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The Endpoint Region of the Electron Spectrum in Inclusive Semileptonic Heavy Quark Decay

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ABSTRACT

I examine the relationship between the inclusive and sum-over-exclusive-resonances pictures for the electron spectrum of semileptonic heavy quark decay. The analysis shows that one should *expect* the electron spectrum to be suppressed near the endpoint compared to that obtained from a free-quark-decay-type model with an endpoint adjusted to the physical endpoint. This conclusion removes the need for nonresonant contributions in the endpoint region and is consistent with arguments that free-quark-decay-type models are, in principle, "dual" to a sum over resonant channels.

I. Introduction

The endpoint region of the electron spectrum induced by the quark-level semileptonic decay $b \to ue\bar{\nu}_e$ is potentially important for the measurement of the Cabibbo-Kobayashi-Maskawa (CKM) parameter [1] V_{ub}. The endpoint region is crucial to this measurement since, with $V_{ub} \ll V_{cb}$, only electron energies E_e with $\frac{m_B^2-m_D^2}{2m_B} \lesssim E_e \leq \frac{m_B^2-m_\pi^2}{2m_B}$ are useful for this purpose: for E_e much below this interval the spectrum is dominated by decays induced by $b \to ce\bar{\nu}_e$. However, the extraction of V_{ub} requires that theory be able to calculate the rate $\frac{d\Gamma}{dE_e}$ in this region apart from the overall factor of $|V_{ub}|^2$ arising from the CKM matrix.

While there is general agreement that the free quark decay model (which, in its QCD-improved form [2] we hereafter denote by ACCMM) for $b \to u$ transitions is valid in the limit $m_b \to \infty$ over most of the Dalitz plot, there is an ongoing discussion of its validity in the endpoint region. The applicability of the free quark decay model in this region is questionable because the endpoint $E_e^{max}(m_X)$ for a hadronic final state of mass m_X is

$$E_e^{max}(m_X) = \frac{m_B^2 - m_X^2}{2m_B} \quad . \tag{1}$$

The highest electron energies are therefore associated with the lightest hadronic recoil masses, but the free quark decay model is only expected to be valid for m_X above the resonance region.

This potential defect of the free quark decay model (as well as its QCD-improved version in ACCMM) was emphasized in Refs. [3,4]. To assess the magnitude of the uncertainty associated with using the model in the resonance region, Refs. [3,4] (hereafter called ISGW) calculated the endpoint region spectrum by explicitly summing over the electron spectra for the exclusive meson resonance channels predicted by the quark model. ISGW concluded that the rate in the endpoint region was considerably *smaller* than that predicted by the ACCMM model, and that there was a large uncertainty in the endpoint rate and spectral shape, corresponding to roughly a factor two uncertainty in V_{ub}. This pessimistic assessment has been disputed. One argument holds that the ACCMM model will provide a good approximation to the decay at all m_X. This view [6] is based on the idea that the quark-level calculation will be "dual" to the hadronic-level calculation even at low m_X, and its proponents point to the success of the perturbative picture for τ decay as an empirical basis for their optimism. (We will see below that duality *will* be realized, but that this was not the problem.) A second criticism [7] of the ISGW conclusions argues that the much smaller endpoint rate arises because ISGW sums over only the resonance spectrum. These critics associate the discrepancy with large recoil u quarks which appear to contribute to the endpoint region at the quark level, but which are suppressed in the hadronic picture because they are unlikely to lead to low-mass hadronic states. They argue that such large momentum u quarks will produce jets which are ignored in the resonance picture, and that low mass jets (*e.g.*, low mass $\pi\pi$ pairs) will fill in the gap between the

ISGW and ACCMM pictures. An outgrowth of this criticism has been the introduction of a "hybrid" model [7] (hereafter called the RDB model) which adds nonresonant effects to an ISGW-like picture.

II. The Basic Idea

In this paper I will analyze the relation between free quark decay models (and in particular the ACCMM model) and resonance models (in particular that of ISGW). The analysis indicates that the two models are in one-to-one correspondence *without* the addition of nonresonant contributions. It also shows that the endpoint region suppression found by ISGW by explicit calculation is a general feature with a very simple origin so that *it could have been predicted from a careful analysis of the structure of the Dalitz plot for the free quark decay model itself.* The effect arises from a peculiar kinematic circumstance: in the free quark decay model the highest electron energies are associated not with the *lowest* m_X but rather with the *highest*.

The essentials of the argument can be understood by considering the free quark decay model within the context of the constituent quark model in the "extreme spectator limit" that *all* strong interactions are switched off. In this case a free b quark will decay in the presence of a free spectator antiquark (taken to be $\bar{d}$ for concreteness) into $ue\bar{\nu}_e$. This model clearly must give exactly the same electron spectrum as free quark decay in the absence of the spectator antiquark, but it is instructive to see how it does so. At the quark level, the $b \to ue\bar{\nu}_e$ Dalitz plot for $\frac{d^2\Gamma}{dq^2 dE_e}$ is as shown in Fig. 1. It has $0 \le E_e \le \frac{m_b^2 - m_u^2}{2m_b} \equiv E_e^{max}[quark]$ and $0 \le q^2 \le (m_b - m_u)^2$. Let's now reinterpret this process in the presence of the $\bar{d}$ quark in the extreme spectator limit defined above. In this picture the mass of the decaying "meson" is $m_b + m_d$, while the invariant mass of the produced hadronic system is uniquely determined by q^2 to be

$$m_X^2 = \frac{(m_b + m_d)(m_b m_d + m_u^2) - m_d q^2}{m_b} \tag{2}$$

so that it lies in the range $m_X^{min} \equiv m_u + m_d \le m_X \le \left[\frac{(m_b + m_d)(m_b m_d + m_u^2)}{m_b}\right]^{1/2} \equiv m_X^{max}$. (The low end of this range corresponds to those decays in which the u is left at rest;

the upper end corresponds to the u recoiling at its maximum momentum $\frac{m_b^2 - m_u^2}{2m_b}$). We may now regard the decay as an integral (which will later become a sum) over decays to exclusive channels with masses m_X. Each such "exclusive channel" will have its own Dalitz plot with kinematic boundaries defined by the decaying masses $m_b + m_d$ and m_X. Figure 1 also shows the Dalitz plot for the decay to m_X^{min} and the corresponding diagram for m_X^{max}. Although the Dalitz plot for m_X^{min} reaches the same maximum value of q^2 for the same electron energy, *it extends to an electron energy $E_e^{max}[hadron]$ higher than $E_e^{max}[quark]$!* The plot for m_X^{max}, on the other hand, peaks at a lower q^2 and at a lower E_e than the $b \to ue\bar{\nu}_e$ plot, but it has *exactly the same maximum electron energy.*

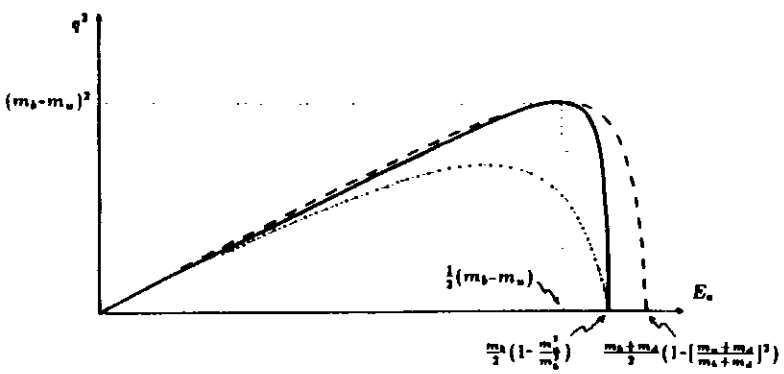

Fig. 1: the kinematically allowed regions for $b \to ue\bar{\nu}_e$ (solid line), $\bar{B} \to X(m_X^{min})e\bar{\nu}_e$ (dashed line), and $\bar{B} \to X(m_X^{max})e\bar{\nu}_e$ (dot-dashed line).

The reconciliation of these two superficially contradictory pictures is simple and instructive. How is it possible that the Dalitz plot for decay to a particular "hadronic" final state extends to larger E_e than that of free quark decay? Since the integral over m_X of rates in the (E_e, q^2) plane must be the same, the rate for decay to m_X^{min} must *vanish* in

the region with $E_e > E_e^{max}[quark]$. For a normal hadron this would of course not happen, but here it does: the state with m_X^{min} would, in fact, only be produced at the single *point* at the top of the Dalitz plot with $E_e = \frac{1}{2}(m_b - m_u)$ and $q^2 = (m_b - m_u)^2$. This is evident from Eq. (2): in our extreme spectator model each "state" of mass m_X contributes in an infinitely narrow band of q^2 within its Dalitz plot. This band structure has a very simple interpretation. Consider, for example, the state with m_X^{min}. It may be viewed as a $u\bar{d}$ "bound state" with a relative momentum wavefunction with support only at relative momentum zero. Such a state would have a form factor with support only at "zero recoil" corresponding to a $\bar{B}$ at rest decaying only to the state with m_X^{min} at rest. The states of our extreme quark model with other values of m_X are not, of course, produced at the top of their Dalitz plots. The top of the Dalitz plot for a given m_X corresponds to the production of that state at rest, while in this extreme model states with mass m_X can only be produced moving with the total momentum of the up quark which is required to "create" the mass m_X. Thus, in particular, the state with m_X^{max} can only be produced with $q^2 = 0$, *i.e.*, along the very *bottom* of its Dalitz plot and with energies ranging from 0 to $E_e^{max}[quark]$ as required to match onto the free quark decay picture. These observations support the opinion expressed in Ref. [7] that the rate contributed by the highest momentum u quarks at the quark level should not be lost in the hadronization process. However, they also show that this fact does not invalidate the conclusions of ISGW, but rather, once understood, substantiates them.

Indeed, from this analysis we can draw several conclusions. One is the obvious one that in this extreme "hadronization" of the free quark decay model, it and the "sum-over-exclusive-resonances" models are exact and dual in the extreme, *i.e.*, they are equivalent. (This is true without or with perturbative QCD corrections). The most critical conclusion, however, is that it would be incorrect to associate the maximum *kinematically* allowed electron energy $E_e^{max}[hadron]$ (associated with the lightest exclusive hadronic final state of mass m_X^{min}) with the $b \to ue\bar{\nu}_e$ electron endpoint $E_e^{max}[quark]$: the latter energy is less than the former and corresponds instead to the endpoint for decay to the heaviest *dynamically allowed exclusive channel with mass m_X^{max}*. As a result, the extreme spectator model

predicts an electron spectrum with an endpoint $E_e^{max}[quark]$ corresponding to m_X^{max}, followed by a gap of length $\simeq \frac{1}{2}m_d$ in which there are *no events* out to the kinematically allowed endpoint $E_e^{max}[hadron]$ associated with m_X^{min}. This somewhat non-intuitive gap arises because even though the quark and hadron pictures have the same "Q value" ($Q \equiv m_B - m_X^{min} = m_b - m_u$), the final state masses are both irrelevant at relativistic momenta ($E \simeq p + \frac{m^2}{2p} \simeq p$). I will argue in the following that this simple picture is correct up to the usual smearing corrections associated with duality, so that the population of the gap region is controlled by nonperturbative physics beyond the scope of the free quark decay model. I will also argue that the gap might cover the whole region beyond $E_e^{max}(m_D)$, in which case QCD in the form of the free quark decay model would not provide a theoretical underpinning for the use of the ACCMM model in the endpoint region. The extraction of V_{ub} from this spectrum would in this case be subject to large theoretical uncertainties.

III. Getting More Realistic

The extreme version of the constituent quark model considered in the preceeding Section corresponds in some ways to a world in which Λ_{QCD} is much less than the light quark masses m_u, m_d. In such a world, the low-lying $b\bar{d}$ and $u\bar{d}$ states would be nonrelativistic Coulombic states with $\alpha_s^{effective} \ll 1$. As a result, the full Dalitz plot distributions for $B \to X_u e\nu_e$ for the low-lying states X, could be calculated using nonrelativistic wave-function methods, and one can easily show that the events in such Dalitz plots will be concentrated in narrow q^2 bands (of width $\Delta q^2 \sim \alpha_s m_B m_X \ll q^2_{max}$) near q^2_{max}. For more massive states X the nonrelativistic picture will not apply, but in such states one would still expect only a small momentum distribution and so a form factor that is once again peaked near the same q^2 as it was in the extreme model of Section II. (The high-mass states will also have widths; the impact of this effect will be discussed below). For $\Lambda_{QCD} \ll m_u$, m_d, there will be a parallel change in the free quark decay picture: it will be perturbed by gluon emission which will broaden the u-quark jets. Of course, with such a small α_s, the effect on the Dalitz plot would be small and local: $\frac{d^2\Gamma}{dq^2 dE_e}$ would receive corrections of relative order $(\frac{\alpha_s}{\pi})$ and there would still be a very strong correlation between the *jet*

energy and the electron-neutrino mass q^2. Thus, this slightly more realistic example shows that there are reasons to expect the extreme picture of Section II to evolve smoothly as strong interactions are turned on.

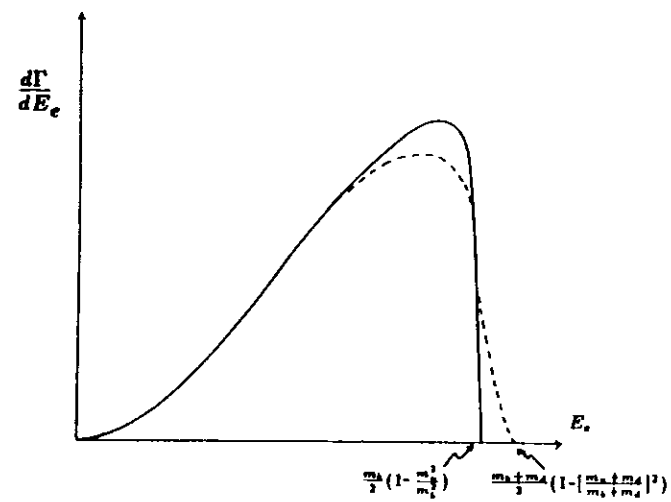

Fig. 2: an illustration of the effect of hadronization on the electron spectrum in $\bar{B} \to Xe\bar{\nu}_e$: the solid line is the spectrum from the free quark decay $b \to ue\bar{\nu}_e$; the dashed line shows rate "leaking" to higher E_e.

This analysis also leads to a conclusion not emphasized in ISGW: the electron spectrum will display two components with a break at the electron energy $E_e^{max}[quark]$ corresponding to $m_X^{max} \sim (m_b m_d)^{\frac{1}{2}}$ (see Fig. 2). In the extreme free quark limit of Section II, the entire electron spectrum falls below this energy, but once interactions are turned on a given q^2 will populate not the single value of m_X^2 given by Eq. (2), but rather a band of masses of width Δm_X^2 around m_X^2. The dependence of Δm_X^2 on m_X^2 will be determined by the dynamics of the system, but clearly the "leakage" of rate into the region of electron energies beyond those available in the free quark model will be in response to turning on

these strong interactions. This is an effect which is beyond the scope of the parton model, once again emphasizing that this region is one to which the free quark decay model is inapplicable. It should be noted that the ACCMM model includes some elements of this effect by folding their parton-level results against some "fermi motion" in the initial $\bar{B}$ meson. The "leakage" we show in Fig. 2 can also be seen in Fig. 5 of the first of Refs. [2].

Although this line of reasoning indicates that, as $m_b \to \infty$, low mass hadronic states should not contribute significantly to the electron spectrum in the endpoint region, we have not yet addressed one of the specific criticisms [7] of the ISGW picture: its neglect of pair creation. We begin by analyzing these effects in a $\Lambda_{QCD} \ll m_u, m_d$ world (even though the arguments presented show that in this case there is no need to provide a mechanism like that of the RDB model to fill in the "missing endpoint strength" of the ACCMM model). In the case of small Λ_{QCD}, the low-lying states cannot decay, so the arguments already given for them are unaffected. The issue arises, however, for transitions to states with $\Delta M \equiv m_X - (m_u + m_d) \gg 2m_d$ which will be important as $m_b \to \infty$. Although such states will live in the nonperturbative (confinement) region of QCD, we can still draw some clear conclusions about the importance of pair creation effects on their production. First, we note that the $\bar{B}$ itself would remain nonrelativistic, so for $\Lambda_{QCD} \ll m_u, m_d$, there would be only a very small probability (of order $(\alpha_s^{\text{effective}})^2$) of there being an extra pair in the initial state. Since the decay is short distance, the probability of pair creation by the vertex is also of this order. Thus, if there is to be an important pair creation effect, it will have to arise from decays of the final state. It is implausible that such effects would be significant. First of all, the natural frequencies of the relativistic $u\bar{d}$ states are their inverse radii $\sim \left[\frac{\Delta m}{b}\right]^{-1} \sim \frac{\Lambda_{QCD}^2}{\Delta m} \ll m_d$, where b is the QCD string tension ($b \sim \Lambda_{QCD}^2$), so perturbative production of pairs will be supressed by both α_s^2 and large energy denominators. Nonperturbative pair creation will be much smaller. (We note that the created pair will have to tunnel a distance of the order of $\frac{m_d}{b}$ through a potential barrier of height m_d so that pair creation will be suppressed in this model by a Schwinger factor $\exp(-m_d^2/b) \ll 1$.) Thus, at least in this somewhat less extreme model, pair creation would seem to be unimportant. Once again, this is consistent with what one expects from

perturbative corrections to free quark decay. (Incidentally, although it would not seem to have important effects on the Dalitz plot, pair creation can help us to make a connection to the QCD jet picture. When a u-quark with large momentum $\vec{p}$ is projected into the $u\bar{d}$ meson basis, it will appear as a coherent superposition of states with total momentum in a band near $\vec{p}$ with a width determined by the initial nonrelativistic wavefunction. These states will have a distribution of masses sharply peaked around the m_X of the extreme model of Section II; they will also be in a superposition of internal angular momentum states which reflects the fact that in the $u\bar{d}$ rest frame the relative momentum vector $\vec{p}_u - \vec{p}_{\bar{d}}$ is nearly parallel to $\vec{p}$ before projection into the $u\bar{d}$ meson basis. If each state with mass m_X were to decay independently from an unpolarized state, it would produce a fat jet with $\langle p_T \rangle \sim m_X \sim (m_b m_d)^{1/2}$. The observed behavior $\langle p_T \rangle \sim$ constant (up to logarithms) arises by taking the angular superposition into account. Of course in a rate calculation such interferences play no role and we recover the rate obtained by summing over noninterfering resonances. There will also be interferences between states with different radial quantum numbers. At high radial excitation, the decay amplitude for fixed angular momentum will be a rapidly varying function of the decay product center-of-mass momentum k so that interference terms will have zero expectation value when averaged over a small range of k. The total decay rate will therefore be a smooth noninterfering function of k, and we will again recover the rate obtained by naively summing over noninterfering resonances.)

Note that while the $\Lambda_{QCD} \to 0$ limit could be misleading on the importance of pair creation effects, it is difficult to see how it could be misleading on the issue of the *relation* between the ACCMM and ISGW pictures. After all, these pictures would both apply in that limit, and there is no reason to expect that a new process like pair creation which *neither* model takes into account should enter into the relationship between them when Λ_{QCD} takes its observed value.

We can also see the equivalence in principle of the ACCMM and ISGW pictures in the limit $N_c \to \infty$. In this limit mesons are free of additional pairs and the narrow resonance approximation holds. Thus, the inclusive cross section of the ACCMM picture would as $N_c \to \infty$ be realized *exactly* as sum over exclusive channels $\bar{B} \to X_i e\bar{\nu}_e$ with X_i the

narrow nd resonances. As with the $\Lambda_{QCD} \to 0$ limit, this does not prove that nonresonant effects are unimportant in nature; it only makes it doubtful that they are relevant to any discrepancy between the ACCMM and ISGW pictures.

IV. Extrapolating to the Real Case

In nature none of our limiting cases apply. Nevertheless, we believe they suffice to establish that nonresonant effects are not relevant to the *relation* between the ACCMM and ISGW pictures. It remains to decide whether the lessons of our simple examples can be extrapolated to reach the conclusion that, when the ACCMM model is adjusted so that its endpoint coincides with the physical endpoint for $\bar{B} \to X_u e \bar{\nu}_e$, it can be expected to overestimate the rate in the endpoint region.

Let's begin by considering the $\bar{B} \to \pi$ form factor f_+. Using either the quark model or vector meson dominance one finds that this form factor has an expansion about q^2_{max} given by

$$f_+^{B\to\pi}(q^2) = f_+^{B\to\pi}(q^2_{max})\left[1 - \frac{1}{6} r^2_{B\pi}\left(q^2_{max} - q^2\right) + \ldots\right] \tag{3a}$$

with

$$r^2_{B\pi} \sim \frac{1}{m_b \Lambda_{QCD}} \tag{3b}$$

(Although not central to the argument, in writing this I have not assumed dominance of the lightest B^*, but rather some weighted average of B^* resonances separated from the B by a typical hadronic spacing.) Since $0 \le q^2_{max} - q^2 \le m_b^2$ while the characteristic scale of $f^{B\to\pi}$ is $m_b \Lambda_{QCD}$, the $\bar{B} \to \pi$ contribution will be concentrated in a band of q^2 near q^2_{max}. Thus the $\bar{B} \to \pi$ Dalitz plot in nature will be in accord with our earlier conclusions. Similar arguments can be made for other low-lying states. (It should be noted that the appearance of m_b in the argument just given is potentially misleading. We know from heavy quark symmetry [8] that any $\bar{B} \to X$ form factor will, as $m_b \to \infty$, have a shape which (in the $\bar{B}$ rest frame) depends only on E_X, the recoil energy of X. This shape depends only on the dynamics of the light degrees of freedom of QCD, and is thus governed by the scale set by Λ_{QCD} (or the light hadron spectrum). The scale m_b entered only through the use of the

momentum transfer $q^2 = (p_B - p_X)^2$ as a variable: heavy quark symmetry tells us that $v_B \cdot p_X$ (where v_B is the four-velocity of the $\bar{B}$) is a more useful variable since it removes spurious dependence of the form factors on m_b. Thus from the perspective of heavy quark symmetry it would be more appropriate to reach the physically equivalent conclusion that $f_+^{B\to\pi}$ is expected to fall with E_π with a typical hadronic scale $E_{QCD} \sim 1$ GeV and to therefore be localized near the top of the Dalitz plot.)

Duality also leads us to expect that the hadronic recoil energy E_X will be associated with a recoil invariant mass $m_X \simeq (2E_X[m_B - m_b])^{\frac{1}{2}}$ corresponding to the relation $m_X \sim (2E_u m_d)^{\frac{1}{2}}$ of the extreme spectator model. This follows from the realization that the lepton four-momentum q is set by the short-distance process $b \to u e \bar{\nu}_e$. We therefore expect the bottom of the Dalitz plot to be populated by states with m_X around $(m_b \Lambda)^{\frac{1}{2}}$, where $\Lambda \equiv m_B - m_b$ is the nonperturbative mass associated with the light degrees of freedom in the $\bar{B}$ meson. It follows that all relevant thresholds have turned on for $E_e^{max} - E_e \gtrsim \frac{\Lambda}{2}$ so that the ACCMM picture will hold over all but a vanishingly small fraction of the spectrum as $m_b \to \infty$.

Although this region is a vanishingly small *fraction* of the spectrum as $m_b \to \infty$, we expect it to cover a finite range of electron energies. In the extreme model of Section II it covers a fixed energy range of length $\frac{1}{2} m_d$ as $m_b \to \infty$. If m_d is the usual constituent quark mass, then this gap is about 150 MeV, compared to the full length of the endpoint region of 330 MeV. From the duality argument given above we can expect this gap to be of length $\frac{\Lambda}{2}$. In models, Λ ranges from about 300 to 600 MeV (*i.e.*, m_b ranges from about 4.7 to 5.0 GeV), in which case the gap could cover the whole endpoint region. The quark model of ISGW provides another estimate of the extent of this region. It suggests that the $b \to u e \bar{\nu}_e$ transition strongly excites final states X with masses up to about 1.8 GeV, once again indicating that the gap covers the whole endpoint region. Note that it is a coincidence that the mass m_X^{max} corresponds roughly to that of the D meson: recall that it is proportional to $m_b^{\frac{1}{2}}$. However, given this coincidence (or even the potential for it given existing theoretical uncertainties) the use of the ACCMM picture in the region beyond the $b \to c e \bar{\nu}_e$ endpoint to extract V_{ub} is questionable.

V. Summary and Conclusions

I have shown solely from consideration of the kinematics of free quark decay that there are strong reasons to doubt the validity of an ACCMM-type picture for the endpoint region of the electron spectrum of semileptonic $b \to u$ decays. In the extreme spectator approximation, this model produces a spectrum with an electron endpoint which is below the physical endpoint. I have also discussed how nonperturbative strong interaction corrections lead to a nonvanishing rate above the spectator endpoint up to the physical endpoint, and argued that in this region the ACCMM model is not underwritten by perturbative QCD, but is rather a model for nonperturbative effects with the same *a priori* status as any other such model. The possibility that an adjustment of the ACCM model to the $\bar{B} \to D$ endpoint will compensate for these nonperturbative effects seems remote. The physics of the $b \to c$ endpoint is very different as $m_X^{max} \simeq m_X^{min}$ in this case, so that $\bar{B} \to D$ and $\bar{B} \to D^*$ dominate the inclusive rate, with each state persisting in populating its Dalitz plot from q^2_{max} to $q^2 = 0$.

Given this conclusion, there is no need to repair the discrepancy between inclusive and exclusive resonance pictures of semileptonic decay. However, I have discussed the relationship between the two pictures and drawn the conclusion that they are "dual" without the addition of effects arising from nonresonant processes like those postulated in the RDB model.

Although the prospects for accurately describing the inclusive electron spectrum in the endpoint region are as a result bleak, it may not matter. It now seems plausible that heavy quark symmetry [8] will allow an extraction of V_{ub} from a comparison of exclusive semileptonic decays of $\bar{B}$ and D mesons to identical hadronic final states.

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