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ADDITIONAL CP ODD OBSERVABLES IN Z DECAYS

G. Valencia^(a) and A. Soni^{(b)*}

^(a) *Theory Division, CERN
CH-1211, Geneva 23*

and

^(b) *Physics Department
Brookhaven National Laboratory, Upton, NY 11973*

ABSTRACT

Recently, T -odd observables in Z -boson decays have been studied from the point of view of effective Lagrangians. We consider additional CP -odd observables that appear in conjunction with absorptive phases. As an example we discuss the possibility of observing a CP violating energy asymmetry in the decays $Z \rightarrow BX$ and $Z \rightarrow \bar{B}X$, and we relate this to the presence of an electroweak dipole moment of the b -quark. We estimate that expected LEP performance could yield a sensitivity to dipole moments of order 10^{-17} e-cm.

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1. Introduction

Recently, there has been some effort to identify signals that are sensitive to CP violation at the high energies available at present and future machines. Particular emphasis has been placed on the signals that can occur in Z decays and that can be studied at LEP or SLC. In this paper we propose yet another type of observables sensitive to non-standard mechanisms for CP violation. They are similar to others that have been considered in the case of flavor-changing couplings to the Z .^[1]

As a general rule it has been found that if CP violation originates exclusively in the phase of a three generation KM matrix, its effects will be very small at high energies. This is due to the near degeneracy of the u and c quarks at energies where the relevant mass scale is m_Z .^{*} Based on such observations one expects that any CP violation that is found in Z decays will most likely be a signal for new physics. The question is then, what is the best way to parameterize this possible new physics, and how to relate it to experimental observables. Unfortunately, one finds a very large number of unknown parameters in the CP violating sector of popular extensions of the standard model. In view of this, many authors have recently undertaken a systematic study of possible new physics in terms of an effective Lagrangian.^[2] Within this approach, one identifies CP violating operators in a model independent way. One can then look at the possible signals and classify them as being sensitive to some of the operators that appear in the general effective Lagrangian. While the philosophy of such an approach is appropriate for a general search for physics beyond the standard model, one loses the insight provided by the study of specific models. In particular, these studies have concentrated on processes that occur at tree-level in the effective Lagrangian, in the hope that loop processes would be somehow suppressed. In this paper we will construct a specific example, within the framework of a simple model, where this is not necessarily the case. This will result in the appearance of additional observables.

^{*} See e.g. Bernabeu et. al. Ref. 1.

For illustrative purposes we will work in a model with an extended Higgs sector to benefit from the simplicity of obtaining a dipole moment at the one loop level. In these^[3] models, after electroweak symmetry breaking, one is left with a large number of physical scalars, both neutral and charged. Depending on the number of scalars in the model, and on the way they are introduced, CP violation will appear in the couplings of some of the physical scalars to the fermions. Also, one typically has couplings proportional to the masses of the particles involved, and one thus expects them to become more important as higher energies are probed (if new massive particles appear).

A CP violating observable that has received much attention is the electric dipole moment of the neutron. In this paper we will investigate a similar observable, namely the electroweak dipole form factor in the couplings of fermions to the Z boson. To be specific we will consider the b-quark and we will comment on both the t-quark and the τ -lepton.^[4]

2. Asymmetries

The coupling of the Z boson to the b-quark in the standard model is given by:

$$i \frac{g}{4 \cos \theta_W} \gamma_\mu (g_V - g_A \gamma_5) \quad (2.1)$$

with $g_V = (1 - 4/3 \sin^2 \theta_W)$ and $g_A = 1$. In general, this tree-level vertex will be dressed by QCD and electroweak radiative corrections. We will not consider the effect of these corrections except to notice that the couplings g_V and g_A will in general become form factors which may contain absorptive phases.^[5]

We will also consider an effective vertex with a dipole moment form, arising from an (for the moment) unspecified underlying model that violates CP. In the next section we will discuss the form of this effective coupling in the context of a model with an extended Higgs sector. Typically, in an effective coupling of a

fermion to the photon of the form:

$$i\tilde{d}(q^2)\bar{\Psi}\sigma_{\mu\nu}\gamma_5\Psi F^{\mu\nu} \quad (2.2)$$

the value of $\tilde{d}(q^2)$ at $q^2 = 0$ is defined to be the electric dipole moment of the fermion. By electroweak dipole moment we mean the simple generalization of Eq. (2.2) to fermion couplings to the Z -boson:

$$id(q^2)\bar{\Psi}\sigma_{\mu\nu}\gamma_5\Psi Z^{\mu\nu} \quad (2.3)$$

We are interested in exploring this coupling in decays of the Z -boson. This means that we will really be considering $d(q^2 = m_Z^2)$. Eq. (2.3) induces a term in the $Zb\bar{b}$ vertex given by (see Fig. 1):

$$i\frac{g}{4\cos\theta_W}d\sigma_{\mu\nu}k^\nu\gamma_5, \quad (2.4)$$

where d should be understood to mean $d(q^2 = m_Z^2)$ from now on. The variation of the form factor $d(q^2)$ with q^2 is expected to be characterized by a scale Λ typical of the new physics that generates the effective interaction. It is expected to introduce minimal modifications into an already uncertain calculation, and is therefore, typically neglected. We will show in our specific example, where $\Lambda \sim m_Z$, that this q^2 dependence of d may have an important consequence by allowing the form factor $d(q^2)$ to have absorptive phases. These new phases are the ones that we will use to generate our observables via their interference with the CP violating phase in d .

We will thus allow the dipole moment d in Eq. (2.4) to be complex. As written in Eq. (2.4), the imaginary part of d will then correspond to the absorptive part of the loop diagrams that give rise to it. As we shall see in the example within the Higgs model, such phases are in general expected and they need not be small. We

will, from now on, take all dipole moments to be in units of GeV^{-1} and use the notation:

$$d_I \equiv \text{Im}d(q^2 = m_Z^2) \quad (2.5)$$

The interference of the standard model vertex, and the effective dipole moment, will give rise to CP violating observables. These observables can be of two types. They can be even under the naive T operation, like partial rate or energy asymmetries, in which case the generated observables will, in addition to the CP violating phase, require an absorptive phase. They can also be odd under the naive T operation as in the case of triple product correlations. In the latter case, no such absorptive phases are required, however, signals can be faked by CP conserving higher order contributions to the given process.

If we now consider the basic process $Z(k) \rightarrow b(p)\bar{b}(p')$, and look at the interference term that will give rise to the CP odd observables we find the simple correlation:

$$\sim m_b \text{Im}(d^* g_A) k \cdot (p - p') \cdots \sim m_b d_I (p^2 - p'^2) \cdots \quad (2.6)$$

where we have not written the terms that contain the quark spins because we will assume that such spins are unobservable. We have also taken $g_A = 1$ in the last expression. It is clear that this term will vanish in the case where both quarks are on shell, it will not vanish when we treat the quarks as partons that will give rise to jets. In that case, this new CP-odd correlation simply splits the average value of the invariant masses of the jets originating in the quark and the anti-quark.

If we write Eq. (2.6) in the Z rest frame, we can see how it can give rise to CP odd asymmetries:

$$\sim m_b d_I m_Z (E_b - E_{\bar{b}}) \quad (2.7)$$

With this interpretation, it is natural to seek for manifestations of this type of correlation in energy asymmetries. It is important to remember that this was the only term in the interference of the standard model and dipole moment amplitudes,

that **did not** involve explicitly the spin of the quarks. This leads us to speculate that this type of correlation has the better chance of surviving the hadronization process. Clearly this point needs further study.

A detailed study of the effect of a correlation like Eq. (2.7) in the hadronization process is beyond the scope of this paper, and we will content ourselves with a simple estimate of a possible asymmetry. First, let us consider the hard gluon emission that gives rise to three jet events. The amplitude for this process is calculated from the two diagrams obtained when one of the quarks in Fig. 1 radiates a gluon, and the $Z - b\bar{b}$ vertex is given by Eq. (2.1) and Eq. (2.4). The standard model vertex gives rise to the usual 3-jet formula with its known infrared problems. We will also assume that the term with d^2 is very small and neglect it.^{*} The term of interest will thus be the CP violating interference.

If we label the momenta as $Z(k) \rightarrow b(p)\bar{b}(p')g(q)$ and define the variables:

$$\begin{aligned} s &= (k - q)^2 \\ t &= (k - p)^2 \\ t' &= (k - p')^2 \end{aligned} \tag{2.8}$$

we can write the interference term as (averaging over the Z polarization and summing over the gluon polarization):

$$\begin{aligned} \frac{d\Gamma_{int}}{dt dt'} &= \frac{1}{(2\pi)^3} \frac{1}{96m_Z^3} \left(\frac{g}{4 \cos \theta_W} \right)^2 (16\pi\alpha_S) 32m_b d_I \\ &\cdot \left[\left(\frac{t' - m_b^2}{t - m_b^2} \right) - \left(\frac{t - m_b^2}{t' - m_b^2} \right) \right] \end{aligned} \tag{2.9}$$

It is instructive to rewrite this distribution in the Z rest frame. For that purpose

^{*} This is fine for the asymmetries we want, however, the reader must keep in mind that the best limit for the τ -lepton edm (from existing experiments) does not come from an asymmetry proportional to d but rather from a term $\sim d^2$ in a cross-section.^[6] However, the asymmetries that are linear in d , should produce better bounds when improved experiments are available.

we introduce the variables:

$$x_i = \frac{2E_i}{m_Z} \quad (2.10)$$

to obtain:

$$\frac{d\Gamma_{int}}{dx_b dx_{\bar{b}}} = m_Z \frac{2\alpha\alpha_S m_b d_I}{3\pi \sin^2 2\theta_W} \frac{(x_{\bar{b}} - x_b)(x_b + x_{\bar{b}} - 2)}{(1 - x_b)(1 - x_{\bar{b}})} \quad (2.11)$$

If we integrate this differential decay rate over phase space, we see that it vanishes. This is consistent with the observation that the integration region is symmetric in p^2 and p'^2 . As argued previously, we will thus look for effects of this interference term in energy asymmetries. Our simple minded model will consist of using Eq. (2.11) to find:

$$\begin{aligned} \langle E_b \rangle - \langle E_{\bar{b}} \rangle &= \frac{2}{\Gamma} m_Z \frac{2\alpha\alpha_S m_b d_I}{3\pi \sin^2 2\theta_W} \\ &\quad \cdot \frac{m_Z}{2} \int dx_b dx_{\bar{b}} x_b \frac{(x_{\bar{b}} - x_b)(x_b + x_{\bar{b}} - 2)}{(1 - x_b)(1 - x_{\bar{b}})} \end{aligned} \quad (2.12)$$

We denote by Γ the total width for the Z -boson to decay into three jets, and we will not need its explicit value.

We then obtain a normalized energy asymmetry by dividing our result by the average energy of the b -quark jet in the absence of CP violation. This one we obtain from the usual formulas:

$$\begin{aligned} \Gamma_0 &\equiv \Gamma(Z \rightarrow b\bar{b}) \\ &= \frac{\alpha m_Z}{4 \sin^2 2\theta_W} (1 + g_V^2) (1 + \mathcal{O}(\frac{m_b^2}{m_Z^2})) \\ \Gamma &= \Gamma_0 \frac{2\alpha_s}{3\pi} \int dx_b dx_{\bar{b}} \frac{(x_b^2 + x_{\bar{b}}^2)}{(1 - x_b)(1 - x_{\bar{b}})} \\ \langle E_b \rangle &= \frac{\Gamma_0}{\Gamma} \frac{2\alpha_s}{3\pi} \frac{m_Z}{2} \int dx_b dx_{\bar{b}} \frac{x_b(x_b^2 + x_{\bar{b}}^2)}{(1 - x_b)(1 - x_{\bar{b}})} \end{aligned} \quad (2.13)$$

Given the rough nature of our calculation, a very careful treatment of the infrared and collinear behavior of this distribution is not called for. Instead, we will apply

the following simple cut. We require the invariant mass of any pair of jets to be larger than a certain value. This value is chosen so that:

$$\langle E_b \rangle \approx 0.8 \frac{m_Z}{2}$$

This corresponds to the invariant mass of any pair of jets being larger than 5% of the Z -mass. The motivation for this number is simple. It provides a realistic three-jet event, without getting into the kinematic region where phase space would make the rate too small. With all these results we finally obtain:

$$\left| \frac{\langle E_b \rangle - \langle E_{\bar{b}} \rangle}{\langle E_b \rangle + \langle E_{\bar{b}} \rangle} \right| \approx 0.1 m_b |d_I| \quad (2.14)$$

Experimentally one could try to look for these differences in average energies at the two or three jet level. It would perhaps be simpler to tag the flavor of the jets by looking for a b -flavored particle. For example, one could look for events with a B^- coming from the b and a B^+ coming from the $\bar{b}$. The CP violating correlation would show up as a difference in the average energies of the B^- and B^+ .

$$\frac{\Delta E}{E} \equiv \frac{\langle E_{B^-} \rangle - \langle E_{B^+} \rangle}{\langle E_{B^-} \rangle + \langle E_{B^+} \rangle} \quad (2.15)$$

As a first estimate we could argue that a sizeable fraction of the b -quark energy ends up in the B meson, and thus, that the energy asymmetry at the meson level is expected to be of the same order as the one at the quark level, Eq. (2.14). This rough estimate applies as well to other hadrons containing the b quark, and it is perhaps possible to combine several channels to increase the sensitivity of the signal. One would have to check that asymmetries in different channels do not have opposite signs.

From simple counting of the available independent four-momenta one can convince oneself that if the Z polarization is not known, there can be no triple product correlations in this decay. Moreover, by inspection of the terms we left out in

Eq. (2.6), one finds that in order to have a triple product it is necessary to construct an observable that is sensitive to the spin of the quarks. The only way in which this quark polarization becomes observable is if the b -quark decays weakly as a free quark, rather than as a B meson. A very heavy quark may in fact decay weakly as a quark,^[7] and therefore it should be possible to construct these latter observables for a heavy t -quark.^[8] For the b -quark, however, this is not what we expect. Perhaps this spin information may survive the hadronization process if the b -quark turns into a hyperon (like Λ_b). We will not consider this case here, but just note that signals like the one we have discussed could be the best suited for looking at CP violation in quark couplings. This is not the case for leptons, where the decay $Z \rightarrow \tau^+\tau^-$ is followed by weak decays of the τ -leptons that effectively measure their polarization.^[4] Leptonic modes are a good place to look for triple product correlations.

We have only mentioned energy asymmetries, but it is also possible to define rate asymmetries that will be sensitive to the kind of CP-odd interference terms that we have been discussing. The rate asymmetries appear because the new term causes the probability for a $\bar{b}$ -quark turning into a B^+ to be different from that of a b -quark turning into a B^- , for example. An example of such rate asymmetry would be:

$$\frac{\Gamma(Z \rightarrow B^- B^{*+} X) - \Gamma(Z \rightarrow B^+ B^{*-} X)}{\Gamma(Z \rightarrow B^- B^{*+} X) + \Gamma(Z \rightarrow B^+ B^{*-} X)} \quad (2.16)$$

We have not found a satisfactory model to estimate this type of asymmetries, but we do not expect them to be much different from the energy asymmetries that we have discussed.

3. d_b in multi-Higgs models

How large is d_b likely to be? We can use the experimental upper bound on the neutron electric dipole moment as the value for d_N . The Leningrad and Grenoble numbers are:^[9]

$$\begin{aligned} d_N &= (-1.4 \pm 0.6) \cdot 10^{-25} \text{ e - cm.} \\ d_N &= (-0.3 \pm 0.5) \cdot 10^{-25} \text{ e - cm.} \end{aligned} \tag{3.1}$$

We can then use the fact that fermion dipole moments scale as a typical mass to the third power in models with an extended Higgs sector. The case of the neutron is of course more complicated, and there are many competing mechanisms producing its electric dipole moment.^[10] However, most contributions enter at about the same level, and we can roughly say that the typical size of the neutron edm in multi-Higgs models from all the different mechanisms tends to be comparable to the edm of a constituent quark of mass around 450 MeV .^[11] If we use this naive scaling we find^{*}

$$\begin{aligned} \frac{e}{4 \sin \theta_W \cos \theta_W} d_b &\sim \left(\frac{m_b}{m_s} \right)^3 \cdot 10^{-25} \text{ e - cm.} \sim 1.5 \times 10^{-22} \text{ e - cm.} \\ d_I &\sim 1.2 \times 10^{-8} \text{ GeV}^{-1} \end{aligned} \tag{3.2}$$

Unfortunately this is much too small to produce any measurable asymmetry. However, we obviously cannot discount the possibility of a different mechanism generating a larger dipole moment.

To motivate our claims that the absorptive part of d can be as large as its dispersive part, and that a reasonable value for d_I is obtained with our naive scaling, consider the diagram of Fig. 2. In general, the form of the couplings

* This is a very rough argument and we are being conservative. The case of the neutron EDM is quite complicated by non-perturbative QCD effects. If it becomes necessary one should try to free this bound from neutron EDM data.

between the scalars and the fermions is:

$$2^{3/4} G_F^{1/2} m_b (\alpha + i\beta \gamma_5) \quad (3.3)$$

It is the simultaneous presence of scalar and pseudoscalar couplings of a physical neutral Higgs to fermions that signals the violation of CP. Our result for this diagram is:

$$d = \frac{-1}{16\pi^2} 2\sqrt{2} G_F g_V \alpha \beta \frac{m_b^3}{m_Z^2} \left[\text{li}_2\left(\frac{-m_Z^2}{m_H^2}\right) + \log\left(\frac{m_H^2 + m_Z^2}{m_H^2}\right) \log\left(\frac{-m_Z^2}{m_H^2}\right) \right] \quad (3.4)$$

so it has an absorptive part:

$$d_I = \frac{1}{16\pi^2} 2\sqrt{2} G_F g_V \alpha \beta \frac{m_b^3}{m_Z^2} \pi \log\left(1 + \frac{m_Z^2}{m_H^2}\right) \quad (3.5)$$

if we take $m_H \sim m_Z$ and $\alpha\beta \sim \mathcal{O}(1)$ we obtain $d_I \approx 5. \times 10^{-9} \text{ GeV}^{-1}$. This result is indeed of the same order as the one we found earlier using naive scaling arguments.[†]

Of course, in a complete calculation, one would have to sum over all the scalars and fermions that can contribute. One would also have to consider all the one loop diagrams. However, our purpose here was merely to give an estimate for the size of this typical term.

[†] One can find more rigorous constrains on these angles, see for example the last paper of Ref. 3.

4. Discussion

A possible way to look for a b -quark dipole moment, d_b , is thus by measuring such asymmetries. We can calculate the sensitivity of these signals to d_b . For 10^7 Z decays one expects around 6.0×10^5 $Z \rightarrow B^- X$ events (we have also included $B^{*-} \rightarrow B^- \gamma$). At the few σ level one would then be able to observe an asymmetry as low as a few parts in 10^3 . This translates into a sensitivity to the absorptive part of d_b , d_I of $\sim 0.002 \text{ GeV}^{-1}$.

We have identified a class of observables sensitive to the absorptive part of CP violating couplings of the Z to fermions. These signals have been missed by the effective Lagrangian approach, because it has only been carried out at tree level. Within that approach, our signals appear when one goes to one loop. Our specific example would be given by a loop diagram consisting of the standard model $Z \rightarrow b\bar{b}$ coupling, followed by an effective CP-violating four fermion interaction.[†] We have shown, within a simple model, that the additional absorptive phases required for these signals need not be small.

The interest of these CP odd signals lies in the fact that they do not directly require a measurement of the fermion spin. This is to be contrasted with other studies that require the observation of fermion polarization to signal real (dispersive) CP violating form factors. This fermion polarization can be measured indirectly in the case of the τ -lepton, but it seems unlikely that this can be done for quarks. The kind of signals we discussed requires some particle identification. We have found an example where one only has to identify a B meson.

Unfortunately, the signals studied in this paper appear to be much too small for the expected sensitivity of LEP results. However, the situation is not as bad as it seems when one considers that we have not tried to find an optimal signal. We were just illustrating a point with a simple example. It is conceivable that one can find signals that do not have the helicity suppression of our example. The dipole

[†] We thank C. Burgess for discussions on this point.

moment is also suppressed by too many small masses (at the Z -mass scale the b -quark is light!) in our example. This is clearly an attribute of the multi-Higgs models and not a general feature.

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FIGURE CAPTIONS

- 1) Effective $Zb\bar{b}$ coupling
- 2) Diagram giving an absorptive part to d in a model where CP is violated by the couplings of an extended Higgs sector.

FIGURE 1

FIGURE 2