B Physics
in the Next Millennium

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Talk presented at HQ98,
Workshop on HEAVY QUARKS AT FIXED TARGET,
Batavia, Illinois, October 1998

Abstract. As we approach the turn of the century, the Standard Model is still consistent with all our experimental observations and the path to a more complete picture of the fundamental constituents and their interactions has yet to be clearly identified. Beauty flavored hadrons have provided crucial experimental information on several fundamental parameters of the Standard Model and may lead to one of the most challenging tests of its validity and provide some clues on the path towards a more complete theory. Several experiments will try to explore this rich phenomenology in the next few years. Their physics goals and discovery potential will be compared.

INTRODUCTION

The investigation of $B$ meson decays has provided a wealth of information on one of the least understood aspects of the Standard Model: the quark mixing that underlies the complex pattern of charge-changing transition in the quark sector. This pattern is summarized by a 3 x 3 unitary matrix, the Cabibbo-Kobayashi-Maskawa (CKM) matrix:

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$ (1)

A commonly used approximate parameterization was originally proposed by Wolfenstein [1]. It reflects the hierarchy between the magnitude of matrix elements

1) Work supported by the National Science Foundation.
belonging to different diagonals. The 3 diagonal elements and the 2 elements just above the diagonal are real and positive. It is defined in first order as:

\[ V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}. \] (2)

There are several reasons why the experimental determination of the CKM parameters is interesting. On one hand, it is important to test that it is indeed a unitary matrix, as dictated by the Standard Model. On the other hand, the complex phase that is inherent in the 3-generation CKM matrix can be an explanation for the phenomenon of CP violation, so far observed only in the neutral K meson system. This violation is expected to be responsible for baryon dominance in our world and thus the understanding of its mechanisms has profound implications for our understanding of the origin and evolution of the universe.

The b quark provides a unique opportunity to study several CKM parameters. The study of semileptonic decays allows the measurement of \(|V_{cb}|\) and \(|V_{ub}|\). \(B^0 - \bar{B}^0\) mixing provides information on \(V_{td}\) and \(V_{ts}\). These different measurements provide independent constraints on the ‘unitarity triangle’ shown in Fig. 1. A more accurate determination of the magnitude of \(V_{ub}/V_{cb}\) and of the mixing parameters can pin down two sides of this triangle. Note that one side has a length equal to one by construction. In addition, several experiments will try to get some information on the angles \(\alpha\), \(\beta\) and \(\gamma\).

**FIGURE 1.** The regions in \(\rho - \eta\) space (shaded) consistent with measurements of CP violation in \(K^0\) decay (\(\epsilon\)), \(V_{ub}/V_{cb}\) in semileptonic B decay, \(B^0_d\) mixing, and the excluded region from limits on \(B^0_s\) mixing. The allowed region is defined by the overlap of the 3 permitted areas, and is where the apex of the CKM triangle sits. The bands represent \(\pm 1\sigma\) errors. The large width of the \(B_d\) mixing band is dominated by the uncertainty in the parameter \(f_B\). Here the range is taken as \(240 > f_B > 160\) MeV.
The knowledge of these angles will answer some very fundamental questions:
(1) Is the CKM phase of the three generation Standard Model the only source of \( CP \) violation?
(2) Is there new physics in the quark sector?

**FUTURE FACILITIES FOR \( B \) PHYSICS**

The next decade will see a blooming of experimental facilities planning to explore the \( B \) decay phenomenology with increasing sensitivity to different observables and various final states.

Table 1 summarizes the main properties of the experiments that will take data in the near future. Among them there are upgraded versions of previous experiments that have contributed to our present knowledge of \( B \) physics and some new facilities, HERA-B, a fixed target experiment at HERA, Hamburg, Germany, and the two experiments taking data at the new asymmetric \( e^+e^- \) \( B \)-factories, BaBar at SLAC and Belle at KEK.

A few years later, ATLAS and CMS should start taking data at the new LHC pp collider and they are also planning to address some of the \( B \) physics issues discussed below. The experiments at hadronic machines discussed so far are pursuing \( B \) physics, but they have all been optimized for their main goal, high \( p_T \) physics. They take advantage of the high cross section for \( b \) production, but have not been designed to study \( b \) decays. Two experiments have been proposed to exploit the full discovery potential offered by the high cross section and richness of final states accessible at hadron machines: LHCb, approved to take data at LHC, and BTeV, planning to take data at Fermilab. BTeV is an official R&D project at Fermilab.

### TABLE 1. \( B \) experiments in the near future.

|                | CLEO III  | BaBar-Belle | HERA-B    | CDF-D0    |
|----------------|-----------|-------------|-----------|-----------|
| \( L (cm^{-2}s^{-1}) \) | 1.7\times10^{33} | 3\times10^{33} | (Int.Rate)40 MHz | 2\times10^{32} |
| \( \sigma_{b\bar{b}} \)   | 1.15 nb   | 1.15 nb     | \approx 10 nb | 100 \( \mu \)b |
| \( \sigma_{b\bar{b}}/\sigma_{had} \) | 0.25 | 0.25 | \approx 10^{-6} | \approx 10^{-3} |
| Trigger         | all \( B \)'s | all \( B \)'s | \( \psi \) | high \( p_{T} \) \( \mu \)'s |
| Time res.       | very modest | modest | good | good |
| PID             | \( e,\mu,\pi,K,p \) | \( e,\mu,\pi,K,p \) | \( e,\mu,\pi,K,p \) | \( e,\mu \) |

### TABLE 2. \( B \) experiments starting around 2005.

|                | \( e^+e^- \) B-factories | ATLAS/CMS | LHCb | BTeV |
|----------------|---------------------------|-----------|------|------|
| \( L (cm^{-2}s^{-1}) \) | \( 10^{34} \) | \( 10^{33} \) (first run) | \( 1.5\times10^{32} \) | \( 2 \times 10^{32} \) |
| \( \sigma_{b\bar{b}} \) | \( 1.15 nb \) | \( 500 \mu \)b | \( 500 \mu \)b | \( 100 \mu \)b |
| \( \sigma_{b\bar{b}}/\sigma_{had} \) | 0.25 | \( \approx 5 \times 10^{-3} \) | \( \approx 5 \times 10^{-3} \) | \( \approx 10^{-3} \) |
| L1 Trigger | all \( B \)'s | high \( p_{T} \) \( \mu \)'s | medium \( p_{T} \) \( \mu, e, h \)' detached vertices | |
| Time res. | modest | good | very good | very good |
| PID | \( e,\mu,\pi,K,p \) | \( e,\mu \) | \( e,\mu,\pi,K,p \) | \( e,\mu,\pi,K,p \) |
Table 2 summarizes the most distinctive features of this next round of experiments that are expected to take data around the year 2005.

The traditional advantage of $e^+e^-$ machines operating at the $\Upsilon(4S)$ are their low non-$B$ background. In addition, the final state is composed just of a $B\bar{B}$ meson pair, making it easy to apply powerful kinematical constraints to identify specific final states or to reconstruct inclusive decays, like $b \to s\gamma$ or decays with missing particles like neutrinos. On the other hand, in order to measure rare decays or tiny $CP$ asymmetries it is necessary to collect huge data samples, posing a significant challenge to the accelerator physicists striving to design machines of ever increasing luminosity.

Experiments taking place at hadronic facilities have the advantage of copious production of $b$-flavored hadrons. On the other hand, their main challenge is the identification of the interesting $b$ events from the much more frequent ‘minimum bias’ events. The key detector element in this endeavour has been a high resolution vertex detector, as the distinctive feature of $b$ decays in this environment is that their lifetime is longer than the one of the light quark products. CDF has been quite successful in exploiting this feature as a tool for $b$ physics.

Experiments at hadron machines designed for $b$ physics have observed that the forward region is the most favorable to the study of $b$ decays. Several characteristics of hadronic $b$ production favor the forward direction as the region of choice for the detector acceptance. Fig. 2 shows that the $b$ quarks are produced at the Tevatron with a relatively flat pseudo-rapidity distribution, where the pseudo-rapidity $\eta$ is defined as $\eta = -\ln(\tan(\theta/2))$ where $\theta$ is the polar angle with respect to the beam axis. Note that the more forward the $b$, the higher its Lorentz boost is, as shown in Fig. 2, thus making it easier to identify the $b$ decays by their detached decay vertices. Finally, Fig. 3 shows the correlation in the production angles of the $b$ and

**FIGURE 2.** The $B$ yield plotted versus $\eta$ (left), $\beta\gamma$ of the $B$ plotted versus $\eta$ (right). Both plots are for the Tevatron.
quarks. Note that in the forward directions the pair shows a strong correlation in their production angle. On the other hand, in the central region there isn’t any correlation.

BTeV and LHCb have several features in common. In particular, both experiments take advantage of the open detector geometry in the forward direction to include a Ring Imaging Cherenkov detector, allowing an excellent discrimination between \( \pi \)'s, \( p \)'s and \( K \)'s, crucial to some of the measurements discussed below. The most distinctive feature of the BTeV experiment is a unique vertex detector, based on high resolution pixel devices inside a dipole magnetic field, associated with fast trigger processors that will provide the detached vertex information at the first level trigger. This feature is critical to achieve high efficiency for hadronic decay modes, like \( B \rightarrow \pi^+\pi^- \). In addition, it is a two arm spectrometer and takes advantage of the extended luminous region of the Tevatron \( (\sigma_Z \approx 30 \text{ cm}) \) to utilize also multiple interactions per crossing. These features more than compensate the lower \( \sigma_{\bar{b}b} \) than LHCb and the two experiments are quite competitive.

A SCENARIO FOR THE UNFOLDING OF THE CP ASYMMETRIES

In the Standard Model, \( CP \) violation in \( B \) decays may occur whenever there are at least two weak decay amplitudes with different CKM coefficients that lead to a given final state. In the charged \( B \) decay the two decay mechanisms are provided by two competing decay diagrams, for instance the spectator quark decay and the so called ‘penguin’ diagrams. On the other hand, in neutral \( B \) decays, because of \( B^o - \bar{B}^o \) mixing, a \( B^o \) may decay to a final state \( f \) via two paths: \( B^o \rightarrow B^o \rightarrow f \) or \( B^o \rightarrow \bar{B}^o \rightarrow f \). The phases in the second path differ from the phases in the first

\[ \text{FIGURE 3. The production angle (in degrees) for a hadron containing a } b \text{ quark plotted versus the production angle (in degrees) for a hadron containing a } \bar{b} \text{ quark.} \]
because of the phase in the mixing diagram and sometimes because of the phase difference between $B^0 \to f$ and $\bar{B}^0 \to f$. In the case of charged $B$ decays, we have only direct $CP$ violation, whereas in the case of neutral $B$ decays we can have both $CP$ violation induced by mixing and direct $CP$ violation. In this paper we cannot summarize all the facets of this rich phenomenology, discussed in other excellent reviews [2], [3]. As an illustration of the challenges involved in the measurement, we recall that for neutral $B$ decays to $CP$ eigenstates, only the mixing contribution is present and the time dependent asymmetry can be expressed as:

$$A(f_{CP}) \equiv \frac{\Gamma(B^0(t) \to f_{CP}) - \Gamma(\bar{B}^0(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(\bar{B}^0(t) \to f_{CP})} = \chi \sin(2\phi_i - \Phi_M) \frac{x}{1 + x^2} \quad (3)$$

where $\chi = \pm 1$ is the sign of the $CP$ parity of the eigenstate, $\phi_i$ are the $CP$ violating phases related to the relevant CKM parameters, $\Phi_M$ is the phase in the $B^0 - \bar{B}^0$ mixing and $x \equiv \Delta M/\Gamma$ characterizing $B^0 - \bar{B}^0$ mixing. The difference $2\phi_i - \Phi_M$ is related to the quark mixing parameters: different $CP$ asymmetries will provide information on different angles of the unitarity triangle.

In order to measure the $CP$ asymmetries there are three crucial ingredients: adequate data samples, as often it is necessary to measure tiny differences between final states that have a quite small branching fraction, the ability of tagging the flavor of the initial meson and finally an adequate suppression of backgrounds.

The development of a variety of flavor tagging techniques in the different experimental configurations has been one of the most active area of investigation towards the development of the physics analysis tools at different facilities. Some of the tagging techniques, like the charge of the $\mu$’s produced in semi-leptonic decays, are common to most experiments, others are environment-specific. For example, $e^+e^-$ b-factories can try to take advantage of the low momentum leptons produced in the cascade $B \to D \to K^{(*)}\ell\nu$. On the other hand, hadronic machines can take advantage of same side tagging, exploiting the correlation between the flavor of the $B$ hadron and the charge of the pion produced in close association with it. Table 3 illustrates a comparison between the tagging efficiency of different approaches.

Table 4 shows the prospects for the $\sin 2\beta$ measurement by the different experi-
TABLE 4. Prospects for $\sin 2\beta$ with 1 year of running at the nominal luminosity

| Experiment | $\delta \sin 2\beta$ | Remarks |
|------------|----------------------|---------|
| BaBar      | $\pm 0.09$           | using $\psi K^0$ [6] assuming $\sin(2\beta)=0.7$ |
| Belle      | $\pm 0.11$           | using $\psi K^0$ [7] |
| HERA-B     | $\pm 0.13$           | using $\psi K_S$ [8] |
| CDF        | $\pm 0.09$           | using $\psi K_S$ [5] |
| D0         | $\pm 0.11$           | using $\psi K_S$ [9] |
| BTeV       | $\pm 0.013$          | using $\psi K_S$ [4] |
| LHCb       | $\pm 0.017-0.011$    | using $\psi K_S$ and $\sin(2\beta)=0-0.866$ [10] |
| ATLAS      | $\pm 0.018$          | using $\psi K_S$ [11] |
| CMS        | $\pm 0.058$          | using $\psi K_S$ [12] |

TABLE 5. Prospects for $\sin 2\alpha$ with 1 year of running at nominal luminosity

| Experiment | $\delta \sin 2\alpha$ | Remarks |
|------------|------------------------|---------|
| BaBar      | $\pm 0.29$             | using $\pi^+\pi^-$ [6] |
| Belle      | $\pm 0.27$             | using $\pi^+\pi^-$ (assuming no penguin) [7] |
| CDF        | $\pm 0.22$             | using $\pi^+\pi^-$ and assuming PID=TOF+dE/dx [5] |
| BTeV       | $\pm 0.026$            | using $\pi^+\pi^-$ (no penguin) [4] |
| LHCb       | $\pm 0.05$             | using $\pi^+\pi^-$ (no penguin) [10] |
| ATLAS      | $\pm 0.1 \sin(2\alpha) \oplus 0.011$ | using $\pi^+\pi^-$ (no penguin,) [11] |
| CMS        | $\pm 0.067$            | using $\pi^+\pi^-$ (no penguin, statistical error only) [12] |

ments. Note that the projections are taken from proposals and simulation studies performed by the proponents of the various experiments and do not necessarily share the same level of realism. The data shown here and in the following discussion should be taken as indicating some trends rather than as a detailed quantitative comparison.

The determination of the angle $\sin 2\alpha$ is a much more complex issue. The ‘golden mode’ in this case used to be the decay $B^0 \rightarrow \pi^+\pi^-$. However ‘penguin pollution’ [13] complicates the relationship between the measured asymmetries and $\sin 2\alpha$. In addition to the spectator diagram, that would provide a contribution to $A_{CP}$ according to the formulation discussed above, the penguin diagram adds a term proportional to $\cos(xt)$. The fraction of penguin contribution needs to be known to extract $\alpha$ [14]. Note that the different experiments simulate the effects of penguin pollution with very different degrees of approximation. In general, the label ‘no penguin’ refers to simulations that assume that the penguin pollution is negligible. Moreover, recent CLEO results [15] have shown that the branching fraction for this decay may be quite smaller than anticipated, its upper limit at 90% C.L. being $0.8 \times 10^{-5}$, thus seriously affecting the prospects of $e^+e^-$ b-factories. Lastly, a state of the art hadron identification system is necessary to single out this final state from other two-body decay modes of the $B_d$ and $B_s$ mesons, as illustrated by Fig. 4. The data are taken from the BTeV simulation studies but apply to all the experiments taking data at hadronic facilities, thus showing that the excellent
particle identification featured by LHCb and BTeV are crucial to make a reliable measurement. The normalization between the different decay modes is obtained assuming $\mathcal{B}(B \to K^+\pi^-) = 1.5 \times 10^{-5}$ and $\mathcal{B}(B \to \pi^+\pi^-) = 0.75 \times 10^{-5}$, according to the recent CLEO results [15], and $\mathcal{B}(B_s \to K^+K^-) = \mathcal{B}(B_d \to K^+K^-)$ and $\mathcal{B}(B_s \to K^+\pi^-) = \mathcal{B}(B_d \to \pi^+\pi^-)$.

The determination of the angle $\gamma$ introduces new challenges. In principle, decay modes of the $B_S$ meson to $CP$ eigenstates, like $\rho K_S$, could be used. However the same ‘penguin pollution’ problems alluded to in the discussion of $\sin 2\alpha$ are present here and they are even more difficult to be disentangled than in the previous case because of the vector-pseudoscalar nature of the final state. An alternative approach can be used to extract the angle $\gamma$ from the decays $B_S \to D^\pm S K^{\mp}$, where a time-dependent $CP$ violation can result from the interference between the direct decay and the mixing induced decays [16]. BTeV and LHCb have studied the possibility of extracting the angle $\gamma$ with this approach. They project errors of $\pm 8^\circ$ and $\pm 10^\circ$, respectively.

Another method for extracting $\gamma$ has been proposed by Atwood, Dunietz and Soni [17], who refined a method suggested originally by Gronau and Wyler [18]. A large $CP$ asymmetry can result from the interference between the decays $B^- \to K^-D^0, D^0 \to f$, where $f$ is a doubly-suppressed Cabibbo decay of the $D^0$ (for example, $f = K^+\pi^-$, and $B^- \to K^-D^0, D^0 \to f$). Since $B^- \to K^-D^0$ is color-suppressed and $B^- \to K^-D^0$ is color allowed, the overall amplitude for the two decays are expected to be approximately equal in magnitude. The weak phase between them is $\gamma$. The subtleties of extracting the CKM angle from the measurements of two different states are discussed in Ref. [4].

Finally, Gronau and Rosner [19] originally proposed a method based on the study

![Figure 4](image-url)

**FIGURE 4.** Invariant mass distribution for all the $B \to h^+h^-$ final states, where $h$ denotes either a $\pi$ or a $K$, and the mass is computed assuming that both the particles are $\pi$’s. The plot on the left shows all the individual background contributions and the plot on the right shows the sum of all the channels, properly normalized (see text). The plot refers to the Tevatron.
of the decays $B \to K\pi$. The use of these decay modes is complicated by rescattering processes and $SU(3)$ breaking effects, as pointed out in several subsequent papers. However the intense theoretical effort to understand these decay modes of the neutral and charged $B$ meson can ultimately provide a good strategy to extract the angle $\gamma$. A recent analysis by A. Buras and G. Fleischer [20] examines all the hadronic effects in great detail and gives some promising strategies to use this approach more effectively.

A complementary constraint to the unitarity triangle is provided by the measurement of $B_s\bar{B}_s$ mixing, using the ratio:

$$\frac{|V_{td}|^2}{|V_{ts}|} = \xi^2 \frac{m_{B_s}}{m_{B_d}} \times \frac{\Delta m_d}{\Delta m_s}$$

where $\xi = f_{B_s}\sqrt{B_{B_s}}/f_B\sqrt{B_B} = 1.15 \pm 0.05$ is the $SU(3)$ breaking term, estimated from lattice and QCD sum rules. The time resolution is crucial in this measurement. The projected proper time resolution for BTeV is about 30 fs [4], and for LHCb is 43 fs [10], whereas for CDF is 60 fs (possibly down to 46 fs with an additional silicon layer) [21] and for ATLAS is 64 fs. BTeV expects to be able to measure $\Delta m_s$ at least up to 51 ps$^{-1}$ within a reasonable time scale. LHCb expects to measure $\Delta m_s$ with a statistical significance of at least 5 $\sigma$ if the true value of $\Delta m_s \leq 48$ ps$^{-1}$ or exclude values of $\Delta M_s$ at 95% C.L. up to 58 ps$^{-1}$ (corresponding to a value of $x_s \equiv \Delta M_s/\Gamma_s = 91$). For comparison, CDF claims to be able to make this measurement if $x_s \leq 20$, D0 claims to be able to make this measurement if $x_s \leq 16$ and ATLAS and CMS if $x_s \leq 38$. Note that the extraction of $|V_{td}/V_{ts}|$ with this method minimizes the theoretical uncertainty and therefore this observation will have a significant impact on our understanding of the CKM matrix.

**CONCLUSIONS**

This paper illustrates how different experiments will contribute to a precision determination of the angles and sides involved in the unitarity triangle and thus provide a crucial test of the validity of the CKM picture of quark mixing and $CP$ violation. In addition, they will perform detailed studies of rare $B$ decays, thus providing complementary tests of the Standard Model and useful constraints on more exotic models, like SUSY or a more complex Higgs sector. In the next year, experiments at asymmetric $e^+e^-$ $B$ factories, Babar and Belle, will start collecting data. They are likely to make the first significant measurements of $\sin 2\beta$. In the same time period, the symmetric $B$ factory experiment CLEO will start with its III upgraded version. If it proves easier to make luminosity with a single ring symmetric energy machine, they may be the first to see direct $CP$ violation and will continue their measurements of rare $B$ decays that have already provided quite interesting results [15]. With the start of Tevatron Run II, CDF and D0 will try to beat the the $e^+e^-$ machines to the first measurements of $\sin 2\beta$. HERA-B will also enter the race. Ultimately, crucial measurements on $B_s$ mixing, $\sin 2\alpha$, $\gamma$ and very
rare $B$ decays are likely to be made at forward experiments at hadron machines, LHCb or BTeV, where the $B$ rates are large, the vertexing is accurate and the particle identification is excellent. These measurements are crucial to a complete and accurate picture of this complex phenomenology.

ACKNOWLEDGEMENTS

The author would like to thank J. Butler and H. Cheung, as they distinguished themselves among the organizers for their indefatigable dedication to the rich scientific program and the smooth running of this very enjoyable conference. In addition, many thanks are due to S. Stone, I. Bigi and A.I. Sanda for interesting discussions. Lastly I would like to thank Julia Stone for many pleasant interludes during the writing of this manuscript.

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