Heavy Quark Decays

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1 Introduction

Heavy quark decays are central to the international effort to test the Standard Model, and the b quark has emerged as the focus of this program. Studies of the b quark include detailed investigations of semileptonic and hadronic decays, as well as increasingly sensitive measurements of rare decays. With major new b-physics initiatives getting under way at nearly all high energy physics labs, the prospects for definitive tests of the Standard Model, or the discovery of physics beyond it, are excellent.

Flavor physics is interesting because the weak eigenstates of the quarks are mixtures of the mass eigenstates. With three generations, the mixing is described by the Cabibbo-Kobayashi-Maskawa matrix [1] (Fig. 1).

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \qquad \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Figure 1: CKM matrix and Wolfenstein parameterization.

Unitarity and the arbitrariness of phases allows the nine complex elements to be reduced to four parameters, as most familiarly parameterized by Wolfenstein [2]. These parameters cannot be predicted, and their determination is one of our most practical needs. Furthermore, redundant measurements provide powerful tests of the validity of the Standard Model.

Specific measurements include direct determinations of the magnitudes of the CKM parameters in a variety of processes, and detailed studies of CP violation, principally in s and b decays. "Overconstraining" the matrix thus is a matter of measuring the lengths of the sides of the unitarity triangle, as well as its angles,

$\alpha = arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$, $\beta = arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$, and $\gamma = arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$. We already know quite a bit: $\lambda \simeq 0.22$, $A \simeq 0.8$, and ρ and η are bounded from past measurements. We urgently need precise determinations.

Another powerful probe of the limits of the Standard Model is provided by rare decays, especially rare b decays. There are many observables and many challenging measurements. They require very large data samples and mastery of strong-interaction effects that obscure our view of the underlying electroweak physics.

The objective of this review is to report some of the recent developments in heavy-quark decays, hopefully painting a picture of our overall state of knowledge and the pressing open questions. Not included are the crucial topics of lifetimes and mixing, covered elsewhere in these proceedings [3]. In Section 2, I describe the current status of semileptonic B decays and the determination of the CKM parameters $|V_{cb}|$ and $|V_{ub}|$. The focus of Section 3 is rare charmless decays, both two-body hadronic decays and $b \to s\gamma$. Section 4 addresses the interpretation of the various results and implications for the CKM matrix. In Section 5, I mention a few results and near-term prospects in charm physics. This review ends in Section 6 with a brief summary and a survey of the outlook for the not-too-distant future.

The roster of experimental players in this business is growing with the first operation of several new facilities: KEK-B/BELLE, PEP-II/BaBar, CESR/CLEO III, and HERA-B. Many recent advances in b physics have been made by the CLEO experiment working with B mesons just above threshold at the $\Upsilon(4S)$ resonance. CLEO has two distinct data samples: 3.3 million $B\overline{B}$ events in the original CLEO II detector and 6.4 million events obtained since 1996 with CLEO II.V, upgraded to include a silicon vertex detector and other improvements. The data sample for CLEO II.V exceeded the project goal as a result of the excellent performance of the CESR storage ring, which reached a luminosity of 0.8×10^{33} cm^{-2}s^{-1} by the end of the run. The ALEPH, DELPHI, L3, and OPAL experiments at LEP and the SLD experiment at the SLC, have investigated faster-moving B's produced in Z^0 decays. Each LEP experiment collected roughly 0.9 million $b\overline{b}$ pairs. With dramatically improved SLC performance toward the end of its run, SLD was able to obtain about 100 thousand $b\overline{b}$'s, with the extra advantages of polarized beams and outstanding vertexing. During Run I, the Tevatron experiments D0 and, especially, CDF demonstrated that forefront b physics can be done in a $p\overline{p}$ environment. CDF's 100 pb^{-1} sample, clean lepton triggers, and ability to tag displaced B vertices produced competitive measurements not just of lifetimes and mixing, but also of some rare B decays. There are also a number of current experiments specializing in charm physics, both in e^+e^- (BES) and in fixed-target mode (FOCUS, SELEX, E789, E791). Results from these are beginning to emerge, and the next few years should see many interesting developments.

2 B Semileptonic decays

B physics is all about Standard Model tests and the determination of CKM parameters. Semileptonic decays are the core of this program. Precise measurements of $|V_{cb}|$ and $|V_{ub}|$ are the main goals. Because semileptonic decays are our main tool, it is essential that we understand this tool very well. The last few years have seen important developments in both theory and experiment. We have benefited greatly from the increasingly sophisticated application of new theoretical techniques, including Heavy Quark Effective Theory (HQET) and lattice gauge calculations. There has been enhanced coordination between experimentalists and theorists, and the more recent formation of inter-experiment working groups is also proving fruitful. The challenge has been recognized as having two essential components: the extraction of all possible information from the package of measurements, and consistent and realistic assessment of theoretical uncertainties. In this section, I address three main topics in B semileptonic decays. First, I review some long-standing puzzles in the measurements. Following that, I assess the state of knowledge of $|V_{cb}|$ and of $|V_{ub}|$.

2.1 Puzzles in semileptonic B decays

Inclusive semileptonic B decay is a beautifully simple process. Inclusive $b \to c\ell\nu$ provides the most straightforward way to determine $|V_{cb}|$, one which is again acknowledged as competitive with exclusive determinations. Inclusive $b \to u\ell\nu$ gave us the first demonstration that V_{ub} is nonzero [4, 5], and while its interpretation is fraught with model uncertainties, it remains an important measurement. Figure 2 is CLEO's snapshot of the entire picture of semileptonic B decay in the near-threshold environment of the $\Upsilon(4S)$. The semileptonic branching fraction and the shape of the lepton momentum spectrum are determined using a lepton-tagged procedure in which charge and angular correlations allow separation of the primary $b \to \ell$ and secondary $b \to c \to \ell$ leptons [6]. Evidence for charmless decays is revealed as an excess in the region of the kinematic end point of the $b \to c\ell\nu$ lepton spectrum [7].

The simplicity of the semileptonic decay makes it all the more vexing that it has been the cause of a great deal of anxiety. There are two main puzzles. Why is the B semileptonic branching fraction measured at the $\Upsilon(4S)$ so small? Why is the B semileptonic branching fraction measured at the $\Upsilon(4S)$ smaller than that at the Z^0? The left-hand graph in Fig. 3 shows an assessment by Neubert of the problem as of about two years ago [8]. Naive considerations suggest a B semileptonic branching fraction of at least 12%, while experiment has consistently given values smaller than this. Mechanisms that enhance hadronic B decays can reduce the semileptonic branching fraction, but only by increasing n_c, the number of charm quarks per B. The data from the $\Upsilon(4S)$ did not bear this out. The fact that the branching fraction is smaller at the $\Upsilon(4S)$ is a separate matter that is also quite perplexing. The

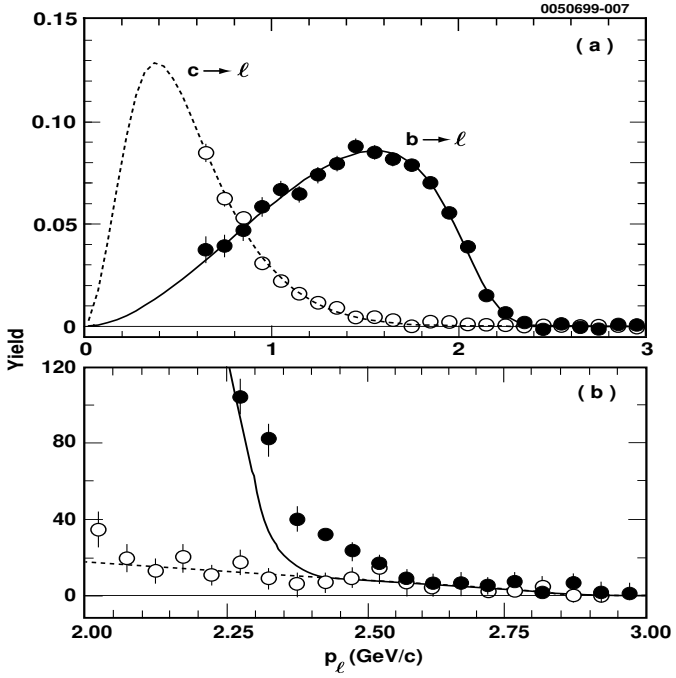

Figure 2: CLEO's measured lepton spectra: (a) $B \to Xe\nu$ from lepton-tagged analysis; (b) end-point region for $B \to X\ell\nu$ showing excess due to $b \to u\ell\nu$.

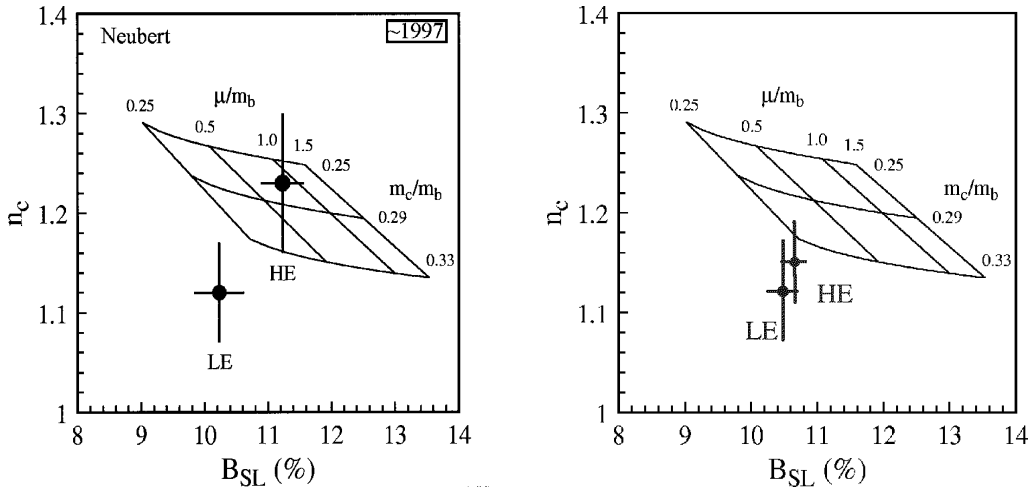

Figure 3: Theory "comfort zone" for $\mathcal{B}(B \to X\ell\nu)$ and charm multiplicity n_c. Parameters are the m_c/m_b quark-mass ratio and the normalization scale μ. The points on the left (right) are experimental values as of 1997 (1999) for experiments at the Z^0 (HE) and $\Upsilon(4S)$ (LE).

dominant B mesons at the Z^0 are the same as those at the $\Upsilon(4S)$, and the inclusion of higher-mass b-flavored particles at higher energy would be expected to reduce the average semileptonic branching fraction.

No new data from CLEO have been presented since 1997. There have been new developments on both the semileptonic branching fraction [9] and n_c [10] fronts from the LEP experiments.

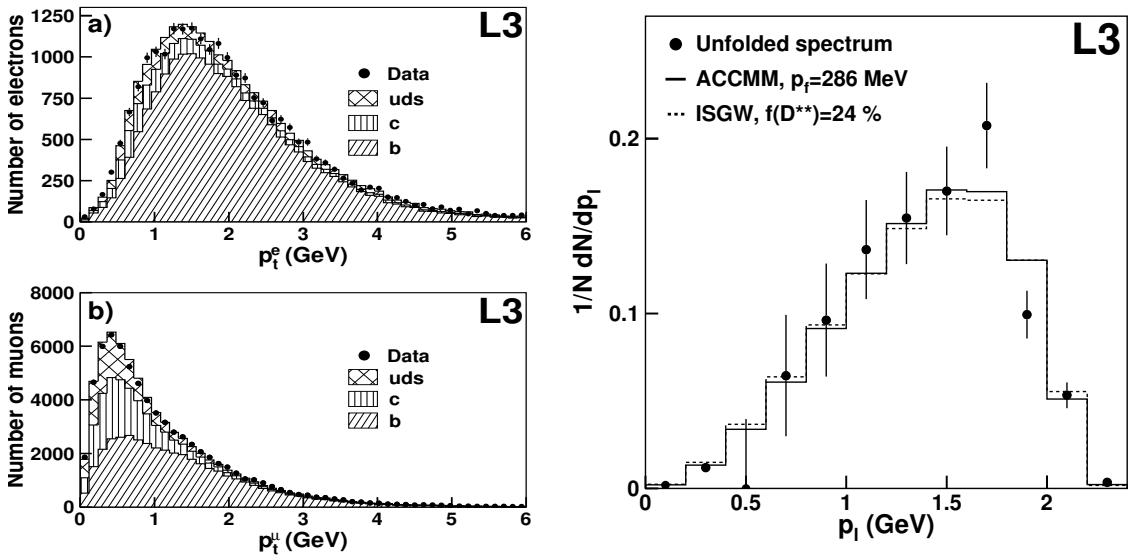

Figure 4: Left: Distributions of transverse momentum with respect to the closest jet for (a) electrons and (b) muons in L3 data. Right: Spectrum of lepton momentum in the rest frame of the decaying b hadron.

DELPHI [11], L3 [12], and OPAL [13] have all presented new measurements of the B semileptonic branching fraction. They use a variety of techniques with second-lepton, B-vertex, and jet-charge tagging, with neural nets employed to separate primary, secondary and background leptons. L3 uses two separate analyses based on double-tag methods to determine simultaneously the Z^0 b-quark fraction R_b and $\mathcal{B}(B \to X\ell\nu)$. One analysis uses a displaced-vertex b tag, while the other demands a high-p_t lepton. The observed lepton p_t distributions and the unfolded momentum in the b rest frame are shown in Fig. 4. The result of this measurement of $\mathcal{B}(B \to X\ell\nu)$, and of the most recent measurements from the other four LEP experiments, are summarized in Table 1. The new Z^0 average, $\mathcal{B}(B \to X\ell\nu) = (10.63 \pm 0.17)\%$, represents a significant decrease from the $(11.1 \pm 0.3)\%$ average of the high energy measurement circa 1997. The PDG value for the semileptonic branching fraction at the $\Upsilon(4S)$ is $(10.45 \pm 0.21)\%$, quite compatible with the new Z^0 average. This may still overstate the difference, however, because the PDG average has an aggressively small error

considering the experimental and theoretical errors of the input measurements and the spread among them.

Experiment	$\mathcal{B}(B \to X\ell\nu)$ (%)
ALEPH 1992-93 data (preliminary 1995)	$11.01 \pm 0.10 \pm 0.30$
DELPHI 1992-1995 data (preliminary 1999)	$10.65 \pm 0.07 \pm 0.43$
L3 1994-95 data (preliminary 1999)	$10.16 \pm 0.13 \pm 0.29$
OPAL 1992-95 data (1999)	$10.83 \pm 0.10 \pm 0.26$
LEP average	10.63 ± 0.17

Table 1: Recent measurements of $\mathcal{B}(B \to X\ell\nu)$ from LEP experiments.

New measurements of the multiplicity of charm quarks per b decay have been reported by ALEPH [14] and DELPHI [15]. Combining these with an earlier OPAL measurement [16] leads to a new correlated average of $n_c = 1.151 \pm 0.022 \pm 0.022 \pm 0.051$ [10], where the errors are statistical, systematic, and that due to input branching fractions. CLEO's previous number, $n_c = 1.10 \pm 0.05$ becomes 1.12 ± 0.05 when consistent branching fractions are used, again in very good agreement.

The right-hand graph of Fig. 3 is an update of Neubert's original comparison. It is clear from that graph that the gap between high-energy and low-energy measurements has narrowed considerably. The low-energy data still lies outside the theory comfort zone, but the puzzle seems much less compelling than it did previously.

2.2 Determination of $|V_{cb}|$

We determine the CKM parameter $|V_{cb}|$ by two techniques, both involving semileptonic decays $b \to c\ell\nu$. The favored method has been to use the rate for the exclusive semileptonic decay $B \to D^*\ell\nu$ (or $B \to D\ell\nu$) at zero recoil. A method that languished in disrepute for some years, but which has been rehabilitated, is to use the inclusive semileptonic decay rate. Both approaches are rooted in HQET, and there is extensive theoretical guidance on extracting $|V_{cb}|$ and estimating its uncertainty [17].

The connection between V_{cb} and the semileptonic width Γ_{SL} from HQET and the operator product expansion (OPE) is as follows:

$$\Gamma_{SL}(B) = \frac{G_F^2 m_b^5 |V(cb)|^2}{192\pi^3}\left[z_0\left(1 - \frac{\mu_\pi^2 - \mu_G^2}{2m_b^2}\right) - 2\left(1 - \frac{m_c^2}{m_b^2}\right)^4 \frac{\mu_G^2}{m_b^2} - \frac{2\alpha_S}{3\pi} z_0^{(1)} + ...\right] \quad (1)$$

Three HQET parameters appear in the expansion. $\overline{\Lambda}$ connects the quark mass with the meson mass. μ_π^2 (or its relative λ_1) relates to the average kinetic energy of the b quark. μ_G^2 (λ_2) is connected to the hyperfine splitting. Bigi judges that a "prudent"

theoretical uncertainty for the extraction of $|V_{cb}|$ by this procedure is $\sim 6\%$ [17]. The contributions of the uncertainties in the experimental inputs, the B semileptonic branching fraction ($(10.5 \pm 0.2 \pm 0.4)\%$), and the average B lifetime (1.61 ± 0.02 ps) are small in comparison. The result is $|V_{cb}| = (40. \pm 0.4 \pm 2.4) \times 10^{-3}$.

On the exclusive front, HQ symmetry tells us that a heavy-light meson decaying at rest really is not changing at all. A measurement of the decay rate of $B \to D^* \ell^- \overline{\nu}$ at maximum q^2 ($w = 1$) gives $\mathcal{F}(1)V_{cb}$:

$$\begin{aligned} \frac{d\Gamma}{dw} &= \frac{G_F^2}{48\pi^3}|V(cb)|^2 m_{D^*}(m_B - m_{D^*})^2 \mathcal{F}^2(w)\mathcal{G}(w), \text{ where} \\ w &= (m_B^2 + m_{D^*}^2 - q^2)/(2m_B m_{D^*}) \end{aligned} \tag{2}$$

Add the form-factor normalization $\mathcal{F}(1)$ from theory and we are done. There has been continuing evolution in thinking about $\mathcal{F}(1)$, and some controversy [18]. Bigi [17] suggests $\mathcal{F}(1) = 0.88 \pm 0.08$, with a smaller value and a much bigger error than earlier suggestions.

A new measurement of $B \to D^* \ell^- \overline{\nu}$ has been reported by DELPHI [19], joining ALEPH [20], OPAL [21], and CLEO [22]. The new DELPHI measurement (Fig. 5) is based on ~ 5500 tagged decays and has the best precision. (CLEO has so far reported on only one sixth of its total data sample.)

Table 2 summarizes the results on $|V_{cb}|$ from $B \to D^* \ell^- \overline{\nu}$, following the LEP V_{cb} working group [23], and Bigi's proposal for $\mathcal{F}(1)$. Everything agrees very well. The exclusive $|V_{cb}|$ result is consistent with the inclusive, and the overall precision is comparable.

Experiment	V_{cb} $(\times 10^{-3})$
ALEPH [20]	$36.6 \pm 2.4 \pm 1.8$
DELPHI [19]	$41.2 \pm 1.6 \pm 2.8$
OPAL [21]	$38.9 \pm 2.2 \pm 3.1$
LEP weighted average	$38.4 \pm 1.1 \pm 2.2 \pm 2.2$
CLEO[22]	$39.4 \pm 2.1 \pm 2.0 \pm 1.4$

Table 2: Determinations of $|V_{cb}|$ using $B \to D^* \ell^- \overline{\nu}$ decays at $\omega = 1$.

Both extraction procedures rely on the HQET/OPE approach, which is beautiful but largely unvalidated by experiment. Experimental tests are needed, and measurements of the parameters $\overline{\Lambda}$ and λ_1/μ_π^2 would be extremely valuable. Measurements of the moments of the hadronic mass and lepton energy in B decays have been proposed to do this [24, 25, 26, 27]. CLEO has made a preliminary measurement of this type [28], the results of which are shown in Fig. 5. The mass moments and lepton-energy moments do not admit a common solution, and the discrepancy is significant.

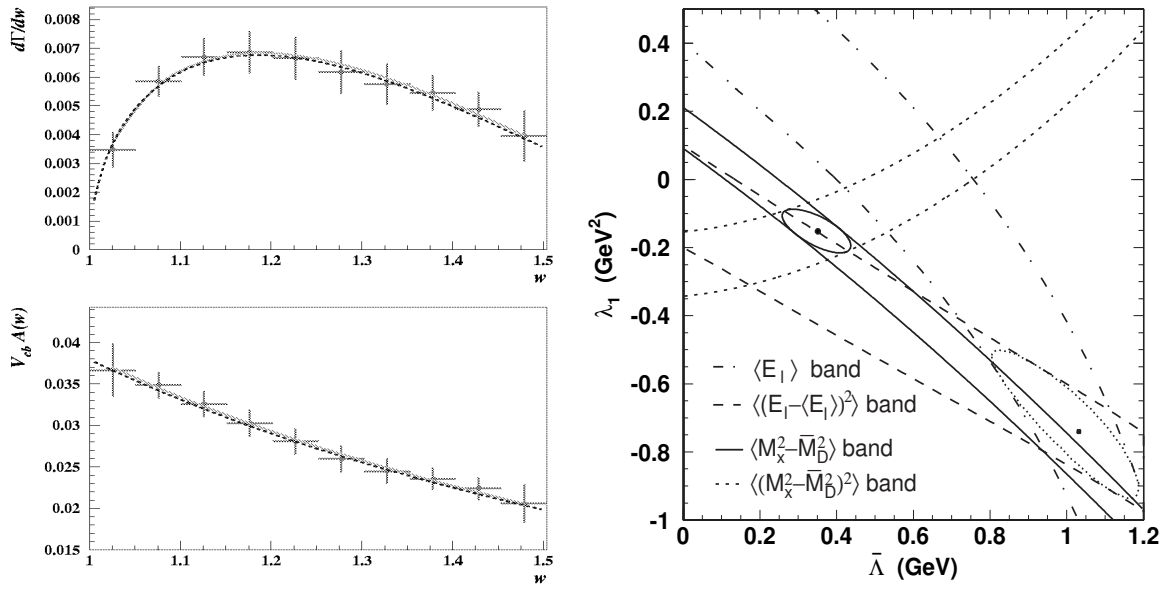

Figure 5: Left: Preliminary DELPHI results on $B \to D^* \ell^- \overline{\nu}$. The upper graph is the unfolded distribution of differential decay width, and the lower graph shows the extraction of $\mathcal{F}(1)|V_{cb}|$. Right: Bands in HQET/OPE parameters λ_1 and Λ found in CLEO's preliminary analysis of the first two moments of the B semileptonic decay recoil-mass-squared and lepton-energy moments. The 1σ error ellipses are shown.

Perhaps one (or both) of the measurements is flawed, or perhaps there is something wrong with the theoretical approach. Some have suggested that the assumption of quark/hadron duality should be scrutinized. CLEO is updating its measurements with more data and a better understanding of the experimental systematics.

2.3 Determination of $|V_{ub}|$

Compared to $|V_{ub}|$, $|V_{cb}|$ was easy. The advantages afforded by heavy-quark symmetry in studying $b \to c\ell\nu$ do not carry over to the heavy-to-light transition of $b \to u\ell\nu$. Extraction of $|V_{ub}|$ is highly model-dependent, the experiments are tougher, and the achievable precision will likely always be less. The CLEO and ARGUS discovery measurements for $b \to u\ell\nu$ [4, 5], and the subsequent confirmation in CLEO II data [7] were based on the nonzero excess of leptons near and above the kinematic limit for $b \to c\ell\nu$ at the $\Upsilon(4S)$. The measurement of the yield is straightforward, but because only a tiny corner of the $b \to u\ell\nu$ phase space is sampled, models [29, 30, 31] must be used to extrapolate to the total rate. It is very difficult to assess the theoretical uncertainty, and my preference is to be very cautious: $|V_{ub}/V_{cb}| = 0.08 \pm 0.02$.

In the past few years, ALEPH [32], L3 [33], and DELPHI [34] have all presented ambitious analyses that seek to measure the $b \to u\ell\nu$ component in b decays at the Z^0. The strategy is to reconstruct the charmless hadronic mass m_X in $b \to X\ell\nu$, and to enrich the sample in $b \to u\ell\nu$ by demanding m_X to be less than ~ 1.6 GeV/c^2. Discrimination between $b \to u$-like and $b \to c$-like decays is based on many event details, including displaced vertices, transverse momentum, presence of kaons, and other features, combined for maximum discrimination with neural nets. This technique exploits the advantages of production at the Z^0: well-separated jets and fast-moving B's, but it requires very detailed understanding of $b \to c\ell\nu$. The DELPHI $b \to u\ell\nu$ lepton-energy distribution in the B rest frame is shown in Fig. 6. It is fitted to signal and background components to extract $|V_{ub}/V_{cb}|$. The LEP $|V_{ub}|$ working group [23] combines the three LEP measurements to obtain an average of $|V_{ub}| = (4.05^{+0.62}_{-0.74}) \times 10^{-3}$, very consistent with CLEO. Because more of the spectrum is measured than in the end-point analysis, the extraction of $|V_{ub}|$ should have less theoretical uncertainty in principle. Unfortunately, dealing with the enormous $b \to c\ell\nu$ component introduces different uncertainties that are also very difficult to quantify.

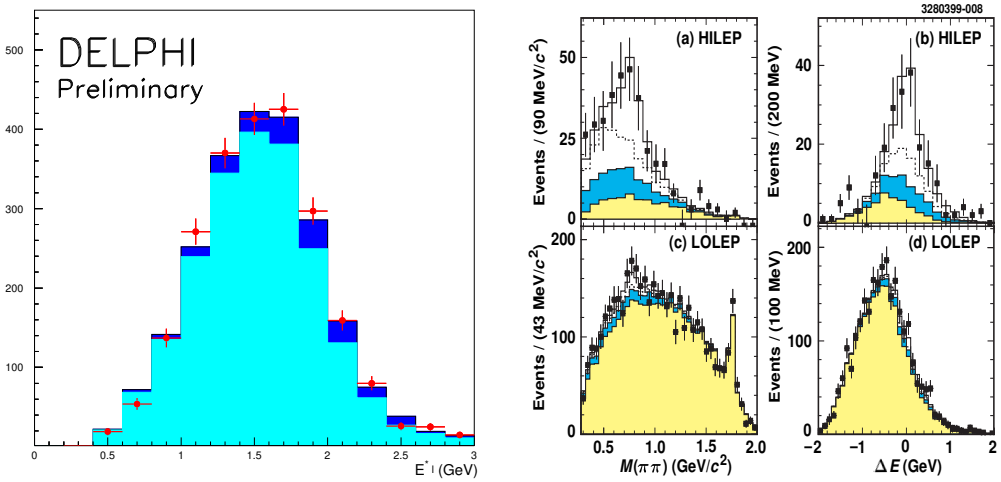

Figure 6: Left: The lepton energy in the B-meson rest frame for the DELPHI $b \to u$-enriched sample. The light-shaded histogram is the fitted background and the dark-shaded histogram is the fitted signal. Right: Fit projections for CLEO's $B \to \rho\ell\nu$ analysis showing signal and background components in two momentum ranges (HILEP: $p > 2.3$GeV, LOLEP: $2.0 < p < 2.3$GeV/c.

The first measurement of the exclusive charmless semileptonic decays $B \to \pi/\rho\ell\nu$ by CLEO [35] was a milestone in the determination of $|V_{ub}|$. Conventional wisdom has held that the extraction of $|V_{ub}|$ from exclusive decays would be less model-dependent than the earlier end-point measurements. The main reason for this prejudice has been

that tools like light-cone sum rules and lattice QCD, along with experimental input from charm decays, would provide necessary form-factor information.

CLEO has presented a new analysis of $B \to \rho\ell\nu$ [36] with higher efficiency than full reconstruction. Binned maximum-likelihood fits are made of the lepton energy, ΔE and candidate mass to parameterizations for $B \to \rho\ell\nu$, $B \to \pi\ell\nu$, $B \to \omega\ell\nu$, other $b \to u\ell\nu$, continuum, and fake leptons. The data sample is divided according to lepton-momentum, with the greatest sensitivity to $B \to \rho\ell\nu$ in the highest bin ($> 2.3\mathrm{GeV}/c$). Several models [30, 37] are used to evaluate efficiencies and extract $|V_{ub}|$. This measurement is averaged with the previously published CLEO results [35], to give $\mathcal{B}(B^0 \to \rho^-\ell^+\nu) = (2.57\pm0.29^{+0.33}_{-0.46}\pm0.41)\times10^{-4}$ and $|V_{ub}| = (3.25\pm0.14^{+0.21}_{-0.29}\pm 0.55) \times 10^{-3}$. The experimental uncertainties in this measurement are smaller than the theoretical uncertainty. Further progress will depend on advances in theory with guidance from experiment. This analysis included a first measurement of the q^2 distribution for $B \to \rho\ell\nu$, but the data are not yet sufficiently precise to discriminate among models.

3 Rare B decays

Rare decays have provided much of the excitement in B physics during the past several years. As data samples have grown, the roster of rare processes that have come within the reach of experiment has lengthened steadily. The discovery of the electroweak penguin decay $b \to s\gamma$, first exclusively [38] and later inclusively [39], was a major milestone in two ways. First, it excluded a broad range of physics beyond the Standard Model by coming in very close to expectations [40]. Second, it was a first signal of the major role of penguin processes in B decays, a feature that has greatly influenced expectations for studies of CP violation.

The principal source for new measurements of rare b decays has been the nearly 20 million B mesons in the CLEO II/II.V data sample. Contributions have also been made by ALEPH, and by CDF and D0 in searches for modes with dileptons.

3.1 Charmless two-body B decays

CLEO has made great strides in filling in the table of charmless two-body decays. The implications of these measurements for the future B program are significant. The principal contributing processes, $b \to s$ penguins and $b \to u$ trees, are shown in Fig. 7. Interference between tree and penguin diagrams opens a window on the unitarity-triangle angle γ in measurements of decay rates. CLEO measurements of $B \to \pi\pi$, $B \to \pi\rho$, and other modes define the strategies for future CP-violation searches, including the determination of α. Searches for direct CP violation could provide our first glimpse of physics beyond the Standard Model.

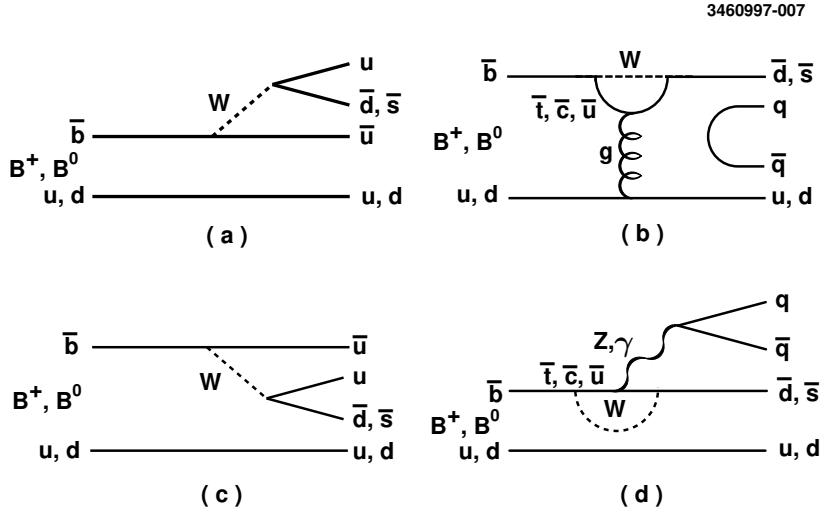

Figure 7: Principal contributors to charmless B decays: (a) external W-emission, (b) gluonic penguin, (c) internal W-emission, (d) external electroweak penguin.

CLEO's two-body charmless decay analyses share a common set of tools that take advantage of the features of $B\overline{B}$ production at the $\Upsilon(4S)$. Candidates are identified based on the beam-constrained mass, $M_B = \sqrt{E^2_{beam} - |\vec{p}|^2}$, and the difference between the beam energy and the measured energy of the B candidate's daughters, $\Delta E = E_1 + E_2 - E_{beam}$. For signal events, M_B must be close to the known B-meson mass ($\sigma(M_B) \simeq 2.5$ MeV), and ΔE must be close to zero ($\sigma(\Delta E) \simeq 15 - 25$ MeV, depending on the mode). Two-body B decays have considerable background from continuum $e^+e^- \to q\overline{q}$, for which the cross section is roughly three times higher than $B\overline{B}$. The jet-like continuum background is aggressively suppressed with event-shape cuts based on numerous input variables that are combined into a linear multivariate (Fisher) discriminant. Residual continuum background is estimated with data collected 60 MeV below the $\Upsilon(4S)$ resonance. In addition to the common selection criteria, there are a number of signal-specific cuts including resonance mass, particle identification and helicity angles.

After imposition of loose cuts, final signals are extracted with unbinned maximum likelihood fits to ~ 7 quantities, including M_B, ΔE, resonant masses (ρ, K^*, η, η', ω), particle ID, helicity angles, and continuum-suppression variables. In addition to the fits, cut-and-count analyses are performed for confirmation. All of CLEO's new preliminary results have been obtained using between 5.8 million and the full 9.7 million $B\overline{B}$ events in the combined CLEO II and CLEO II.V data sets.

Results from CLEO's updated search for the decays $B \to h^+h^-$ [41] are shown in Fig. 8. The full likelihood fit of $B \to \pi^+\pi^-$ and $B \to K^\pm\pi^\mp$ gives the confidence-level contours shown, with 11.7σ and 4.2σ statistical significance, respectively. (There is

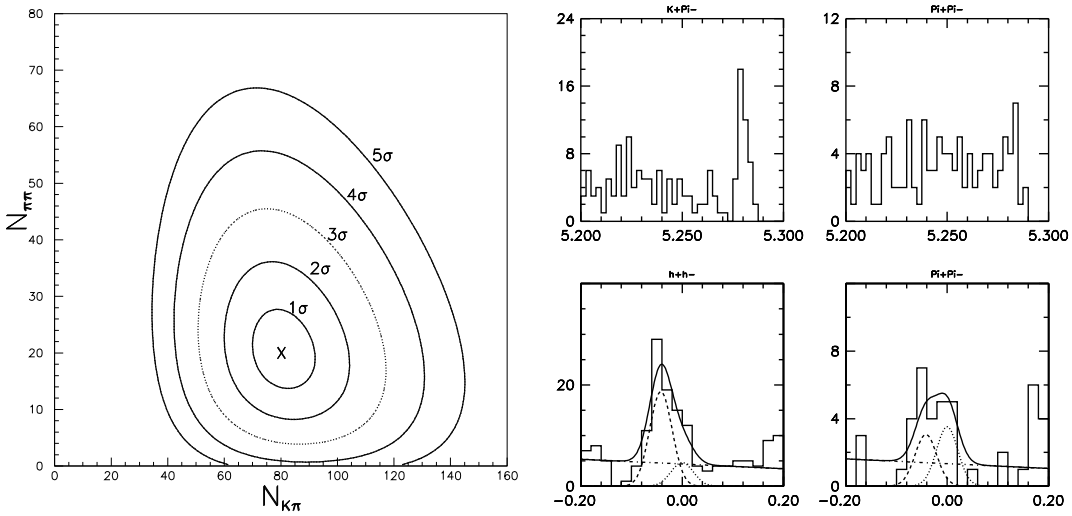

Figure 8: Left: Likelihood contours (statistical errors only) for the maximum likelihood fit yields for $B \to \pi^+\pi^-$ vs. $B \to K^\pm\pi^\mp$. Right: Projections of $K\pi$ and $\pi\pi$ events onto M_B and ΔE.

no evidence for $B \to K^+K^-$.) The projected signal for the $K^\pm\pi^\mp$ mode is extremely strong, while that for $\pi^+\pi^-$ is much less compelling. Projections onto ΔE for the undifferentiated h^+h^- events analyzed as $\pi^+\pi^-$ again show the dominance of $K^\pm\pi^\mp$, with no clear indication of a $\pi^+\pi^-$ signal. For the events satisfying particle-ID criteria for $\pi^+\pi^-$, however, it is clear that a $\pi^+\pi^-$ component is needed in addition to the misidentified $K^\pm\pi^\mp$ to explain the distribution. The results for the branching fractions of these modes are given in Table 3.

This first measurement of $B \to \pi^+\pi^-$ provides a long-awaited piece of the rare-decay puzzle, and it confirms that studies of this mode, and its future use in CP-violation measurements, are greatly complicated by "penguin pollution." This study is only one piece of a growing picture, however, and CLEO has also presented new results on the closely related decay modes $B^+ \to K^0h^+$ and $B^+ \to h^+\pi^0$, also summarized in Table 3 [41]. In this case there are statistically significant signals for $K^0\pi^+$ (7.6σ) and $K^+\pi^0$ (6.1σ), but not for $\pi^+\pi^0$, reinforcing the picture of penguin dominance. In addition, there has been a first neasurement of the decay to $K^0\pi^0$, providing a complete set of four $K\pi$ branching fractions.

As the available sample of charmless hadronic B decays grows, it becomes possible to search for direct CP violation. CP asymmetries are possible when two or more contributing diagrams differ in weak and strong phases. CLEO has presented

Mode	$\mathcal{E}(\%)$	$\mathcal{B}_{fit}(10^{-6})$	Signif.(std. dev.)	$\mathcal{B}(10^{-6})$
$\pi^+\pi^-$	45	$4.7^{+1.8}_{-1.5}$	4.2	$4.7^{+1.8}_{-1.5} \pm 0.6$
$\pi^+\pi^0$	41	$5.4^{+2.1}_{-2.0} \pm 1.5$	3.2	< 12
$K^+\pi^-$	45	$18.8^{+2.8}_{-2.6}$	11.7	$18.8^{+2.8}_{-2.6} \pm 1.3$
$K^+\pi^0$	38	$12.1^{+3.0}_{-2.8}$	6.1	$12.1^{+3.0+2.1}_{-2.8-1.4}$
$K^0\pi^+$	14	$18.2^{+4.6}_{-4.0}$	7.6	$18.2^{+4.6}_{-4.0} \pm 1.6$
$K^0\pi^0$	11	$14.8^{+5.9}_{-5.1}$	4.7	$14.8^{+5.9+2.4}_{-5.1-3.3}$
K^+K^-	45		0.	< 2.0
$K^+\overline{K}^0$	14		1.1	< 5.1

Table 3: Results from CLEO's $B \to h^+h^-$ analysis. The reconstruction efficiency $\mathcal{E}$ includes branching fractions for $K^0 \to K^0_S \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$. We quote the central-value branching fraction in $\pi^\pm\pi^0$ for convenience only; the statistical significance for this mode is insufficient for a first observation.

preliminary measurements of the asymmetry

$$\mathcal{A} \equiv \frac{\mathcal{B}(b \to f) - \mathcal{B}(\overline{b} \to \overline{f})}{\mathcal{B}(b \to f) + \mathcal{B}(\overline{b} \to \overline{f})}$$

for five charmless two-body final states f ($K^-\pi^+$, $K^-\pi^0$, $K^0_s\pi^+$, $K^-\eta'$, $\omega\pi^+$) [42]. Within the Standard Model, theoretical expectations for these asymmetries range up to ~ 0.10 [43]. Using the full CLEO II/II.V data sample, the statistical precision on $\mathcal{A}$ is between ± 0.12 and ± 0.25 for the modes studied. While these measurements are not yet a powerful test of the Standard Model, increasing event samples could render the larger asymmetries measurable within a few years.

The growing recognition that $B \to \pi\pi$ will not provide an easy route to the unitarity triangle parameter α has stimulated the search for alternatives. The most promising avenue was suggested by Snyder and Quinn [44]. They observe that a full Dalitz analysis of $B \to \pi^+\pi^-\pi^0$ exploits interference among the different $B \to \rho\pi$ modes to remove ambiguities due to unknown phases. This provides a determination of α to within about 6° with a sample of ~ 1000 $B \to \rho\pi$ decays, assuming the sample to be essentially background-free.

CLEO has presented preliminary results of searches for B decays into final states with a K^*, ρ, ω, or ϕ meson and a second low-mass meson [45, 46]. The results for all modes investigated are summarized in Table 4.

Figure 9 shows the likelihood contours and beam-constrained mass distributions for $B^+ \to \rho^0 h^+$ candidates. There is clear evidence of a signal, which translates into a branching fraction measurement $\mathcal{B}(B^+ \to \rho^0\pi^+) = (1.5 \pm 0.5 \pm 0.4) \times 10^{-5}$. There is no significant signal for $B^+ \to \rho^0 K^+$, with a 90% confidence-level upper limit of

Final state	Yield(events)	$\epsilon(\%)$	$\epsilon\mathcal{B}_s(\%)$	Signif.	B(10^{-6})	90% UL(10^{-6})
$\omega\pi^+$	$28.5^{+8.2}_{-7.3}$	29	26	6.2	$11.3^{+3.3}_{-2.9} \pm 1.5$	17
$\omega\pi^0$	$1.5^{+3.5}_{-1.5}$	22	19	0.6	$0.8^{+1.9}_{-0.8} \pm 0.5$	5.8
ωK^+	$7.9^{+6.0}_{-4.7}$	29	26	2.1	$3.2^{+2.4}_{-1.9} \pm 0.8$	8.0
ωK^0	$7.0^{+3.8}_{-2.9}$	24	7.4	3.9	$10.0^{+5.4}_{-4.2} \pm 1.5$	21
ωh^+	$35.6^{+8.9}_{-8.0}$	29	26	7.3	$14.3^{+3.6}_{-3.2} \pm 2.1$	21
$\omega\rho^+$	$10.8^{+6.6}_{-5.3}$	7.1	6.3	2.8	$18^{+11}_{-9} \pm 6$	47
$\omega\rho^0$	$3.7^{+6.0}_{-3.7}$	18	16	0.9	$0.0^{+5.7\,+2.9}_{-0.0\,-0.0}$	11
ωK^{*+}	$1.0^{+3.6}_{-1.0}$	6.8	2.0	0.3	$5^{+19}_{-5} \pm 6$	52
ωK^{*0}	$7.0^{+5.2}_{-3.9}$	14	8.3	2.3	$9.1^{+6.7}_{-5.1} \pm 1.9$	19
$\rho^0\pi^+$	$26.1^{+9.1}_{-8.0}$	30	30	5.2	$15^{+5}_{-5} \pm 4$	
$\rho^-\pi^+$	$28.5^{+8.9}_{-7.9}$	12	12	5.6	$35^{+11}_{-10} \pm 5$	
$\rho^0\pi^0$	$3.4^{+5.2}_{-3.4}$	34	34			5.1
$\rho^0 K^+$	$14.8^{+8.8}_{-7.7}$	28	28			22
$\rho^- K^+$	$8.3^{+6.3}_{-5.0}$	11	11			25
$\rho^0 K^0$	$8.2^{+4.9}_{-3.9}$		10	2.7		27
$K^{*0}\pi^+$	$12.3^{+5.7}_{-4.7}$		18			27
$K^{*0}\pi^0$	$0.1^{+2.8}_{-0.1}$	37	24			4.2
$K^{*0}_{K^+\pi^-}K^+$	$0.0^{+2.1}_{-0.0}$		18			12
$K^{*+}_{K^0\pi^+}\pi^-$	$10.8^{+4.3}_{-3.5}$		7	5.2	$23^{+9}_{-7} \pm 3$	
$K^{*+}_{K^+\pi^0}\pi^-$	$5.7^{+4.3}_{-3.2}$		4.1	2.5	$20^{+15\,+3}_{-11\,-4}$	
$K^{*+}\pi^-$				5.9	$22^{+8\,+4}_{-6\,-5}$	
$K^{*+}_{K^0\pi^+}K^-$	$0.0^{+0.9}_{-0.0}$		7	0.0		8
$K^{*+}_{K^+\pi^0}K^-$	$0.0^{+1.3}_{-0.0}$		4.1	0.0		17
$K^{*+}K^-$				0.0		6
$\phi\pi^+$		54	27	0.0		4.0
$\phi\pi^0$		35	17	0.0		5.4
ϕK^+	$2.4^{+3.0}_{-1.9}$	53	26	1.3	$1.6^{+1.9}_{-1.2} \pm 0.2$	5.9
ϕK^0	$4.3^{+3.2}_{-2.3}$	41	7.0	2.6	$10.7^{+7.8}_{-5.7} \pm 1.1$	28

Table 4: Results of searches for decays $B \to PV$. Reconstruction efficiencies (ϵ) and total detection efficiencies including secondary branching fractions ($\epsilon\mathcal{B}_s$) are shown, as are the statistical significance, branching fractions ($\mathcal{B}$) and/or upper limits (UL).

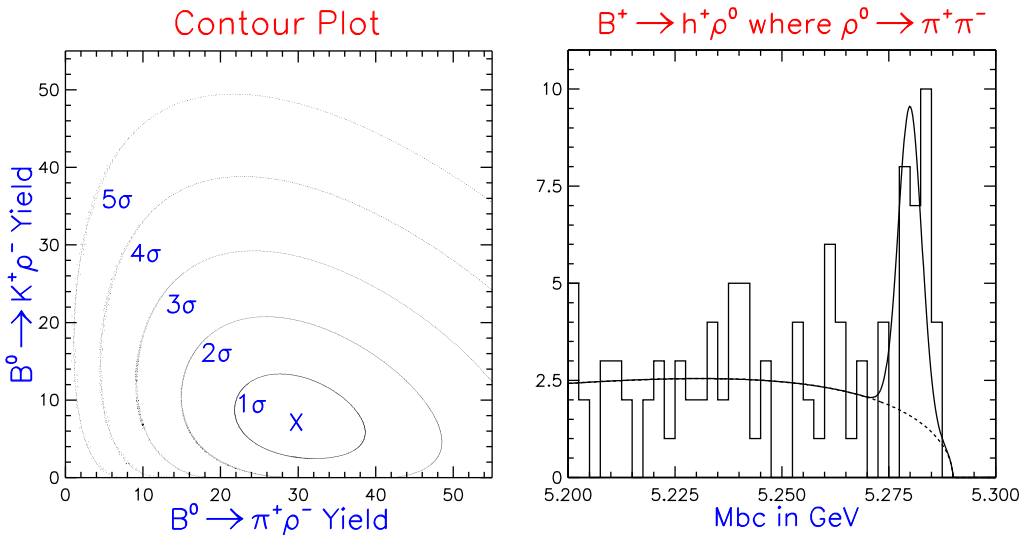

Figure 9: Likelihood contours (left) and projections onto beam-constrained mass (right) for $B^+ \to h^+\rho^0$ candidates.

$\mathcal{B}(B^+ \to \rho^0 K^+) < 2.2 \times 10^{-5}$. The situation is similar for $B^0 \to \rho^\pm h^\mp$, for which the significant $B^0 \to K^{*+}\pi^-$ background demands a cut on the helicity angle. Again there is a measurement for the $\rho\pi$ mode ($\mathcal{B}(B^0 \to \rho^\pm\pi^\mp) = (3.5^{+1.1}_{-1.0} \pm 0.5) \times 10^{-5}$), and only an upper limit for ρK ($\mathcal{B}(B^0 \to \rho^\pm K^\mp) < 2.5 \times 10^{-5}$ at 90% confidence level).

These measurements allow us to assess the feasibility of measuring α with $B \to \rho\pi$. More than 100 fb^{-1} will be needed to obtain the specified 1000 events. This sample will require several years of an asymmetric B factory to accumulate, and the need to reduce and understand backgrounds will be a major challenge.

Among the other measurements reported in [46] is the intriguing observation of the decay $B^+ \to \omega\pi^+$. Figure 10 shows the projected distributions of beam-constrained mass and ΔE. The signal is solid, and the measured branching fraction $\mathcal{B}(B^+ \to \omega\pi^+) = (11.3^{+3.3}_{-2.9} \pm 1.5) \times 10^{-6}$ agrees well with CLEO's measurement for $B \to \rho^0\pi^+$, as expected from isospin. While the branching fraction for $B^+ \to \omega\pi^+$ is consistent with CLEO's published upper limit on this mode [47], the new upper limit on $B \to \omega K^+$ conflicts with the previously reported observation [47]. There is no obvious explanation for this change other than a fluctuation in the previous search. The new measurement is an improvement over the first in several ways. The data sample has almost tripled and analysis-procedure improvements have increased the reconstruction efficiencies by between 10% and 20%.

A "poster child" for the challenge of interpreting charmless hadronic B decays is the decay $B \to \eta' K$. In 1998, CLEO reported an unexpectedly large branching

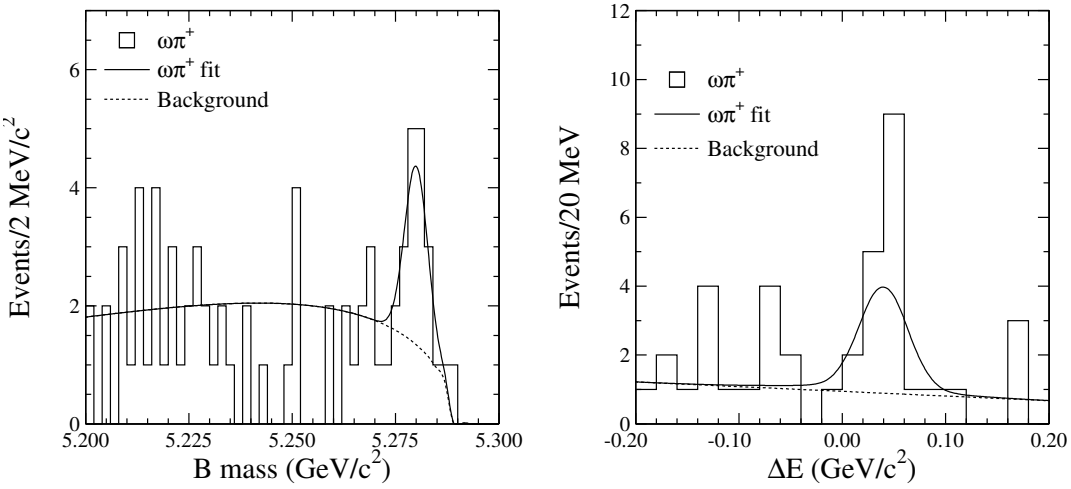

Figure 10: Projections onto beam-constrained mass and ΔE for $B \to \omega\pi^+$.

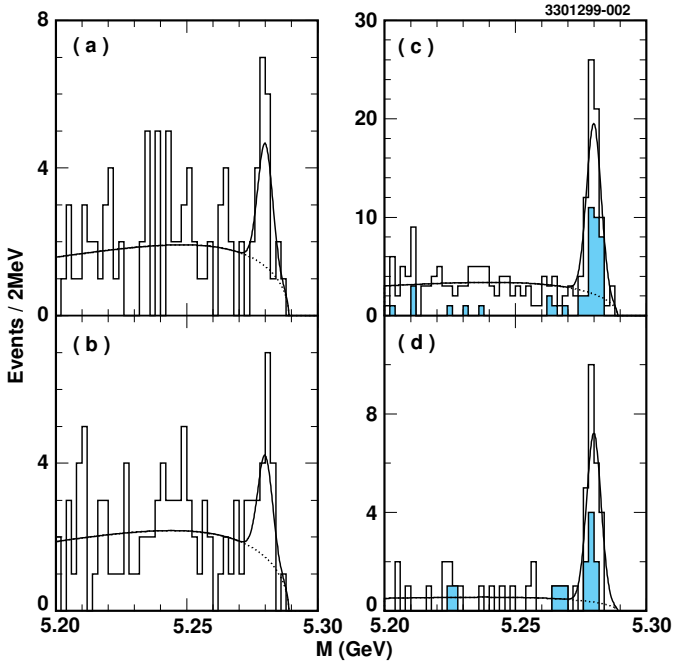

Figure 11: Projections onto beam-constrained mass for (a) $B \to \eta K^{*+}$, (b) $B \to \eta K^{*0}$, (c) $B \to \eta' K^+$, and (d) $B \to \eta' K^0$. The shaded histograms in (c) and (d) correspond to $\eta' \to \eta\pi\pi$, $\eta \to \gamma\gamma$, while the unshaded histograms are $\eta' \to \rho\gamma$. The solid (dashed) lines show the projections of the full fit (background only).

fraction for this mode [48], stimulating considerable theoretical interest. An updated search for two-body B decays to η and η' has now been reported [49], and the mystery has not gone away. The distributions of beam-constrained mass for $B \to \eta K^*$ and $B \to \eta' K$ are shown in Fig. 11. The branching fractions for the modes with clear signals are $\mathcal{B}(B^+ \to \eta' K^+) = (6.5^{+1.5}_{-1.4} \pm 0.9) \times 10^{-5}$ and $\mathcal{B}(B^0 \to \eta' K^0) = (4.7^{+2.7}_{-1.4} \pm 0.9) \times 10^{-5}$. These exceed all theoretical predictions [50, 51, 52]. No statistically significant signal is observed among the 17 other modes involving η and η'. A few of these limits are impinging on the predicted Standard Model range.

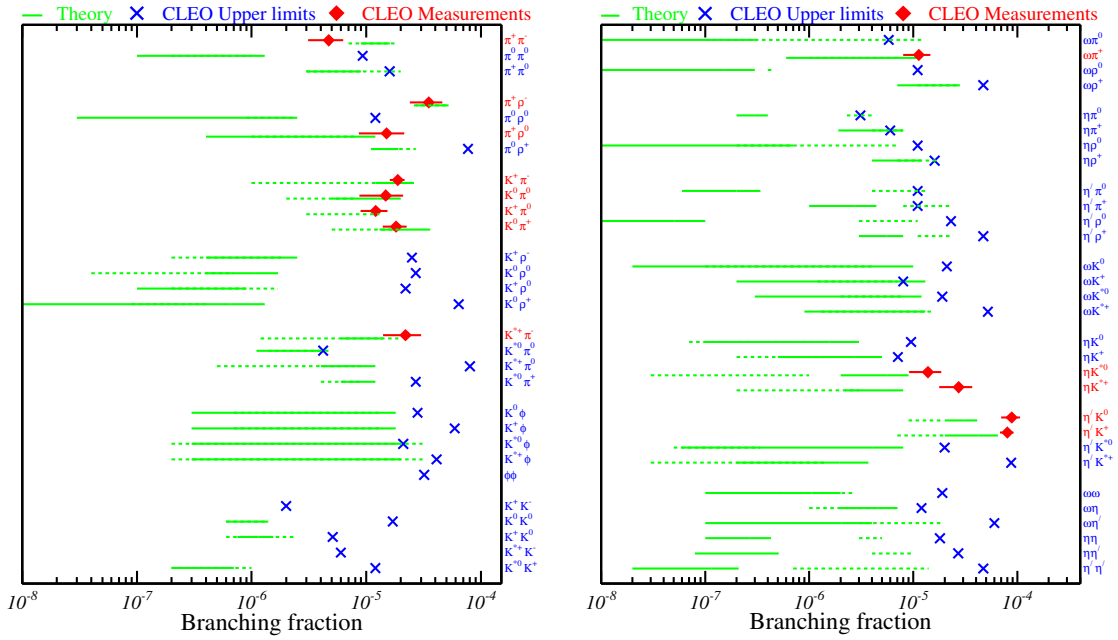

Figure 12: Summary graphs of CLEO rare-B measurements (left) for $B \to K\pi$ and (right) for other rare modes. The points with errors represent measured branching fractions for modes with definite observations, while the crosses are 90% confidence-level upper limits. The lines give the range of theoretical predictions.

Figure 12 shows summary graphs for all CLEO-measured rare two-body B-decay processes. Comparisons with theoretical predictions are included. Perhaps the most impressive feature of the work done is the breadth of the set of modes that have been measured. This prepares us for global analyses of rare charmless hadronic decays in which multiple measurements of related modes are used to extract detailed information about the CKM matrix. I return to this question in Section 4.

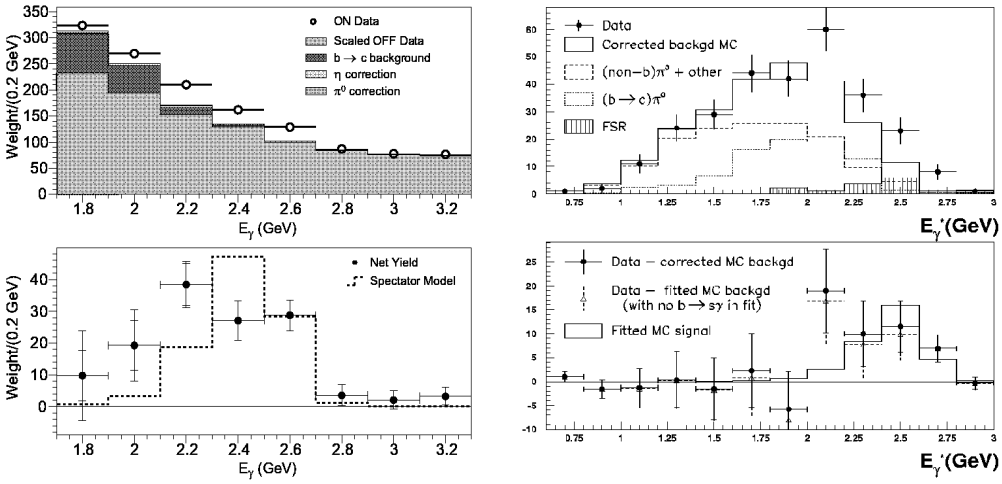

Figure 13: Left: CLEO inclusive photon spectrum (top) for On- and Below-$\Upsilon(4S)$ data, and (bottom) fully background-subtracted. Right: ALEPH photon spectrum, measured in the rest frame of the reconstructed jet, both raw and background-subtracted.

3.2 $b \to s\gamma$ and $b \to s\ell^+\ell^-$

Inclusive measurements of $b \to s\gamma$ provide powerful constraints on physics beyond the Standard Model. CLEO has recently presented an updated analysis of 3.3 million $B\overline{B}$ events [53]. The technique is an amalgam of continuum suppression through shape variables with a neural net and pseudo-reconstruction of $B \to X_s\gamma$. For the latter, the X_s consists of a charged or neutral kaon and up to four pions, one of which can be a π^0. The photon spectrum is shown in Fig. 13, and the branching fraction measurement is $\mathcal{B} = (3.15 \pm 0.35 \pm 0.32 \pm 0.26) \times 10^{-4}$, where the errors are statistical, systematic, and model-dependent, respectively. ALEPH has also presented an inclusive measurement of $b \to s\gamma$ [54]. In their analysis, non-B backgrounds are suppressed with an opposite-hemisphere lifetime tag. As for CLEO, a pseudo-reconstruction approach is employed, in which $B \to X_s\gamma$ is assembled from between one and eight tracks, K_s^0's and π^0's. The photon spectrum is shown in Fig. 13. ALEPH's result is $\mathcal{B} = (3.11 \pm 0.80 \pm 0.72) \times 10^{-4}$, very consistent with CLEO's.

It has recently been recognized that additional sensitivity to new physics is provided by the rate asymmetry

$$\mathcal{A} = \frac{\Gamma(b \to s\gamma) - \Gamma(\overline{b} \to \overline{s}\gamma)}{\Gamma(b \to s\gamma) + \Gamma(\overline{b} \to \overline{s}\gamma)} \ .$$

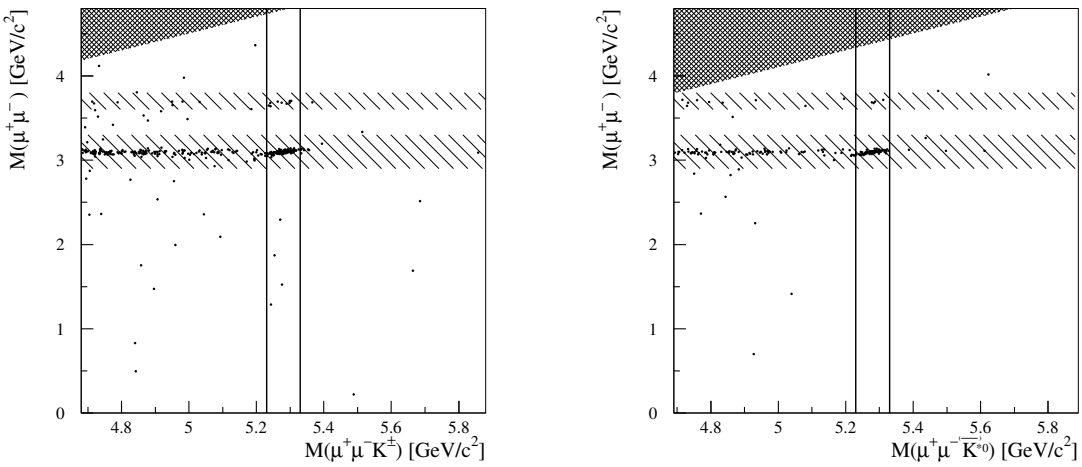

Figure 14: Plots of $\mu^+\mu^-$ mass vs. B-candidate mass for (left) $B \to \mu^+\mu^- K^\pm$ and (right) $B^0 \to \mu^+\mu^- K^{*0}$. Cross-hatched bands are excluded charmonium regions.

Some non-Standard Model predictions give asymmetries as large as 40% [55, 56]. CLEO's updated study of inclusive $b \to s\gamma$ [53] includes an extension of the pseudo-reconstruction analysis to measure this asymmetry. The strangeness content of the X_s system can be used to tag the flavor of the decaying B, but mistags and untaggable states must be carefully accounted for. CLEO finds $\mathcal{A} = (0.16 \pm 0.14 \pm 0.05) \times (1.0 \pm 0.14)$, with both additive and multiplicative (mistagging rate) systematic uncertainties. The 90% confidence-level range on $\mathcal{A}$ is $-0.09 < \mathcal{A} < 0.42$.

A probe of non-Standard Model physics similar to $b \to s\gamma$ is provided by $b \to s\ell^+\ell^-$. CDF dominates the search for the exclusive decays $B \to K/K^*\mu^+\mu^-$ [57], with a very large sample of hadronically produced B's and the capability to tag B production by displaced vertices. Figure 14 shows the distributions of $M(\mu^+\mu^-)$ vs. $M(K/K^*\mu^+\mu^-)$ for the CDF data. The background is largely confined to the easily excluded J/ψ and ψ' dilepton mass bands, leaving a very clean measurement. CDF obtains the 90% confidence limits $\mathcal{B}(B^+ \to K^+\mu^+\mu^-) < 5.2 \times 10^{-6}$ (Standard Model prediction: $0.3 - 0.7 \times 10^{-6}$), and $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-) < 4.0 \times 10^{-6}$ (Standard Model: $1 - 4 \times 10^{-6}$). With a data sample of 2 fb^{-1} expected for Run II, the observation of this mode should not be far off.

Because interpretation of the exclusive decays is somewhat problematic (as for $b \to s\gamma$), inclusive measurements would have some advantage. Both D0 [58] and CLEO [59] have reported inclusive analyses. For D0, this is a search for lepton

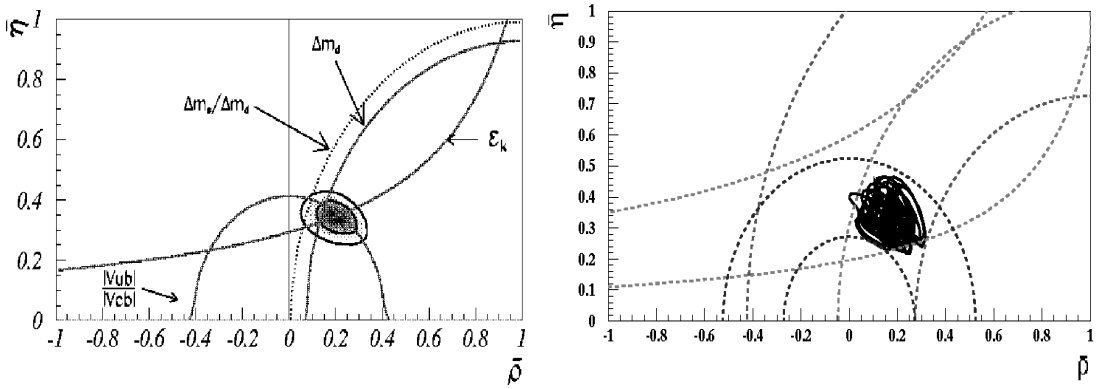

Figure 15: Left: Allowed region for $\overline{\rho}$ and $\overline{\eta}$ from Parodi *et al.* [61], with 68% and 95% confidence-level contours. Right: Allowed region according to Plaszczynski [64]. Small contours represents different theoretical models, with the envelope giving the overall 95% confidence-level range. The curves are the usual experimental constraints.

pairs with masses between the charmonium region and the B meson, a window that includes only a portion of $b \to s\ell^+\ell^-$, but which is very clean. CLEO employs a pseudo-reconstruction technique similar to the $b \to s\gamma$ procedure. All limits obtained are an order of magnitude or more above Standard Model expectation.

4 Interpretation—CKM

Information relevant to the determination of the CKM parameters is being accumulated at an accelerating rate. While principal responsibility for its interpretation in these proceedings falls to Adam Falk [60], I will briefly comment on the conventional view and then highlight a speculative interpretation of CLEO's rare-B-decay data.

A number of authors have incorporated the principal constraints from B decay ($|V_{ub}/V_{cb}|$, Δm_d, and the limit on Δm_s) with input from K^0_L CP violation ($|\epsilon_K|$) in global fits to obtain the Wolfenstein parameters $\overline{\rho}$ and $\overline{\eta}$, and the angles α, β, and γ of the unitarity triangle. Parodi *et al.* [61] and Mele [62] have performed maximum likelihood fits that assign Gaussian errors to several theoretical inputs. The fits of Parodi *et al.* give the solution shown on the left-hand side of Fig. 15, leading to $\overline{\rho} = 0.202^{+0.053}_{-0.059}$ and $\overline{\eta} = 0.340 \pm 0.035$, which in turn give $\sin 2\alpha = -0.26^{+0.29}_{-0.28}$, $\sin 2\beta = 0.725^{+0.050}_{-0.060}$ and $\gamma = (59.5^{+8.5}_{-7.5})$ degrees.

Stone has pointed out the danger of underestimating the overall uncertainty when assuming Gaussian errors for theoretical inputs [63]. Plaszczynski [64] has taken a much more cautious approach, considering all theoretical models on an equal basis and presenting the full spread in the resulting parameter values as shown in Fig. 15.

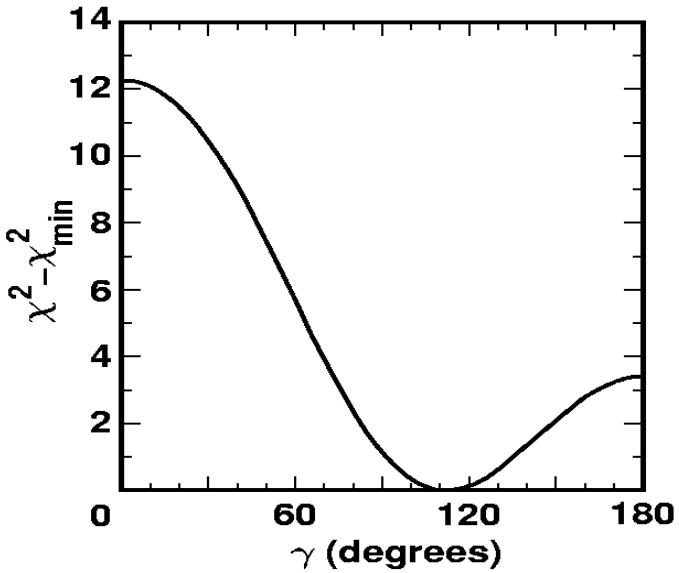

Figure 16: χ^2 vs. γ for CLEO's fit to CP-averaged charmless B branching fractions.

He obtains the larger ranges $0 \leq \overline{\rho} \leq 0.3$ and $0.2 \leq \overline{\eta} \leq 0.45$, leading to $0.50 \leq \sin 2\beta \leq 0.85$ and $-0.95 \leq \sin 2\alpha \leq 0.50$. Of course everything is consistent with CDF's first direct measurement, $\sin 2\beta = 0.79^{+0.41}_{-0.44}$ [65].

Because rare hadronic B decays incorporate both penguin and $b \to u$ tree processes, their rates and CP asymmetries carry information about weak phases. In particular, it has been suggested by several authors that combinations of measured rates can be used to extract the value of γ, the phase of V^*_{ub}. The first suggestions [66, 67, 68] focused on the $B \to K\pi$ branching fractions, but these approaches do not set significant bounds on γ with current data.

A much more aggressive procedure to extract maximal information from the data has been suggested by Hou, Smith, and Würthwein [69]. They assume factorization holds and write the B-decay amplitudes in terms of five parameters: $\gamma = Arg(V^*_{ub})$, $|V_{ub}/V_{cb}|$, R_{su} (incorporating information about quark masses), $F^{B\to\pi}$ ($B \to \pi$ form factor), and $A_0^{B\to\rho}$ ($B \to \rho$ form factor). The CP-averaged branching fractions for 14 of CLEO's measured charmless two-body decays [41, 46] were fitted with this parameterization. (Modes with η and η' were excluded based on their anomalies.) The constraint $|V_{ub}/V_{cb}| = 0.08 \pm 0.02$ was imposed. The result of the fit is shown in Fig. 16. The minimum χ^2 (10.3 for 10 degrees of freedom) occurs for $\gamma = 113^{+25}_{-23}$ degrees. The other fit parameters all give very reasonable values. This result agrees with earlier observations that CLEO data favor $\cos\gamma < 0$ [70, 71].

This is an intriguing result. The reasonable values of the fit parameters other than γ suggest that there may be some validity, in spite of the very model-dependent

assumptions. On the other hand, this may be nothing more than a misleading coincidence. Skepticism is appropriate.

5 Other topics

It is impossible to report exhaustively on all of the activity in heavy-quark decays within a single review. While my focus has been on CKM tests and measurements relevant to CP violation, there is other work that is also having impact. Even in the B sector I have had to ignore some work, including CLEO and LEP studies of hadronic decays and exclusive semileptonic decays to charm, that are important elements of a comprehensive understanding of B decay.

Charm physics remains an extremely valuable complement to b physics in our program of Standard Model testing. Because the expected rates for rare FCNC processes are extremely small, the potential to see new physics in $D\overline{D}$ mixing, in rare D-meson decays or in CP-violating processes is great. Additionally, studies of semileptonic and leptonic charm decays are an important adjunct to the CKM measurements, with potential to reduce model uncertainties in the extraction of V_{ub} and other parameters. A number of experiments have presented new results on charm decays, with much more on the way. This is a very broad program, the components of which have been the subject of several excellent recent reviews, including that of lifetimes and mixing elsewhere in these proceedings [3].

As in B physics, studies of hadronic charm decays [72] are important for developing a comprehensive understanding of heavy flavors, probing questions of final-state interactions and interference effects. Both meson and baryon decays are useful in this effort, and previously reported results from E791, CLEO, and other experiments will be greatly enhanced by FOCUS and SELEX.

A number of new form-factor measurements for semileptonic D and D_s decays have been presented in the past year by E687 [73]. FOCUS will soon have results from larger samples, and CLEO will also extend previous studies to their full data set. In tandem with HQET, these measurements will significantly reduce model uncertainties in the extraction of $|V_{ub}|$ from data on semileptonic B decays. Measurements of heavy-meson decay constants in leptonic decays of charmed mesons provide input to B-physics analyses and tests of lattice calculations.

New limits on rare or forbidden charm decays [74] have been presented by E791. A blind search for 24 modes was performed, with no signals observed in any and 90% confidence-level upper limits that range from $\sim 10^{-3}$ or 10^{-4} for $K/\pi\ell^+\ell^-$ to less than $\sim 10^{-5}$ for $\ell^+\ell^-$. Again, FOCUS will benefit from much greater statistics, with improvements in sensitivity for these modes of an order of magnitude or better.

6 Summary and conclusion

The past several years have seen steady progress on a broad program of Standard Model tests in B decays, but there remains much to be done.

The embarrassment of the $Z^0/\Upsilon(4S)$ disagreement on the B semileptonic branching fraction has eased. The basic experimental observation that there are too few semileptonic decays for the observed multiplicity of charm quarks is still with us, but it is not of crisis proportions. Theoretical tools for describing semileptonic decays have matured, but underlying assumptions like quark-hadron duality must be scrutinized. Hints of inconsistency between HQET-inspired interpretations of CLEO's hadronic-mass and lepton-energy moments in semileptonic B decays are troubling. A great deal more data and a great deal of work will be required to reach a final conclusion on the values of V_{ub} and V_{cb}. Intensive theory/experiment collaboration is a big plus.

In rare B decays, we have a number of major developments. The decay $B \to \pi\pi$ has been observed, and the rare hadronic decay picture is filling in with more measurements and tighter limits.

We stand on the verge of truly powerful tests of the Standard Model. First, efforts to measure CP asymmetries and CDF's first measurement of $\sin 2\beta$ are opening salvoes in the next phase of the campaign to make redundant measurements of the sides and angles of the unitarity triangle. So far, fits to the usual experimental constraints show the Standard Model to be holding up well, but this is only the beginning.

The exciting future of heavy flavor physics is well documented elsewhere in these proceedings. The three e^+e^- B factories, complemented by the upgraded Tevatron detectors, will produce a wealth of new physics. It is to be hoped that these facilities, their successor e^+e^- machines of still higher luminosity, and specialized detectors at hadron colliders, will carry us well beyond the Standard Model.

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