Kirk McDonald
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Estimates of Sensitivity to CP-Violation in B Decays in Experiments at Hadron Colliders

The HEPAP Subpanel on the U.S. Program of High Energy Physics Research in the 1990's has requested a response to the following:

> "Please estimate the value of the CP-violation parameter $\sin(2\beta)$ for which a three standard deviation signal would be observed in two years of running. [The parameter $\sin(2\beta)$ is the asymmetry parameter measured in the CP eigenstate modes such as ψK_S.] State the luminosity you have assumed and what limits that luminosity. Make explicit your assumptions about which tagging modes, and which CP eigenstate modes, are useful. Make a similar estimate of the sensitivity for measuring $\sin(2\alpha)$ in the decay $B^0 \to \pi^+\pi^-$, assuming a branching ratio of 2×10^{-5}. In all cases, assume 10^7 seconds of useful running time per year.
>
> It would be useful to show these estimates on a plot of the theoretically allowed region in two dimensions $[\sin(2\alpha), \sin(2\beta)]$. Since the allowed region depends on the top quark mass, separate plots should be made for three masses: 100, 150, and 200 GeV/c^2."

We first present some comments on the theoretically allowed region, based on consultation with David London. We then present estimates of the sensitivity to CP-violating asymmetries in the decays $B_d^0(\bar{B}_d^0) \to J/\psi K_S^0$ and $\pi^+\pi^-$, followed by a discussion of the assumptions in the various steps of the estimation.

Theoretical Parameter Space for CP-Violating Asymmetries

We propose to study CP-violating effects in the neutral B-meson system by measuring the decay asymmetry

$$A(t) = \frac{\Gamma(B(t) \to f) - \Gamma(\bar{B}(t) \to \bar{f})}{\Gamma(B(t) \to f) + \Gamma(\bar{B}(t) \to \bar{f})},$$

where $B(t)$ ($\bar{B}(t)$) is a state which at $t = 0$ was a B ($\bar{B}$) meson. When the final state f is a CP eigenstate ($f = \pm\bar{f}$, and hence the B must be neutral), the asymmetry can be written

$$A(t) = \sin 2\phi \sin x_q(t/\tau),$$

where $x_q = \Delta M/\Gamma$ is the mixing parameter for the B_q system ($q = d, s$). The angle ϕ is an interior angle of the so-called unitarity triangle that represents the (approximate) constraint on CKM matrix elements that $V_{ub}^\star - V_{us}V_{cb}^\star + V_{td} = 0$. As particular cases we have

$$\phi = \beta = \text{ angle between } V_{td} \text{ and the real axis, for } B_d^0 \to J/\psi K_S^0;$$
$$\phi = \alpha = \text{ angle between } V_{td} \text{ and } V_{ub}^* \text{ for } B_d^0 \to \pi^+\pi^-.$$

The beauty of B physics is that the CKM-matrix parameters are directly related to an experimentally observable quantity, without corrections due to uncertainties in the top-quark mass, hadronic form factors, or final-state effects. This statement is true only to the extent that the relevant decays are governed by a single amplitude; penguin diagrams may contribute corrections. Recent papers by Gronau [P.R.L. **63**, 1451 (1989)], and by London and Peccei [Phys. Lett. **223**, 257 (1989)] demonstrate that for the decay $B_d^0 \to J/\psi K_S^0$ we can still write $\phi = \beta$ in the presence of penguin corrections, and that the corrections to $\phi = \alpha$ for $B_d^0 \to \pi^+\pi^-$ are at most 20%.

Prior to making the direct measurements of $\sin(2\alpha)$ and $\sin(2\beta)$, constraints on these can be made using our present knowledge of the CKM-matrix parameters, but the constraints are sensitive to the top-quark mass. These constraints are sketched on the following page for $M_t = 100$, 150, and 200 GeV/c^2. They were calculated using the parametrization of the CKM matrix that

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\rho\lambda^3 e^{-i\delta} \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho e^{i\delta}) & -A\lambda^2 & 1 \end{pmatrix}.$$

The parameter λ is the Cabibbo angle ($\lambda = 0.22$), and $A = 1$ to good accuracy from analyses of the B-meson lifetime. Three additional experimental results are used to constrain the CKM-matrix elements, but the latter are allowed to move within limits implied by variation of the experimental results with $\pm 1.5\sigma$ (*i.e.*, a 90% confidence interval):

$|\epsilon| = (2.28 \pm 0.02) \times 10^{-3}$ from K decay;

$x_d = 0.72. \pm 0.10$ from B_d-$\bar{B}_d$ mixing at ARGUS and CLEO;

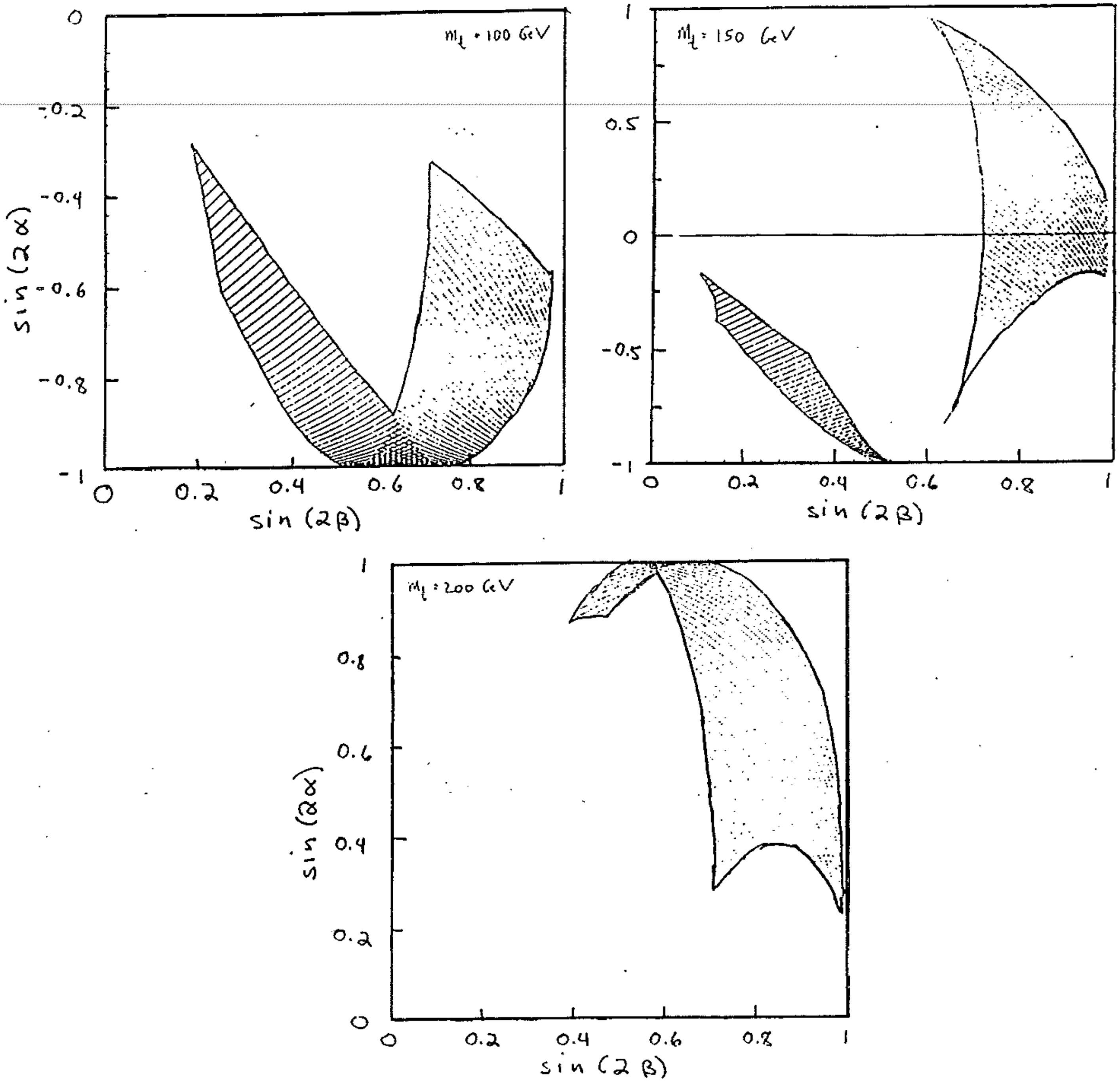
$\rho = 0.53 \pm 0.18$ from $|V_{ub}/V_{cb}| = 0.115 \pm 0.018$ at ARGUS and CLEO.

Also,

$$\sin(2\beta) = \mathrm{Im}\left(\frac{V_{td}}{V_{td}^\star}\right) = \frac{2\rho\sin\delta(1-\rho\cos\delta)}{1+\rho^2-2\rho\cos\delta},$$

$$\sin(2\alpha) = \mathrm{Im}\left(\frac{V_{ub}}{V_{ub}^\star}\right)\left(\frac{V_{td}}{V_{td}^\star}\right) = \frac{2\sin\delta(\cos\delta-\rho)}{1+\rho^2-2\rho\cos\delta}.$$

From the figures, we infer that $\sin(2\beta)$ and $\sin(2\alpha)$ cannot both be small, but that α could be near 90° for $M_t \sim 150$ GeV/c^2.



The shaded areas of the plots are the allowed regions (90% confidence) of $\sin(2\beta)$ and $\sin(2\alpha)$ based on present experimental knowledge, for top-quark masses 100, 150, and 200 GeV/c^2. Note the different vertical scales.

A B-physics experiment at the SSC could measure $\sin(2\beta)$ and $\sin(2\alpha)$ to better than three standard deviations in two years of running for $|\sin(2\beta)| > 0.016$ and $|\sin(2\alpha)| > 0.018$.

Sensitivity to $\sin(2\beta)$ **via** $B_d^0 \to J/\psi K_S^0$

Suppose we have collected N reconstructed and tagged events of the type $B_d^0(\bar{B}_d^0) \to J/\psi K_S^0$. At a hadron collider a typical B travels 2 mm before it decays, permitting a good measurement of the decay time. Then by analysis of the time-resolved decay asymmetry

$$A(t) = \frac{\Gamma(B(t) \to f) - \Gamma(\bar{B}(t) \to \bar{f})}{\Gamma(B(t) \to f) + \Gamma(\bar{B}(t) \to \bar{f})} = \sin(2\beta) \sin x_q(t/\tau),$$

we can obtain a measurement of $\sin(2\beta)$ with statistical significance of S standard deviations where

$$S = \frac{\sin(2\beta)}{\sigma(\sin(2\beta))} = \sqrt{N} \frac{\sin(2\beta)}{1 - \sin^2(2\beta)}.$$

The minimum value of $\sin(2\beta)$ that could be resolved to three standard deviations with N events is then

$$\sin(2\beta)_{\min,3\sigma} = \frac{3}{\sqrt{N+9}}.$$

However, we should take into account two possibilities that reduce the statistical significance:

1. A fraction p of the N events have been wrongly tagged. [Note that $0 < p < 1/2$.]
2. For each true $B_d^0(\bar{B}_d^0) \to J/\psi K_S^0$ event reconstructed we have b false reconstructions that have zero asymmetry. Then $1/b$ is the signal-to-noise ratio for this channel.

If there are no errors on our knowledge of p and b, we have

$$\sin(2\beta)_{\min,3\sigma} = \frac{3(1+b)}{(1-2p)\sqrt{N(1+b)+9}}.$$

Sensitivity to $\sin(2\beta)$ via $B_d^0 \to J/\psi K_S^0$ at the SSC

- Luminosity . . . . 10^{32} cm^{-2}sec^{-1}.
- Two standard running years of 10^7 sec $\Rightarrow$ . . . . 2 fb^{-1}.
- $\sigma_{B\bar{B}} = 500$ μb at the SSC $\Rightarrow$ . . . . 10^{12} B-$\bar{B}$ pairs.
- 3/4 B_d^0 or $\bar{B}_d^0$ per B-$\bar{B}$ pair $\Rightarrow$ . . . . 7.5×10^{11} B_d^0.
- B.R. for $B^0 \to J/\psi K_S^0$; $J/\psi \to e^+e^-$; $K_S^0 \to \pi^+\pi^-$:
  $(5 \times 10^{-4})(0.07)(0.69) = 2.4 \times 10^{-5}$
  $\Rightarrow$ . . . . 1.8×10^7 $B^0 \to e^+e^-\pi^+\pi^-$.
- Geometric acceptance (with P_T cut) for $B^0 \to e^+e^-\pi^+\pi^-$ is 0.3;
  Vertex and tracking efficiency ~ 0.33
  $\Rightarrow$ . . . . 1.8×10^6 reconstructed $B^0 \to e^+e^-\pi^+\pi^-$.
- For a CP-violation analysis we need a tag on the second B.
  Use the decays $B \to e\nu X$ and $B \to \mu\nu X$.
  The electron tagging efficiency is
  (0.5 geometric acceptance + P_T cut)
  $\cdot$(0.1 branching fraction)
  $\cdot$(0.5 vertex and tracking efficiency)
  $= 0.025$.
  Similarly we estimate a muon tagging efficiency of 0.025
  $\Rightarrow$ total tagging efficiency of 0.05
  $\Rightarrow$ . . . . 90,000 tagged, reconstructed $B^0 \to e^+e^-\pi^+\pi^-$.
- We also expect $\sim$ 65,000 tagged, reconstructed $B^0 \to \mu^+\mu^-\pi^+\pi^-$.
- $\Rightarrow$ . . . . 155,000 tagged, reconstructed $B^0 \to J/\psi K_S^0$.
- Mistagging factor: $1 - 2p \sim 0.5$.
- Background-to-signal ratio $b \sim 0.1$.
- $\Rightarrow$ . . . . $\sin(2\beta)_{\min,3\sigma} = 0.016$.

Sensitivity to $\sin(2\alpha)$ via $B_d^0 \to \pi^+\pi^-$ at the SSC

- Luminosity . . . . 10^{32} cm^{-2}sec^{-1}.
- Two standard running years of 10^7 sec $\Rightarrow$ . . . . 2 fb^{-1}.
- $\sigma_{B\bar{B}} = 500\ \mu$b at the SSC $\Rightarrow$ . . . . 10^{12} B-$\bar{B}$ pairs.
- 3/4 B_d^0 or $\bar{B}_d^0$ per B-$\bar{B}$ pair $\Rightarrow$ . . . . 7.5×10^{11} B_d^0.
- B.R. for $B^0 \to \pi^+\pi^- = 2 \times 10^{-5} \Rightarrow$ . . . . . 1.5×10^7 $B^0 \to \pi^+\pi^-$.
- Geometric acceptance for $B^0 \to -\pi^+\pi^-$ is 0.8;
  Vertex and tracking efficiency ~ 0.33
  $\Rightarrow$ . . . . 4×10^6 reconstructed $B^0 \to \pi^+\pi^-$.
- For a CP-violation analysis we need a tag on the second B.
  Use the decays $B \to e\nu X$ and $B \to \mu\nu X$.
  The overall tagging efficiency is 0.05
  $\Rightarrow$ . . . . 200,000 tagged, reconstructed $B^0 \to \pi^+\pi^-$.
- Mistagging factor: $1 - 2p \sim 0.5$.
- Background-to-signal ratio could be only $b \sim 1$.
- $\Rightarrow$ . . . . $\sin(2\alpha)_{\min,3\sigma} = 0.018$.

Comments on Assumptions in the Estimates

1. While a luminosity of 10^{32} cm^{-2}s^{-1} is low by the design standards of the SSC it does imply a 10-MHz event rate. This is the eventual goal of our proposed B-physics experiment (BCD), but in the early running a luminosity of 10^{31} is more realistic.

   The luminosity at the TEV I should reach 10^{31} *without the Main Ring Upgrade, and* 5×10^{31} *with it.*

2. The cross section for B-$\bar{B}$ pairs at the SSC is not well known due to uncertainty in the very low x gluon structure function. A value of 500 μb is in the center of the range commonly anticipated.

   The cross section at TEV I is commonly taken as 45 μ*b.*

3. We do not expect to reconstruct π^0's, and so will not be sensitive to $K_S^0 \to \pi^0\pi^0$.

4. While the geometric acceptance for $B \to e^+e^-\pi^+\pi^-$ will be $\sim$ 0.8, electron identification will require a P_T cut of at least 1 GeV/c, reducing the acceptance to ~ 0.3.

5. To maintain a vertexing and tracking efficiency ~ 0.33 in the high-multiplicity environment of the SSC will require a detector with large numbers of channels. We propose (at least) an order of magnitude more detector elements than now in use at LEP, SLC, or TEV I, but will encounter multiplicities only 2-3 times larger.

6. Muons will be identified only at forward and intermediate angles, reducing the geometric acceptance for $B \to \mu^+\mu^-\pi^+\pi^-$ to about 0.6. The requirement that the muons penetrate the steel absorbers reduces to acceptance to about 0.2.

   An experiment at TEV I would likely forego the muon option due to lack of space.

7. The use of semileptonic decays for tagging (according to the

charge of the leading lepton with a secondary vertex) limits the total tagging efficiency to about 0.05. A tag based on the charge of the leading particle to a secondary vertex might have greater efficiency, but is difficult to implement at high luminosity.

With only an electron tag at TEV I, the tagging efficiency would be limited to 0.025.

8. We estimate the mistagging probability p. At a hadron collider the tagging B could be either a B_u, a B_d, or a B_s (or their antiparticles), which we presume to be produced in the ratio

$$B_u : B_d : B_s = \frac{1-\epsilon}{2} : \frac{1-\epsilon}{2} : \epsilon.$$

Here we will use $\epsilon = 0.25$. In our tags it is unlikely that we will reconstruct which of the three kinds of B's caused the tag. The neutral B's can oscillate to their antiparticles before decaying, and we deduce that

$$1 - 2p = \frac{1-\epsilon}{2} + \frac{1-\epsilon}{2}\frac{1}{1+x_d^2} + \epsilon\frac{1}{1+x_s^2} \sim 0.6,$$

supposing the mixing parameters have values $x_d = 0.75$ and $x_s = 10$. This presumes we cannot use a measurement of the proper time of the decay of the tagging B to improve the efficiency.

There is also the possibility of a mistag because we tag on the charge of tertiary particle of the wrong sign. If this occurs with 5% probability it would reduce $1 - 2p$ from 0.6 to 0.5.

9. While the decay $B_d \to J/\psi K_S^0$ is sometimes called background free, this is not entirely so. At a hadron collider, the mass resolution must be sufficient to distinguish the decay $B_s \to J/\psi K_S^0$. Also, decays $B_d \to J/\psi K_S^0 X$ could be troublesome, especially if X is neutral. However the J/ψ-K_S^0 invariant-mass spectrum from such events is essentially flat from about 4 GeV/c^2 to $M_B - M_\pi$.

Again, if the mass resolution is significantly better than M_π there will be little problem.

Of some concern are decays $B \to J\psi X$ in which X does not reconstruct to the secondary vertex of the J/ψ. Then we might form a false J/ψ-K_S^0 using a K_S^0 from the rest of the event. Because of the long lifetime of the K_S^0 we will have only limited accuracy of reconstruction of a secondary vertex for it, and we might have to pay a significant price if we must require a clear secondary vertex for the K_S^0.

An interesting question is whether a vertex detector is needed at all for $B_d \to J/\psi K_S^0$? In a Monte Carlo study of this decay we also combined the J/ψ with all other K_S^0 in the SSC event, and found about 20:1 signal-to-noise assuming a 25-MeV/c^2 mass resolution. This signal is reduced by the ratio of J/ψ production from $B_d \to J/\psi K_S^0$ to that from any source, and so likely drops below 1:1. A vertex detector is needed at the SSC. [However, we estimate that at CDF where only high-P_T decays are detected with pseudorapidity $|\eta| < 1$, the signal-to-noise for $B_d \to J/\psi K_S^0$ is 2:1 even without a vertex detector!]

Here we suppose the background-to-signal for $B_d \to J/\psi K_S^0$ at the SSC is $b \sim 0.1$.

10. For the decay $B_d \to \pi^+\pi^-$ the signal-to-noise will not be nearly as good. Monte Carlo simulations of the rejection power of the vertex detector against $\pi^+\pi^-$ combinations actually from the primary vertex but yielding an apparent secondary vertex suggest that we may have $b \sim 1$.

11. *The sensitivity for an experiment at the upgraded TEV I follows from pp. 6-7, noting the adjustments in items 1, 2, 6, and 7:*

$$\sin(2\beta)_{\min,3\sigma} = 0.14, \qquad \sin(2\alpha)_{\min,3\sigma} = 0.11.$$

Closing Remark

While our optimistic estimates are extremely encouraging that the reach of B physics at the SSC will be vast, the experiment is difficult. We strongly feel that there should be an opportunity for an intermediate hadron-collider experiment in the 1990's to explore the many technical challenges, while doing significant B physics short of CP violation. A study of B_s-$\bar{B}_s$ mixing is an example of an excellent interim physics goal for such a program. The BCD collaboration will likely propose a 'mini-BCD' experiment at TEV I later this year, and will consider this as part of our long-range program foreseen at the SSC.