MASS SHIFTS OF INTERMEDIATE VECTOR BOSONS
INDUCED BY NEW INTERACTIONS ^{*)}

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ABSTRACT

Departures of the vector boson masses from the predictions of the standard model are studied as a possible window to new physics. An estimate of the mass shifts is presented in two different models recently proposed to explain the anomalous $\lambda^+\lambda^-\gamma$ events seen at the collider. In both cases there is a cancellation of the leading term and the mass shifts are of the same order of magnitude as the standard radiative corrections in one of the models (scalar particle) while they are too small to be detectable in the other case (excited lepton).

*) Work partially supported by the CAICYT.

The enormous success of the standard model in accommodating a huge amount of experimental facts has led to a perhaps insufficiently founded confidence in the ultimate elementarity of gauge particles and interactions. In this respect, the grand unification idea is the most extreme exponent of this belief: no new physics and no further layers of substructure will be found up to the grand unification scale at 10^{15} GeV. Challenging this idea of no further energy scale beyond the Fermi, Grand Unification and Planck scales is the concept of compositeness of Higgs scalars (Technicolor) and/or the nowadays more popular approach of supersymmetry where a plethora of new phenomena and a rich particle spectrum is expected. In these latter instances, the "new physics" should show up not too far away from present-day energies. Even more extreme than those views is the position entertained by many theorists. They endow leptons and quarks with internal structure and sustain that weak bosons are composite. Recently, an experimental result has produced an intense boost of interest on these matters. Indeed, anomalous radiative events $l^+l^-\gamma$ have been reported ¹⁾. They cannot be interpreted as standard photon emission in the leptonic decay of the Z^0 boson. Various explanations have been proposed to accommodate for these experimental data. All of them require drastic departures from the standard electroweak model. Thus, the threshold of "new physics" being so close to the Fermi scale, it is surprising, to say the least, that so many predictions of the standard model do fit so nicely the data. Naively one would expect that this "new physics" involved in the anomalous radiative events induces corrections to the standard model predictions which are much bigger than the standard radiative corrections.

In this paper we examine the expected shifts to the masses of the $W^\pm$ and Z^0 bosons in two of the currently popular models proposed to account for the $Z^0 \rightarrow l^+l^-\gamma$ events. These models should provide a definite frame to estimate the possible effects of new interactions on the mass parameters of the electroweak interactions and should be given no further significance beyond that.

Let us state briefly the two models denoted by a) and

b) in what follows. Model a) is given by the effective lagrangian^{#1}:

$$\mathcal{L} = \frac{k}{\Lambda} \bar{L} \sigma^{\mu\nu} l_R B_{\mu\nu} + \text{h.c.}$$

where L stands for an excited lepton field which, for simplicity, has been assumed to be a weak isosinglet, l stands for the ordinary electron or muon and $B_{\mu\nu}$ is the usual U(1) field strength, k is an arbitrary dimensionless coupling constant and Λ is a parameter with dimensions of energy which sets the scale of the new interaction.

In model b) a scalar particle is introduced whose interactions are described by the lagrangian

$$\mathcal{L} = \frac{k}{\Lambda} \epsilon^{\alpha\beta\gamma\delta} \vec{F}_{\alpha\beta} \cdot \vec{F}_{\gamma\delta} X$$

where $\vec{F}_{\alpha\beta}$ is the field strength associated with the weak isotriplet field $\vec{W}_\alpha$. As before, X is a singlet under SU(2)^{#2}.

The electroweak parameters, i.e. Fermi's constant G_F , fine structure constant α and Weinberg's angle θ_W are extracted from low energy processes such as muon decay, Coulomb scattering and neutral current processes involving neutrinos, respectively. The lowest order determination of the gauge boson masses is obtained from the comparison of a tree order calculation with experiment. However, these mass values get corrections when radiative corrections are included⁴⁾. They change in the first place because the theoretical cross sections for the low energy processes that were used to define the lowest order masses are corrected and, of course, because of the direct vacuum polarization contributions to the vector boson propagator itself (evaluated on mass shell). In the standard model it turns out that the bulk of the corrections to the $W^\pm$, Z^0 masses comes from the selfenergy insertions of the weak boson propagators⁵⁾. Vertex corrections, box diagrams and self-energies of external legs give only small contributions to the weak boson mass shifts. Our strategy consists in evaluating the contribution to the self-energy of the intermediate vector bosons due to loops with a heavy lepton

(model a) and with a heavy scalar (model b). We thus ignore any other source of mass shifts like vertices, boxes and selfenergies of external legs. In the case of model a) this can be argued to be true. In model b) it is probably the main contribution. In any case, a complete evaluation is out of the scope of this paper and probably devoid of much significance for both models correspond to nonrenormalizable interactions and we can only hope to roughly estimate the corresponding effects.

Our calculation involves the evaluation of diagrams in figs. 1 and 2 which correspond to model a) and b) respectively. The wavy lines stand generically for vector boson γ , W and Z and the corresponding vacuum polarization functions will be denoted by $\Delta\pi_{ij}(q^2)$. The corresponding mass shifts of intermediate vector bosons are ⁵⁾.

$$\delta M_W^2 = \Delta\pi_{WW}(M_W^2) + \left\{ -\Delta\pi_{WW}(q^2) - \frac{c}{s} M_Z^2 \frac{\Delta\pi_{ZY}(q^2)}{q^2} - M_W^2 \frac{\Delta\pi_{YY}(q^2)}{q^2} \right\}_{q^2=0} \quad (1)$$

$$\delta M_Z^2 = \Delta\pi_{ZZ}(M_Z^2) + \left\{ -\frac{1}{c} \Delta\pi_{WW}(q^2) - \frac{s^2 - c^2}{cs} M_Z^2 \frac{\Delta\pi_{ZY}(q^2)}{q^2} - M_Z^2 \frac{\Delta\pi_{YY}(q^2)}{q^2} \right\}_{q^2=0}$$

where $c = \cos\theta_W$ and $s = \sin\theta_W$.

In both models one naively expects, just by dimensional arguments that the various vacuum polarization functions $\Delta\pi_{ij}(q^2)$ diverge quadratically with the cut-off Λ . This behaviour would lead to unacceptably large mass shifts for vector bosons when the parameters of the model are fixed in the light of the radiative decay events observed at the collider and in a more general context it would put very stringent limits for the onset of new physics. However this will turn out not to be the case as we shall see shortly by explicit calculation. Let us proceed separately for each of both models.

Model a

In this case only two functions, $\Delta\pi_{\gamma Z}$ and $\Delta\pi_{ZZ}$ enter in the discussion. They differ only by the coupling in the vertices, i.e.

$$\Delta\pi_{ij}^{\mu\nu} = \frac{f_i f_j}{\Lambda^2} \Delta\pi^{\mu\nu} \quad (2)$$

where $f_Z = ks$ and $f_\gamma = kc$. Now, if we define

$$\Delta\pi^{\mu\nu}(q) = \left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \right) \Delta\pi(q^2) \quad (3)$$

then, a straightforward calculation leads to

$$\begin{aligned} \Delta\pi(q^2) = \frac{q^4}{\pi^2} & \left\{ \left[\frac{1}{6} \ln \frac{\Lambda^2}{M^2} - \frac{1}{6} \left(1 + 2 \frac{M^2}{q^2} \right) \left(1 - \frac{M^2}{q^2} \right)^2 \ln \left(\frac{q^2 - M^2}{M^2} \right) + \frac{1}{9} + \right. \right. \\ & \left. \left. + \frac{1}{3} \frac{M^2}{q^2} - \frac{1}{3} \frac{M^4}{q^4} \right] + 0 \left(\frac{M^2}{\Lambda^2}, \frac{q^2}{\Lambda^2} \right) \right\} \end{aligned} \quad (4)$$

where M is the mass of the excited lepton.

It is worth noticing, as advertized before, that the quadratic piece in Λ^2 vanishes identically in $\Delta\pi(q^2)$ and that the remaining piece, being thus proportional to q^4 , does not produce any W boson mass shift since the term $\Delta\pi_{\gamma Z}/q^2$ that enters in eq. (1) vanishes when evaluated at $q^2=0$. The shift in the Z^0 mass is simply given by $\Delta\pi_{ZZ}(M_Z^2)$:

$$\begin{aligned} \delta M_Z^2 = \left(\frac{k^2}{e^2} \frac{M^2}{\Lambda^2} \right) s^2 \frac{\alpha}{\pi} \frac{M_Z^4}{M^2} & \frac{2}{3} \left\{ \ln \frac{\Lambda^2}{M^2} - \left(1 + 2 \frac{M_Z^2}{M^2} \right) \left(1 - \frac{M_Z^2}{M^2} \right)^2 \ln \left(\frac{M_Z^2 - M^2}{M^2} \right) + \right. \\ & \left. + \frac{2}{3} + 2 \frac{M^2}{M_Z^2} - 2 \frac{M^4}{M_Z^4} \right\} \end{aligned} \quad (5)$$

Putting into this formula the values $M=75$ GeV (required to explain the anomalous events) and $\Lambda=1$ TeV, we obtain

$$\delta M_Z = \left(\frac{k^2}{e^2} \frac{M^2}{\Lambda^2} \right) (160 \text{ MeV}) \quad (6)$$

which is small even if we allow the factor $\frac{k^2}{e^2} \frac{M^2}{\Lambda^2}$ to be $O(1)$, as required ²⁾ to enhance the event rate for $Z^0 \rightarrow l^+ l^- \gamma$ to the experimentally observed magnitude ¹⁾.

Model b

The contribution of diagrams in figure 2 is easily seen to be of the form

$$\Delta\pi_{ij}^{(1)}(q^2) = \frac{f_{ij}^1}{\pi^2} \frac{q^2}{\Lambda^2} I(M_1, M, q^2) \quad (7)$$

where f_{ij}^1 stands for the couplings involved in the various vacuum polarization functions. The label 1 refers to the vector boson in the loop ($l=\gamma, Z$, or W , see fig. 2). The function $I(M_1, M, q^2)$ reads explicitly:

$$I(M_1, M, q^2) = \frac{1}{\pi^2} \int_0^1 dx \int d^4k \frac{k^2}{[k^2 + xM_1^2 + (1-x)M^2 - (1-x)xq^2]^2} \quad (8)$$

Contrarily to what happens in case a) no cancellation of the quadratic divergences occurs at this stage. However, when fed into eq.(1) these quadratic terms (in the cutoff momentum Λ) combine to zero. After performing the momentum and parametric integrations in eq. (8) and keeping only the leading (logarithmic) terms in Λ and the Λ independent terms one finally gets:

$$\begin{aligned} \delta M_W^2 &= \frac{M_W^4}{\Lambda^2} \frac{2}{3} \frac{k^2}{\pi^2} \left(\ln \frac{\Lambda^2}{M^2} + \delta_W \right) \\ \delta M_Z^2 &= \frac{M_W^2 M_Z^2}{\Lambda^2} \frac{2}{3} \frac{k^2}{\pi^2} \left(\ln \frac{\Lambda^2}{M^2} + \delta_Z \right) \end{aligned} \quad (9)$$

where δ_W and δ_Z are awkward expressions in the masses M_Z and M and, for the cases of interest, their numerical values are small compared with $\ln \frac{\Lambda^2}{M^2}$.

Before we go into the numerical estimates of these eqs. we would like to stress that the cancellation of quadratic divergences above is automatically built in because of the $SU(2) \times U(1)$ symmetry of the effective lagrangian. In fact, if one had assumed completely unrelated couplings for the scalar-vector boson vertices no cancellation would have followed and the suppression factor $M_{Z,W}^2/\Lambda^2$ in $\delta M_{Z,W}^2$ would be absent.

If we take the numerical values $M=50$ GeV, $\Lambda=1$ TeV and $k^2/4\pi=1$ which have been entertained in ref. 3), we obtain

$$\delta M_W \simeq 840 \text{ MeV} \quad \text{and} \quad \delta M_Z \simeq 1160 \text{ MeV} \quad (10)$$

These mass shifts are rather large but nevertheless of the same

order of magnitude as the standard electroweak corrections which amount to about 3 GeV. Since the mass of the Z^0 boson should be measured at LEP with a 100-200 MeV resolution the shifts in eq.(10) are definitely detectable. Of course, for the present situation (a scalar with $M=50$ GeV) this is a rather indirect way to learn about the new particles for they can be produced directly in present accelerators (they have been already produced if the above explanation for the anomalous events is correct). However, it could well be that in the next run of the $p\bar{p}$ collider those events are seen not to be there and still the whole picture of a scale for new physics makes sense. Therefore, in such an instance, the detection of deviations from the standard model predictions for the mass of the intermediate vector bosons at LEP or elsewhere should supply important insight into the question of particle substructure. To get some feeling as to what expect in a situation like this we give the estimated $\delta M_{W,Z}$ for $M=250$ GeV and $\Lambda=1$ TeV:

$$\delta M_W = 430 \text{ MeV} \quad \text{and} \quad \delta M_Z = 520 \text{ MeV} \quad (11)$$

To close this paper we briefly summarize our findings. We have estimated the mass shifts of the intermediate vector bosons in the context of two currently popular models that go beyond the standard model incorporating new particles and interactions. In spite of the fact that these models were primarily designed to allow for very large couplings of the Z^0 boson to photons, those corrections turn out not to blow up (quadratically) without control because of a cancellation which can be directly traced (in model b) to the underlying $SU(2) \times U(1)$ symmetry. In the case of the excited lepton (model a), these corrections lie possibly beyond experimental detectability but in the scalar particle case (model b) the experimental detection would be possible. This may be relevant, if the mass of the scalar is too large to be reached in the next run of experiments (in such case, of course, the scalar is not the one postulated to explain the $l^+l^-\gamma$ events).

One of us (J.A.G.) thanks M. Jacob and the CERN Theory Division for their kind hospitality.

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FOOTNOTES

- ≠1 This model has been considered recently in ref. (2).
- ≠2 See ref. (3) for a discussion of this model in the context of subconstituent models.

FIGURE CAPTIONS

Fig. 1.- Vector boson vacuum polarization matrix due to a loop with a heavy lepton L and an ordinary lepton l . The index i,j refers to γ and Z .

Fig. 2.- Vector boson vacuum polarization matrix due to a loop with a scalar X and a vector boson l . The index i,j,l refers to γ , Z and W .

FIG. 1

FIG. 2