

Searching for Anomalous Weak Couplings of Heavy Flavors at the SLC and LEP *

THOMAS. G. RIZZO

Stanford Linear Accelerator Center

Stanford University, Stanford, CA 94309

Abstract

The existence of anomalous electric($\tilde{\kappa}$) and/or magnetic(κ) dipole moment couplings between the heavy flavor fermions (c, b, τ) and the Z boson can cause significant shifts in the values of several electroweak observables currently being probed at both the SLC and LEP. Using the good agreement between existing data and the predictions of the Standard Model we obtain strict bounds on the possible strength of these new interactions for all of the heavy flavors. The decay $Z \rightarrow b\bar{b}$, however, provides some possible hint of new physics. The corresponding anomalous couplings of τ 's to photons is briefly examined.

Submitted to Physical Review **D**.

*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

The Standard Model(SM) continues to provide an excellent description of almost all aspects of existing experimental data[1] especially in light of the possible discovery of the top quark by the CDF Collaboration at the Tevatron[2] in the mass range anticipated by analyses of precision electroweak data[3]. Even with its many successes we know the SM cannot be the whole story and the eventual discovery of new physics beyond the SM has long been anticipated. Of course, we can not predict in what form or exactly where this crack in the SM may first appear so all possible avenues to its discovery must be explored. One possibility would be the production of a new particle(*e.g.*, a Z') or set of particles(*e.g.*, SUSY) not contained within the SM framework at some high energy collider. A second possibility might be the observation of a rare K, D, τ or B decay either forbidden by the SM or with a rate that is completely at variance with SM expectations. A last, but still quite promising, possibility would be a deviation from SM predictions in high precision measurements. The first scenario obviously has the clear advantage in that the new physics is clean and distinct whereas in the last two cases we perhaps learn little more than the SM is incomplete. Of course, the new physics possibilities *are* limited by the details of what is found experimentally. However, for many observables it is likely that several different new physics scenarios could lead to the same prediction and substantial analysis would be required in order to clarify such a situation.

Among the possible ways new physics may manifest itself, one that has been getting ever-increasing attention is the anomalous coupling of heavy flavor fermions to the conventional SM gauge bosons, *i.e.*, Z, W, γ , and g . In the case of a neutral, on-shell gauge boson, these anomalous couplings take the form of either electric or magnetic dipole form factors; electric dipole moments are inherently CP -violating. These two types of new couplings represent the lowest dimensional non-renormalizable operators which can be added to the usual SM Lagrangian which signal new physics entering from some large mass scale. Since the

top is the heaviest fermion the presumption has been that its couplings would be the most sensitive to the existence of this new high mass scale physics. From this expectation it follows that the possibility that the top may possess anomalous couplings has received the most attention in the literature[4, 5]. Of course one might extend this same argument to *all* of the fermions of the third generation, t , b , τ and perhaps as well to c . Since these particles have been around for quite some time and much data has been accumulated about their properties, it seems quite natural to ask if these well-known heavy flavor fermions possess anomalous couplings or, at the very least, to ask what the limits are on such couplings from existing data. τ 's have in fact received some attention in this respect[6] especially in regards to a possible CP -violation associated with an electric dipole moment interaction with the Z . If such couplings *were* ever to be found we would certainly need to investigate and understand how they arose. Our approach to analyzing the effects of such hypothetical couplings is purely phenomenological. We do not seek to address the possible origin of these anomalous fermion couplings should they exist. We wish only to examine how the new interactions would numerically modify electroweak observables at SLD and LEP so that they can be discovered if they do indeed exist.

In this paper we will make use of the latest data from both the LEP Collaborations[3] and the SLD[7] to place simultaneous constraints on the possible anomalous electric and magnetic dipole couplings of b , c , and τ to the Z . (An early analysis along these lines using only the data on the Z partial widths and assuming only one of the two possible anomalous couplings is nonzero at a time was presented in [8].) The analysis presented below employs the $Z \rightarrow b\bar{b}$, $c\bar{c}$ and $\tau\bar{\tau}$ partial widths together with the corresponding forward-backward asymmetries, A_{FB} , from LEP as well as the polarized forward-backward asymmetries, A_{FB}^{pol} , for b 's and c 's from SLD. In the τ case, the integrated final state τ polarization, P_τ , is also employed. In an additional separate analysis for the τ , which tests $e - \mu - \tau$ universality,

we also make use of the corresponding partial width and forward-backward asymmetry data for both e and μ as well as the SLD measurement of the left-right asymmetry, A_{LR} . Note that although we do not examine any CP -violating asymmetry, we are still able to obtain a rather strong constraint on the potential existence of electric dipole moments for these heavy fermions. The limits we obtain on such couplings are either comparable to or superior than those in the existing literature where CP -violating observables are employed.

To begin, we need to define the generalized form of the interaction of the heavy fermions with the Z to set our normalization and other conventions. If we define κ and $\tilde{\kappa}$ the as real parts of the magnetic and electric dipole form factors evaluated at $q^2 = M_Z^2$, our interaction Lagrangian can be written as

$$\mathcal{L} = \frac{g}{2c_w} \bar{f} \left[\gamma_\mu (v_f - a_f \gamma_5) + \frac{i}{2m_f} \sigma_{\mu\nu} q^\nu (\kappa_f^Z - i\tilde{\kappa}_f^Z \gamma_5) \right] f Z^\mu, \quad (1)$$

where g is the standard weak coupling, $c_w = \cos\theta_W$, m_f is the fermion mass, and q is the Z 's four-momentum. At the Z pole this interaction leads to the following symbolic result for the $e^+e^- \rightarrow f\bar{f}$ unpolarized differential cross section at the tree level in the effective Born approximation

$$\begin{aligned} \frac{1}{\beta} \frac{d\sigma}{dz} &\sim (v_e^2 + a_e^2) \left[(v_f^2 + a_f^2)(1 + \beta^2 z^2) + (v_f^2 - a_f^2)(1 - \beta^2) \right] \\ &+ 2\beta z (2v_e a_e) \left[2v_f a_f + 2\kappa_f^Z a_f \right] \\ &+ (v_e^2 + a_e^2) \left[r_f \left[(\kappa_f^Z)^2 + (\tilde{\kappa}_f^Z)^2 \right] (1 - \beta^2 z^2) + (\kappa_f^Z)^2 - (\tilde{\kappa}_f^Z)^2 + 4v_f \kappa_f^Z \right], \end{aligned} \quad (2)$$

where $z = \cos\theta$, $r_f = \frac{M_Z^2}{4m_f^2}$, and $\beta^2 = 1 - \frac{1}{r_f}$. It is important to notice that for all of the heavy fermions under discussion r_f is $O(10^2)$ or larger. From this equation we can immediately write down a correspondingly symbolic expression for the angular integrated $Z \rightarrow f\bar{f}$ partial

width, Γ_f , as

$$\begin{aligned} \frac{1}{K\beta}\Gamma_f &= D = (v_f^2 + a_f^2)(1 + \beta^2/3) + (v_f^2 - a_f^2)(1 - \beta^2) + r_f \left[(\kappa_f^Z)^2 + (\tilde{\kappa}_f^Z)^2 \right] \\ &+ (\kappa_f^Z)^2 - (\tilde{\kappa}_f^Z)^2 + 4v_f\kappa_f^Z, \end{aligned} \quad (3)$$

where the overall normalization factor, K , is given by

$$K = \frac{N_c G_F M_Z^3}{8\pi\sqrt{2}}, \quad (4)$$

with N_c being the number of colors of the final state fermion, G_F , the Fermi constant and M_Z , the Z boson mass. Similarly for the forward-backward asymmetry, we obtain

$$A_{FB}^f = \frac{3}{4} A_e A_f, \quad (5)$$

where as usual

$$A_e = \frac{2v_e a_e}{v_e^2 + a_e^2}, \quad (6)$$

while for the heavy fermions with anomalous couplings, A_f differs somewhat from the usual expression in the SM. We find instead

$$A_f = \frac{4}{3}\beta(2v_f a_f + 2\kappa_f^Z a_f)/D, \quad (7)$$

and D is defined above. Of course, A_f reverts to its usual form in the limit that $\kappa_f^Z, \tilde{\kappa}_f^Z \rightarrow 0$, with $\beta \rightarrow 1$. The other asymmetries are also easily found; $A_{LR} = A_e$ maintains its SM form while the polarized forward-backward asymmetry can still be written in the SM form

$$A_{FB}^{pol}(f) = \frac{3}{4} A_f, \quad (8)$$

with the value of A_f now given as above. It is important to observe that A_{LR} is completely insensitive to the existence of any anomalous couplings that might be possessed by the *final* state fermions. To round out the usual list of observables, we find that the expression for the angular averaged polarization of the τ in Z decay now can be expressed as

$$P_\tau = -\frac{2v_\tau a_\tau(1 + \beta^2/3) + 2a_\tau \kappa_\tau^Z}{(v_\tau^2 + a_\tau^2)(1 + \beta^2/3) + r_\tau[(\kappa_\tau^Z)^2 + (\tilde{\kappa}_\tau^Z)^2](1 - \beta^2/3) + 2v_\tau \kappa_\tau^Z}, \quad (9)$$

which reduces to the conventional SM result in the same limit as described above. It is very important to note that $P_\tau \neq -A_\tau$ even in the $\beta^2 \rightarrow 1$ limit when either κ_τ^Z or $\tilde{\kappa}_\tau^Z$ is non-zero. (We will assume in our analysis that no new physics enters the $\tau\nu_\tau W$ vertex so that the measured values of P_τ can be interpreted as in the SM.) Looking at the expressions for the above observables we see that they are all even functions of $\tilde{\kappa}_f^Z$ while both even and odd terms in κ_f^Z appear. This is to be expected since $\tilde{\kappa}_f^Z$ is a coefficient of a CP -violating interaction, *i.e.*, the electric dipole moment operator. Since we are only dealing with CP -even quantities the bounds we obtain on $\tilde{\kappa}_f^Z$'s will be on their possible absolute values. Note that in the case of the D parameter and in the denominator of the expression for P_τ , *both* quadratic $\tilde{\kappa}_f^Z$ and κ_f^Z terms are scaled by $r_f \geq 100$, as pointed out above, and which leads to a significantly enhancement in the sensitivity of the various observables to both these parameters. In particular, for the b and c cases this implies that all these observables are also, at least roughly, even functions of κ_f^Z . This approximation will be badly violated in the case of the τ asymmetries since the SM term is suppressed by the small value of v_τ which thus allows the linear κ_τ^Z term in the numerators of both asymmetry expressions to make a very considerable contribution.

How do the existence of non-zero values for κ^Z and/or $\tilde{\kappa}^Z$ numerically influence the Z -pole observables? Let us first consider the case of b and c quarks where the three specific

quantities we will deal with are $R_{b,c} = \Gamma_{b,c}/\Gamma_{had}$, $A_{FB}^{b,c}$, and $A_{FB}^{pol}(b, c)$. To define the predictions of the SM we make use of the electroweak library in ZFITTER4.8[9] which has been augmented to include the recent $O(\alpha\alpha_s^2)$ results of Avdeev, Fleischer, Mikhailov and Tarasov[10]. We fix the input parameters as $M_Z = 91.1888$ GeV, $M_H = 300$ GeV, and $\alpha_s(M_Z) = 0.125$ from Ref.3 and take three representative values of the top mass, $m_t = 165, 175$, and 185 GeV to scan the range suggested by both electroweak fits[3] as well as the CDF top search[2]. (Our results are not particularly sensitive to variations in the choices of M_H or $\alpha_s(M_Z)$.) To include some of the theoretical uncertainties into the analysis, we vary the default parameter choices in ZFITTER and examine the spread in the predictions; we then use the average of these values as the SM prediction and treat the standard deviation from this average as a theory error which is included as an additional uncertainty in the analysis below. (By varying these ZFITTER default parameters we are allowing, *e.g.*, for different treatments of the hadronic vacuum polarization and different approaches for the resummation of terms beyond those of leading order in α .)

We begin with the charm case. Fig.1a shows the variation in the value of R_c in comparison to that of the SM, for a fixed value of m_t , as either $\tilde{\kappa}_c^Z$ or κ_c^Z become non-zero. The three predictions corresponding to the three top mass choices lie underneath a single curve. As expected, the $\tilde{\kappa}_c^Z$ result is symmetric under $\tilde{\kappa}_c^Z \rightarrow -\tilde{\kappa}_c^Z$ while that for κ_c^Z is nearly so. $\tilde{\kappa}_c^Z$ or κ_c^Z non-zero thus leads to an *increase* in R_c with values as small as 0.005 leading to a 4% shift from the SM expectation. For m_t fixed, determining the ratio of either A_{FB}^c or $A_{FB}^{pol}(c)$ to their SM values amounts simply to calculating A_c/A_c^{SM} which we show in Fig.1b. This ratio exhibits a behaviour similar to R_c in its response to either $\tilde{\kappa}_c^Z$ or κ_c^Z non-zero except that these now lead to a *decrease* in A_c . Values of these parameters of order 0.005 lead to shifts in A_c of order 5%. Again, the results for the three different m_t choices lie beneath a single curve. Combining the results of these two figures together we obtain Fig.1c

which also shows the data point obtained by combining the charm results from LEP[3] on R_c and A_{FB}^c together with those from the SLD[7] on $A_{FB}^{pol}(c)$, assuming $m_t = 175$ GeV. The value and error for A_c was obtained by combining the LEP and SLD results for the two respective asymmetries. (The position of the data point moves only slightly if the other m_t values are assumed. As we will see, this makes little difference in the final results as the errors on the charm data are still quite large.) The solid(dashed) curves in the upper portion of the figure show the predictions when $\kappa_c^Z(\tilde{\kappa}_c^Z)$ is non-zero with the diamonds representing steps in both these parameters in units of 0.002. Since the central values of the width and asymmetry measurements lie in the quadrant opposite to that predicted by non-zero values of either $\tilde{\kappa}_c^Z$ or κ_c^Z , we anticipate that rather strong bounds should be obtained. This is done by performing a χ^2 fit to the values of R_c , A_{FB}^c , and $A_{FB}^{pol}(c)$ for fixed m_t and allowing $\tilde{\kappa}_c^Z$ and/or κ_c^Z to freely vary. Of course the SM prediction itself is little more than about 1σ from the central value of the data. If we take $m_t = 165, 175$, or 185 GeV, and *assume* that $\tilde{\kappa}_c^Z = 0$, we find the following 95% CL bounds on κ_c^Z : $(-5.8 \text{ to } 5.3) \cdot 10^{-3}$, $(-5.9 \text{ to } 5.4) \cdot 10^{-3}$, $(-6.0 \text{ to } 5.4) \cdot 10^{-3}$. If on the contrary we make the opposite assumption and take $\kappa_c^Z = 0$, we find that $|\tilde{\kappa}_c^Z| < (5.6, 5.7, 5.8) \cdot 10^{-3}$ for the same m_t choices, respectively. If *both* $\tilde{\kappa}_c^Z$ and κ_c^Z are permitted to be non-zero simultaneously we obtain the 95% CL region shown in Fig.1d. Amongst other things this plot shows is that the absolute value of the $c\bar{c}Z$ electric dipole moment is $< 5.7 \cdot 10^{-17}$ e-cm in conventional units, independently of whether a magnetic dipole moment *also* exists and independently of the precise value of m_t . This result is a significant improvement over that which was obtained previously[8] with stronger assumptions. We note in passing that the positions of the three χ^2 minima correspond to $\tilde{\kappa}_c^Z = 0$ with $\kappa_c^Z = (-0.29_{-3.1}^{+3.4}, -0.35_{-3.1}^{+3.3}, -0.42_{-3.2}^{+3.3}) \cdot 10^{-3}$, all of which lie quite close to the origin in Fig.1d.

Let us now turn to the case of b 's where we will follow a similar procedure. Due to the larger b -quark mass we anticipate somewhat poorer limits than what was obtained in the charm case. However, a new wrinkle emerges in the b case in that the existing data *prefer* non-zero values for the anomalous couplings. The $Z \rightarrow b\bar{b}$ situation is, of course, very interesting since it has been known for some time that R_b lies[3] about 2σ above its SM predicted value. For $m_t = 175$ GeV, the LEP value of A_{FB}^b is about 1σ low and the value of $A_{FB}^{pol}(b)$ from SLD[7] also lies a bit below the SM prediction but with larger errors. Figs.2a and 2b show how both R_b and A_b vary with either $\tilde{\kappa}_b^Z$ or κ_b^Z non-zero; again, in both cases the results for the three different values of the top mass lie underneath a single curve. Both observables are found to have comparable sensitivity to the existence of anomalous couplings. Note that non-zero values of either $\tilde{\kappa}_b^Z$ or κ_b^Z will push the SM predictions closer to the data, *i.e.*, they lower A_b while increasing R_b . This is perhaps seen more clearly in Fig.2c which not only shows the model predictions but also the data points for $m_t=165, 175$ or 185 GeV. Anomalous couplings will certainly lead to a better fit than does the SM. Let us first assume that $\tilde{\kappa}_b^Z = 0$ and find the allowed ranges for κ_b^Z . For $m_t = 165$ GeV the 95% CL allowed range is determined to be $(-1.11 \text{ to } -0.03) \cdot 10^{-2}$; the SM point lies 2.1σ away from the minimum, just outside the 95% CL allowed range. For $m_t = 175$ GeV, a secondary χ^2 minimum develops so that the allowed ranges for κ_b^Z are $(-1.18 \text{ to } -0.14) \cdot 10^{-2}$ or $(2.28 \text{ to } 2.95) \cdot 10^{-2}$ and the SM lies more than 2.3σ away from the χ^2 minimum best fit. Similarly, for $m_t = 185$ GeV, the allowed κ_b^Z ranges are $(-1.23 \text{ to } -0.24) \cdot 10^{-2}$ and $(2.21 \text{ to } 3.15) \cdot 10^{-2}$ with the SM now being about 2.6σ away from the corresponding best fit. A similar situation occurs in the reverse case where we assume that $\kappa_b^Z = 0$ and we look for the 95% CL bounds on $|\tilde{\kappa}_b^Z|$. For $m_t = 165, 175, 185$ GeV, the allowed ranges are $(0.15 \text{ to } 1.89) \cdot 10^{-2}$, $(0.66 \text{ to } 1.99) \cdot 10^{-2}$, and $(0.85 \text{ to } 2.07) \cdot 10^{-2}$. The SM point lies 2.0σ , 2.4σ , and 2.8σ away from the χ^2 minima in these three cases, respectively.

If we allow both $\tilde{\kappa}_b^Z$ and κ_b^Z to be present simultaneously we arrive at the plot shown in Fig.2d. Note that for $m_t > 175$ GeV the SM lies outside of the two parameter 95% CL region. Clearly we cannot yet make any claim for the existence of new physics but it is clear from this analysis that the observables associated with the $Z \rightarrow b\bar{b}$ mode should be closely monitored. If we *ignore* the hole near the origin, the limits obtained above on $\tilde{\kappa}_b^Z$ can be re-written in more conventional units at $\tilde{\kappa}_b^Z \leq 6.0 \cdot 10^{-16}$ e-cm. For completeness, we note the approximate positions of the χ^2 minima for $m_t = 165, 175$, and 185 GeV: $(\kappa_b^Z, |\tilde{\kappa}_b^Z|) = (-6.61 \cdot 10^{-3}, 0)$, $(3.64 \cdot 10^{-3}, 1.67 \cdot 10^{-2})$, and $(8.56 \cdot 10^{-3}, 1.86 \cdot 10^{-2})$, respectively.

We now turn to the case of τ 's. There are two possible approaches: (i) one can simply follow the same approach as employed above for c and b with the substitution of P_τ for $A_{FB}^{pol}(b, c)$ as long as we remember that $P_\tau \neq -A_\tau$. We call this the ‘standard’ approach. In principle we might also include the additional constraint arising from the full angular dependent τ polarization (as conventionally represented by the ‘ A_e ’ term). However, this extra information is obtained under the assumption of a specific form of the angular dependence of the τ polarization which is somewhat modified when anomalous couplings are present. To avoid this complexity we will not include the angular dependent information in the present analysis. The additional constraints obtainable by its inclusion are not, however, expected to be significant since the *odd* term in the angular distribution is only weakly dependent on the existence of anomalous couplings due to its proportionality to v_τ . A more general approach to handling the full angular dependence of the τ polarization is now underway.

A second possibility is to redefine what we mean by the SM prediction for the various observables. In this approach, we assume $e - \mu$ universality and use the other leptonic data from LEP and SLD to *define* the SM prediction. We call this the ‘universality’ approach. As an example, we now define the SM prediction for the $Z \rightarrow \tau\bar{\tau}$ partial width to be the error

weighted average of the the $Z \rightarrow e\bar{e}$ and $Z \rightarrow \mu\bar{\mu}$ partial widths corrected for the $\tau\bar{\tau}$ phase space. The resulting bounds we obtain in this approach are very insensitive to the values we assume for the top mass, m_t .

Taking the ‘standard’ approach, we plot in Figs.3a-c the variation in the SM prediction for the $Z \rightarrow \tau\bar{\tau}$ partial width(Γ_τ), the τ forward-backward asymmetry and the τ polarization when either $\tilde{\kappa}_\tau^Z$ or κ_τ^Z is non-zero for the usual three choices of m_t . In Fig.3a, as usual, we see that there is no observable sensitivity to the choice of m_t when the ratio to the SM prediction is taken for either κ_τ^Z or $\tilde{\kappa}_\tau^Z$ non-zero. Since v_τ is very small and r_τ is so large the κ_τ^Z non-zero curve is almost perfectly symmetric about the origin. The value of Γ_τ varies only a few per cent as the anomalous couplings range over ± 0.005 . In both Figs.3b and 3c we see something different than in all of the other results so far obtained, *i.e.*, the $\tilde{\kappa}_\tau^Z$ and κ_τ^Z non-zero scenarios behave very differently. This is due to (i) the presence of κ_τ^Z (but not $\tilde{\kappa}_\tau^Z$!) appearing linearly in the numerators for the expressions of both A_τ and P_τ and (ii) the fact that v_τ is very small. In these two figures we also note for the first time a barely observable separation between the $m_t = 165, 175$ and 185 GeV model predictions. We also observe that the asymmetries are quite sensitive to anomalous couplings with variations as large as 10% away from SM expectations.

In Fig.3d we compare the shifts in the $Z \rightarrow \tau\bar{\tau}$ partial width and P_τ for non-zero values of $\tilde{\kappa}_\tau^Z$ or κ_τ^Z since these are at present the most accurately determined quantities; steps of 0.001 are indicted by the diamonds. (Note that close to the SM point there is no separation in the $m_t = 165, 175$, and 185 GeV predictions.) The results of the LEP measurements normalized to the SM expectations with $m_t = 175$ GeV is also shown. If we perform a χ^2 fit to the data, limits on both $\tilde{\kappa}_\tau^Z$ and κ_τ^Z are obtained in the usual manner. For $\tilde{\kappa}_\tau^Z = 0$, we obtain the following 95% CL ranges for κ_τ^Z : $(-3.04 \text{ to } 0.88) \cdot 10^{-3}$, $(-2.90$

to $2.09 \cdot 10^{-3}$, and $(-2.75 \text{ to } 2.32) \cdot 10^{-3}$ for $m_t = 165, 175$ and 185 GeV respectively. In the reverse case, the corresponding upper bounds on $|\tilde{\kappa}_\tau^Z|$ are found to be $(2.9, 3.0, 3.1) \cdot 10^{-3}$. If both $\tilde{\kappa}_\tau^Z$ and κ_τ^Z are non-zero we obtain the allowed regions shown in Fig.3e. The χ^2 minima all occur at $\tilde{\kappa}_\tau^Z = 0$ with $\kappa_\tau^Z = (-1.95_{-0.60}^{+0.81}, -1.74_{-0.65}^{+0.95}, -1.50_{-0.72}^{+1.20}) \cdot 10^{-3}$, respectively. Note that for any value of m_t , we obtain a 95% CL limit on τ electric dipole moment of less than $2.1 \cdot 10^{-17}$ e-cm which is quite comparable to that obtained by the OPAL Collaboration[11] through the use of CP -violating observables.

Turning now to the universality approach, we repeat the analysis above using the LEP and SLD e and μ data to define the SM predictions. Of course the results in Figs.3a-d are unmodified with only the position of the data point changing in Fig.3d to reflect the change in the SM prediction. The result of this analysis leads to the additional curve in Fig.3e where we see that results comparable to but a bit weaker than the conventional analysis are obtained. The χ^2 minimum now occurs at $(\kappa_\tau^Z, |\tilde{\kappa}_\tau^Z|) = (0.29_{-1.66}^{+1.52}, 1.87_{-0.78}^{+1.79}) \cdot 10^{-3}$. For $\tilde{\kappa}_\tau^Z = 0$, we obtain the 95% CL range for κ_τ^Z : $(-2.96 \text{ to } 3.27) \cdot 10^{-3}$ and, for $\kappa_\tau^Z = 0$, we obtain the bound $|\tilde{\kappa}_\tau^Z| \leq 3.20 \cdot 10^{-3}$.

Interestingly, a procedure similar to that above which employs lepton universality can be used to obtain reasonably strong limits on the corresponding anomalous $\tau\bar{\tau}\gamma$ couplings[12]. If we compare the three cross sections for $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, and $\tau\bar{\tau}$ at TRISTAN energies[13](and properly subtract out the t -channel pole in the e^+e^- case), limits on universality violation can be used to place constraints on $\tilde{\kappa}_\tau^\gamma$ and κ_τ^γ *provided* we assume that the anomalous Z couplings can be neglected. Fig.4 shows a comparison of the R ratio expected in the τ case with anomalous couplings to that of the SM assuming universality but with finite τ mass corrections for TRISTAN energies. At an average center of mass energy $\sqrt{s} \simeq 57.8$ GeV, these ratios are very well determined[13] and we find from the 95% CL

upper limit on the ratio $R_\tau/R_{e\mu} < 1.10$ that $|\tilde{\kappa}_\tau^\gamma| \leq 2.8 \cdot 10^{-2}$ when $\kappa_\tau^\gamma = 0$ and correspondingly, when $\tilde{\kappa}_\tau^\gamma = 0$, κ_τ^γ lies in the 95% CL interval $(-1.9 \text{ to } 4.2) \cdot 10^{-2}$. (These constraints may be improved somewhat by using additional data such as A_{FB}^τ .) Although these bounds are inferior to those obtained on the corresponding Z couplings (due to lower statistics and reduced sensitivity), they are substantially better than those found in the existing literature which were arrived at by other methods. For example, Grifols and Mendez[14] examined the radiative decay $Z \rightarrow \tau\bar{\tau}\gamma$ and obtained an upper bound on $|\kappa_\tau^\gamma|$ of 0.11 by looking for excess events.

In this paper we have undertaken a systematic search for the effects of anomalous electric or magnetic dipole moment type couplings between the heavy flavor fermions and the Z based on precision data from the SLC and LEP. For the b and c quarks $R_{b,c}$, $A_{FB}^{b,c}$, and $A_{FB}^{pol}(b,c)$ were used *simultaneously* to obtain our results. In the τ case, our first approach followed that for the quark case but replaced A_{FB}^{pol} with P_τ while our second approach employed lepton universality. The results of this analysis can be summarized as follows:

(i) The constraints we obtained on the anomalous couplings of the τ and charm were found to be reasonably insensitive to the details of the SM radiative corrections which were expressed via variations in m_t . This was quite forcefully demonstrated in the τ case where the universality limit was used as the reference SM. All of the observables played a role in obtaining the allowed ranges. The individual numerical results are summarized for comparison in Tables 1 and 2. It is important to note that the constraints obtained in the charm case are inferior to those obtained for τ 's even though they have comparable masses. Of course, the data in the case for τ 's is more precise which is the major source of the difference. In the b case, the larger fermion mass reduces sensitivity while the data itself shows some preference for the existence of anomalous couplings. The limits we obtain are generally stronger than those derived previously and neither τ 's nor charm showed any

indication of anomalous couplings. The inclusion of the angular-dependent τ polarization data from LEP is not expected to make any significant effect on these results but is a subject of further study.

(ii) The situation in the b case is quite different than either charm or τ in that it shows a much greater sensitivity to variations in m_t and that non-zero values of the anomalous couplings are somewhat more favored by the fits. For example, with $m_t = 175$ GeV, the SM lies just outside the 95% CL region in the two-parameter fits and a bit further outside this CL range for the two, one-parameter fits (see Tables 1 and 2). The reason for this is immediately clear from Fig. 2c, *i.e.*, the presence of the anomalous couplings induces a larger value for R_b while simultaneously decreasing A_b , which is just the direction taken by the present data. Although we can make no claim for new physics at the current level of statistics it is clear that all observables related to the decay $Z \rightarrow b\bar{b}$ should be watched carefully and scrutinized.

(iii) The universality approach for τ 's was extended to the γ case using TRISTAN data under the assumption that the contribution of the corresponding anomalous Z couplings were suppressed. The limits so obtained are a significant improvement over those already existing in the literature.

The possible existence anomalous couplings of the heavy fermions to the Z may provide a clue to new physics beyond the Standard Model.

ACKNOWLEDGEMENTS

The author like to thank A. Kagan, D. Atwood, J.L. Hewett, T. Barklow, S. Wagner, T. Junk, P. Rowson, M. Hildreth and P. Burrows for discussions related to this work. Special thanks go to S. Wagner for a careful reading of the manuscript. He would also like to thank the members of the Argonne National Laboratory High Energy Theory Group for use of

their computing facilities.

References

- [1] J.L. Rosner, summary talk presented at the *Eighth Meeting of the Division of Particles and Fields*, Albuquerque, NM, August 2-6, 1994. See also, J.L. Rosner, EFI report EFI 94-38, 1994.
- [2] F. Abe *et al.*, CDF Collaboration, Phys. Rev. **D50**, 2966 (1994).
- [3] D. Schaile, talk presented at, and LEP reports LEPEWWG/94-02, LEPTAU/94-02, LEPLINE/94-01, and LEPHF/94-03, submitted to the 27th *International Conference on High Energy Physics*, Glasgow, Scotland, July 20-27, 1994.
- [4] G. Kane, G.A. Ladinsky and C.P. Yuan, Phys. Rev. **D45**, 124 (1992); C.P. Yuan, Phys. Rev. **D45**, 782 (1992); D. Atwood, A. Aeppli and A. Soni, Phys. Rev. Lett. **69**, 2754 (1992); D. Atwood, A. Kagan and T.G. Rizzo, SLAC report SLAC-PUB-6580, 1994.
- [5] M. Peskin, talk presented at the *Second International Workshop on Physics and Experiments at Linear e^+e^- Collider*, Waikoloa, HI, April 1993; M. Peskin and C.R. Schmidt, talk presented at the *First Workshop on Linear Colliders*, Saariselkä, Finland, September 1991; P. Zerwas, *ibid.*; W. Bernreuther *et al.*, in *Proceedings of the Workshop on e^+e^- Collisions at 500 GeV, The Physics Potential*, (DESY, Hamburg) ed. by P. Igo-Kemenes and J.H. Kühn, 1992; A. Djouadi, ENSLAPP-A-365-92 (1992); M. Frigeni and R. Rattazzi, Phys. Lett. **B269**, 412 (1991); R.D. Peccei, S. Persis and X. Zhang, Nucl. Phys. **B349**, 305 (1991); D.O. Carlson, E. Malkawi and C.-P. Yuan, Michigan State report MSUHEP-94/05, 1994; T.G. Rizzo, SLAC report SLAC-PUB-6512, 1994. Indirect limits on κ_t^g and $\tilde{\kappa}_t^g$ from the decay $b \rightarrow s\gamma$ were considered by J.L. Hewett and T.G. Rizzo, Phys. Rev. **D49**, 319 (1994).

- [6] A. Grifols and A. Mendez, Phys. Lett. **B255**, 611 (1991) and erratum Phys. Lett. **B259**, 512 (1991); B. Ananthanarayan and S.D. Rindani Phys. Rev. Lett. **73**, 1215 (1994); F. del Aguila and M. Sher, Phys. Lett. **B252**, 116 (1990); R. Escribano and E. Masso, Phys. Lett. **B301**, 419 (1993); W. Bernreuther, O. Nachtmann and P. Overmann, Phys. Rev. **D48**, 78 (1993); G. Couture, Phys. Lett. **B305**, 306 (1993) and Phys. Lett. **B272**, 404 (1991); G. Domokos *et al.*, Phys. Rev. **D32**, 247 (1985); J. Reid, M. Samuel, K.A. Milton and T.G. Rizzo, Phys. Rev. **D30**, 245 (1984). See also, P.D. Acton *et al.*, OPAL Collaboration, Phys. Lett. **B281**, 305 (1992); D. Buskulic *et al.*, ALEPH Collaboration, Phys. Lett. **B297**, 459 (1992).
- [7] K. Abe *et al.*, SLD Collaboration, Phys. Rev. Lett. **73**, 25 (1994) and SLAC report SLAC-PUB-6607, 1994. See also the presentations by M.E. King, D. Williams and G. Baranko, SLD Collaboration, given at the *Eighth Meeting of the Division of Particles and Fields*, Albuquerque, NM, August 2-6, 1994 and by S. Wagner at the *27th International Conference on High Energy Physics*, Glasgow, Scotland, July 20-27, 1994.
- [8] R. Escribano and E. Masso, Barcelona report UAB-FT-317, 1993.
- [9] The ZFITTER package: D. Bardin *et al.*, Z. Phys. **C44**, 493 (1989); Nucl. Phys. **B351**, 1 (1991); Phys. Lett. **B255**, 290 (1991); CERN report CERN-TH-6443/92, 1992. The author would like to thank S. Riemann for providing him with an updated version of this code.
- [10] L. Avdeev, J. Fleischer, S. Mikhailov and O. Tarasov, Univ. of Bielefeld report BI-TP-93/60, 1994.
- [11] A. Höcker, OPAL Collaboration, Universität Bonn thesis, BONN-IB-94-17, May 1994.

- [12] T.G. Rizzo, talk given at the *Workshop on the Tau-Charm Factory in the Era of B-Factories and CESR*, SLAC, August 15-16, 1994.
- [13] C. Velissaris, *et al.*, AMY Collaboration, Phys. Lett. **B331**, 227 (1994); B. Howell, *et al.*, TOPAZ Collaboration, Phys. Lett. **B291**, 206 (1992); K. Abe, *et al.*, VENUS Collaboration, Z. Phys. **C48**, 13 (1990).
- [14] See the analysis by A. Grifols and A. Mendez in Ref.6.

m_t	c	b	τ
165	−5.8 to 5.3	−11.1 to −0.3	−3.04 to 0.88
175	−5.9 to 5.4	−11.8 to −1.4	−2.90 to 2.09
		22.8 to 29.5	
185	−6.0 to 5.4	−12.3 to −2.4	−2.75 to 2.32
		22.1 to 31.5	
U	—	—	−2.96 to 3.27

Table 1: Individual 95% CL allowed ranges for κ^Z in units of 10^{-3} . ‘U’ corresponds to the universality approach for τ ’s described in the text.

m_t	c	b	τ
165	< 5.6	1.5 to 18.9	< 2.9
175	< 5.7	6.6 to 19.9	< 3.0
185	< 5.8	8.5 to 20.7	< 3.1
U	—	—	< 3.2

Table 2: Individual 95% CL allowed ranges for $|\tilde{\kappa}^Z|$ in units of 10^{-3} . ‘U’ corresponds to the universality approach for τ ’s as described in the text.

Figure Captions

Figure 1. (a) R_c and (b) A_c variations due to non-zero values for either $\tilde{\kappa}_c^Z$ (dashes) or κ_c^Z (solid). The predictions for $m_t = 165, 175$, and 185 GeV lie underneath a single curve. (c) R_c vs. A_c for non-zero values of $\tilde{\kappa}_c^Z$ (dashed) or κ_c^Z (solid) in comparison to the LEP and SLD data which is plotted assuming $m_t = 175$ GeV in the calculations of the SM predictions. As noted in the text, the position and error associated with A_c comes from combining the SLD results for A_{FB}^{pol} as well as the LEP determinations of A_{FB}^c . The diamonds correspond to incremental changes in either $\tilde{\kappa}_c^Z$ or κ_c^Z away from zero in steps of 0.002 . The upper(lower) solid curve is for κ_c^Z positive(negative). (d) 95% CL allowed region in the $\tilde{\kappa}_c^Z$ - κ_c^Z plane resulting from a fit to LEP data on R_c and A_{FB}^c and SLD data on $A_{FB}^{pol}(c)$ with $m_t = 165$ (dashed), 175 (solid), or 185 (dotted) GeV. The allowed region lies between the lower axis and the particular curve.

Figure 2. Same as Figs.1a-d but with $c \rightarrow b$. In (c) the data is now displayed assuming SM predictions with $m_t = 165$ (dashes), 175 (solid) or 185 (dotted) GeV. The diamonds are now increments of 0.02 in either $\tilde{\kappa}_b^Z$ or κ_b^Z with the upper solid curve corresponding to *negative* values of κ_b^Z . The allowed region in (d) lies between pairs of curves of similar type.

Figure 3. Variation in the SM predictions for (a) the τ partial width of the Z , (b) the τ forward-backward asymmetry and (c) final state τ polarization for non-zero values of either $\tilde{\kappa}_\tau^Z$ or κ_τ^Z . In (a) the solid(dashed) curve corresponds to variations in $\kappa_\tau^Z(\tilde{\kappa}_\tau^Z)$ for the usual three choices of m_t . In (b) and (c) the $\tilde{\kappa}_\tau^Z$ non-zero case corresponds to the horizontal dashed curve for all three values of m_t whereas the steeper dashed(solid,dotted) curves correspond to non-zero κ_τ^Z with $m_t = 165(175, 185)$ GeV. (d) Γ_τ vs P_τ with $\tilde{\kappa}_\tau^Z(\kappa_\tau^Z)$

varying in steps of 0.001 along the dashed(dotted) curve with positive(negative) values of κ_τ^Z being to the left(right) of the SM point. The combined LEP result assuming $m_t = 175$ GeV in the SM calculation is shown as the data point. (e) Same as Fig.1d but now for the case of τ 's. The outer square dotted curve is the resulting bound obtained from the $e - \mu - \tau$ universality analysis. The allowed region lies below the curves.

Figure 4. The ratio of the $e^+e^- \rightarrow \tau\bar{\tau}$ cross section to that for $e^+e^- \rightarrow e^+e^-, \mu^+\mu^-$ at TRISTAN energies($\sqrt{s} \simeq 57.8$ GeV) as a function of $\tilde{\kappa}_\tau^\gamma$ (dots) or κ_τ^γ (solid). The horizontal dashed line represents the 95% CL upper limit on the cross section ratio.