Heavy Flavor Physics

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This paper reviews the discovery of the B_c meson and advances in D meson spectroscopy, b-hadron lifetimes and the CKM matrix elements V_{td}, V_{cb}, and V_{ub}. It also looks at recent developments in $D-\bar{D}$ mixing, rare hadronic B decays and $b \to s\gamma$.

I. INTRODUCTION

The study of heavy flavors began over 20 years ago, and continues to be of fundamental interest. The third quark generation remains the least well known corner of the weak interaction, and heavy quark decays may have the best access to physics beyond the standard model. Extracting the weak interaction parameters from heavy flavor decays is possible only if we can disentangle the weak interaction physics from the omnipresent strong interaction effects. Thanks to advances in both theory and experiment, there has been steady progress doing this.

The main contributors to heavy quark measurements are e^+e^- colliders operating at the $\Upsilon(4S)$ and at the Z^0, hadron colliders and fixed target experiments. As will be seen below, the experiments have complementary strengths that have led to advances in a broad range of topics.

This paper starts with a discussion of two recent advances in heavy quark spectroscopy, the discovery of the B_c and the first observation of one of the broad D resonances. It then moves to a discussion of b-hadron lifetimes, followed by sections on each of the three CKM matrix elements, V_{td}, V_{cb} and V_{ub}. The final sections cover rare processes, including $D-\bar{D}$ mixing, and, briefly, the decays $B \to \rho\pi$ and $b \to s\gamma$.

II. HEAVY QUARK STATES

A. The B_c

This year there is a new addition to the heavy quark family, the B_c . The B_c was discovered by CDF in the decay mode $B_c \to J/\psi\ell\nu$ [1]. Figure 1 shows the $J/\psi-\ell$ invariant mass distribution. The data are consistent with expectations for the B_c and backgrounds. CDF finds $m_{B_c} = 6.40 \pm 0.39 \pm 0.13$ GeV . The OPAL collaboration has two B_c candidates with in the mode $B \to J/\psi\pi$ with an expected background of 0.62 ± 0.06 events, both have mass near 6.30 GeV . The predictions of about 6.25 GeV [2] are compatible with these values.

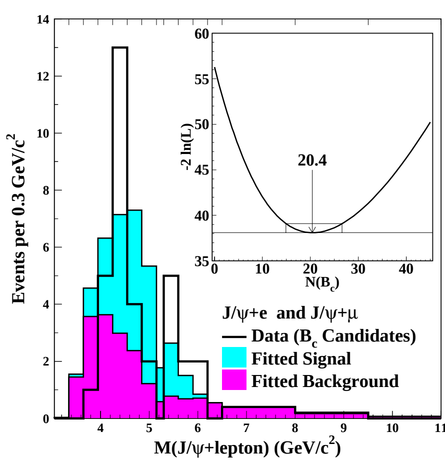

FIG. 1. CDF. The $J/\psi\ell$ invariant mass distribution for the $B_c \to J/\psi X\ell\nu$ candidates (histogram), the calculated background (dark histogram) and B_c signal (light histogram). The inset shows the results of a fit for the B_c mass.

The lifetime distribution of the B_c sample from CDF is shown in Figure 2. A fit gives $\tau_{B_c} = 0.46^{+0.18}_{-0.16} \pm 0.03$ ps. The B_c is interesting in that either the b-quark or the c-quark can decay; annihilation is also possible but is suppressed. A very naive guess, then, is that the width of the B_c is the sum of the B and D meson widths, corresponding to a lifetime of 0.3 ps. This guess isn't far off - operator product expansion calculations give the range of 0.4 to 0.7 ps [3], compatible with the CDF value.

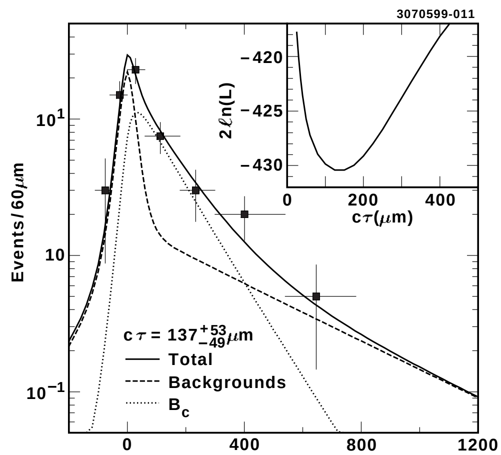

FIG. 2. CDF. The lifetime distribution of B_c candidates (points), the expectation for a B_c sample with a lifetime of 137 μm (shaded histogram) and the expectation for the background (dashed curve).

B. D-meson spectroscopy

There is also a new member in the D-meson family, the first broad $L = 1$ resonance. The spectroscopy of D-mesons is shown in Figure 3. HQET takes advantage of the heavy mass of the charm quark to make predictions about some of the features of the mass spectrum and the transitions between states [4]. In the limit of an infinitely massive charm quark, the charm quark mass would have no influence on the physics. One implication of this is that the mass splittings between D meson states should be the same as the splittings of the B meson states, as is very nearly the case. Also in the limit of an infinitely heavy quark, the spin of the heavy quark decouples from the dynamics. This decoupling implies that there is a new conserved quantity, the total angular momentum of the system excluding the charm quark, j_q. This decoupling of the mass and spin is not new: the same thing happens in the hydrogen atom where, for example, the spin of the proton enters only at the level of the hyperfine splitting.

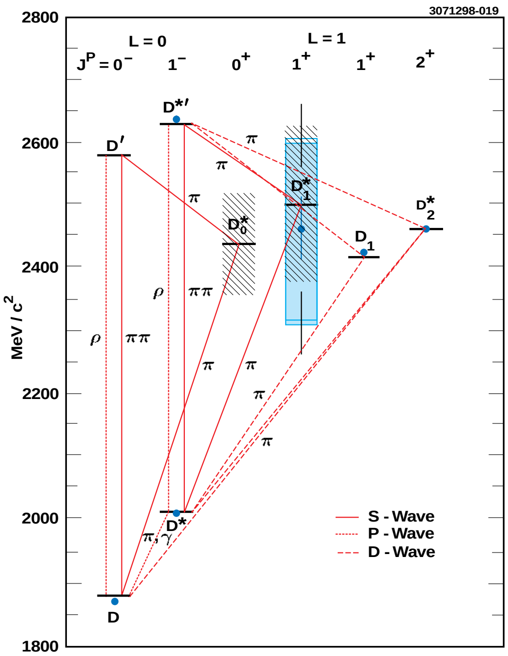

FIG. 3. D meson spectroscopy. The dots and gray areas indicate measured values while the lines and hatched areas indicate predictions.

Consider the $L = 1$ D mesons, which I will refer to as the D_J states. There are four such states, tabulated with their J^P and j_q quantum numbers in Table I. Two states have $j_q = 1/2$ and two have $j_q = 3/2$. Up to the hyperfine splittings, we expect the two $j_q = 1/2$ states to have the same masses; the same is true for the two $j_q = 3/2$ states.

What about the decays, which are to $D\pi$ and $D^*\pi$? Conservation of j_q implies that the decays of the $j_q = 3/2$ states must be through a d-wave; they are consequently narrow resonances. By contrast, the s-wave transition is open to the D_0^* and D_1^* so these are expected to be broad. Not surprisingly, the narrow states have been seen, while the broad ones have not.

TABLE I. Properties of the $L = 1$ D-mesons. j_q conservation allows only d-wave decays for the $D_1(2420)$ and s-wave decays for the D_1^* state.

State	J^P	j_q	Mass	Width	Decay Mode	Partial wave	HQET allowed
D_0^*	0^+	1/2	–	broad?	$D\pi$	s-wave	s
D_1^*	1^+	1/2	–	broad?	$D^*\pi$	s,d-wave	s
D_1	1^+	3/2	2422.2 ± 1.8 MeV	$18.9^{+4.6}_{-3.5}$ MeV	$D^*\pi$	s,d-wave	d
D_2^*	2^+	3/2	2458.9 ± 2.0 MeV	23 ± 5 MeV	$D\pi, D^*\pi$	d-wave	d

At this conference, CLEO showed the first observation of one of the broad resonances, with the quantum numbers $D_1^0(j_q = 1/2)$ whose properties match those expected for the D_1^*. CLEO reconstructs the D_J states ($D_1(2420)^0$, $D_1^0(j = 1/2)$ and $D_2^*(2460)^0$) in the decay chain $B \to D_J\pi$ with $D_J \to D^*\pi$. It is thus sensitive to the D_1^*, the D_1 and the D_2^*. Their analysis takes advantage not only of the invariant mass distribution, but also the angular distributions expected for the various partial waves. They fit for the amplitudes and phases of the 1^+ d-wave, the 1^+ s-wave, the 2^+ d-wave, a non-resonant contribution, the interference between the two 1^+ partial waves, and the mass and width of the 1^+ s-wave state. The backgrounds appear daunting in the mass plot, shown in Figure 4a, but the power of the angular information is apparent in Figure 4b, where events are weighted by the compatibility of the decay angles with the 1^+ s-wave partial wave. Here the broad resonance stands out more distinctly. They find

$$m\big(D_1^0(j_q = 1/2)\big) = 2.461^{+0.041}_{-0.034} \pm 0.010 \pm 0.032\mathrm{G}eV \tag{1}$$

$$,\ \big(D_1^0(j_q = 1/2)\big) = 290^{+101}_{-79} \pm 26 \pm 36\mathrm{M}eV; \tag{2}$$

both support the theoretical predictions.

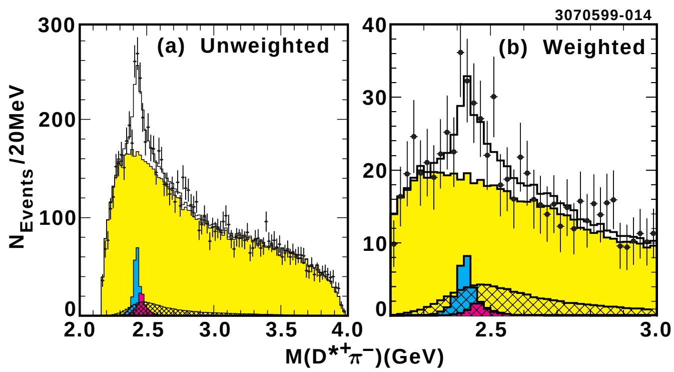

FIG. 4. CLEO. The $D^{*+}\pi^-$ invariant mass of D_J candidates for data (points), background (light gray), $D_1(2420)^0$ (medium gray), $D_2^*(2460)^0$ (dark gray) and $D_1^0(j = 1/2)$ (cross-hatched). (a) Unweighted and (b) Weighted according to the angular distributions expected for a 1^+ s-wave decay.

III. LIFETIMES

We move now to the lifetimes of the heavy flavor states. Lifetimes are necessary to extract $|V_{ub}|$ and $|V_{cb}|$ from data. They also test local duality, the assumption that if one sums over many final states, thereby averaging over a broad range in q^2, long distance effects can be ignored. A very similar assumption is made in extracting $|V_{ub}|$ and $|V_{cb}|$ from inclusive $b \to u\ell\nu$ and $b \to c\ell\nu$ decays.

One new lifetime measurement that is particularly impressive is SLD's measurement of τ_{B^-}/τ_{B^0} [5]. Because of SLD's superb vertex detector, the measurement is one of the best, in spite of using a factor of 10 less data than is available to each of the LEP experiments. The analysis sums the charges of tracks emerging from decay vertices that are displaced from the interaction point. For vertices with large invariant mass, this sum is correct 80% of the time. They use their beam polarization to check that their Monte Carlo simulates this properly; they also get a minor improvement by deweighting B^+ candidates when they are found at a polar angle where B^- mesons prevail. Figure 5 shows the net charge of the reconstructed vertices. The lifetimes extracted from the decay length distributions are $\tau_{B^-} = 1.686 \pm 0.025 \pm 0.042$ ps, $\tau_{B^0} = 1.589 \pm 0.026 \pm 0.055$ ps and $\tau_{B^-}/\tau_{B^0} = 1.061^{+0.031}_{-0.029} \pm 0.027$. Measurements of τ_{B^-}/τ_{B^0} are summarized in Figure 6. The world average value is consistent with expectations.

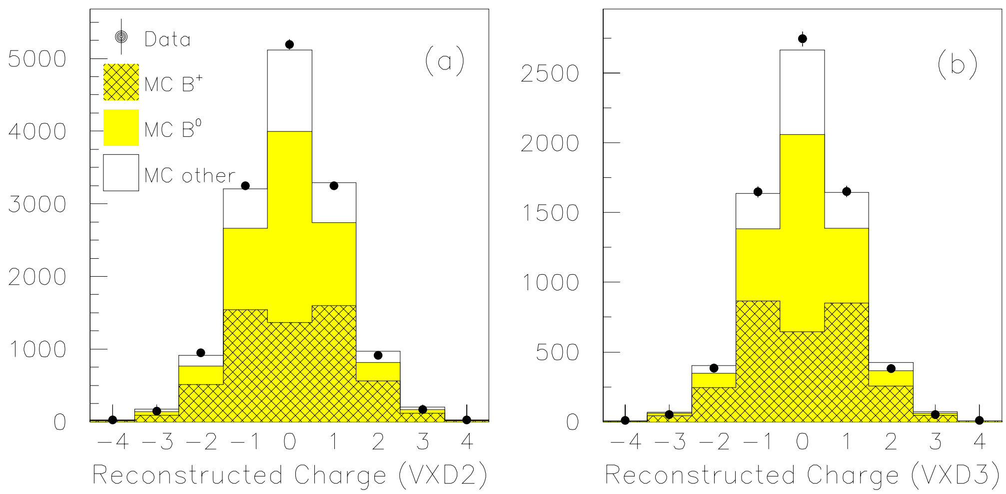

FIG. 5. SLD. The net charge of reconstructed vertices for data (points) and for simulated b decays (histograms).

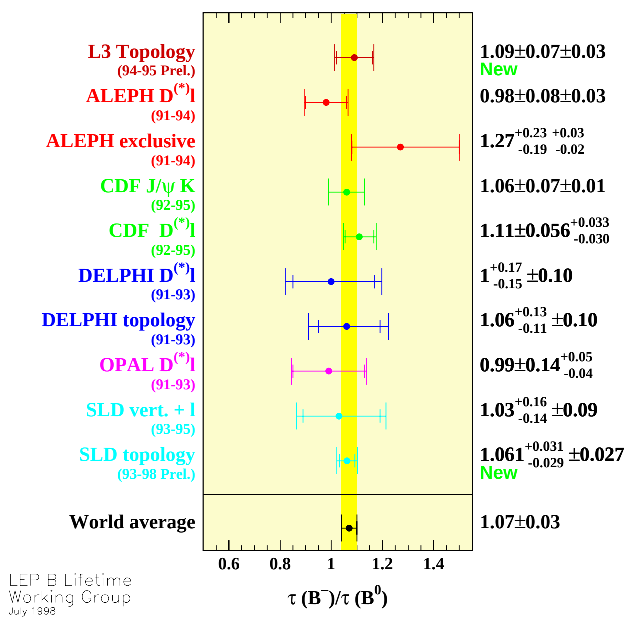

FIG. 6. Summary of measurements of τ_{B^-}/τ_{B^0} [6].

Figure 7 summarizes all the b-hadron lifetime results. Most are consistent with operator product expansion calculations. The possible exception is Λ_b, which is somewhat lower than predicted, perhaps an indication of the special challenges of calculating the decay rates of baryons.

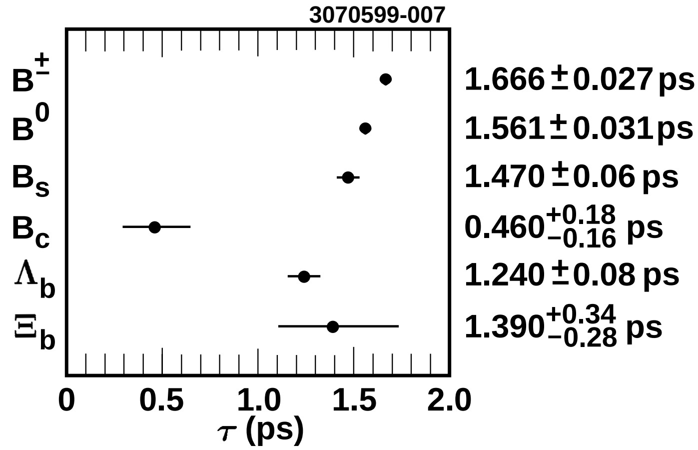

FIG. 7. Measured lifetimes of the b-hadrons [6], [1]. Values are from the LEP B Lifetimes Working Group, SLD and CDF.

IV. QUARK MIXING

A. V_{td}

Our best information on the CKM matrix element V_{td} comes from B_d and B_s mixing. If one starts with a pure $\bar{B}_s$ state, then if $\Delta, = 0$, the probability of observing it decay as a B_s as a function of the decay time is given by

$$P(\bar{B}_s \to B_s) = ,_{B_s} e^{-\Gamma_{B_s} t} \sin^2 \left(\frac{\Delta m_s t}{2} \right). \tag{3}$$

Inside the exponential decay envelope, there are oscillations whose period is inversely proportional to the mass difference between the B_s states, Δm_s. The experiments attempt to observe these oscillations. In the standard model, oscillations arise from the familiar box diagram, and Δm_s and Δm_d are given by

$$\Delta m_q = \frac{G_F^2}{6\pi^2} B_{B_q} f_{B_q}^2 M_{B_q} m_t^2 |V_{tb}^* V_{tq}|^2 \eta_B \frac{S(x_t)}{x_t} \tag{4}$$

where q is s or d, M_{B_q} and m_t are the B_q meson and top quark masses, $x_t = (m_t/m_W)^2$, η_B is a perturbative QCD correction and $S(x_t)$ is the Inami-Lim function. The values used here are the running top quark mass $\bar{m}_t(m_t) = 165 \pm 5$ GeV , $\eta_B = 0.55 \pm 0.01$ [8] and the parametrization $S(x_t) = 2.46(m_t/(170\mathrm{G}e\mathrm{V}))^{1.52}$ [7]. The factors $B_{B_q} f_{B_q}^2$, the bag parameter and B_q meson decay constant, suffer from large uncertainties. The best values now come from lattice calculations. I use those from Terry Draper's summary at Lattice '98, $\sqrt{B_{B_d}} f_{B_d} = 215^{+40}_{-30}$ MeV and $\sqrt{B_{B_s}} f_{B_s} / \sqrt{B_{B_d}} f_{B_d} = 1.14^{+0.07}_{-0.06}$ [9].

Measurements of Δm_d have been stable for several years. They are summarized in Figure 8, along with the current world average value of 0.477 ± 0.017 ps^{-1}. These values give $|V_{td}| = 0.0081^{+0.0012}_{-0.0015}$, where the error is dominated by the uncertainty in $\sqrt{B_{B_d}} f_{B_d}$.

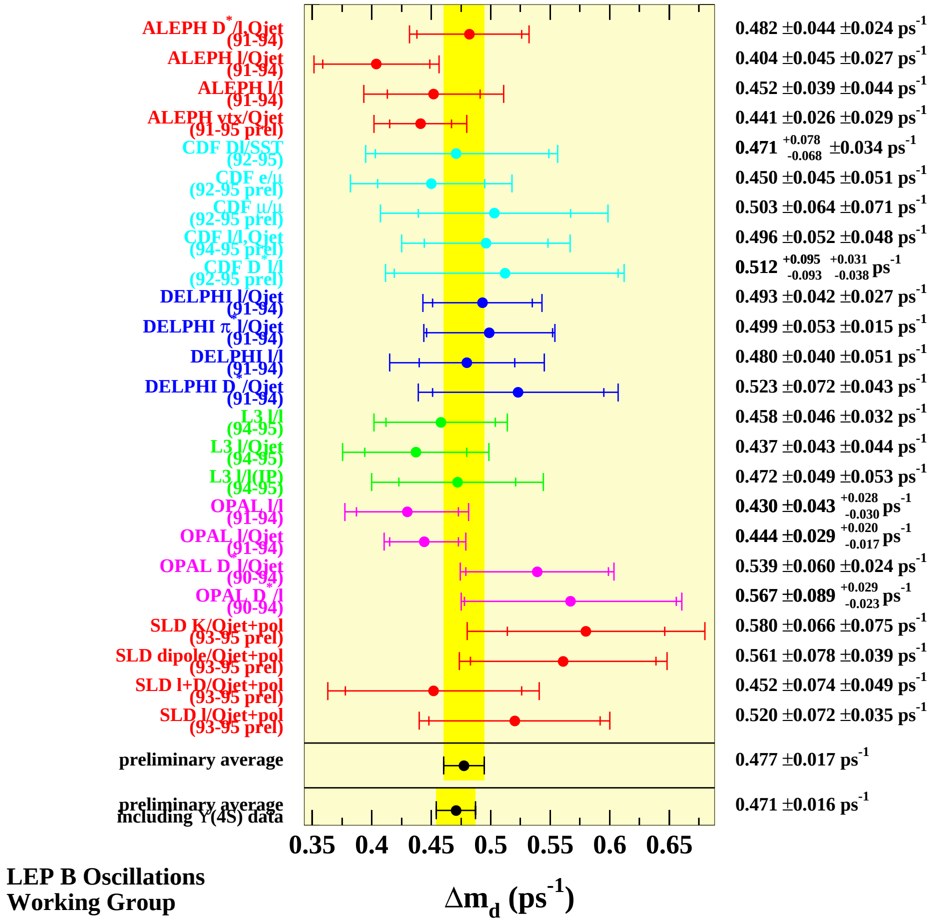

FIG. 8. LEP B Oscillations Working Group. Summary of measurements of Δm_d.

The advantage of measuring Δm_s is that the ratio

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \frac{B_{B_s} f_{B_s}^2}{B_{B_d} f_{B_d}^2} \left| \frac{V_{tb}^* V_{ts}}{V_{tb}^* V_{td}} \right|^2, \tag{5}$$

depends on $(\sqrt{B_{B_d}} f_{B_d})/(\sqrt{B_{B_s}} f_{B_s})$, which is better known than either of the decay constants separately. For V_{ts}, the common practice is to assume the unitarity of the CKM matrix and use the measured value of V_{cb}.

Experimentally, B_s oscillations are much more difficult to detect than B_d oscillations. The challenge is partly statistical, and accordingly relies heavily on events at very short times where the sample is largest. Furthermore, for typical LEP time resolutions, the oscillations become difficult to resolve for $\Delta m_s > 15$ ps^{-1}, roughly in the middle of standard model expectations.

The essential ingredients of the measurement are the time of the B_s decay, and the flavor b or $\bar{b}$ at the time of production and at the moment of decay. The b flavor at decay is almost always determined by the charge of the lepton from semileptonic decay, though DELPHI and ALEPH have used fully reconstructed hadronic B_s decays and SLD has been able to use the charge difference between the secondary (B_s) and tertiary (D_s) decay vertices. Tagging of the b flavor at production is preformed using many more methods. Tags in the same hemisphere as the mixing candidate include the jet charge, the charge of a fragmentation kaon, and the polar angle of the b (SLD). Opposite hemisphere tags include the charge of a hard lepton, the jet charge, the charges of final state kaons, the net charge of tracks from the primary vertex, and the net charge of particles not from the primary vertex. Most of the analyses, which are rather sophisticated, use multiple tags for each event and form a combined likelihood.

Measurements have been made by ALEPH [10], DELPHI [11], OPAL [12], SLD [13] and CDF [14]. Figures 9 and 10 show the lifetime distributions from the two most sensitive analyses. One is from ALEPH and includes all leptons consistent with coming from b-hadron decay. In this analysis, B_s 's comprise only 10% of the sample, but the sample is very large. By contrast, the DELPHI analysis fully reconstructs $B_s \to D_s \ell \nu$ events. The sample is much smaller than for the inclusive lepton analysis, but the purity is 40%.

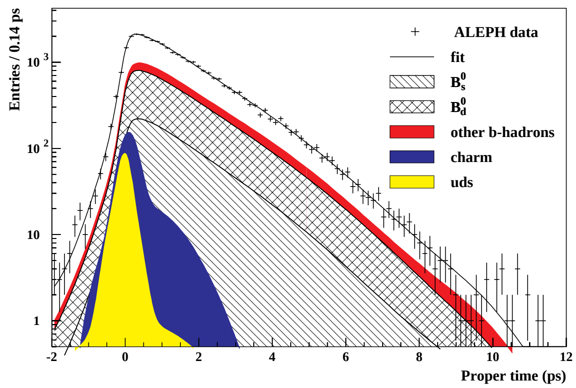

FIG. 9. ALEPH [10]. Reconstructed proper time distributions of the selected events in data. The contributions from the various components are indicated. The curve is the result of a fit.

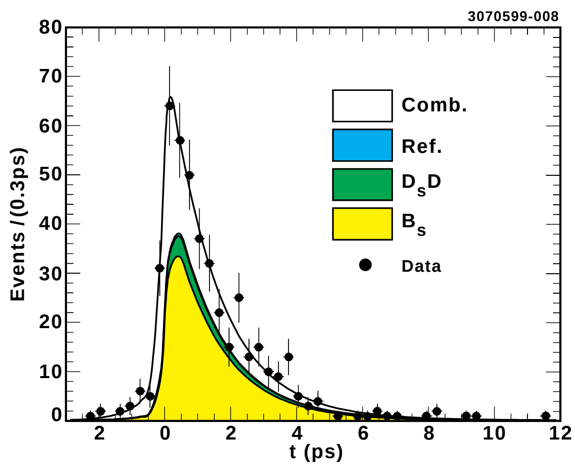

FIG. 10. DELPHI [11]. Reconstructed proper time distributions of the selected events in data. The curve is the result of a fit.

Figure 11 shows the sensitivity of the various measurements. For purposes of the figure, each analysis fixed the value of Δm_s to 10 ps^{-1}and then fit for the oscillation amplitude. This amplitude should be unity if 10 ps^{-1}is the true value of Δm_s and zero if it is not. The average Δm_s is consistent with zero and differs from unity by about 2σ, indicating that Δm_s differs from 10 ps^{-1}.

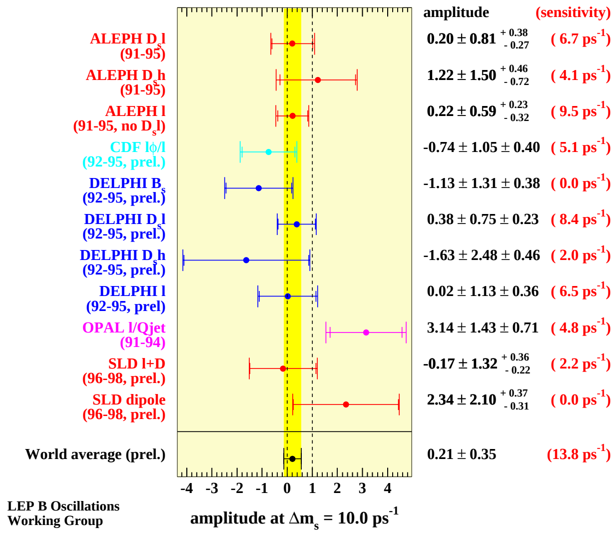

FIG. 11. LEP B Oscillations Working Group. The B_s mixing amplitude measurements for $\Delta m_s = 10\text{ps}^{-1}$.

To extract a limit on Δm_s, the experiments scan over a range of Δm_s values and fit for the oscillation amplitude at each trial value. The combined results are shown in Figure 12. An observation of oscillations would consist of a statistically significant bump up to unity, at the correct value of Δm_s, with an amplitude of zero elsewhere. An amplitude of unity is excluded up to the triangle, giving $\Delta m_s < 12.4\ \text{ps}^{-1}$. This is a considerable improvement over the PDG 98 value [15] of 9.1 ps^{-1}. The limit on Δm_s corresponds to the 95% confidence bound, $|V_{td}| < 0.0097$. This bound is more restrictive than that provided by Δm_d.

Using the lattice value of $f_{B_s}\sqrt{B_{B_s}}$, the expected range is $15\text{ps}^{-1} < \Delta m_s < 25\text{ps}^{-1}$. Much of this range may be accessible to SLD if it collects more data or to CDF during Run II.

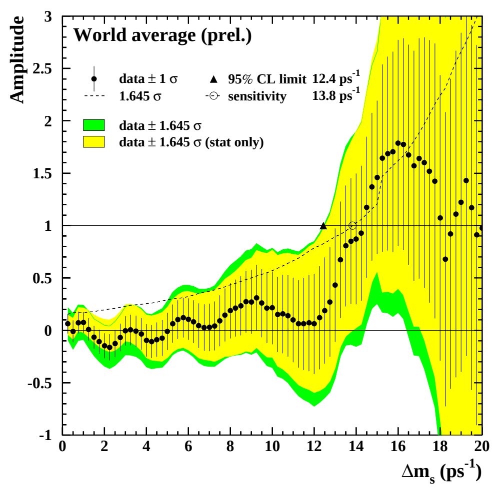

FIG. 12. LEP B Oscillations Working Group. Best fit B_s mixing amplitude as a function of Δm_s. The current limit is $\Delta m_s < 12.4\ \text{ps}^{-1}$.

B. Check of Lattice-Calculated Decay Constants

Extraction of V_{td} from mixing relies heavily on lattice calculations, so it is important to check the lattice results experimentally. The best test uses the decay $D_s \to \ell\nu$, an annihilation decay whose rate is proportional to the D_s decay constant. Because of helicity suppression, the $e\nu$ final state is very much suppressed, and only the $\mu\nu$ and $\tau\nu$ final states have been measured.

The most precise measurement is from CLEO, which uses the decay chain $D_s^* \to D_s\gamma$ followed by $D_s \to \mu\nu$. The neutrino momentum is determined from the missing energy and momentum. The mass difference between the D_s^* candidate and the D_s candidate is shown in Figure 13. There is an excess of $\mu\nu$ events over the background, which is measured directly using $e\nu$ combinations.

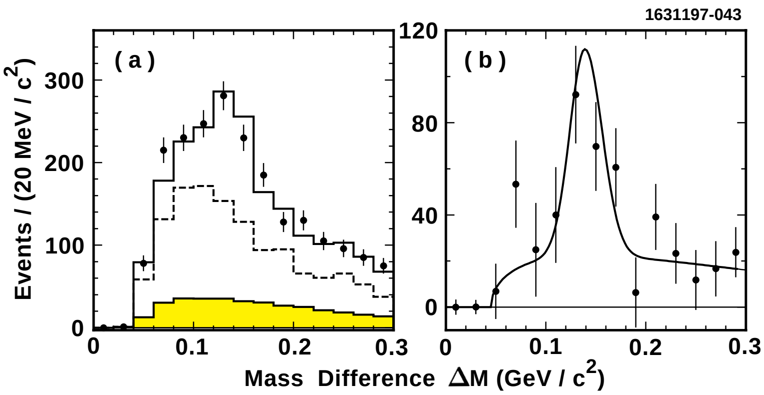

FIG. 13. CLEO. (a) $M(D_s^{*+}) - M(D_s^+)$ for muon data (solid points), electron data (dashed histogram), and the excess of muon fakes over electron fakes (shaded histogram). (The dashed and shaded histograms are not summed.) (b) Muon data after subtraction of the backgrounds shown in (a) with the fit superimposed.

Figure 14 summarizes the status of the D_s decay constant. Agreement between the world average measurement and the lattice result is excellent within the 20% precision of the comparison. For the lattice value I have taken one that has been corrected upward by 10% for quenching based on the indication of the first unquenched lattice calculations of the MILC collaboration. The lattice spacing for this calculation was large, and it is suspected by MILC and others that the correction could be larger than this, perhaps 25%. Further lattice results will be very interesting. Currently, however, the usefulness of the comparison is limited by the experimental uncertainties.

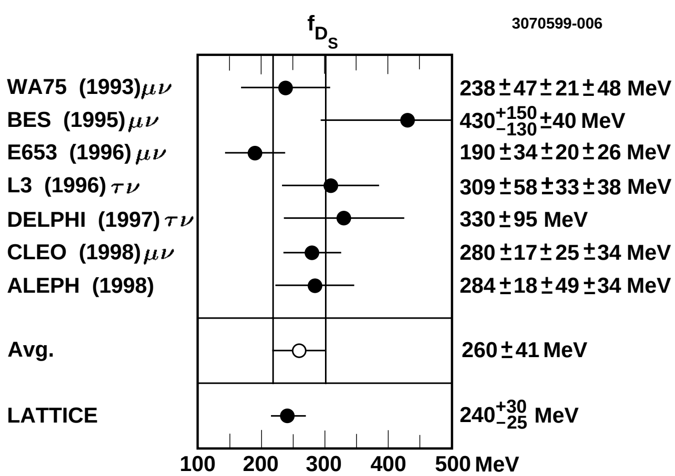

FIG. 14. Summary of measurements of the D_s decay constant, f_{D_s}, using leptonic decays [16], and the predicted value of f_{D_s} from the lattice [9].

C. V_{cb}

The CKM matrix element V_{cb} is measured using the semileptonic decay $b \to c\ell\nu$. There are two approaches to $|V_{cb}|$ of comparable sensitivity. One relies on the exclusive decay $B \to D^*\ell\nu$ (or, less precisely, $B \to D\ell\nu$), and the other uses all leptons produced in b decays. Here we will look at the second approach. Experimentally, the challenge of this approach is to distinguish leptons from the desired $b \to c\ell^-\nu$ decay from those produced via $b \to c \to s\ell^+\nu$. If one includes very soft leptons ($P_\ell < 0.6$ GeV), then leptons from the decay chain $b \to c\bar{c}s$ followed by $\bar{c} \to \bar{s}\ell^-\nu$ must also be subtracted. The most powerful approach is to tag the flavor of the b using the other $\bar{b}$ in the event, and then match the charge of the lepton with that of the b. This has been the approach of ARGUS [17] and CLEO [18] at the $\Upsilon(4S)$.

The other measurements come from the LEP experiments [19] [20] [21] [22]. The measurement is more difficult at the Z^0 because fragmentation smears the measured momentum, thereby blurring the line between signal and background and distorting the lepton momentum spectrum. In addition, early analyses suffered from contamination by charm and light quark events, which could not be measured separately as at the $\Upsilon(4S)$. All of the current LEP measurements suppress the $udsc$ background by requiring a displaced b decay vertex. Very recently, contamination by leptons from $b \to c\bar{c}s$ have been reduced, thanks to studies of this process, first by CLEO [23] and more recently by ALEPH [24], DELPHI [25] and SLD [26]. Because of the smaller data samples, the LEP experiments have resisted tagging the flavor of the b to suppress the dominant background $b \to c \to s\ell^+\nu$ (the exception is a very recent analysis by DELPHI [27]); however, a recent analysis by OPAL accomplishes this using a neural net based on the muon and jet variables. As shown in Figure 15, it does a fine job of distinguishing signal from background.

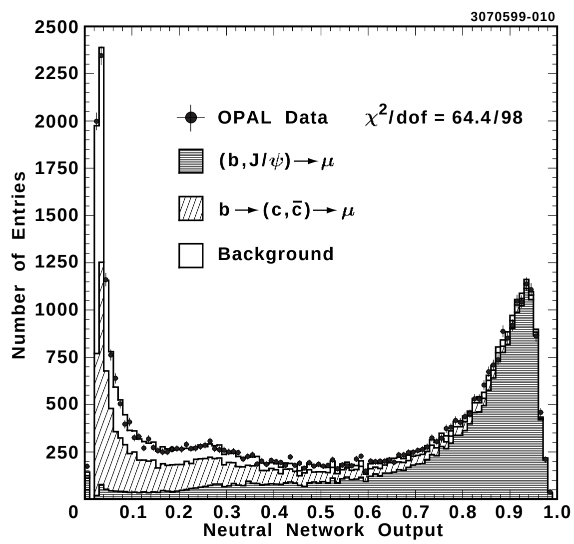

FIG. 15. OPAL. The output of a neural net used to distinguish $b \to c\ell\nu$ decays from background.

The experimental results are summarized in Figure 16. The $\Upsilon(4S)$ and Z^0 semileptonic branching fractions can differ due to the different combinations of b hadrons produced at the two types of machine. The more interesting physical quantity is the $b \to c\ell\nu$ width, since this is expected to be the same for all b hadrons within about 2%. It is derived from the inclusive branching fractions by subtracting the tiny $b \to u\ell\nu$ contribution $(1.5 \pm 1.0)\%$ [29] and normalizing to the appropriate lifetime: the average B meson lifetime for the $\Upsilon(4S)$ and the average b hadron lifetime for the Z^0 result. The $\Upsilon(4S)$ and Z^0 results differ by about 10%, corresponding to two standard deviations. The error on the average has been scaled accordingly.

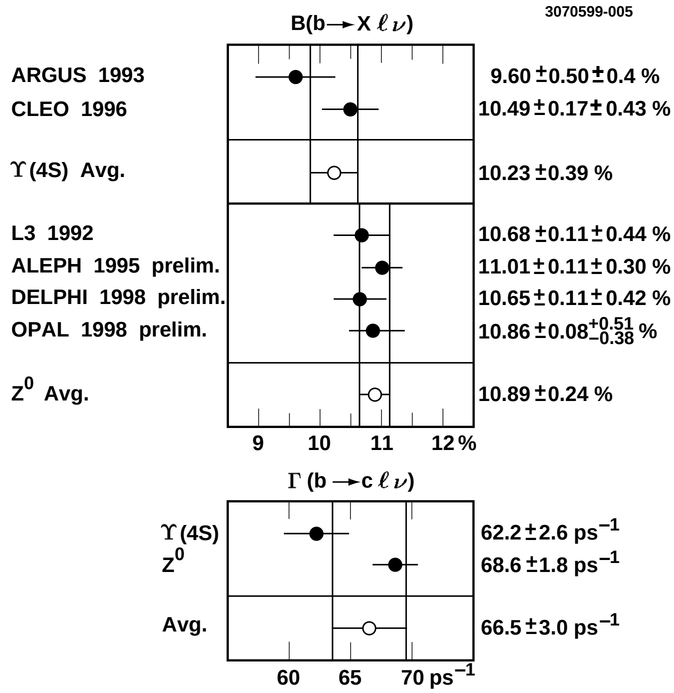

FIG. 16. Summary of measurements of the b semileptonic branching fraction and $b \to c\ell\nu$ width. The LEP average is from P. Gagnon [28].

The semileptonic width gives us $|V_{cb}|$. A calculation by Ball, Beneke and Brown [30] gives $V_{cb} = 0.0396 \pm 0.0009(\text{expt.}) \pm 0.0014(\text{theor.})$ and one by Bigi, Shifman and Uraltsev [31] gives $V_{cb} = 0.0415 \pm 0.0009(\text{expt.}) \pm 0.0010(\text{theor.})$. These values differ by 5% even though their uncertainties are largely correlated.

To estimate the uncertainty realistically, its useful to look at the calculations of the semileptonic width, which use an operator product expansion in $1/m_b$ and α_s [32]. The resulting expression is a function of two matrix elements, λ_1 and λ_2 and the b quark mass. The matrix element λ_1 is the negative of the average momentum squared of the b quark inside the meson, and estimates are that it lies somewhere between 0 and $-0.7\mathrm{G}e\mathrm{V}^2$ [33]. The matrix element λ_2 gives the energy of the hyperfine interaction in the meson, and is easily obtained from the $B^* - B$ mass difference and is 0.12 GeV . The third parameter is the b quark mass. It is common to recast the b quark mass as the parameter $\bar{\Lambda}$, the difference between the meson and quark masses. Calculations generally give values in the range $240 < \bar{\Lambda} < 640$ MeV [34]. The uncertainty in λ_1 and $\bar{\Lambda}$ dominate the theoretical uncertainty in $|V_{cb}|$, both as determined using the inclusive semileptonic width and using $B \to D^*\ell\nu$ decays. Varying them over the above ranges gives

$$|V_{cb}| = 0.0403 \pm 0.0009(\text{expt.}) \pm 0.0025(\text{theor.}) \tag{6}$$

from the inclusive measurements. The theoretical error also includes small contributions from perturbative corrections, terms of order $1/m_b^3$, and the assumption of duality. This value of $|V_{cb}|$ is to be compared with

$$|V_{cb}| = 0.0387 \pm 0.0031 \tag{7}$$

obtained from $D^*\ell\nu$ decays [35]. The two values agree well. Unfortunately, because their theoretical errors are correlated, these two values cannot be easily combined.

An exciting development of the last few years is the realization that λ_1 and $\bar{\Lambda}$ may be extracted directly from the data. Voloshin pointed out that the mean and root-mean-square width of the lepton spectrum are functions of λ_1 and $\bar{\Lambda}$ [36]. Falk, Luke and Savage pointed out that the same is true of the invariant mass distribution of the final state hadrons [37]. Very recently, Ligeti, Luke, Manohar and Wise have related the photon spectrum of $b \to s\gamma$ decays to these same parameters [38]. These topics were reviewed at this conference by Z. Ligeti [39]. By allowing us to pin down λ_1 and $\bar{\Lambda}$, these approaches could lead to a value of V_{cb} with a precision of 3% in the next few years. A preliminary effort to use these techniques is underway [40].

D. V_{ub}

Semileptonic decays are also the best avenue to $|V_{ub}|$. $|V_{ub}|$ is exceptionally difficult experimentally, both because $b \to u\ell\nu$ semileptonic decays are swamped by the $b \to c\ell\nu$ decays and also because their form factors are poorly known.

There have been two strategies toward V_{ub} . In the first, one takes advantage of the fact that the inclusive $b \to u\ell\nu$ decay is better understood theoretically than the individual exclusive modes [41]. Inclusive analyses have been done by ALEPH [42], DELPHI [43], and L3 [44]. Typically, they sum over all $b \to u\ell\nu$ final states and avoid selection criteria that would restrict the accepted phase space. The drawback to this approach is the large remaining $b \to c\ell\nu$ background. The results of an ALEPH neural net analysis is shown in Figure 17. In order to achieve their precision, the analysis had to establish the level of the $b \to c\ell\nu$ background to better than 3% of itself. Doing so presses, and may exceed, the current understanding of $b \to c\ell\nu$ decays, given the 10% discrepancy between the $b \to c\ell\nu$ decay widths measured at the $\Upsilon(4S)$ and Z^0. The results of the $b \to u\ell\nu$ analyses are summarized in Figure 18.

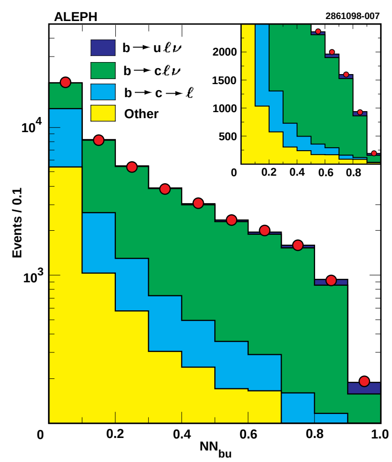

FIG. 17. Aleph $b \to u\ell\nu$ analysis. The output of a neural net for data (points) for simulated signal and backgrounds (histograms).

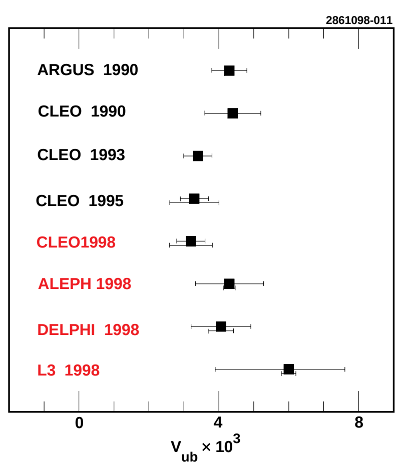

FIG. 18. Summary of measurements of $|V_{ub}|$. The upper three results are based on the lepton endpoint, the CLEO results of 1995 and 1998 use $B \to \rho\ell\nu$ and $B \to \pi\ell\nu$ decays and the ALEPH, DELPHI and L3 results use inclusive lepton analyses. Where two error bars are shown, the upper one is the experimental error and the lower one reflects the model dependence.

The second approach is to reconstruct a particular $b \to u\ell\nu$ decay mode. CLEO has done this for $B \to \pi\ell\nu$ and $B \to \rho\ell\nu$ [45]. As shown in Figure 19, this method is relatively free of background. It has the problem, however, that the value of V_{ub} extracted relies on knowledge of the form factors, which remain poorly understood in spite of extended theoretical efforts [46] [47] [48] [49] [50]. Based on their measurements of the exclusive modes, CLEO finds $V_{ub} = (3.25 \pm 0.14^{+0.21}_{-0.29} \pm 0.55) \times 10^{-3}$ where the final error covers most of the form factor calculations now on the market.

Based on all the current measurements, our current knowledge can be summarized as $|V_{ub}| = 0.0036 \pm 0.0008$.

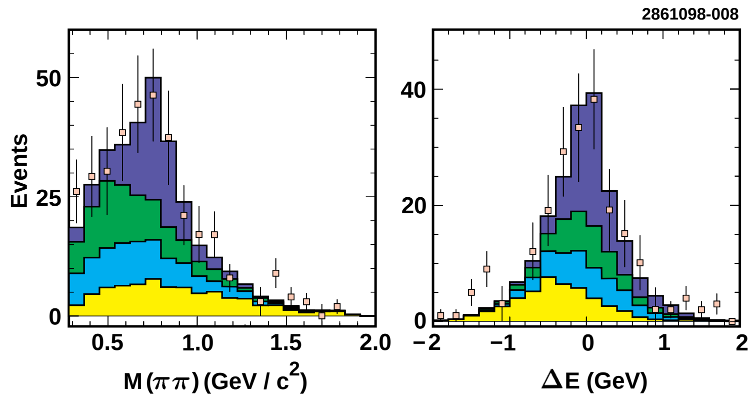

FIG. 19. CLEO study of $B \to \rho\ell\nu$. The invariant mass of ρ candidates for data (points), of simulated signal (dark hist.), misreconstructed signal (med. dark hist.), crossfeed from other $b \to u\ell\nu$ modes (med. light hist.) and $b \to c\ell\nu$ background (light hist.).

What can we hope for in the future? On the inclusive side, it may be possible to reduce the uncertainty in the parameters entering the calculations of $b \to u\ell\nu$ by relating them to other measureable quantities, such as the photon energy spectrum from $b \to s\gamma$. In parallel, experimental understanding of the backgrounds will surely advance, and it may be possible to measure the hadronic recoil mass spectrum, which has been calculated theoretically. On the exclusive mode side, there are active efforts to compute the form factors, or the shapes of the form factors may be measured directly, with normalization provided by the lattice. As proof of principle, the CLEO distribution in q^2 of the $B \to \rho\ell\nu$ sample is shown in Figure 20. Both the inclusive and the exclusive approaches may yield measurements $|V_{ub}|$ with precisions of 10% or better in the next 5 years.

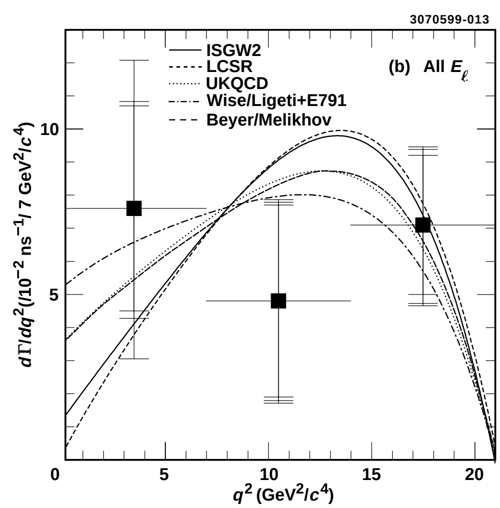

FIG. 20. CLEO study of $B \to \rho\ell\nu$. The q^2 distribution of the $B \to \rho\ell\nu$ sample.

V. RARE PROCESSES

A. $D^0 - \bar{D}^0$ Mixing

The first rare process is $D^0 - \bar{D}^0$ mixing. In the standard model this is expected to be very small, thanks both to Cabibbo suppression and to the GIM mechanism in the box diagram. Some models, however, predict large mixing, such as two Higgs-doublet models and models with leptoquarks. Measurements can bound these models.

One measurement approach is to tag the flavor of a D^0 using the $D^*+ \to D^0\pi^+$ decay, and then look for the rare $K^+\pi^-$ or $K^+\pi^-\pi^+\pi^-$ final state. In order to distinguish mixing from doubly-Cabibbo-suppressed (DCS) decays, one must study the time dependence of the decays. The DCS decay has the usual time dependence $\propto e^{-t}$, while mixing through the box diagram, parametrized by $x = \Delta M/,$, has the time dependence $\propto te^{-t}$ and mixing through long distance effects, parametrized by $y = \Delta, /2,$, has the time dependence $\propto t^2e^{-t}$. This approach has been used by E691 [51], CLEO [52] [53], ALEPH [56], and E791 [54] [55]. Another approach uses the same tagging method, but reconstructs semileptonic decays. This approach, which is free of the DCS contribution, has been taken by E791 [57].

The most restrictive search is one presented at this conference by CLEO using $D^0 \to K^+\pi^-$ decays [53]. Their $K^+\pi^-$ signal is shown in Figure 21, along with the time distribution of the events. The lifetime distribution does not support a large mixed contribution.

Figure 22 summarizes the current bounds on $D^0 - \bar{D}^0$ mixing. Here $R_{Mix} = \frac{1}{2}(x^2 + y^2)$ and $\phi = tan^{-1}(-\frac{2\Delta M}{\Delta\Gamma}) + \delta_s$, where δ_s is the strong phase difference between the $D^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^+\pi^-$ amplitudes and is believed to be small. Also shown is a limit on y that was presented at this conference by E791 [55]. They derive this limit from the lifetime difference between the D mass eigenstates (from $D^0 \to K^-\pi^+$ decay) and the CP even eigenstate decaying to K^+K^-.

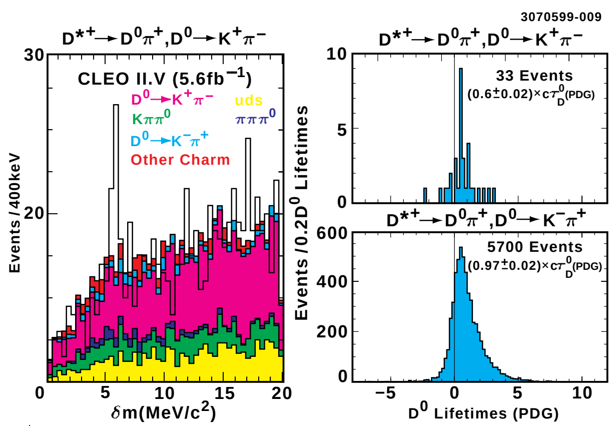

FIG. 21. CLEO. (a) The $D^0 \to K^+\pi^-$ (wrong-sign) signal; (b) the lifetime distributions of the wrong-sign and (c) right-sign samples.

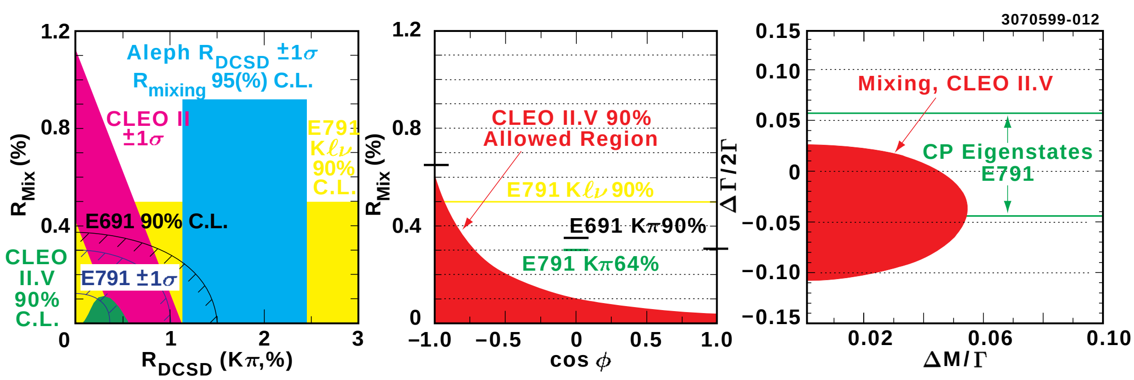

FIG. 22. Current bounds on $D - \bar{D}$ mixing.

B. Rare B Decays

Like $D-\bar{D}$ mixing, rare B decays have the potential to expose new physics. These decays are also the route to the CKM angles α, via time-dependent CP asymmetries in $B \to \pi^+\pi^-$ and its vector-pseudoscalar siblings, and γ, via amplitude relations among modes such as $B \to K^+\pi^-$ and $B \to K^0\pi^+$ [58]. Some rare B decays are also expected to exhibit large direct CP violation.

1. $B \to \rho\pi$

This conference saw the first observation of a $b \to u$ transition in a hadronic decay, in the mode $B \to \rho^0\pi^-$ [59]. The analysis, by CLEO, observes a signal of $26.1^{+9.1}_{-8.0}$ events (see Figure 23), corresponding to a branching fraction of $(1.5 \pm 0.5 \pm 0.4) \times 10^{-5}$. Bediaga *et al.* [60] have suggested extracting the CKM angel γ from the $\pi^+\pi^-\pi^-$ Dalitz plot. Since this conference, CLEO has also reported the observation of $B^0 \to \rho^+\pi^-$ with a branching fraction of $(3.5^{+1.1}_{-1.0} \pm 0.5) \times 10^{-5}$. This mode is key to extracting the CKM phases from $B \to \pi\pi$ decays in the presence of penguin amplitudes, and happily, the branching fraction is substantial.

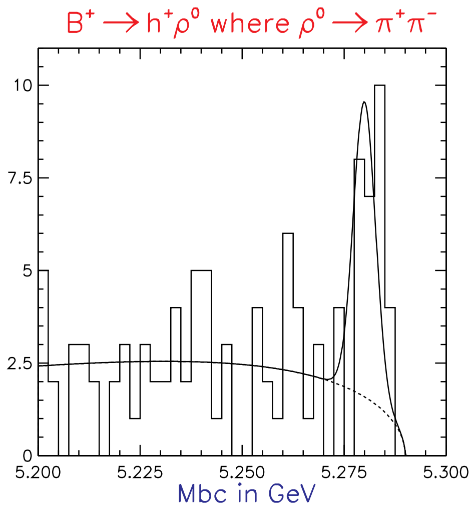

FIG. 23. CLEO. The mass distribution of $B^- \to \rho^0\pi^-$ candidates (histogram) with the fit superimposed (curve).

In the last few years, there has been growing recognition of the problems facing the extraction of weak parameters from rare B decays. One of these is penguin pollution [61], which refers to shifts in the amplitudes and phases of certain decays due to the presence of unwanted penguin diagrams, the bugaboo of the $B \to \pi\pi$ decay. More recently, Donoghue *et al.* and others [62] have pointed out that final state rescattering can be large for B decays. This topic was reviewed at this conference by A. Petrov [63]. If large, this rescattering would invalidate some methods proposed for extracting the CKM angle γ. While the size of such effects can in principle be extracted from future measurements, doing so will take time and extensive dialogue between theory and experiment. In the last few years, elaborate strategies have been developed to extract α in spite of penguin pollution, and recently, Neubert and Rosner have proposed a method for determining γ that is insensitive to rescattering [64].

2. $b \to s\gamma$

The $b \to s\gamma$ decay has provided important constraints on models of new physics such as supersymmetry and models with two Higgs doublets. This comes about because a penguin mediated by a charged Higgs particle would add constructively with the standard W-mediated penguin, increasing the rate. Observation at the standard model rate then bounds the Higgs contribution, at least for those models without destructive interference from additional amplitudes. The current CLEO branching fraction is $(3.15 \pm 0.35 \pm 0.35 \pm 0.26) \times 10^{-4}$. ALEPH has measured $(3.11 \pm 0.80 \pm 0.72) \times 10^{-4}$, consistent with the CLEO value but with considerably larger errors. The results agree well with the standard model expectations, now calculated to next-to-leading order [65]. The $b \to s\gamma$ constraint rules out H^+ masses below 240 GeV subject to the caveat above [66]. This and other constraints [67] [68] [69] on two higgs doublet models are shown in Figure 24.

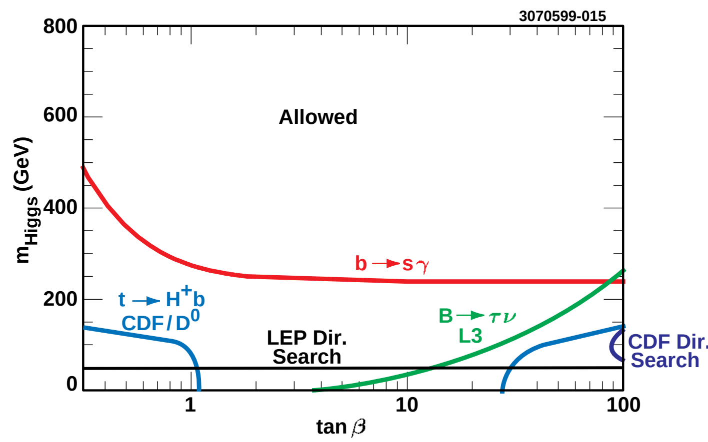

FIG. 24. Current bounds on the parameters $tan\beta$ and the $H^{\pm}$ mass for models with two Higgs doublets (Model II).

VI. CONCLUSIONS

In the next few years, we will be rich in facilities for heavy flavor physics. We can expect

- Precision CKM measurements
- Rare decays
- CP violation

Heavy quark physics has tremendous potential for exploring the weak interaction and revealing physics beyond the standard model. With the development of the operator product expansion, the theoretical framework for analyzing their decays is now on solid footing. This advance coupled with the array of superb heavy flavor experiments – both those now in operation and those that will start up soon – is opening the door to precision measurements of fundamental parameters using heavy quarks. Full realization of this potential, however, will not be quick. Rather it will be the outcome of an extended conversation between experiment and theory.

VII. ACKNOWLEDGEMENTS

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