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SEARCHES FOR A NEW GAUGE BOSON AT DIFFERENT LEP PHASES

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A B S T R A C T

It is shown that a systematic search of a new Z' of extended gauge origin could be carried through at three different LEP phases. The final bounds for the mixing angle, in case of negative searches, would be $|\theta_M| \lesssim 0.025$ for the most general model. For the mass, the general limits which depend on the model would be in any case competitive with those derivable at future collider measurements.

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1. INTRODUCTION

In this seminar, I will show that one of the several remarkable features of LEP would be that of allowing a search for the existence of one extra vector boson of extended gauge origin and mass up to a few hundred GeV in a very systematic and exhaustive way. This search would proceed in different steps, corresponding to three various phases of the machine that I will call phases 1, 1a and 2, respectively. They would roughly correspond to a first stage with total energy $E \lesssim 110$ GeV and $\int L dt \approx 100$ pb⁻¹, an intermediate stage with either initial beam longitudinal polarization or very high luminosity ($\sim 10^8$ Zs) available, and a final state with $E_{max} = 200$ GeV, $\int L dt \lesssim 500$ pb⁻¹. Each of these phases would be able to reveal and to identify different signals of the new Z' generated by independent parameters. Thus, a negative search at LEP would, at least, set limits on all the parameters of the involved models that would be, in general, competitive with those achievable in future pp, pp collider experiments.

Since the theoretical framework involving a new gauge boson has already been exhaustively discussed in several excellent papers, I will be limited to the essential notations and parametrizations. More systematic treatments can be found elsewhere [1].

2. NEW GAUGE BOSON PARAMETERS

A proper theoretical discussion requires now some preliminary definitions. I will consider the case in which an extra boson exists, generated by an extended gauge symmetry. In particular, I will concentrate on two general classes of models: those with just one extra U(1) symmetry and those with a previous left-right symmetry. In the first case, one is left with a gauge group

$$G_1 = SU(2)_L \times U(1)_Y \times U(1)_{Y'} \quad (1)$$

such that

$$Q = I_{3L} + \frac{1}{2} Y \quad (2)$$

i.e., the new gauge boson Z'_0 is simply associated to a neutral generator that does not contribute to the electric charge. In the second case, one will have eventually a gauge group

$$G_{LR} = SU(2)_L \times SU(2)_R \times U(1)_{B-L} \quad (3)$$

with

$$Q = I_{3L} + I_{3R} + (B-L)/2 \quad (4)$$

In both cases, one will be able to write down the following expression for the neutral current Lagrangian:

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$$-L_N = j_{\mu}^{em} \cdot A^{\mu} + j_{\mu}^{Z_0} Z_0^{\mu} + j_{\mu}^{Z'_0} Z'^0_{\mu} \quad (5)$$

where A^{μ} is the photon field and Z_0, Z'_0 are the "mathematical" gauge bosons. The first one is coupled to the current

$$j^{Z_0} = \frac{g_L^2}{\sqrt{g_L^2 - e^2}} [j_{3L} - \frac{e^2}{g_L^2} j_{em}] \quad (6)$$

while the second one would be coupled, in case (1), to the current

$$j^{Z'_0} = g_{Y'} j_{Y'} \quad (7)$$

and in case (3) to the current

$$j^{Z'_0}_{(LR)} = g_Y [g_{LR} j_{3R} - 1/(2g_{LR}) j_{B-L}] \quad (8)$$

with

$$g_{LR} = \sqrt{g_R^2/g_Y^2} - 1 \quad (9)$$

(g_L, Y_R are the various gauge couplings).

Z_0, Z'_0 are the physical gauge bosons Z, Z' are the mass eigenstates. If the mathematical Z_0, Z'_0 mass matrix is written as

$$M^2_0 \equiv \begin{bmatrix} A & B \\ B & C \end{bmatrix} \quad (10)$$

then

$$\begin{bmatrix} Z \\ Z' \end{bmatrix} = \begin{bmatrix} \cos \theta_M & \sin \theta_M \\ -\sin \theta_M & \cos \theta_M \end{bmatrix} \begin{bmatrix} Z_0 \\ Z'_0 \end{bmatrix} \equiv D \begin{bmatrix} Z_0 \\ Z'_0 \end{bmatrix} \quad (11)$$

Since the various theoretical frameworks fix the mathematical Z_0, Z'_0 couplings, one sees that to specify the effect of the physical states one needs to know, besides their masses $M_Z, M_{Z'}$, the mixing angle θ_M as well. Note that the latter is a model-dependent quantity. In fact, from the properties of the diagonalizing matrix D, one finds the exact relation:

$$\tan^2 \theta_M = y - 1 - y/1 - 2/y \quad (12)$$

where $y = a^2/x^2$ and

$$a = 1/\epsilon - 1 ; \quad \epsilon = \frac{M_Z^2}{M_{Z'}^2} \quad (13)$$

$$x = \sqrt{2} B/M_Z^2 \quad (14)$$

showing that θ_M is related to M_Z and $M_{Z'}$, via the off-diagonal element B, fixed by the unknown Higgs structure of the different models. Thus, a perfectly reasonable choice of parameters would be that of $M_Z, M_{Z'}$ and x; for the latter, the properties of the matrix D, Eq. (11) fix the upper bound

$$x < a/\sqrt{2} \quad (15)$$

Alternatively, a popular choice is that of M_Z, ϵ, θ_M . I shall follow this notation, since the existing experimental bounds [2] are given for θ_M, ϵ , rather than for x, ϵ .

Quite generally, the effects of a non-directly produced Z' on a certain physical observable measurable in e^+e^- collisions at LEP will be of two kinds:

(i) virtual effects, produced by the exchange of a virtual Z' ;

(ii) mixing effects, corresponding to the shift of the properties of the physical Z from those of the mathematical Z_0 , which is involved in the existing theoretical formulae. The shift affects both the couplings of Z_0 to fermions and the Z_0 mass that appears in the various definitions of $\sin^2\theta \equiv s^2$. This second effect, actually, can be reabsorbed in a redefinition of s^2 , identical to the one which we would obtain by allowing a modification at tree level of the ρ parameter [3]. I will define the effect of this shift as

$$\delta\rho_{Z'} = \frac{M_{Z_0}^2 - M_Z^2}{M_{Z_0}^2} \equiv \frac{A - M_Z^2}{M_{Z_0}^2} = a \sin^2\theta_M > 0 \quad (16)$$

A general property of this term is that, on Z resonance, it will always appear in the various theoretical predictions multiplied by the same coefficient that multiplies the one-loop correction term $\Delta\rho(0)$, defined as [4]

$$\Delta\rho(0) \equiv -\frac{\Pi_W(0)}{M_W^2} + \frac{\Pi_Z(0)}{M_Z^2} \quad (17)$$

whose (known) property is to be quadratic in the mass of a heavy top and/or of heavy (split) new particles (or sparticles). Thus, if a certain prescription is given that eliminates $\Delta\rho(0)$ from a certain observable, the same prescription will automatically eliminate the mass-shift effect $\delta\rho_{Z'}$ [3].

Away from Z resonance, and for small values of the mixing angle (consistent with the existing experimental limits [2]), the virtual contribution coming from the Z' exchange is generally dominating. However, on top of the Z resonance, this contribution vanishes exactly and one is left with mixing effects only. I will concentrate now on the shift of the Z couplings to fermions. In other words, I will write the neutral current Lagrangian as:

$$-L_N = j_\mu^{e.m.} A^\mu + j_\mu^Z Z^\mu + j_\mu^{Z'} Z'^\mu \quad (18)$$

where

$$j_\mu^Z = \cos\theta_M j_\mu^{Z_0} + \sin\theta_M j_\mu^{Z'_0} \quad (19)$$

Defining the fermionic couplings as

$$j_\mu^{Z(f)} = \bar{f} [\gamma_\mu v_f^Z + \gamma_\mu \gamma_5 a_f^Z] f \quad (20)$$

one sees that

$$v_a|Z = \cos\theta_M v_a|Z_0 + \sin\theta_M v_a|Z'_0 = v_a|Z_0 + \theta_M v_a|Z'_0 + O(\theta_M^2) \quad (21)$$

Thus, a measurement of the physical Z couplings can isolate the pure θ_M effect. In general, though, a physical observable on Z resonance will also depend on the mass shift term $\delta\rho_{Z'}$, Eq. (16), that introduces an extra dependence on $M_{Z'}$.

To conclude this introduction, I have still to specify the class of models of type (7) [one extra $U(1)_Y$] that I will consider. Following the common philosophy, I will assume that the extra $U(1)_Y$ can be of the most general E_6 origin. This leads to an extra Z' of the following nature [5]:

$$Z'_0 = \cos\beta Z'_\chi + \sin\beta Z'_\psi \quad (22)$$

where Z'_χ, Z'_ψ correspond to different symmetry breaking patterns down to the final low energy symmetry group of Eq. (1). In the following, I will assume $g_\chi = g_\psi = g_Y$, but allow $\cos\beta$ to vary in its full range. On the contrary, α_{LR} , Eq. (9), will be allowed to vary in its meaningful range [6]

$$1/3 < \alpha_{LR} \leq 1/2 \quad (23)$$

Note that the L-R symmetric model with the value $\alpha_{LR} = 1/3$ produces the same results as the extra $U(1)_Y$ model with $\cos\beta = 1$. This known [6] property will provide a useful check of the relevant theoretical expressions.

The experimental information on the parameter θ_M is shown in Fig. 1 at variable $\cos\beta$. The corresponding limits on $M_{Z'}$ can also be derived [2,7].

Fig. 1 Lower limits on $M_{Z'}$, $\equiv M_Z$ and allowed $\theta_M \equiv \theta$ range for an E_6 gauge boson, taken from Ref. [2] (constrained $\equiv \rho_{tree} = 1$).

In the following, I will assume the (rather conservative) limit

$$M_{Z'} \gtrsim 130 \text{ GeV} \quad (24)$$

coming from low-energy neutral current data [2]. Alternatively, a value of ~ 150 GeV could be taken [7]. This would not alter the next discussion appreciably.

3. SEARCH FOR MIXING EFFECTS: PHASE 1

I assume a preliminary measurement of M_Z to have been performed to an accuracy of ~ 50 MeV. I also assume a number of Zs of order 10^6 to have been produced.

A very relevant quantity for Z' searches would then be the Z leptonic width [8]. From the theoretical expression at tree level,

$$\Gamma_{Z \rightarrow \ell\bar{\ell}} |_{M_Z} = \frac{N}{12\pi} M_Z [v_\ell^2 + a_\ell^2] \quad (25)$$

[where $N = 1$ for leptons and $\sim 3(1 + \alpha_s/\pi)$ for quarks] it is relatively easy to derive the mixing effect due to the extra Z'. In fact, it is sufficient to compute this contribution at tree level, ignoring Z' effects on radiative corrections (this is rigorously licit for values of θ_M not vanishingly small, which will be relevant for this discussion; for $\theta_M \rightarrow 0$, one has to be more careful, as illustrated in Sirlin's talk).

Consider for simplicity the deviation of, e.g., the muonic width from its value computed in the Standard Model (SM) (the latter value can be found tabulated in previous works [9]). This reads, in the two classes of models, Eqs. (22), (8):

$$\frac{\delta\Gamma_{Z \rightarrow \mu\bar{\mu}}}{M_Z} = \frac{\Gamma_{Z \rightarrow \mu\bar{\mu}}}{M_Z} \left(\frac{-2\cos\theta}{6} - \frac{1}{3} \sin\theta \right) + \delta\rho_Z, \quad (26)$$

$$\frac{\delta\Gamma_{Z \rightarrow \mu\bar{\mu}}^{(LR)}}{M_Z} = \frac{\Gamma_{Z \rightarrow \mu\bar{\mu}}}{M_Z} [\theta_M (-a_{LR}) + \delta\rho_Z], \quad (27)$$

To illustrate the effect of the shift at variable $\cos\theta$, it is better to consider the two mixing effects separately. In fact, the mass shift $\delta\rho_Z$ term is always positive, and of a typical size of a few per cent. The coupling shift, conversely, can be of both signs depending on $\cos\theta$ in the extra U(1) case, Eq. (26), while it remains positive in the L-R symmetric model, Eq. (27). From Fig. 1 and Ref. [2], it is possible to draw the allowed ranges of the coupling shifts at variable $\cos\theta$ and a_{LR} . As one sees from Fig. 2, this can become strongly negative, up to values

Fig. 2 Allowed range of variation of the coupling shift effect on the muonic Z width for the two models, Eq. (22) full lines, and Eq. (8) dashed lines, taken from Ref. [12].

of ~ 10 MeV, for certain values of $\cos\theta = -0.5$. Even adding a few per cent contribution from the positive $\delta\rho_Z$ term, this would leave a characteristic signature (a width smaller than that predicted by the SM) that, to my knowledge, no other types of extra physics could generate. In alternative, the positive shift that might be produced by Eq. (27) in the case of a Z' of left-right symmetry origin or by Eq. (26) for values of $\cos\theta \neq -0.5$ would also be large and hardly explainable by other known mechanisms. Note that the maximum size of the expected overall theoretical and experimental error on the width (obtained by including the possible uncertainty coming from the top mass) would be of $\sim \pm 2$ MeV, well below the maximum possible Z' effects.

If a signal of clear deviation from the SM prediction, consistent with that produced by a new Z', were observed in the leptonic width, the next goal would be that of identifying the parameters of the model. In practice, each of the two considered cases is defined by (at least) three parameters, i.e., θ_M , $\cos\theta$ (or a_{LR}) and $\delta\rho_Z \sim \alpha\theta_M^2$. Clearly, this program requires the availability of other suitable measurable quantities. An immediate possibility [8] would be that of considering the ratio

$$R' \equiv \frac{3}{59} \frac{\Gamma_5}{\Gamma_{\mu\bar{\mu}}} ; \quad \Gamma_5 \equiv \Gamma_{Z \rightarrow u,d,s,c,b} \quad (28)$$

In fact, the theoretical expression of R' in the two cases, Eqs. (8) and (22), is such that one can isolate the $\delta\rho_Z$ parameter in a certain linear combination of R' and $\Gamma_{Z \rightarrow \mu\bar{\mu}}$. More precisely, one finds [8]:

$$R' + \frac{50}{59} \frac{\Gamma_{Z \rightarrow \mu\bar{\mu}}}{M_Z} \left(\frac{9}{\alpha(M_Z)} \right) = [R' + \frac{50}{59} \frac{\Gamma_{Z \rightarrow \mu\bar{\mu}}}{\alpha(M_Z)}]_{SM} + \frac{4}{3} \delta\rho_Z, \quad (29)$$

from which, taking into account the experimental and theoretical uncertainties, one should be able to derive $\delta\rho_Z$ to about 1 %. Then, to fix the remaining parameters, another quantity would be required.

A convenient possibility would be provided by the final τ polarization A_τ , to be measured in a not too distant future still belonging to phase 1 [10]. If a measurement of A_τ were available, from the three observables $\gamma \equiv 9/\alpha(M_Z) \Gamma_{Z \rightarrow \mu\bar{\mu}}/M_Z$, R' and A_τ it would then become possible to define two linear combinations that would be free of $\delta\rho_Z$ and, therefore, of the one-loop term $\Delta r(0)$ as well, according to the previous discussion [3]. For these quantities, the residual theoretical error from the SM would be therefore practically negligible. In particular, one could consider the two observables [11]:

$$R' - \frac{1}{3} \gamma \equiv [R' - \frac{1}{3} \gamma]_{SM} + n \quad (30)$$

$$R' - \frac{10}{59} A_\tau \equiv [R' - \frac{10}{59} A_\tau]_{SM} + q \quad (31)$$

The theoretical expression of the variations n, q produced by the two kinds of considered Z' has been computed elsewhere [12]. From that, one can derive the region in the plane of the variations (n, q) belonging to the two models shown in Fig. 3. The evaluation of $(\theta_M, \cos\theta)$ or (θ_M, a_{LR}) can then proceed in a standard way [12]. In particular, it would be possible to derive the new limits on θ_M stemming from a negative result of the previous searches at the expected experimental accuracies of phase 1 [11]. These are shown in Fig. 4, again at variable $\cos\theta$, together with the previous limits from Ref. [2]. As one sees, a much more uniform limit would now be achieved, i.e.,

$$|\theta_M| \lesssim 0.025 - 0.030 \quad (32)$$

over the full $\cos\theta$ range.

Fig. 3 Allowed region in the plane of the variables (n, q) , Eqs. (30) and (31), for the two models of Eqs. (22) and (8), taken from Ref. [12]. The rectangle around the origin represents the overall uncertainty.

Fig. 4 Limits on $|\theta_M|$ stemming from a negative Z' search at LEP1, from Ref. [11].

The previous discussion has assumed that the extra Z' was of some extended gauge nature. However, other possible models exist that predict the existence of a new Z' from rather different theoretical origins. In particular, the new Z' could arise from models that do not require the existence of any Higgs boson. Examples of such a situation are either composite models of (W, Z) bosons [13] or models with a strongly interacting electroweak sector [14]. If a signal of deviation from the SM prediction were seen in the (n, q) plane, it would become important to isolate the theoretical model that could produce it. In fact, as shown in Fig. 5, this possibility would not be automatically provided at this stage, since several regions of possible confusion between the various models (Y, Y_L, Z^*) correspond to three different versions of composite (W, Z) models, while model Z_V corresponds to that of Ref. [14]) would still remain [12]. This residual confusion could only be eliminated by proper measurements belonging to phase 1a, as shown in the next section.

Fig. 5 The same as in Fig. 3, but including the allowed regions of models (Y, Y_L, Z^*, Z_V) , from Ref. [12].

4. FULL IDENTIFICATION OF THE THEORETICAL MODEL: PHASE 1a

The possibility that longitudinally polarized initial beams become available at LEP and the theoretical motivations for this effort have been the subject of an entire yellow book [9], and I will not discuss them now. Here I will only show one of the (several) outcomes of this fascinating eventuality. If longitudinal polarization became available, it would be possible to measure three specific polarized asymmetries, i.e., the quantities:

$$A_{LR}^{(h)} \equiv A = \frac{\sigma(e^+e_L^- \rightarrow \text{had}) - \sigma(e^+e_R^- \rightarrow \text{had})}{\sigma(e^+e_L^- \rightarrow \text{had}) - \sigma(e^+e_R^- \rightarrow \text{had})} \quad (33)$$

$$A_{\text{FB}}^{b,c}(\text{pol}) \equiv A^{b,c} \equiv \frac{1}{P} \frac{(N_{\text{F},\text{P}}^{b,c} - N_{\text{F},\text{P}}^{b,c,-}) - (N_{\text{B},\text{P}}^{b,c} - N_{\text{B},\text{P}}^{b,c,-})}{(N_{\text{F},\text{P}}^{b,c} - N_{\text{F},\text{P}}^{b,c,-}) + (N_{\text{B},\text{P}}^{b,c} - N_{\text{B},\text{P}}^{b,c,-})} \quad (34)$$

The theoretical properties of these observables have been exhaustively discussed in the literature [4,15,16]. Their main feature is that, on Z resonance, they would provide independent measurements of the initial lepton (A) and of the final quarks ($A^{b,c}$) couplings to the Z. From these three quantities, one could generate two linear combinations [17]

$$\tilde{\chi}_b = A^b - \frac{1}{15} A = \tilde{\chi}_b^{\text{SM}} + x \quad (35)$$

$$\tilde{\chi}_c = A^c - \frac{9}{25} A = \tilde{\chi}_c^{\text{SM}} + y \quad (36)$$

that would be free of oblique EW radiative corrections. These quantities would feel the effect of a new Z' of extended gauge origin. However, from their properties, they would not feel the effect of a new Z' of (Y, Y_L, Z^*, Z_γ) origin [3]. Therefore, they would be a unique filter for observation (or exclusion) of the models of Eqs. (22) and (8) [18], as shown by Fig. 6.

Fig. 6 Allowed domain in the plane of the variables (x, y) , Eqs. (35) and (36) for the two models, Eqs. (22) and (8), from Ref. [18]. The rectangle corresponds to the overall uncertainties (left-right symmetric models are confined on a segment in the figure).

One should stress that an alternative and completely equivalent possibility would be provided if the set $(A, A^{b,c})$ were replaced by the set $(A_\tau, A_{\text{FB}}^{b,c})$ including the previously mentioned final τ polarization and the unpolarized forward-backward asymmetries for b, c quarks (but also s, c would do). In fact, one could then replace A by A_τ and $A^{b,c}$ by [19]

$$\tilde{A}_{b,c} \equiv \frac{A_{\text{FB}}^{b,c}}{A_\tau} - \left\{ \frac{1/15}{9/25} A_\tau \right. \quad (37)$$

With a very high luminosity ($\sim 10^8$ Zs) [20] the experimental error on $A_{\text{FB}}^{b,c}$ [21] and A_τ [10] would then become such as to allow for a measurement of Eqs. (37) to nearly the same accuracy as that of Eqs. (35) and (36), and an analogous identification of a new Z' signal could be performed (for $M_{Z'}$ not much smaller than ~ 92 GeV [16]).

In conclusion, I have shown that at the end of phases I and Ia, one would be able to draw definite conclusions about a possible new Z' . These would not give, though, any precise indication about its mass. The only possible statement that one might derive from the new bound of Eq. (32), by combining it with the existing experimental limits [2], would be that

$$M_{Z'} \gtrsim 150 \text{ GeV} \quad (38)$$

implying that this particle could in principle be directly produced at LEP2, phase 2. Even if this were not the case, it would still be possible, though, to obtain very interesting information in this phase by considering those virtual effects (vanishing on top of Z) that would now be dominant. This will be discussed in the final section.

5. SEARCH OF VIRTUAL Z' EFFECTS AT LEP2

A detailed analysis of virtual effects of a new Z' on a number of quantities that should be measured at LEP2 has been recently performed [22]. The result of the investigation is that, under realistic experimental conditions, the best quantity in this respect is the ratio R' previously defined by Eq. (28), with the understanding that an analogous quantity might be used if the top were sufficiently light to be produced in that phase. Figure 7 shows the effect on R' of a specific couple of representative models of the two classes, Eqs. (22) and (8) at variable $\sqrt{s}$ for $M_{Z'} = 250$ GeV, showing that the effect would be large and positive. As thoroughly discussed in Ref. [22], this would be due to a positive interference of an increase in the hadronic numerator of R' with a decrease of its leptonic denominator.

Figures 8 and 9 show the effect of a new Z' of the most general kind, Eqs. (22) and (8) at $\sqrt{s} = 200$ GeV and variable $M_{Z'}$. Again, as one sees, the effect would be very large over a sizeable fraction of the possible values of $(\cos\theta, \alpha_{\text{LR}})$ up to rather large masses. This would lead to an identification of the signal, e.g., for certain particular values of $\cos\theta$, up to values of $M_{Z'} \approx 400$ GeV (for the same values of $\cos\theta$, the direct production at LEP2 would fail for $M_{Z'} \gtrsim 300$ GeV [7]). Moreover, from a combined measurement of R' and of the hadronic longitudinal polarization asymmetry A_{LR}^h (assuming that the latter can be actually measured at LEP2) a clear identification of the theoretical model would also be possible in the relevant mass range, as discussed in Ref. [22].

Fig. 7 Effects on the ratio R' , Eq. (28), of a couple of representative models of the classes, Eqs. (8) and (22) at variable $\sqrt{s}$ and $M_{Z'} = 250$ GeV, from Ref. [22].

Fig. 8 Effects of a Z' of variable mass on the ratio R' for $\sqrt{s} = 200$ GeV in the model of Eq. (22), from Ref. [22].

Fig. 9 Same as Fig. 7 for the model of Eq. (8), from Ref. [22].

6. CONCLUSIONS

In conclusion, from a combination of experiments at three different LEP phases, it would be possible to search in a systematic and consistent way for the existence of a new Z' of extended gauge origin down to values of the mixing angle $|\theta_M| \gtrsim 0.025$ (phase 1) and up to values of the mass $M_{Z'} \lesssim 400$ GeV (phase 2). These limits would be competitive with those obtainable at future collider experiments, particularly those for θ_M . If no evidence of a new Z' were brought up by these searches, the surviving range of allowed parameters for such a hypothetical particle might begin to appear, to say the least, discouraging.

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