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Two-body Modes of B Mesons and The CP-b Triangle[1]

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Abstract

The study of charmless two-body decays of B mesons is currently one of the hottest topics in B physics. QCD factorization provides the theoretical framework for a systematic analysis of such decays. A global fit to $B \to \pi K, \pi\pi$ branching fractions, combined with knowledge on $|V_{ub}|$, establishes the existence of a CP-violating phase in the bottom sector of the CKM matrix and tends to favor values of γ near 90°, somewhat larger than those suggested by the standard analysis of the unitarity triangle. A novel construction of the unitarity triangle is presented, which is independent of B–$\bar{B}$ and K–$\bar{K}$ mixing. It can provide stringent tests of the Standard Model with small theoretical uncertainties.

[1]Invited plenary talk presented at the 6^{th} International Workshop on *Heavy Quarks and Leptons*, Vietri sul mare, Salerno, Italy (May 27–June 1, 2002), and at the International High-Energy Physics Conference on *Quantum Chromodynamics*, Montpellier, France (July 2–9, 2002)

1 Introduction

Measurements of $|V_{ub}|$ in semileptonic decays, $|V_{td}|$ in B–$\bar{B}$ mixing, and $\mathrm{Im}(V_{td}^2)$ from CP violation in K–$\bar{K}$ and B–$\bar{B}$ mixing have firmly established the existence of a CP-violating phase in the CKM matrix. The present situation, often referred to as the "standard analysis" of the unitarity triangle, is summarized in Figure 1.

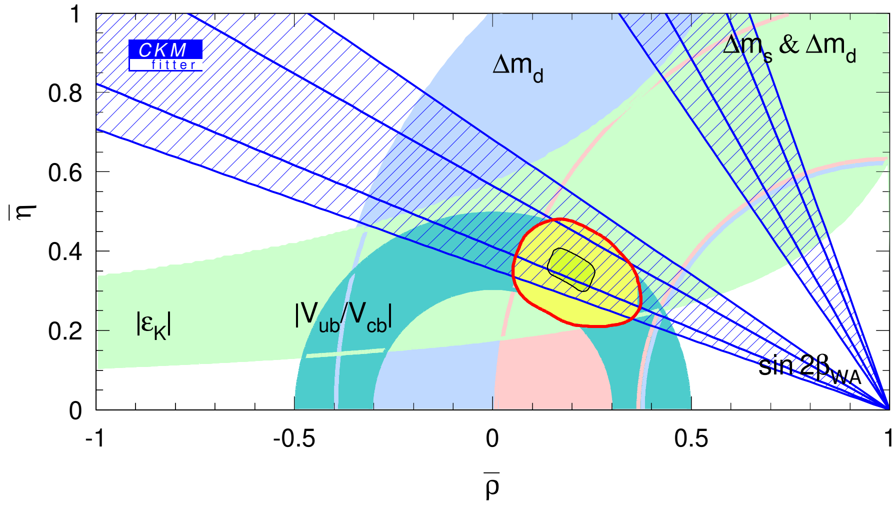

Figure 1: Standard constraints on the apex $(\bar{\rho}, \bar{\eta})$ of the unitarity triangle [1].

Three comments are in order concerning this analysis:

1. The measurements of CP asymmetries in kaon physics (ϵ_K and ϵ'/ϵ) and B–$\bar{B}$ mixing ($\sin 2\beta$) probe the imaginary part of V_{td} and so establish CP violation in the top sector of the CKM matrix.[2] The CKM model predicts that the imaginary part of V_{td} is related, by three-generation unitarity, to the imaginary part of V_{ub}, and that those two elements are (to an excellent approximation) the only sources of CP violation in flavor-changing processes. In order to test this prediction, the next step must be to explore the CP-violating phase $\gamma = \arg(V_{ub}^*)$ in the bottom sector of the CKM matrix. In this talk I argue that the analysis of charmless hadronic B decays has by now established unambiguously that $\arg(V_{ub}^*) \neq 0$.

2. With the exception of the $\sin 2\beta$ measurement, the standard analysis is limited by large theoretical uncertainties, which dominate the widths of the various bands in the figure. These uncertainties enter via the calculation of hadronic matrix elements. I will discuss some novel methods to constrain the unitarity triangle using charmless hadronic B decays, which are afflicted by smaller hadronic uncertainties and hence provide powerful new tests of the Standard Model, which can complement the standard analysis.

[2] Here I adopt the standard phase conventions for the CKM matrix. The corresponding convention-independent statement is that $\mathrm{Im}[(V_{td}V_{ts}^*)/(V_{cd}V_{cs}^*)] \neq 0$ and $\mathrm{Im}[(V_{td}V_{tb}^*)/(V_{cd}V_{cb}^*)] \neq 0$.

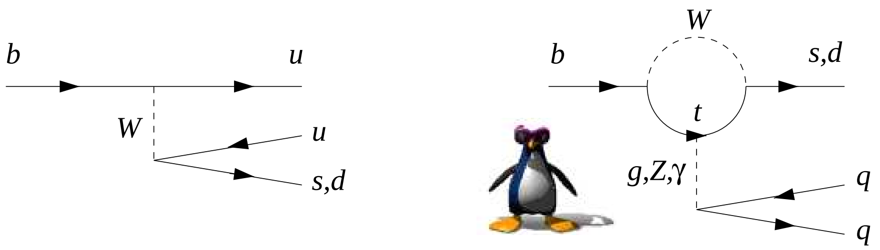

Figure 2: Tree and penguin topologies in charmless hadronic B decays.

3. With the exception of the measurement of $|V_{ub}|$ in semileptonic B decays, the standard constraints are sensitive to meson–antimeson mixing. Mixing amplitudes are of second order in weak interactions and hence might be most susceptible to effects from physics beyond the Standard Model. The new constraints on $(\bar{\rho}, \bar{\eta})$ discussed below allow a construction of the unitarity triangle that is over-constrained and independent of B–$\bar{B}$ and K–$\bar{K}$ mixing. It is in this sense orthogonal to the standard analysis.

The phase γ can be probed via tree–penguin interference in decays such as $B \to \pi K, \pi\pi$, for which the underlying flavor topologies are illustrated in Figure 2. Experiment teaches us that amplitude interference is sizable in these decays. Information about γ can be obtained not only from the measurement of direct CP asymmetries ($\sim \sin\gamma$), but also from the study of CP-averaged branching fractions ($\sim \cos\gamma$). The challenge is, of course, to gain theoretical control over the hadronic physics entering the tree-to-penguin ratios in the various decays.

2 QCD Factorization

Hadronic weak decays simplify greatly in the heavy-quark limit $m_b \gg \Lambda_{\mathrm{QCD}}$. The underlying physics is that a fast-moving light meson produced by a point-like source (the effective weak Hamiltonian) decouples from soft QCD interactions [2, 3, 4]. A systematic implementation of this color transparency argument is provided by the QCD factorization approach [5, 6]. This scheme makes rigorous predictions in the heavy-quark limit, some of which have been proven to all orders of perturbation theory [7]. One can hardly overemphasize the importance of controlling nonleptonic decay amplitudes in the heavy-quark limit. While a few years ago reliable calculations of such amplitudes appeared to be out of reach, we are now in a situation where hadronic uncertainties enter only at the level of power corrections suppressed by the heavy b-quark mass.

The workings of QCD factorization are illustrated in Figure 3. The graph on the left shows how in the familiar construction of the effective weak Hamiltonian hard gluon effects with virtualities $\mu \gg m_b$ can be calculated and factorized into Wilson coefficients $C_i(\mu)$. The graphs on the right illustrate how, in a similar way, hard gluon effects with $\mu \sim m_b$ can be calculated and factorized into perturbative hard-scattering kernels

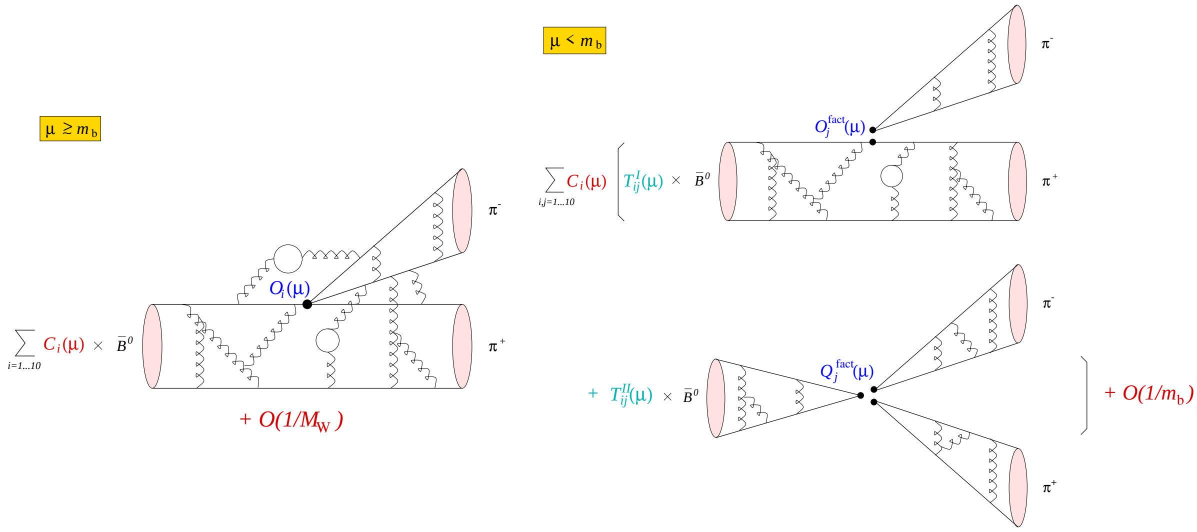

Figure 3: Factorization of short- and long-distance contributions into running couplings and hadronic matrix elements. Left: Integrating out hard gluons ($k \sim M_W$) in the construction of the effective weak Hamiltonian. Right: Integrating out hard gluons ($k \sim m_b$) in the construction of the effective, factorized transition operator in QCD factorization.

$T_{ij}(\mu)$. What remains after this step are factorized decay amplitudes, in which all gluon exchange between the emission meson at the "upper vertex" and the remaining hadronic system are integrated out. In the heavy-quark limit, such "nonfactorizable gluons" are hard because of color transparency. Note that this does not imply that nonleptonic amplitudes in the heavy-quark limit are perturbative. (In this respect, our approach is more general that the pQCD scheme [8].) Important nonperturbative effects remain, which can be parameterized in terms of meson decay constants, $B \to M$ transition form factors, and meson light-cone distribution amplitudes. These quantities are an input to the factorization formula, ideally taken from experiment. Theoretical expressions for decay amplitudes obtained using the QCD factorization approach are complicated and depend on many input parameters. When discussing the theoretical uncertainties and limitations of this scheme it is important to distinguish between different classes of parameters. In order of phenomenological importance, these are Standard Model parameters ($\bar{\rho}$, $\bar{\eta}$, m_s, m_c, α_s), the renormalization scale (μ), hadronic quantities that can (at least in principle) be determined from data (decay constants, transition form factors), and hadronic quantities that can only indirectly be constrained by data (light-cone distribution amplitudes).

The most important question with regard to phenomenological applications of QCD factorization is that about the numerical size of power corrections. While the importance of the heavy-quark limit to the workings of factorization is evident from a comparison of nonfactorizable effects seen in kaon, charm and beauty decays [9], and while there is a lot of evidence (from spectroscopy, exclusive semileptonic decays, and various inclusive decays) that power corrections are small at the b-quark scale, it is nevertheless important to address the issue of power corrections in a systematic way. Much effort has been devoted in the past few years to the study of power-suppressed effects, which in general violate factorization. The most important power corrections are proportional to the ratios $2m_K^2/(m_s m_b)$ or $2m_\pi^2/(m_q m_b)$ with $q = u, d$, which are inversely proportional to light-quark masses. Such twist-3 corrections make up for a significant portion of the penguin amplitudes in B decays into light pseudoscalar mesons. It is important that these penguin contributions are calculable despite their power suppression and hence can be included reliably [6]. At the same order, there appear logarithmically divergent twist-3 corrections to the leading-twist hard spectator interactions. These corrections are universal, and their effect can be absorbed into a redefinition of a single hadronic parameter λ_B.

Perhaps the largest uncertainty from power corrections is due to weak annihilation contributions, for which both of the valence quarks of the initial B meson participate in the weak interactions [8, 10]. Annihilation amplitudes violate factorization and thus cannot be reliably computed using the QCD factorization approach. Although we find that with default parameter values the annihilation amplitudes are typically small, their effects can become sizable when the large model uncertainties in their estimate are taken into account [6]. Other types of power corrections, such as soft nonfactorizable gluon exchange, have been investigated using QCD sum rules [11] and the renormalon calculus [12, 13]. No large corrections of this type have been identified.

While it is a conceptual challenge to gain a better control over the leading power corrections to QCD factorization, perhaps using the framework of the soft-collinear effective theory [14, 15, 16], it is important that this approach makes many testable predictions. Their comparison with experimental data can teach us a lot about the importance of power-suppressed effects.

3 Testing Factorization in $B \to \pi K, \pi\pi$ Decays

Deriving constraints on the unitarity triangle from charmless hadronic B decays requires controlling the interference of tree and penguin topologies. This means that one must be able to predict not only the magnitudes of these contributions, but also their relative strong-interaction phase. Fortunately, the crucial aspects of such calculations can be tested using experimental data.

The magnitude of the leading $B \to \pi\pi$ tree amplitude can be probed in the decays $B^\pm \to \pi^\pm\pi^0$, which to an excellent approximation do not receive any penguin contributions. The QCD factorization approach makes an absolute prediction for the corresponding branching ratio [6],

$$\mathrm{Br}(B^\pm \to \pi^\pm\pi^0) = \left[5.3\,^{+0.8}_{-0.4}\,(\mathrm{pars.}) \pm 0.3\,(\mathrm{power})\right] \cdot 10^{-6} \times \left[\frac{|V_{ub}|}{0.0035}\,\frac{F_0^{B\to\pi}(0)}{0.28}\right]^2 ,$$

which compares well with the experimental result $(4.9 \pm 1.1) \times 10^{-6}$ [17]. The theoretical uncertainties quoted are due to input parameter variations and to the modeling of power corrections. An additional uncertainty comes from the present error on $|V_{ub}|$ and the $B \to \pi$ form factor.

The magnitude of the leading $B \to \pi K$ penguin amplitude can be probed in the decays $B^\pm \to \pi^\pm K^0$, which to an excellent approximation do not receive any tree contributions. Combining it with the measurement of the tree amplitude just described, a tree-to-penguin ratio can be determined via the relation

$$\varepsilon_{\rm exp} = \left|\frac{T}{P}\right| = \tan\theta_C \, \frac{f_K}{f_\pi} \left[\frac{2\mathrm{Br}(B^\pm \to \pi^\pm \pi^0)}{\mathrm{Br}(B^\pm \to \pi^\pm K^0)}\right]^{1/2} = 0.205 \pm 0.025 \,.$$

The experimental value of this ratio is in good agreement with the theoretical prediction $\varepsilon_{\rm th} = 0.23 \pm 0.04\,(\text{pars.}) \pm 0.04\,(\text{power}) \pm 0.05\,(V_{ub})$ [6], which is independent of form factors but proportional to $|V_{ub}/V_{cb}|$. This is a highly nontrivial test of the QCD factorization approach. Recall that when the first measurements of charmless hadronic decays appeared several authors remarked that the penguin amplitudes were much larger than expected based on naive factorization models. We now see that QCD factorization naturally reproduces the correct magnitude of the tree-to-penguin ratio. This observation also shows that there is no need to supplement the QCD factorization predictions in an ad hoc way by adding enhanced phenomenological penguin amplitudes, such as the "nonperturbative charming penguins" introduced in [18].

QCD factorization predicts that most strong-interaction phases in charmless hadronic B decays are parametrically suppressed in the heavy-quark limit, because

$$\sin\phi_{\rm st} = O[\alpha_s(m_b), \Lambda_{\rm QCD}/m_b] \,.$$

This implies small direct CP asymmetries since, e.g., $A_{\rm CP}(\pi^+K^-) \approx -2\,|T/P|\sin\gamma\,\sin\phi_{\rm st}$. The suppression results as a consequence of systematic cancellations of soft contributions, which are missed in phenomenological models of final-state interactions. In other schemes the strong-interaction phases are predicted to be larger, and therefore larger CP asymmetries are expected. Present data show no evidence for large direct CP asymmetries in charmless decays [17], but the errors are still too large to distinguish between different theoretical predictions. An important exception is the direct CP asymmetry for the decays $B \to \pi^\pm K^\mp$, which is already measured with high precision. The current world average, $A_{\rm CP}(\pi^+K^-) = -0.05 \pm 0.05$ [17], implies a rather small value of the corresponding strong-interaction phase, which is consistent with the expectation that this phase be suppressed in the heavy-quark limit. Specifically, for γ in the range between 60° and 90°, I obtain $\phi_{\rm st} = (8 \pm 10)^\circ$. Simple physical arguments suggest that the relevant strong-interaction phases in the decays $B \to \pi^\pm K^\mp$ and $B^\mp \to \pi^0 K^\mp$ should be very similar [19]. This observation will become important below.

4 Establishing CP Violation in the Bottom Sector

Various ratios of CP-averaged $B \to \pi K, \pi\pi$ branching fractions exhibit a strong dependence on γ and $|V_{ub}|$. It is thus possible to derive constraints on $\bar\rho$ and $\bar\eta$ from a global

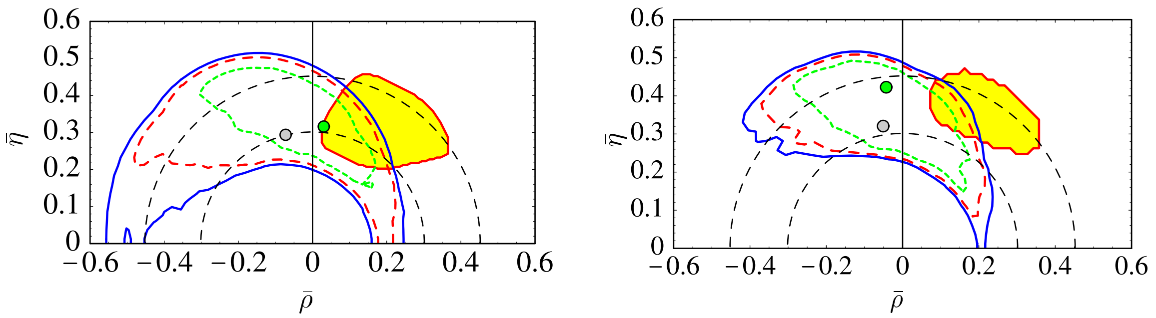

Figure 4: 95% (solid blue), 90% (dashed red) and 68% (short-dashed green) confidence level contours in the $(\bar\rho, \bar\eta)$ plane obtained from rare hadronic B decays (dark green dot = overall best fit; light gray dot = best fit for the default parameter set). The circled yellow region shows the result of the standard CKM fit. Left: status in spring 2001; right: update for summer 2002.

analysis of the data in the context of the QCD factorization approach, provided conservative error estimates for power corrections are included. A comprehensive discussion of such an analysis was presented in [6], to which I refer the reader for details. The original result obtained in that paper is reproduced in the left plot in Figure 4. It reflects the status of the data as of spring 2001. The right plot shows an update of this analysis using the latest experimental data [17]. I have also updated two input parameters in order to take into account recent theoretical developments. The new analysis uses $m_s = (100 \pm 25)\,\text{MeV}$ at $\mu = 2\,\text{GeV}$, and $f_B = (200 \pm 30)\,\text{MeV}$. The values adopted in [6] were $m_s = (110 \pm 25)\,\text{MeV}$ and $f_B = (180 \pm 40)\,\text{MeV}$.

The fit is excellent, which $\chi^2 = 0.5$ for three degrees of freedom. There is no problem in accounting for all of the experimental data simultaneously. The inclusion of model estimates of weak annihilation effects enlarges the allowed regions in the $(\bar\rho, \bar\eta)$ plane but is not required to fit the data. Leaving out all annihilation contributions, one still obtains a good fit ($\chi^2 = 0.7$) and similar best-fit values for the Wolfenstein parameters. The comparison of the two plots shown in the figure indicates the effect of the increase in experimental precision between spring 2001 and summer 2002. The most important conclusion from this analysis is that, with the new data, the combination of results from rare hadronic B decays with the $|V_{ub}|$ measurement in semileptonic decays (dashed circles) excludes $\bar\eta = 0$ and so establishes the existence of a CP-violating phase in the bottom sector of the CKM matrix.

The allowed regions obtained from the fit to charmless hadronic decays are compatible with the standard fit (shown by the yellow region), but tend to favor larger γ values. This tendency has been reinforced with the new data. The same trend is seen in an analysis that does not rely on QCD factorization but instead employs general amplitude parameterizations and flavor symmetries [20]. It is tantalizing to speculate about the possible origin of a (still hypothetical) disagreement between the allowed $(\bar\rho, \bar\eta)$ regions obtained from the standard analysis and from charmless hadronic B decays. A conventional explanation of such a discrepancy might be that the errors in lattice calculations of the relevant matrix elements for B_d–$\bar{B}_d$ and B_s–$\bar{B}_s$ mixing have been underestimated. In fact, in a recent paper the value $\xi = (f_{B_s}\sqrt{B_s})/(f_{B_d}\sqrt{B_d}) = 1.32 \pm 0.10$ was obtained [21], which is significantly larger than the result $\xi = 1.15 \pm 0.05$ used in previous analyses of the unitarity triangle. With such large ξ, values of γ in the vicinity of 90° are no longer excluded by the $\Delta m_s/\Delta m_d$ bound.

A more exciting possibility is, of course, to invoke New Physics to explain the discrepancy. Assume first that in charmless hadronic B decays one probes the true value of the CKM phase γ. In this case a discrepancy with the standard analysis would most likely be due to a New Physics contribution to B–$\bar{B}$ mixing. For instance, there could be New Physics affecting B_s–$\bar{B}_s$ mixing. Eliminating the corresponding constraint from the standard analysis one finds that larger values of γ are allowed. This possibility will hopefully soon be checked, when B_s–$\bar{B}_s$ mixing will be explored at the Tevatron. Alternatively, there could be New Physics affecting B_d–$\bar{B}_d$ mixing. In this case one should eliminate the constraints arising from the measurements of Δm_d, $\Delta m_s/\Delta m_d$, and $\sin 2\beta$ from the standard analysis. Then only the constraints from K–$\bar{K}$ mixing and semileptonic B decays remain, which allow for large values of γ. A different possibility would be that the mixing amplitudes are unaffected by New Physics, but that there exist non-standard contributions to $b \to s$ or $b \to d$ FCNC transitions, e.g. from penguin and box diagrams involving the exchange of new heavy particles. (A more exotic model with light SUSY particles has also been considered [22].) In this case, γ measured in $B \to \pi K, \pi\pi$ decays would be a combination of the CKM angle and some new CP-violating phase. Many examples of New Physics models that could yield a significant additional phase have been explored in [23]. A clean test of this possibility would be the measurement of the time-dependent CP asymmetry in $B \to \phi K_S$ decays, which in the Standard Model is due to the interference of a (real) $b \to s\bar{s}s$ penguin amplitude with the B_d–$\bar{B}_d$ mixing amplitude. If there was a New Physics phase $\phi_{\rm NP}$ of the penguin amplitude, then the CP asymmetry in $B \to \phi K_S$ would measure $\sin 2(\beta + \phi_{\rm NP})$, which when compared with the value of $\sin 2\beta$ measured in $B \to J/\psi\, K_S$ decays would reveal the existence of the phase $\phi_{\rm NP}$ [24]. Note that this strategy would not be invalidated even if there was a New Physics contribution to B_d–$\bar{B}_d$ mixing. In this case β would no longer be given by the CKM phase, but this effect would cancel out in the comparison of the two decay modes.

5 A Mixing-Independent Construction of The Unitarity Triangle

If the trend toward larger γ values revealed by the analysis of charmless hadronic B decays persists, one will want to check the compatibility with the standard analysis using measurements whose theoretical interpretation is "clean" in the sense that it only relies on assumptions that can be tested using experimental data. Here I propose a novel construction of the unitarity triangle (which I call the CP-b triangle, because it establishes a CP-violating phase in the b sector of the CKM matrix) which has this property, is over-determined, and can be performed using already existing data. Most

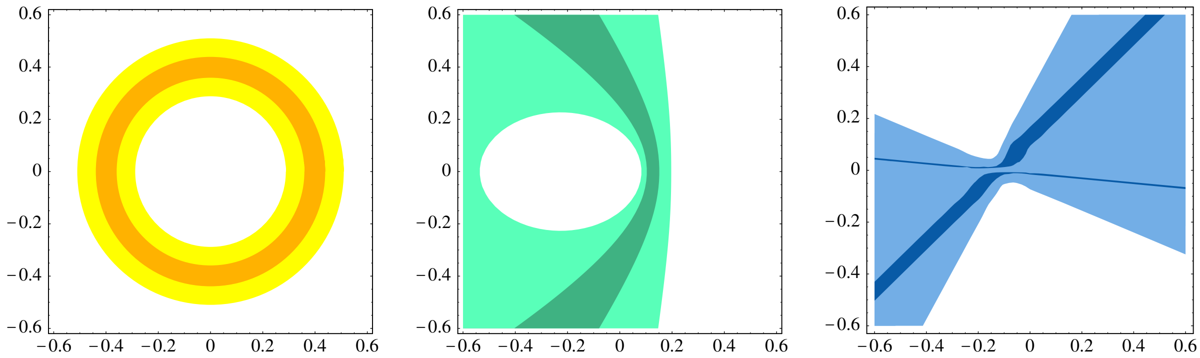

Figure 5: The three constraints in the $(\bar{\rho}, \bar{\eta})$ plane used in the construction of the CP-b triangle (see text for explanation). Experimental errors are shown at 1σ. In each plot, the dark band shows the theoretical uncertainty, which is much smaller than the experimental error. This shows the great potential of these methods once the data will become more precise.

importantly, this construction is insensitive to potential New Physics effects in B–$\bar{B}$ or K–$\bar{K}$ mixing. I will argue that the theoretical uncertainties limiting this construction are considerably smaller than for the standard analysis.

The first ingredient is the ratio $|V_{ub}/V_{cb}|$ extracted from semileptonic B decays, whose current value is $|V_{ub}/V_{cb}| = 0.090 \pm 0.025$. Several strategies have been proposed to determine $|V_{ub}|$ with a theoretical accuracy of about 10% [25, 26, 27, 28, 29], which would be a significant improvement. The first plot in Figure 5 shows the corresponding constraint in the $(\bar{\rho}, \bar{\eta})$ plane. Here and below the narrow, dark-colored band shows the theoretical uncertainty, while the lighter band gives the current value.

The second ingredient is a constraint derived from the ratio of the CP-averaged branching fractions for the decays $B^\pm \to \pi^\pm K_S$ and $B^\pm \to \pi^0 K^\pm$, using a generalization of the method suggested in [30]. The experimental inputs to this analysis are the tree-to-penguin ratio $\varepsilon_{\rm exp} = 0.205 \pm 0.025$ mentioned earlier, and the ratio

$$R_* = \frac{\mathrm{Br}(B^+ \to \pi^+ K^0) + \mathrm{Br}(B^- \to \pi^- \bar{K}^0)}{2[\mathrm{Br}(B^+ \to \pi^0 K^+) + \mathrm{Br}(B^- \to \pi^0 K^-)]} = 0.78 \pm 0.11$$

of two CP-averaged $B \to \pi K$ branching fractions [17]. Without any recourse to QCD factorization this method provides a bound on $\cos\gamma$, which can be turned into a determination of $\cos\gamma$ (for fixed value of $|V_{ub}|/V_{cb}|$) when information on the relevant strong-interaction phase ϕ is available. I have argued at the end of section 3 that the phase ϕ is bound by experimental data (and very general theoretical arguments) to be small, of order $(8 \pm 10)^\circ$. (In the future, this phase can be determined directly from the direct CP asymmetry in $B^\pm \to \pi^0 K^\pm$ decays.) It is thus conservative to assume that $\cos\phi > 0.8$, corresponding to $|\phi| < 37^\circ$. With this assumption, the corresponding allowed region in the $(\bar{\rho}, \bar{\eta})$ plane was analysed in [6], to which I refer the reader for details. The resulting constraint is shown in the second plot in Figure 5.

The third constraint comes from a measurement of the time-dependent CP asymmetry $S_{\pi\pi} = \sin 2\alpha_{\rm eff}$ in $B \to \pi^+\pi^-$ decays. The present experimental situation is unfortunately unclear, since the measurements by BaBar ($S_{\pi\pi} = -0.01 \pm 0.37 \pm 0.07$) and Belle ($S_{\pi\pi} = -1.21\,^{+0.38}_{-0.27}\,^{+0.16}_{-0.13}$) are inconsistent with each other [17]. The naive average of these results gives $S_{\pi\pi} = -0.64 \pm 0.42$ (with an inflated error). The theoretical expression for the asymmetry is

$$S_{\pi\pi} = \frac{2\,\mathrm{Im}\,\lambda_{\pi\pi}}{1+|\lambda_{\pi\pi}|^2}\,, \quad \text{where} \quad \lambda_{\pi\pi} = e^{-i\phi_d}\,\frac{e^{-i\gamma}+(P/T)_{\pi\pi}}{e^{+i\gamma}+(P/T)_{\pi\pi}}\,.$$

Here ϕ_d is the CP-violating phase of the B_d–$\bar B_d$ mixing amplitude, which in the Standard Model equals 2β. Usually, it is argued that for small P/T ratio the quantity $\lambda_{\pi\pi}$ is approximately given by $e^{-2i(\beta+\gamma)} = e^{2i\alpha}$, and so apart from a "penguin pollution" the asymmetry $S_{\pi\pi} \approx \sin 2\alpha$. Here I adopt a different strategy [6]. In order to become insensitive to possible New Physics contributions to the mixing amplitude, I use the experimental value $\sin\phi_d = 0.78 \pm 0.08$ [17] and write $e^{-i\phi_d} = \pm\sqrt{1-\sin^2\phi_d} - i\sin\phi_d$, with a sign ambiguity in the real part. (The plus sign is suggested by the standard fit of the unitarity triangle.) A measurement of $S_{\pi\pi}$ can then be translated into a constraint on γ (or $\bar\rho$ and $\bar\eta$), which remains valid even if the $\sin\phi_d$ measurement is affected by New Physics. The result obtained with the current experimental values and assuming $\cos\phi_d > 0$ is shown in the third plot in Figure 5. The resulting bands for $\cos\phi_d < 0$ are obtained by a reflection about the $\bar\rho$ axis. This follows because the expression for $S_{\pi\pi}$ is invariant under the simultaneous replacements $e^{-i\phi_d} \to -e^{i\phi_d}$ and $\gamma \to -\gamma$.

Each of the three constraints in Figure 5 are, at present, limited by rather large experimental errors, while comparison with Figure 1 shows that the theoretical limitations are smaller than for the standard analysis. Yet, even at the present level of accuracy it is interesting to combine the three constraints and construct the resulting allowed regions for the apex of the unitarity triangle. The result is shown in Figure 6. Note that the lines corresponding to the new constraints intersect the circles representing the $|V_{ub}|$ constraint at large angles, indicating that the three measurements used in the construction of the CP-b triangle give highly complementary information on $\bar\rho$ and $\bar\eta$. There are four allowed regions, two corresponding to $\cos\phi_d > 0$ (dark shading) and two to $\cos\phi_d < 0$ (light shading). If we use the information that the measured value of ϵ_K requires a positive value of $\bar\eta$, then only the two solutions in the upper half-plane remain. One of these regions (corresponding to $\cos\phi_d > 0$) is close to the standard fit, though once again somewhat larger γ values are preferred. (If only the BaBar result is used for $S_{\pi\pi}$, then this region is shifted toward yet larger values of γ.) I stress that this agreement is highly nontrivial, since with the exception of $|V_{ub}|$ none of the standard constraints are used in this construction. Interestingly, there is a second allowed region (corresponding to $\cos\phi_d < 0$) which would be consistent with the constraint from ϵ_K (see Figure 1) and the global analysis of charmless hadronic decays (see Figure 4), but inconsistent with the constraints derived from $\sin 2\beta$ and $\Delta m_s/\Delta m_d$. Such a solution would require a significant New Physics contribution to B–$\bar B$ mixing.

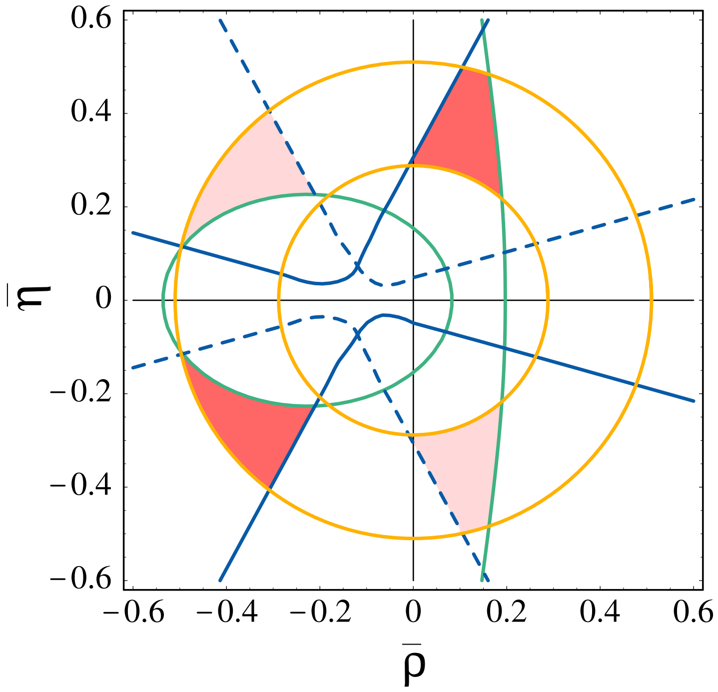

Figure 6: Allowed regions in the $(\bar{\rho}, \bar{\eta})$ plane obtained from the construction of the CP-b triangle. The dashed lines and light-shaded areas refer to $\cos\phi_d < 0$.

6 Outlook

After the by now precise measurement of $\sin 2\beta$, the study of charmless two-body modes of B mesons is presently the next hottest topic in B physics. QCD factorization provides the theoretical framework for a systematic analysis of hadronic B decay amplitudes based on the heavy-quark expansion. This theory has already passed successfully several nontrivial tests, and will be tested more thoroughly with more precise data.

A global fit to $B \to \pi K, \pi\pi$ decays establishes the existence of a CP-violating phase in the bottom sector of the CKM matrix and tends to favor values of γ near 90°, somewhat larger than the value suggested by the standard analysis of the unitarity triangle. If this trend were real, it would suggest several possibilities for new flavor physics beyond the Standard Model, ranging from new contributions to B–$\bar{B}$ mixing to non-standard FCNC transitions of the type $b \to sg$ or $b \to s\bar{q}q$. In the future, the construction of the CP-b triangle will provide stringent tests of the Standard Model with small theoretical uncertainties.

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