics via special $\bar{b} \rightarrow \bar{s}s\bar{s}$ operators or effects on the $\bar{b} \rightarrow \bar{s}$ penguin. Some features of any new amplitude can be extracted from the data in a model-independent way if one uses both rate and asymmetry information [26]. While the effective value of $\sin 2\beta$ in $B^0 \rightarrow \phi K_S$ seems to differ from its expected value by more than 2σ , CP asymmetries in $B \rightarrow K_S(K^+K^-)_{CP=+}$ do not seem anomalous.

The rate for $B \rightarrow \eta' K_S$ is not a problem for the standard model if one allows for a modest flavor-singlet penguin contribution in addition to the standard penguin amplitude. The CP asymmetries for this process are in accord with the expectations of the standard model at the 1σ level or better. Effects of the singlet penguin amplitude may also be visible elsewhere, for example in $B^+ \rightarrow p\bar{p}K^+$.

Various ratios of $B \rightarrow K\pi$ rates, when combined with information on CP asymmetries, show promise for constraining phases in the CKM matrix. These tests have shown a steady improvement in accuracy since the asymmetric B factories have been operating. One expects further progress as instantaneous and accumulated e^+e^- luminosities increase, and as hadron colliders begin to provide important contributions. The decays $B^+ \rightarrow \pi^+\eta$ and $B^+ \rightarrow \pi^+\eta'$ show promise for displaying large CP asymmetries [33] since they involve contributions of different amplitudes with comparable magnitudes.

Rare decays of nonstrange and strange B 's involving photons or lepton pairs are beginning to be studied in detail, and the LHC will be able to look for the rare and interesting $B_s \rightarrow \mu^+\mu^-$ decay which can greatly exceed its standard model value in some theories. In the near term the prospects for learning about the $B_s-\bar{B}_s$ mixing amplitude are good. One hopes that this will be an early prize of Run II at the Tevatron. The study of CP violation and branching ratios in B_s decays will be an almost exclusive province of hadron colliders, whose potentialities will be limited only by the versatility of detectors. Surprises in spectroscopy, as illustrated by the low-lying positive-parity $c\bar{s}$ candidates, still can occur, and one is sure to find more surprises at the Tevatron and the LHC. Finally, one can search for objects related to the properties of b quarks, such as the exotic isosinglet quarks h , with improved sensitivity in Run II of the Tevatron and with greatly expanded reach at the LHC.

Acknowledgements. I wish to thank my collaborators on some of the topics mentioned here: Troy Andre, Cheng-Wei Chiang, Michael Gronau, Zumin Luo, and Denis Suprun. Michael Gronau and Hassan Jawahery also made helpful comments on the manuscript. This work was supported in part by the United States Department of Energy under Grant No. DE FG02 90ER40560.

References

1. L. Wolfenstein: Phys. Rev. Lett. **51**, 1945 (1983).
2. M. Battaglia et al.: to appear as a CERN Yellow Report, based on the Workshop on CKM Unitarity Triangle (CERN 2002-2003), Geneva, Switzerland, preprint hep-ph/0304132
3. A. Höcker et al.: Eur. Phys. J. C **21** (2001) 225; Updated results may be found on the web site <http://ckmfitter.in2p3.fr/>
4. M. Ciuchini et al.: JHEP **0107**, 013 (2001)
5. P.F. Harrison et al.: *The BaBar Physics Book: Physics at an Asymmetric B Factory*, SLAC Report No. SLAC-R-0504, 1998
6. J.L. Rosner: in *Flavor Physics for the Millennium* (TASI 2000), edited by J.L. Rosner (World Scientific, Singapore, 2001), p. 431
7. BaBar Collaboration, B. Aubert et al.: Phys. Rev. Lett. **89**, 201802 (2002)
8. Belle Collaboration, K. Abe et al.: Phys. Rev. D **66**, 071102 (2002)
9. Y. Nir: presented at XXXI International Conference on High Energy Physics, Amsterdam, July, 2002, Nucl. Phys. B Proc. Suppl. **117**, 111 (2003)
10. A. Ali and D. London: Eur. Phys. J. C **18** (2001) 665
11. M. Gronau and D. London: Phys. Rev. Lett. **65**, 3381 (1990)
12. M. Gronau and J.L. Rosner: Phys. Rev. D **65**, 013004 (2002); **65** (2002) 079901(E); **65** (2002) 093012
13. M. Gronau and J.L. Rosner: Phys. Rev. D **66**, 053003 (2002); **66** (2002) 119901(E)
14. J.P. Silva and L. Wolfenstein: Phys. Rev. D **49**, 1151 (1994)
15. M. Gronau, O.F. Hernandez, D. London, and J.L. Rosner: Phys. Rev. D **50**, 4529 (1994); **52** (1995) 6356; **52** (1995) 6374
16. J. Charles: Phys. Rev. D **59**, 054007 (1999)
17. M. Gronau and J.L. Rosner: Phys. Rev. D **53**, 2516 (1996); Phys. Rev. Lett. **76**, 1200 (1996)
18. Z. Luo and J.L. Rosner: Phys. Rev. D **65**, 054027 (2002)
19. BaBar Collaboration, B. Aubert et al.: Phys. Rev. Lett. **89**, 281802 (2002)
20. Belle Collaboration, K. Abe et al.: hep-ex/0301032, submitted to Phys. Rev. D.
21. Y. Grossman and M. Worah: Phys. Lett. B **395**, 241 (1997)
22. G. Hamel de Monchenault: 38th Rencontres de Moriond on Electroweak Interactions and Unified Theories, Les Arcs, France, 15–22 March 2003, hep-ex/0305055
23. Belle Collaboration, K. Abe et al.: Phys. Rev. D **67**, 031102 (2003)
24. BaBar Collaboration, B. Aubert et al.: SLAC-Report No. SLAC-PUB-9684, hep-ex/0303029, 38th Rencontres de Moriond on Electroweak Interactions and Unified Theories, Les Arcs, France, 15–22 March 2003
25. G. Hiller: Phys. Rev. D **66**, 071502 (2002); M. Ciuchini and L. Silvestrini: Phys. Rev. Lett. **89**, 231802 (2002); A. Datta: Phys. Rev. D **66**, 071702 (2002); M. Raidal: Phys. Rev. Lett. **89**, 231803 (2002); B. Dutta, C.S. Kim, and S. Oh: Phys. Rev. Lett. **90**, 011801 (2003); S. Khalil and E. Kou: Phys. Rev. D **67**, 055009 (2003) and hep-ph/0303214; G.L. Kane, P. Ko, H. Wang, C. Kolda, J.h. Park, and L.T. Wang: Phys. Rev. Lett. **90**, 141803 (2003); S. Baek: Phys. Rev. D **67**, 096004 (2003); A. Kundu and T. Mitra: Phys. Rev. D **67**, 116005 (2003); K. Agashe and C.D. Carone, hep-ph/0304229

26. C.-W. Chiang and J.L. Rosner: hep-ph/0302094, to be published in Phys. Rev. D.
27. Y. Grossman, Z. Ligeti, Y. Nir, and H. Quinn: SLAC Report No. SLAC-PUB-9670, hep-ph/0303171 (unpublished)
28. M. Gronau and J.L. Rosner: Phys. Lett. B **564**, 90 (2003)
29. A.S. Dighe, M. Gronau, and J.L. Rosner: Phys. Lett. B **367**, 357 (1996); **377** (1996) 325(E)
30. A.S. Dighe, M. Gronau, and J.L. Rosner: Phys. Rev. Lett. **79**, 4333 (1997)
31. C.-W. Chiang and J.L. Rosner, Phys. Rev. D **65**, 074035 (2002)
32. H.-K. Fu, X.-G. He, and Y.-K. Hsiao: preprint hep-ph/0304242
33. C.-W. Chiang, M. Gronau, and J. L. Rosner: Enrico Fermi Institute Report No. 03-24, hep-ph/0306021, submitted to Phys. Rev. D.
34. M. Beneke and M. Neubert: Nucl. Phys. B **651**, 225 (2003)
35. Belle Collaboration, K. Abe et al.: Phys. Rev. Lett. **88**, 181803 (2002)
36. J.L. Rosner: Enrico Fermi Institute Report No. 03-11, hep-ex/0303079, to be published in Phys. Rev. D.
37. R. Fleischer and T. Mannel: Phys. Rev. D **57**, 2752 (1998)
38. BaBar Collaboration, B. Aubert et al.: quoted by S. Playfer at LHCb Workshop, CERN, February 2003
39. Belle Collaboration: presented by T. Tomura at 38th Rencontres de Moriond on Electroweak Interactions and Unified Theories, Les Arcs, France, 15–22 March 2003, hep-ex/0305036
40. CLEO Collaboration, A. Bornheim et al.: Cornell Laboratory of Nuclear Science Report No. CLNS-03-1816, hep-ex/0302026, submitted to Phys. Rev. D.
41. J.L. Rosner: 38th Rencontres de Moriond on Electroweak Interactions and Unified Theories, Les Arcs, France, 15–22 March 2003, Enrico Fermi Institute Report No. 03-16, hep-ph/0304200
42. LEP B Oscillations Working Group: <http://lepboseb.web.cern.ch/LEPBOSC/>
43. M. Gronau and J.L. Rosner: Phys. Rev. D **57**, 6843 (1998)
44. M. Gronau, J.L. Rosner, and D. London: Phys. Rev. Lett. **73**, 21 (1994)
45. R. Fleischer: Phys. Lett. B **365**, 399 (1994); N.G. Deshpande and X.-G. He: Phys. Rev. Lett. **74**, 26 (1995); **74** (1995) 4099(E)
46. M. Neubert and J.L. Rosner: Phys. Lett. B **441**, 403 (1998); Phys. Rev. Lett. **81**, 5076 (1998); M. Neubert: JHEP **9902**, 014 (1999)
47. S. Barshay, D. Rein, and L.M. Sehgal: Phys. Lett. B **259**, 475 (1991)
48. M.R. Ahmady and E. Kou: Phys. Rev. D **59**, 054014 (1999)
49. CLEO Collaboration, S.J. Richichi et al.: Phys. Rev. Lett. **85**, 520 (2000)
50. BaBar Collaboration, B. Aubert et al.: SLAC Report No. SLAC-PUB-9962, hep-ex/0303039, 38th Rencontres de Moriond on QCD and High Energy Hadronic Interactions, 22–29 March, 2003, Les Arcs, France
51. C. Bobeth, T. Ewerth, F. Kruger, and J. Urban: Phys. Rev. D **64**, 074104 (2001)
52. G. Hiller: presented at 5th International Conference on Hyperons, Charm and Beauty Hadrons (BEACH 2002), Vancouver, Canada, 25–29 June 2002, Nucl. Phys. B Proc. Suppl. **115**, 76 (2003)
53. See in particular the presentations on b physics reach of CMS by V. Ciulli and of ATLAS by M. Smizanska, this conference
54. D. Becirevic: 38th Rencontres de Moriond on Electroweak Interactions and Unified Theories, Les Arcs, France, 15–22 March 2003
55. R. Fleischer: Phys. Lett. B **459**, 306 (1999)
56. R. Jesik and M. Pettini: in *B Physics at the Tevatron: Run II and Beyond*, Fermilab Report No. FERMILAB-PUB-01/197, hep-ph/0201071, p. 179. [See especially Fig. 6.12(b)]
57. M. Gronau and J.L. Rosner: Phys. Lett. B **482**, 71 (2000)
58. M. Gronau and J.L. Rosner: Phys. Rev. D **65**, 113008 (2002)
59. M. Gronau: Phys. Lett. B **492**, 297 (2000)
60. A. Ali and F. Barreiro: Zeit. Phys. C **30**, 635 (1986)
61. M. Gronau, A. Nippe, and J.L. Rosner: Phys. Rev. D **47**, 1988 (1993)
62. M. Gronau and J.L. Rosner: Phys. Rev. Lett. **72**, 195 (1994); Phys. Rev. D **49**, 254 (1994); **63** (2001) 054006; **64** (2001) 099902(E)
63. E. Eichten, C. Hill, and C. Quigg: Phys. Rev. Lett. **71**, 4116 (1993)
64. BaBar Collaboration, B. Aubert et al.: SLAC Report No. SLAC-PUB-9711, hep-ex/0304021
65. CLEO Collaboration, D. Besson et al.: Cornell University Report No. CLNS 03/1826, hep-ex/0305100, submitted to Phys. Rev. D.
66. Particle Data Group, K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002)
67. A. De Rújula, H. Georgi, and S.L. Glashow: Phys. Rev. Lett. **37**, 785 (1976)
68. J.L. Rosner: Comments on Nucl. Part. Phys. **16** (1986) 109
69. M. Lu, M. Wise, and N. Isgur: Phys. Rev. D **45**, 1553 (1992)
70. T. Barnes, F. Close, and H.J. Lipkin: preprint hep-ph/0305025
71. W.A. Bardeen, E. Eichten, and C.T. Hill: Fermilab Report No. FERMILAB-PUB-03-071-T, hep-ph/0305049
72. W.A. Bardeen and C.T. Hill: Phys. Rev. D **49**, 409 (1994). Chiral partners of the ground states of heavy mesons were independently predicted by M. A. Nowak, M. Rho, and I. Zahed: Phys. Rev. D **48**, 4370 (1993). See also D. Ebert, T. Feldmann, R. Friedrich, and H. Reinhardt: Nucl. Phys. B **434**, 619 (1995); D. Ebert, T. Feldmann, and H. Reinhardt: Phys. Lett. B **388**, 154 (1996)
73. R.N. Cahn and J.D. Jackson: Lawrence Berkeley National Laboratory Report No. LBNL-52572, hep-ph/0305012 (unpublished)
74. S. Godfrey, preprint hep-ph/0305122 (unpublished)
75. P. Colangelo and F. De Fazio: INFN Bari Report No. BARI-TH-03-462, hep-ph/0305140 (unpublished)
76. See, e.g., the talk by K. Honscheid on the physics reach of BTeV, this conference
77. See, e.g., the talk by M. Musy on the physics reach of LHCb, this conference
78. F. Gürsey, P. Ramond, and P. Sikivie: Phys. Lett. B **60**, 177 (1976)
79. J.L. Rosner: Phys. Rev. D **61**, 097303 (2000)
80. Z. Luo and J.L. Rosner: Enrico Fermi Institute Report No. 03-25, hep-ph/0305262, submitted to Phys. Rev. D.