Experimental Status of $B$ Physics

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Abstract. A short summary is given of the current status of $B$ physics. Reasons for physics beyond the Standard Model are discussed. Constraints on New Physics are given using measurements of $B$ mixing, $B_d$ mixing, and CP violation, along with $|V_{ub}|$. Future goals, and upcoming new experiments are also mentioned.

INTRODUCTION

“New Physics” (NP) refers to physics beyond the “Standard Model,” the paradigm that we have constructed to explain our current high energy physics data [1]. We know, however, that NP is required to explain certain global phenomena including the Baryon asymmetry of the Universe, without which we could not exist, or the “Dark Matter,” found first by Zwicky studying rotation curves of galaxies [2]. An even more mysterious phenomena called “Dark Energy” may also have a connection to particle physics experiments [3], perhaps via “Extra Dimensions” [4]. The fundamental goals of $B$ decay studies are to discover, or help interpret, NP found elsewhere. Additional goals include measuring “fundamental constants” revealed to us by studying Weak interactions and understand the theory of strong interactions, QCD, necessary to interpret our measurements.

Baryogenesis

When the Universe began with the Big Bang, there was an equal amount of matter and antimatter. Now we have mostly matter. How did it happen? A. Sakharov gave three necessary conditions: Baryon (B) number violation, departure from thermal equilibrium, and C and CP violation [5]. (The operation of Charge Conjugation (C) takes particle to anti-particle and Parity (P) takes a vector $\mathbf{p}$ to $-\mathbf{p}$.)

These criteria are all satisfied by the Standard Model. B is violated in Electroweak theory at high temperature, though baryon minus lepton number is conserved; in addition we need quantum tunneling, which is powerfully suppressed at the low temperatures that we now have. Non-thermal equilibrium is provided by the electroweak phase transition. C and CP are violated by weak interactions. However the violation is too small. The
ratio of the number of baryons to the number of photons in the Universe needs to be \( \sim 6 \times 10^{-10} \), while the SM can provide only \( \sim 10^{-20} \). Therefore, there must be new physics.

### The Hierarchy Problem

Definition from the WIKIPEDIA encyclopedia [6]: “In theoretical physics, a hierarchy problem occurs when the fundamental parameters (couplings or masses) of some Lagrangian are vastly different (usually larger) than the parameters measured by experiment. This can happen because measured parameters are related to the fundamental parameters by a prescription known as renormalization. Typically the renormalized parameters are closely related to the fundamental parameters, but in some cases, it appears that there has been a delicate cancellation between the fundamental quantity and the quantum corrections to it.”

Our worry is why the Planck scale at \( \sim 10^{19} \text{ GeV} \) is so much higher than the scale at which we expect to find the Higgs Boson, \( \sim 100 \text{ GeV} \). We expect the explanation lies in physics beyond the Standard Model.

### THE BASICS: QUARK MIXING AND THE CKM MATRIX

The CKM matrix parameterizes the mixing between the mass eigenstates and weak eigenstates as couplings between the charge +2/3 and -1/3 quarks. I use here the Wolfenstein approximation [7] good to order \( \lambda^3 \) in the real part and \( \lambda^4 \) in the imaginary part:

\[
V_{\text{CKM}} = \left( \begin{array}{ccc}
1 - \lambda^2 / 2 & \lambda & A \lambda^3 (\rho - i \eta (1 - \lambda^2 / 2)) \\
-\lambda & 1 - \lambda^2 / 2 - i \eta A^2 \lambda^4 & A \lambda^2 (1 + i \eta \lambda^2) \\
A \lambda^3 (1 - \rho - i \eta) & -A \lambda^2 & 1
\end{array} \right). \tag{1}
\]

In the Standard Model \( A, \lambda, \rho \) and \( \eta \) are fundamental constants of nature like \( G \), or \( \alpha_{\text{EM}} \); \( \eta \) multiplies \( i \) and is responsible for all Standard Model CP violation. We know \( \lambda = 0.226 \), \( A \sim 0.8 \) and we have constraints on \( \rho \) and \( \eta \).

Applying unitarity constraints allows us to construct the six independent triangles shown in Fig. 1. Another basis for the CKM matrix are four angles labelled as \( \chi \) (sometimes called \( \beta_S \)), \( \chi' \) and any two of \( \alpha, \beta \) and \( \gamma \) since \( \alpha + \beta + \gamma = \pi \) [8]. (These angles are also shown in Fig. 1.)

\( B \) meson decays can occur through various processes. Some decay diagrams are shown in Fig. 2. The simple spectator diagram is dominant. Semileptonic decays, discussed next, proceed through this diagram.

### SEMILEPTONIC DECAYS AND LIFETIMES

These are the simplest decays to describe theoretically. The transformation of the virtual \( W^- \) to a lepton-antineutrino pair proceeds through the axial-vector current just as in
FIGURE 1. The 6 CKM triangles resulting from applying unitarity constraints to the indicated row and column. The CP violating angles are also shown.

FIGURE 2. Some $B$ decay diagrams.

pion decay. Because of their relative simplicity, semileptonic decays are used to probe the $b \to c$ and $b \to u$ transitions. The overall semileptonic branching ratio, $B_{SL}$ is defined as $B(\to X e^{-}\bar{\nu})$ equal to $B(\to X \mu^{-}\bar{\nu})$ and has a measured value of $(10.2 \pm 0.9)\%$ and $(10.5 \pm 0.8)\%$, for $B^-$ and $\bar{B}^0$ mesons, respectively. The average for these mesons is much better measured as $(10.87 \pm 0.17)\%$ [9].

The rather long average $B$ lifetime, $\sim 1.5$ ps is an important aspect of $B$ decays and is a crucial property allowing for more precise measurements of CP violation and other properties. The lifetime ratio $\tau_{B^-}/\tau_{\bar{B}^0} = 1.071 \pm 0.0009$ clearly demonstrates a longer, but not much longer lifetime for charged versus neutral $B$ mesons.

Measurements of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ have been made using both exclusive decays to specific final states, such as $B \to D^{*} l^{-}\bar{\nu}$ and inclusive final states. Values have been compiled by the Heavy Flavor Averaging Group [10]. $|V_{cb}|$ is measured to be $0.038 \pm 0.001$ from exclusive decays using Heavy Quark Effective Theory (HQET) [9]. Inclusive decays have also been used and good precision has been achieved, although the accuracy depends critically on whether or not the assumption of “duality” is indeed correct. Measurements of $|V_{ub}|$ have also been made also using
exclusive and inclusive decays. It is in the range of $3 - 4 \times 10^{-3}$. The main uncertainties are theoretical since there isn’t a firm theoretical basis similar to HQET that can be used. The combination $|V_{ub}/V_{cb}| \approx \lambda^2 \sqrt{\rho^2 + \eta^2}$.

**CURRENT B DECAY EXPERIMENTS**

**Current $e^+ e^-$ Experiments**

The BaBar and Belle collaborations both work at $e^+ e^-$ colliders, with asymmetric energies, at a center-of-mass energy equal to the mass of the $\Upsilon(4S)$ resonance. Here there is almost equal production of both $B^- B^+$ and $\bar{B}^0 B^0$ pairs, totaling 1 nb of cross section on top of 3 nb of background quark-antiquark production. The asymmetric energies are necessary to boost the $B^0$ mesons so that CP violation measurements can be made; the time integrated asymmetries would otherwise vanish as they are in $J^{PC} = 1^{--}$ states [11]. The boost, however, is small so the decay time resolution is only $\sim 900$ fs r.m.s.

CLEO and ARGUS collected data on the $\Upsilon$ resonances using symmetric $e^+ e^-$ machines. CLEO is now concentrating in studying charm meson decays at lower energies. It is also worth noting that many $e^+ e^-$ experiments have provided a wealth of interesting data including the aforementioned ones and experiments at LEP (operating at the $Z^0$ resonance) and the PEP and PETRA machines (operating near 30 GeV).

Both CLEO and Belle have taken data at the $\Upsilon(5S)$ resonance. CLEO has determined the $B_S$ fraction $\sim 16\%$ of the 0.3 nb $b\bar{b}$ cross-section, about 1/20 the production rate at the $\Upsilon(4S)$[12]. Not only is the yield small but the proper time resolution is not sufficient to allow time dependent CP violation measurements.

**Current Hadron Collider Experiments**

The CDF and D0 experiments at the Fermilab Tevatron are designed to study high energy phenomena, such as finding the top-quark and Higgs boson. However, they have some $b$ capabilities and are well suited to study the $B_S$ meson, which cannot be studied with $e^+ e^-$ colliders. The most important measurement that may be within reach of these experiments is that of $B_S$ mixing. Production of $b$-flavored hadrons is a large 100 $\mu$b at the 2 TeV center-of-mass energy of the Tevatron. Unfortunately the detectors are as not fully equipped as dedicated heavy flavor experiments. They lack the excellent particle identification and crystal based electromagnetic calorimetry of the state-of-the-art $e^+ e^-$ experiments. They do, however, have good $\sim 100$ fs decay time resolution [13].

**$B_D$ AND $B_S$ MIXING**

A diagram for $B_d$ mixing is shown in Fig. 2(e). For $B_S$ mixing just replace the $d$ quarks with $s$ quarks. The flavor eigenstates, degenerate in pure QCD mix under the
The probability $R = \left( \frac{B^0 \to \bar{B}^0}{B^0 \to B^0} \right)$ as a function of time from the OPAL experiment.

weak interactions. Designating the base states as $\{|1>,|2>\} \equiv \{|B^0>,|\bar{B}^0>\}$, the Hamiltonian is

$$H = M = -\frac{i}{2} \Gamma = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} = -\frac{i}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}. \tag{2}$$

Diagonalizing the matrix we find the mass difference $\Delta m = m_{B^0} - m_{B^0} = 2|M_{12}|$. For $B_d$ we predict $\Delta \Gamma \sim 0.1$. The probability for a $B^0$ meson to appear as a $\bar{B}^0$ as a function of time is given by $0.5 GeV \ e^{-\Gamma t} [1 + \cos(\Delta \Gamma t)]$. $R$ is often defined as the ratio $\left( \frac{B^0 \to \bar{B}^0}{B^0 \to B^0} \right)$. $B_d$ mixing was first discovered by the ARGUS experiment [14]. (There was a previous measurement by UA1 indicating mixing for a mixture of $B^0_d$ and $B^0_s$ [15].) At the time it was quite a surprise, since $m_t$ was thought to be in the 30 GeV range. It is usual to define $R$ as probability for a $B^0$ to materialize as a $\bar{B}^0$ divided by the probability it decays as a $B^0$. An early mixing result from OPAL is shown in Fig. 3 [16]. The world average value for $\Delta m_d$ is a very precise $0.509 \pm 0.005 \text{ ps}^{-1}$ [9]. The measurement is dominated by the BaBar and Belle experiments.

The probability of mixing is given by [17] as

$$x \equiv \frac{\Delta m}{\Gamma} = \frac{G_F^2}{6\pi^2}B_B f_B^2 m_B \tau_B |V_{tb}^* V_{td}|^2 m_t^2 F \left( \frac{m_t^2}{M_W^2} \right) \eta_{QCD}, \tag{3}$$

where $B_B$ is a parameter related to the probability of the $d$ and $\bar{b}$ quarks forming a hadron and must be estimated theoretically, $F$ is a known function which increases approximately as $m_t^2$, and $\eta_{QCD}$ is a QCD correction, with value about 0.8. By far the largest uncertainty arises from the unknown decay constant, $f_B$. In principle $f_B$ can be

\footnote{This is because the fraction of final states that of the same CP parity that both $B^0$ and $\bar{B}^0$ can decay into is very small. This is not the case for $B_S$.}
measured. The decay rate of the annihilation process \( B^- \rightarrow \ell^- \bar{\nu} \) is proportional to the product of \( f_B^2 |V_{ub}|^2 \). This is a very difficult process to measure, and even if this were done, the uncertainty on \( V_{ub} \) will lead to an imprecise result. Our current best hope is to rely on unquenched lattice QCD which can use the measurements of the analogous \( D^+ \rightarrow \mu^+ \nu \) decay as check. These checks are currently in progress at CLEO-c \[18\].

Since
\[
|V_{tb}^* V_{td}|^2 \sin^2 \theta = (1 - r - i h)^2,
\]
(4)
measuring mixing gives a circle centered at (1,0) in the \((r, h)\) plane. This could in principle be a very powerful constraint. Unfortunately, the parameter \( B_B \) is not experimentally accessible and \( f_B \) must be calculated; the errors on the calculations are quite large.

\( B^0_s \) mesons can mix in a similar fashion to \( B^0_d \) mesons. The diagram in Fig. 2(e) is modified by substituting \( s \) quarks for \( d \) quarks, thereby changing the relevant CKM matrix element from \( V_{td} \) to \( V_{ts} \). Measuring \( x_s \) allows us to use ratio of \( x_d / x_s \) to provide constraints on the CKM parameters \( r \) and \( h \). We still obtain a circle in the \((r, h)\) plane centered at (1,0):
\[
|V_{td}|^2 = (1 - r - i h)^2 + h^2,
\]
(5)
Now however we must calculate only the SU(3) broken ratios \( B_{B_d}/B_{B_s} \) and \( f_{B_d}/f_{B_s} \).

\( B^0_s \) mixing has been searched for at LEP, the Tevatron, and the SLC. A combined analysis has been performed. The probability, \( \mathcal{P}(t) \) for a \( B_s \) to oscillate into a \( \bar{B}_s \) is given as
\[
\mathcal{P}(t) (B_s \rightarrow \bar{B}_s) = \frac{1}{2} \Gamma_s e^{-\Gamma_s t} [1 + \cos(\Delta m_s t)] ,
\]
(6)
where \( t \) is the proper time.

To combine different experiments a framework has been established where each experiment finds a amplitude \( A \) for each test frequency \( \omega \), defined as
\[
\mathcal{P}(t) = \frac{1}{2} \Gamma_s e^{-\Gamma_s t} [1 + A \cos(\omega t)] .
\]
(7)
Fig. 4 shows the world average measured amplitude \( A \) as a function of the test frequency \( \omega = \Delta m_s \) \[10\]. For each frequency the expected result is either zero for no mixing or one for mixing. No other value is physical, although measurement errors admit other values. The data do indeed cross one at a \( \Delta m_s \) of 16 ps\(^{-1}\), however here the error on \( A \) is about 0.6, precluding a statistically significant discovery. The quoted upper limit at 95% confidence level is 16.6 ps\(^{-1}\). This is the point where the value of \( A \) plus 1.645 times the error on \( A \) reach one. Also, one should be aware that all the points are strongly correlated.

As this work was being completed the D0 experiment announced that they had limited the \( \Delta m_s \) between 17 ps\(^{-1}\) and 21 ps\(^{-1}\) at 90% confidence level \[19\]. Fig. 5 shows their amplitude analysis results. Clearly the significance of the result, although limited, relies on seeing an amplitude in excess of the expected value of 1, in fact, nearly at 3. Further
FIGURE 4. Combined experimental values of the amplitude $A$ versus the test frequency $\omega = \Delta m_s$ as defined in equation 7. The inner (outer) envelopes give the 95% confidence levels using statistical (statistical and systematic) errors. The “sensitivity” shown at 20.0 ps$^{-1}$ is the likely place a 95% c.l. upper limit could be set. Data will be needed to confirm this result. The inferred values of $\rho$ and $\eta$ are within the range expected by fits to other parameters (see Fig. 8), and are consistent with Standard Model expectations.

FIGURE 5. $B^0_s$ oscillation amplitude as a function of oscillation frequency, $\Delta m_s$ from D0. The red (solid) line shows the $\alpha = 1$ axis for reference. The dashed line shows the expected limit including both statistical and systematic uncertainties.
CP VIOLATION MEASUREMENTS

Introduction

CP violation can occur because of the imaginary term in the CKM matrix, proportional to $\eta$ in the Wolfenstein representation [11].

Decays of neutral $K$ mesons were the first to show CP violating effects. In this decade the BaBar and Belle experiments provided precision measurement of one of the four CP violating angles ($\beta$) and gave first measurements of two other angles ($\alpha$ and $\gamma$).

Consider the case of a process $B \to f$ that goes via two amplitudes $A$ and $B$ each of which has a strong part e.g. $s_{A}$ and a weak part $w_{A}$. Then we have

$$G(B \to f) = \left| A \right| e^{i(s_{A} + w_{A})} + \left| B \right| e^{i(s_{B} + w_{B})} \right|^{2} \quad (8)$$

$$G(B \to f) = \left| A \right| e^{i(s_{A} - w_{A})} + \left| B \right| e^{i(s_{B} - w_{B})} \right|^{2} \quad (9)$$

$$\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f}) = 2 \left| A \right| \left| B \right| \sin(s_{A} - s_{B}) \sin(w_{A} - w_{B}) \right|^{2} \quad (10)$$

Any two amplitudes will do, though it's better that they be of approximately equal size. Thus charged $B$ decays can exhibit CP violation as well as neutral $B$ decays. In some cases, we will see that it is possible to guarantee that $|\sin(s_{A} - s_{B})|$ is unity, so we can get information on the weak phases. In the case of neutral $B$ decays, mixing can be the second amplitude.

Formalism of CP Violation in Neutral $B$ Decays

For neutral mesons we can construct the CP eigenstates

$$|B_{0}^{0}\rangle = \frac{1}{\sqrt{2}} \left( |B^{0}\rangle - |\bar{B}^{0}\rangle \right), \quad |B_{2}^{0}\rangle = \frac{1}{\sqrt{2}} \left( |B^{0}\rangle + |\bar{B}^{0}\rangle \right), \quad \text{where} \quad (11)$$

$$CP |B_{0}^{0}\rangle = |B_{1}^{0}\rangle, \quad CP |B_{2}^{0}\rangle = - |B_{2}^{0}\rangle. \quad (12)$$

Since $B^{0}$ and $\bar{B}^{0}$ can mix, the mass eigenstates are a superposition of $a |B^{0}\rangle + b |\bar{B}^{0}\rangle$ which obey the Schrodinger equation

$$i \frac{d}{dt} \begin{pmatrix} a \\ b \end{pmatrix} = \mathcal{H} \begin{pmatrix} a \\ b \end{pmatrix} = \left( M - \frac{i}{2} \Gamma \right) \begin{pmatrix} a \\ b \end{pmatrix}. \quad (13)$$

If CP is not conserved then the eigenvectors, the mass eigenstates $|B_{L}\rangle$ and $|B_{H}\rangle$, are not the CP eigenstates but are

$$|B_{L}\rangle = p |B^{0}\rangle + q |\bar{B}^{0}\rangle, \quad |B_{H}\rangle = p |B^{0}\rangle - q |\bar{B}^{0}\rangle, \quad \text{where} \quad (14)$$

$$p = \frac{1}{\sqrt{2}} \frac{1 + \varepsilon_{B}}{\sqrt{1 + |\varepsilon_{B}|^{2}}}, \quad q = \frac{1}{\sqrt{2}} \frac{1 - \varepsilon_{B}}{\sqrt{1 + |\varepsilon_{B}|^{2}}}. \quad (15)$$

CP is violated if $\varepsilon_{B} \neq 0$, which occurs if $|q/p| \neq 1$. 

Experimental Status of $B$ Physics
**CP violation for B via interference of mixing and decays**

Here we choose a final state $f$ which is accessible to both $B^0$ and $\overline{B}^0$ decays. The second amplitude necessary for interference is provided by mixing. It is necessary only that $f$ be accessible directly from either state; however if $f$ is a CP eigenstate the situation is far simpler. For CP eigenstates $CP\langle f_{CP}\rangle = \pm |f_{CP}\rangle$. It is useful to define the amplitudes $A = \langle f_{CP}|\mathcal{H}|B^0\rangle$, $\overline{A} = \langle f_{CP}|\mathcal{H}|\overline{B}^0\rangle$. If $|A| \neq 1$, then we have “direct” CP violation in the decay amplitude, which we will discuss in detail later. Here CP can be violated by having

$$\lambda = \frac{q}{p} \frac{\overline{A}}{A} \neq 1,$$

which requires only that $\lambda$ acquire a non-zero phase, i.e. $|\lambda|$ could be unity and CP violation can occur.

A comment on neutral $B$ production at $e^+e^-$ colliders is in order. At the $\Upsilon(4S)$ resonance there is coherent production of $B^0\overline{B}^0$ pairs. This puts the $B$'s in a $C = -1$ state. In hadron colliders, or at $e^+e^-$ machines operating at the $Z^0$, the $B$'s are produced incoherently. The asymmetry is defined as

$$a_{f_{CP}} = \frac{\Gamma(B^0(t) \rightarrow f_{CP}) - \Gamma(\overline{B}^0(t) \rightarrow f_{CP})}{\Gamma(B^0(t) \rightarrow f_{CP}) + \Gamma(\overline{B}^0(t) \rightarrow f_{CP})},$$

which for $|q/p| = 1$ gives

$$a_{f_{CP}} = \frac{(1 - |\lambda|^2) \cos(\Delta mt) - 2\text{Im}\lambda \sin(\Delta mt)}{1 + |\lambda|^2}.$$

For the cases where there is only one decay amplitude $A$, $|\lambda|$ equals 1, and we have

$$a_{f_{CP}} = -\text{Im}\lambda \sin(\Delta mt).$$

Only the amplitude, $-\text{Im}\lambda$ contains information about the level of CP violation, the sine term is determined only by $B_d$ mixing; the time integrated asymmetry is given by

$$a_{f_{CP}} = -\frac{x}{1 + x^2} \text{Im}\lambda = -0.48\text{Im}\lambda.$$

This is quite lucky as the maximum size of the coefficient for any $x$ is $-0.5$.

Let us now find out how $\text{Im}\lambda$ relates to the CKM parameters. Recall $\lambda = \frac{q}{p} \frac{\overline{A}}{A}$. The first term is the part that comes from mixing:

$$\frac{q}{p} = (V_{tb}^* V_{td})^2 = \frac{(1 - \rho - i\eta)^2}{(1 - \rho + i\eta)(1 - \rho - i\eta)} = e^{-2\beta}$$

and

$$\text{Im} \frac{q}{p} = -\frac{2(1 - \rho)\eta}{(1 - \rho)^2 + \eta^2} = \sin(2\beta).$$
To evaluate the decay part we need to consider specific final states. Let's consider the final state $J/\psi K_s$. The decay process proceeds via the diagram in Fig. 2(b), where the $c\bar{c}$ forms a $J/\psi$. Here we do not get a phase from the decay part because

$$\frac{\mathcal{A}}{A} = \frac{(V_{cb}V_{cs}^*)^2}{|V_{cb}V_{cs}|^2}$$

(23)

is real to order $1/\lambda^4$.

In this case the final state is a state of negative $CP$, i.e. $CP|J/\psi K_s\rangle = -|J/\psi K_s\rangle$. This introduces an additional minus sign in the result for $\text{Im}\lambda$. Before finishing discussion of this final state we need to consider in more detail the presence of the $K_s$ in the final state.

$$\frac{(q/p)_{K}}{K} = \frac{(V_{cd}V_{cs})^2}{|V_{cd}V_{cs}|^2}$$

(24)

which is real to order $\lambda^4$. It is necessary to include this term, however, since there are other formulations of the CKM matrix than Wolfenstein, which have the phase in a different location. It is important that the physics predictions not depend on the CKM convention.2

### CP Violation Measurements

The CP asymmetry $\sin(2\beta)$ has been measured by both Belle and BaBar using both CP+ and CP- final states. Most of the latter are $J/\psi K_s$, while most of the former are $J/\psi K_L$. Fig. 6 shows the raw asymmetries and the fit results for $(c\bar{c})K_S$ (top) and $J/\psi K_L$ (bottom) [20]. The world average value of $\sin(2\beta)$ is $0.685 \pm 0.032$ [10].

The Belle collaboration pioneered the measurement of $\gamma$ using the charged decays $B^\pm \rightarrow D^0 K^\mp$, where the $D^0 \rightarrow K_S \pi^+ \pi^-$. Here $D^0$ decays cannot be distinguished from $\bar{D}^0$ decays, and they interfere. Measurements from BaBar and Belle have been reported. BaBar averages in additional information from $D^{*0} K^+$ and $D^0 \bar{K}^{0*}$, finding $\gamma = (67 \pm 28 \pm 13 \pm 11)^0$ and Belle, omitting the last mode, obtains $\gamma = (67_{-15}^{+14} \pm 13 \pm 11)^0$, where the last error is due the parametrization of the $D^0$ decay Dalitz plot, and could be helped greatly by CLEO-c measurements of the CP+ and CP- Dalitz plots [21, 22].

The angle $\alpha$ can be probed by measuring processes such as $B^0 \rightarrow \pi^+ \pi^-$ or $\rho^+ \rho^-$ as shown in Fig. 7(a), because the combination of weak phases in the mixing amplitude and the $b \rightarrow u$ decay amplitude are $\sin(2(\beta + \gamma)) = \sin(2(180 - \alpha)) = -\sin(2\alpha)$. Unfortunately, the Penguin diagram in Fig. 7(b) has no weak phase and can be significant in these processes. Thus the Penguin process can "pollute" the measurement of $\alpha$ in

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2 Here we don’t include CP violation in the neutral kaon since it is much smaller than what is expected in the $B$ decay. The term of order $\lambda^4$ in $V_{cs}$ is necessary to explain $K^0$ CP violation.
FIGURE 6. $\Delta t$ distributions from Belle for the events with $q_{\xi_f} = -1$ (open points) and $q_{\xi_f} = +1$ (solid points) with all modes combined (top), asymmetry between $q_{\xi_f} = -1$ and $q_{\xi_f} = +1$ samples with $0 < r \leq 0.5$ (middle), and with $0.5 < r \leq 1$ (bottom). The variable $r$ refers to the probability of the correctness of the flavor tag, where $r=1$ is almost assuredly correct, while $r=0$ conveys no information. The results of the global unbinned maximum-likelihood fit ($\sin(2\beta)=0.728$) are also shown.

FIGURE 7. Tree (a) and Penguin (b) processes for neutral $B$ decay into either $\pi^+\pi^-$ or $\rho^+\rho^-$. these modes, but it can be limited by using the upper limit on the branching ratio for $B^0 \rightarrow \rho^0\rho^0$ as shown by Grossman and Quinn [23]. BaBar first used this final state for CP violation measurement by showing that it is almost fully polarized and that the Penguin term could be usefully limited. Currently we have $\alpha = (96 \pm 13 \pm 11)^\circ$, where the last error is due to the possible Penguin contribution [21].
LIMITS ON NEW PHYSICS

Constraints on the Wolfenstein $\rho$ and $\eta$ parameters are given by many measurements and summarized in Fig. 8 [24]. (For alternative fits see Ref. [25].) This plot is based on measurements of $|V_{ub}/V_{cb}|$, $B^0 - \bar{B}^0$ mixing, upper limits on $B_S$ mixing and the CP violation measurements discussed here of $\alpha$, $\beta$ and $\gamma$ as well as CP violation in the $K_L^0$ system.

Agashe et al. have established limits on New Physics (NP) arising via $B^0$ mixing [26], using a method that was modified from that first used by Grossman et al. and Ligeti [27]. They assume that NP in tree level processes, such as those used to measure $|V_{ub}|$ is negligible. They then parameterize NP in terms of an amplitude $h$ and a phase $\phi$ as

$$
\Delta m_d = |1 + h_d e^{2i\phi_d}| \Delta m_{d}^{SM}, \quad S_{\psi K} = \sin[2\beta + 2\theta_d],
$$

where $\theta_d = \text{arg}(1 + h_d e^{2i\phi_d})$. The CP asymmetry in $B^+ \rightarrow DK^+$, $A_{DK}$, is also a SM tree level transition and therefore is unaffected by NP; $A_{DK} \sim \tan\gamma = \frac{2}{\rho}$. Note that $A_{DK}$ depends only on $\rho$, $\eta$ in a combination different than $V_{ub}$. The CP asymmetry in $B^0 \rightarrow \rho^+ \rho^-$, $S_{\rho \rho}$, is given by $S_{\rho \rho} \propto \sin(2\gamma + 2\beta + 2\theta_d)$. Thus, $S_{\rho \rho}$ also depends only on $\rho$, $\eta$ after subtracting the phase of $B_d$ mixing (including the NP phase) using $S_{\psi K}^{exp}$. Thus $\rho$, $\eta$ can be determined even in presence of NP. The allowed size of NP admits a range for $h_d$ of $h_d = 0 - 0.4$, for $2\sigma_d = \pi - 2\pi$. This is demonstrated in Fig. 9 where the $h_d - \sigma_d$ allowed regions are shown. Thus, the data do not yet exclude substantial contributions to NP via $B_d$ mixing. In the case of NP via $B_S$ mixing, there are almost no restrictions.
A hint of NP may be showing up in measurements of CP violation in Penguin decays. A data summary is shown in Fig. 10. The trend is for these modes to have asymmetries below that in $J/\psi K_S$ related modes. These modes may have additional amplitudes, but calculations tend to show that these would result in positive asymmetries, opposite to the observed effect [28]. Each mode must be considered individually so averaging them is not a reasonable approach.

$$\sin(2\beta^{\text{eff}})/\sin(2\Phi_1^{\text{eff}})$$

### FIGURE 10

Measurement of $\sin(2\beta)$ in Penguin dominated modes versus that in $(c\tau)_s$ modes. Note that $\sin(2\beta)$ is sometimes called $\sin(2\Phi_1)$. The superscript “eff” indicates that no attempt has been made to correct for the possible presence of a $\cos(\Delta m t)$ term, see equation 18.
The future of heavy physics may well be the provenance of experiments at CERN starting in \( \sim 2008 \) when significant data will be taken by experiments at the LHC, a proton-proton collider with 14 TeV of energy in the center-of-mass.

Three experiments are equipped to study \( B \) decays. The LHCb experiment is the only one specifically designed for this purpose. The ATLAS and CMS experiments can, however, make some useful measurements; they are intended to run a very high luminosity, \( 10^{34}\text{cm}^{-2}\text{s}^{-1} \), while LHCb will run around \( 2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1} \). While CMS and ATLAS are designed to measure new high mass particles in the central region, LHCb will detect \( b \)-flavored hadrons produced in the forward direction along one of the beams. The production mechanism tends to put both particles in the detector acceptance, crucial for flavor tagging, i.e. distinguish the flavor of the \( b \)'s at birth.

A sketch of the LHCb detector is shown in Fig. 11. A silicon strip detector called “VELO” is used to measure decay vertices. The detectors are segmented along the radial and azimuthal directions. The layout is shown Fig. 12, the sensor geometry in (b) and a photograph in (c). There are two ring imaging Cherenkov counters used to distinguish pions from kaons, required because of the large range of momenta (1-100 GeV/c) that occur. An electromagnetic calorimeter constructed from scintillating fibers and lead detects \( \gamma \)'s, \( \pi^0 \)'s and \( \eta \)'s; it also identifies electrons. The iron filter after the hadron calorimeter (HCAL) interspersed with the chambers M2-M5 is used to identify muons. The calorimetry, both electromagnetic and hadronic provide real time information used in the first trigger level (called Level 0) for charged particles or neutral energy at transverse momenta that are likely to come from \( b \) decays. A “pile-up” device is also used to identify beam crossings with more than one interaction. More details about the detector can be found in [29].

The KEK accelerator has produced very impressive luminosities and there are plans to improve it. This concept is called “Super-Belle.” There would be both machine and detector improvements allowing running up to an instantaneous luminosity of \( \sim 5 \times 10^{35}\text{cm}^{-2}\text{s}^{-1} \). Currently, this is a proposal that has yet to be acted on. Another similar proposal was also formulated by the “Super-BaBar” group. It however has not been supported by SLAC or the U. S. Dept. of Energy.

A group in Frascati, Italy has been exploring the possibility of using recirculating electron linacs as the basis of a novel \( e^+e^- \) collider in the Upsilon region [30]. This machine would not have appreciable synchrotron radiation, so current detector technologies would work just fine. However, the number of interactions per crossing could be large.

**CONCLUSIONS**

The study of the decays of \( b \)-flavored hadrons has advanced greatly from its early beginnings. We have one precision measurement, namely that of \( \sin(2\beta) \) and initial measurements of \( \alpha \) and \( \gamma \). Yet much more needs to be done. \( |V_{ub}| \) needs to be made more precise by improvements in QCD calculations and comparisons with charmless semileptonic decays in the appropriate kinematic regions suitable for reliable theoretical
FIGURE 11. A sketch of the LHCb detector showing the Vertex Locator (VELO), the two RICH subsystems, the tracking trigger stations (TT) before the magnet, the tracking stations after the magnet (T1-T3), the Scintillating Pad detector (SPD), the Preshower (PS), the Electromagnetic Calorimeter (ECAL), the Hadronic Calorimeter (HCAL) and the Muon Stations (M1-M5).

predictions. Measurements of CP violation in $B_s$ decays are of prime importance. After the termination of current experimental efforts in flavor physics in the U. S. at the end of this decade, experimental progress will depend on experiments at the LHC, in particular LHCb, and at Belle or a possible Super-Belle in Japan. These experiments will be essential in interpreting the New Physics we expect to find at the LHC.

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(a) VELO with RF-foil, 21 \(r \phi\) detector stations, and two upstream \(r\) stations for the Pile Up system.

(b) \(r\) and \(\phi\) sensors. For each sensor, 2 readout strips are indicated by dotted lines, for illustration.

(c) Prototype Si sensor with readout electronics

**FIGURE 12.** The LHCb Vertex Locator (VELO)
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30. J. Albert et al., [physics/0512235]: http://www.lnf.infn.it/conference/superb06/