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HEAVY FLAVORS

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Abstract

Recent results on Heavy Flavor decays are reviewed. Many new results on rare decays, primarily from the B-Factory experiments *BABAR* and Belle are presented. Decays are classified according to their hadronic structure, and the theoretical issues surrounding the strong interaction effects are discussed. Special attention is given to more theoretically clean measurements.

1 Introduction

The organizing concept most commonly used to summarize our understanding of heavy quark and lepton decays is the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix.[1] The Wolfenstein parameterization's expansion in powers of $\lambda = 0.22$ describes the hierarchy of weak decay processes, and the unitary triangle connecting V_{ub} and V_{td} provides a way to compare B decays, B^0 and B_s mixing, and CP violation measurements. While the weak interaction is the focus of most heavy flavor measurements, in general, effects of the strong interaction cannot be ignored. Even in those few cases where hadronic uncertainties are small, this knowledge comes from an understanding of strong interaction effects. The current experimental limits on the unitary triangle, Fig. 1, make this plain; except for the $\sin 2\beta$ and $\sin 2\alpha$ measurements the allowed regions are dominated by hadronic uncertainties.

Instead of the CKM matrix, let us use the strong interaction structure as an organizing principle for heavy flavor decays. Considering the structure of strong interaction effects, we divide the subject into decays with two hadronic currents, decays with one hadronic current, and decays without hadronic currents. These are non-leptonic, semi-leptonic, and leptonic decays respectively. The effect of hadronic matrix elements on meson mixing is somewhat different; that subject is treated as a fourth topic.

Recent results from the B-factory experiments *BABAR* and Belle, the charm experiments CLEO-c and BES, and from the Tevatron experiments CDF and D0 are presented. In this review, we focus primarily on rare decays and omit

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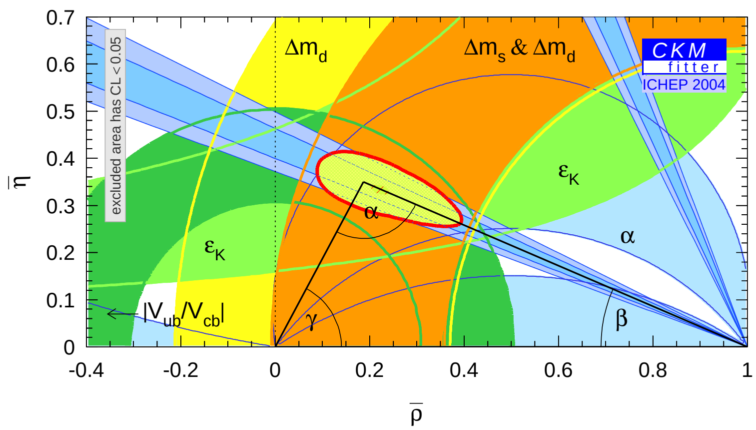

Figure 1: Current constraints on the unitarity triangle of the CKM matrix, from Ref.[2].

a number of other interesting topics. Unfortunately, we will not be able to discuss any of the numerous results concerning the $b \to c$ transition or any of the new results in D_s, B_c or Υ spectroscopy. Finally, the Heavy Flavor Averaging Group[3] summarizes the most recent results for all of the topics discussed in this review, and is an invaluable resource.

2 B Meson Decays with Two Hadronic Currents

2.1 Theoretical tools

Two of the theoretical tools used to understand heavy flavor non-leptonic decays are factorization and the operator product expansion. In the QCD-factorization model of Neubert and collaborators[4], the matrix element for B meson decay into two mesons is factorized as:

$$\begin{aligned} \langle M_1' M_2' | Q_i | \bar{B} \rangle = \sum_{\{M_1, M_2\} \in \{M_1', M_2'\}} & F_j^{B \to M_1} T_{ij}^I * f_{M_2} \Phi_{M_2} \\ & + T_i^{II} * f_B \Phi_B * f_{M_1'} \Phi_{M_1'} * f_{M_2'} \Phi_{M_2'} \end{aligned} \quad (1)$$

where the first term is the naive factorization model[5] and the second term includes the leading $\sim 1/m_B$ contribution from hard gluon exchanges. The components in the leading term in Eqn. 1 are a form-factor $F^{B \to M_1}$ unique to meson M_1, a transition matrix element $T_{M_1 M_2}$ containing the 4-quark operator, a meson decay constant f_{M_2}, and a light-cone wave-function ϕ_{M_2}. The matrix elements, describing the weak interaction and short-distance physics between the 4 quarks, are calculated using the operator product expansion (OPE).[6] In the OPE expansion each term has a different Lorentz and color structure, and the short-distance physics, from W propagators, t-quark loops, and their QCD

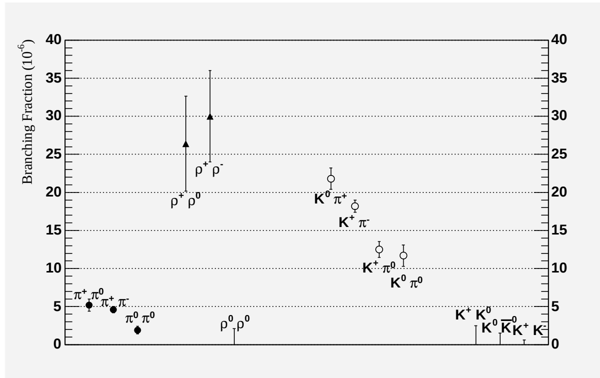

Figure 2: Summary of branching fraction measurements for a selection of charmless two-body decays, averaged from measurements by *BABAR* and Belle.[3]

corrections, are contained in a Wilson coefficient. The corresponding 4-quark operators $\mathcal{O}_i$ are then factorized into the appropriate form-factor and decay constant terms. Finally, the sub-leading term in Eqn.1, describing the hard gluon exchange between the two mesons, is parameterized in terms of a second matrix element and the relevant decay constants.

In contrast to the factorization approach, in the diagrammatic approach the amplitude for non-leptonic B decays is written directly as the sum of various diagrams.[7] The relative importance of tree, penguin, color-suppressed tree, exchange, annihilation, and electro-weak penguin amplitudes are guided by both theoretical calculations and experiment, but calculations are made in terms of model-dependent diagrammatic parameters. Both isospin and SU(3) symmetries are employed to relate various parameters, and the parameters for each diagram are ultimately derived from measurement. One advantage of the diagrammatic approach is that it allows rule-of-thumb estimates for amplitudes.

2.2 Charmless two-body B decays

Decays of the B-meson to two light pseudo-scalar mesons are the simplest case of charmless non-leptonic decays, and are of great interest both for the study of B-decays and for *CP* violation. The current experimental data is summarized in Fig. 2.

There are a number of fits in the recent literature, to the branching fractions and asymmetries for $B \to \pi\pi$ and $B \to K\pi$. For example a fit using the QCD-factorization analysis as a model cannot reproduce the data without large non-factorizable contributions[2], while diagrammatic fits match the data with large color-suppressed tree contributions[8]. The conclusion in these and other analyses that QCD-factorization does not quantitatively reproduce the data is an important, although perhaps backward, step in understanding

B-meson decays. While the phenomenological analyses may fit the data, it is not obvious that it will be possible to distinguish among various explanations for the breakdown of factorization, such as charming penguins[9], non-factorizable annihilation graphs, large color-suppressed tree amplitudes, or final state rescattering[10], from measurements.

These theoretical difficulties may be avoided in certain ratios of branching ratios. Now there are two interesting ratios of $B \to K\pi$ rates measured with better than 10% precision. The Lipkin ratio [11]

$$R_L = 2\frac{\Gamma(B^+ \to K^+\pi^0) + \Gamma(B^0 \to K^0\pi^0)}{\Gamma(B^+ \to K^0\pi^+) + \Gamma(B^0 \to K^+\pi^-)} \approx 1 + \mathcal{O}(\{T + P_{EW}\}/P)^2 \qquad (2)$$

should be equal to one to within a few percent, and thus is sensitive to new physics effects[12]. New results on both branching fractions from *BABAR* and Belle now yield a ratio $R_L = 1.12 \pm 0.07$, consistent with the expectation. Next, the Fleischer-Mannel ratio[13]

$$R_{FM} = \frac{\Gamma(B^0 \to K^+\pi^-) + \Gamma(\overline{B}^0 \to K^-\pi^+)}{\Gamma(B^+ \to K^0\pi^+) + \Gamma(B^- \to \overline{K}^0\pi^-)} \qquad (3)$$

bounds the value of $\cos\gamma$ if the ratio is less than one. The current value of $R_{FM} = 0.82 \pm 0.06$ bounds the unitarity triangle angle $\gamma < 75^0$ at the 95% confidence level. This constraint is in accord with the preferred unitarity triangle region.

In addition, there is a striking difference in the pattern between the $\pi\pi$ decays and the $\rho\rho$ decays. In the naive factorization picture we would expect the observed ratio

$$\frac{\mathcal{B}(B^0 \to \rho^+\rho^-)}{\mathcal{B}(B^0 \to \pi^+\pi^-)} = 6.5 \pm 1.5 \qquad (4)$$

to be given by the ratio of decay constants and form-factors, or roughly a ratio of 4.4, which is a reasonable match to the data. On the other hand the ratio of rates

$$\frac{\Gamma(B^0 \to \rho^0\rho^0)}{\Gamma(B^+ \to \rho^+\rho^0)} << \frac{\Gamma(B^0 \to \pi^0\pi^0)}{\Gamma(B^+ \to \pi^+\pi^0)} \qquad (5)$$

are much different. The diagrammatic analyses[8] fit the large $B^0 \to \pi^0\pi^0$ rate as coming from both the $b \to d$ penguin and the color suppressed tree amplitudes. Why isn't a similar enhancement seen in $B^0 \to \rho^0\rho^0$? In the operator product expansion, there are two gluonic penguin operators $\mathcal{O}_4$ and $\mathcal{O}_6$. Both contribute, with roughly equal Wilson coefficients, to decays to two pseudoscalars, but only the $\mathcal{O}_4$ operator is present for decays to two vectors. Even without a large penguin contribution, a color-suppressed tree amplitude as large as in the $B^0 \to \pi^0\pi^0$ case enhanced by the large ratio of decay constants and form-factors would yield a value of $\mathcal{B}(B^0 \to \rho^0\rho^0)$ larger than is observed. More detailed theoretical effort on the $B \to \rho\rho$ decays is clearly needed. Lastly, the isospin relations for the $\rho\rho$ decays demand that the ratio

$$\frac{\Gamma(B^+ \to \rho^+\rho^0)}{\Gamma(B^0 \to \rho^+\rho^-)} = 0.81 \pm 0.26 \qquad (6)$$

be equal to 0.5. Better measurements will provide a necessary test for isospin-breaking amplitudes, such as electro-weak penguins.

2.3 Polarization in B decays to two vectors

Decays of the B into two spin-one particles, or vectors, have an additional observable, the polarization of the final state. In this case, there are three possible polarizations, where both mesons have helicity zero (longitudinal), plus one or minus one (transverse). The polarization may be determined from the angular distributions, as

$$\frac{d^2\Lambda}{d\cos\theta_1 d\cos\theta_2} \sim \frac{1}{4}(1-f_L)\sin^2\theta_1\sin^2\theta_2 + f_L\cos^2\theta_1\cos^2\theta_2 \qquad (7)$$

where the angles θ_1 and θ_2 are the helicity angles of the vector mesons, and f_L is the longitudinal polarization fraction. For B decays into two light vector mesons, the expectation had been that the longitudinal polarization would dominate. For either tree or gluonic penguin amplitudes, the amplitude may be expressed as $(V-A)\times(V-A)$. In this case, the final state quarks will be left-handed, and anti-quarks will be right-handed. Opposite helicity quarks are suppressed by a factor of m_V/m_B, the typical helicity suppression factor. Note that the spectator quark may adopt any helicity to conserve angular momentum. Thus, the longitudinal polarization has no mass suppression, but the transverse polarization amplitude is suppressed as $\sim m_V/m_B$, where m_V is the mass of the vector meson. This is the observed pattern for $B^0 \to \rho^+\rho^-$, where *BABAR* and Belle observe an average polarization of $f_L = 0.99\,^{+0.05}_{-0.04}$.

Results from *BABAR* on the polarization of $B^0 \to \phi K^{*0}$ are shown in Fig 3, where the decay distribution angles are shown. Both longitudinal and transverse polarizations are clearly present, and the current average from *BABAR* and Belle is $f_L = 0.52 \pm 0.042$. This decay is presumed to occur solely through a gluonic penguin amplitude, so a longitudinal polarization fraction close to one was also expected. Attempts to explain the observed polarization fraction of 0.5 have invoked non-factorizable annihilation amplitudes[15], chromodipole amplitudes[16], and new physics[12]. Understanding the large transverse polarization in ϕK^* will continue to be a theoretical challenge.

3 B Meson Decays with One Hadronic Current

Next let us consider B meson decays with a single hadronic current. Decays of this kind include $B \to X\ell\nu$, $B \to X\gamma$, or $B \to X\ell^+\ell^-$, where X is a hadronic system. Here, of course, the leptonic or photonic current does cleanly factorize from the hadronic current, making them simpler to understand theoretically than the two hadronic current case. In addition, exclusive decays can be studied with lattice QCD techniques, something not currently possible with two hadronic current decays.

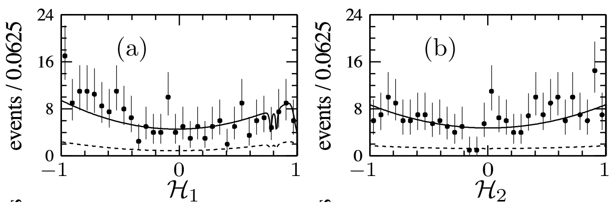

Figure 3: Helicity angle distributions for ϕ and K^{*0}, where $\mathcal{H} = \cos\theta$, for $B^0 \to \phi K^*0$ decays from *BABAR* [14]. The dotted lines are the background contribution.

3.1 Shape function

However, all the one hadronic current decays suffer from a common non-perturbative contribution which is analogous to the Fermi motion of the b-quark inside the B meson. This extra momentum, or shape function, smears out the leptonic or photonic current, and must be taken from experiment. A recent Belle result measuring the photon energy in inclusive $B \to s\gamma$ decays is shown in Fig 4a. This distribution may be used to fit a parameterization of the shape function, and the shape function can then be used, at leading twist, in the description of the $B \to X\ell\nu$ decay[17].

3.2 Inclusive decays

All the decays with one hadronic current may be observed exclusively, with the final state hadrons seen in particular mesons, or inclusively, integrated over many possible mesons. Fully inclusive measurements are closer to the quark final state, assuming quark-hadron duality, while exclusive decays require a final state form-factor, from lattice QCD for instance. The common wisdom has been that exclusive decays are easier experimentally, with smaller backgrounds and better understanding of the detection efficiency. However, recent results from *BABAR* and Belle, using new techniques possible with their large datasets, are changing this situation.

Starting with fully inclusive measurements, Belle's new result for inclusive $b \to s\gamma$ and *BABAR*'s new result for inclusive $b \to u\ell\nu$ are shown in Fig 4. In both cases there are large continuum backgrounds, subtracted with off-resonance data, and B-related backgrounds, that are subtracted using simulations. Both experiments have large off-resonance data samples and detailed simulations with good models of B decays, permitting background estimates with reasonable statistical and systematic errors.

3.3 $|V_{ub}|$

A new method, used by both *BABAR* and Belle, uses a sample of exclusively reconstructed B decays, in states $B \to D^{(*)}\, n\pi^{\pm}\, mK^{\pm}\, qK^0_S\, p\pi^0$, as a way to

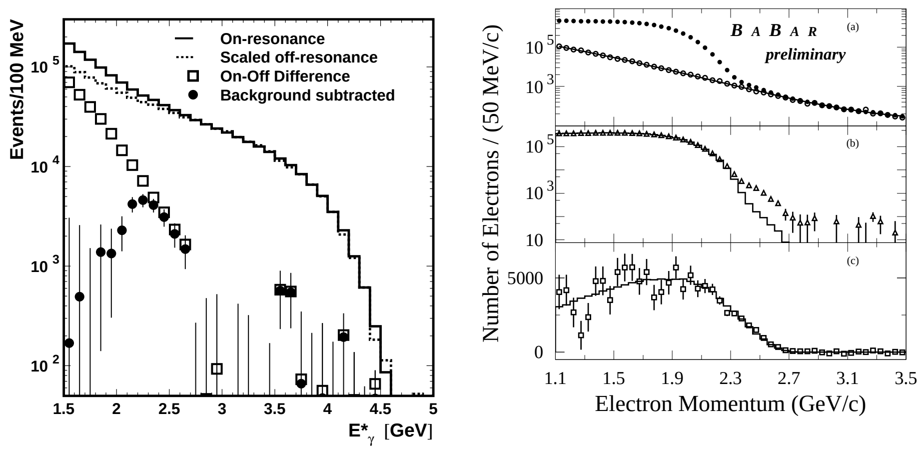

Figure 4: a) Belle's measurement of inclusive $b \to s\gamma$ [18], and b) *BABAR*'s measurement of inclusive $b \to u\ell\nu$ [19].

study a sample of inclusive B in the *recoil* of the reconstructed B. Fig. 5a shows the large sample of reconstructed B's, for events with a high momentum lepton. This sample is used to detect $b \to u\ell\nu$, as shown in Fig 5b, with very good signal to background. The theoretical uncertainties in such inclusive measurements, mainly associated with the shape function, are a topic of much current interest.

Values of $|V_{ub}|$ from this measurement, as well as other inclusive measurements, cluster around $|V_{ub}| \sim 4.7 \times 10^{-3}$, as summarized in Fig. 6. Previous measurements using exclusive modes, from CLEO, *BABAR*, and Belle, cluster around $|V_{ub}| \sim 3.2 \times 10^{-3}$. Both sets of measurements have systematic errors, mostly theoretical, around 0.5×10^3. While experimental systematics may play a role, the most likely source of this discrepancy is the theoretical understanding of these decays. The use of experimentally derived shape function parameters[21] may help the inclusive measurements, while exclusive results will depend on better form-factor calculations.

3.4 Electroweak penguin decays

The electroweak penguins decays, $b \to s\gamma$ and $b \to s\ell^+\ell^-$, like the semi-leptonic decays also are affected by shape function uncertainties. In addition, higher order corrections or the renormalization of the operator product expansion, are a large effect in the width for these decays. The current measurements of branching fractions for exclusive decays $B \to K^*\gamma$ agree with calculations, although the theoretical errors are large. The recent Belle measurement of the inclusive $b \to s\gamma$ rate agrees well with the calculations, and the experimental error is of the same order as the theoretical uncertainty. The current *CP* asymmetry measurements are consistent with zero, which constricts some new physics models.

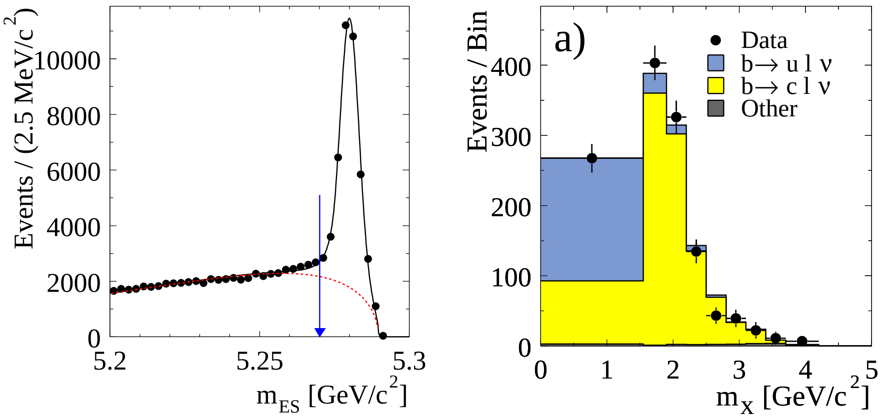

Figure 5: *BABAR*'s measurement of inclusive $b \to u\ell\nu$ using the recoil method[20]: a) the exclusively reconstructed B's energy-substituted mass, b) the m_X distribution

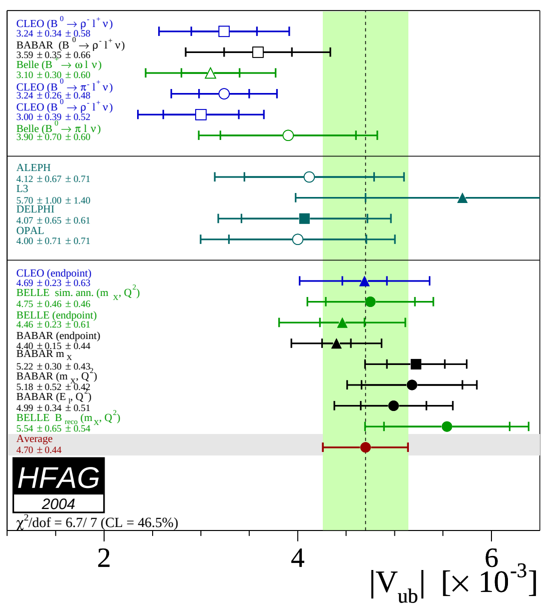

Figure 6: Summary of $|V_{ub}|$ measurements.

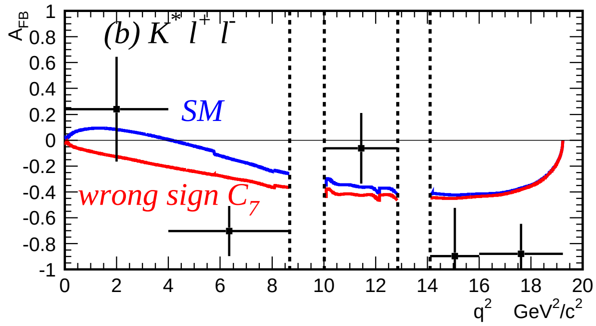

Figure 7: Belle's measurement of the forward-background asymmetry in $B \to K\ell^+\ell^-$ events [22]

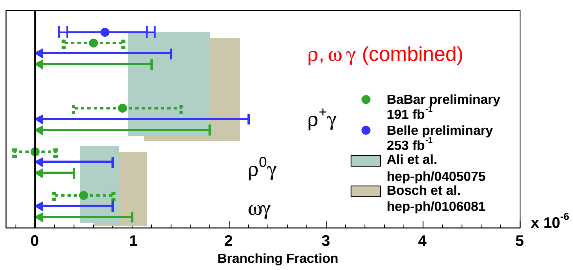

Figure 8: Summary of limits on searches for $b \to d\gamma$ decays. Dotted points reflect central values, solid lines the 90% C.L. upper limits

There are new results for $b \to s\ell^+\ell^-$, including measurements of the kinematics and forward-backward asymmetry for these decays, as shown in Fig 7. This asymmetry will be an especially good way to search for new physics affects.

There are new searches for decays $B \to \rho\gamma$ and $B \to \omega\gamma$, sensitive to the ratio $(|V_{td}|/|V_{ts}|)^2$. The current status of these decays is shown in Fig 8, where the current limits from *BABAR* and Belle have reached into the expected range of values. With theoretical errors from Ref.[23], the constraint on the unitarity triangle from these limits is comparable to the current limits from B_s mixing.

4 B and D Meson Decays with No Hadronic Currents

Next, we consider purely leptonic decays of both B and D mesons. With no final state hadrons, the strong interaction physics is contained in a single meson decay constant, making these the simplest decays to understand theoretically. The

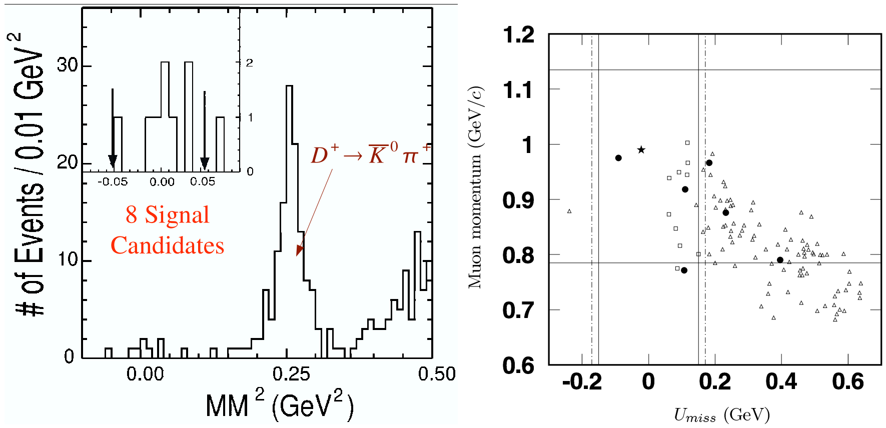

Figure 9: CLEO-c[24] and BES[25] results on the decay $D^{\pm} \to \mu^{\pm}\nu_{\mu}$.

CDF and D0 experiments searched for the decays $B \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-$. No signal was seen, and limits for the B_s decay were set at $\mathcal{B}(B_s \to \mu^+\mu^-) < 3.8(5.8) \times 10^{-7}$ from D0 (CDF). This decay and the process $b \to s\ell^+\ell^-$ are sensitive in very similar ways to new physics models, as may be expected from the similarity of their Feynman diagrams.

The meson decay constants can be directly measured from the decay rate into leptonic final states. The CLEO-c and BES experiments have searched for the decay $D^{\pm} \to \mu^{\pm}\nu_{\mu}$, using $D^{\pm}$ from the $\psi(3770)$, as shown in Fig. 9. The CLEO-c experiment observed 8 signal candidates, with a background of one event, corresponding to a decay constant of $f_{D^+} = 201 \pm 41 \pm 17\,\mathrm{MeV}$.

5 B_s Meson Mixing and Lifetimes

Both meson mixing and lifetime measurements fall somewhat outside the zero, one, or two, hadronic current classification. Like the leptonic decays, the mixing rate depends on the meson decay constants. They also depend on additional hadronic factors, describing how the quarks are contained in the meson. Not surprisingly, these hadronic uncertainties may be partially cancelled in ratios such as $\Delta m_{B_s}/\Delta m_{B_d}$. While the Tevatron experiments will require data samples of order $2\,\mathrm{fb}^{-1}$ to observe B_s mixing, there is a new measurement of the B_s lifetime difference, between long and short-lived B_s'es. The decay time distribution for B_s, from CDF, is shown in Fig. 10. A value for the lifetime difference of $\Delta\Gamma/\Gamma = 0.65^{+0.25}_{-0.33} \pm 0.01$ps was found. This value is consistent with the expected value at roughly the 2σ level.

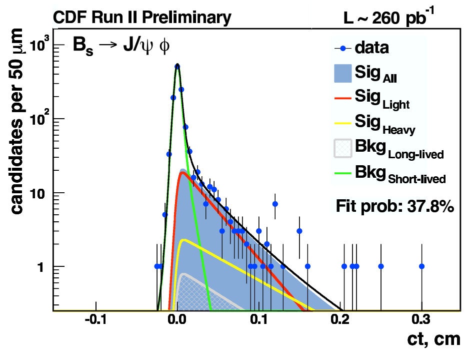

Figure 10: Decay time distribution for $B_s \to J/\psi\,\phi$ from CDF.

6 Conclusion

Heavy flavor physics is currently the subject of intense experimental and theoretical activity. In this review of rare B and D decays, I have separated measurements according to their hadronic structure. One common theme is that the precision of many of the experimental measurements is at or better than the level of the theoretical errors or understanding. Thus those measurements, exploiting ratios, asymmetries, or polarization, that cancel or reduce theoretical uncertainties are well suited for exploring the weak interaction, via the unitarity triangle, or for searching for new physics. The field of heavy flavor physics is so rich that there are many such examples.

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