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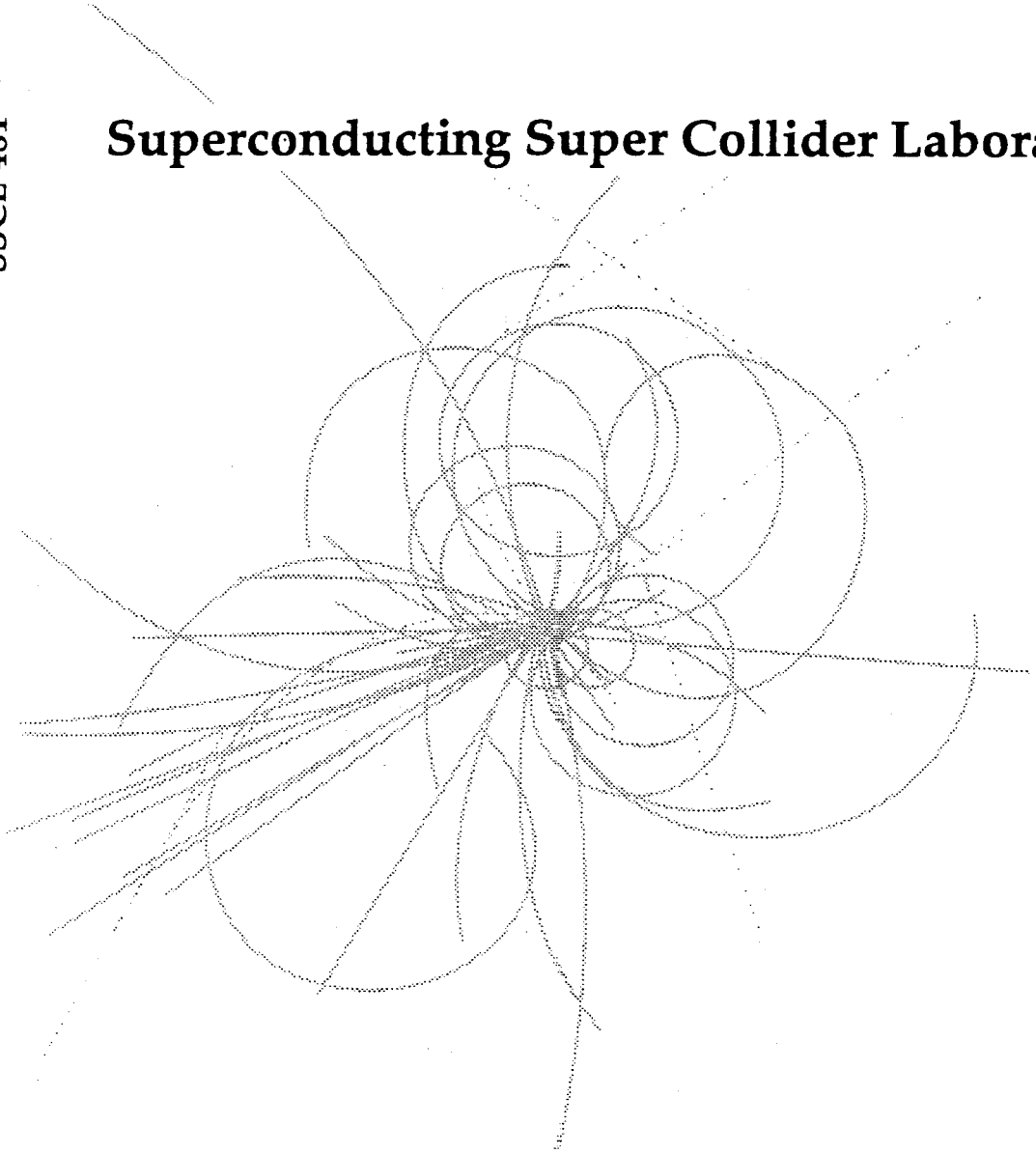

Model Independent Test of the Standard Model

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1.0 INTRODUCTION

Soon after I delivered this talk, the director general announced that KEK will go ahead with the construction of the B factory. We look forward to spectacular physics from KEK in the 1990s.

In preparation for this exciting physics, considerable theoretical progress has been made in the past few years. Some of this progress has been discussed during this workshop. In this talk, I will discuss the future theoretical perspective. I will also offer some comments on the topics discussed in the workshop.

2.0 K MESON PHYSICS

It is K physics which revealed CP violation. This fascinating asymmetry led us to the present B factory plan. Yet, except for the fact that $\epsilon \neq 0$, not much quantitative information has been obtained from CP violation in K decays. This is due to our inability to compute ϵ in terms of the fundamental parameters of the Lagrangian. For example, our computation of ϵ is ambiguous by a bag factor which is believed to be between 0.3 and 1.

The theoretical problem with ϵ'/ϵ is worse.[1] It can be written, in general, as

$$\epsilon'/\epsilon = \frac{e^{i(\delta_2-\delta_0+\frac{\pi}{2})}}{\sqrt{2}} \frac{\mathrm{Re}\, A_2}{\mathrm{Re}\, A_0} \left(\frac{\mathrm{Im}\, A_0}{\mathrm{Re}\, A_0} - \frac{\mathrm{Im}\, A_2}{\mathrm{Re}\, A_2} \right),$$

where $A_I = \left\langle (\pi\pi)_I \, |H_w| \, K^0 \right\rangle$, and I denotes the isospin of the two-pion state. Noting that

$$\left| \frac{\mathrm{Re}\, A_0}{\mathrm{Re}\, A_2} \right| = \frac{1}{w} \sim 20,$$

we can write

$$|\epsilon'/\epsilon| \approx \frac{w}{2} \left| \frac{\mathrm{Im}\, A_0}{\mathrm{Re}\, A_0} \left(1 - 20 \frac{\mathrm{Im}\, A_2}{\mathrm{Im}\, A_0} \right) \right|.$$

The source of $\mathrm{Im}\, A_I$ in the standard model is given in Figure 1. It is clear that $\mathrm{Im}\, A_2$ is a higher order term in a power series expansion of weak gauge coupling constant g. Originally, these higher order terms were ignored, and the theoretical prediction

$$\epsilon'/\epsilon \sim 10^{-3}$$

was widely given. Here, too, the ambiguity in evaluating the $\langle \pi\pi \, |H_w| \, K \rangle$ matrix element leads to more than 50% uncertainty in the prediction. With the increase in the lower bound

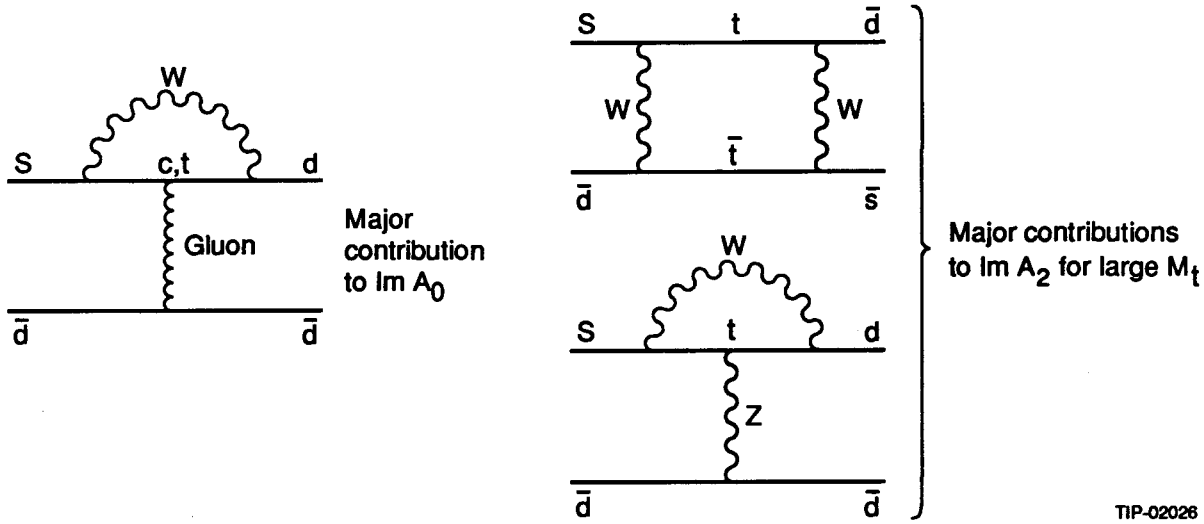

Figure 1. The Gluon Exchange Diagram Gives Rise to Only the $\Delta I = 1/2$ Amplitude. W and Z exchange diagrams, while higher order in the electroweak coupling constant, can give rise to the $\Delta I = 3/2$ amplitude.

on the top quark mass, and the factor of 20 kinematical enhancement of $\mathrm{Im}\, A_2$, there has been a realization that, in fact, the contribution from $\mathrm{Im}\, A_2$ can cancel that from $\mathrm{Im}\, A_0$. This type of cancellation renders hopeless any attempt to extract physics out of ϵ'.

While observation of $\epsilon' \neq 0$ is extremely important, as it presents clear judgement over the super weak model, the actual value of ϵ' is unlikely to offer any additional constraint on the standard model. The reason for my emphasis on this gloomy point is the following: This is the area which offers the greatest potential for an improvement in the theoretical front, during the next five years. In the near future, we should be more confident about the B_K factor. This advancement will come from two fronts—lattice computations and chiral weak lagrangian approach—in evaluating the weak matrix elements.

2.1 Lattice

The lattice results have been reviewed in this workshop.[2] The results on the pseudoscalar decay constant and the bag factor seem very promising. Before we have any confidence in using the lattice results for B_K, it is important to check whether the lattice approach offers an understanding of the $\Delta I = 1/2$ rule.

2.2 Chiral Weak Dynamics

Before any scheme is accepted as a viable approach for evaluating the $K \to 2\pi$ matrix element, it has to explain the age-old puzzle: the $\Delta I = 1/2$ rule. It has been shown that chiral weak dynamics (CWD) offers an explanation of the puzzle.[3] In fact, it is easy to show that the σ propagator in the decay

$$K \to \sigma \to 2\pi$$

enhances the penguin amplitude so that the observed $\Delta I = 1/2$ enhancement can be understood. This approach will be used to evaluate the B_K factor in the near future.

I believe that the lattice and the chiral dynamics will play a complementary role. For example, if indeed the CWD is the correct scheme for evaluating the matrix elements, the evidence for the σ excitation should be found in the lattice evaluation of the $K \to 2\pi$ matrix elements. Some evidence for such scalar excitation is indeed found.[4] More work along this line is urged.

3.0 LATTICE EVALUATION OF f_B

Martinelli has presented[5] an analysis from which he concludes:

$$f_B \geq 165\,\mathrm{MeV}.$$

From the point of view of the B factory, this is extremely interesting. In Figure 2, we show the minimum CP asymmetry in the $\psi\, K_s$ channel computed within the range of parameter space shown in the box. Note that the minimum asymmetry quickly jumps from 12% to $\sim$ 30% if f_B is varied from 80 to 160 MeV. This leads to a factor-of-10 reduction in the luminosity needed to observe the CP asymmetry. While this is very pleasant, it is very important to strive for every bit of luminoisty for the B factory—after all, we are proposing a precision test of the standard model.

From the experimental value of $B\bar{B}$ mixing, it seems safe to assume that

$$f_B \geq 80\,\mathrm{MeV}.$$

This leads to 12% ψK_s asymmetry for $m_t = 200\,\mathrm{GeV}$. For now we shall refrain from being excessively optimistic.

4.0 HEAVY QUARK SYMMETRY[6]

In QCD, quarks are labeled only by their masses. Also, the quark spin decouples from the dynamics in the $m_q \to \infty$ limit. Thus there is SU($2N$) symmetry in the limit N number of quarks have infinite mass. Since it is clear that QCD governs the dynamics of strong interaction, this symmetry must be respected in the heavy quark system. The main question, however, is the size of corrections when it is applied to D and B mesons.

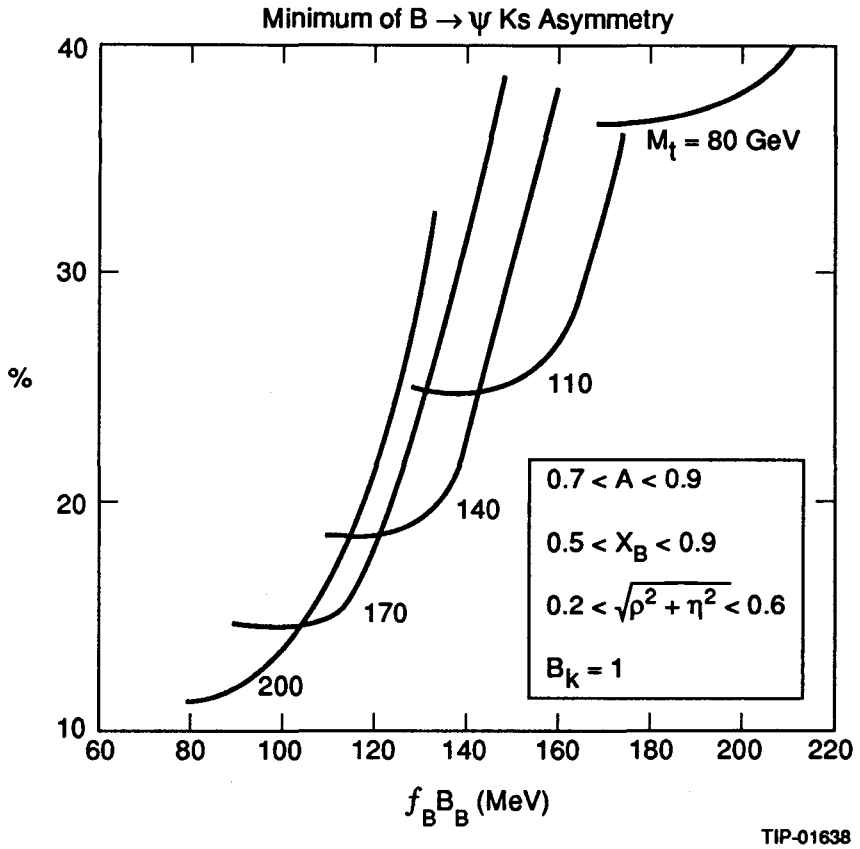

Figure 2. The Minimum ψK_s Asymmetry as a Function of m_t and f_B. The other parameters shown in the box are varied within their specified range to obtain the minimum asymmetry.

Martinelli[5] gives the M dependence of $f_M\sqrt{M}$ computed on the lattice as:

$$f\sqrt{M} = \text{const}\left(1 - \frac{1.2\,\text{GeV}}{M}\right).$$

If $\frac{1}{M}$ correction of this size is present for all predictions, the applicability of the heavy quark symmetry is marginal for the B system and not very good for the D system. Some predictions are protected from this type of correction. More work is needed to assign corrections to predictions given by the symmetry.

5.0 CP ASYMMETRY IN B DECAYS

The asymmetry between $B \to f$ and $\bar{B} \to f$ decay is given by

$$\frac{\Gamma(B \to f) - \Gamma(\bar{B} \to f)}{\Gamma(B \to f) + \Gamma(\bar{B} \to f)} \sim \text{Im}\left(\frac{p}{q}\rho\right),$$

where

$$\frac{p}{q} = \left(\frac{M_{12} - \frac{i}{2}\Gamma_{12}}{M_{12}^* - \frac{i}{2}\Gamma_{12}^*} \right)^{1/2} \quad \text{and} \quad \rho = \frac{A(B \to f)}{A(\bar{B} \to f)}.$$

Since $|\Gamma_{12}| \ll |M_{12}|$ is a very good approximation, we have

$$\frac{p}{q} = e^{i\phi_M},$$

where ϕ_M is the argument of M_{12}, which can be expressed in terms of the phases of the KM matrix elements. On the other hand, the presence of penguin diagrams makes ρ more complicated. Here we shall comment on the theoretical predictability of ρ.

5.1 Penguin Pollution[7]

The accuracy in predicting ρ is process dependent. Figure 3 shows the quark diagrams responsible for decays with $f = \psi K_s$, and $\pi\pi$.

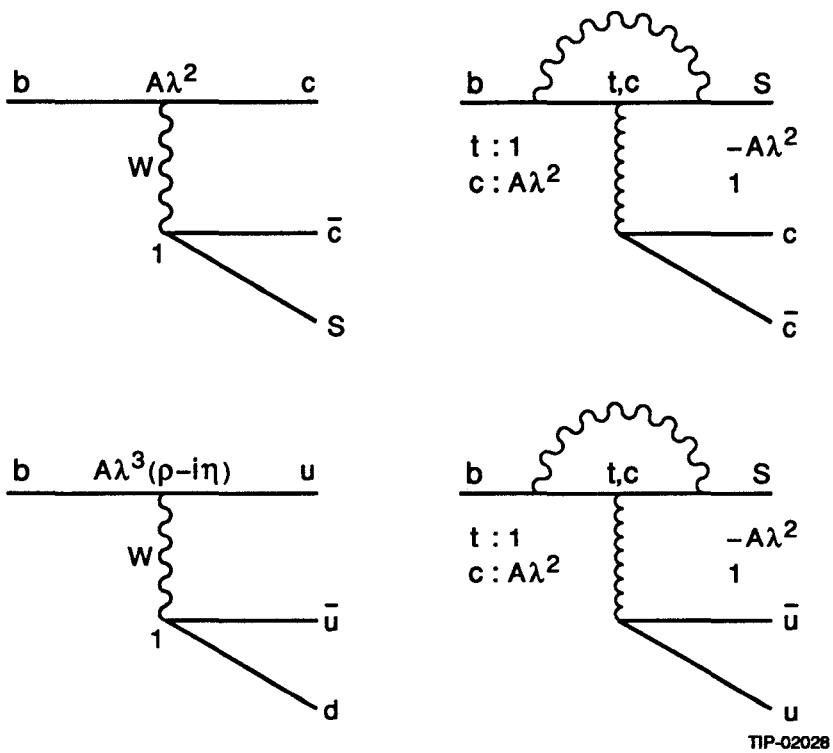

Figure 3. Quark Diagrams Responsible for $B \to \psi K_s$ and $\pi\pi$ Decays. The KM matrix element in the Wolfenstein parameterization is also given.

The amplitudes can be written in terms of KM matrix elements and the constants $a \ldots e$, which depend on hadronic dynamics.

$$\frac{A(B \to \psi K_s)}{A(\bar{B} \to \psi K_s)} = \frac{a\,A\lambda^2 + b\,A\lambda^2}{a(A\lambda^2)^* + b(A\lambda^2)^*} = 1;$$

$$\frac{A(B \to \pi\pi)}{A(\bar{B} \to \pi\pi)} = \frac{c(\rho - i\eta) + d(1 - \rho + i\eta) + e}{c(\rho + i\eta) + d(1 - \rho - i\eta) + e}$$

$$= f(a, d, e).$$

Note that all quantities which depend on the hadronic dynamics cancel for the ψK_s decay, while for $\pi\pi$ decay, the dependence on the hadronic dynamics persists. This is called penguin pollution.

5.2 Penguin Trapping[8]

There is a technique to separate the penguin contribution from the tree graph contribution. There are two independent isospin amplitudes to describe three different charge modes of $B \to 2\pi$ decays:

$$\begin{array}{ll} B^+ \to \pi^+\pi^0 & A^{+0} = 3A_2 \\ B^0 \to \pi^+\pi^- & A^{+-} = \sqrt{2}(A_2 - A_0) \\ B^0 \to \pi^0\pi^0 & A^{00} = 2A_2 + A_1. \end{array}$$

From these relations, we write

$$A^{00} + \frac{1}{\sqrt{2}}A^{+-} - A^{+0} = 0,$$

which describes a triangle on the complex plane. The three amplitudes for the charge conjugate decays satisfy a similar relation. These triangles are shown in Figure 4. We fix the relative orientation so that A^{+-} and $\bar{A}^{+-}$ have a relative angle $\arg\left[\frac{p}{q}\rho(\pi^+\pi^-)\right]$. This is a measurable quantity:

$$a = \sin^{-1}\left(\left|\frac{\bar{A}^{+-}}{A^{+-}}\right| \frac{Asym(\pi^+\pi^-)}{\sin\Delta mt}\right).$$

Note that, since A^{+0} and $\bar{A}^{+0}$ do not contain the penguin contribution, their relative phase is $2\arg V_{ub}$. Thus, with above definition of angle a, the angle between $\bar{A}^{-0}$ and A^{+0} is given by $2\arg V_{ub} + \phi_M = \phi_u$. Note also that if there is no penguin contribution, $a = \phi_u$.

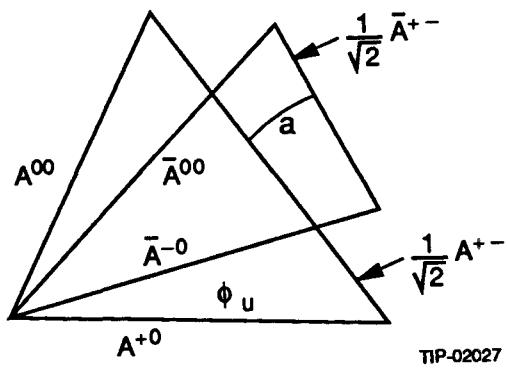

Figure 4. Three Amplitudes for Decays $B^+ \to \pi^+\pi^0, B^0 \to \pi^+\pi^-, B^0 \to \pi^0\pi^0$ Form a Triangle. This triangle and the corresponding one for the three charge conjugate decays are shown here. Note that the relative orientation of the two triangles can be obtained from the CP asymmetry. ϕ_u is one of the unitarity triangle.

We thus see that by measuring the rate for $6\pi\pi$ channels, both the phase and the magnitude of the penguin contribution as well as ϕ_u can be obtained.

5.3 Determination of ϕ_s [9]

Consider measurements of

$$B \to D^0 + K + X_n,$$
$$B \to \bar{D}^0 + K + X_n,$$
$$B \to D_1 + K + X_n,$$

where $D_1 = \frac{1}{\sqrt{2}}(D^0 + \bar{D}^0)$; B, K, and X_n can be charged or neutral; and X_n can be any identified state which does not contain charm. The first two decays proceed through the tree graphs, as shown in Figure 5. The third decay proceeds through the interference of these two amplitudes.

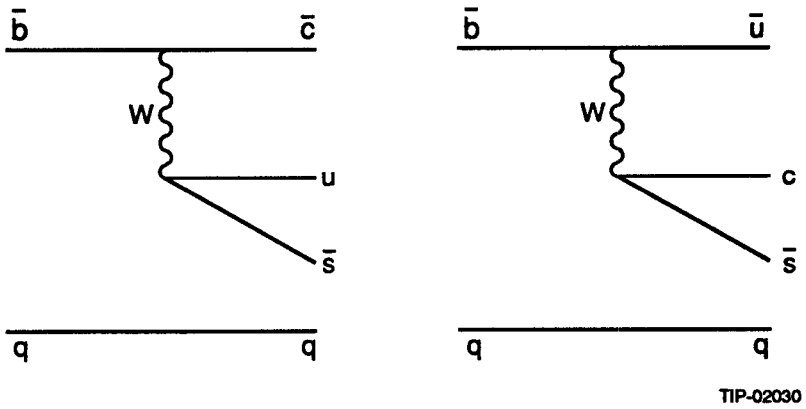

Figure 5. Quark Diagrams Responsible for (a) $B \to D^0 + K + X_n$, (b) $B \to \bar{D}^0 + K + X_n$, and $B \to D_1 + K + X_n$. For the third decay, these two diagrams interfere.

Adopting Wolfenstein's representation,

$$
\begin{aligned}
A_{Dn} &= |A_{Dn}|\, e^{i\delta_{Dn}}, \\
A_{\bar{D}n} &= |A_{\bar{D}n}|\, e^{i\delta_{\bar{D}n}} \exp i(\arg V_{ub}), \\
A_{D_1 n} &= \frac{1}{\sqrt{2}}(A_{Dn} + A_{\bar{D}n}),
\end{aligned}
$$

where δ represents the strong final state interaction phase. The amplitudes for the charge conjugate decays are:

$$
\begin{aligned}
\bar{B} \to \bar{D}^0 + \bar{K} + \bar{X}_n \qquad & \bar{A}_{\bar{D}\bar{n}} = |A_{Dn}|\, e^{i\delta_{Dn}} \\
\bar{B} \to D^0 + \bar{K} + \bar{X}_n \qquad & \bar{A}_{D\bar{n}} = |A_{\bar{D}n}|\, e^{i\delta_{\bar{D}n}} \exp i\,\{-\arg V_{ub}\} \\
\bar{B} \to D_1 + \bar{K} + \bar{X}_n \qquad & \bar{A}_{D_1\bar{n}} = \tfrac{1}{\sqrt{2}}\left(\bar{A}_{\bar{D}\bar{n}} + \bar{A}_{D\bar{n}}\right).
\end{aligned}
$$

Now, note that we can draw two triangles (Figure 6) to describe the relationship between these amplitudes:

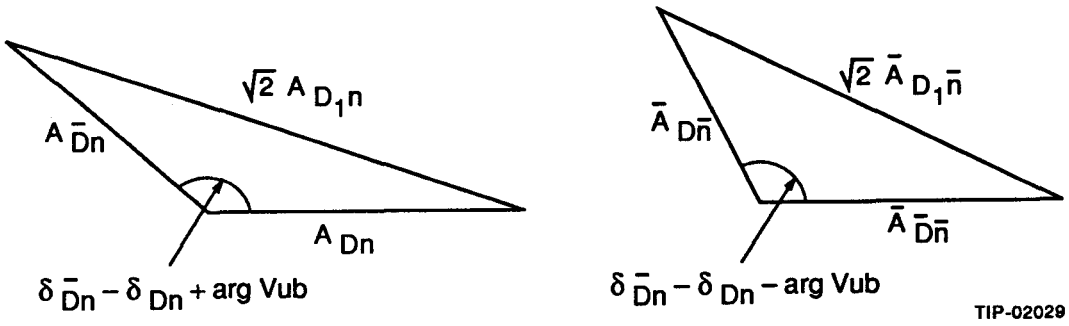

Figure 6. Triangles Which Give the Phase Relationship Between the Three Amplitudes. Note that any difference in shape between the two triangles is a sign of CP violations.

Thus $\arg V_{ub}$ can be obtained free of ambiguities of strong final state interaction.

6.0 CONCLUSION

We anticipate much interesting physics to come out of the B factory. Also, much-needed ingredients to plan the experiment at B factory will come from ARGUS and CLEO II in the next two or three years. On the theoretical front, it is necessary to make some progress in quantifying the prediction of K decay amplitudes. Promising efforts along this direction are the lattice and the chiral weak dynamics approach. Finally, we point out that all three angles of the unitarity triangle can be obtained from experiments. Unlike in K decays, there is very little theoretical uncertainty in determination of these angles. A check to see if these angles add up to 180° is a quantitative test of

the standard model. Given these angles and measured V_{cb}, we can obtain V_{ub}, and V_{td} from the unitarity triangle. These can be checked. Any violation of the unitarity triangle constraints implies physics beyond the standard model.

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