Chapter 1

Sketch of the Analysis

We try to orient the reader by providing a preview of the rest of this document, including a brief survey of the relevant physics topics and an overview of the analysis itself.

1.1 Particle Physics

The Standard Model provides a nearly complete description of physics at the scale of elementary particles, describing three of the four fundamental interactions in the framework of relativistic quantum field theory, the combination of special relativity and quantum mechanics appropriate for the regime of high energies and small distances.

In this framework, matter is made of particles known as fermions, which are divided into two categories: quarks (which do interact via the strong interaction) and leptons (which do not). Essentially all of the naturally-occurring matter on our planet (and in the universe) is composed from only two kinds of quarks (u and d) and one kind of lepton (e). But our understanding of the fundamental forces has greatly benefited from studying the entire set of fermions, which in turn tests our theories of ordinary matter.

The predominance of the lightest quarks and leptons that we observe in the universe today has not always been the case. In fact, most cosmological models predict the creation of equal amounts of matter and antimatter in the Big Bang, a proportion that astronomical observation has shown no longer holds today. One ingredient in the explanation for the disappearance of antimatter is a mechanism called CP violation, but in the Standard Model, the predicted magnitude of this effect is not sufficient to account for the observed deficit. By creating and studying the lesser-known quarks and leptons and their antiparticle partners in the laboratory, particle physicists hope to learn the answers to this mystery and other equally fundamental questions.

1.2 The $b \to u \ell \nu$ Decay

One feature of the Standard Model is a phenomenon called "flavor change," in which a quark of one particular type (or flavor) can change into another by emitting the (charged) force carrier of the weak interaction. Fig 1.1 illustrates an example of one such transition, where a b quark decays into a u quark and a W boson. The focus of this analysis are those decays where the W subsequently decays into an $(\ell\ \nu_\ell)$ pair, as shown.

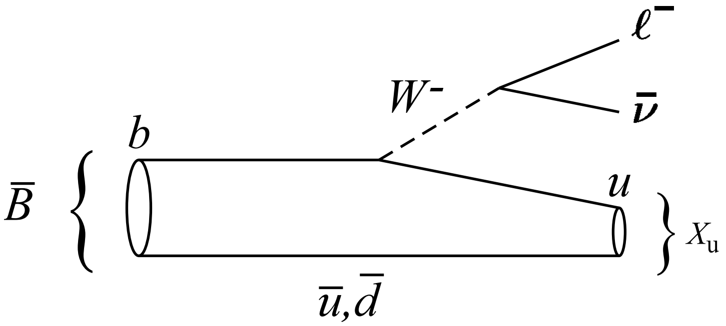

Figure 1.1: Feynman diagram for $b \to u\,\ell\,\nu$ decay. A b quark embedded in a $\overline{B}$ meson decays weakly into a charged W^- boson and a light u quark. Subsequently, the W may decay into a lepton and neutrino. In this Feynman diagram and others like it, time runs from left to right, and the orthogonal coordinate describes spatial separation.

The amplitude for $b \to u$ decay is proportional to the size of a parameter known as V_{ub}, one element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix that governs the general changing or "mixing" of quark flavors. Many experimental and theoretical constraints allow for the implicit determination of the nine elements of this matrix with reasonable accuracy, but at present, V_{ub} remains one of the parameters that is least well-constrained by direct measurement. An excellent avenue for improving knowledge of its magnitude, $|V_{ub}|$, is through direct study of $b \to u$ decays as they occur in the the B meson system, particularly when the short-lived W decays leptonically as shown above. As a convenient short-hand, we label such decays as simply $b \to u\,\ell\,\nu$. An outstanding challenge in these kinds of experimental measurements, however, is the identification of the $b \to u\,\ell\,\nu$ decays amongst the backdrop of an enormous number of other channels for B decay. A final hurdle is that subsequent extraction of $|V_{ub}|$ itself is further plagued by large theoretical uncertainties, some of which are fundamentally unquantifiable.

The chief complication is that quarks are bound by the strong force into particles known as hadrons, and do not occur "bare" in nature. The binding involves the exchange of very "soft" or low-momentum gluons, the force carriers of the strong interaction. At CLEO, for instance, the b quark is always bound to another "spectator quark" ($\bar{u}$ or $\bar{d}$) to form a particle called the B meson. Similarly, this property of quark "confinement" forces the u quark born in the b decay to bind with other quarks to form a complex, generally multi-particle hadronic system, denoted generically as X_u in the figure. The $b \to u$ decay of interest is thus deeply entangled with—even obscured by—the strong physics of quark binding. These bound-state effects greatly complicate the theoretical analysis of $b \to u\,\ell\,\nu$ decays, and makes the problem of extracting $|V_{ub}|$ from experimental measurements nearly intractable.

Recent progress on the non-perturbative strong physics has been made with the development of a rigorous framework known as Heavy Quark Effective Theory (HQET). This analysis provides a systematic way of organizing calculations into an expansion in powers of $1/M_B$, with unknown parameters introduced at every order. It is generally believed that these parameters are universal across all B decays, and so can be determined with input from other experimental measurements. The formalism benefits from tying predictions to the underlying theory of QCD in a well-defined way, and provides for the first time a structure for evaluating many of the uncertainties typically overlooked or ignored when using phenomenological models.

1.3 Relevance of Weak Annihilation

Within the HQET framework, the $b \to u\,\ell\,\nu$ decay can be expanded as a series of operators that contain various combinations of the quark fields and parameters that encapsulate the non-perturbative physics. While the infinite expansion is formally sufficient for the calculation of all inclusive observables,[1] practical treatments are necessarily reduced to including only the first few terms. The neglected terms are then treated as corrections to the leading or next-to-leading predictions for decay rates and spectra.

One of the operators that arises at third order ($1/M_B^3$) in the expansion describes an effective interaction known as "weak annihilation," a contribution roughly analogous to the purely leptonic decay $B^\pm \to \ell^\pm\,\nu_\ell$. In that simpler decay, the two partner quarks inside the B meson annihilate into a W which again decays into a lepton and neutrino. In the more complicated hadronic environment of a $B \to X_u\,\ell\,\nu$ transition, however, the contributions from annihilation processes are more difficult to control theoretically, due to irreducible strong interactions between the "annihilating" pair of quarks and the remaining quarks and gluons, making evaluation of the weak annihilation term an outstanding problem.

Traditional calculations of $b \to u\,\ell\,\nu$ neglect the contribution of weak annihila-

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[1] An inclusive measurement focuses only on the details of the lepton and neutrino, summing over all possible X_u final states. The theoretical motivation for this concept is the idea of quark-hadron duality, the notion that when a sufficient number of hadronic final states are included in the measurement, calculations at the quark level should accurately describe the real physics, albeit with non-perturbative corrections as specified by the HQET expansion. The irreducible bound-state effects of each particular resonance X_u become insignificant—in some sense, they "average out" in the consideration of a nearly exhaustive list of possible final states.

tion by truncating the operator expansion at lower order. Predictions for experimental spectra and even methodologies for the extraction of $|V_{ub}|$ are thus subject to an additional uncertainty due to the neglect of this term (and indeed, many others) in the heavy quark expansion. Since the uncertainty is itself difficult to quantify on either the phenomenological or experimental fronts, measurements of $|V_{ub}|$ in B decays are subject to an unknown uncertainty related to weak annihilation effects.

The goal of this analysis is to take one small step on the road toward a precision measurement of $|V_{ub}|$. Our contribution is an attempt to quantify or otherwise constrain the magnitude of weak annihilation effects, especially with regard to the inclusive measurements of $b \to u\,\ell\,\nu$ used to determine $|V_{ub}|$.

The general kinematic features of weak annihilation make it clear that its contribution will be concentrated near the kinematic endpoints of the lepton energy and q^2 spectra. We explore this region for evidence of weak annihilation effects by comparing the spectrum observed in data with a carefully crafted cocktail of simulated data samples that includes a standard leading-order description of the $b \to u\,\ell\,\nu$ rate but that also, for the first time, allows for a possible contribution from weak annihilation. Since there is no clear prediction for the size or extent of weak annihilation effects, we instead attempt to map out the *relationship* between the standard $b \to u\,\ell\,\nu$ rate as typically modeled and potential contributions from weak annihilation. Ultimately, the true $b \to u\,\ell\,\nu$ rate is given by the sum of both contributions, so we quantify our results as a bound on the error made by neglecting the weak annihilation term.

1.4 The Analysis

The analysis uses a sample of B decay events culled from an enormous sample of B decays collected from electron-positron (e^+e^-) collisions at the Cornell Electron Storage Ring, located at the edge of the Cornell University campus in Ithaca, NY. Special criteria devised for this analysis are used to select the events that are likely to have proceeded specifically along the $B \to X_u\,\ell\,\nu$ channel. The selection is designed to be as inclusive as possible, including all possible hadronic systems X_u, and focuses chiefly on the properties of the characteristic lepton and neutrino.

Although we observe the lepton from the B decay directly, we are limited to deducing information about the neutrino based on other observables in the event, since it has vanishingly small probability for interacting with any of the active elements of our detector. Although the neutrino escapes entirely undetected, it carries away some portion of the initial momentum and energy and is thus made visible by its absence. By carefully examining everything else in the event that was detected, we compute the “missing” energy and momentum, and thus infer the neutrino direction and energy.

In order to study and understand the physics and backgrounds of this analysis, we need an accurate and complete simulation of $b \to u\,\ell\,\nu$ decays. Inclusive calculations are correct only in an average sense, however: their faithfulness to the real world only holds when looking on sufficiently coarse scales, above the $\mathcal{O}(100)$ MeV level. In answer to this need, we've developed a "hybrid" Monte Carlo generation package that combines aspects of known exclusive states with the more general requirements imposed by the inclusive theory. This software simulation tool gives us a realistic picture of how the signal decays might appear in the real world.

Although there are no detailed phenomenological predictions for weak annihilation, we employ a simple model that evinces the broad features expected of the process. By widely varying the parameters of this model, we generate a series of possible manifestations of weak annihilation in the $b \to u\,\ell\,\nu$ data sample. Armed with knowledge of the different sources expected to contribute to an observed spectrum, we apply a fitting procedure to determine the relative contributions from the dominant $b \to c\,\ell\,\nu$ background, the $b \to u\,\ell\,\nu$ signal as ordinarily modeled, and our model of weak annihilation. In this fashion, we develop a data-driven estimate of the size of weak annihilation effects, over a broad range of possible weak annihilation scenarios.

Ultimately, we measure a contribution from weak annihilation that is statistically consistent with zero, and set an upper limit on the relative importance of these effects in modeling (and measuring) inclusive $b \to u\,\ell\,\nu$.

1.5 Organization of the Document

The chapters that follow break the analysis into smaller pieces, and are organized as follows. Chapter 2 tries to provide a context for the analysis program as a whole, and then briefly reviews the Standard Model, the physics of the weak sector, and the decay of the B meson. This chapter, rather conversational in style, marks the transition from armchair generalities about particle physics to the more detailed discussion in subsequent chapters of the particulars of this analysis.[2] Chapter 3 provides a more in-depth discussion of the phenomenology of $b \to u\,\ell\,\nu$ decays, with an emphasis on what the current theoretical challenges are in this area. Chapter 4 describes in broad strokes the experimental facilities with which the data were collected.[3] The next chapter (Ch 5) outlines the analysis technique in detail, focusing on the preparation of a data sample expected to be rich in $b \to u\,\ell\,\nu$ with well-understood efficiencies and errors. Chapter 6 begins with a description of a model for weak annihilation, and then describes how the data

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[2] As such, Ch 2 may exhaust the casual reader, to whom I address the following: it won't get any better if you keep reading, and no, we didn't see anything interesting.

[3] The CLEO-aware reader is encouraged to skip these three chapters (Ch 2–4) and head directly to Ch 5; do not pass Go, do not collect $200.

were analyzed for the extraction of a limit on the contribution of this process to other measurements of $b \to u\,\ell\,\nu$. Chapter 7 covers sources of systematic error and how the sensitivity to each was translated into a quantitative uncertainty estimate. The last chapter wraps things up with a terse summary of the analysis and a look at things to come. Finally, a few appendices in the back explain more fully some of the tools and algorithms developed for the analysis.