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Introduction to Physics Studies at an Asymmetric e^+e^- B-Factory

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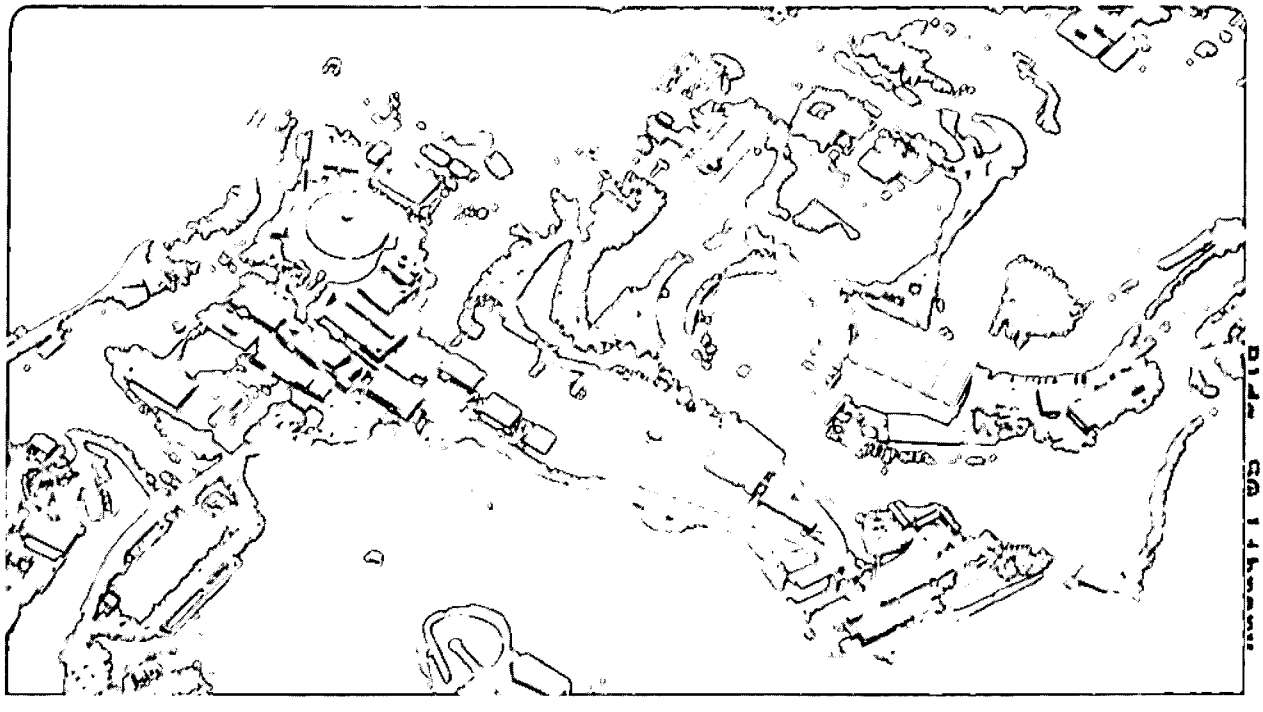

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Introduction to Physics Studies at an Asymmetric e^+e^- B-Factory[1]

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ABSTRACT

In this paper we present a brief summary of the *CP* violation physics to be undertaken at an asymmetric e^+e^- B factory.

1. GENERAL INTRODUCTION

We are aware of only two manifestations of *CP* symmetry violation: the huge preponderance of matter over antimatter in the visible universe and the small violation observed in the decay of neutral K mesons. The first manifestation is indirect evidence of *CP* violation: it relies on our aesthetic sense that in the Big Bang cosmology the universe started symmetrically without a preponderance of matter over antimatter. If in the beginning the Universe was symmetric, then somewhere in its subsequent development there must have been a process that violated *CP* symmetry. The second manifestation is a prima facie case of *CP* violation, but one that is difficult to study because of its small size.

Despite almost three decades of often remarkable experiments, little is known about the origin of *CP* violation in K meson decay. The Standard Model, with a suitable choice of parameters, can account for this *CP* violation, but so can other models. Furthermore, this Standard Model explanation of *CP* violation in K meson decays falls many orders of magnitude below what is needed to explain the other manifestation of *CP* violation, namely, the matter-antimatter asymmetry of the visible universe. Currently we are stuck without a clear understanding: the two manifestations could reflect an underlying common origin outside the Standard Model, or they could be separate phenomena, one within and one outside the Standard Model. Clearly there is a lot to be understood and we are only in our infancy in studies of *CP* violation.

One of the drivers behind studying *CP* violation in B meson decay is the expectation of very large effects if the Standard Model explanation of *CP* violation for K meson decay holds. Unlike the part-per-thousand effect seen in K meson decay, violations in the tens of percent are quite possible. Also, violations in many different decay modes can be studied, with well predicted relations among them.

Because the large effects expected in B meson decay occur in modes that are relatively rare, a very large number of B mesons are needed. Large numbers are produced in high energy hadron colliders and in high luminosity e^+e^- colliders generically called B-factories. The pros and cons of using hadron colliders or electron-positron colliders have been, and continue to be, vigorously discussed [1]. In this talk I'll describe only the approach based on e^+e^- colliders.

In the last few years, progress toward such a collider program has been impressive in all fronts: the machine design and related R&D program, the physics and detector planning and the development of a broad community of physicists interested in pursuing the physics through this approach.

On the machine front, the many initial ideas for B-factories have coalesced to one basic approach: the asymmetric B-factory initially proposed in 1987 [2] and subsequently developed in great detail [3,4,5,6,7]. This basic approach is being pursued in three variants: the SLAC/LBL/LLNL design proposed for the PEP tunnel, the Cornell design for the CESR tunnel and the

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KEK design for the TRISTAN tunnel. The design at KEK may yet evolve to use a new smaller tunnel instead of the TRISTAN tunnel. It is remarkable that these three designs achieve the same luminosity with tunnels of such different circumferences, ranging from 765m to 3600m. In general, the differences in circumference have been compensated by different technical choices for parameters, components and interaction region geometries. The evolution of the three designs and their related R&D programs are much of the subject of this workshop and are extensively discussed in these Proceedings. For the purposes of the physics discussion below, we assume that asymmetric B-factories are capable of delivering the design luminosity of 3 10^{33} cm^{-2} sec^{-1}, or equivalently 30 fb^{-1} per year.

In the physics arena, the principal progress has been in understanding how to analyze many different decay modes. The case for pursuing an asymmetric B-factory was based initially on the analysis of only two reactions: the decay $B \to \psi K_S^0$ (with $\psi \to \mu^+ \mu^-$ or e^+e^-, and $K_S^0 \to \pi^+ \pi^-$), and the decay $B \to \pi^+ \pi^-$. Both final states of these decays are CP eigenstates. Additional modes are now well studied; they include other decays to CP eigenstates as well as decays to states that are not pure CP eigenstates. In the Standard Model, the asymmetry in each of these modes measures one of the angles of the unitarity triangle. The availability of many more modes has two beneficial effects: it lowers the amount of luminosity necessary to measure the angles of the unitarity triangle to a given precision, and it allows internal consistency checks by comparing modes that measure the same angle. The net effect of adding these new decay modes is to lower the luminosity required to measure the angles by about a factor of three relative to using only the $B \to \psi K_S^0$ and $B \to \pi^+ \pi^-$ modes. Further improvements may ensue as more modes are studied.

One item still unresolved is whether an asymmetric B-factory will in fact be built. A large community of physicists in the U.S. and in Japan are seriously developing the designs for accelerators and experimental programs. The recent HEPAP Subpanel on U.S. Program of High Energy Physics Research gave the asymmetric B-factory very high marks and made recommendations to proceed with the B-factory under certain fiscal assumptions for the U.S. high energy physics program [8]. In Japan, there exists optimism that KEK will be allowed to proceed with building the accelerator at a date not yet specified. The impressive work that has been carried out so far and that will be carried further at this workshop will place the community in a strong position to move quickly on the experimental program once a B-factory is finally launched.

2. *CP* VIOLATION AT AN ASYMMETRIC *B*-FACTORY: DECAY TO *CP* EIGENSTATES

The most interesting decays to study CP violation in the B meson system are those that arise from the interference between the amplitude for direct decay and the amplitude for the decay proceeding through particle-antiparticle mixing, as shown in Figure 1. Although CP violation may be observable in decays that do not involve mixing, such as in charged B meson decays, these decays are generally expected to have smaller asymmetries in the Standard Model and, in any case, do not relate cleanly to the angles of the unitarity triangle without major and uncertain hadronic corrections. The angles, their relation to the CKM matrix elements and their relation to various neutral B meson decays are shown in Figure 2 and in Table 1. The basic tree level diagrams involved are shown in Figure 3.

Neutral B meson decays have therefore acquired a central role in the study of CP violation in B meson decays. Of these decays, the decays into CP eigenstates are most easily discussed since the asymmetry can be measured essentially with a simple counting experiment. The classical modes $B \to \psi K_S^0$ and $B \to \pi^+ \pi^-$ are examples of such decays.

The way these experiments are carried out in the asymmetric B-factory is as follows. The energy in the center of mass is tuned to the $\Upsilon(4S)$, where the production cross section is enhanced. The $\Upsilon(4S)$ is

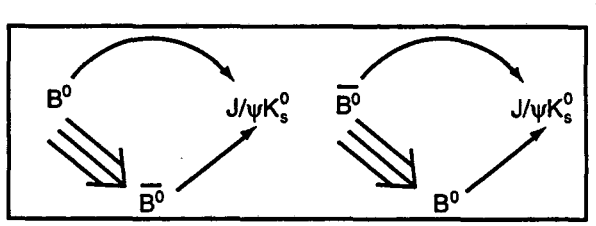

Figure 1. The B^0 or $\overline{B^0}$ can decay via two routes, one direct and one involving mixing. The interference has different magnitudes for B^0 and $\overline{B^0}$.

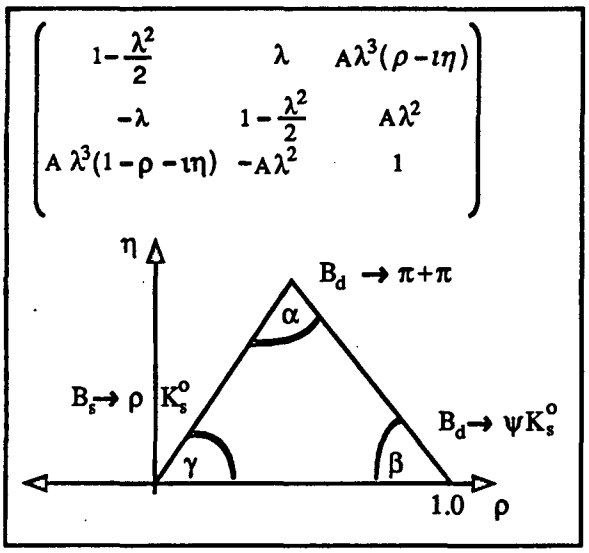

Figure 2. The unitarity triangle is a graphic representation of the unitarity of the CKM matrix, here expressed in the Wolftenstein parametrization.

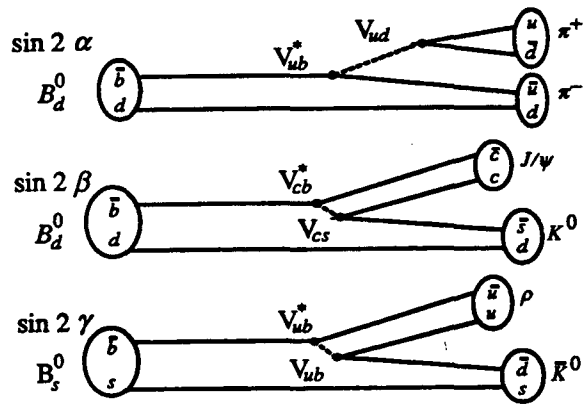

Figure 3. Tree level diagrams involved in the measurement of the angles of the unitarity triangle α, β, and γ.

boosted significantly in the laboratory frame. It decays into two B mesons which are themselves boosted with very similar boosts as the masses of the $\Upsilon(4S)$ is nearly identical to the sum of the masses of the two B mesons. The observables are the decay products of the two B mesons and the separation distance of the two decays, as is shown in Figure 4. When the decay is to two neutral B mesons, one decay is the decay of interest and the other is used to tag the nature of the parent particle. Generally we distinguish four cases: the tagging decay can indicate a particle or an antiparticle and the tagging decay can occur before or after the decay of interest. The decay distributions as a function of the separation for these four cases are shown in Figure 5 under certain assumptions for the decay $B \to \psi K_S^0$. The pair-wise difference of these distributions is a direct measurement of CP violation.

The full expression for the decay distribution to a CP eigenstate is:

$$CP(B\overline{B}) = \text{odd}$$
$$R(B^0\overline{B}^0 \to B^0\psi K_S) \propto e^{-\Gamma(t'+t)}\{1+\sin\phi\sin[\chi\Gamma(t'-t)]\}$$
$$R(B^0\overline{B}^0 \to \overline{B}^0\psi K_S) \propto e^{-\Gamma(t'+t)}\{1-\sin\phi\sin[\chi\Gamma(t'-t)]\}$$

Table 1. The relation of asymmetries and decay modes.

	B_d Decay Mode	A_{CP} Measures	B_s Decay Mode	A_{CP} Measures
$\bar{b} \to \bar{c}c\bar{s}$	$J/\psi\ K_S^0[K_L^0]$, $\chi K_S^0[K_L^0]$, $\eta_c K_S^0[K_L^0]$	$-\sin 2\beta$	$D_S^+ D_S^-$	0
$\bar{b} \to \bar{c}c\bar{d}$	D^+D^-	$-\sin 2\beta$	$J/\psi\ K_S^0[K_L^0]$	0
$\bar{b} \to \bar{u}u\bar{d}$	$\pi^+\pi^-$, $\rho\pi^0$, $\omega\pi^0$	$\sin 2\alpha$	$\rho K_S^0[K_L^0]$, $\omega K_S^0[K_L^0]$	$-\sin 2\gamma$
$\bar{b} \to \bar{s}s\bar{s}$	$\phi K_S^0[K_L^0]$	$-\sin 2\beta$	$\eta'\eta'$	0
$\bar{b} \to \bar{c}u\bar{s}, \bar{u}c\bar{s}$	$D_{CP}^0 K^{*0}$	$\sin 2\gamma$		
$\bar{b} \to \bar{s}s\bar{d}$	$K_S^0 K_S^0$	0	$\phi K_S^0[K_L^0]$	$\sin 2\beta$

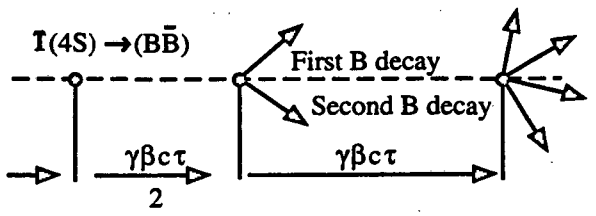

Figure 4. Schematic decay of a B^0 and $\overline{B}^0$ at an asymmetric B-factory.

$$CP(B\overline{B}) = \text{even}$$
$$R(B^0\overline{B}^0 \to B^0 \psi K_S) \propto e^{-\Gamma(t'+t)}\{1 - \sin\phi \sin[\chi\Gamma(t'+t)]\}$$
$$R(B^0\overline{B}^0 \to \overline{B}^0 \psi K_S) \propto e^{-\Gamma(t'+t)}\{1 + \sin\phi \sin[\chi\Gamma(t'+t)]\}$$

Where:

- R is the rate of the decay process, t and t' are the times at which the ψK_S^0 and the flavor-specific decay occur, respectively
- $\chi = \Delta m/\Gamma$ where Δm is the mass difference between the two neutral B meson mass eigenstates and Γ is the resonance width of the B and B^0, and
- ϕ is the CP violation angle in the unitarity triangle

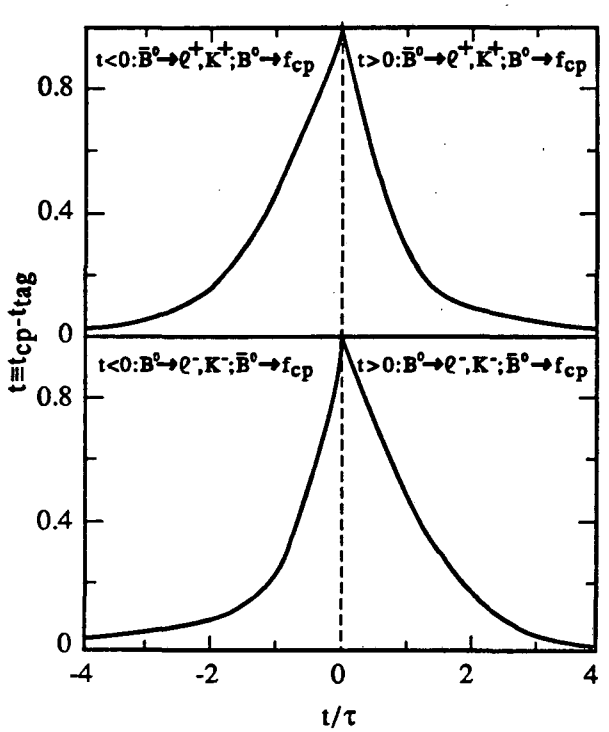

Figure 5. Distribution of decays into the state ψK_S as a function of the separation between B^0 and $\overline{B}^0$ decay.

The above equation shows that the measured asymmetry is odd under the reversal of the time difference between the decay of the two Bs if the initial state is CP-odd (like at the $\Upsilon(4S)$) and even if the initial CP state is even. This means that a time-averaged measurement of the asymmetry starting with the $\Upsilon(4S)$ would vanish exactly; therefore, it is imperative to study the distribution of decays as a function of the separation, as was done in Figure 5.

In principle, it would be ideal to start with a CP-even state, since for this case we need not study the time distribution of the decays to see CP violation. This had been proposed for symmetric B-factories where the time separation of the decays cannot be observed. To achieve this starting point, the operating energy would be tuned just above BB^* threshold so as to have a $B\overline{B}\gamma$ final state with a $B\overline{B}$ pair in an even CP state. This approach does not appear competitive, as the measured cross section is six to ten times smaller than the cross section for $B\overline{B}$ production at the $\Upsilon(4S)$[9].

3. DECAY TO OTHER STATES

It is possible to measure CP violation in decays that are not pure CP eigenstates. The analysis is considerably more involved, as the angular distribution of the final states must be used when different partial waves contribute to different CP parities. Many channels exist with this characteristic—for example, the decay to two vector particles, such as $B \to D^{*+} D^{*-}$ or ψK^{*0}, or decay to three particles, such as $B \to \psi K_S^0 \pi^0$. Dunietz et al. have written a comprehensive review on how to obtain CP-violating asymmetries from angular correlations [10].

Other classes of decays can also be used. Decays to states that are not CP eigenstates but are self-conjugate collections of quarks can also be quite useful in determining asymmetries. These are decays such as $B \to \rho^\pm \pi^\mp$ and $B \to a_1^\pm \pi^\mp$. Aleksan et al. have analyzed these modes and conclude that they are even better candidates than the classical $B \to \pi^+ \pi^-$ mode for the determination of the angle α [11].

4. ACCURACY IN MEASURING CP VIOLATION

The range of angles that is possible while still maintaining consistency with all present-day experiments is very large, as is shown in Figure 6. Clearly we know very little about the CP violation aspects of the CKM mixing matrix.

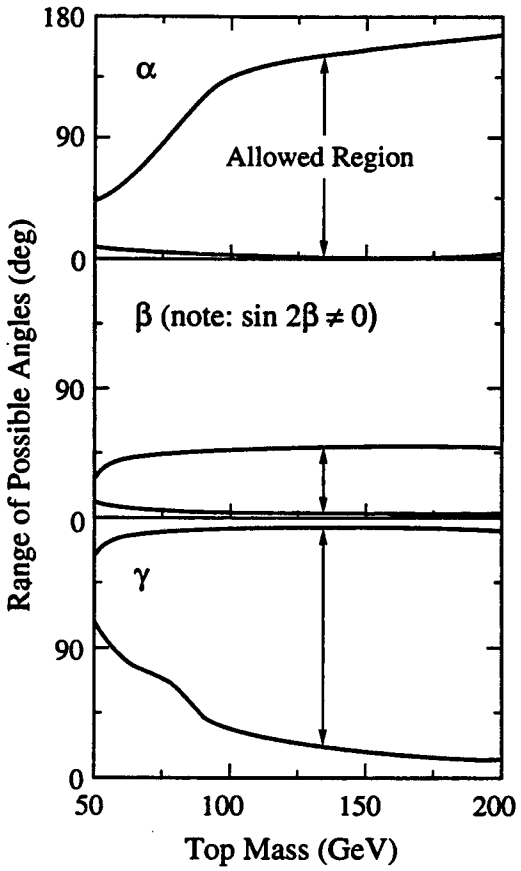

Figure 6. Range of angles α, β, and γ allowed by our present knowledge of the CKM matrix.

To determine the accuracy of the measurements of the angles, a great deal of work has been done in simulating the physics using a fairly realistic detector. Simulations by the various groups agree fairly well. A typical set of numbers is shown in Table 2 from the simulations for the SLAC/LBL/LLNL proposal. The uncertainty in the angles α and β are quite small and very detailed knowledge would be gained after a relatively short time at full luminosity. The third angle, γ, is very difficult to measure. The traditional measurement is through $B_S \to \rho\ K_S^0$. Because the B_S is expected to mix rapidly, and the product of cross section and branching ratio is small, the error in the measurement is quite large. New ideas have been proposed for measuring the angle γ, through a combination of self tagging decays of the form $B^\pm \to D^0_{1(2)} X^\pm$, where $D^0_{1(2)}$ is a CP-even (odd) state and $\chi^\pm$ is any hadronic state with the flavor of a $K^\pm$ [12] or of the form $B_d^0 \to D_{1(2)} K^*$ where $D_{1(2)}$ is a CP eigenmode of a D^0 or $\overline{D}^0$ and K^* is tagged by the charged K flavor in the decay to $K\pi$ [13].

In a recent review paper, Witherell [14] has speculated on what our understanding might be in the year 2001, after a few years of operation of a B-factory. A dramatic way to display our present state of ignorance is shown in Figure 7, which shows the range of triangles that are possible, given all known experimental results in mid-1992, with a few assumptions like the mass of the top quark. In contrast,

Table 2. Measurement precision on unitarity angles.

e^+e^- Measurement Precision on Unitarity Angles					
Angle	Decay mode	Branching fraction	Tagging efficiency (%)	Reconstruction efficiency (%)	Measurement error in 30 fb^{-1}
sin 2β	$J/\psi K_S^0$	4×10^{-4}	45	58	0.10
	D^+D^-	6×10^{-4}	45	46	0.14
	$J/\psi K^{*0}$	12×10^{-4}	45	30	0.17
	$D^{*+}D^{*-}$	16×10^{-4}	45	28	0.08
	Combined				0.054
sin 2α	$\pi^+ \pi^-$	2×10^{-5}	45	43	0.18
	$\rho^\pm \pi^\mp$	6×10^{-6}	37	58	0.12
	$a_1^\pm \pi^\mp$	6×10^{-5}	32	60	0.18
	Combined				0.086
sin 2γ	ρK_S^0	1×10^{-4}			0.34

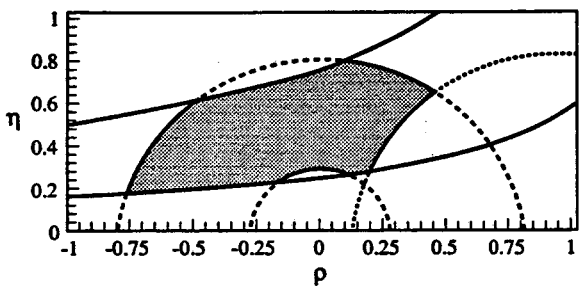

Figure 7. The shaded region represents the range of the apices for the unitarity triangle allowed by present experiments with the additional assumptions of m_t = 100 GeV and V_{cb} = 0.044 [Ref. 14].

Figure 8 shows what we would expect to know in the year 2001 from a comparable but more precise set of measurements exclusive of *CP*-violation experiments in the *B* system. The narrowing of the region is made possible in part by measurements at the *B*-factory and in part by progress in the study of *K* decays elsewhere. If the world is fully consistent in the year 2001 and *CP* is accounted for by the three-generation Standard Model, then the region defined by the *CP*-violation experiments measuring the angles α and β is shown in Figure 9. We see that a very stringent test of the Standard Model explanation would be possible by comparison of Figures 8 and 9.

5. PHYSICS BEYOND THE STANDARD MODEL

The situation shown in Figures 8 and 9 could be dramatically different, with the region defined by the two sets of experiments being completely disjoint.

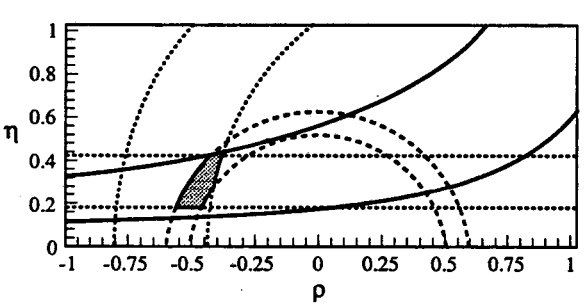

Figure 8. Range of the unitarity triangle after a few years of *B*-factory operation derived from measurements exclusive of α and β. The values assumed are: ε'/ε = 3.5 = 1.0 × 10 10^{-4}, V_{ub}/V_{cb} = 0.12 ± 0.01, χ_s = 7 ± 2 [Ref. 14].

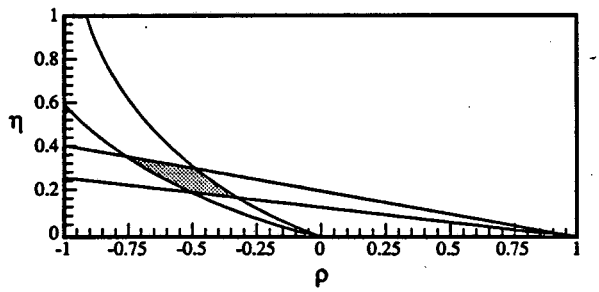

Figure 9. Range of unitarity triangle derived from a measurement of α and β alone. The values assumed are sin 2β = 0.32 ± 0.06; sin 2α = 0.56 ± 0.08 [Ref. 14].

This would indicate physics beyond the Standard Model. The pattern of *CP* violation expected in the Standard Model would be disrupted by new physics, principally by affecting the mixing amplitude. Many of the models for new physics have been analyzed by Dib et al., for their effect on *CP*-violation asymmetries [15].

There are, of course, instances in which the measurement of the angles α and β is not modified by the new physics, and the discovery of the new physics must be sought elsewhere. There are also instances in which a different underlying physics could mimic some Standard Model results. A recent such analysis has been done by Winstein showing that a particular variant of the superweak model could mimic some Standard Model results for the *CP* asymmetry measured by the angles α and β [16]. This ambiguity is shown in Figure 10. For this particular example,

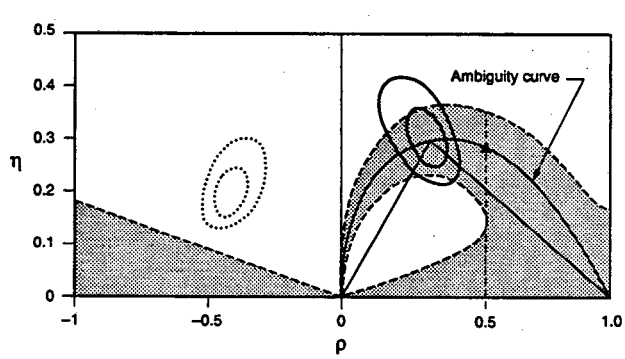

Figure 10. The shaded area represents the region where a 5% and 10% determination of sin(2β) and sin(2α) respectively do not distinguish the predictions of the standard model from those of the superweak model at a level of 3σ as described in reference [16].

there is a variety of handles beyond the measurement of α and β to distinguish the two models. For instance, an asymmetry observed in charged B meson decay would rule out the model. Similarly, a nonzero measurement of ε'/ε in the K system would resolve the ambiguity. Measurement of the third angle, γ, could also distinguish the two models.

6. SUMMARY AND CONCLUSIONS

The asymmetric B-factory has made the mystery of CP violation vulnerable to attack. Large number of events can be produced at the $\Upsilon(4S)$. B reconstruction at this energy using the beam energy constraint offers very high mass resolution, typically a factor of 10 better than that possible without such a constraint. The low multiplicities make possible high reconstruction and tagging efficiencies. The boost in the center of mass makes possible the study of the time development of the decays, an essential ingredient if we are to exploit the resonance-enhanced B production at the $\Upsilon(4S)$. The time evolution of the decays provides a powerful check on the systematic errors of the experiment. The relatively low energy of the decays and the powerful detector technology developed for this energy range make possible the study of a wide variety of decay channels, not only decreasing the integrated luminosity necessary to determine the CP-violation angles, but also providing a wealth of experiments that test the underlying physics. Finally, beyond the measurement of CP violation in B decays, the huge sample of events will permit studies of two-photon physics, tau physics, charm quark physics, and quarkonium studies of unprecedented precision.

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