CERN-TH.5204/88

SEARCHES OF NEW VECTOR BOSONS AT THE Z PEAK

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A B S T R A C T

We illustrate three different realistic strategies that would lead to clear evidence for a new vector boson from e^+e^- measurements at the Z peak. The first one assumes that polarized initial beams are available; in the second case, this request is replaced by that of a measurement of the final τ polarization and, finally, only measurements of unpolarized quantities are used. We show that in the first case a very strong selection of candidate models would be achieved. This selection would become less and less stringent in the second and in the third case, although a number of unexpectedly simple and spectacular results could still be obtained.

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A realistic strategy to identify in a clean way virtual signals of a new vector boson Z' of very general origin has been proposed very recently [1]. This strategy generalizes an original suggestion of Cvetic and Lynn [2] and concentrates on special combinations of observables, free of those theoretical terms generating possible corrections to the tree-level predictions that would be formally identical to a redefinition of the ρ parameter. If polarized asymmetries of e^+e^- annihilation on top of the Z resonance were measured, one would be able to define in this spirit the two "twiddled" quantities:

$$\tilde{A}^{(b)} \equiv A^{(b)} - \frac{1}{15} A_{LR} \quad (1)$$

$$\tilde{A}^{(c)} \equiv A^{(c)} - \frac{9}{25} A_{LR} \quad (2)$$

where $A^{(b),(c)}$ are polarized forward-backward asymmetries of $e^+e^- \rightarrow b\bar{b}, c\bar{c}$ and A_{LR} is the longitudinal polarization asymmetry of $e^+e^- \rightarrow \text{hadrons}$, whose properties have been exhaustively discussed elsewhere [3,4]. Such combinations would only be sensitive to contributions from "genuine" new physics, typically to those modifying the physical Z coupling to fermions. One might therefore define the deviations from the Minimal Standard Model predictions as:

$$x \equiv \tilde{A}^{(b)} - \tilde{A}^{(b)}(MSM) \quad (3)$$

$$y \equiv \tilde{A}^{(c)} - \tilde{A}^{(c)}(MSM) \quad (4)$$

and perform a detailed analysis of the effects on x, y of a new vector boson Z' of very general origin. In particular, the cases of a Z' originating from an E_6 gauge group, or from left-right symmetric models, or from a class of composite models, or from a strongly interacting electroweak sector were considered [1], and it was shown that the additional use of other suitable "twiddled" observables like:

$$\tilde{f} \equiv \frac{g}{\alpha} \frac{\Gamma_{Z \rightarrow l\bar{l}}}{M_Z} - \frac{1}{3} A_{LR}; \quad (5)$$

$$\tilde{\rho} \equiv \frac{M_W^2}{M_Z^2} \left[\frac{2}{1 + \sqrt{1 - \frac{4\mu^2}{M_Z^2}}} \right] - \frac{1}{2} A_{LR}; \quad \mu^2 = (37.286 \text{ eV})^2 \quad (6)$$

could eventually lead to an almost complete identification of the underlying model.

More recently [5], a similar strategy has been proposed, that would apply if no initial beam polarization were available. In this case, one could still define two observables formally analogous to Eqs. (5) and (6) by simply replacing the longitudinal polarization asymmetry A_{LR} by the final τ polarization asymmetry A_{τ} , whose properties have also been exhaustively discussed elsewhere [6]. Since A_{τ} is expected to be measured with worse accuracy than A_{LR} , this would lead to a less complete but still interesting identification programme, which has been qualitatively illustrated in Ref. [5].

Technically speaking, the rôle of the observables A_{LR} , A_{τ} in this game is that of washing out the aforementioned disturbing contribution called V_{ρ} in Ref. [1]. Quite generally, combinations of different observables can certainly be built that meet the same request, i.e., are V_{ρ} -free, and do not contain A_{LR} or A_{τ} . The aim of this paper is to show that one can actually define (at least) two such "completely unpolarized" variables which would allow for a partial, but spectacularly simple, Z' identification. This might well be considered as a first stage, e.g., during the first year of running at LEP or SLC, in a more complete identification programme that only polarized measurements would provide.

To make this paper reasonably self-consistent, we shall first review the two situations corresponding to the availability of measurements of x, y , Eqs. (1) and (2), and of the variables:

$$\hat{Z} \equiv \hat{J} - \hat{J}^{(MSM)} \quad (7)$$

$$\hat{W} \equiv \hat{\xi} - \hat{\xi}^{(MSM)} \quad (8)$$

where $\hat{\gamma}$, $\hat{\xi}$ are defined as in Eqs. (5) and (6) but with the replacement $A_{LR} \rightarrow A_{\tau}$. The effects of a Z' of different origin on x , y , $\hat{z}$, $\hat{w}$ have been computed in Refs. [1,5], and the regions in the (x, y) , $(\hat{w}, \hat{z})$ planes corresponding to various models have been drawn. No specific limitation on the parameter space was used in that case (apart from a few special models). In particular, the already existing experimental information for the various mixing angles and masses was not exploited, thus leading in the domains of the involved variables more space than what would actually be available. This experimental information has been carefully taken into account in this paper. In particular, for the most general class of E_6 models that was considered [7]:

$$Z'_0 = \alpha Z'_0 \psi + \beta Z'_0 \chi \quad (9)$$

$$\alpha^2 + \beta^2 = 1$$

$$Z = \cos \theta_M Z_0 + \sin \theta_M Z'_0 \quad (10)$$

we have used the bounds for the mixing angle at variable α, β computed by Amaldi et al. [8]. This leads to allowed regions in the (x, y) and $(\hat{w}, \hat{z})$ planes that are more realistic and sensibly reduced with respect to the more qualitative ones given in Refs. [1,5].

We begin our analysis with the (x, y) variables. From our detailed previous discussions in Ref. [1] and in a subsequent paper [9], it follows that these variables will not feel the effect of a Z' coming from the general composite models that we have considered [10] or from a strongly interacting electroweak sector [11]. They will thus only react to a Z' of extended gauge origin. In this respect, these variables are, to our knowledge, unique, and one should consider them as genuine new gauge boson indicators.

The allowed region for an E_6 generated Z' in the (x, y) plane is depicted in Fig. 1. The "dead" region around the origin corresponds to the estimated experimental [12] and theoretical [3,4] errors on x, y . As one sees, at the realistic computed accuracies, there would be plenty of room available for a clear observation of such an effect. This would remain true even if the experimental error on x and y were increased by a not unreasonable amount, as one can easily verify from inspection of Fig. 1, owing to the asymmetric "banana" shape of the allowed region.

A final, particularly relevant property of the (x, y) variables appears when the class of "canonical" left-right symmetric models [2,13] is considered. It turns out, in fact, that the ratio y/x is fixed in this case:

$$\overset{(LR)}{y} \approx \frac{27}{20} \overset{(LR)}{x} \quad (11)$$

independently of the ratio g_L/g_R , which is a free parameter in this class of models. Thus, no matter what specific left-right symmetry is considered, its effect will have to fall on the same line depicted in Fig. 1 (note that the experimental limits in this case have actually been given for $g_L = g_R$ [8], although other possible cases would produce similar bounds). This beautiful property, which would not be valid for other choices of observables, allows us to consider x and y as strong potential left-right symmetry "discriminators". Note that, as a consequence of these features, a large fraction of the allowed region in the (x, y) plane is left that could only indicate a Z' of E_6 origin.

A quite similar analysis can be performed using the $(\hat{w}, \hat{z})$ variables. The main difference with respect to the previous case is that these variables will also react to signals coming from a general Z' of non-extended gauge origin. The corresponding situation is represented in Fig. 1. As one sees, the potentially allowed region is definitely bigger than the "dead" region, which would now correspond to the expected experimental precision on measurements of γ [14] and A_τ [6] at LEP and of the M_W/M_Z ratio at ACOL [14], and to the corresponding theoretical uncertainties [15,16,6]. In this allowed region, a number of characteristic and relevant features appear. As one sees, although a large overlapping between composite models and gauge models is left, a region still survives which is only belonging to a Z' of extended gauge nature. Although the identification of left-right symmetric models is now much less general, because of the extra parameters entering the charged variable $\hat{w}$, it seems reasonable to ascribe to such models an almost vanishing $\hat{w}$ value [1]. Thus, they would be confined in a narrow strip surrounding the $\hat{z}$ axis, in the positive $\hat{z}$ direction for g_R not unreasonably smaller than g_L . Also, a definite fraction of the allowed region would only compete to a Z' of either composite model origin or due to a strongly interacting electroweak sector ($Z' \equiv Z_V$), with little confusion between these "non-orthodox" candidates. Thus, these variables alone might also allow for very interesting conclusions to be drawn, particularly if a Z' of "non-orthodox" origin turned out to be the relevant one.

One might wonder whether combinations of observables can be built that are still $\nabla\rho$ -free but do not request the use of any polarization measurement. To understand the problem in more detail, we write down the explicit expression of the "non-twiddled" observables:

$$\begin{aligned} \mathcal{F} &\equiv \frac{g}{\alpha} \frac{\Gamma_{Z \rightarrow e\bar{e}}}{M_Z} = \left[1 + \frac{2}{3} v_0 + O(v_0^2) + \nabla\rho + \dots \right] + \mathcal{F}^{(N.P.)} \quad (12) \\ \xi &\equiv \frac{M_W^2}{M_Z^2} \frac{2}{\left[1 + \sqrt{1 - \frac{4\mu^2}{M_Z^2}} \right]} = \left[1 + v_0^2 + O'(v_0^2) + \frac{3}{2} \nabla\rho + \dots \right] + \mathcal{F}^{(N.P.)}; \\ v_0 &= \left[2 \sqrt{1 - \frac{4\mu^2}{M_Z^2}} - 1 \right] \quad (13) \end{aligned}$$

where $(\delta\gamma, \delta\xi)^{(N.P.)}$ are the deviations due to the mixing of a new Z' of general origin and the first bracket on the right-hand side of Eqs. (12) and (13) contains corrections to the tree-level expression coming from the Minimal Standard Model and from any other kind of New Physics (heavy particles or sparticles, non-canonical Higgses, Z_0 - Z' mass shift...), the latter ones being included in the $\nabla\rho$ term.

In order to follow the rules of our game we must generate a couple of observables that are $\nabla\rho$ free and therefore we need a third proper experimental

quantity. A simple possibility, that would be a very realistic one during the first running at LEP 100 and SLC, is to consider the ratio at the Z peak:

$$R_Z \equiv \frac{3}{59} \frac{\Gamma_{(Z \rightarrow u, d, s, c, b)}}{\Gamma_{(Z \rightarrow e \bar{e})}} \Big|_Z \quad (14)$$

which should be measured to a relative accuracy of 0.5×10^{-2} [17]. The theoretical expression for this quantity in the Minimal Standard Model has been estimated [15]. In our simplified notation, the complete expression would read:

$$R_Z = \left[1 + v_0 + O(v_0^2) + \frac{1}{2} \nabla_p + \dots \right] + \delta R_Z^{(N.P.)} \quad (15)$$

where $\delta R_Z^{(N.P.)}$ would be, again, the effect of the mixing of a new Z' . The first bracket contains corrections to the tree level result coming from ∇_p , as in Eqs. (12), (13), and from the Minimal Standard Model. In these corrections we also include the QCD factor $\sim(\alpha_s/\pi)$, assuming an uncertainty on this quantity of approximately 0.01 from future measurements. This error adds to the (small) estimated theoretical uncertainty [15] and makes a total error on R_Z of approximately 0.01-0.02.

To pursue our game, we now define the first brackets on the right-hand side of Eqs. (12), (13) and (15) as $\gamma^{(0)}$, $\xi^{(0)}$, $R_Z^{(0)}$ respectively, and introduce the two following variables:

$$n \equiv \left[R_Z - \frac{1}{2} \gamma \right] - \left[R_Z^{(0)} - \frac{1}{2} \gamma^{(0)} \right] \quad (16)$$

$$p \equiv \left[R_Z - \frac{1}{3} \xi \right] - \left[R_Z^{(0)} - \frac{1}{3} \xi^{(0)} \right] \quad (17)$$

Note that the two second brackets on the right-hand side are now, as one can easily verify, free of the disturbing ∇_p contribution and therefore completely evaluable in the Minimal Standard Model; this makes n and p perfectly analogous to the previous (x, y) or $(\hat{w}, \hat{z})$ quantities. Thus, the same kind of analysis of the effects coming from a new Z' can be performed. We write these effects here, for sake of completeness, for the different models that we have considered. In particular, retaining as usually first-order terms in the mixing angles, we find (using the notations of Refs. [1] and [9] for the various parameters):

E₆:

$$n \simeq \frac{4}{3} \theta_n \left[\frac{\sqrt{10}}{3} \alpha + \frac{2}{\sqrt{6}} \beta \right] \quad (18)$$

$$p \simeq \frac{5}{6} \theta_n \left[\frac{\sqrt{10}}{3} \alpha + \frac{2}{\sqrt{6}} \beta \right] = \frac{5}{8} n \quad (19)$$

L-R symmetry

$$n \simeq x_N \left[2\kappa_R - \frac{5}{3} \right] \quad (20)$$

$$p \simeq -\frac{2}{3} x_N + \frac{1}{3} \frac{\theta_+^2}{\varepsilon_+} \quad (21)$$

Composite Y model

$$n \simeq -\frac{1}{2} \varepsilon_Y = 2p; \quad \delta \left[\mathcal{R}_2 + \frac{1}{2} \mathcal{Y} - \frac{2}{3} \xi \right]^{(N.P.)} = 0 \quad (22)$$

Composite Y_L model

$$n \simeq \frac{5}{6} \varepsilon + \frac{2}{9} \varepsilon (1 + 4\kappa_Y^2); \quad n > 0 \quad (23)$$

$$p \simeq \frac{5}{6} \varepsilon - \frac{\varepsilon}{9} (1 - 4\kappa_Y^2); \quad p > 0 \quad (24)$$

Excited Z* model

$$n = \frac{2}{3} (x_W + \varepsilon_W) \quad (25)$$

$$p = \frac{1}{3} (x_W + \varepsilon_W) - \frac{1}{3} \Omega_W \quad (26)$$

Strongly interacting electroweak sector (Z_v)

$$n \simeq -2 x_v = \frac{3}{4} p; \quad n, p < 0 \quad \delta [\mathcal{R}_2 - 2\mathcal{Y} + \xi]^{(N.P.)} = 0 \quad (27)$$

Figure 3 shows the allowed region in the (n,p) plane, taking all the already existing experimental constraints into account [8,9]. Again, as one sees, the size of the allowed region is overwhelming that of the dead region around the origin. In the allowed domain, it is practically impossible to discriminate effects of extended gauge origin from effects due to general composite models, the exception being represented by the Z_v effect that would be sufficiently clearly

discriminated. Note, however, that the effect of any Z' of the most general E_6 origin must fall on the line:

$$n = \frac{8}{5} p$$

$$\delta \left[R_z + \frac{5}{6} \mathcal{Y} - \frac{8}{15} \{ \right]^{(N.P.)} = 0 \quad (28)$$

This spectacular result, which could allow for a simple clear and preliminary "yes/no" test of the E_6 symmetry, is a consequence of the chosen definitions of n, p and of the fact that R_z , Eq. (14), only contains the hadronic (u,d,s,c,b) partial width and does not include a $t\bar{t}$ decay (which, on the other hand, appears at the moment the correct attitude if the limit $m_t \gtrsim 50$ GeV [18] is trusted). In this respect, the unpolarized (n,p) variables behave as " E_6 discriminators", just as (x,y) with respect to L-R symmetric models.

The conclusion of this paper is that each considered strategy contains promising features of its own that make it a potential clean indicator of some kind of New Physics. Obviously, the best situation would be by far one where all the three different analyses could be performed together, which will be possible when polarized initial beams will become available. However, we believe to have shown that very interesting preliminary results could already be obtained by each of the two considered alternatives, which will certainly become operative in a very near future.

ACKNOWLEDGEMENTS

It is a pleasure to thank Alain Blondel for several stimulating discussions. One of us (F.M.R.) wants to thank the Theoretical Physics Division at CERN for kind hospitality and support.

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FIGURE CAPTIONS

Fig. 1 Allowed domains for variables x and y . The banana shape domain corresponds to all E_6 models and the straight line to all left-right symmetric models. The special (superstring-inspired) η model corresponds to the dotted-dashed line. The expected experimental accuracy in x, y measurements determines the size of the dead region around $x = y = 0$.

Fig. 2 Allowed domains for $\hat{z}$ and $\hat{w}$ variables. In addition to E_6 and left-right models (hatched region) we have represented the allowed domains for composite models, a line for the Y boson, a cross-hatched region for the Y_L boson, a domain lying on the right of the $\hat{z} = 4/3\hat{w}$ line for excited Z^* bosons and the line corresponding to the strongly interacting model with Z_v boson.

Fig. 3 Allowed domains for n and p variables. All E models fall on the line $n = 8/5p$. Left-right models with $\frac{1}{2}g_L^2 \leq g_R^2 \leq g_L^2$ fall in the hatched domain with n and p negative. The Y boson corresponds to the short segment $n = 2p$ for n, p negative, whereas the Y_L boson should fall in the cross-hatched region for positive n, p values. Excited Z^* bosons allow for a broader region on the left of the $n = 2p$ line and the strongly interacting model (Z_v boson) fall on the line $n = 3/4p > 0$.

- Fig. 1 -

- Fig. 2 -

- Fig. 3 -