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B Physics at SSC*

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Abstract

A review of prospects for B physics experiments at the Superconducting Super Collider (SSC) is undertaken, with the assumption that the Fermilab Tevatron and the e^+e^- B factory are in full operation by the time B physics experiments are performed at SSC. Various topics of interest are classified according to their merits.

1.0 INTRODUCTION

Experimental studies of K decays played a major role in formulating the standard model of electroweak interaction. Even today, there are many experiments on K decays taking data or being set up at various laboratories, including Brookhaven and KEK. B meson experiments are expected to take over the role played by K meson experiments in the near future. We are hopeful that further advances in our knowledge of electroweak interactions will be realized with a series of experiments on B decays. Just as K meson decays have been an active area of research over the past three decades, B decay experiments are expected to yield many interesting results for the next three to four decades.

The Superconducting Super Collider (SSC) is a natural place to study B decays because high-energy pp collisions produce B mesons copiously. Since completion of SSC is nearly 10 years away, however, careful planning of B experiments is necessary. It is unreasonable to hope that there will be no competition. The asymmetric e^+e^- B factory should be producing results. The Tevatron at Fermilab should be producing results with the main injector. The Large Hadron Collider (LHC) should be operating at that time. Any experimental result at SSC must represent a major improvement over the existing one at that time.

To make an impact in our understanding of electroweak interaction, these experiments must be precision rather than exploratory. As with K decays, precision experiments call for special-purpose detectors that measure few phenomena well, rather than general-purpose detectors that attempt to cover all phenomena. In designing a detector for B experiments, a specific decay mode must first be chosen. There will be many generations of detectors to follow, as is the case in K-decay experiments. One detector need not be capable of doing everything.

All this is good, but it is important to be realistic. A well-chosen series of upgrades, perhaps, allows one to construct a number of special-purpose detectors that, in due time, cover a wide range of decays. Planning for such a program at SSC requires an overview of B physics. This note provides a shopping list of B decays that might be studied at SSC. In order for a decay to make the list, it has to satisfy two conditions:

1. Physics behind the decay is interesting.
2. When the experimental result is out (10 years from now), it is either a new result or is considerably better than the existing result.

As is clear below, I have made extensive use of the study contained in the Expression of Interest for the BCD collaboration[1] as a measure of SSC capabilities. As a measure

of e^+e^- asymmetric collider capabilities, I have used the results from the PEP upgrade proposal submitted to SLAC,[2] and the KEK asymmetric B factory proposal.[3]

Note that the use of BCD capability as a measure of SSC capability is contrary to my insistence that special-purpose detectors are necessary for B physics at SSC. BCD is a general-purpose detector in the colliding beam mode. Often accurate position measurements of vertices are necessary to arrive at the physics. For this purpose, either gas-jet or fixed-target experiments may prove to be more effective. My excuse here is that I had only one month to prepare this document. This shortcoming must be corrected in future considerations.

2.0 SSC VS. OTHER HADRON ACCELERATORS

Table 1 shows the projected capabilities of various hadron accelerators obtained from Reference 1.

TABLE 1. B-$\bar{B}$ Production at Hadron Accelerators. In this comparison we suppose that all the experiments operate at 10^7 interactions/sec and that corresponding luminosity $\mathcal{L}$ can be achieved. We then consider $\sigma_{b\bar{b}}/\sigma_{\rm tot}$ as the figure of merit of the various accelerator options.

Accelerator	$\sqrt{s}$ (TeV)	$\sigma_{b\bar{b}}$ (μb)	$\sigma_{\rm tot}$ (mb)	$\sigma_{b\bar{b}}/\sigma_{\rm tot}$	$\mathcal{L}_{\rm ave}$ (cm^{-2}sec^{-1})	$N_{b\bar{b}}/10^7$ sec.	Figure of Merit
TEV II (p-W)	0.04	0.003	6	5×10^{-5}	1.7×10^{33}	1.7×10^7	1/2500
SSC (p-Si)	0.2	3	15	1/5000	6.7×10^{32}	2×10^{10}	1/25
RHIC (p-p)	0.5	10	40	1/4000	2.5×10^{32}	2.5×10^{10}	1/20
TEV I (p-$\bar{p}$)	1.8	40	40	1/1000	2.5×10^{32}	10^{11}	1/5
LHC (p-p)	16	250	75	1/300	1.3×10^{32}	3.3×10^{11}	2/3
SSC (p-p)	40	500	100	1/200	10^{32}	5×10^{11}	1

From Table 1, it is immediately clear that compared to TEV I (p-$\bar{p}$), SSC (p-p) does not afford a major improvement in $N_{b\bar{b}}$. The factor of 5 improvement must be combined with another factor of 5 improvement in $\sigma_{b\bar{b}}/\sigma_{tot}$.

3.0 SSC VS. e^+e^- ASYMMETRIC COLLIDER

3.1 CP Asymmetries (CP Eigen State)

Tables 2 and 3 give the capability of BCD and the asymmetric B factory based on PEP.[2]

TABLE 2. Minimum $\sin 2\phi$ Which Can Be Measured at the 3σ Level With BCD.[1]

Angle	Mode	Tag	Tagged Events	$1-2p$	b	x_q	D	$\sin 2\varphi_{\min,3\sigma}$
φ_1	$B_d^0 \to J/\psi K_S^0$	$e^\pm$	14,400	0.60	0.1	0.7	0.47	0.094
φ_1	$B_d^0 \to J/\psi K_S^0$	$K^\pm$	110,000	0.40	0.1	0.7	0.47	0.053
φ_2	$B_d^0 \to \pi^+\pi^-$	$e^\pm$	60,000	0.60	1.0	0.7	0.47	0.062
φ_2	$B_d^0 \to \pi^+\pi^-$	$K^\pm$	460,000	0.40	1.0	0.7	0.47	0.033
φ_3	$B_s^0 \to \rho^0 K_S^0$	$e^\pm$	400	0.60	1.0	~ 10	0.64	0.55
φ_3	$B_s^0 \to \rho^0 K_S^0$	$K^\pm$	3500	0.40	1.0	~ 10	0.64	0.28
φ_3	$B_s^0 \to K^+K^-$	$e^\pm$	1560	0.60	~ 0.1	~ 10	0.64	0.21
φ_3	$B_s^0 \to K^+K^-$	$K^\pm$	13,800	0.40	~ 0.1	~ 10	0.64	0.10
φ_4	$B_s^0 \to J/\psi\phi$	$K^\pm$	160,000	0.40	~ 0.1	~ 10	0.64	0.031

TABLE 3. 1σ Error Expected at the B Factory.[2]

Mode	Assumed branching fraction	Tagging efficiency (%)	Reconstruction efficiency (%)	$\sigma(\sin 2\phi)$ (30 fb^{-1})
$B^0 \to J/\psi K_s$	7.4×10^{-4}	45	58	0.077
$\to D^+D^-$	6×10^{-4}	45	46	0.14
$\to J/\psi \bar{K}^{*0}$	1.25×10^{-4}	45	30	0.17
$\to D^{*+}D^{*-}$	16×10^{-4}	45	28	0.08
Combined (2β)				0.050
$B^0 \to \pi^+\pi^-$	2×10^{-5}	45	43	0.18
$\to \rho^\pm\pi^\pm$	6×10^{-6}	37	58	0.12
$\to a_1{}^\pm\pi^\pm$	6×10^{-5}	32	60	0.18
Combined (2α)				0.086

Consider the expected 1σ error for various asymmetries at SSC and at the B factory:

$$\begin{array}{lll} & \text{SSC} & e^+e^- \\ \sin 2\phi_c = \sin 2\beta & 0.017 & 0.05 \\ \sin 2\phi_u = \sin 2\alpha & 0.01 & 0.086 \\ \sin 2\phi_s = \sin 2\gamma & 0.01 & - \end{array} \tag{1}$$

Thus SSC experiments have the potential for a new measurement of $\sin 2\phi_s$, an order of magnitude improvement in $\sin 2\phi_u$, and a factor of 3 improvement in $\sin 2\phi_c$.

3.2 Other Decays Connected to CP Violation

Table 4 shows the capabilities of the BCD detector for decays often mentioned in connection with CP violation.

TABLE 4. Rate Estimates for Self-tagging B Decays.[1] B.R.(B) is the branching ratio for the two-body B decay, estimated according to Chau. B.R.(Tot) is the product of B.R.(B) and the secondary branching ratios. Eff. is the product of the geometric acceptance in a detector configuration C+I+F and a factor 0.33 for the efficiency of tracking and vertexing. The reconstructed event samples are for an integrated luminosity of 1 fb^{-1}, collectable in 1 year of running at a luminosity of $10^{32}\,\text{cm}^{-2}\text{sec}^{-1}$.

Decay Mode	All-Charged Daughters	B.R.(B)	B.R.(Tot)	Eff.	Recon. Decays
$B^+ \to \rho^0 K^+$	$\pi^+\pi^- K^+$	10^{-5}	10^{-5}	0.20	7.3×10^5
$B_d^0 \to K^{*+}\pi^-$	$\pi^+\pi^-\pi^+\pi^-$	10^{-4}	2.2×10^{-5}	0.08	6.7×10^5
$B_s^0 \to K^{*+}K^-$	$\pi^+\pi^-\pi^+K^-$	2×10^{-4}	6.7×10^{-5}	0.08	1.3×10^6

The number of $B\bar{B}$ events expected in the e^+e^- collider is 3×10^7. There is a potential for a factor of 100 improvement in the number of reconstructed events for these decays at SSC.

I conclude that, except for the CP asymmetry in $B \to \psi K_S$, substantial improvement in all other CP asymmetries may be possible. I stress that the ψK_S asymmetry measurement at SSC represents only a factor of 3 improvement over the B factory. This measurement, by itself, does not justify building a detector at SSC.

Here, I stress again that *a dedicated experiment to measure any one of these asymmetries down to a 1% level or better* (a factor of 5 better than the projection made above), *is worth thinking about.*

4.0 SHOPPING LIST

The $\star$ system indicates the degree of interest for a particular process at the time SSC experiments start. I assume that the e^+e^- B factory is already in operation and yielding results. I also fold in possible theoretical ambiguities in comparing theory with experiments. Again I stress that no simulation studies have been made, and measurements that are impossible at SSC may be included in the list.

4.1 $\star\star\star\star$ Class

Under the $\star\star\star\star$ Class, we list asymmetry measurements of ϕ_c, and ratios of decay rates which lead to determination of ϕ_u and ϕ_s. These have very little theoretical ambiguities. *Any potential for improvement in our knowledge of ϕ_c, ϕ_u, and ϕ_s should be seriously pursued.*

(1) $B \to \psi K_S$, $\psi' K_S$.

In the Appendix A, I show that

$$\frac{\Gamma(B \to \psi K_S) - \Gamma(\bar{B} \to \psi K_S)}{\Gamma(B \to \psi K_S) + \Gamma(\bar{B} \to \psi K_S)} = \sin \Delta m t \sin 2\phi_c$$

does not have any theoretical ambiguity (down to a fraction of 1% level); thus any improvement on this measurement has a potential to limit understanding of the origin of the standard model. For example, a guess at the Yukawa coupling matrix at the grand unified scale has recently been attempted.[4] These schemes lead to predictions for the KM matrix. In particular, the ψK_S asymmetry can be predicted. This measurement may become crucial to obtaining the correct grand unified theory. Also, we have argued[5] that the ψK_S asymmetry may be the best place to test the CPT symmetry. We have pointed out that the existing bound on CPT violation is only at the 10% level.

BCD collaboration has found that tagging with $K^{\pm}$, originating from the decay of the partner B, considerably improves statistics. Various tagging methods should be carefully studied. The capability to identify particles may be the feature necessary for the SSC B detector.

A dedicated experiment that reduces the error on the ψK_S asymmetry down to the 1% level is an interesting prospect for future considerations.

(2) $B_d \to D^+ D^-$, $D^{\pm *} D^{\mp}$.

These final states are CP eigen states, and everything that can be said about the ψK_S asymmetry can be said about the asymmetries for these decays. The quark decay diagrams, however, are suppressed by a factor of λ, the sine of the Cabibbo angle. The asymmetry for $D^{\pm *} D^{\mp}$ decays is defined by

$$\frac{\Gamma(B \to D^{+*} D^-) - \Gamma(\bar{B} \to D^{-*} D^+)}{\Gamma(B \to D^{+*} D^-) + \Gamma(\bar{B} \to D^{-*} D^+)}.$$

(3) $B_d \to D^0 M$ $\qquad f_D : K_S\rho^0,\ K_S\phi,\ K_S\eta,\ \rho\pi,\ K^+K^-,\ \rho\rho,\ K_1^*\pi^0.$

$\quad\ \hookrightarrow f_D$

Here M can be π^0 or ρ^0. These cascade decays have definite CP parities.[6] From the statistical point of view, the asymmetries from these decays can be combined, taking into account the CP parity of the final state. It is seen that these modes together constitute a substantial branching fraction. Just as in the ψK_S asymmetry, there is no theoretical ambiguity.

(4) Relative decay rates for $B^0 \to \pi^+\pi^-$, $\pi^0\pi^0$, $B^\pm \to \pi^\pm\pi^0$, and asymmetry for $B^0 \to \pi^+\pi^-$.

In Appendix A, I show[7] how ϕ_u can be deduced from the ratio of $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^+\pi^0$ decay rates and the asymmetry for $B^0 \to \pi^+\pi^-$. This method gets around the problem of penguin pollution, and thus there is no theoretical ambiguity.

(5) Relative decay rates for D^0KX_n, $\bar{D}^0KX_n$, and $D_{1,2}KX_n$.

In Appendix A, I show[7] how ϕ_s can be deduced from the ratio of these three decay rates. By $D_{\frac{1}{2}}$, we mean a definite linear combination: $\frac{1}{\sqrt{2}}(D^0 \pm \bar{D}^0)$, and it can be identified by the final state. For example,

$$D \to K_S\rho^0$$

gives a definite CP parity "$-$" state and is associated with decay of D_2.

$$D \to \pi^+\pi^-, K^+K^-$$

gives a definite CP parity "$+$" state and is associated with decay of D_1. Note that an "almost" inclusive study can be made. The angle ϕ_s can be determined for each X_n, and it must be independent of X_n. Thus information from each X_n can be statistically combined.

4.2 $\star\star\star$ Class

Under the $\star\star\star$ Class, we list those decay modes which are sensitive to CP violation. Asymmetries formed by these decay modes may not be trivially related to the parameters of the standard model. This should not discourage anyone from pursuing these modes—after all, CP violations in K decays are of this class.

(6) $B_d \to \psi K^{*0}$, $\psi' K^{*0}$, $D^{+*}D^{-*}$, $D\bar{D}K_S$.

These decay modes have final states that can be in both even and odd orbital angular momenta. Thus they are mixtures of CP parity states. When the different

CP parity states are not discriminated, the effective CP asymmetry is reduced by a factor $(1-r)/(1+r)$,

$$r = \frac{\Gamma(B \to X_+)}{\Gamma(B \to X_-)},$$

where $X_\pm$ are above decay modes with CP parity $\pm$. In Reference 8 it is shown that various helicity states are CP eigen states for above decay modes. It is quite possible that one of the helicity states dominates, and the final state may indeed be a CP eigen state. This possibility may be investigated further by CLEO, ARGUS, and the B factory before SSC experiments start.

(7) $B \to \pi^+\pi^-$.

The asymmetry in this decay mode is related to ϕ_u. It is likely that the penguin contribution is small, so that this decay deserves $\star\star\star\star$. Information on the penguin contribution will be available in the near future from CLEO and ARGUS. Until then, $1 \sim 10\%$ hadronic correction to the asymmetry prediction cannot be excluded.

(8) $B_s \to \rho^0 K_S$, $\pi^0 K_S$, K^+K^-, K^*K, $\phi\pi$.

SSC may compete better with e^+e^- B factories in studying B_s decays than in studying B_d decays. At B factories, B_s is studied at $\Upsilon(5S)$. Compared to B_d, which is produced at $\Upsilon(4S)$, the production rate for B_s is down by a factor of $O(10)$, and the background problem is expected to be much worse.

The decay modes above are CP eigen states, and their CP asymmetries are related to $\sin 2\phi_s$. As discussed in Appendix A, the penguin pollution is expected to be much larger than $B \to \pi^+\pi^-$ decay.

(9) $B^\pm \to K^\pm\rho^0$, $K^\pm\pi^0$.

Any asymmetry in these decays implies CP violation. The value of expected asymmetries, however, depends on final state interaction phases and cannot be predicted. Nevertheless, these are self-tagging, and they may be more accessible to experiments.

(10) $B \to D(KX)^\pm$

$\hookrightarrow K_S\pi^0$, $K_S\rho^0$, $K_S\omega$, $K_S\phi$, ...

Physics of these decays is first discussed in Reference 9. Advantages of these decays are: (1) they are self-tagging, and (2) the branching fraction is large. The values of asymmetries depend on final state interaction phases and cannot be predicted.

(11) $B^\pm \to \mu^+\mu^- + X_n^{\text{nonstrange}}$ $\qquad X_n^{\text{nonstrange}} = \pi, \pi\pi, \rho, \rho\pi, \ldots$.

Physics of these decays is discussed in Reference 10. Figure 1 is a diagram of these decays.

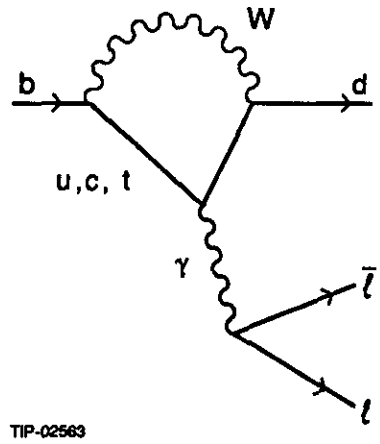

Figure 1. $B^{\pm} \to \mu^+\mu^- + X_n^{\text{nonstrange}}$.

CP asymmetry depends on the final state interaction phase and cannot be predicted. B_d and B_s decays through $\mu^+\mu^+ + X$ modes can lead to predictable CP asymmetries. These decays are Cabibbo-suppressed and also require tagging. For these reasons, they are not discussed here.

Note that we expect the $B \to \psi + X_n$ process to interfere with these decays.[11] The

$$\hookrightarrow \mu^+\mu^-$$

asymmetry can be studied as functions of $Q^2_{\mu\mu}$. They are expected to be maximal at the tail of ψ, where the short- and long-distance effects have comparable size.

4.3 $\star\star$ Class

The $\star\star$ Class of decays consists of those that lead to tests of the standard model at the one-loop level. Also included are those decays with CP asymmetries which are expected to be very small in the standard model.

(12) $B_s^0 \to \psi\phi,\ \psi\eta,\ D_s\bar{D}_s$.

Figures 2 and 3 are diagrams of these decays.

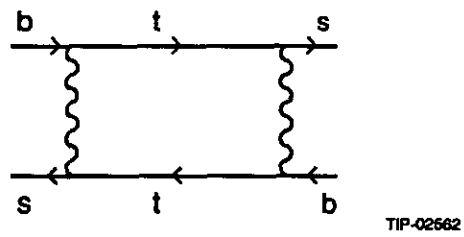

Figure 2. The Dominant Contribution to $B_s - \bar{B}_s$ Mixing.

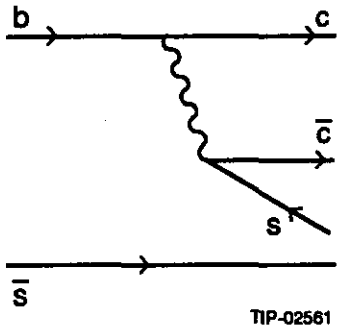

Figure 3. The Dominant Diagram for $B_s^0 \to \psi\phi, \psi\eta, D_s\bar{D}_s$ Decays.

Note that the first family (u, d) does not appear at the leading order. As is well known, all three families must participate in producing CP violation. Thus CP asymmetries in these decays are expected to be very small. This should be tested.

(13) $B_s - \bar{B}_s$ mixing.

Determination of $x_s = \Delta m(B_s)/\Gamma(B_s)$ tests the standard model at the $O(10\%)$ level. Note that

$$\frac{x_s}{x_d} = \frac{f_{B_s}^2 |V_{ts}V_{tb}^*|^2}{f_{B_d}^2 |V_{td}V_{tb}^*|^2} = \frac{f_{B_s}^2}{f_{B_d}^2} \frac{1}{\lambda^2(1-\rho)^2 + \eta^2}.$$

If $f_{B_s}^2/f_{B_d}^2$ is known, the ratio x_s/x_d severely constrains the allowed (ρ, η) plane. Unfortunately, for the foreseeable future, it is unlikely that $f_{B_s}^2/f_{B_d}^2$ can be determined to better than 10%. Since x_s is expected to be large:

$$x_s \sim x_d/\lambda^2 \sim 20,$$

the time-integrated analysis does not allow a quantitative measurement of x_s. BCD points out that 5σ determination of x_s can be made using self-tagging modes:

$$B_s \to D_s^- \pi^+, D_s^- \pi^+ \pi^+ \pi^-, \bar{D}^0 K^{*0},$$

and, of course, the leptonic decays.

While the KEK e^+e^- asymmetric collider will not study B_s decays, it is likely that some information on x_s will be available from the Tevatron at FNAL. Thus the SSC contribution to this measurement must focus on decreasing the error on x_s down to the $O(10\%)$ level.

(14) $B_d \to \mu^+\mu^- + X$

$B_s \to \mu^+\mu^- + X.$

This process occurs through a diagram (Figure 4).

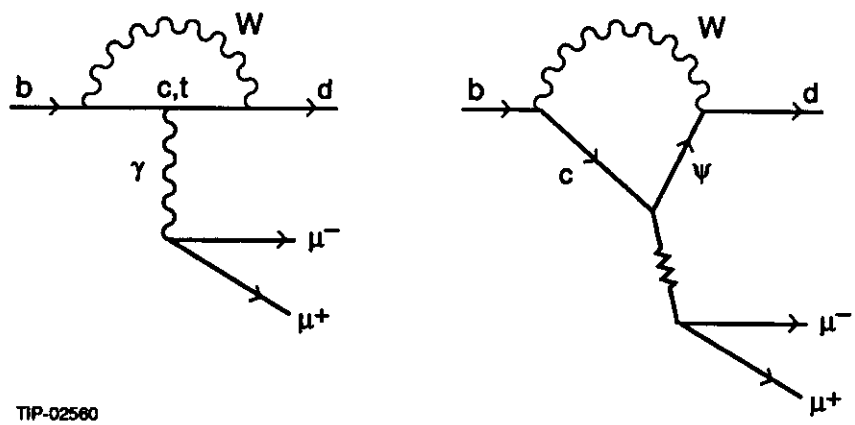

Figure 4. The Short-distance and Long-distance Contributions to $B_d \to \mu^+\mu^- + X, B_s \to \mu^+\mu^- + X$.

An interesting interference pattern is predicted,[11] allowing a test of the standard model at the one-loop level. Since the u-quark contribution in the loop is expected to be small, only the second and third families contribute to this decay. Thus CP-violating asymmetry is expected to be very small.

The invariant mass distribution for the dilepton[11] is given in Figure 5.

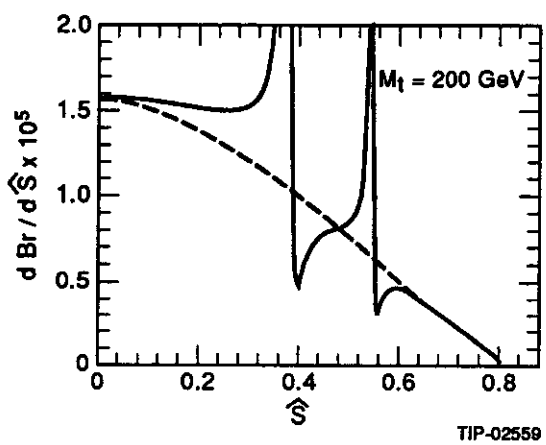

Figure 5. The Invariant Mass Distribution for l^+l^-. Note that the interference effect is quite large in the region within $\sim 1\,\mathrm{GeV}$ of ψ and ψ'.

(15) $B_d \to Kl^+l^-$ $\quad B_d \to K^*l^+l^-$
$B_s \to \phi\mu^+\mu^-$ $\quad B_s \to K^+K^-\mu^+\mu^-$.
These are exclusive decays discussed in (14). The invariant dilepton mass distribution,

$$d\Gamma(B \to \mu^+\mu^- + X_n)/dQ^2_{\mu\mu},$$

for $X_n = K, K^*$ is given[12] in Figure 6.

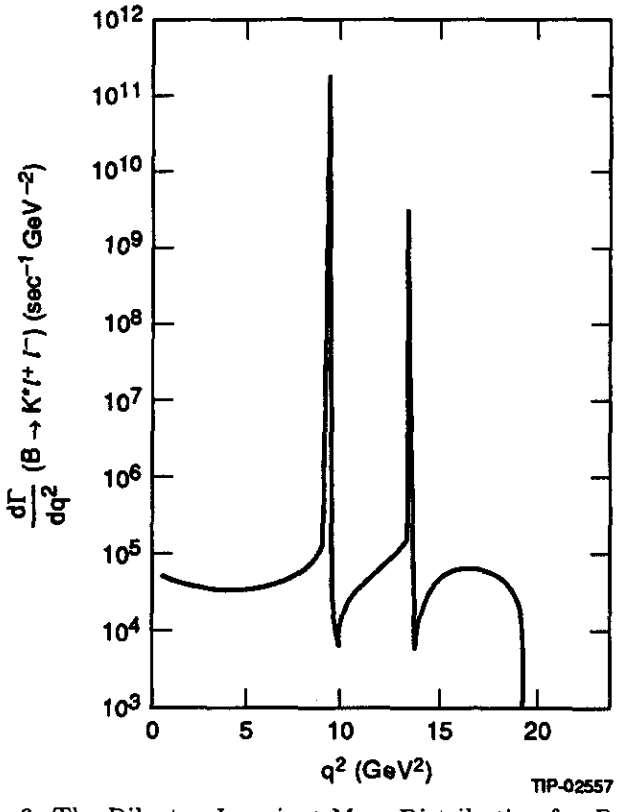

Figure 6. The Dilepton Invariant Mass Distribution for $B_d \to K^*l^+l^-$.

(16) Rare decays $B_d \to \mu^+\mu^-$, $B_s \to \mu^+\mu^-$.
Unlike in the case of $K \to \mu\mu$, theoretical ambiguity in predicting the branching ratio for these decays is expected to be small. The width of these decays is given by

$$\Gamma(B_q \to \mu^+\mu^-) = \left(\frac{G_F\alpha}{4\pi\sin^2\theta_w}\right)^2 \frac{f^2_{B_q}}{8\pi} m_{B_q} m^2_\mu \left(1 - \frac{4m^2_\mu}{m^2_B}\right) \left|V_{tq}V^*_{tb}C\left(\frac{m_t}{m_W}\right)\right|^2.$$

See Figure 7.

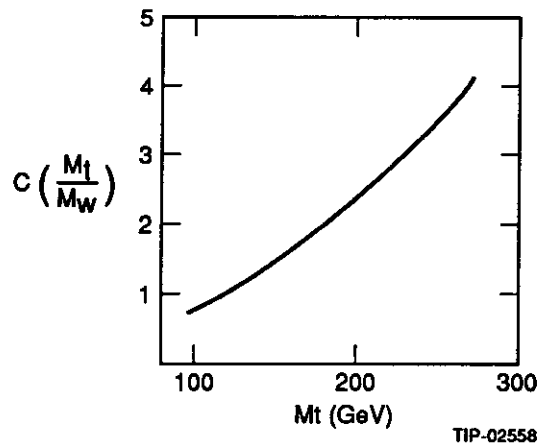

Figure 7. $C(x)$ as a Function of $x = m_t$.

For $m_t = 200\,\mathrm{GeV}$ and $f_{B_q} = 150\,\mathrm{MeV}$, we obtain

$$Br(B_d \to \mu\mu) = 4.3 \times 10^{-11}$$
$$Br(B_s \to \mu\mu) = 8.6 \times 10^{-10}.$$

At this branching ratio, the possibility of detecting these decays is marginal, and both backgrounds and triggering methods must be considered carefully.

4.4 $\star$ Class

The $\star$ Class includes those decays that occur at the tree level in the standard model but play a crucial role in further progress.

(17) $B^+ \to \mu\nu, \tau\nu$

The branching ratios for $B \to \mu\nu$ and $B \to \tau\nu$ decays are expected to be $\sim 10^{-5}$ and $\sim 10^{-3}$, respectively. As is well known,

$$B \sim f_B^2 |V_{bu}|^2 m_l^3,$$

and f_B can be measured through this decay. $O(100)$ $B \to \mu\nu$ decays are expected in the e^+e^- B factory. It will be interesting to devise a method to improve this measurement.

4.5 All-or-Nothing Class

There are several decays which I classify as "all-or-nothing" decays. These are totally outside the standard model, and any positive result in this category will revolutionize physics. I do not recommend a dedicated experiment to look for these effects. Nevertheless, awareness of their existence is very important, as some of them can be looked at as a by-product.

(18) $B^+ \to \mu e, \tau\mu, e\tau$.

(19) $B\overline{B} \to l^+l^- + X$.

Careful study of positions at which l^+ and l^- are emitted may reveal CPT violation,[5] as discussed in Appendix B. Also, CPT violation may appear as a modification to CP-asymmetry predictions.

Table 5 presents a summary of these potential decay studies.

TABLE 5. Summary of Potential SSC Experiments.

	Physics	Merit	Comments	BR Estimate
$B_d \to \psi K_S$				ψK_S : 4×10^{-4}
$\psi' K_S$		$\star\star\star\star$		$\psi' K_S$: 1×10^{-3}
$D^+ D^-$	$\sin 2\phi_c$			$D^+ D^-$: $\cdot 10^{-5}$
$D^{\pm *} D^{\mp}$				$D^{\pm *} D^{\mp}$.
$B_d \to \psi K^*$				
$\psi' K^*$				
$D^{*+} D^{*-}$	$\sin 2\phi_c$	$\star\star\star$	not pure CP	4×10^{-3}
$D\bar{D} K_S$			eigen state	
$B_d \to D^0 M$	$\sin 2\phi_c$	$\star\star\star\star$	CP parity of	$D\pi^0 \sim 0.4\%$
$\hookrightarrow f_D$			$f_D M$ state	
$M = \pi^0, \rho^0$				$D\rho^0 \sim 2\%$
$D^0 \to K_S \rho^0$			+	$K_S \rho^0$: 0.2%
$K_S \omega \quad f_D$			+	$K_S \omega$: 1%
$K_s' \phi$			+	$K_S \phi$: 0.4%
$K_S \eta$			+	
$\rho\pi$			+	
$K^+ K^-$			−	$K^+ K^-$: 0.4%
$\rho\rho$			−	
$K^{0*} \pi^0$			−	$K^* \pi^0$: 2%
$\hookrightarrow K_S$				
$B_d^0 \to \pi^+ \pi^-$	$\sin 2\phi_u$	$\star\star\star$	$1 \sim 10\%$ Penguin	2×10^{-5}
			pollution	
decay rates				
$B_d \to \pi^+ \pi^-, \pi^0 \pi^0$	ϕ_u	$\star\star\star\star$		10^{-5}
$B^+ \to \pi^+ \pi^0$				
$B_s \to \rho^0 K_S$	$\sin 2\phi_s$	$\star\star\star$	$1 \sim 50\%$ Penguin	10^{-5}
			pollution	
$\pi^0 K_S$				10^{-5}
$K^+ K^-$				10^{-6}
$K^* K$				10^{-6}
$\phi\pi$				10^{-6}

TABLE 5. (Continued)

	Physics	Merit	Comments	BR Estimate
Decay rate $B_d \to D^0 + K + X_n$ $\bar{D}^0 + K + X_n$ $D_1 + K + X_n$	$\sin 2\phi_s$	$\star\star\star\star$	Branching fraction for all three decays must be measured. X_n must be detected	2% for given X_n
$B_s \to \psi\phi, \psi\eta$ $D_s\bar{D}_s$	CP Asymm= 0	$\star\star$		10^{-4} 3%
$B^+ \to \rho^+ K^0$	CP Asym $(1 \sim 10)\%$	$\star\star\star$	self-trapping	$10^{-5} \sim 10^{-6}$
$B^\pm \to D_1(KX)^\pm$ $\hookrightarrow K_S + \pi^0$ ρ^0 ω ϕ	CP asym	$\star\star\star$	self-tagging	$\sim 1\%$
$B_s \to D_s^- \pi^+$ $D_s^- \pi^+\pi^+\pi^-$ $\bar{D}^0 K^{*0}$	$B_s - \bar{B}_s$ mixing	$\star\star$	must do better than Tevatron	
$B_d \to \mu^+\mu^- + X$ $B_s \to \mu^+\mu^- + X$	predictable interference between long & short dist.	$\star\star$ $\star\star$		
$B_n^\pm \to \mu^+\mu^- + X_n^\pm$ $X_n = \pi, \rho, \pi\pi, \rho\pi$	CP violation at $Q^2_{\mu\mu} \sim m_\rho^2$	$\star\star\star$		
$B_d \to Kl^+l^-$ $K^*l^+l^-$ $B_s \to \phi l^+l^-$ $\to K^+K^-l^+l^-$	test of the standard model at the loop level	$\star\star$		
$B_{d,s} \to \mu^+\mu^-$	test of the st. model at the loop level	$\star\star$	background analysis is needed	$B_d : 4.3 \times 10^{-11}$ $B_s : 8.6 \times 10^{-10}$
$B_d^+ \to \mu\nu$	measure f_B	$\star$		10^{-5}
$B_{d,s} \to \tau^+\tau^-$ $B_u^+ \to \tau\nu$	same as above	$\star\star$	challenging decays to detect	

5.0 CONCLUSION

There are quite a few more one-star and zero-star decays that we have not covered. Going through this list, it is clear that one feature of a detector is most important: *maximal reconstruction efficiency.* This implies good particle ID, momentum measurements, and vertex detection: nothing you did not already know.

ACKNOWLEDGEMENTS

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APPENDIX A
CP Asymmetry

A.1 Notation

For completeness and for fixing the notation, I describe here a well-known fact about the CP asymmetry for $B_0 \to f$ where f is a CP eigen state. The unitarity triangle is shown in Figure A-1, where the widely used notation for the angles is given.

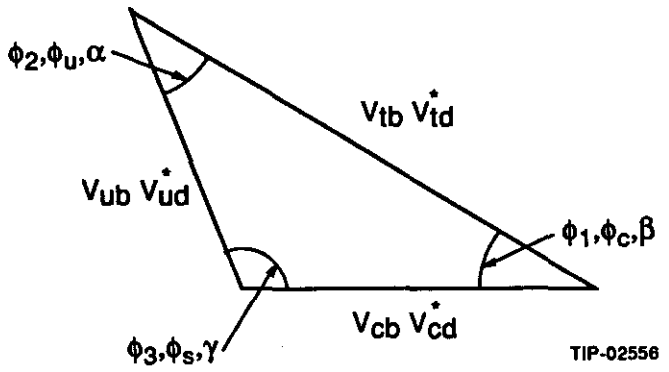

Figure A-1. Unitarity Triangle with Different Notations.

The CP asymmetry associated with each of the angles is given below:

angle	major decay mode
ϕ_2, ϕ_u, α	$B_d \to \pi\pi$
ϕ_1, ϕ_u, β	$B_d \to \psi K_S$
ϕ_3, ϕ_s, γ	$B_s \to \rho K_S$.

The Kobayash-Maskawa (KM) model predicts that

$$\phi_u + \phi_c + \phi_s = \pi.$$

Thus, the importance of the precision measurement cannot be overemphasized.

A.2 CP Asymmetry in B Decays

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

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

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. Next, we shall comment on the theoretical predictability of ρ.

A.3 Penguin Pollution

The accuracy in predicting ρ is process-dependent. Figure A-2 shows the quark diagrams responsible for decays with $f = \psi K_s$ and $\pi\pi$.

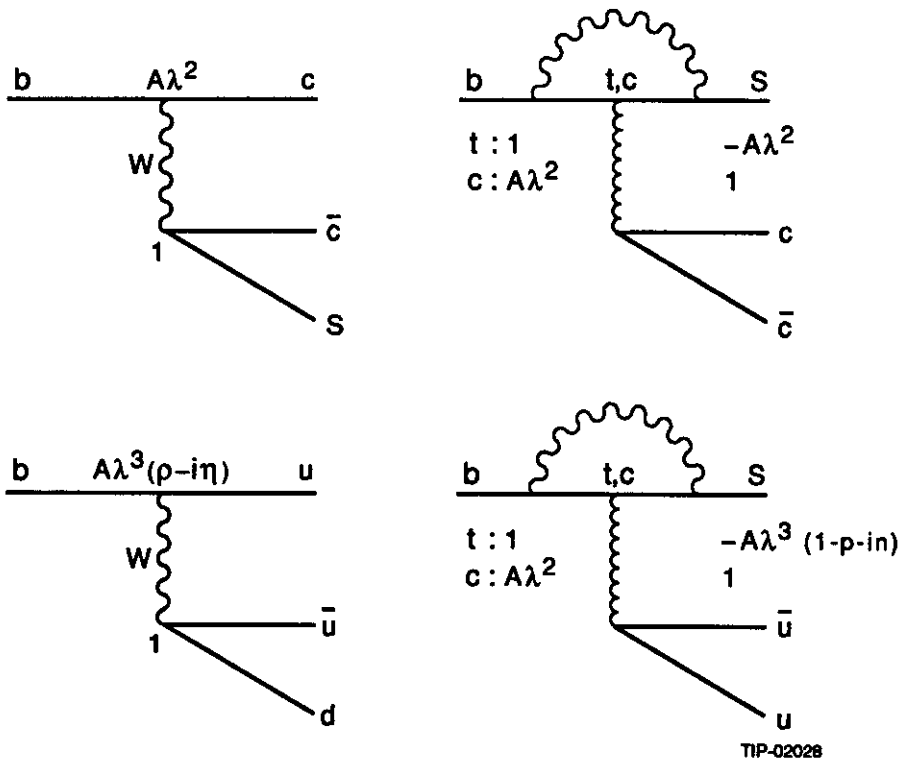

Figure A-2. Quark Diagrams Responsible for $B \to \psi K_s$ and $\pi\pi$ Decays. The KM matrix element in the Wolfenstein parameterization is also given.

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 that 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.

A.4 Penguin Trapping

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:

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

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 5. Since

$$\rho(\pi^+\pi^-) = \frac{\bar{A}^{+-}}{A^{+-}},$$

the relative orientation of the two triangles is fixed by an angle a:

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

Note that A^{+0} and $\bar{A}^{+0}$ do not contain the penguin contribution, and their relative phase is $2\arg V_{ub}$. Thus 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, $\vec{A}^{+0} \parallel \vec{A}^{+-}$ and $a = \phi_u$. Figure A-3 shows three amplitudes for the $B \to 2\pi$ decays.

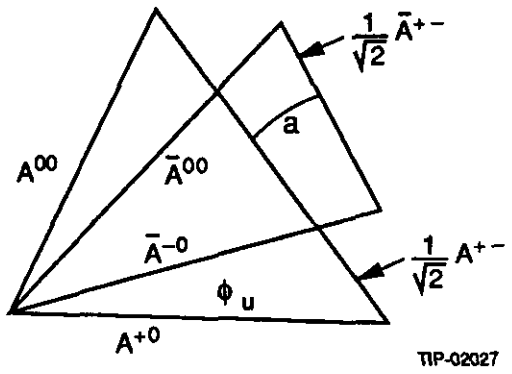

Figure A-3. Three Amplitudes for Decays $B^+ \to \pi^+\pi^0, B^0 \to \pi^+\pi^-, B^0 \to \pi^0\pi^0$ Form a Triangle. This triangle and the corresponding one for the three charge conjugate decays are shown here. Note that the relative orientation of the two triangles can be obtained from the CP asymmetry. 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.

A.5 Determination of ϕ_s

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 (see Figure A-4).

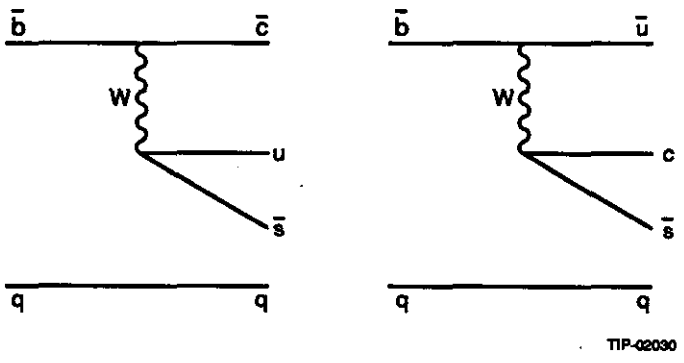

Figure A-4. Quark Diagrams Responsible for (a) $B \to D^0 + K + X_n$, (b) $B \to \bar{D}^0 + K + X_n$, and $B \to D_1 + K + X_n$. For the third decay, these two diagrams interfere.

Adopting Wolfenstein's representation,

$$A_{Dn} = |A_{Dn}|\, e^{i\delta_{Dn}},$$

$$A_{\bar{D}n} = |A_{\bar{D}n}|\, e^{i\delta_{\bar{D}n}} \exp i(\arg V_{ub}),$$

$$A_{D_1 n} = \frac{1}{\sqrt{2}}(A_{Dn} + A_{\bar{D}n}),$$

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

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

Now, note in Figure A-5 that we can draw two triangles:

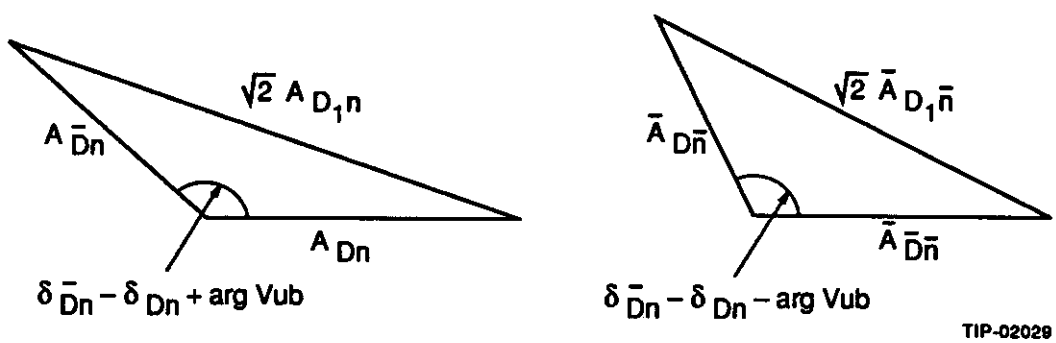

Figure A-5. Triangles Which Give the Phase Relationship Between the Three Amplitudes. Note that any difference in shape between the two triangles is a sign of CP violations. Thus $\arg V_{ub}$ can be obtained free of ambiguities of strong final-state interaction.

APPENDIX B
CPT Violation

Listed here are expressions that are useful in searching for CPT violation. The details can be found in Reference 5. The parameter s characterizes the CPT violation.

Let $N^{\pm\pm}$ denote the number of events for

$$(B\overline{B})_{C=-} \to l^{\pm}l^{\pm} + \text{ anything}$$

and N^{+-} denote that for

$$(B\overline{B})_{C=-} \to l^{+}l^{-} + \text{ anything.}$$

Here, C is the charge conjugation quantum number for the $B - \overline{B}$ state. Straightforward but tedious computation gives:

$$N^{\pm\pm} = \frac{e^{-\Gamma(t_1+t_2)}}{2(1+s^2)}\big(1 - \cos\Delta m(t_1 - t_2)\big);$$

$$N^{+-} = \frac{e^{-\Gamma(t_1+t_2)}}{(1+s^2)}\big(1 + 2s^2 + \cos\Delta m(t_1 - t_2)\big).$$

Let $N_{+}^{\pm\pm}$ denote the number of events for

$$(B\overline{B})_{C=+} \to l^{\pm}l^{\pm} + \text{ anything}$$

and N_{+}^{+-} denote that for

$$(B\overline{B})_{C=+} \to l^{+}l^{-} + \text{ anything.}$$

We obtain:

$$N_{+}^{+-} = \frac{e^{-\Gamma(t_1+t_2)}}{(1+s^2)^2}\Big[1 + \cos\Delta m(t_1 + t_2) + s^2\big(1 + 2\cos\Delta m t_1 + 2\cos\Delta m t_2 - \cos\Delta m(t_1 - t_2)\big) + 2s^4\Big]; \quad \text{(B.1)}$$

$$N_{+}^{\pm\pm} = \frac{e^{-\Gamma(t_1+t_2)}}{2(1+s^2)^2}\Big[1 - \cos\Delta m(t_1 + t_2) + s^2\big(3 - 2\cos\Delta m t_1 - 2\cos\Delta m t_2 + \cos\Delta m(t_1 - t_2)\big)\Big]. \quad \text{(B.2)}$$

The expressions above are valid for real s of arbitrary size.

We now discuss the consequences of CPT and CP violations on the asymmetries that involve $B\overline{B}$ mixing. Let $N^{\pm}_{(\psi K_S;C=\pm)}$ be the number of events corresponding to the process,

$$(B\overline{B})_{C=\pm} \to (l^{\pm} + X) + (\psi K_S).$$

If the CPT symmetry-breaking effect is large, it will be detected in the $B\overline{B}$ mixing. Thus, in analyzing the asymmetry in $N^{\pm}_{(\psi K_S;C=\pm)}$, we assume that the CPT-violating parameter s is small and real.

With this approximation, we can compute the number of events:

$$\begin{aligned} N^{\pm}_{(\psi K_S;C=-1)} \sim 1 &\pm \operatorname{Im}\lambda \ \sin\Delta m(t_1 - t_2) \\ &\pm s \ \operatorname{Re}\lambda \left[\cos\Delta m(t_1 - t_2) - 1\right]. \end{aligned}$$

In this section, t_1 and t_2 denote times corresponding to the leptonic decay and the ψK_S decay, respectively.

$$\begin{aligned} N^{\pm}_{(\psi K_S;C=+1)} \sim 1 &\mp \operatorname{Im}\lambda \ \sin\Delta m(t_1 + t_2) \\ &\pm s \ \operatorname{Re}\lambda \left[1 - 2\cos\Delta m t_1 + \cos\Delta m(t_1 + t_2)\right], \end{aligned}$$

where $\lambda = e^{-i\phi}\rho$.

Finally, we record here the time-integrated asymmetry:

$$a_{(\psi K_S;C=-)} \equiv \frac{N^{+}_{(\psi K_S;C=-)} - N^{-}_{(\psi K_S;C=-)}}{N^{+}_{(\psi K_S;C=-)} + N^{-}_{(\psi K_S;C=-)}} = -s \ \operatorname{Re}\lambda \frac{x^2}{1+x^2}. \tag{B.3}$$

We note that the effect is linear in s in contrast with the dilepton mode discussed in the previous section.

Finally, I emphasize that interesting asymmetry in decay times can exist in the dilepton events if Im s is nonvanishing.

$$N^{+-}_{\pm} \sim 1 + \cos\Delta m(t_1 \pm t_2) - 2\operatorname{Im} \ s \begin{pmatrix} \sin\Delta m t_1 - \sin\Delta m t_2 \\ \sin\Delta m(t_1 - t_2) \end{pmatrix}. \tag{B.4}$$

That is, there is a tendency to have either l^+ or l^- emitted first.