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Hadronic and Semileptonic Decays of Heavy Quark States

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ABSTRACT

I review the latest progress on the observation of new heavy mesons and the non-rare decays of heavy mesons.

1 Introduction

The study of heavy quark states and their decays has been an especially fruitful line of effort in particle physics. We have learned about the structure of the CKM matrix and gained valuable insight into interactions between quarks. This continues to be one of the most active parts of our field.

First I should define what I mean by a heavy quark state. This means a hadron with a c or a b quark in it. They divide into two classes: mesons are a bound quark-anti-quark pair and baryons are a bound state of three quarks or anti-quarks. Heavy mesons are further divided into $c\bar{c}$ and $b\bar{b}$ pairs, called quarkonia, which have their flavor closed or hidden. The decays of these are dominated by strong and electromagnetic interactions and are not covered in detail here due to lack of space and time. The study of quarkonia and their decays is a vital window on the interaction between two quarks. See for example recent CLEO results on hadronic transitions of the Υ(2S) to Υ(1S) [1] and mass splittings between χ_b(1P) states, [2] Fermilab's E835 on charmonium to photons, [3] and many new results on charmonium from BES. [4] Heavy baryons, those with at least one c or b quark, are another very active field which is also not covered here due to lack of space and time.

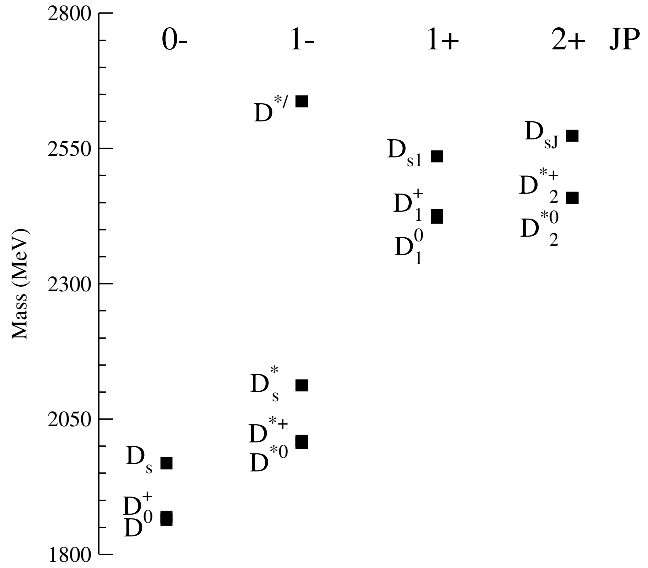

Figure 1: *Masses of the charm flavored mesons.*

My focus is on the heavy mesons that exhibit open flavor and whose dominant decay modes are governed by the weak interaction. First I will discuss the observation of two new heavy mesons. One, the $D^{*'}$, is the first observation of a radial excitation in a heavy-light quark system. The second, the B_c, is the last of the ground state mesons. Next I will discuss the decays of the heavy quark states and point out that the attraction in studying them is to extract measures of the CKM Matrix elements. I discuss the lifetimes of these states. Then I focus on the hadronic decays of heavy mesons which we describe with the factorization model. Finally I cover semileptonic decays of heavy mesons and the very successful description of them, the Heavy Quark Effective Theory. In all these discussions I try to highlight relevant new measurements.

2 New Heavy Mesons

Figure 1 shows the spectrum of masses of the heavy mesons with the charm flavor. [5)] Among the interesting features of the spectrum is that the lowest lying $\mathrm{J^P} = 1^-$ states, the D^*'s, are just about one pion mass above their corresponding $\mathrm{J^P} = 0^-$ ground states. This leaves little phase space for the decay pion. This fact makes the D^* a very clean tag in heavy flavor physics. The $\mathrm{J^P} = 1^+$ and 2^+ states are collectively known as the D^{**}'s. The $\mathrm{J^P} = 1^-$ state labeled the $D^{*'}$ is a new result from DELPHI. [6)]

2.1 First Radial Excitation of a D Meson

QCD inspired [7)] and relativistic quark [8)] models predict a radial excitation of the D^* at 2.63–2.64 GeV. This would decay dominantly to $D^*\pi\pi$ and possibly to $D^*\rho$, while P-wave single pion decays would be suppressed. Such a state would have a narrow width.

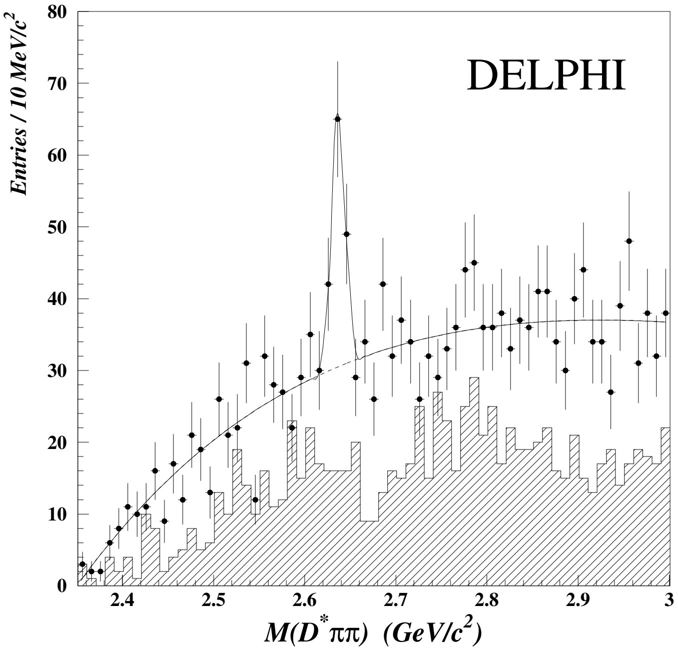

Figure 2: *Invariant mass of the ($D^{*+}\pi^+\pi^-$) in dots. The distribution for the wrong sign ($D^{*+}\pi^+\pi^+$) is the hatched histogram.*

DELPHI finds D^0's in the $K\pi$ and $K\pi\pi$ channels. These are combined with one charged pion to form the D^{*+} candidate. They start with nearly 7000 such tags with a signal-to-noise of about three to two. They clearly see the D_1^0 and D_2^{*0} at the expected masses when they combine their D^{*+} signal with a single charged pion. To observe the $D^{*'}$ they use a heavy flavor enriched sample and combine the D^{*+} with two oppositely charged pions requiring all the tracks to form a common vertex. They see a clear peak of 66 ± 14 events rising above the background as can be seen in Figure 2. They see no peak in the wrong sign distribution. The mass that they find is $2637 \pm 2 \pm 6$ MeV. The width is smaller than their resolution and they set an upper limit on the width of 15 MeV at the 95% Confidence Level. This state is identified as the $D^{*'}$ because of the observed mass and width rather than any knowledge of its decay properties.

2.2 The B_c Meson

Figure 3 shows the spectrum of masses of the heavy mesons with the bottom flavor. [5] The most interesting feature on it is the new B_c meson from CDF. [9] The B_c is a bound state of the b and $\bar{c}$ quarks, and its decays should be rich in the lowest lying charmonium state, the J/ψ. Non-relativistic quark models [10] predict that the mass of B_c should be 6.2–6.3 GeV and that there should be a rich spectroscopy of excited states. Hints of the B_c have previously been seen at LEP. [11]

CDF begins with a clean sample of $J/\psi \rightarrow \ell^+\ell^-$ with a vertex displaced from the primary vertex. A third track is also required to originate from this vertex. The

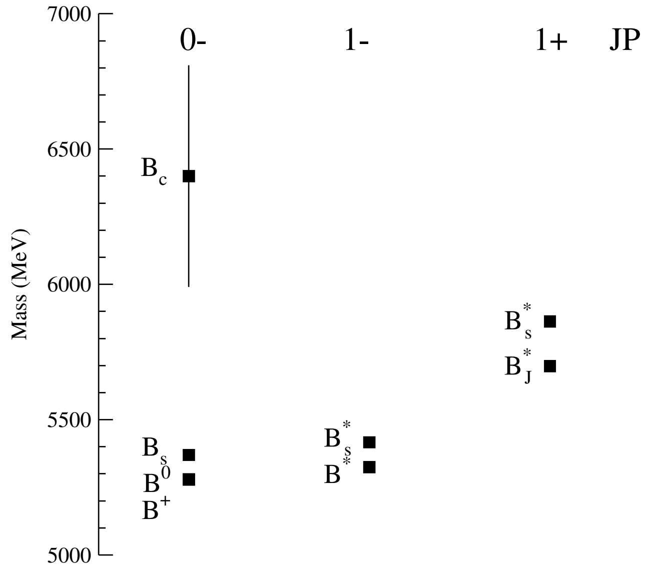

Figure 3: *Masses of the bottom flavored mesons.*

decay $B^+ \to J/\psi K^+$ is vetoed with a cut around the known B^+ mass. The third track is then required to be a lepton which should pick up the semileptonic decay of the B_c. Background is dominated by fake leptons from misidentified hadrons, conversions, decays in flight, and others. These can be measured from the data giving good confidence that any excess observed is from the B_c. Figure 4 shows the mass distribution of the three leptons with the estimate of the background.

The mass is extracted by performing a log-likelihood fit to the mass distribution with a Monte Carlo model of the signal with variable B_c mass. The minimum of the fit gives the mass $6.40 \pm 0.39 \pm 0.13$ GeV, and the number of signal events, $20.4^{+6.2}_{-5.5}$. Also the decay distance can be measured with an accuracy of about 25 μm and a measurement of the lifetime obtained. The result is $0.46^{+0.18}_{-0.16} \pm 0.03$ ps which is consistent with models where the B_c decay is dominated by the decay of the c quark.

It is interesting to note that these two new heavy mesons, the $D^{*'}$ and B_c, while occupying opposite ends of the meson family both point to deeper understanding of quark interactions. The $D^{*'}$ is the first observation of a radial excitation in a heavy-light quark system. Is this the opening of a new door on the study of quark interactions as the observation of quarkonia was 25 years ago? The B_c is the last and most elusive of the ground state mesons. The study of it and its excited states are a severe test of our understanding of quark interactions.

3 Lifetimes of Heavy Quark States

Figure 5 shows the Feynman diagrams for hadronic and semileptonic b quark decays. Similar diagrams can be drawn for c quark decays. They show that the rate of heavy quark decay depends on the CKM matrix element V_{cb} for the b quark and V_{cs} for the c quark. Thus by studying the lifetime of heavy quark states we can hope to extract

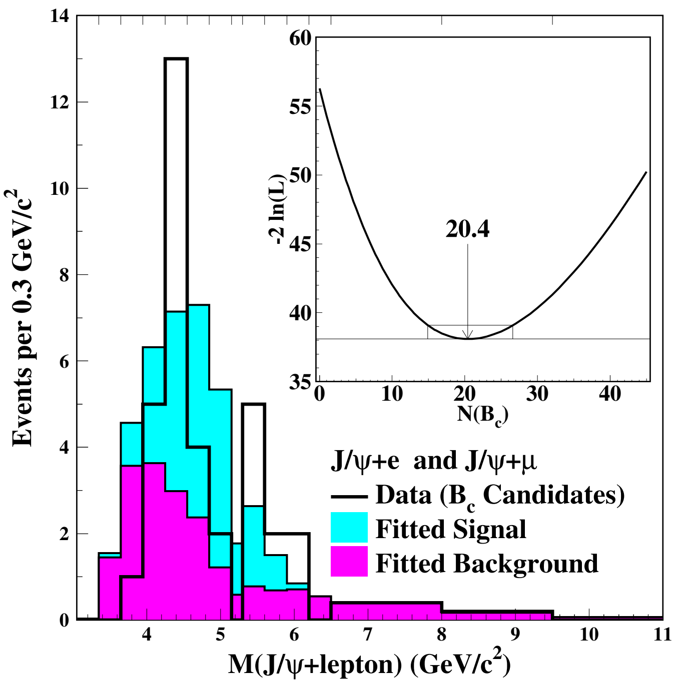

Figure 4: *The $J/\psi\ell$ mass distribution from CDF showing the data (open histogram), background (dark histogram), and fitted signal (light histogram). The inset shows the log-likelihood as a function of the number of fitted signal events.*

these matrix elements. Figure 6 shows the current state of the lifetimes of the weakly decaying charm flavored hadrons. [5] The wide disparity in lifetimes among the charm hadrons shows that extracting CKM matrix elements from the hadron lifetimes is more complex than the naive model of free quark decay. Why should the D^+ lifetime be almost three times the D^0? Figure 7 shows the bottom hadron lifetimes [5] where the situation is improved, but there is still more variation among the lifetimes to make reliable extraction of CKM matrix elements very difficult.

A quick glance at the particle data book will clearly reveal that measurements of the charm hadron lifetimes are dominated by Fermilab E687. The dominance in this field by the Fermilab fixed target experiments is likely to continue judging by the very preliminary results we saw at the poster session from the upgrade to E687, E831/FOCUS. The upgraded CLEO detector, with a new silicon strip vertex detector and a large sample of clean e^+e^- luminosity, is also making precision measurements of charm lifetimes. [12] For example, for the D^0, CLEO has a sample of 3610 D^0's with a background of under 3%. They have an impact parameter resolution of about 30 μm and few other sources of error. Their preliminary result $\tau_{D^0} = 0.403 \pm 0.009^{+0.007}_{-0.011}$ ps compares well to E687's $\tau_{D^0} = 0.413 \pm 0.004 \pm 0.003$. CLEO has more than a factor of two more data in hand, has been cautious with the systematic errors, and should achieve final errors close to the E687 standard. CLEO also has preliminary measurements of the D^+ and D_s lifetimes with good precision.

There are many new measurements of bottom hadron lifetimes. SLD has tremen-

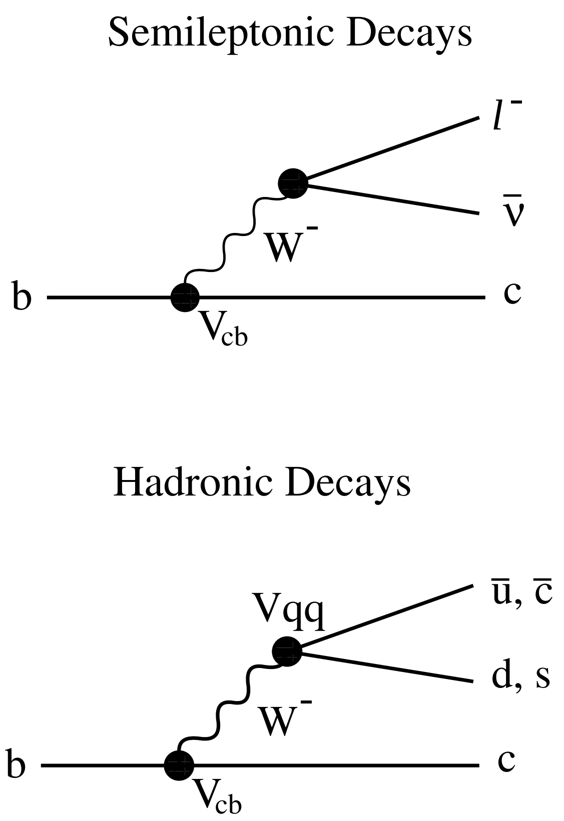

Figure 5: *Feynman diagrams for b quark decays.*

dous resolution on the flight distance due to their CCD Pixel vertex detector and the small size and stability of SLC beam spot. [13] Figure 8 shows their distributions of the decay length for the B^+ and B^0. CDF also makes measurements of the B^+, B^0, and B_s lifetimes taking advantage of their large statistics in the clean J/ψ modes. [14] OPAL makes measurements of the B_s lifetime using $D_s\ell$ combinations and the Λ_b lifetime using $\Lambda_c\ell$ combinations. [15]

Figure 9 shows why the free quark model does not describe the lifetime of the heavy hadrons. In hadronic decays the spectator quark in the meson can interact with the heavy quark's decay products and, for example in the case of the charged B, the color allowed external spectator diagrams for two body decays interfere with the color suppressed internal spectator diagrams. For the D's, which are dominated by two-body decays these effects are very important. For the B's, which because of their higher mass are not dominated by two body decays, these effects are much less important.

4 Hadronic Decays and Factorization

The successful model of two body hadronic decays of heavy mesons is called factorization. It breaks the process into two parts. There is a short distance part with the color allowed external spectator diagram having an amplitude proportional to a_1 and the color suppressed internal spectator diagram proportional to a_2. The long distance part is pa-

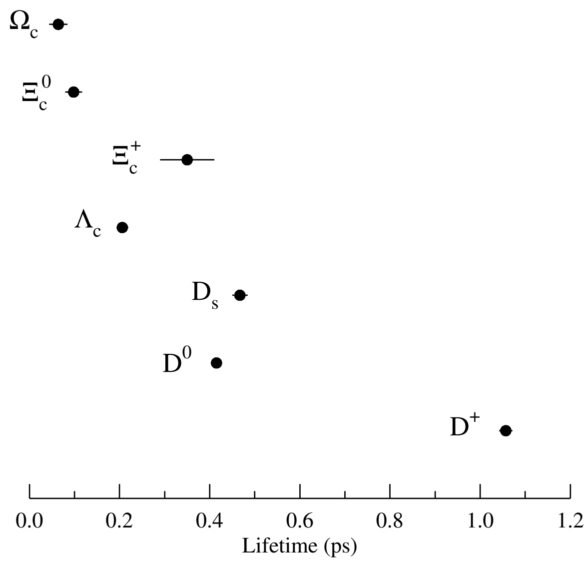

Figure 6: *Lifetimes of the charm flavored hadrons.*

rameterized with decay constants and form factors. For a recent review see [16] which formalizes this brief overview. For example in the factorization model

$$\mathcal{B}(\bar{B}^0 \to D^+\pi^-) \propto a_1^2 \tag{1}$$

$$\mathcal{B}(\bar{B}^0 \to D^0\pi^0) \propto a_2^2 \tag{2}$$

$$\mathcal{B}(B^- \to D^0\pi^-) \propto |a_1 + xa_2|^2 \tag{3}$$

where x depends on π and D decay constants and form factors. A comparison over many decay modes yields rough agreement on the values of a_1 and a_2. See [17] for a unified test of factorization in B decays by CLEO. The more complicated situation in D decays is reviewed in [18]. These reviews show that the color suppressed internal spectator diagram interferes constructively in B decays and destructively in D decays. Said another way the sign of a_2/a_1 is positive in B decays, but negative in D decays. The reason for this is discussed below.

One crucial assumption of factorization is that there are not final state interactions (FSI), but rather that the decay products separate and do not interact after their creation by the weak process. FSI, has been observed in charm decays although factorization, with correction for FSI effects, does seem to be a good model of their decays. FSI has yet to be observed in B decays.

CLEO presents a preliminary analysis of $B \to D^*\rho$ decays which sees evidence for FSI in two-body B decays, but also agrees with one of the predictions of the factorization. Figure 10 shows the three angles which describe these decays. The distribution in the 3D space of these angles is described by three helicity amplitudes, which in the absence of FSI should be real. CLEO has about 200 neutral B decays and 130 charged B decays with low background. A maximum likelihood fit with acceptance and smearing corrections is

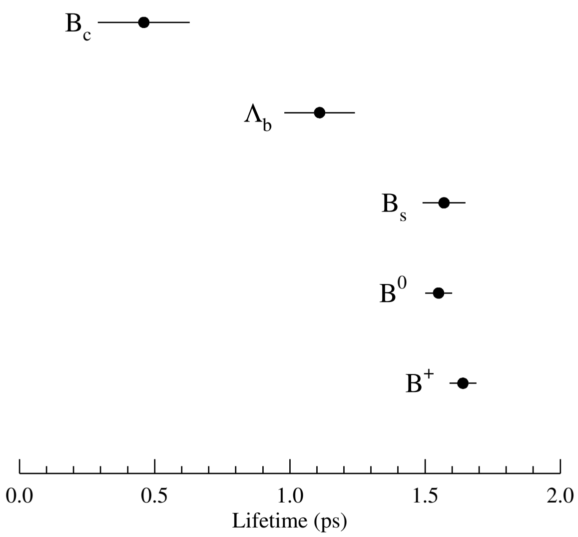

Figure 7: *Lifetimes of the bottom flavored hadrons.*

performed in the 3D space. Figure 11 shows the projection of the data and the best fit onto each of the three angles for the neutral B decay mode. It is clearly visible in this fit that the decay products are almost completely longitudinally polarized. This agrees with a prediction of factorization which is that the amount of longitudinal polarization of the D^* in $B \to D^*\rho$ should be the same as that of the D^* in $B \to D^*\ell\bar{\nu}$ at $q^2 = m_\rho^2$. The longitudinal polarization of the D^* in $B \to D^*\ell\bar{\nu}$ at $q^2 = m_\rho^2$ is measured to be around 90%. [19] The fits also give significant imaginary contributions to the helicity amplitudes. This preliminary result mirrors the situation in charm decays where evidence for FSI is clear, but the predictions of the factorization model remain a good guide to the two-body hadronic decays of the heavy quark states. Also this is the first evidence for FSI in B decays.

The one remaining mystery is why does the contribution of the color suppressed internal spectator diagram change sign between B and D decays. The reason is the running of α_s. The different energy scales of B and D decays lead to a much larger value of α_s for D decays. The relation between α_s and the factorization parameters a_1 and a_2 is shown in Figure 12 and discussed in detail in a recent review. [20]

These many complications make it impossible to extract CKM matrix elements from the total decay rates, from the lifetime measurements, or from hadronic decays of heavy quark states. Thus we turn to the semileptonic decays.

5 Semileptonic Decays and the Heavy Quark Effective Theory

Clearly the effect of QCD is going to be much reduced in the semileptonic decays of the heavy quark states. Thus the complications discussed above in the hadronic decays do not apply. The first thought is to look at the total rate for the semileptonic decay. We

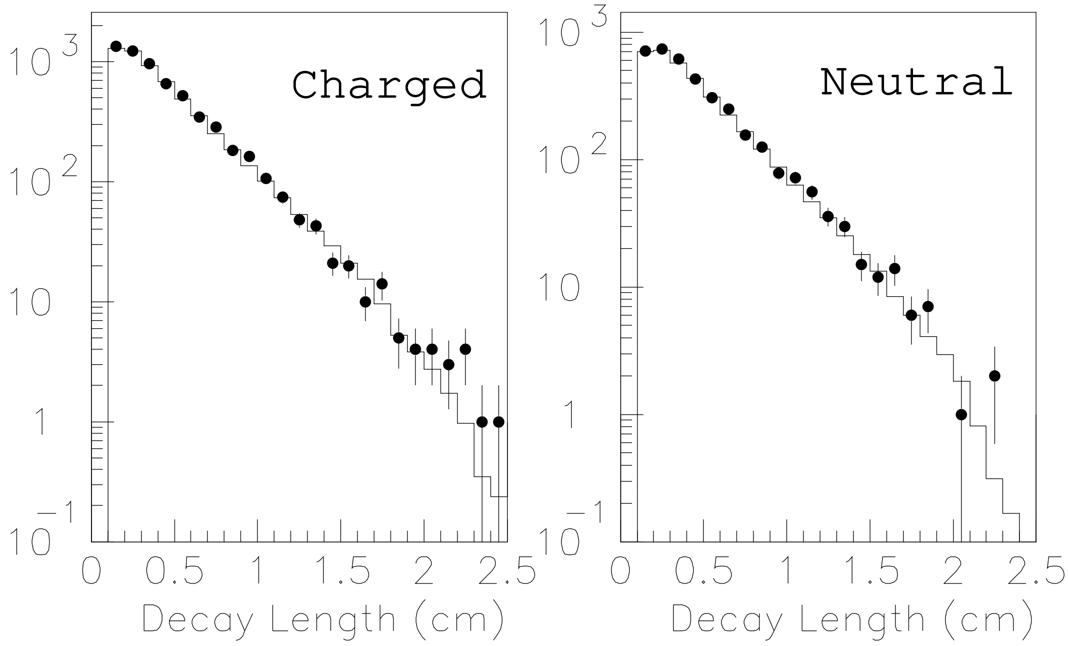

Figure 8: *SLD measurements of the decay length for B^+ and B^0.*

immediately encounter a problem. See [21] for a more thorough review after which this discussion is taken. Measurements by Argus and CLEO at the $\Upsilon(4S)$ give $\mathcal{B}(b \to q\ell\bar{\nu}) = (10.18 \pm 0.40)\%$. At LEP and SLC where besides the B^0 and B^+ accessible in $\Upsilon(4S)$ decays there is also the B_s and b-baryons which should lead to a smaller semileptonic branching ratio. The latest result from LEP and SLC is $(11.06 \pm 0.19)\%$, [22] which is a bit under two standard deviations from the $\Upsilon(4S)$ measure in the opposite direction from the expectation. This is a long standing discrepancy, but I nevertheless forge ahead and calculate V_{cb} using the appropriate average b lifetime:

$$|V_{cb}| = (3.87 \pm 0.21) \times 10^{-2} \ (\Upsilon(4S)) \quad (4)$$

$$|V_{cb}| = (4.14 \pm 0.16) \times 10^{-2} \ (\text{LEP}). \quad (5)$$

These agree better due to the error introduced by the lifetime and other smaller effects and are 4% measures of the matrix element, but the not understood difference between the $\Upsilon(4S)$ and LEP measurements leaves us uncomfortable.

There is another problem in semileptonic B decays. Calculations tend to expect $\mathcal{B}(b \to q\ell\bar{\nu})$ to be 12.5%, and have difficulty accommodating the measurements which are below 12%. One solution, that B's may have a larger than negligible rate to rare processes, is not discussed here, but see Bill Ford's talk at this conference on rare B decays. The more pedestrian solution is that the $b \to c\bar{c}s$ branching fraction is larger than measurements. The common way to check this is to count the number of charm quarks per b decay. This is done by making inclusive measurements of charm rates in b decays. At both LEP and the $\Upsilon(4S)$ these measurements have been done and they yield

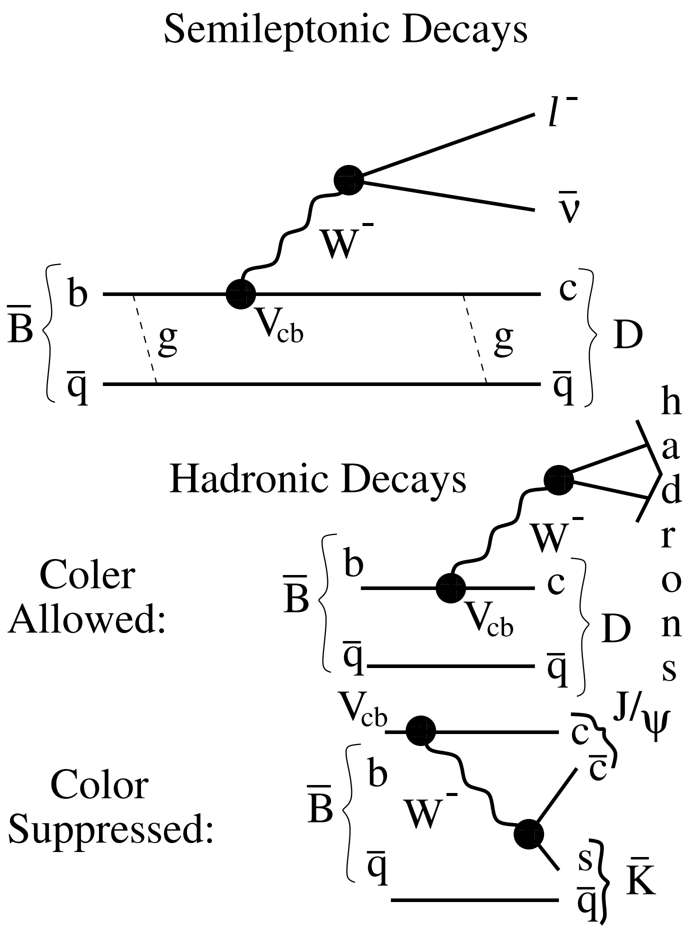

Figure 9: *Feynman diagrams for B meson decays.*

$n_c = 1.202 \pm 0.067$ and 1.119 ± 0.053 respectively, again differing by something like two standard deviations as much of the error is common from charm branching fractions. Both of these are smaller than the value that would lead to a small semileptonic b branching fraction, but the errors are large enough to soothe the discomfort.

A different approach to charm counting in b decays is shown by a recent analysis from DELPHI. [23] Here they take advantage of methods to enhance the heavy flavor content of generic $Z \to q\bar{q}$ events based on track impact parameters first used to measure the $Z \to b\bar{b}$ rate. They find that the probability for the event hemisphere to be a b depends on how many charm quarks the b has decayed to as can be seen in Figure 13. They then fit the observed probability distribution to the various contributions and extract $n_c = 1.147 \pm 0.041$. Unfortunately this does little to clear up the discrepancy as it lies right between the LEP and $\Upsilon(4S)$ measures discussed above, but it does continue to put pressure on the theoretical calculations of $\mathcal{B}(b \to q\ell\bar{\nu})$.

We then turn to exclusive semileptonic decay modes of heavy quark states as a way to extract the CKM matrix elements unambiguously. This field has been transformed by the Heavy Quark Effective Theory (HQET). [24] Briefly HQET treats heavy mesons like the hydrogen atom noting that they both have a heavy core with a light wave function

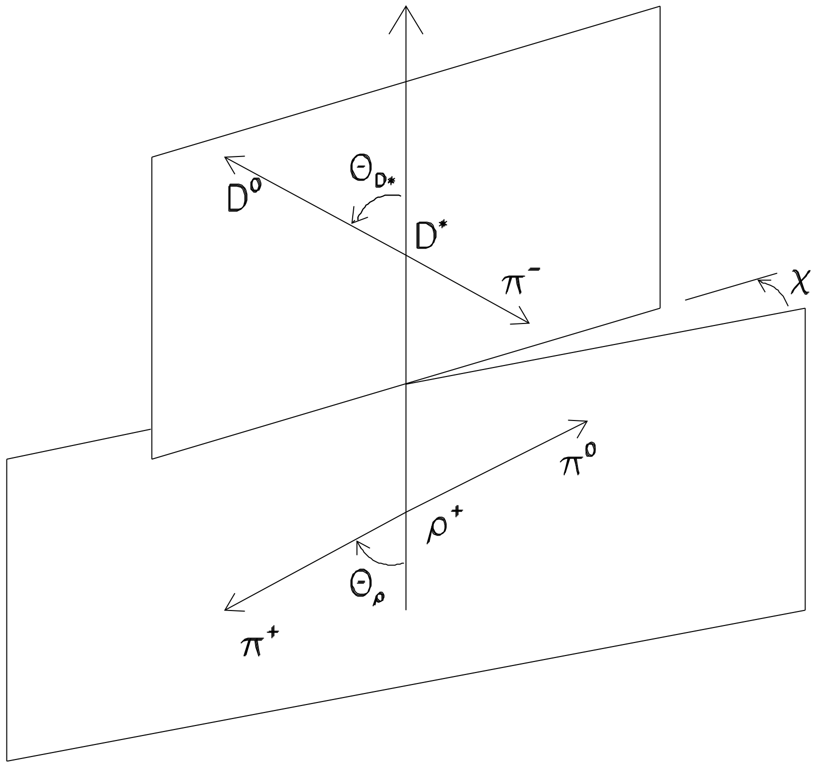

Figure 10: *The three angles, θ_{D^*}, θ_ρ, and χ, which describe the $B \to D^*\rho$ decay.*

bound to it nearly independent of the mass of heavy core. Thus a heavy state to heavy state transition factorizes into a heavy to heavy part, which can be calculated, and a light part, which is universal. Carried to conclusion this implies that there is one universal form factor that describes the dynamics of heavy to heavy transitions and when there is no recoil the overlap of the light part of the wave function before and after the transition, called $\mathcal{F}(1)$, is equal to one. Thus at zero recoil the rate for the heavy to heavy transition has as its only unknown the the relevant CKM matrix element. There are some real world problems. Experimentally zero recoil transitions are the most difficult to observe. The overlap of the light wave functions is only exactly one if the mass of the heavy core is infinite. In the case of the $b \to c$ transition the corrections are of order $\Lambda_{\rm QCD}/m_b$ and have been calculated to give $\mathcal{F}(1) = 0.91 \pm 0.03$ in the case of $B \to D^*\ell\bar{\nu}$ and $\mathcal{F}(1) = 0.98 \pm 0.07$ in the case of $B \to D\ell\bar{\nu}$. At this conference we heard from Aida El-Khadra that lattice QCD calculations expect to much improve the error on the latter number. Finally the universal form factor function is unknown and we use a Taylor expansion around zero recoil.

This formalism has been used at both the Υ(4S) and LEP to analyze the $B \to D^*\ell\bar{\nu}$ and $B \to D\ell\bar{\nu}$ decays and the results are summarized in Table 1 where $\hat{\rho}^2$ is the first parameter of the Taylor expansion of the universal form factor. This V_{cb} is consistent across many experiments giving more confidence in this method. Also that the extracted

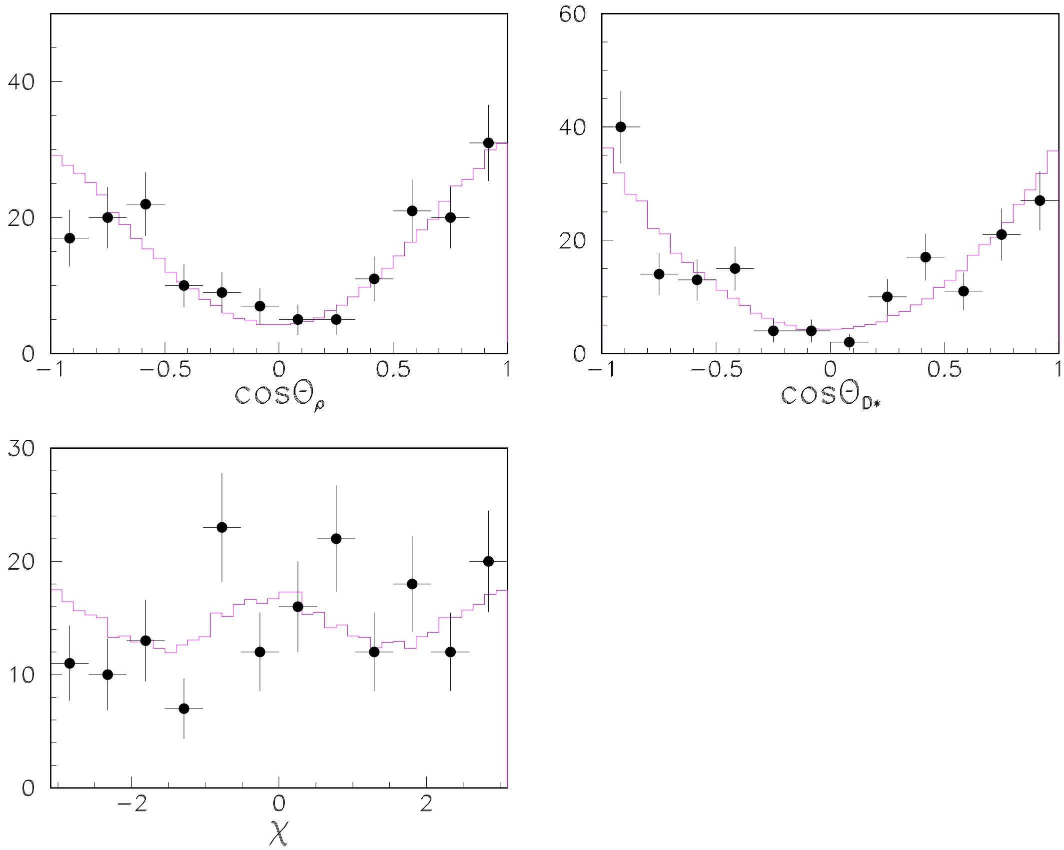

Figure 11: *The CLEO data, dots, and projection of the fit, histogram, to the angular distribution of the* $B^0 \to D^{*+}\rho^-$ *decay mode.*

Table 1: *Summary of exclusive semileptonic* B *decay measures of* V_{cb}*.*

Mode	$\lvert V_{cb}\rvert \times 10^{-2}$	$\hat{\rho}^2$
$B \to D^*\ell\bar{\nu}$	3.87 ± 0.31	0.71 ± 0.11
$B \to D\ell\bar{\nu}$	3.94 ± 0.50	0.66 ± 0.19

Taylor expansion parameter of the universal form factor agrees between the two modes is a confirmation of one of the predictions of HQET.

CLEO has redone the $B \to D\ell\bar{\nu}$ analysis with a different technique. They take correlated $D\ell$ pairs and use kinematics to separate the $D\ell\bar{\nu}$ signal from $D^*\ell\bar{\nu}$, $D^{**}\ell\bar{\nu}$, and non-resonant backgrounds. From this preliminary analysis they extract $\Gamma(B \to D\ell\bar{\nu}) = (14.4 \pm 1.2 \pm 1.4)/\text{ns}$, $\mathcal{B}(B^- \to D^0\ell^-\bar{\nu}) = (2.33 \pm 0.19 \pm 0.24)\%$, $\mathcal{B}(\bar{B}^0 \to D^+\ell^-\bar{\nu}) = (2.25 \pm 0.19 \pm 0.22)\%$, $\mathcal{F}(1)V_{cb} = (4.8 \pm 0.8) \times 10^{-2}$, and $\hat{\rho}^2 = 0.81 \pm 0.17$. These are in good agreement with the averages in Table 1 and are not included in them.

Another test of HQET is to directly measure the form factors in $B \to D^*\ell\bar{\nu}$ by measuring the angular distribution of the decay products. Again if the b and c quarks were infinitely heavy the form factors would be one, but finite mass effects make them deviate from one. CLEO has done this measurement [25] and again the predictions of HQET are in agreement with the data.

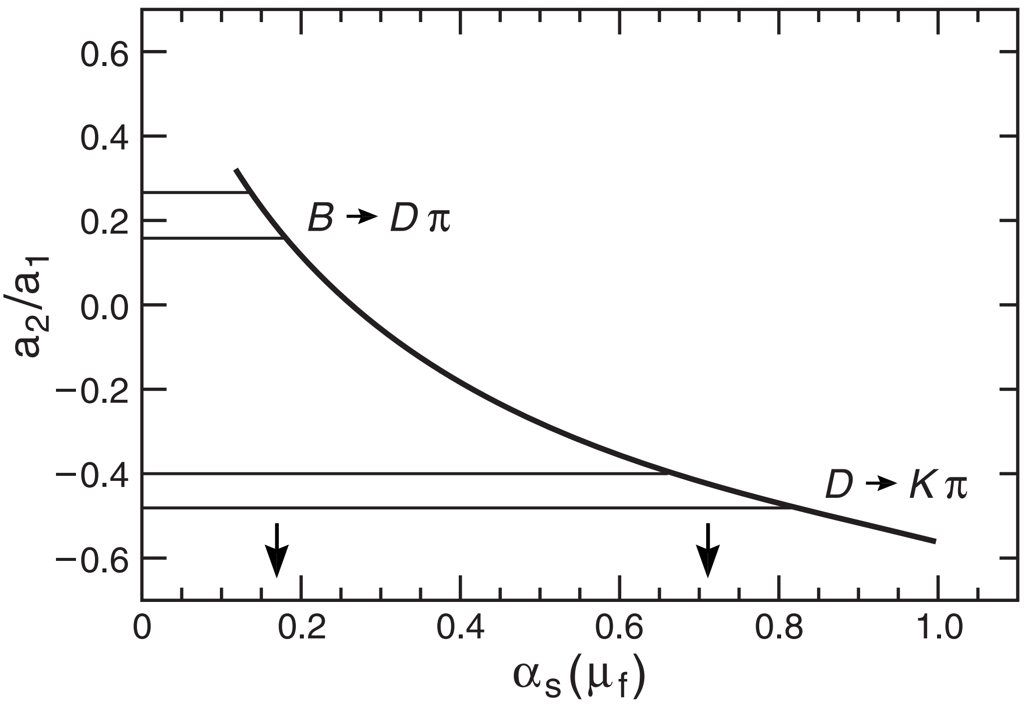

Figure 12: *The relation between the factorization parameters a_1/a_2 and α_s as a function of energy scale. The appropriate scales for B and D decays are indicated.*

This has also been done by Fermilab E791 in $D \to K^*\ell\bar{\nu}$. [26] Figure 14 shows their result. It is clear here that experiment is way ahead of theory. Unfortunately the machinery of HQET has much greater difficulty with the strange quark which is not heavy enough. Thus despite the experimental accuracy shown here the best measures of V_{cs} come from deep inelastic scattering rather than D decays.

6 Conclusion

There are many other new results for which I did not have the time or space to cover. There have been the first statistically limited attempts to observe CP-violation in the B system, [27] a new measurement of B^0 mixing, [28] new measurements of B decays to charmonium, [29] and studies of Cabibbo suppressed D decays. [30] See also Guy Blaylock's presentation at this conference on CP-violation and mixing in the D system.

The next year will see the start of four new experiments dedicated to the study of heavy quarks. BaBar at PEP-II and BELLE at KEKB are asymmetric B factories. CLEO III at CESR-3 is a symmetric B factory. HERA-B at HERA will produce b's in proton collisions on wire targets. All aim to have data sets that are an order of magnitude larger than the existing CLEO data set. Thus many exciting new heavy quark results including but not limited to the observation of CP-violation in the B system can be expected in the near future.

The study of heavy quarks continues to be a driving force in high energy physics. The results reviewed here cover a wide spectrum from the observation of new heavy quark

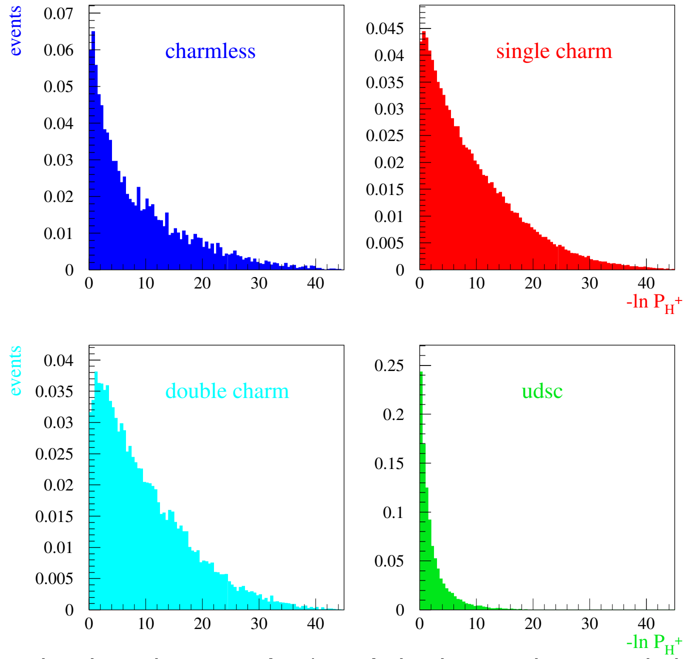

Figure 13: *The distribution of* $-\ln$ *of the hemisphere probability to be a b from the DELPHI simulation for the various processes shown.*

states, measurements of the lifetimes of such states, the first evidence for FSI in B decays, and the continuing attempt to measure elements of the CKM matrix and test HQET by studying the dynamics of inclusive semileptonic decays of heavy quark states. Results such as these continue to be both a vital window on the workings of both the strong and weak interactions and severe tests of theories that have been developed to describe these interactions. Such interplay will only grow more dynamic in the near future.

7 Acknowledgments

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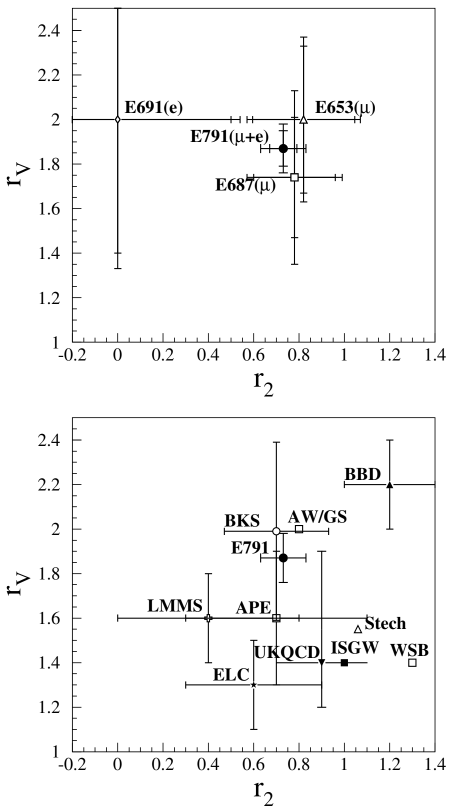

Figure 14: *Comparison of the experimental measure of the form factor ratios r_V and r_2 in $D \to K^* \ell \bar{\nu}$ from E791 with other experiments and with theoretical predictions. The top plot compares the experiments and the bottom compares the E791 measurement with predictions.*

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