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SPECIAL FEATURES OF Z COUPLINGS TO FERMIONS AND NEW PHYSICS DETECTION

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ABSTRACT

We consider a number of observable Z couplings to fermions that will be measured in the very near future in the first phase (no polarization, $E < 110$ GeV, luminosity $< 10^{31}$) of LEP 100. We show that the effect on these quantities of a large number of models predicting a new vector boson Z' is such that one can generate couples of linear combinations of the couplings (and of the W/Z mass ratio) in whose plane several models (with at least two free parameters) remain simply associated to a straight line. This allows us to establish a correspondence between points of some plane of experimental variables and models that might lead to a complete identification of the latter ones or, in the most pessimistic case, to new and much stricter bounds on their parameters.

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The possibility that accurate measurements of the Z couplings to fermions in e^+e^- annihilation on Z resonance can provide clean and spectacular evidence in favour of models of New Physics that predict the existence of (at least) one new vector boson Z' has been recently investigated in some detail for the case of longitudinally polarized initial beams [1,2], and also for the case in which no initial beam polarization is available [3,4]. Both analyses lead to a number of results that would allow us to perform unexpectedly simple and impressive yes/no tests of some of the considered models.

A fundamental ingredient in this search was that of a proper selection of the experimental quantities, in the sense that choosing certain specific combinations of observables, the test of a certain model turned out to be much more immediate than it would have been with different choices. In fact, a correspondence seemed to exist between the theoretical scheme and those experimental observables that seemed to be the proper ones to test it in the most unbiased way. In the specific case of a general left-right symmetry [5], for instance, certain combinations of longitudinally-polarized asymmetries appeared as the right tool to test the model in a simple and economical way [4,6].

The picture without polarization was also analyzed in Refs. [3,4] and certain preliminary interesting conclusions could already be drawn. The aim of this letter is to consider in more detail this realistic situation of the first years of running at LEP100 and SLC, and to try to develop a general strategy and some clear criteria to identify, within the set of observable quantities that are likely to be measured at the required experimental (and theoretical) accuracy, those combinations that appear as the natural candidates to be "assigned" to the different considered New Physics models. The general philosophy will be that of considering sets of experimental "variables" such that, in the space that remains defined by them (where a small "dead area" around the origin corresponds to the non-observation of any clean effect beyond the minimal standard model), the allowed region for any scheme is as simple and characteristic as possible. Thus, the consequence of finding the experimental point in an allowed region should be unambiguously positive evidence for a certain model and negative evidence for other ones. As a by-product of our approach, we shall also derive the new bounds for the considered possibilities that would correspond to the "dead region", i.e., to the non-observation of any clean effect. As we shall show, these bounds would be impressively stricter (in some cases, by almost one order of magnitude) than those already existing, leading to a much smaller allowed range for the parameters. Thus, in the most pessimistic case, strong limitations on the still allowed models would at least be achieved.

To begin our analysis, we shall choose the basic experimental quantities from which the suitable linear combinations will be built. Guided by the previous

existing studies [7], we shall concentrate our attention here on the following four quantities:

$$\mathcal{F} \equiv \frac{9}{\alpha} \frac{\Gamma_{Z \rightarrow \ell \bar{\ell}}}{\sqrt{s}} \Big|_{\sqrt{s} = M_Z} \quad (1)$$

$$\mathcal{R}_Z' \equiv \frac{3}{5g} \frac{\Gamma_{Z \rightarrow u, d, s, c, b}}{\Gamma_{Z \rightarrow \ell \bar{\ell}}} \Big|_{\sqrt{s} = M_Z} \quad (2)$$

$$A_\tau \equiv \frac{N(\tau_L) - N(\tau_R)}{N(\tau_L) + N(\tau_R)} \Big|_{\sqrt{s} = M_Z} \quad (3)$$

$$\xi \equiv 2M_W^2 / [M_Z^2 (1 + \sqrt{1 - 4\mu^2/M_Z^2})]; \quad \mu = 37.286 \text{ eV} \quad (4)$$

which should be measured soon at LEP100, SLC and ACOL (we assume a preliminary measurement of M_Z to, say, ± 50 MeV [7]). The reason why we concentrate here on these observables is that they appear to be suitably "clean", i.e., their overall theoretical and experimental uncertainty is sufficiently small to allow possible small effects to be revealed [7,8]. All the following considerations would obtain, though, for other new observables, enjoying the same "cleanness" property that might be considered in future studies.

The starting point of our method, which has been exhaustively illustrated in Ref. [2], is to generate observables that are free of residual contaminations from unknown virtual effects of the " ∇_ρ " kind [2] (formally analogous to a redefinition of the ρ parameter) due, e.g., to one-loop quadratic terms in new heavy particles (including the top) or sparticles, or to tree effects from unconventional Higgses, or from (mathematical) Z_0 -(physical) Z mass splittings. Using the notation of Ref. [2], we shall thus write:

$$\mathcal{F} \simeq [\mathcal{F}]^{(o)} + [\nabla_\rho] + [\mathcal{F}]^{\text{GNP}} \quad (5)$$

$$\mathcal{R}_Z' \simeq [\mathcal{R}_Z']^{(o)} + \frac{1}{2} [\nabla_\rho] + [\mathcal{R}_Z']^{\text{GNP}} \quad (6)$$

$$A_\tau \simeq [A_\tau]^{(o)} + 3 [\nabla_\rho] + [A_\tau]^{\text{GNP}} \quad (7)$$

$$\xi \simeq [\xi]^{(o)} + \frac{3}{2} [\nabla_\rho] + [\xi]^{\text{GNP}} \quad (8)$$

and we shall assume, according to the existing studies [7,8], that the overall theoretical and experimental uncertainties for these quantities are:

$$\delta \mathcal{F} \simeq \pm 0.020; \quad \delta \mathcal{R}'_Z \simeq \pm 0.020; \quad \delta A_Z \simeq \pm 0.020; \quad \delta \xi \simeq \pm 0.010$$

$$\delta \equiv \{ \delta^{exp}, \delta^{(o)} \} \quad (9)$$

Clearly, from Eqs. (5)-(8), we can build three linear combinations that are ∇p -free and can therefore be utilized as genuine New Physics filters. The actual choice of the three combinations is, to a certain extent, arbitrary. To give some general criteria to fix it, a good starting point is to consider the expressions of the "Genuine New Physics" components in several models and to derive, whenever possible, special features of such contributions that might naturally lead to an identification of the most suitable combinations. We begin this analysis with the case of a model of New Physics in which a previous E_6 symmetry exists [9], which leads to the existence of a new Z' and to a modified physical Z current parametrized as [10]

$$\overline{J}_\mu^Z \simeq \overline{J}_\mu^{Z_0} + \Theta_M [\sin \beta \overline{J}_\mu^{Z_\psi} + \cos \beta \overline{J}_\mu^{Z_\chi}] \quad (10)$$

Here Z_0 is the mathematical MSM vector boson and we only retain, according to our general philosophy, first-order terms in the mixing angle Θ_M , which is known to be small from the already existing experimental information [10] (a more rigorous treatment including next-order terms, that would not change the main results of this letter, will be given in a longer paper [11]).

Defining the physical Z couplings to a generic fermion f as:

$$\overline{J}_\mu^Z(f) \equiv \overline{f} [\overline{v}_f \not{J}_\mu + a_f \not{J}_\mu \not{J}_5] f \quad (11)$$

we find that for the considered E_6 model:

$$\overline{v}_e = \overline{v}_e^{Z_0} + \frac{e}{4c} \Theta_M [4 \cos \beta / \sqrt{6}] \quad (12)$$

$$a_e = a_e^{Z_0} - \frac{e}{4c} \Theta_M [\sin \beta \sqrt{10}/3 + 2 \cos \beta / \sqrt{6}] \quad (13)$$

$$\overline{v}_u = \overline{v}_u^{Z_0} \quad (14)$$

$$a_u = a_u^{Z_0} - \frac{e}{4c} \Theta_M [\sin \beta \sqrt{10}/3 - 2 \cos \beta / \sqrt{6}] \quad (15)$$

$$\overline{v}_d = \overline{v}_d^{Z_0} - \frac{e}{4c} \Theta_M [4 \cos \beta / \sqrt{6}] \quad (16)$$

$$a_d = a_d^{z_0} - \frac{e}{4c} \theta_M \left[\sin \beta \sqrt{10}/3 + 2 \cos \beta / \sqrt{6} \right] \quad (17)$$

$$v_\nu = v_\nu^{z_0} + \frac{e}{4c} \theta_M \left[\sin \beta \sqrt{10}/6 + 3 \cos \beta / \sqrt{6} \right] \quad (18)$$

$$a_\nu = a_\nu^{z_0} - \frac{e}{4c} \theta_M \left[\sin \beta \sqrt{10}/6 + 3 \cos \beta / \sqrt{6} \right] \quad (19)$$

$$e \equiv |e|; \quad c \equiv \left\{ \frac{1}{2} \left[1 + \sqrt{1 - 4\mu^2/M_Z^2} \right] \right\}^{1/2} \equiv \left\{ \frac{3+v_0}{4} \right\}^{1/2}$$

From the general expression of the partial width of Z into fermions at tree level:

$$\Gamma_{Z \rightarrow f\bar{f}} \equiv \Gamma_f = \frac{N M_Z}{12\pi} [v_f^2 + a_f^2] \equiv \Gamma_f(\theta_M=0) + \delta \Gamma_f(\theta_M) \quad (20)$$

$$N = \begin{cases} 1 & f = e, \nu \\ 3 & f = u, d \end{cases}$$

it is now straightforward to derive the tree-level effect of the new Z' on Eqs. (5) and (6). Note that, since only two effective Z' parameters, i.e., $\theta_M \sin \beta$, $\theta_M \cos \beta$, appear in the expression Eq. (20) to first order in θ_M , one expects to find two independent linear relationships between the four (e, ν, u, d) fermionic shifts. The first one is actually the (known) equation:

$$\delta \Gamma_e + \delta \Gamma_\nu + \delta \Gamma_u + \delta \Gamma_d = 0. \quad (21)$$

which simply reflects the fact that in the considered model the sum over an SU(5) multiplet of the Z_0 charges vanishes. The second relationship leads to an interesting and, to our knowledge, new equation. In our approximated scheme, where terms of $O(\theta_M^2, v_0^2, \theta_M v_0)$ are systematically neglected [11], it reads:

$$\begin{aligned}\delta \Gamma_e &= \frac{1}{3} [2 \delta \Gamma_u + 3 \delta \Gamma_d] = \\ &= \frac{1}{3} [\delta \Gamma_u + \delta \Gamma_d + \delta \Gamma_s + \delta \Gamma_c + \delta \Gamma_b] \equiv \frac{1}{3} \delta \Gamma_h\end{aligned}\quad (22)$$

where Γ_h is the partial width of Z into the five known quarks (the latter ones at the level of accuracy that is of interest here, can be all considered massless) that appears in the numerator of Eqs. (2) and (6).

Equation (22) states that to first order in θ_M the Z' effects on Γ_h and on Γ_λ are simply proportional for all choices of $\cos \beta$ within the general E_6 model Eq. (10). A short computation then gives for Eqs. (5) and (6):

$$\delta^{(G.N.P.)} \simeq \theta_M \left[-\sin \beta \sqrt{10}/3 - 2 \cos \beta / \sqrt{6} \right] \quad (23)$$

$$R_2^{(G.N.P.)} \simeq \frac{9}{59} \theta_M \left[-\sin \beta \sqrt{10}/3 - 2 \cos \beta / \sqrt{6} \right] = \frac{9}{59} \delta^{(G.N.P.)} \quad (24)$$

For the remaining two variables Eqs. (7) and (8), one has on the other hand in the same situation:

$$A_\tau^{(G.N.P.)} \simeq \theta_M \left[-4 \cos \beta / \sqrt{6} \right] \quad (25)$$

$$\left\{ \begin{array}{l} (G.N.P.) \\ \end{array} \right\} = 0 \quad (26)$$

the last equation being a consequence of the fact that the full Z' contribution to ξ in this model is absorbed into the obscure ∇_ρ block [2]. From Eqs. (23)-(26),

it appears that two V_p -free filters can be built for which the effect of an E_6 generated Z' will be simply proportional. For example, the two quantities :

$$n \equiv \left[R'_Z - \frac{1}{2} \mathcal{F} \right] - \left[R'_Z - \frac{1}{2} \mathcal{F} \right]^{(0)} \quad (27)$$

$$p \equiv \left[R'_Z - \frac{1}{3} \mathcal{F} \right] - \left[R'_Z - \frac{1}{3} \mathcal{F} \right]^{(0)} \quad (28)$$

as well as an arbitrary general linear combination of them would meet this request. In the plane of these variables, the allowed region for the model of Eq. (10) would obviously be a straight line [4]. This fact, which is a consequence of the formal expression of the Z couplings to fermions in the model, might provide a spectacularly simple yes/no test of this possible type of New Physics.

An interesting possibility that appears at this stage is that of building a couple of variables, in the plane of which a general class of Z composite models [12] enjoys the same simple property of belonging to a straight line. Thus, since for the most general left-right symmetric model such suitable variables have already been identified [4], all these models predicting a new Z' would be associated to a well-defined couple of observables that would minimize the model's allowed region.

A review of the properties of new weak vector bosons of composite origin has been given recently [13]. We shall consider here the case of an isoscalar boson Y' . As is known [12], there can be in this case two "orthogonal" situations, corresponding to a Y' coupling to the usual weak hypercharge current or to a Y' coupling to the left-handed part of the current only. In full generality, we shall thus write:

$$\overline{J}_\mu^{Y'} = a \overline{J}_\mu^Y + b \overline{J}_\mu^{Y_L} \quad (29)$$

where Y , Y_L correspond to the two orthogonal situations and $a^2 + b^2 = 1$. The effects of this model on the previous filters can easily be derived from the expressions of the Z couplings to fermions in this case, whose detailed form will be given elsewhere [11]. A priori, a good observable for such a Y' appears to be the V_p -free quantity:

$$q \equiv \left[R'_Z - \frac{10}{5g} A_Z \right] - \left[R'_Z - \frac{10}{5g} A_Z \right]^{(0)} \quad (30)$$

which, also being defined by ratios of observables, is independent of the overall normalization of the Z coupling to fermions. This filter would thus be "blind" to

the Y component of Y' [2] and the effect of this type of New Physics on it would be:

$$q^{(Y')} = \frac{5b}{6} \varepsilon_{\chi} \quad (31)$$

For the variables n,p in Eqs. (27) and (28) the Y' effect would be on the other hand:

$$n^{(Y')} = -\frac{a}{2} \varepsilon_Y + b \left[\frac{5}{6} \varepsilon_{\chi} + \frac{2}{3} \varepsilon_{\chi} (1 + 4 \chi^2) \right] \quad (32)$$

$$p^{(Y')} = -\frac{a}{4} \varepsilon_Y + b \left[\frac{5}{6} \varepsilon_{\chi} - \frac{\varepsilon_{\chi}}{3} (1 - 4 \chi^2) \right] \quad (33)$$

Thus, an immediate possibility exists to generate a linear combination of n and p for which the Y' effect is simply proportional to that on q. The desired linear combination is precisely:

$$r = 2p - n \equiv \left[R_2 + \frac{1}{2} \delta - \frac{2}{3} \zeta \right] - \left[R_2 + \frac{1}{2} \delta - \frac{2}{3} \zeta \right]^{(0)} \quad (34)$$

for which one has

$$r^{(Y')} = \frac{7}{18} b \varepsilon_{\chi} = \frac{7}{15} q^{(Y')} \quad (35)$$

Thus, in the (r,q) plane, one has the property that the most general composite model of the type of Eq. (29) will belong to a line for every choice of (a,b), in analogy with the corresponding situation in the (n,p) plane. Noting that r, which is a linear combination of n and p, still isolates, combined with any linear combination of these variables, E_6 models on a straight line in the corresponding plane, we can conclude that for the two general models Eqs. (10) and (29), a suitable set of observables is represented by the three quantities n, r, q [Eqs. (27), (34), (30)]. In the plane of the first two variables, the most general E_6 model [Eq. (10)] belongs to a straight line; similarly, the most general Y' [Eq. (29)] would be located on a straight line in the plane of q and r.

To make a more general analysis, we have also considered the effects on n, r, q of three other models predicting a new Z' that are, to our knowledge, still popular nowadays. The first one is a left-right symmetric model [14] with a free g_L/g_R ratio; the second one is an excited Z^* model [12] and the third one a model with a Zv boson originating from a strongly interacting weak sector [15]. All these models have already been discussed in previous papers [2,13] and we refer to those references for more details. Their effect on the r, p, q variables can be easily computed from the given expressions of Eqs. (1)-(4). Its explicit expression

will be given elsewhere [11]. Here, we only summarize graphically the main results of our computation.

Figure 1 shows the allowed regions of the models in the (r,n) variables derived from the existing limitations on the involved parameters [10,13]. As one sees, a major part of the plane is occupied by the considered models with several regions of possible confusion. In particular, an overlapping exists between the Z^* and the left-right symmetric models Z' (we have only considered here the case $\frac{1}{2}g_L^2 < g_R^2 < g_L^2$), between the E_6 Z' and the general composite Y' case (we have only plotted the two orthogonal cases Y and Y_L) and between the E_6 and the left-right symmetric Z' . Note, however, that the allowed region for all the models is systematically quite larger than the "dead" one. Thus, first exciting preliminary evidence of a new Z' and a strong selection of candidate models could already arise from this analysis, i.e., from the combined measurements of the three quantities γ , R_Z and ξ [Eqs. (1), (2), (4)].

If a measurement of the final τ polarization [Eq. (3)] were available and the q variable [Eq. (30)] could be combined with r [Eq. (34)] [we recall that this would imply the combined use of the four quantities Eqs.(1)-(4)], this already promising picture would be even more drastically improved, as one can see from Fig. 2. The impressive reduction of the allowed region for the models in the (r,q) plane is due to the fact that the q variable, being defined by V_p -free ratios of observables, will be "blind" to the Z^* and Z_v models, as shown in Ref. [2]. The allowed region for E_6 has been derived by the existing data [10], while the most general Y' model belongs, from our previous discussion, to the depicted line (in fact, only the Y_L constraint of the model would be seen). Thus, a minimal region of confusion would survive between Z^* and Z_v , between Y_L and (a fraction of) E_6 and between another fraction of E_6 and the left-right symmetric models. To eliminate the two last sources of confusion would require the introduction of longitudinal polarized asymmetries, which might be done in a second stage at LEP100, SLC, as thoroughly discussed in previous papers [4]. Meanwhile, we can see from Fig. 2 that the combined measurements of the quantities Eqs. (1)-(4) would give an impressive simple and clean yes/no test of all the relevant models with a new vector boson Z' that we have examined.

To conclude our analysis, we have considered a situation in which the experimental point should fall into the "dead" region of the full set of (n,r,q) variables, thus generating bounds for the involved parameters of this kind of New Physics corresponding to the boundary of the dead area.

Figure 3 shows the results of our analysis for the case of the E_6 model, where a comparison with the existing limits [10] is possible (the more general analysis

of other models is given elsewhere [11]). We have plotted the allowed region for θ_M versus $\cos\beta$ that would correspond to the dead region generated by the overall errors on (n,r,q) corresponding to Eq. (9). Note that the bounds for θ_M would in this case be drastically stricter (in some $\cos\beta$ range, by almost one order of magnitude) than the existing ones. In practice, for any choice of $\cos\beta$, the mixing angle would always be limited, in the most optimistic case, by

$$|\theta_M| \leq 0.03 \quad (36)$$

Thus, if the experimental result should (unfairly) fall into the dead region, the possibility of a sizeable Z_0 - Z_0' mixing in the E_6 model would be almost completely ruled out.

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FIGURE CAPTIONS

Fig. 1 : Allowed domains for variables n and r . All E_6 models fall on the line $n = 4r$ and left-right models with $\frac{1}{2}g_L^2 < g_R^2 < g_L^2$ fall in the hatched domain with n, r negative. The Y boson domain is the short segment on the negative n axis, whereas the Y_L boson domain is the cross-hatched region for positive n, r values. Excited Z^* bosons lie in the half-plane $r < 0$ and the strongly interacting model Z_V bosons fall on the line $n = 3/5 r < 0$. The central box represents the dead region due to experimental accuracy.

Fig. 2 : Allowed domains for variables q and r . E_6 models fall inside the elliptic domain and the left-right models inside the hatched region with q, r negative. Any combination of Y and Y_L bosons has to lie on the line $q = (15/7)r > 0$, whereas the excited Z^* and the strongly interacting model Z_V bosons lie on the negative r axis.

Fig. 3 : Limits on Z - Z' mixing angles in E_6 models versus the parameter β :

———— present limits (Amaldi et al., [10])
 ----- lower limits accessible at LEP100.

Fig. 1

Fig. 2

Fig. 3