

Right-Handed Currents in B Decay Revisited *

Thomas G. Rizzo

Stanford Linear Accelerator Center
Stanford CA 94309, USA

Abstract

We critically re-examine the case for and against a sizeable right-handed component in the $b \rightarrow c$ charged current coupling with a strength ξ relative to the conventional left-handed current. Using data from CLEO on the decay $B \rightarrow D^* \ell \nu$, as well as our knowledge of V_{cb} extracted from both inclusive and exclusive processes, we are able to determine the presently allowed parameter space for ξ via HQET. We then identify several observables which could be measured at B factories to either strengthen these constraints or otherwise observe right-handed currents. This parameter space region is found to be consistent with the low degree of Λ_b polarization as determined by ALEPH as well as the measurements of the charged lepton and neutrino energy spectra from b decay made by L3. We discuss how future measurements of semileptonic decay distributions may distinguish between exotic Λ_b depolarization mechanisms and the existence of right-handed currents. Within the parameter space allowed by CLEO, using the Left-Right Symmetric Model as a guide, we perform a detailed search for specific sub-regions which can lead to a reduction in both the B semileptonic branching fraction as well as the the average yield of charmed quarks in B decay. The results provide a concrete realization of an earlier suggestion by Voloshin but may lead to potential difficulties with certain penguin mediated decay processes.

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1 Introduction

The new generation of B factories soon to come on line will open up an additional window on potential physics beyond the Standard Model(SM). Unlike the situation at new higher energy colliders, the physics beyond the SM will appear indirectly, *e.g.*, as deviations from SM expectations in decay rates, distributions and/or asymmetries obtained through precision measurements. Such measurements may be as important in probing the SM as are those currently performed by LEP/SLC and the Tevatron at higher energies and will rival others associated with the observation of CP violation in the B system.

Perhaps the most fundamental of all quantities associated with b quark decay is the chirality of its charged current coupling. The possibility that the $b \rightarrow c$ charged current(CC) may have a sizeable right-handed(RH) component has been the subject of speculation for some time. Early on, Gronau and Wakaizumi, as well as a number of other authors[1], speculated that the $b \rightarrow c$ coupling might be almost, if not *purely*, RH. Thanks to measurements performed by both the CLEO[2] and L3[3] Collaborations, to which we return at some length below, we now know that this hypothesis cannot be true. The relative strength of the RH $b \rightarrow c$ coupling in comparison to the corresponding SM left-handed(LH) coupling must be somewhat less than unity; the leptonic current in the decay is highly constrained to be LH. It is important to observe that the results of these experiments cannot exclude a RH coupling of modest strength. Other data, such as the apparently small value of the Λ_b polarization observed in Z decay[4] by ALEPH, qualitatively support the hypothesis of potentially sizeable RH couplings unless some exotic depolarization mechanisms are at work. Thus the current experimental situation remains unsatisfying and is far from resolving the issue of the presence of RH couplings in $b \rightarrow c$ transitions. On the theoretical side, in a completely different context, Voloshin[5] has recently suggested that a RH $b \rightarrow c$ coupling of

modest strength may help to resolve the well-known B semileptonic branching fraction(B_ℓ) and charm counting(n_c) problems[6]. Thus we are left with the questions: given the present data, it is possible that such a RH coupling actually exists and can it assist with the B_ℓ and n_c problems? How can future B factory data help clarify this situation?

In this paper we will examine the simultaneous compatibility of the CLEO and, to a lesser extent, the L3 constraints on the RH $b \rightarrow c$ coupling and the desire to address the charm counting/branching fraction problem along the lines suggested by Voloshin. The important role played by the ALEPH Λ_b polarization measurement is also examined. This discussion stresses both what we can learn from the current data about possible $b \rightarrow c$ RH couplings and what can be learned through future precision measurements at B factories to resolve the present ambiguous situation. Most of this analysis, associated with the constraints from the CLEO, L3 and ALEPH data, can be performed in a completely *model-independent* fashion without any reference as to the possible origin of the $b \rightarrow c$ RH coupling. However, in order to subsequently approach the $n_c - B_\ell$ problem a more rigid theoretical framework, such as the Left-Right Symmetric Model(LRM)[7], needs to be invoked. Other more general frameworks are possible but are beyond the scope of the present paper.

This paper is organized as follows. In Section 2, we re-examine and update the constraints imposed on the relative strength of the RH to LH $b \rightarrow c$ coupling due to current experimental data from CLEO, ALEPH and L3 using a model-independent approach and relying on Heavy Quark Effective Theory. As we will see there is a tantalizing, though still not compelling, hint of RH interactions in the CLEO data. The importance of both the small observed Λ_b polarization as a possible, though still ambiguous, signature for RH currents is discussed. We also examine how this scenario may be distinguished from the SM with exotic depolarization mechanisms. The present ALEPH data is shown to be consistent with a moderately strong RH current coupling. In examining how we can extract further

information from the present data and with an eye towards future measurements we discuss several new observables and their potential usefulness in probing for RH couplings. Many of these observables have either not been measured or have yet to be examined with any degree of precision. Several of these quantities can be probed at the Z or during the first year of running at the new B factories. In Section 3, we present an overview of the LRM and discuss the meaning of the current experimental constraints within this specific context keeping detailed discussion of the required LRM particle content to a minimum. As we do not want to restrict or constrain ourselves to a specific version of this model, we tacitly avoid at this point any discussion of loop processes which may involve the full particle spectrum of a realistic, probably supersymmetric LRM. In Section 4 we describe the nonleptonic $b \rightarrow c$ decays in the presence of RH currents and their associated decay widths including LO and estimates of the NLO QCD corrections based upon what is currently known in the case of the SM. In Section 5, we use the LRM as input to scan the full model parameter space allowed by the CLEO data to discover and identify sub-regions that will lead to a simultaneously decrease in the values of both B_ℓ and n_c in comparison to the SM expectations. While such regions are shown to exist they occur in only a small, fine-tuned, fraction of the entire parameter space volume. Our summary and conclusions can be found in Section 6. In the Appendix we speculate on the possible forms of V_R and point out how certain penguin processes can lead to difficulties with the solutions to the $n_c - B_\ell$ problem that we've obtained.

2 Constraints on Right-Handed $b \rightarrow c$ Couplings

2.1 Model-Independent Notation

Allowing for both LH and RH $b \rightarrow c$ couplings while, following Voloshin, maintaining the leptonic current as purely LH to satisfy the well-known μ decay constraints[8] without fine-

tuning neutrino masses, the general four-fermion interaction describing B semileptonic decay can be written as

$$\mathcal{H}_{sl} = \frac{4G_F}{\sqrt{2}} V_{cb}^L [(\bar{c}_L \gamma_\mu b_L) + \xi(\bar{c}_R \gamma_\mu b_R)] (\bar{\ell}_L \gamma^\mu \nu_L), \quad (1)$$

where here we will treat ξ as a *complex* parameter, $\xi = |\xi|e^{i\Delta}$, though CP violation will be ignored in the discussion that follows[9]. As we will see the additional phase degree of freedom will play a very important role in obtaining signals and constraints on RH currents. We recall that in the original Gronau and Wakaizumi scenario the leptonic current in B decays was also RH[1] and neutrino masses were tuned to allow for the semileptonic decay process. How do we ascertain the allowed range of ξ ? Again following Voloshin, the first place to obtain a constraint is inclusive semileptonic b decay at the quark level. The most obvious observable is the inclusive decay partial width that can be written as

$$\Gamma(b \rightarrow c\ell\nu) \sim |V_{cb}^L|^2 f(x)\eta_L \left[1 + |\xi|^2 + 2\text{Re}(\xi) \frac{g(x)\eta_R}{f(x)\eta_L} \right]. \quad (2)$$

For zero mass leptons, f, g are the well-known kinematic phase space functions[5, 10, 11] of the ratio $x = m_c/m_b \simeq 0.29$:

$$\begin{aligned} f &= (1-x^4)(1-8x^2+x^4) - 24x^4 \ln x, \\ g &= -2x[(1-x^2)(1+10x^2+x^4) + 12x^2(1+x^2) \ln x], \end{aligned} \quad (3)$$

and for $x = 0.29$ we find $f \simeq 0.542$ and $g \simeq -0.196$. For semileptonic decay to τ 's, the corresponding phase space suppression factors can be decomposed as $f_\tau = (I_1 + I_2)/2$ and $g_\tau = (I_1 - I_2)/2$ in terms of the integrals

$$\begin{aligned} I_1 &= \int_{y^2}^{\Delta} ds Z \left[\Delta(4s - y^2) + 2\Delta\Sigma(1 + 2y^2/s) - (\Sigma + 2s)(2s + y^2) \right], \\ I_2 &= \int_{y^2}^{\Delta} ds Z \left[\Sigma(4s - y^2) + 2\Delta\Sigma(1 + 2y^2/s) - (\Delta + 2s)(2s + y^2) \right], \end{aligned} \quad (4)$$

where $y = m_\tau/m_b$, $\Sigma = (1+x)^2$ and $\Delta = (1-x)^2$ with

$$Z = \left[1 - \frac{y^2}{s}\right]^2 \left[(\Sigma - s)(\Delta - s)\right]^{1/2}. \quad (5)$$

Numerically, one finds $f_\tau \simeq 0.122$ and $g_\tau \simeq -0.0490$ for $x = 0.29$ and $y \simeq 0.372$. Note that when RH currents are present the ratio of the b semileptonic decay width to τ 's to that for massless leptons becomes a weak function of ξ with overall variations of order a few per cent; this dependence occurs due to a mismatch in the phase space ratios: $g_\tau/f_\tau \neq g/f$. This effect is most likely too small to be observed experimentally, however, but should be kept in mind.

The parameters $\eta_{L,R}$ represent both perturbative and non-perturbative strong interaction corrections which also depend on x as well as the lepton mass and the relevant strong interaction scale μ . When needed in the numerical discussion below we will *assume* that the effects of all strong interaction corrections in the $b \rightarrow c$ semileptonic decay are at least approximately insensitive to the chirality of the charged current coupling, *i.e.*, $\eta_L = \eta_R = \eta$ as was done Voloshin. (Certainly, an explicit calculation needs to be performed to verify this assumption.) To leading order in QCD for massless leptons and with $x = 0.29$ one has the perturbative contributions $\eta = 1 - \frac{2\alpha_s}{3\pi}(2.53) + \mathcal{O}(\alpha_s^2)$ whereas for τ 's one obtains $\eta = 1 - \frac{2\alpha_s}{3\pi}(2.11) + \mathcal{O}(\alpha_s^2)$ [12]. The complete NLO expressions are not yet available in either case. Only the terms of order $\alpha_s^2\beta_0$, with β_0 being the one-loop QCD beta function, are known at present[13], so for now we will truncate these corrections at this order but include them in our detailed numerical analysis below.

It is amusing to note that the existence of a RH coupling means that a measurement of the partial width Γ yields not the true but an *effective* value of V_{cb}^L from inclusive data

when the result is interpreted in terms of the SM, *i.e.*,

$$|V_{cb}^L|_{eff}^{inc} = |V_{cb}^L| \cdot \left[1 + |\xi|^2 + 2\text{Re}(\xi)\frac{g}{f} \right]^{1/2}. \quad (6)$$

under the assumption that $\eta_L = \eta_R$. This result will have important consequences for us below.

To obtain more information from this inclusive decay additional observables are required. Indeed, many authors have speculated about how one can experimentally extract information about potential RH couplings in inclusive semileptonic b decay. Dittmar and Was[14] suggested examining simultaneously both the charged lepton and neutrino, *i.e.*, missing energy, spectra arising from b semileptonic decay at the Z peak. When one looks at the squared matrix element for this process in the free-quark limit, after all traces are performed, the sensitivity to ξ becomes immediately transparent:

$$|\mathcal{M}|^2 \simeq p_\ell \cdot p_c p_\nu \cdot p_b + |\xi|^2 p_\ell \cdot p_b p_\nu \cdot p_c - m_b m_c p_\ell \cdot p_\nu \text{Re}(\xi), \quad (7)$$

with the p_i labelling the corresponding particle four-momentum. The ξ sensitivity is seen to be particularly enhanced due to the large value of the ratio $m_c/m_b \simeq 0.29$ with the phase of ξ playing a very important role. (For completeness we note that one can find the full expression for the resulting unpolarized charged lepton spectra in the Z rest frame at leading order is given by Fujikawa and Kawamoto[10]. The corresponding neutrino spectrum can be trivially obtained through the interchange of the LH and RH couplings.) Interestingly, as mentioned earlier, L3[3] performed a simultaneous measurement of both the charged lepton and missing energy spectra in b decay and excluded very large values of ξ , *i.e.*, purely RH couplings, by more than 6σ and $\xi \simeq 1$, *i.e.*, purely vector couplings, by more than 3σ . They did not, however, attempt a fit to ξ as the required sensitivity to $\xi \ll 1$ was not available once detector cuts and hadronic as well as other systematic uncertainties were taken into account.

However, values of $|\xi| \ll 1$ were certainly not excluded and we will attempt to further quantify these results below.

We now turn to each of the three experiments CLEO, ALEPH and L3 and survey the constraints that they are presently imposing on ξ and what can be learned from comparable measurements at future B factories even if relatively low integrated luminosities are available.

2.2 CLEO

In addition to inclusive semileptonic decay one may hope to obtain information on possible RH coupling through exclusive decay measurements due to the enriched nature of the accessible final states. In this regard CLEO[2] has performed a detailed examination of both the $B \rightarrow D$ and $B \rightarrow D^*$ exclusive semileptonic modes. In the $B \rightarrow D$ case the impact of RH currents is well known to be rather minimal for massless leptons since the final state and the corresponding hadronic matrix element are rather simple. In this case, their only effect is to scale the anticipated partial rate by an overall factor, $|1 - \xi|^2$, to which we will return below. A more complex and interesting pattern occurs for the $B \rightarrow D^*$ case.

The CLEO analysis[2] that examined the exclusive decay $B \rightarrow D^*(\rightarrow D\pi)\ell\nu$ sought to extract form factor information and, in particular, to measure the forward-backward asymmetry of the charged lepton, A_{FB} , the average D^* polarization, Γ_L/Γ_T , as well as V_{cb}^L . The data sample of ~ 780 events employed in their analysis resulted from an initial set of $2.6 \cdot 10^6$ $B\bar{B}$'s corresponding to an integrated luminosity of $\simeq 2.4 fb^{-1}$ at the $\Upsilon(4S)$. Following the general analysis as presented in Ref.[2, 15], one begins with an initially four-fold differential distribution but this is a bit unwieldy. Integration over two of the three decay angles (the others of which we will subsequently return to below) leads to the following

double differential decay distribution for this process in the massless lepton limit:

$$\frac{d^2\Gamma}{dq^2 dz} \sim |V_{cb}^L|^2 P q^2 \left[(1-z)^2 |H_+|^2 + (1+z)^2 |H_-|^2 + 2(1-z^2) |H_0|^2 \right], \quad (8)$$

where P is the D^* momentum in the B frame, q^2 is the four-momentum transfer from the B to the D^* and $z = \cos \theta_\ell$ with θ_ℓ being the decay angle of the ℓ in the virtual W rest frame. P is given by

$$P = \frac{1}{2M} \left[(M^2 - m^2 - q^2)^2 - 4m^2 q^2 \right]^{1/2}, \quad (9)$$

and the helicity amplitudes $H_{\pm,0}$ are functions of q^2 which are generally expressed in terms of the conventional form factors $A_{1,2}$ and V as

$$\begin{aligned} H_{\pm}(q^2) &= (M+m)A_1(q^2) \mp \frac{2MP}{(M+m)}V(q^2), \\ H_0(q^2) &= [2m\sqrt{q^2}]^{-1} \left[(M^2 - m^2 - q^2)(M+m)A_1(q^2) - \frac{4M^2 P^2}{(M+m)}A_2(q^2) \right], \end{aligned} \quad (10)$$

where $M(m)$ is the mass of the $B(D^*)$. Meticulously following Neubert[16] one may use suggestive versions of the above form factors that have very well defined limits when Heavy Quark Effective Theory(HQET) becomes exact:

$$\begin{aligned} A_1(q^2) &= \frac{(M+m)}{2\sqrt{Mm}} \left[1 - \frac{q^2}{(M+m)^2} \right] h(w), \\ A_2(q^2) &= \frac{(M+m)}{2\sqrt{Mm}} R_2(w) h(w), \\ V(q^2) &= \frac{(M+m)}{2\sqrt{Mm}} R_1(w) h(w). \end{aligned} \quad (11)$$

Here we define as usual $w = (M^2 + m^2 - q^2)/(2Mm)$. In the exact HQET limit both $R_{1,2} \rightarrow 1$ and $h(w)$ becomes the Isgur-Wise function so that the R_i can be considered as representing

small corrections in both α_s and $1/m$ to the case of pure leading order HQET. Generically, h has a linear form, $h(w) = h(1)[1 - \rho^2(w - 1)]$ although other structures are possible.

While the forward-backward asymmetry can be obtained by integration of the expressions above, the ratio Γ_L/Γ_T can be determined from the decay angular distribution of the D in the D^* frame when $D^* \rightarrow D\pi$ ($\cos \theta_V$, in the notation of Ref.[2]). Following Ref.[2, 15] we can write the relevant double-differential distribution in this case as

$$\frac{d^2\Gamma}{dq^2 d \cos \theta_V} \sim Pq^2 \left[(|H_+|^2 + |H_-|^2)(1 - \cos^2 \theta_V) + 2|H_0|^2 \cos^2 \theta_V \right]. \quad (12)$$

Γ_L/Γ_T essentially probes the relative weights of the H_0 and H_{\pm} helicity amplitudes as we will see shortly.

So far this discussion has been quite general. To include the effects of $\xi \neq 0$ in comparison to SM expectations we simply make the replacements $V \rightarrow V(1 + \xi)$ and $A_{1,2} \rightarrow A_{1,2}(1 - \xi)$ in the expressions for the helicity amplitudes above and recall that ξ is complex. This follows directly from the rescaling of the LH and RH current amplitudes as seen in Eq.(1). Once particular expressions for $R_{1,2}$ and h are assumed we may directly calculate A_{FB} , Γ_L/Γ_T , as well as the total decay rate, which then gives us $V_{cb}^L{}^{exc}(D^*)$. We obtain

$$\begin{aligned} A_{FB} &= \frac{\int dq^2 [\int_0^{z_0} - \int_{-z_0}^0] dz \frac{d^2\Gamma}{dq^2 dz}}{\int dq^2 \int_{-z_0}^{z_0} dz \frac{d^2\Gamma}{dq^2 dz}}, \\ \frac{\Gamma_L}{\Gamma_T} &= \frac{\int dq^2 2z_0(1 - z_0^2/3)Pq^2 H_0^2}{\int dq^2 z_0(1 + z_0^2/3)Pq^2 (H_+^2 + H_-^2)}, \end{aligned} \quad (13)$$

where $z_0(q^2)$ expresses a potential minimum lepton momentum cut used to identify the event:

$$z_0 = \min \left[1, -\frac{4Mp_\ell^{cut} - M^2 - q^2 - m^2}{2PM} \right]. \quad (14)$$

CLEO, for example, employs a typical lepton momentum cut of $\simeq 1$ GeV. These expressions can be re-written to clearly display their ξ dependence as

$$\begin{aligned}
 A_{FB} &= \frac{(1 - |\xi|^2)C}{(1 + |\xi|^2)A - 2B\text{Re}(\xi)}, \\
 \frac{\Gamma_L}{\Gamma_T} &= \frac{4}{3} \frac{[1 + |\xi|^2 - 2\text{Re}(\xi)]D}{(1 + |\xi|^2)E + 2F\text{Re}(\xi)}.
 \end{aligned}
 \tag{15}$$

Experimentally, CLEO[2] finds $A_{FB} = 0.197 \pm 0.037$ and $\Gamma_L/\Gamma_T = 1.55 \pm 0.29$, which are of course both consistent with SM/HQET expectations. Here $A - F$ are a simple set of numbers which result from performing the double integration over the relevant kinematics. For a fixed set of $R_{1,2}$ and h , the values of $A - F$ are completely determined subject to experimental cuts, and these results can be combined to constrain ξ . In addition, from the expression for the overall partial width we also obtain

$$|V_{cb}^L|_{eff}^{exc}(D^*) = |V_{cb}^L| \cdot \left[1 + |\xi|^2 - 2\text{Re}(\xi) \frac{B}{A} \right]^{1/2},
 \tag{16}$$

when the value is again interpreted in the SM; this result should then be compared with Eq.(6). Note that since one finds that $-B/A \neq g/f$, the apparent values of V_{cb}^L extracted from exclusive $B \rightarrow D^*$ and inclusive measurements will be *different* when $\text{Re}(\xi) \neq 0$. Demanding that the *true* V_{cb}^L take on the same value in both cases imposes an extra constraint on ξ . In order to employ this additional constraint we use the specific numerical results as provided in the recent review of both inclusive and exclusive semileptonic decay data by Buras[17] to obtain $V_{cb}^L{}^{exc}(D^*)/V_{cb}^L{}^{inc} = 0.967 \pm 0.105$. This value is completely consistent with unity, as anticipated, but will still provides an additional requirement on ξ . A similar situation, as mentioned above, occurs in the case of $B \rightarrow D$ semileptonic decays where we now would

find simply

$$|V_{cb}^L|_{eff}^{exc}(D) = |V_{cb}^L| \cdot \left[1 + |\xi|^2 - 2Re(\xi) \right]^{1/2}, \quad (17)$$

which should be compared with that from the D^* mode above. Given the present experimental situation[2] adding this additional constraint will not influence the results of the fit obtained below. However, future measurements may make this an important input into analyses of RH currents.

Our procedure is the following: for a fixed set of $R_{1,2}(w)$ and $h(w)$ we calculate the integrals $A - F$ and then perform a simultaneous χ^2 fit to the CLEO results on A_{FB} and Γ_L/Γ_T as well as to the ratio $V_{cb}^L{}^{exc}(D^*)/V_{cb}^L{}^{inc}$ treating $|\xi|$ and $c_\Delta = \cos \Delta$ as free parameters (recall, Δ is the phase of ξ). Possible correlations are ignored. We then choose another set of $R_{1,2}$ and h and repeat the process. Each repetition will thus generate a 95% CL allowed region in the $c_\Delta - |\xi|$ plane. To be specific we employ forms of $R_{1,2}(w)$ and $h(w)$ suggested by Neubert[16] and by Close and Wambach(CW)[18] as well as several other sets suggested by the first paper in Ref.[2]. As a typical example, with $R_1^{CW} = 1.15[1 - 0.06(w - 1)]$, $R_2^{CW} = 0.91[1 + 0.04(w - 1)]$ and $\rho^2 = 0.91$ we obtain $A \simeq 0.116$, $B \simeq 0.105$, $C \simeq 0.024$, $D \simeq 0.060$, $E \simeq 0.056$, and $F \simeq 0.044$. These values do indeed reproduce the well known SM expectations[16] in the $\xi \rightarrow 0$ limit.

The results of this fit are shown in Fig. 1 which displays the 95% CL upper bound on $|\xi|$ as a function of c_Δ for several different choices of $R_{1,2}$ and h . The most important features of these results to notice are: (i) the bounds we obtain are not very sensitive to the exact choice of these HQET functions and (ii) the constraints on $|\xi|$ are strongest when ξ is real. We note that Voloshin's preferred range of values of $\xi = 0.14 \pm 0.18$ lie mostly inside the allowed region. It is clear that at the moment the existing constraints on ξ are quite

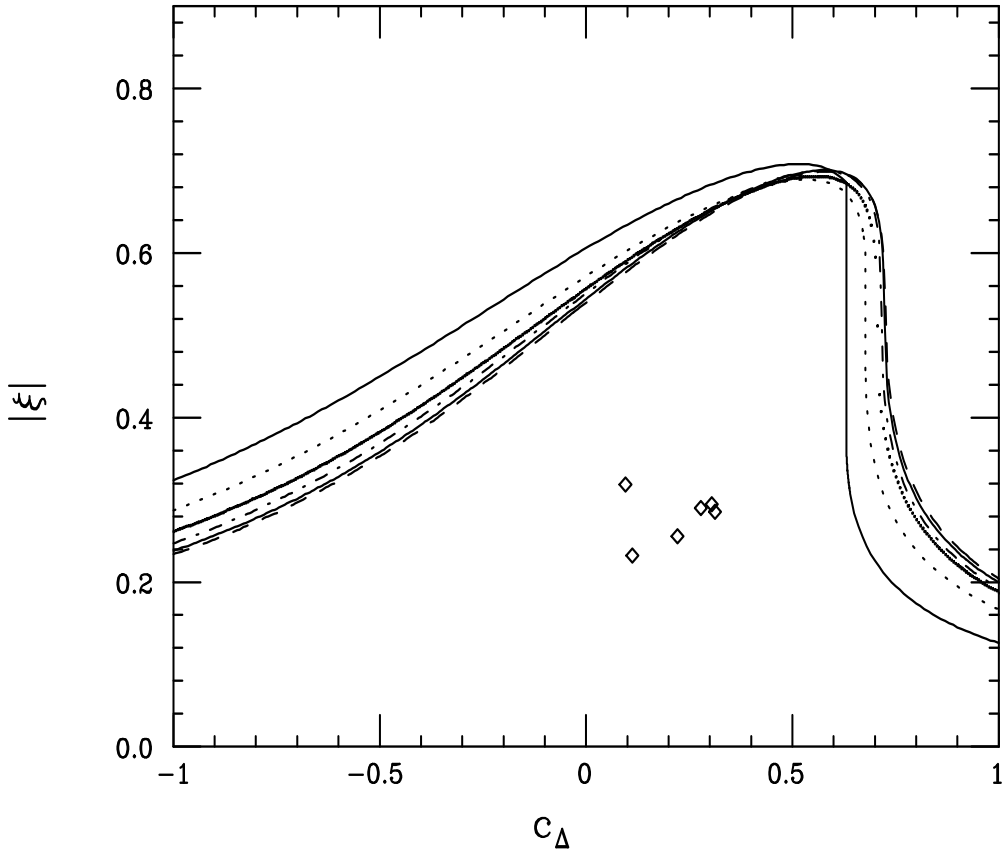


Figure 1: 95% CL allowed region (below the curves) in the $|\xi| - c_\Delta$ plane obtained from a fit to CLEO data as well as the experimental value of the ratio $V_{cb}^{L\ exc}(D^*)/V_{cb}^{L\ inc}$. Each of the six curves corresponds to a unique choice of $R_{1,2}$ and h . The SM limit lies along the horizontal axis at $|\xi| = 0$. The locations of the six χ^2 minima are also shown for completeness and are seen to be reasonably clustered.

poor and that values of $|\xi|$ of order 0.25 are certainly allowed by current data. We note that for the six sets of HQET functions used in this analysis the resulting best fit values for ξ are reasonably clustered and indicate a magnitude $\simeq 0.20 - 0.35$ and a sizeable phase. With the far larger data sets soon to be available from B factories it is quite important for this analysis to be revisited and refined in the not too distant future.

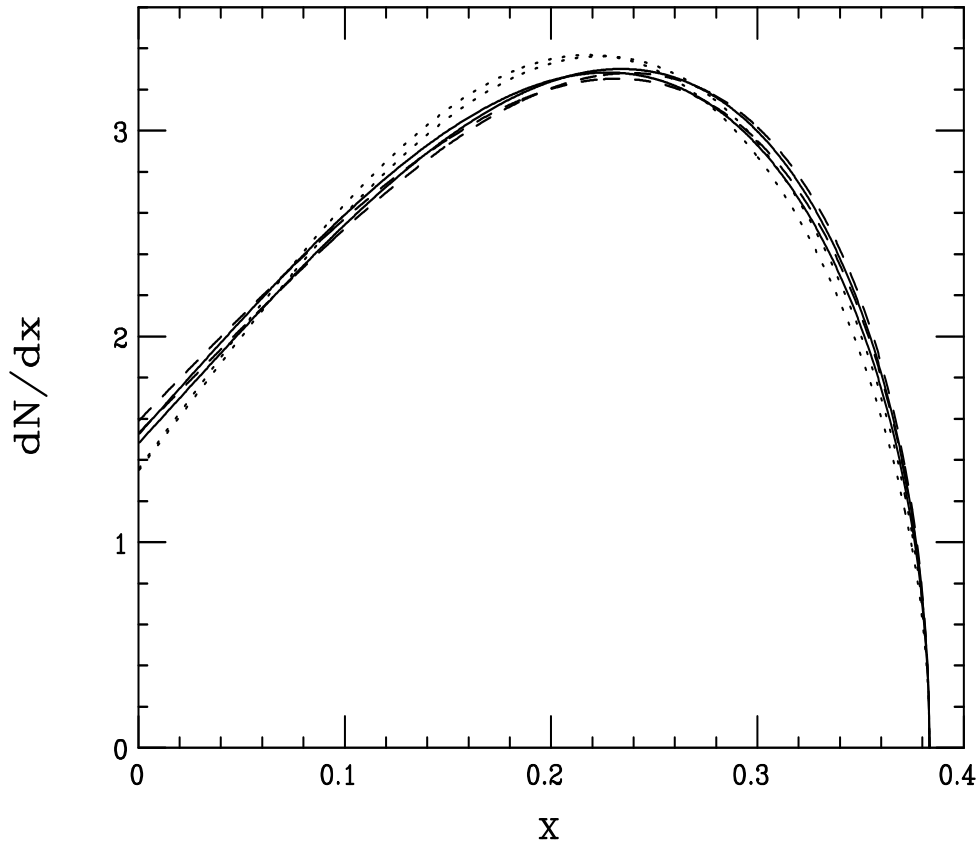


Figure 2: Normalized q^2 distributions for the process $B \rightarrow D^* \ell \nu$. Here $x = q^2/M^2$ and the curves correspond to the SM (solid) and $\lambda = 0.5$ (-0.5) (dotted and dashed, respectively). A possible p_t cut on the charged lepton momenta has been ignored. Results are shown for both the Neubert as well as the Close and Wambach HQET functions corresponding to the pair of curves for each case.

One might ask if there are other observables associated with this exclusive decay

that could allow for some additional sensitivity to RH current interactions[15]. To this end we briefly examine both the q^2 and χ distributions which can be measured using the recoil momentum of the D^* and identifying the angle between the W and D^* event planes, respectively. Once integrated over all other variables, the deviations in both these distributions from the SM expectations are found to be totally controlled by the value of the ratio $\lambda = 2|\xi|c_{\Delta}/(1 + |\xi|^2)$. The form of the q^2 distribution can be obtained immediately from the double differential expression above. Fig. 2, where we have used the HQET functions, R_i , of Neubert[16] and those of Close and Wambach[18], shows that the normalized distribution is only very weakly dependent on the existence of RH currents. Specifically, we see a direct comparison of the SM distribution, $\lambda = 0$, with that expected for the cases of $\lambda = \pm 0.5$. From the figure it appears unlikely that the shape of the q^2 distribution will yield any useful information on RH currents unless very high precision data is obtainable. Note there is little difference between the curves generated with the two different sets of HQET functions.

In the case of the normalized χ distribution, the shape is controlled by a single parameter *if* all the other variables have been completely integrated over, *i.e.*,

$$\frac{dN}{d\chi} = \frac{1}{\pi}(1 - \Omega \cos 2\chi), \quad (18)$$

where

$$\Omega = \frac{\int dq^2 Pq^2 \text{Re}(H_+^* H_-)}{\int dq^2 Pq^2 (H_+^2 + H_-^2 + H_0^2)}, \quad (19)$$

which we may rewrite to show the λ dependence explicitly as

$$\Omega = -\frac{(T_2 + T_1\lambda)}{(2T_1 + T_3) + (2T_2 - T_3)\lambda}, \quad (20)$$

with the T_i being a set of kinematic integrals. In the SM one finds that $\Omega \simeq 0.175(0.192)$ using Neubert(CW) HQET functions. Note that if instead only the even(odd) values of

$\cos \theta_V$ are integrated over, the normalized χ distribution picks up an additional term of the form

$$\frac{dN}{d\chi} \rightarrow \frac{dN}{d\chi} \mp \frac{3}{8} \Sigma \cos \chi, \quad (21)$$

where

$$\Sigma = \frac{\int dq^2 Pq^2 \text{Re} H_0^*(H_+ - H_-)}{\int dq^2 Pq^2 (H_+^2 + H_-^2 + H_0^2)}. \quad (22)$$

For this variable the ξ and c_Δ dependencies become are somewhat more complex and cannot be expressed simply through the parameter λ ; Σ is expressible as

$$\Sigma = \frac{T_4 \frac{(1 - |\xi|^2)}{(1 + |\xi|^2)}}{(2T_1 + T_3) + (2T_2 - T_3)\lambda}, \quad (23)$$

with T_4 being another kinematic integral. In the SM one finds that $\Sigma \simeq -0.25(-0.22)$ for Neubert(CW) HQET functions.

Fig.3 shows that Ω is quite sensitive to positive values of λ so that one may hope to get a reasonable sensitivity to RH interactions if Ω could be precisely measured. Present data from CLEO is found to be consistent[2] with the expectations of the SM for Ω but the statistics are still rather poor. To get an idea of the potential sensitivity we have performed a straightforward two parameter (normalization and Ω) fit to the existing binned data as presented in Ref.[2]. To obtain improved statistics in this first fit we have combined the data in both the $\cos \theta_V > 0$ and $\cos \theta_V < 0$ regions. Unfortunately, the resulting distribution of the data shows little sensitivity to Ω . After background subtraction this fit yields $\Omega = 0.126 \pm 0.120$ at 95% CL which is certainly consistent with the SM. This constraint subsequently implies that λ lies in the 95% CL range $-3.3(-2.8) \leq \lambda \leq 0.71(0.75)$ for Neubert(CW) HQET functions using the results in Fig.3. As one would expect from the low sensitivity to negative λ , our bound in this case is rather poor.

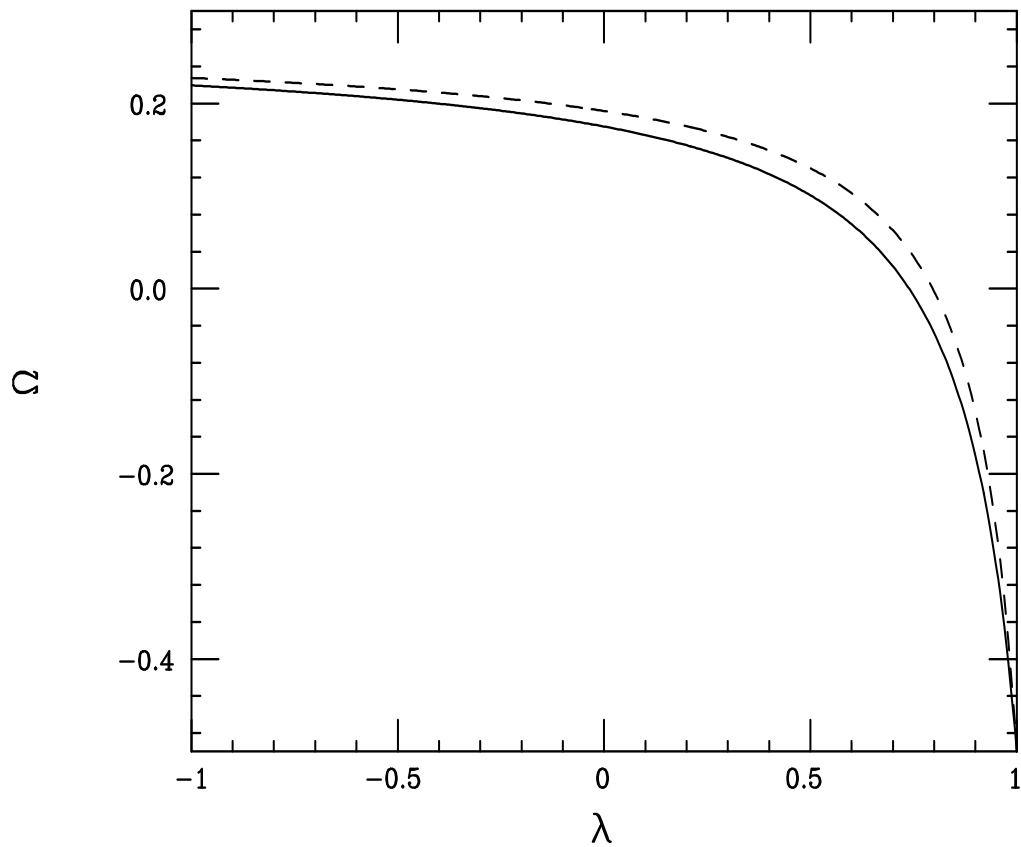


Figure 3: Value of the Ω parameter which controls the shape of the χ distribution as a function of λ . The results are shown for both the Neubert(solid) as well as the Close and Wambach(dashed) HQET functions which are seen to yield quite similar results.

A second more hopeful possibility is to fit the shape of the χ distribution for *both* Ω and Σ by treating the $\cos\theta_V > 0$ and $\cos\theta_V < 0$ regions independently; here there is a loss of statistics but a dramatic increase in sensitivity to RH couplings. Following the same analysis as above we arrive at the results presented in Fig.4 for the allowed region in the $c_\Delta - |\xi|$ plane for Neubert, CW as well as Isgur and Wise[19] HQET functions. Note that the allowed region resulting from this fit is somewhat sensitive to the HQET R_i choice, quite unlike the other observables that we have examined up to this point. Although this result seems to support the possibility that RH currents may indeed be present one must be hesitant to form such a hasty conclusion without further analysis. First, the only believable fit of this kind must be performed by the CLEO Collaboration and we note the apparent strong sensitivity of our result to the choice of the R_i HQET functions. However, it is certainly most clear that our understanding of potential RH currents in b decay would very much profit from higher precision measurements of the χ distribution. This seems possible during the first year of $\Upsilon(4S)$ running of BABAR and BELLE since the CLEO data sample used in this analysis corresponded to only 2.6 million $B\bar{B}$ pairs.

Another question one might ask is what the allowed range for the parameters Ω and Σ are given the CLEO constraints we have extracted from the earlier fit. To obtain such results we need to scan the $|\xi| - c_\Delta$ region below the envelope of curves shown in Fig.1 to get the extrema. We find $0.053 \leq \Omega \leq 0.207$ and $-0.345 \leq \Sigma \leq -0.115$ for the Neubert HQET functions; correspondingly, for the CW HQET functions we obtain $0.089 \leq \Omega \leq 0.218$ and $-0.310 \leq \Sigma \leq -0.106$.

As a final note, if the τ polarization in the decay $B \rightarrow D^*\tau\nu$ can be measured, Wakaizumi has shown[20] that it provides yet another quantity which is fairly sensitive to $\xi \neq 0$. This decay mode will thus yield even more observables which can be used to probe for $b \rightarrow c$ RH currents due to the addition of finite mass terms associated with the τ . Of

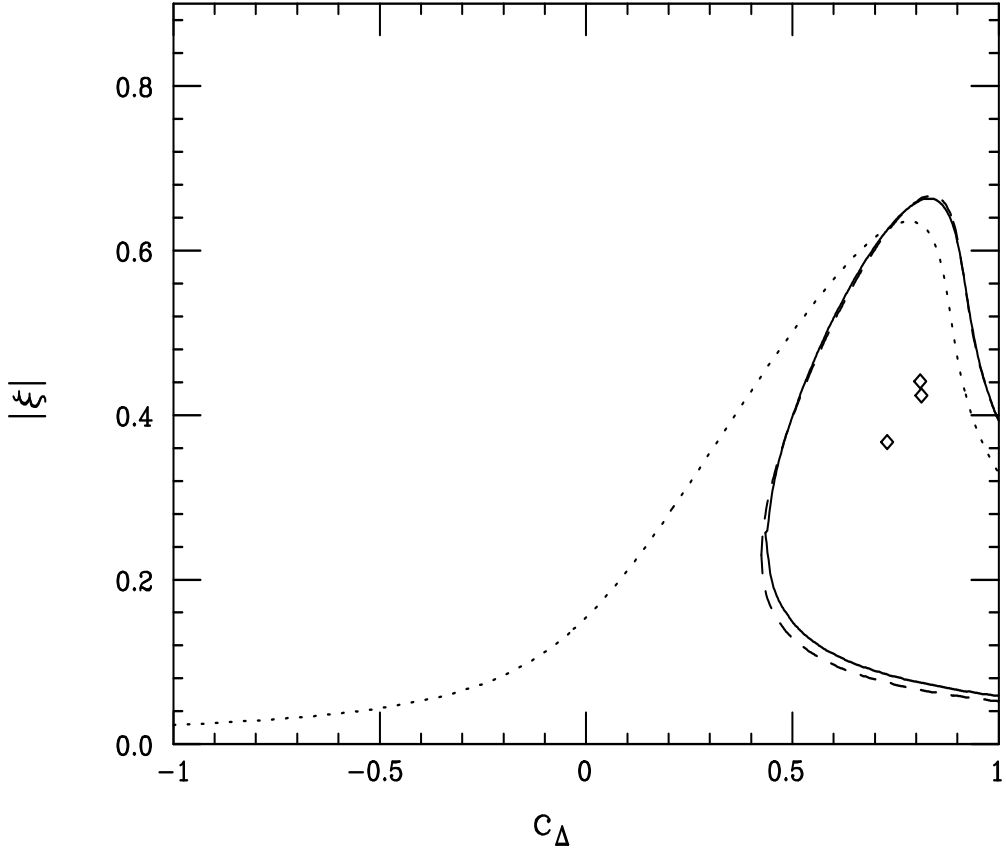


Figure 4: 95% CL fit to the shape of the CLEO χ distribution assuming Neubert(dotted), CW(dashed) or ISGW(solid) HQET functions. The allowed region is either below the dotted line or within the dashed or solid enclosure. As before the diamonds locate the χ^2 minima for the three sets of R_i .

course for this mode there is a loss in statistics due to the additional phase space suppression due to the τ mass as well as the associated τ reconstruction efficiency to be dealt with. An analysis of these prospects is, however, beyond the scope of the present work[9].

2.3 ALEPH

Unfortunately, other data cannot at present improve significantly upon the CLEO bounds without further employing some rather strong assumptions. For example, in principle the low Λ_b polarization observed in Z decay[4] by ALEPH can be used to obtain such a constraint. We recall that a b quark produced at the Z in the SM is highly polarized, *i.e.*, $P = -0.935$ and radiative effects have been shown to reduce this value only slightly[21]. During the hadronization process some of the memory of the original b polarization is lost but it had been anticipated that in the $b \rightarrow \Lambda_b$ process a large part of the original polarization would be kept[22]. Falk and Peskin[22] estimated on the basis of HQET that the resulting Λ_b polarization would be $P = -(0.69 \pm 0.06)$.

The ALEPH analysis is based on $\sim 3 \cdot 10^6$ hadronic Z decays which yielded a sample of 462 ± 31 Λ_b candidates. The method used by ALEPH to extract the value of P for the Λ_b was first suggested by Bonvicini and Randall[23] who noted that the ratio of the average values of the neutrino and lepton energies in semileptonic B decay, $y = \langle E_\ell \rangle / \langle E_\nu \rangle$, was particularly sensitive to the polarization of the b quark. This variable, being an energy ratio, is quite insensitive to b fragmentation, detector acceptance and reconstruction effects as well as the uncertainties in the ratio m_c/m_b . We note that the direct comparison of the average charged lepton and neutrino energies from b quark decays with theoretical expectations, as was done by L3[3], was found to lead to substantial fragmentation uncertainties although values of ξ of order unity were clearly excluded; we will return to the L3 data below. It

has also been found that α_s and $1/m_b^2$ corrections[24] to the parton level expectations for y are quite small (and, hence, will subsequently be ignored). Of course these results have only been explicitly demonstrated in the case of purely LH couplings. In our analysis we will make the reasonable assumption that they remain true when both LH and RH couplings are present.

The averages of E_ℓ and E_ν can be calculated directly from the decay at rest spectra through the boost relations $E_\ell = \gamma(E_\ell^* + \beta p_L^*)$, *etc.*, with $\beta \simeq 1$ and p_L^* being the lepton's momentum in the boost direction. In order to remove selection cut and energy reconstruction errors which produce a bias in y , ALEPH instead determined the ratio of ratios $R_y = y_{data}/y_{MC}(0)$ where $y_{MC}(0)$ is the y value obtained from a Monte Carlo simulation employing the SM in the limit of zero polarization. The value of R_y was then compared with the Monte Carlo-corrected SM theory prediction to extract the value of P . What ALEPH found was $R_y = 1.10 \pm 0.13$ (including systematic errors in quadrature) that then yielded the intriguingly small value $P = -0.23_{-0.23}^{+0.26}$, which is significantly smaller in magnitude, by $\simeq 2\sigma$, than the expectations of Falk and Peskin.

To investigate the double ratio R_y in the case when RH currents are present, we must return to the normalized double-differential charged lepton decay distribution. In the b rest frame to leading order and neglecting the lepton mass we find

$$\frac{dN}{dzd\cos\theta} = \left[\frac{R(x,z) + P\cos\theta Q(x,z)}{(1+|\xi|^2)f(x) + 2\text{Re}(\xi)g(x)} \right], \quad (24)$$

where $z = 2E_\ell/m_b$ and θ is the angle between the b and ℓ momenta with $f(x)$ and $g(x)$ given above. Explicitly, we find that $R = R_{LL} + R_{RR}|\xi|^2 + 2\text{Re}(\xi)R_{RL}$ and $Q = Q_{LL} + Q_{RR}|\xi|^2 +$

$2\text{Re}(\xi)Q_{RL}$ with

$$\begin{aligned}
R_{LL} &= \frac{z^2(1-x^2-z)^2}{(1-z)^3} \left[(1-z)(3-2z+x^2) + 2x^2 \right], \\
R_{RR} &= \frac{6z^2(1-x^2-z)^2}{(1-z)}, \\
R_{LR} &= -\frac{6xz^2(1-x^2-z)^2}{2(1-z)^2},
\end{aligned} \tag{25}$$

and

$$\begin{aligned}
Q_{LL} &= \frac{z^2(1-x^2-z)^2}{(1-z)^3} \left[(1-z)(1-2z+x^2) - 2x^2 \right], \\
Q_{RR} &= \frac{6z^2(1-x^2-z)^2}{(1-z)}, \\
Q_{LR} &= -\frac{6xz^2(1-x^2-z)^2}{2(1-z)^2}.
\end{aligned} \tag{26}$$

These results confirm those obtained by Tsai[25] long ago in a different form and context. The corresponding expressions for the neutrino spectrum can be obtained from the explicit relations above by interchanging the role of the left- and right-handed labels. Using these results we can calculate y following Bonvicini and Randall[23], rescale this value by the SM result assuming $P = 0$, and include the Monte Carlo corrections of ALEPH. Given an assumed value for P we can then fit to the ALEPH data to obtain an allowed region in the $|\xi| - c_\Delta$ plane. The result of this analysis is shown in Fig. 5 and is compared to the CLEO allowed region obtained above *assuming* the estimate of the polarization retention of Falk and Peskin, $P = -(0.69 \pm 0.06)$, is correct. Here we see that at the 95% CL almost the entire plane is allowed except for a possible small region on the lower right which only appears in the case of $P = -0.75$. As P increases in magnitude, we note that the allowed parameter

space region shrinks somewhat in size. We also see from the figure that the location of the best fit is quite sensitive to the assumed true value of the polarization. We note that if there are additional dynamical mechanisms[26] which could lead to a further reduction in the expected value of P in the SM *and* they could be reliably trusted quantitatively, then the limits we would obtain on RH $b \rightarrow c$ couplings might be improved. In the future if the central value obtained by ALEPH was verified and the errors were reduced by a factor of two the size of the allowed region would shrink substantially and form a band approximately $\delta|\xi| \simeq \pm 0.25$ wide on either side of the best fit points shown in the Figure.

If the apparent low value of the polarization as measured by ALEPH is verified by future experiments then there are only two conclusions. Within the SM framework there must be some new source of depolarization and indeed $P \simeq -0.23$. Alternatively, right-handed currents are present and the true value of P is closer to the HQET expectations of $P \simeq -0.69$ but *appears* low when interpreted in terms of the SM. As discussed above, a reduction in the ALEPH error by a factor of two, assuming the same central value, would clearly define a small allowed region when combined with the results from CLEO. Unfortunately, a measurement of R_y *alone*, no matter how precise, will be able to eliminate the possibility of some exotic depolarization mechanism and allow us to conclude that RH couplings exist. However, an analysis of the higher y moments or other possible distributions may be most helpful as suggested by Diaconu *et al.*[23] in an important paper. For simplicity we first consider only the ratio of the second moments of the decay distributions here. (We have not examined moments higher than second.) Within the SM if $x = 0.29$ and $P = -0.23$ we can uniquely predict the value of the quantity $R_{2y} = y_2/y_2(0) = 1.181$, where $y_2 = \langle E_\ell^2 \rangle / \langle E_\nu^2 \rangle$, although α_s and $1/m_b^2$ corrections are somewhat larger here. In the case where RH currents are present and $P = -0.69$, we can invert the R_y relation and find $|\xi|$ as a function of c_Δ and then calculate the corresponding value of R_{2y} . We find in this case that for the central value

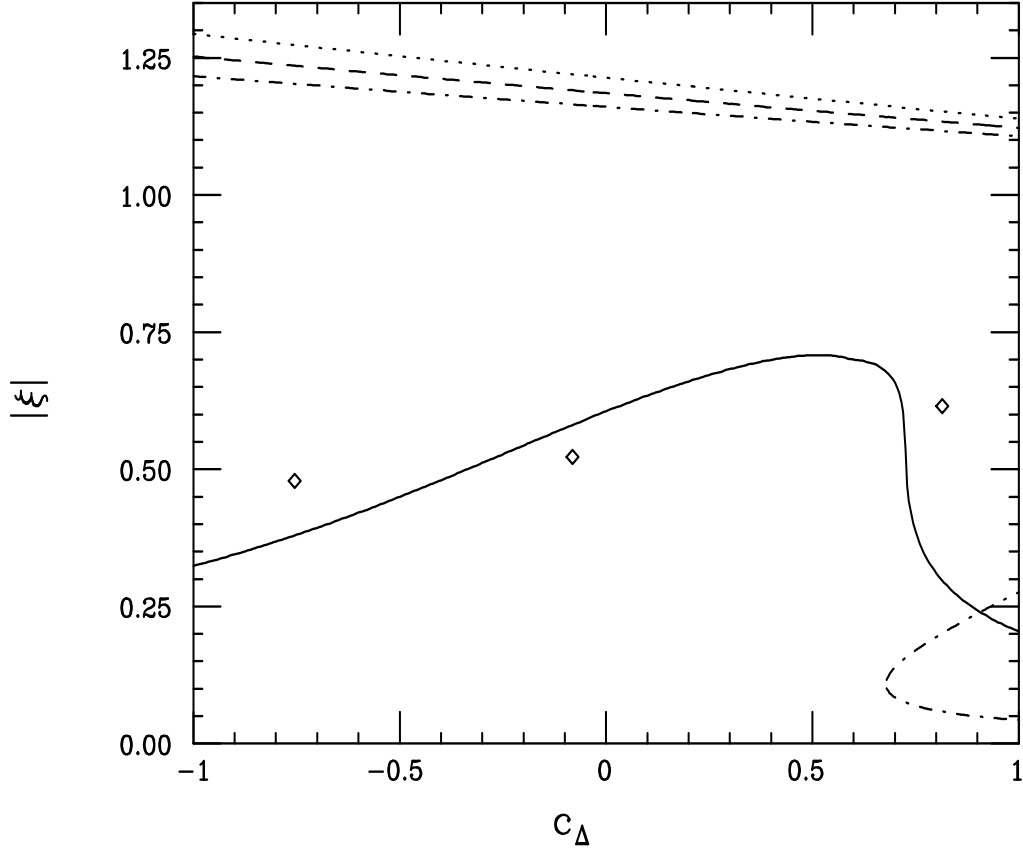


Figure 5: Comparison of the envelope of the 95% CL allowed regions obtained with CLEO data (solid curve) with those obtainable from the ALEPH Λ_b polarization results assuming $P = -(0.69 \pm 0.06)$ corresponding to the dotted, dashed and dash dotted curves. The region below the slightly tilted horizontal curves and outside the ‘nose’ on the lower right-hand side for the case of $P = -0.75$ are allowed. The location of the corresponding χ^2 minima for $P = -0.63, -0.69,$ and -0.75 , respectively, are also displayed from right to left.

$R_y = 1.10$ one obtains $1.198 \leq R_{2y} \leq 1.227$ apart from the above corrections; note that this range does not overlap with the SM expectation but the separation between the two is quite small. It would thus appear that simultaneous very high precision measurements of both R_y and R_{2y} , as well as possible higher moments, are required in order to be able to resolve the ambiguity and determine if RH currents are indeed present in semileptonic b decays. Given the current and anticipated sizes of the errors a determination of at least these first two moments alone will not necessarily prove useful.

As a second possibility we note that Diaconu *et al.* also suggest a number of other variables which can be used to probe the Λ_b polarization. One of these is the difference in the charged lepton and neutrino rapidities, $\Delta\eta = \eta_\ell - \eta_\nu$, where these rapidities are measured with respect to the boost direction. This quantity is directly proportional to the polarization and, being a rapidity difference, is fortunately insensitive to fragmentation uncertainties. We find that with RH currents contributing one obtains

$$\Delta\eta = P \int_{-1}^1 d \cos \theta \eta(1 - |\xi|^2) \frac{\int dz(Q_{LL} - Q_{RR})}{(1 + |\xi|^2)f(x) + 2\text{Re}(\xi)g(x)}, \quad (27)$$

where $\eta = \frac{1}{2} \log \frac{(1 + \cos \theta)}{(1 - \cos \theta)}$. Numerically we confirm the SM result and more generally obtain

$$\Delta\eta \simeq \frac{-0.632P(1 - |\xi|^2)}{(1 + |\xi|^2) + 2|\xi|c_\Delta(-0.362)}, \quad (28)$$

so that in the SM for $P = -0.69(-0.23)$ we would obtain $\Delta\eta = 0.436(0.145)$. In the case of RH currents, repeating the above procedure to find $|\xi|$ as a function of c_Δ from the data on R_y we are led to the prediction that $\Delta\eta = 0.238 - 0.257$, assuming that $P = -0.69$, which is quite different from either the SM expectation with a low value of P or the HQET SM prediction. Again it appears that the RH current and exotic depolarization mechanism possibilities may be separable using precision measurements. However in this case we note

that the required level of precision for this variable is far less than that for R_{2y} giving us some hope that such a separation may indeed be possible at future B factories.

2.4 L3

Following the same approach as above one might attempt to further quantify the L3[3] constraints on ξ by constructing the y values using the results presented in their Table 2 and including some corrections associated with their Monte Carlo. This would then be similar to the ALEPH analysis but now one is actually probing the initial b quark polarization about which there is far less uncertainty. Of course, in principle, only L3 can perform this procedure but our rudimentary study will provide an indication for the location and size of the allowed region associated with their data. If we simply double their errors but then ignore both the α_s and $1/m_b^2$ corrections as well as fragmentation and energy scale uncertainties and neglect any correlations, we can obtain an estimate for the associated allowed region in the $c_\Delta - |\xi|$ plane. This most likely substantially underestimates the present experimental and theoretical uncertainties. Here we also need to input the parton-level polarization, $P = -0.935$. The results of these questionable considerations are shown in Fig. 6 and are compared to the CLEO analysis constraints. From this figure we see that the crude estimate of the L3 constraints and those obtained above from CLEO are not in conflict and even tend to prefer similar regions of the parameter space. The sizes of the two allowed regions are rather comparable and substantially overlap. It is also clear from the figure that the L3 data certainly excludes both a $(V + A) \times (V - A)$ as well as a $V \times (V - A)$ interaction as several σ as claimed. Before we can draw any stronger conclusions, however, this analysis needs to be repeated by L3 themselves with the additional α_s and $1/m_b^2$ corrections included. We can conclude that future spectra determinations from inclusive decays will indeed be useful in probing for RH currents provided high statistics are available and systematic experimental

uncertainties are under control. Since the L3 analysis is based on a sample of only 10^6 Z 's it is clear that a higher statistical study can be performed.

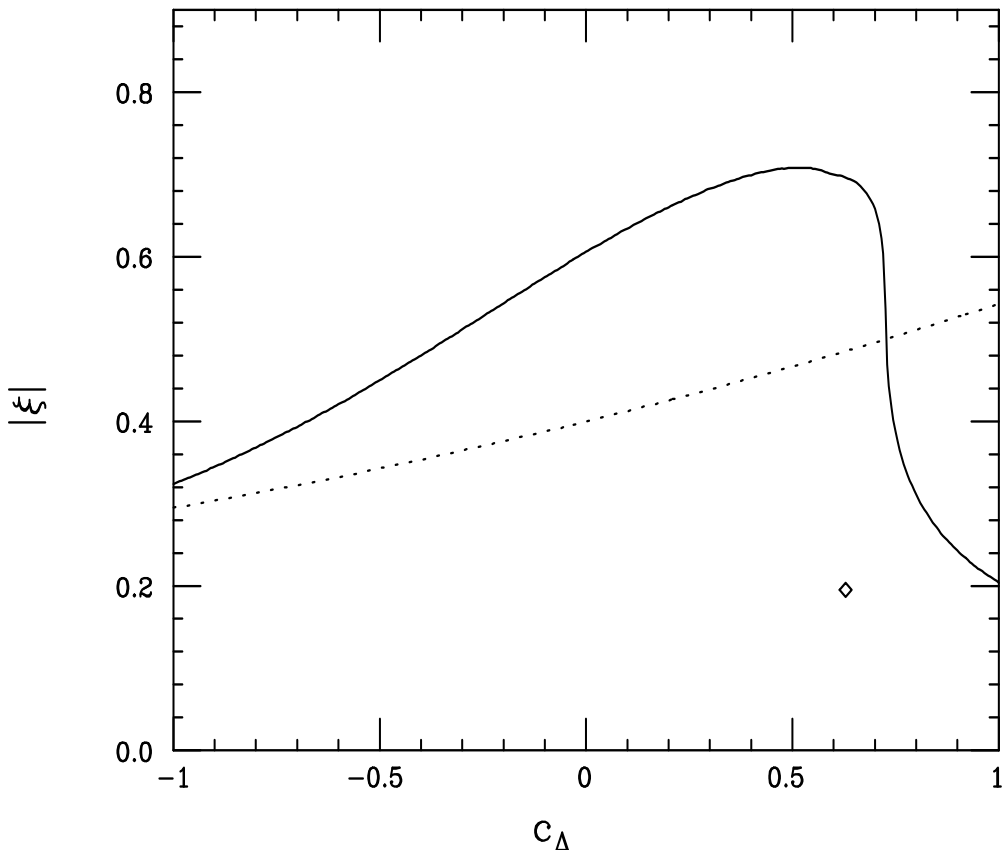


Figure 6: Comparison of the envelope of the 95% CL allowed regions obtained with CLEO data(solid curve) with an estimate of the upper bound obtainable from the analysis of the L3 charged lepton and neutrino data(dotted curve). The location of the χ^2 minima from the L3 analysis is also shown.

3 The Left-Right Model and ξ

If RH currents do exist, given the CLEO allowed region in the $|\xi| - c_\Delta$ plane shown in Fig.1, we want to know if there are any sub-regions of this allowed space that can yield a

simultaneous lowering of the SM predictions for B_ℓ and n_c . To address this question we will need to go beyond the physics described by the effective Hamiltonian in Eq.(1) since, *e.g.*, we need to discuss non-leptonic decay modes such as $b \rightarrow c\bar{u}d(s)$ and $b \rightarrow c\bar{c}s(d)$ and the role RH currents may play in these channels. To do this we need to incorporate the physics of \mathcal{H}_{sl} into a larger framework, *e.g.*, the LRM[7]. We remind the reader that other frameworks, such as R -parity violation schemes, are also possible[27] sources of effective RH currents.

In order to be self-contained let us briefly review the relevant parts of the LRM we need for our discussion below; for details of the model the reader is referred to [7]. The LRM is based on the extended gauge group $SU(2)_L \times SU(2)_R \times U(1)$. Due to this extension there are both new neutral and charged gauge bosons, Z', W_R^\pm , in addition to those present in the Standard Model. In this scenario the left-(right-)handed fermions of the SM are assigned to doublets under the $SU(2)_{L(R)}$ group and a RH neutrino is introduced. The Higgs fields which can directly generate SM fermion masses are thus in *bi-doublet* representations, *i.e.*, they transform as doublets under both $SU(2)$ groups. The LRM is quite robust and possesses a large number of free parameters which play an interdependent role in the calculation of observables and in the existing constraints on the model resulting from various experiments.

As far as B physics and the subsequent discussion are concerned there are several parameters of direct interest. The most obvious free parameter is the ratio of the $SU(2)_R$ and $SU(2)_L$ gauge couplings $0.55 < \kappa = g_R/g_L \leq 2$; the lower limit is a model constraint while the upper one is simply a naturalness assumption. GUT embedding scenarios *generally* suggest that $\kappa \leq 1$ [28]. For simplicity we will assume that $\kappa = 1$ in almost all of our discussion below. The extended gauge symmetry is broken in two stages. First the $SU(2)_L \times SU(2)_R \times U(1)$ symmetry is broken down to the SM via the action of Higgs fields that transform either as doublets or triplets under $SU(2)_R$. This choice of Higgs representation determines both

the mass relationship between the Z' and W_R (analogous to the condition that $\rho = 1$ in the SM with only Higgs doublets and singlets) as well as the nature of neutrino masses; in particular, the Higgs triplet choice which we employ here allows for the implementation of the see-saw mechanism and yields a heavy RH neutrino.

After complete symmetry breaking the resulting $W_L - W_R$ mixing is described by two parameters, a real mixing angle, ϕ , and a phase, ω . Note that it is usually $t = \tan \phi$ which appears in expressions directly related to observables. The additional phase, as always, can be a new source of CP violation. The mixing between W_L and W_R results in the mass eigenstates $W_{1,2}$, with a ratio of masses, $r = M_1^2/M_2^2$, (with $M_2 \simeq M_R$). In most models T is then naturally of order a few times r or less in the large M_2 limit. Of course, W_1 is the state directly being produced at both the Tevatron and LEP II and is identical to the SM W in the $\phi \rightarrow 0$ limit. We note that when ϕ is non-zero, W_1 no longer couples to a purely LH current. Of course if a heavy RH neutrino is indeed realized then the effective *leptonic* current coupling to W_1 remains purely LH as far as all low energy experiments are concerned. As is well-known, one of the strongest set of ‘classical’ constraints on this model arises from polarized μ decay[8], which are trivial to satisfy in the case of a heavy RH neutrino and this justifies the appearance of only LH leptonic couplings in Eq.(1). Removal of these constraints provides significantly more freedom in the remaining LRM parameter space. Thus the tree-level μ decay Hamiltonian is just

$$\mathcal{H}_\mu = \frac{g_L^2 c_\phi^2 (1 + rt^2)}{2M_1^2} (\bar{\nu}_{\mu L} \gamma_\lambda \mu_L) (\bar{e}_L \gamma^\lambda \nu_{eL}), \quad (29)$$

so that the tree-level definition of G_F is simply

$$\frac{G_F}{\sqrt{2}} = \frac{g_L^2 c_\phi^2 (1 + rt^2)}{8M_1^2}. \quad (30)$$

We see that if r and t are of order $\simeq 10^{-2}$ or less the numerical influence of mixing in this

relationship will be quite small.

We note that it is important to be reminded that the extended Higgs sector associated with both the breaking of the LRM group down to $U(1)_{em}$ and the complete generation of fermion masses may also have an important role to play in low energy physics through both the existence of complex Yukawa and/or flavor-changing neutral current type couplings. However, this sector of the LRM is highly model dependent and is of course quite sensitive to the detailed nature of the fermion mass generation problem. For purposes of brevity and simplicity and because tree-level neutral Higgs exchange can little influence the decay processes we are interested in these too will be ignored in the following discussion and we will focus solely on the effects associated with $W_{1,2}$ exchange. We do note that these additional Higgs fields can potentially play a very important role in loop processes as will be briefly discussed later.

Additional parameters arise in the quark sector; in principle the effective mass matrices for the SM fermions may be non-hermitian implying that the two matrices involved in the bi-unitary transformation needed to diagonalize them will be unrelated. This means that the elements of the mixing matrix, V_R , appearing in the RH charged current for quarks will be *unrelated* to the corresponding elements of $V_L = V_{CKM}$. V_R will then involve 3 new angles as well as 6 additional phases all of which are *a priori* unknown parameters[29]. The possibility that V_L and V_R may be unrelated is sometimes overlooked when considering the potential impact of the LRM on low energy physics and there has been very little detailed exploration of this more general situation due to the rather large parameter space. Certainly as the elements of V_R are allowed to vary the impact of the extended gauge sector on B physics in general will be greatly effected.

Some well-known constraints on the LRM, such as Tevatron direct W' searches[30], are quite sensitive to variations in V_R [31] as well as the properties of the RH neutrino and

W_2 masses as low as 450 – 500 GeV can very easily be accommodated by the present data. To be conservative, and with future Tevatron searches in mind, however, we will assume below that $M_2 \geq 720$ GeV[30], *i.e.*, $r \leq 0.012$, for any V_R implying that the magnitude of t is also less than ~ 0.012 . Other constraints on the LRM parameter space involve loop processes such as the $K_L - K_S$ mass difference[32, 33] and $b \rightarrow s\gamma$ [34]. Clearly the bounds obtained from these processes depend not only on the gauge sector but also on *all* the particles that can participate in the loops such as SUSY partners, extra Higgs fields, additional heavy fermions, *etc.*, whose existence is sensitive to the finer details of the model. These possibilities are beyond the necessities of the current discussion where we are solely interested in tree-level B decays. Our philosophy as outlined in the introduction will be to leave for now all discussions of loop graphs which display any sensitivity to the details of the LRM spectrum and take these issues up briefly later.

Using the definitions above for the LRM parameters we can now express ξ in terms of these more fundamental quantities; we find

$$\xi = \frac{\kappa t(1-r)}{(1+rt^2)} \frac{e^{i\omega} V_{cb}^R}{V_{cb}^L}. \quad (31)$$

Note that we can absorb the sign of t into the phase ω here so that t can be treated as a positive parameter in our discussion below. As mentioned above we will take $\kappa = 1$ for simplicity in our numerical analysis below; to first order it simply rescales the value of t . Employing the results from Buras[17] for the value of $V_{cb}^L \text{ }^{inc}(D^*)$ from inclusive B semileptonic decays, we can invert the expression above to obtain

$$|V_{cb}^R| = (39.9 \pm 2.2) \cdot 10^{-3} \frac{|\xi|}{[1 + |\xi|^2 + 2\xi c_\Delta \frac{g}{f}]^{1/2}} \frac{(1+rt^2)}{\kappa t(1-r)}, \quad (32)$$

so that for typical values such as $|\xi| = 0.2$, $c_\Delta=0$, and $x = 0.29$, we obtain

$$|V_{cb}^R| = (0.782 \pm 0.042) \left[\frac{10^{-2}}{\kappa t} \right] [1 + \mathcal{O}(r, rt^2)], \quad (33)$$

which suggests that $|V_{cb}^R|$ is reasonably large and perhaps of order unity over most of the allowed parameter space shown in Fig. 1. From these considerations we learn several things which follow immediately from the unitarity of V_R : (i) A large value for $|V_{cb}^R|$ implies that the sum $|V_{cd}^R|^2 + |V_{cs}^R|^2$ is small thus somewhat suppressing potential RH contributions to the decays $b \rightarrow c\bar{c}s(d)$, which is fortunate for charm counting purposes. If either of these elements were large one might expect a significant increase in n_c due to RH current contributions. As we will see below, just the opposite occurs. As will be noted, this also assists in suppressing RH contributions to $K_L - K_S$ mixing. (ii) Since unitarity requires $|V_{ud}^R|^2 + |V_{us}^R|^2 + |V_{ub}^R|^2 = |V_{ub}^R|^2 + |V_{cb}^R|^2 + |V_{tb}^R|^2$ it follows immediately that $|V_{ud}^R|^2 + |V_{us}^R|^2 > |V_{cb}^R|^2$. However, since $|V_{cb}^R|^2$ is apparently large this inequality implies that the sum $|V_{ud}^R|^2 + |V_{us}^R|^2$ is larger still. This would mean that decay modes such as $b \rightarrow c\bar{u}d(s)$ may receive large RH contributions. We note that if we further assume that $|V_{ud}^R|^2 \ll |V_{us}^R|^2$ these RH contributions may also lead to an increase in K production in B decays[35], which it has been argued is a signal for enhanced $b \rightarrow sg$. Also if $|V_{ud}^R|^2 \ll |V_{us}^R|^2$ one finds that the Tevatron search reach[30] for W_2 would be seriously degraded by about a factor of 2[31] in mass. (iii) It would appear that $|V_{ub}^R|$ will be too small to significantly influence $b \rightarrow u$ processes, though this needs further examination. (iv) A large V_{cb}^R implies that the sum $|V_{td}^R|^2 + |V_{ts}^R|^2$ is also large[27] with implications for the complete structure of V_R that we will ignore for now but will return to haunt us in our discussion below. (v) The fact that unitarity requires $|V_{cb}^R| \leq 1$ itself provides an additional constraint on the remaining LRM parameters.

4 Non-leptonic $b \rightarrow c$ Decays with RH Currents

As a final step in our analysis we need the complete non-leptonic Hamiltonian; at the tree-level this can now be written down immediately. For the sample case of $b \rightarrow c\bar{u}d$ we can write, following the notation in Refs.[11, 36],

$$\mathcal{H}_{nl} = \frac{4G_F}{\sqrt{2}} \left[C_{2L} O_{2L} + C_{12L} O_{12L} + L \rightarrow R \right], \quad (34)$$

where $O_{2L} = (\bar{c}\gamma_\mu P_L b)(\bar{d}\gamma^\mu P_L u)$, $O_{12L} = (\bar{c}\gamma_\mu P_R b)(\bar{d}\gamma^\mu P_L u)$, *etc.* and where $P_{L,R}$ are helicity projection operators. At the *weak* scale the operator coefficients are given by

$$\begin{aligned} C_{2L} &= (V_{cb}^L)(V_{ud}^{L*}), \\ C_{12L} &= \left[\frac{\kappa t(1-r)}{(1+rt^2)} \right] (V_{cb}^R)(V_{ud}^{L*}), \\ C_{12R} &= \left[\frac{\kappa t(1-r)}{(1+rt^2)} \right] (V_{cb}^L)(V_{ud}^{R*}), \\ C_{2R} &= \left[\frac{\kappa^2(r+t^2)}{(1+rt^2)^2} \right] (V_{cb}^R)(V_{ud}^{R*}). \end{aligned} \quad (35)$$

Note that if we neglect the light quark masses the appropriate phase space functions for this particular decay mode will be given by f and g . The modifications necessary for the study of the decay $b \rightarrow c\bar{u}s$ are obvious. Similarly for the corresponding decays $b \rightarrow c\bar{c}s(d)$ we simply change the appropriate CKM factors in the above and employ the appropriate phase space functions, f_c and g_c , which are given by the phase space integrals $I_{1,2}$ in Section 2 with the replacement $y \rightarrow x$. For $x = 0.29$ these are found numerically to be $f_c \simeq 0.222$ and $g_c \simeq -0.086$. The neglect of the strange quark mass, $m_s \simeq 100 - 150 \text{ MeV}$, is found to be an excellent approximation here.

To proceed with this calculation we need to compute the QCD corrections associated with the Renormalization Group running from the weak matching scale down to $\mu \sim m_b$. To this end we follow the analysis of Bagan *et al.*[37] which allows us to write the partial width for this process as

$$\Gamma(b \rightarrow c\bar{u}d(s)) = \Gamma_{SM} \left[1 + \eta_1 + \eta_2 + \eta_3 \right], \quad (36)$$

where $\Gamma_{SM} = 3X_1\Gamma_0 f|V_{cb}^L|^2(|V_{ud}^L|^2 + |V_{us}^L|^2)$, Γ_0 is the canonical μ decay width with the replacement $\mu \rightarrow m_b$, and X_1 represents the results of SM QCD corrections(to which we will return below). The η_i are LRM contributions which given by

$$\begin{aligned} \eta_1 &= \left[\frac{\kappa^2(r+t^2)}{(1+rt^2)} \right] |\xi|^2 y, \\ \eta_2 &= \frac{X_2}{X_1} \left[|\xi|^2 + \frac{\kappa^2 t^2 (1-r)^2}{(1+rt^2)^2} y \right], \\ \eta_3 &= 2 \frac{g}{f} \frac{X_3}{X_1} \text{Re}(\xi) \left[1 + \frac{\kappa^2(r+t^2)}{(1+rt^2)} y \right], \end{aligned} \quad (37)$$

with $y = (|V_{ud}^R|^2 + |V_{us}^R|^2)/(|V_{ud}^L|^2 + |V_{us}^L|^2) \simeq (|V_{ud}^R|^2 + |V_{us}^R|^2)$. As pointed out in the discussion above, if $|V_{cb}^R|$ is large we anticipate that y is near unity. For the decays $b \rightarrow c\bar{c}s(d)$ we make the obvious CKM replacements and the change the $X_i \rightarrow X'_i$, $f, g \rightarrow f_c, g_c$ and let $y \rightarrow y_c$ where $y_c = (|V_{cd}^R|^2 + |V_{cs}^R|^2)/(|V_{cd}^L|^2 + |V_{cs}^L|^2) \simeq 1 - |V_{cb}^R|^2$, with the last near equality resulting from unitarity and the fact that $|V_{ub}^L|^2$ is very small. If $|V_{cb}^R|^2$ is large then clearly y_c must then be small.

At leading order(LO) in QCD the $X_i = X'_i$ are completely calculable and are simple polynomials in the parameter

$$z = \left[\frac{\alpha_s(M_W)}{\alpha_s(\mu)} \right]^{3/23}, \quad (38)$$

and its inverse; here we will assume that $\alpha_s(M_Z) = 0.118$ and $\mu \sim m_b$. Explicitly, we obtain

$$\begin{aligned}
X_1 &= \frac{1}{3} \left[2z^4 + z^{-8} \right], \\
X_2 &= \frac{1}{9} \left[8z^2 + z^{-16} \right], \\
X_3 &= \frac{1}{9} \left[4z^3 + 4z^{-3} + 2z^{-6} - z^{-12} \right],
\end{aligned}
\tag{39}$$

where we have made use of the results of Altarelli and Maiani[12] as well as Cho and Misiak[34]. Note all $X_i \rightarrow 1$ as $z \rightarrow 1$ and the QCD corrections vanish. In the SM, NLO multiplicative corrections to the LO values of X_1 and X'_1 are now known[37] to be $\simeq 1.061$ and $\simeq 1.29$, respectively, for $\mu = m_b$, $x = 0.29$, and using pole quark masses ($m_b = 4.8$ GeV), both of which we adopt in the numerical analysis below. Unfortunately, the corresponding NLO corrections to $X_{2,3}$ and $X'_{2,3}$ are not yet known. The best we can do until such calculations are performed is to follow Voloshin's philosophy and assume the multiplicative corrections in these cases are essentially the same as those for X_1 and X'_1 . Since, as we will see below, we will be more interested in the *shifts* in the values of n_c and B_ℓ due to RH currents than the values themselves, we anticipate that this assumption may be a fair approximation. We note that in making this assumption we are also ignoring the possibility that the detailed LRM particle spectrum may lead to substantial modifications in these SM values, in particular, those contributions arising from penguins. These assumptions need to be verified by future direct calculations.

5 δB_ℓ and δn_c

From the discussion in the previous section we are ready to calculate both $\delta B_\ell = B_\ell(LRM) - B_\ell(SM)$ and $\delta n_c = n_c(LRM) - n_c(SM)$ where the SM results are given by the above expressions in the limit where all RH couplings are turned off. As is well known, the combined experimental and theoretical situation is quite puzzling. From the reviews of both Drell and Sachrajda[6] we see that $B_\ell = 0.1018 \pm 0.0040$ on the $\Upsilon(4S)$ while $B_\ell = 0.1095 \pm 0.0032$ at the Z . Similarly, $n_c = 1.119 \pm 0.053$ and 1.202 ± 0.067 on the $\Upsilon(4S)$ and Z , respectively. Numerically, in the SM limit our calculations essentially reproduce the earlier results of Bagan *et al.*[37] which we have closely followed; in this limit we obtain $B_\ell = 0.123$ and $n_c = 1.24$ for the SM predictions assuming $x = 0.29$ and $\mu = m_b$. We will implicitly assume that there are no new $b \rightarrow no\ charm$ final states, such as $b \rightarrow sg$, which are enhanced due to RH currents. It is clear that if we take these experimental numbers at face value we would like to decrease the theoretical predictions for B_ℓ by $0.015 - 0.020$ and n_c by at least 0.03 .

Our analysis consists of an extensive scan of the model parameter space spanned by $r, t, |\xi|, c_\Delta$ and y and demanding that a number of requirements be satisfied simultaneously. Our input parameters are chosen as follows. We begin by picking a ‘point’ inside of the CLEO allowed region in the $c_\Delta - |\xi|$ plane so that this constraint is already satisfied. We assume the scale size of the $c_\Delta - |\xi|$ grid to be 0.01×0.01 so that there are approximately $1.5 \cdot 10^4$ points in this sample. Next, we choose a value for the two LRM parameters r and t ; for simplicity κ is set to unity. Keeping in mind the CDF/D0[30] bounds and the strong suggestion that t cannot be much larger than r , we let $r = 0.0025, 0.005, 0.0075, 0.010$ or 0.012 and allow t to vary over the range 0 to 0.012 in steps of 0.0005 . (Remember that due to the phase freedom in angle Δ we can treat $t \geq 0$ in this discussion.) Clearly if the W_2 mass is too large and/or the mixing angle is too small the effects of RH currents will not be of a noticeable

magnitude. This restricts our attention to W_2 masses in the approximate range 730 – 1600 GeV. Thus we see that for every choice of c_Δ and $|\xi|$ there are 120 pairs of (r, t) values giving us a total of $\simeq 1.8 \cdot 10^6$ points to examine in the $r - t - |\xi| - c_\Delta$ parameter subspace.

The first constraint we impose is the requirement that $|V_{cb}^R|$ be less than unity by using Eq. (32). Of course if this constraint is not satisfied for any of the r or t values this point on the $c_\Delta - |\xi|$ grid is removed from any further consideration. If satisfied, the result fixes the value of y_c in the subsequent calculations. To proceed we must choose a value of y in the range $0 < y < 1$ which we do in grid steps of 0.01. We then impose our second constraint that $y \geq |V_{cb}^R|^2$ so that only the larger of the y values survive. Out of the original $\simeq 1.8 \cdot 10^8$ points in the five-dimensional $r - t - |\xi| - c_\Delta - y$ parameter space being scanned, only $\simeq 27.5 \cdot 10^6$ survive these first two constraints.

For these remaining points we next calculate δB_ℓ and δn_c for each particular choice of input parameters and impose our final loose requirement that $\delta B_\ell \leq -0.01$ and $\delta n_c \leq -0.025$. Again, if these constraints cannot be met at a particular point on the $c_\Delta - |\xi|$ grid, independently of the chosen values of r, t and y , it is removed. Only 6284 points in the the $r - t - |\xi| - c_\Delta - y$ five-dimensional parameter space now remain; this number is further reduced to 972 if we strengthen our requirement on δn_c to be ≤ -0.03 . It is clear from these numbers that a rather high degree of fine-tuning is required to push B_ℓ and n_c in the proper direction and to produce shifts with interesting magnitudes. For most values of the parameters the resulting shifts in B_ℓ and/or n_c are much too small to be of interest. The combination of these requirements is found to be extremely demanding on the model parameter space, yet two distinct sub-regions do survive.

If one plots the values of δB_ℓ and δn_c for the survivors we find that they essentially lie only along two straight lines in the $\delta B_\ell - \delta n_c$ plane with the choice of line depending

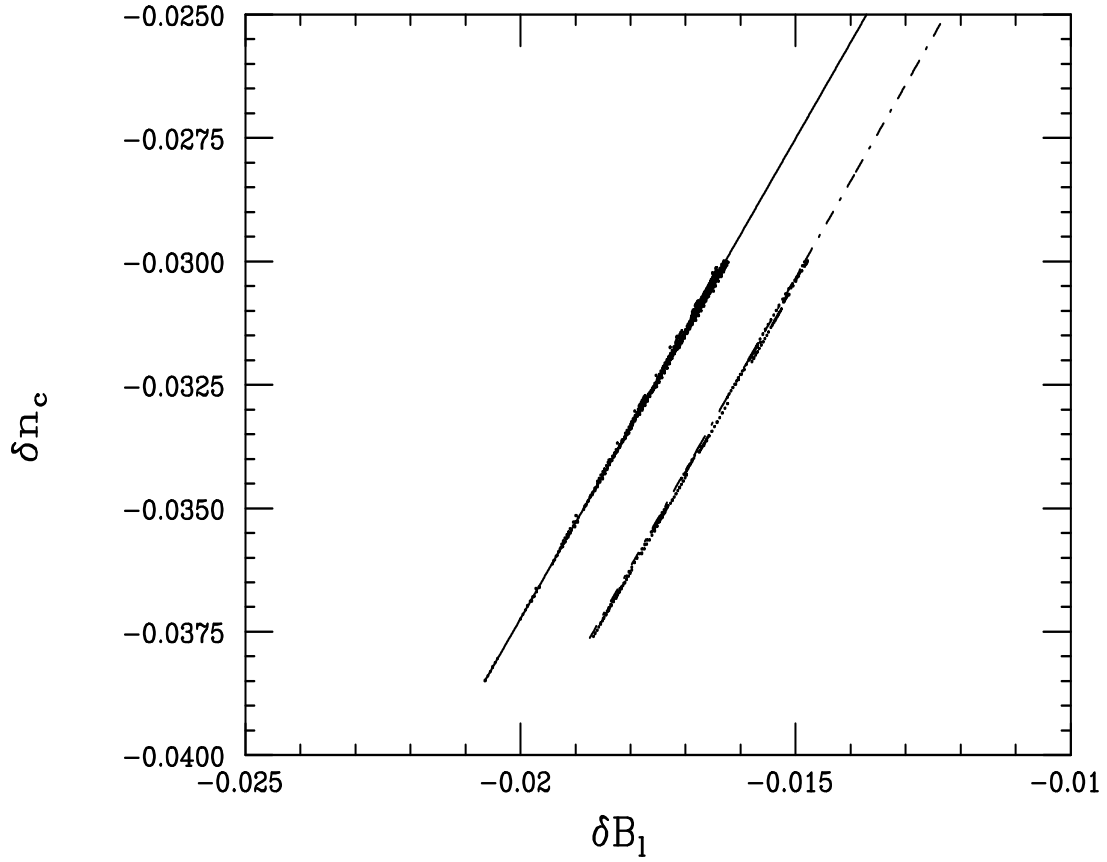


Figure 7: Location of surviving points in the $\delta B_\ell - \delta n_c$ plane. The 972 survivors of the $\delta n_c < -0.03$ cut are shown explicitly. The lines represent smoothed versions of the actual locations. The solid(dash-dotted) line corresponds to the solutions with $c_\Delta > (<)0$.

upon the sign of c_Δ as shown in Fig. 7. The corresponding location of these same points with $\delta n_c \leq -0.03$ projected onto the $c_\Delta - |\xi|$ plane are shown in Fig. 8. It is amusing to note that the points with $c_\Delta > 0$ lie within the region associated with the fit to CLEO's data on the χ distribution in $B \rightarrow D^*(\rightarrow D\pi)\ell\nu$ obtained above. Assuming $\delta n_c \leq -0.025(-0.03)$ approximately 92.5(75.1)% of the survivors are found to lie in the $c_\Delta > 0$ region. The fractional volume of the $\delta n_c \leq -0.025$ parameter space which also allows $\delta n_c \leq -0.03$ is $\simeq 15.5\%$. While the $c_\Delta < 0$ parameter space is only reduced to 51.4% of its previous size by strengthening this δn_c cut, the $c_\Delta > 0$ subspace is drastically reduced to only 12.6% of its previous population by this same cut.

What are some of the various properties of the parameter space points that satisfy all our requirements? Mostly they are exactly what one would naively expect. First, all of the 972 survivors have $t \geq 0.0095$ since larger mixing angles are required to enhance the contributions of the RH currents. Second, in all cases $|V_{cb}^R| \geq 0.908$ and there is a significant preference for larger values of r , *i.e.*, there are only 4(37) cases with $r = 0.0025(0.005)$.

6 Discussion and Conclusions

The chirality of the $b \rightarrow c$ coupling is one of the most important quantities in B physics. The original work of Gronau and Wakaizumi demonstrated to us just how little was actually known about this coupling at that time. Since then, after extensive theoretical and experimental effort, the situation remains far from being completely clarified. While CLEO and ALEPH have certainly demonstrated that the $b \rightarrow c$ coupling is dominantly LH in agreement with the SM, their results remain consistent with the possibility of a sizeable RH coupling. Furthermore, the interpretation of the low value of the Λ_b polarization obtained by L3 remains ambiguous and could either be a first signal for RH currents or simply a sign of our

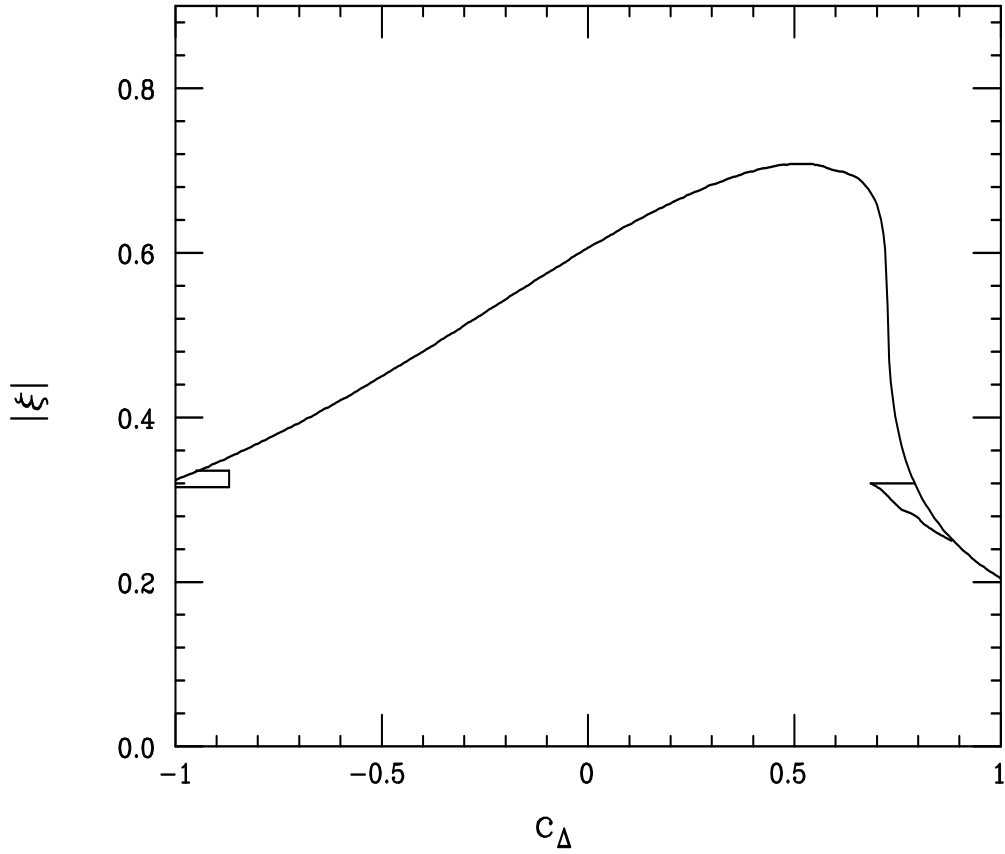


Figure 8: Locations of the zones containing the 972 surviving points in the $c_\Delta - |\xi|$ plane, in comparison to the envelope of that allowed by CLEO at 95% CL, which simultaneously satisfy $\delta n_c \leq -0.03$ and $\delta B_\ell \leq -0.01$.

ignorance of the strong interactions. All of these experimental analyses have been based on relatively small sample sizes and need to be repeated and improved upon.

As we saw in the analysis above, the exclusive $B \rightarrow D^*$ semileptonic decay provides us with a large number of observables that can be used to probe for RH couplings of reasonably small strength. In addition to the overall partial width, expressible in terms of $V_{cb}^{L\ exc}$, the measurements of the $\cos\theta_\ell$ and $\cos\theta_V$ distributions lead directly to the quantities A_{FB} and Γ_L/Γ_T , respectively. By using HQET we performed a fit to the present CLEO results for these quantities and demonstrated that the current bound on the RH coupling strength still remains rather poor especially if it is allowed to be complex. Improved statistics available at upcoming B factories will help tremendously here. Furthermore, while we showed that the q^2 distribution was not very sensitive to RH couplings, the χ distribution was found to be particularly so and yielded tantalizing indications for the existence of RH currents. Present CLEO data was shown to indicate that future measurements of this distribution will be extremely useful in either constraining or discovering RH couplings.

The low Λ_b polarization result obtained by L3 also remains tantalizing and certainly needs updating. Unfortunately, given our incomplete knowledge of QCD, any interpretation of the result in terms of RH currents can not be made at present. However, if high precision measurements of the lepton and missing energy spectra become available with only a factor of a few increase in statistics, we saw in the analysis above that sufficient observables do exist to separate the two possible explanations. Further observables may be found to strengthen any conclusions one may draw from future data.

Under the assumption that $b \rightarrow c$ RH currents *do* exist consistent with the bounds from CLEO, we have tried to address the question raised by Voloshin as to whether such new interactions could assist in solving the long standing problem associated with B_ℓ and n_c . To address this point we needed to go beyond the model independent results of the

previous section and incorporate our $b \rightarrow c$ RH coupling scenario into a larger framework, the most natural one being the LRM. Within this scheme, making a number of assumptions about both the detailed particle spectrum of the model and the nature of the NLO QCD corrections to the RH pieces of the nonleptonic Hamiltonian operator coefficients, we were able to demonstrate that two small regions of the LRM parameter space do exist that push both B_ℓ and n_c in the right directions with sufficient magnitudes to be phenomenologically interesting. These small parameter space regions result from a reasonably highly tuned set of LRM parameters and in all cases V_{cb}^R was found to have a magnitude of order unity.

Hopefully measurements at the new B factories which are soon to turn on will yield signals for physics beyond the Standard Model. Perhaps right-handed currents will be among them.

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APPENDIX

In this Appendix, we outline some of the implications of the scenarios discussed above that lead to lower values of both B_ℓ and $n - c$ while satisfying the CLEO constraints. Such results, for example, may lead one to speculate on just what form the matrix V_R might take if this type of solution to the $B_\ell - n_c$ problem were to be realized. This will directly lead to a number of wide ranging implications in all low energy sectors of the theory and not just in B physics. (In fact, there are too many for us to comment upon here with any depth of discussion.) Unfortunately, we do not yet have available a global analysis of RH current phenomenology for arbitrary forms of V_R with a left-right mixing at the per cent level. Such an analysis would be extremely useful for our discussion but is far beyond the scope of the present paper.

If we hypothesize[33, 36] that in each row or column there is a single element with a magnitude near unity, as is true for the conventional CKM matrix, then there are only two RH mixing matrices which allow for large V_{cb}^R . Following the notation employed in our earlier work[36], we can write these ‘large element’ forms symbolically, neglecting any phases, as

$$\mathcal{M}_C = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \quad \mathcal{M}_D = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \quad (40)$$

with the true V_R being a perturbation about one of these skeletons, just as the CKM is a perturbation about the diagonal unit matrix. As noted elsewhere[36] the structure of these matrices combined with small values of t allow us to easily circumvent the traditional constraints on the LRM from the magnitude of $K_L - K_S$ mixing. However, we also observe here the necessity that at least one of V_{td}^R or V_{ts}^R is large which can lead us to some potential problems with the observed rate for and limits upon the processes $b \rightarrow d, s\gamma$ [27]. As has been

discussed in previous analyses of the $b \rightarrow s\gamma$ process within the context of the LRM[34, 11, 36], interference terms between the RH and LH $W_1 - W_2$ contributions obtain enhancements by helicity-flip factors of m_t/m_b though they are also simultaneously suppressed by a factor of t . While the pure SM piece is proportional to the product $V_{tb}^L V_{td,s}^L$, these new interference terms are correspondingly proportional to either $V_{tb}^L V_{td,s}^R$ or $V_{tb}^R V_{td,s}^L$; the later being quite small in our case. However, here we have seen that at least one of the products $V_{tb}^L V_{td,s}^R$ is of order unity. This implies that in the models we have found here such LH-RH interference terms arising from $W_{1,2} - t$ quark penguins may be dangerously large, by factors of order 10, in at least one of the $b \rightarrow s\gamma$ or $b \rightarrow d\gamma$ modes. Of course one may argue that we are most likely quite ignorant of the true LRM model spectrum and that loop contributions from the non- $W_i - t$ diagrams may eliminate this problem. As is well known, SUSY and charged Higgs exchanges can, for example, yield significant contributions to these penguins and can possibly leading to a fine-tuned cancellation amongst the various pieces. This is an unnatural, yet potentially possible, solution.

As is well-known there are many other non- B physics constraints on the form of V_R which need to be examined. These are mostly concerned with the specific elements $V_{ud,s}^R$; some of these have a rather long, even controversial, history. Many of these constraints have been extensively reviewed in detail some time ago by Langacker and Uma Sankar[33] and as stated above it is beyond the scope of the present paper to discuss them at any length except for several comments. These low-energy constraints include, amongst others, potential violations of CKM universality, as suggested by Wolfenstein[38], and/or violations of PCAC relations, as suggested by Donoghue and Holstein[39]. For the universality constraint, we note that Buras[17] reports $\sum_i |V_{ui}^L{}^{eff}|^2 = 0.9972 \pm 0.0013$, which is more than 2σ below the SM expectation, perhaps hinting at new physics. *If* no other new physics sources enter

other than the existence of V_R , we can use the result of this sum to constrain both $Re(V_{ud,s}^R)$ even when $\kappa t \sim 0.01$. For example, using $|V_{ud}^L| \sim 0.98$ and $|V_{us}^L/V_{ud}^L| \sim 0.22$, this constraint implies

$$-0.133 \pm 0.066 \simeq \left[\frac{\kappa t}{10^{-2}} \right] [|V_{ud}^R| \cos \Delta_d + 0.22|V_{us}^R| \cos \Delta_s], \quad (41)$$

where Δ_i is sum of ω plus the phase of V_{ui}^R . This constraint is easily satisfied for either of the two forms of V_R suggested above assuming reasonable Δ_i . Some possibilities, suggested by an earlier analysis of Matrix D[36] are to either have V_{us}^R essentially unit magnitude but with a rather large phase together with $|V_{ud}^R| \sim \lambda^2 \simeq 0.05$ with arbitrary phase or to have instead $|V_{ud}^R| \sim \lambda \simeq 0.2$ with both $V_{ud,s}^R$ having sizeable phases. (At this point we remind the reader, however, that in extended gauge theories such as the LRM there can be other potentially significant contributions to universality violation, *e.g.*, Z' exchange, as has been discussed by Marciano and Sirlin[40].) Interestingly, such possible solutions are also found to easily satisfy a number of additional constraints including those from PCAC[39] (though these need to be updated), those from muon capture on ${}^3\text{He}$ [41], and those on the phase of g_A/g_V in neutron beta decay[42]. Similarly, the scaling of the strengths of the V, A currents imply that the extracted value of the ratio $(g_A/g_V)/f_\pi$ is exactly the same as in the SM with no violation of the Goldberger-Treiman relation[43] occurring in the presence of RH currents. While safely avoiding all these bounds, however, these solutions do not help in explaining a possible disparity between the values of V_{ud}^L extracted from neutron decay and that obtained from $0^+ \rightarrow 0^+$ and ${}^{19}\text{Ne}$ beta decay[44]. This at the very least would require a quite sizeable V_{ud}^R .

In these same scenarios one might expect somewhat larger effects due to RH currents to now appear in the strange quark sector. Perhaps one of the most significant effects of

RH currents here, apart from overall changes in normalizations of constants, is in the F and D parameters describing hyperon decay. The values extracted for these parameters from $\Delta S = 0$ and $\Delta S = 1$ transitions, corrected for the not yet completely understood $SU(3)$ breaking effects, would appear somewhat different. The reason here is clear: the ratio of the axial-vector to vector coupling constants in the two cases are shifted away from their SM values by different amounts depending on the form of V_R . Although the data remains rather poor, this possibility is not unsupported by the recent analysis of Ratcliffe[45]. The implications are, of course, far reaching and extend as far as tests of the Bjorken Sum Rule[46]. We also remind the reader of the well known[42] potential discrepancy between the value of V_{us} extracted from the vector current coupling in K_{e3} decays and that from hyperon decay data, which probes both axial-vector as well as vector couplings.

Clearly, if a possible signature of RH currents arises in B decays, the search for their influence elsewhere becomes ever more important.

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