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MANIFESTATIONS OF A NEW MASSIVE GAUGE VECTOR BOSON

IN REALISTIC e^+e^- EXPERIMENTS AT $\sqrt{s} = 200$ GeV

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A B S T R A C T

We analyze the manifestations at LEP2 of a new massive gauge boson Z' , with $M_{Z'} > 200$ GeV. A number of possible measurements are reviewed, under realistic experimental assumptions. We find that the two most sensitive quantities are the ratio $R' = \sigma(\text{had})/\sigma(\mu)$ and the longitudinal beam polarization asymmetry of hadron production, A_{LR}^h . In particular, R' would show the effect of a Z' of some specific theoretical origin for $M_{Z'}$ up to 400 GeV, and the combination of R' with A_{LR}^h might lead to a satisfactory determination of the parameters of the model for a Z' of general left-right symmetry origin.

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1. - INTRODUCTION

As the beginning of the operative era at LEP becomes closer and closer, the strategies for searches of still undiscovered particles (both in the Minimal Standard Model and in models of New Physics) via experiments at the "Z factory" ($N_Z > 10^6$) e^+e^- collider energy, $\sqrt{s} = M_Z$, are approaching a final status of realistic knowledge of their (non-small) possibilities and, also, of their intrinsic limits. In the case of direct searches (Higgs, charged or neutral superparticles...) an updated discussion of the most relevant production mechanisms, as well as one of the most dangerous background processes, is by now available [1]; also, the limits on the physical parameters of such particles implied by negative results of their searches have been fixed rather precisely.

In the case of indirect searches of new particles via their virtual effects in precision measurements at the Z resonance, a similar analysis has been recently performed for a very general class of models that predict the existence of one new vector boson Z' . In particular, the most relevant experimental quantities to be measured to reveal unambiguous signals of this new particle, free of unwanted Standard Model "background", have been classified both for the situation in which an initial beam polarization is available [2] and for the alternative, and of more immediate interest, unpolarized case [3]. As a by-product of this analysis, the limits on the mixing angle for a new gauge vector boson Z' , either of a general E_6 origin or of a general left-right symmetry origin, that would be implied by a negative result of such a search at LEP1 have been computed [3], leading to the strict upper bound:

$$|\theta_M| < 0.03 \quad (1)$$

that is, roughly, one order of magnitude smaller than the maximum value still nowadays allowed by the existing experimental data [4].

If the first phase of LEP failed to find any evidence of new particles, their searches would continue at the next LEP2 stage. For direct searches, e.g., of Higgs(es) and/or of supersymmetric particles, a detailed theoretical and experimental analysis already exists [5]. In the case of new gauge boson indirect searches, some preliminary discussion has been given in the literature [6]. The aim of this paper is to present a much more detailed and specific analysis of this problem for values of $M_{Z'}$ larger than the maximum LEP2 energy $\sqrt{s} \approx 200$ GeV, taking fully into account the realistic conditions of a general experiment at $\sqrt{s} = 200$ GeV. In particular, although our investigation will be performed for all values $M_{Z'} > 200$ GeV, we shall be particularly interested in the range $M_{Z'} \gtrsim 300$ GeV, in correspondence to which it might be rather difficult to produce directly a Z' even at the next Tevatron Collider experiments [7].

To clarify our statement, we begin with a discussion of general nature concerning the different information on the physical parameters characterizing a new gauge boson Z' that would be available at the different phases of LEP. We shall assume throughout this paper that the mass of this particle is higher than the maximum energy machine $\sqrt{s} \approx 200$ GeV, so that only indirect Z' evidence can be looked for (note that this is not implied by the existing bounds which would allow for a smaller value of the Z' mass [4]). For $M_{Z'} < 200$ GeV, a direct production at LEP2 would be achievable, and the next (very pleasant) step would be to identify the precise Z' theoretical origin. This would require a completely different analysis that will be given in detail elsewhere.

A convenient couple of parameters to be used to describe the effects of a new Z' of some extended gauge origin are the physical mass ratios $\epsilon \equiv M_{Z'}^2/M_Z^2$, and the mixing angle θ_M . In our convention:

$$J_\mu^Z = \cos \theta_M J_\mu^{Z_0} + \sin \theta_M J_\mu^{Z'_0} \quad (2)$$

where Z_0, Z'_0 are the mathematical gauge vector bosons and Z, Z' the physical ones. These are not the only parameters in the theoretical picture. In general, any specific model will introduce other quantities that will have to be somehow fixed, or measured, together with ϵ and θ_M , to solve the problem of a complete Z' identification.

A point that was stressed in the second of Refs. [2] is that it is always possible to form linear combinations of observables on Z resonance for which the virtual effect of a new Z' does not depend on ϵ . Note that this fact is not an immediate consequence of the vanishing of the Z' exchange graph on Z resonance. In fact, besides those terms depending solely on the mixing angle θ_M that would appear as tree level modifications of the physical Z couplings to fermions, a residual term depending on both ϵ and θ_M would still appear in the theoretical expressions. This term was called $\delta\rho_L^{Z'}$ in the second of Refs. [2] and its expression is:

$$\delta\rho_L^{Z'} = \frac{M_{Z_0}^2 - M_Z^2}{M_Z^2} \simeq \frac{\theta_M^2}{\epsilon} \quad (3)$$

From a formal point of view, the effect of this quantity is identical to that coming from a possible redefinition at tree level of the ρ_L parameter [8], defined as

$$\rho_L = \frac{M_{W^+}^2}{M_{W^0}^2} \Big|_{tree} = 1 + \frac{\sum_i v_i^2 [I_L^{(i)2} - 3I_{3L}^{(i)2}]}{2 \sum_i v_i^2 I_{3L}^{(i)2}} \equiv 1 + \delta\rho_L \quad (4)$$

and therefore, if a certain prescription is given that eliminates $\delta\rho_L$, it will eliminate $\delta\rho_L^{Z'}$ as well. This prescription was actually given and fully discussed in

Refs. [2]. As a consequence, one can define observables that are free of $\delta\rho_L$ and free of $\delta\rho_L^{Z'}$ and, more generally, free of a larger obscure block called ∇_ρ that would also contain possible contributions coming from new heavy particles (including the top) or sparticles, and that would be quadratic in their masses. Such observables would only react to signals of genuine New Physics coming from a new Z' . From the previous discussion and from Eq. (3), one can also understand why these signals could only come from a (sizeable) mixing angle θ_M and would not give any model-independent information on the ratio ϵ , i.e., on the physical Z' mass, and we defer to the second of Refs. [2] for a much more detailed discussion of this important point.

The picture would change completely at the higher energies of LEP2. In this phase, the Z' exchange graph would become increasingly important with increasing energy in our assumed configuration $M_{Z'} > 200$ GeV, and the ϵ parameter would correspondingly play a major rôle. The treatment of the terms of purely mixing angle origin requires now a more detailed discussion, that takes into account the results of the previous indirect search at LEP1. To see this in some detail, consider the expression of the physical coupling of a Z' of a general E_6 origin to the (u,d) quarks. Defining the coupling as:

$$J_\mu^{Z'} = \bar{f} [g_f^V v_f' + g_f^A a_f'] f = -\sin\theta_M J_\mu^{Z_0} + \cos\theta_M J_\mu^{Z_0'} \quad (5)$$

where, in the commonly used notation [9]:

$$J_\mu^{Z_0'} = \sin\beta J_\mu^{Z_0'} + \cos\beta J_\mu^{Z_0'} \quad (6)$$

one easily sees that:

$$v_u' \approx \left[\frac{e}{2c} \right] \left\{ -\frac{\theta_M}{3} \right\} \quad (7)$$

$$a_u' \approx \left[\frac{e}{2c} \right] \left\{ \left[-\sin\beta \frac{\sqrt{10}}{6} + \cos\beta \frac{\sqrt{6}}{6} \right] + \theta_M \right\} \quad (8)$$

$$v_d' \approx \left[\frac{e}{2c} \right] \left\{ \left[-\cos\beta \frac{2\sqrt{6}}{6} \right] + \theta_M \frac{2}{3} \right\} \quad (9)$$

$$a_d' \approx \left[\frac{e}{2c} \right] \left\{ \left[-\sin\beta \frac{\sqrt{10}}{6} - \cos\beta \frac{\sqrt{6}}{6} \right] - \theta_M \right\} \quad (10)$$

where $s^2 = 1-c^2 \approx 0.23$ and we have systematically neglected small higher order terms $[\sim\theta_M^2, \theta_M v \approx \theta_M(1-4s^2), v^2 \dots]$.

The curly bracket in the right-hand side of Eqs. (7)-(10) contains the term without mixing (square bracket) and the mixing effect to lowest θ_M order. Consider the specific case $\sin\beta = -\sqrt{5}/8$, $\cos\beta = \sqrt{3}/8$ corresponding to the superstring inspired η model [10]. For this case, one has:

$$v_u^1(\eta) \simeq \left[\frac{e}{2c} \right] \left\{ -\frac{\theta_M}{3} \right\} \quad (11)$$

$$a_u^1(\eta) \simeq \left[\frac{e}{2c} \right] \left\{ \left[\frac{2}{3} \right] + \theta_M \right\} \quad (12)$$

$$v_d^1(\eta) \simeq \left[\frac{e}{2c} \right] \left\{ \left[-\frac{1}{2} \right] + \frac{2}{3} \theta_M \right\} \quad (13)$$

$$a_d^1(\eta) \simeq \left[\frac{e}{2c} \right] \left\{ \left[\frac{1}{6} \right] - \theta_M \right\} \quad (14)$$

For a Z' mass of order, say, of 300 GeV, the experimental constraints are still consistent [4] with a mixing angle as large as ~ 0.1 . This would affect the dominant Z' - u, d couplings by approximately 15%, and one might fear that neglecting the mixing angle in the various theoretical expressions would then be a dangerous attitude [this would not be the case if the results of a first search at LEP1 were negative and the bound of Eq. (1) were consequently effective].

For the specific situation that we are considering in this paper ($M_{Z'} > 200$ GeV) these problems will mostly disappear. As we shall show in the final section, even a mixing angle $|\theta_M| \sim 0.1$ would affect the interesting measurable quantities by an amount that would still be less than the size of their realistically expected overall error for $M_{Z'} > 250$ GeV. Thus, throughout this paper, we shall ignore the mixing angle completely. For a Z' mass smaller than 250 GeV and for the different problem of the identification of its theoretical origin, the rôle of the mixing angle should be, however, reconsidered with more care.

The previous discussion has already shown that a fundamental component of our strategy, to be fully discussed in Section 2, will be the identification of those experiments whose experimental uncertainty is "suitably" small, i.e., smaller than the virtual effects to be revealed. This necessary condition will strongly select the number of candidate measurements. In fact, as we shall show in Section 3, only two of the conceivable experiments at LEP2 would meet the previous request, i.e., the ratio

$$R^1 = \frac{\sigma(e^+e^- \rightarrow u d s c b)}{\sigma(e^+e^- \rightarrow \mu^+ \mu^-)} \quad (15)$$

and, to a smaller extent, the hadronic longitudinal polarization asymmetry

$$A_{LR}^h = \frac{\sigma_{e_L^- \rightarrow uds\bar{c}b} - \sigma_{e_R^- \rightarrow uds\bar{c}b}}{\sigma_{e_L^- \rightarrow uds\bar{c}b} + \sigma_{e_R^- \rightarrow uds\bar{c}b}} \quad (16)$$

The drastic reduction of the number of candidate experiments will be, though, compensated by the unexpectedly large and, in our opinion, spectacular evidence for a new Z' to which a measurement of the ratio R' , Eq. (15), at $\sqrt{s} = 200$ GeV might already lead. The combination with the extra measurement of Eq. (16) would then improve in several cases this indirect search, leading, for some theoretical model (like that of a Z' of left-right symmetry origin), to a possible "reasonable" identification of the relevant gauge-group parameters. This will be discussed in Section 4, and will be followed by a short final discussion in Section 5.

2. - CHOICE OF THE POSSIBLE CANDIDATE EXPERIMENTS

We begin our analysis with a (necessarily) quick discussion about some possible experiments at LEP2, which will be a fundamental part of our approach. In this section we shall be only interested in a few essential statements; a much more detailed discussion of several points can be found elsewhere [5].

The presence of the abundant radiative tail of the Z and the presence of a W pair production are certainly two of the most important features of experimentation at LEP2. Once these two classes of events have been removed, one is left with a cross-section for $e^+e^- \rightarrow_{Z,\gamma} f\bar{f}$ that is rather small. For instance, $\sigma(e^+e^- \rightarrow \mu^+\mu^-) \approx 2.5$ pb at $\sqrt{s} = 200$ GeV when both muons are requested to carry 80% of the beam momentum.

Under these conditions, the typical event sample for an exposure of 500 pb^{-1} at maximum energy will consist of $N_\mu \approx 1300$ muon (or tau) pairs and of $N_h \approx 8600$ hadronic events for light ($uds\bar{c}b$) quarks. It is assumed in the following that the possible contribution of the top quark does not represent a problem; in other words, either the top is found and analyzed at some energy below 200 GeV, in which case it can be simply included in the measured total hadronic cross-section, or it is not there. If the top threshold is just near the operating point, top events will have dramatically different features and will thus be removed by straightforward cuts that will not affect systematically the sample of events originating from the light quarks.

For the purposes of this paper, we shall focus our attention on the following observables:

- a) the cross-section of muon pair production, $\sigma_{\mu\mu} = \sigma(e^+e^- \rightarrow \mu^+\mu^-) (\sqrt{s})$, that can presumably be measured to $\Delta\sigma_{\mu\mu}/\sigma_{\mu\mu} \approx 5\%$, including systematic errors from the luminosity measurement;
- b) the ratio $R' = (\sigma_{(e^+e^- \rightarrow \text{hadrons})}/\sigma_{(e^+e^- \rightarrow \mu^+\mu^-)}) (\sqrt{s})$, which can include the top, or ignore it, according to our previous discussion. This ratio can be measured with a statistical precision $\Delta R'/R' \sim 1/\sqrt{N_\mu} \approx 3\%$ (systematic errors are presumably negligible);
- c) the muon (or tau) forward-backward) asymmetry, that can be measured with a precision $\Delta A_{FB}^\mu = 1/\sqrt{N_\mu} \approx 3\%$;
- d) assuming (optimistically) that a transverse or longitudinal polarization of $P = 50\%$ can be implemented even at LEP2, one can measure the transverse polarization asymmetry $A_{\perp}^{\mu,h}$ for muons and hadrons with a precision of $1/\sqrt{N_{\mu,h}} P^4 \approx 0.12$ for muons and ~ 0.05 for hadrons and the longitudinal asymmetry $A_{LR}^{\mu,h}$ with a precision of $1/\sqrt{N_{\mu,h}} P^2 \approx 0.06$ for muons and ~ 0.02 for hadrons, having defined all these asymmetries in a, by now, conventional way [11]. Clearly, the possibility of obtaining such a large amount of data with polarized beams seems for the moment quite remote, but we believe that it is anyhow interesting to investigate which benefits would, in that case, be achievable.

In the following, we will study the virtual effect of a new gauge vector boson Z' on $\sigma_{\mu\mu}(\sqrt{s})$, $R'(\sqrt{s})$, $A_{FB}^\mu(\sqrt{s})$, $A_{\perp}^{\mu,h}(\sqrt{s})$ and $A_{LR}^{\mu,h}(\sqrt{s})$ up to the maximal attainable energy. Since the selection process required for exclusive measurements, such as polarized or unpolarized asymmetries for b quarks, is still not sufficiently efficient to yield sizeable samples and meaningful results, we shall ignore them systematically in this paper. Also, W pair production will not be considered here. The reason is that the Z' exchange effect in this case would be necessarily proportional to the mixing angle, and therefore we feel that it should be negligible, under our assumptions, for $M_{Z'} > 250 \text{ GeV}$ [12]. This would not be the case for a Z' of composite nature. The effect in that case should be studied separately, and will be discussed in a different forthcoming paper [13].

3. - Z' EFFECT ON THE SELECTED QUANTITIES

Having selected a number of experiments that we consider as potential candidates for an indirect search of a heavy Z' , we now turn to the theoretical expression of the Z' contribution in particularly relevant models. We shall consider in this paper the two cases of a previous generating E_6 [9], or left-right symmetry [14], extended gauge group. The first case has been defined by Eqs. (2) and (6), in the notation of Ref. [9]. For the second possibility, we shall follow the definitions of Ref. [4]. Introducing the parameter

$$\alpha = \sqrt{\left(\frac{g_R}{g_L}\right)^2 \frac{c^2}{s^2} - 1} \quad (17)$$

we shall have to add to the Z current entering Eq. (2) the "left-right" current:

$$J_{LR} = \sqrt{\frac{3}{5}} \left[\alpha J_{3R} - \frac{1}{2\alpha} J_{B-L} \right] \quad (18)$$

with α ranging from

$$\frac{1}{\sqrt{2}} \lesssim \alpha \lesssim \sqrt{2} \quad (19)$$

corresponding to the theoretical interval [9]

$$\frac{1}{2} g_L^2 \leq g_R^2 \leq g_L^2 \quad (20)$$

In our computations, we shall only retain the tree-level approximation of the various quantities, i.e., the γ , Z and Z' graphs (and their various interferences). Electroweak radiative corrections to one loop and QCD corrections can be, in principle, computed. However, for the purposes of this paper, they can be considered as extra "known" terms. In fact, we shall only be interested in deviations of the final expressions from the Minimal Standard Model predictions. Since the virtual Z' contribution will not be, generally speaking, the leading one, we shall follow the rather reasonable assumption that, in our situation, the dominant part of the radiative corrections can be computed simply ignoring the new Z'. Thus, the only effect of radiative corrections would be that of a (small) rigid shift of both the Standard Model and of the full (i.e., with Z') predictions, and we shall come back to this point in Section 4.

The theoretical expressions of the various quantities at tree level can be easily worked out. In practice, it is sufficient to add to the Standard Model γ and Z contributions (with the physical Z treated as if it were the Standard Model Z_0 , since any extra difference originating from the parameter $\delta\rho_L^{Z'}$, Eq. (3) would be in our situation completely negligible) the Z' term, that can be easily derived from the expressions of the Z' couplings to fermions. The latter ones have been given in the E_6 case for u and d by Eqs. (7)-(10); the coupling to electrons would read, in the same theoretical model:

$$v_e' \simeq \left[\frac{e}{2c} \right] \left[\cos \beta \frac{2\sqrt{6}}{6} \right] \quad (21)$$

$$a'_e \simeq \left[\frac{e}{2c} \right] \left[-\sin\beta \frac{\sqrt{10}}{6} - \cos\beta \frac{\sqrt{6}}{6} \right] \quad (22)$$

In the left-right symmetry case, one would have, for the same couplings:

$$v'_u \simeq \left[\frac{e}{2c} \right] \left[\frac{1}{\alpha} \left(\frac{\alpha^2}{2} - \frac{1}{3} \right) \right] \quad (23)$$

$$a'_u \simeq \left[\frac{e}{2c} \right] \left[\frac{\alpha}{2} \right] \quad (24)$$

$$v'_d \simeq \left[\frac{e}{2c} \right] \left[\frac{1}{\alpha} \left(-\frac{\alpha^2}{2} - \frac{1}{3} \right) \right] \quad (25)$$

$$a'_d \simeq \left[\frac{e}{2c} \right] \left[-\frac{\alpha}{2} \right] \quad (26)$$

$$v'_e \simeq \left[\frac{e}{2c} \right] \left[\frac{1}{\alpha} \left(-\frac{\alpha^2}{2} - 1 \right) \right] \quad (27)$$

$$a'_e \simeq \left[\frac{e}{2c} \right] \left[-\frac{\alpha}{2} \right] \quad (28)$$

where we have, according to our previous discussion, neglected the mixing angle θ_M everywhere.

Let us first consider $\sigma_{\mu\mu}$ and A_{FB}^μ . We have analyzed the corresponding effect of a Z' of variable mass $M_{Z'}$, > 200 GeV for $100 < \sqrt{s} < 200$ GeV in the two theoretical models. The results were rather disappointing, since the effect was systematically smaller than the expected experimental error over the full energy range unless the Z' mass became very close ($M_{Z'} < 250$ GeV) to the maximum considered energy. This fact, that had to be expected from the results of previous investigations [6], shows that a measurement of $\sigma_{\mu\mu}$ and/or of A_{FB}^μ would not be very sensitive to the existence of a heavy Z' , unless the latter was really not far away. For this reason, which is represented schematically in Fig. 1 for two illustrative cases $\cos\beta = \sqrt{3}/8$, $\sin\beta = -\sqrt{5}/8$ (η model) and $g_L = g_R$ at $M_{Z'} = 250$ GeV (the main features remain unchanged in A_{FB}^μ for a more general choice of the E_6 model while for L-R symmetric models the effect decreases when $g_R < g_L$), we have not retained $\sigma_{\mu\mu}$ and A_{FB}^μ as interesting candidates for our specific goal (although A_{FB}^μ might reveal the existence of a Z' for $M_{Z'} \lesssim 300$ GeV, if one is limited to a Z' of left-right symmetry origin with $g_L \simeq g_R$).

The situation would not improve if we considered a measurement of the left-right asymmetry for muons A_{LR}^{μ} . Figure 2 shows the corresponding picture (again for simplicity, for the same two representative models of Fig. 1) for $M_{Z'} = 250$ GeV. As one sees, with a polarization degree $P \approx 50\%$ no clear signal would be seen. The same negative picture would be obtained if the transverse polarization asymmetries for muons and hadrons $A_{\perp}^{\mu,h}$ were measured, as shown again in the same Fig. 2. Thus, none of the four observables that we have considered up to now seems to be able to play the rôle of a promising potential Z' revelator with the only possible exception of A_{FB}^{μ} for very specific values of g_L/g_R in L-R symmetric models.

The hadronic longitudinal polarization, defined by Eq. (16), seems to be more interesting in this respect. This is shown in Fig. 3 for the same representative models of Figs. 1 and 2. As one sees, for $M_{Z'} = 250$ GeV the effect of the new gauge boson is still definitely larger than the expected experimental error. This is particularly true for the left-right symmetric model; one should not forget, though, our previous comments about the feasibility of a longitudinal polarization degree of 50% at $100 < \sqrt{s} < 200$ GeV.

The mildly discouraging picture that we have represented up to now shows a dramatic and positive change when we move to the consideration of the last observable at our disposal, i.e., of the ratio R' [Eq. (15)]. Figure 4 shows the behaviour of this quantity with energy for $M_{Z'} = 250$ GeV (and again the two illustrative models of Figs. 1-3). As one notices, the effect of such a massive Z' at $\sqrt{s} = 200$ GeV is now definitely larger than the experimental error for both models. Moreover, this large effect would remain and would possibly increase over the whole allowed range of both $\cos\beta$ and α . This spectacular fact that was not, to our knowledge, previously known, is due to the properties of the Z' couplings to hadrons that appear in the numerator of Eq. (15); technically speaking, in fact, the big Z' effect originates mostly from the γ - Z' interference term and thus it is dictated by the theoretical expressions given in Eqs. (7)-(10) and (21)-(28). In particular, these would decrease the muon cross-section and increase the hadronic one, thus enhancing the overall effect in the ratio R' . Since the effect in our assumed situation is obviously increasing with the e^+e^- energy, we shall concentrate our next investigation on the behaviour of R' at the maximal LEP energy, $\sqrt{s} = 200$ GeV, for the most general extended gauge models, Eqs. (6)-(7) and (17)-(18), at several Z' masses. We shall also consider, as a possible extra auxiliary tool, the only other potentially interesting variable that we have found till now, i.e., the longitudinal hadronic asymmetry A_{LR}^h , and show that its combined use might add relevant information to that already provided by R' .

4. - Z' EVIDENCE IN R' AND A_{LR}^h AT $\sqrt{s} = 200$ GeV

We have shown in the previous sections that the ratio R' , Eq. (15), appears a very promising candidate to reveal indirect signals of a new gauge boson Z' with $M_{Z'} > 300$ GeV. In this section, we want to make this statement more quantitative. With this aim, we shall fix from now on $\sqrt{s} = 200$ GeV (that we assume to be, we repeat, the maximal LEP energy) and we shall allow the Z' mass to vary.

Our preliminary definition of a "candidate Z' signal" will be that of a Z' effect that deviates from the MSM prediction by an amount that is larger than the experimental error. In fact, this attitude does not take into account possible and unavoidable theoretical uncertainties. These might result from two main sources that we have already mentioned, i.e., the possibility of a not vanishing mixing angle which would affect the theoretical expression of the Z' effect, and the existence of sizeable uncertainties in radiative corrections, that might overwhelm it. We shall show in the final section that the first source of ambiguities can be completely neglected. In the second case, we do not expect, on the basis of several years of computations at the Z peak [1], that the theoretical uncertainty induced by radiative corrections to R' and A_{LR}^h can be competitive with their experimental error. This is particularly supported by the observation of the smooth energy dependence of these observables, that should make the (potentially) dangerous initial state radiation not really disturbing. In fact, we have checked this feeling by means of the computer program Expostar [15], and found that the full initial state radiation effect is well under control, and of the order of a relative few per cent. Other less dangerous corrections [E.W. oblique corrections, vertices and boxes, QCD corrections $\sim(1+\alpha_s/\pi)$] could be computed either numerically or even analytically, and their accuracy could be estimated, but we believe that for the purposes of this preliminary investigation of a "gross", i.e., at tree level, effect, this high precision is not yet requested. To fix a quantitative scale, we shall introduce anyhow everywhere an extra theoretical error of the same size as that of the experimental one and work systematically under this assumption, although we feel that it might be an unduly pessimistic view.

We have considered in our analysis both the general E_6 model, Eq. (6), and the general left-right symmetry model, Eqs. (17)-(18). We show our results for the E_6 case first.

Figure 5 shows the full (i.e., including the Z') tree-level predictions, to be compared with the corresponding MSM term (dot-dashed line), for several Z' masses, as functions of the E_6 symmetry breaking pattern angle $\cos\beta$. From its inspection, we can draw the following main conclusions.

- a) The size of the signal is a steep (and, practically, symmetric) function of $\cos\beta$, that attains a maximum for $|\cos\beta| = 1$ (χ model) and decreases reaching a minimum at $\cos\beta \approx 0$ (ψ model). Note that a measurement of R' would not fix the sign of $\cos\beta$.
- b) For a Z' mass not larger than 250 GeV, a clear signal will appear for every value of $\cos\beta$. The size of the signal would be, in the most pessimistic case $\cos\beta \approx 0$, still larger than a relative 10% and therefore, according to our previous discussion, larger than our assumed overall (i.e., theoretical plus experimental) error. For higher $|\cos\beta|$ values, the size of the signal would increase and become spectacularly large approaching $|\cos\beta| = 1$.
- c) For $M_{Z'} > 250$ GeV, the visible signals correspond to $|\cos\beta|$ values occupying a segment around $|\cos\beta| = 1$ whose length decreases with increasing mass. This decrease is not too fast: the η model Z'_η ($|\cos\beta| = \sqrt{3}/8$) would still be clearly seen (i.e., it would still produce an effect larger than a relative 10%) for $M_{Z'_\eta} \approx 300$ GeV, while a Z'_χ would be seen for the impressive value $M_{Z'_\chi} \approx 400$ GeV! On the other hand, Z' 's belonging to $|\cos\beta|$ values $\lesssim 0.3$ would not be seen by a measurement of R' as soon as their masses became larger than ~ 250 GeV.

One possibility to eliminate this "dead" region, $|\cos\beta| < 0.3$, would be that of finding another observable for which the $|\cos\beta|$ dependence of the Z' effect were "intelligently" different from that of R' , in particular such that the small $|\cos\beta|$ values could be revealed. This might then also lead, via a combination of the measurements of this observable and of R' , to a possible partial identification of both $M_{Z'}$ and $|\cos\beta|$ (at least within certain limits). From the discussion given in Sections 2 and 3, the only possible candidate to do this job appears the hadronic longitudinal asymmetry A_{LR}^h , Eq. (16).

Figure 6 shows, for several Z' masses, the behaviour of A_{LR}^h at variable $|\cos\beta|$. As one sees, the $|\cos\beta|$ dependence is not, unfortunately, of the requested kind. As a consequence, a measurement of A_{LR}^h would not add extra information, in the specific E_6 case, to that already provided by R' . In particular, combined plots of R' versus A_{LR}^h at variable $\cos\beta$ would still be plagued by "dead" regions around $\cos\beta \approx 0$, as shown in Fig. 7. Thus, the chances of seeing a Z' of the most general E_6 origin and of a certain mass, e.g., $M_{Z'} > 250$ GeV, from measurements at LEP2 depend crucially on the specific E_6 symmetry breaking pattern. This seems to be a general property also shared by direct production, e.g., at the Tevatron Collider [7].

In the case of a Z' of the most general left-right symmetry origin, Eqs. (17)-(18), the picture becomes even more interesting. In fact, R' exhibits a behaviour with the symmetry breaking pattern parameter α which is represented in Fig. 8. As one sees, those values of $\alpha \approx \sqrt{2}$, i.e., those corresponding to $g_L = g_R$, would now have trouble to produce a clear Z' signal for larger Z' masses, $M_{Z'} > 250$ GeV, while for smaller α the signal would be cleaner and cleaner. However, the behaviour of A_{LR}^h with α has now the kindness of showing exactly the opposite trend, as shown in Fig. 9. A combined plot of R' and A_{LR}^h might then prove rather interesting for this theoretical model.

Figure 10 shows the aforementioned combined plot. As one sees, the rather remarkable conclusion can be drawn that, for Z' masses as high as 350 GeV, the Z' signal would be still clearly seen practically over the full considered range of α assuming a theoretical error of the same size as that of the experimental one, more pessimistic assumptions (i.e., leading to an overall relative ten per cent error) still maintaining this mass value at about 300 GeV. Thus, even if a measurement of R' alone could already give spectacular evidence for a Z' of left-right symmetry origin for small α values, as one can derive in detail from Fig. 8 (the essential features in this case being practically identical to those of the E_6 generated Z' , as discussed later), the combined use of R' and A_{LR}^h would be an ideal and, to our knowledge, unique tool for left-right symmetry searches at LEP2. This is not particularly surprising after all, since it is a known feature of e^+e^- physics on Z resonance the fact that longitudinal polarization asymmetries act as unique left-right symmetry discriminators [16].

We want to conclude this section with a general comment about the possible confusion between signals of a Z' of E_6 and of left-right symmetry origin, and about the related intrinsic difficulties of identifying simultaneously the mass of the Z' and the values of the parameter(s) of the generating model, at least approximately, from a search like ours. The crucial point that has to be kept in mind is that any evidence of a new Z' , both direct and indirect, which is only based on measurements of the fermionic couplings of the Z' and/or of the Z , will necessarily induce some confusion between the two classes of models that we have considered since the E_6 χ model, $\cos\beta = 1$, must coincide at this level with the left-right symmetry model for $\alpha = \sqrt{2}/3$, i.e., $g_R^2 \approx 1/2 g_L^2$ [17]. Given the unavoidably finite size of the theoretical and experimental errors, this fact will generate, at least, a small finite region of confusion.

In addition to the fixed couple ($\cos\beta=1$, $\alpha=\sqrt{2}/3$), there might be other couples ($\cos\beta, \alpha$) that, by some chance and/or in some particular approximation, would produce an identical effect on some specific experimental quantity. This is clearly illustrated in Fig. 11, where a compared plot of R' for the two models is given for

fixed $M_{Z'} = 350$ GeV. As one sees, for every possible value of $R' \equiv R'_1$ in the relevant range, a certain couple $(\cos\beta, \alpha)_1$ exists such that both $\cos\beta_1$ and α_1 would produce the same R'_1 . Equivalently stated, the observable R' defines a certain function $\cos\beta(\alpha)/R'$ that associates to each α value that value of $\cos\beta$ producing the same R' . The only known property of $\cos\beta(\alpha)|_{R'}$, will be that $\cos\beta(\sqrt{2}/3)|_{R'} \equiv 1$.

In a perfectly similar way, another observable like $A_{LR}^h \equiv A$ will generate a different function $\cos\beta(\alpha)|_A$ such that, however, $\cos\beta(\sqrt{2}/3)|_A$ is still equal to one. In the plane $(\cos\beta, \alpha)$ each observable of this kind would define a certain curve passing through the point $(1, \sqrt{2}/3)$ and defined by the related function $\cos\beta(\alpha)|$. In general, two curves that intersect at one point might have other intersections, and therefore for a given couple of observables there might be more than one common couple $(\cos\beta, \alpha)$.

In the case of the two observables R', A_{LR}^h , the situation is represented in Fig. 12, which shows the predictions of the two theoretical models for different $M_{Z'}$. As one sees, for every $M_{Z'}$ value there are two points of confusion in the (R', A_{LR}^h) plane. Thus, in a finite region between these two points it will be impossible to distinguish between the two models, even if the overall error became substantially smaller. This point should be kept in mind before tackling the problem of trying both to make a prediction for the Z' mass and to identify its theoretical origin. If the experimental point falls in one of these regions of confusion, other independent measurements would still be requested to conclude this fascinating program.

A mildly optimistic view would be to stress that, after all, a sizeable region of no confusion exists, as Fig. 12 shows, where such an identification program could be realistically carried through. One might then, with some luck, come to definite predictions about $M_{Z'}$, and the theoretical model. However, we firmly believe that, to the extent to which the experimental result pointed in a clear way to the existence of a new extended gauge boson Z' , the problem of not being able to identify in a perfect way its theoretical origin should not be considered as a limitation of this outstanding result. The preparation of independent measurements to solve the remaining ambiguity would be an exciting, and pleasant, challenge.

5. - CONCLUSIONS

We have shown in this paper that one experiment exists, i.e., the measurement of the ratio $R' = \sigma(\text{had})/\sigma(\mu)$, feasible for a situation like that of LEP2 at $\sqrt{s} = 200$ GeV, that would act as a particularly effective potential indicator of a heavy Z' ($M_{Z'} > 200$ GeV) of extended gauge origin. The virtual signals would always be clear for $M_{Z'} < 250$ GeV; for higher masses, the identification of the Z' signal would depend on its actual theoretical origin, for some special models allowing a Z' of spectacularly high mass (up to 400 GeV!) to make itself manifest. It should be stressed that, for such models, the direct production at Tevatron would fail for $M_{Z'} > 300$ GeV [7].

We have assumed realistic experimental and theoretical accuracies. This has allowed us to simplify somehow our analysis. In particular, the effects of a possible mixing angle $|\theta_M| < 0.03$ would be systematically smaller than the experimental error, and therefore can be neglected. Analogous conclusions would still be valid for larger values of θ_M still consistent in some models with a large Z' mass. We have actually considered the specific case of the $E_6 \eta$ model with $\theta_\eta = -0.1$ (still allowed for $M_{Z'} \approx 300$ GeV) and found that, even in this case, the effect would be smaller than the experimental error for $M_{Z'} > 250$ GeV. Thus, for this case on which we have concentrated our specific analysis, the mixing angle can be safely neglected. For $M_{Z'} < 250$ GeV, a more complicated analysis might be requested.

A measurement of the hadronic longitudinal polarization asymmetry A_{LR}^h would not add extra information if the new Z' were of E_6 origin. However, if the theoretical origin of the new Z' were that of a left-right symmetry, a combined measurement of R' and A_{LR}^h would lead to an identification of the signal for all the (realistic) values of the involved parameters up to $M_{Z'} \approx 300$ GeV. This, we believe, should be kept in mind if this (appealing) theoretical model were still on the market at the beginning of the LEP2 era.

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FIGURE CAPTIONS

- Fig. 1 $\sigma_{\mu\mu}$ (1a) and A_{FB}^{μ} (1b) versus $\sqrt{s}$ in two illustrative models ($\cos\beta = \sqrt{3}/8$, $\sin\beta = -\sqrt{5}/8$ and $g_L = g_R$ for $M_{Z'} = 250$ GeV. The represented error in all figures is the purely experimental one.
- Fig. 2 A_{LR}^{μ} (2a) and $A_L^{\mu,h}$ (2b) versus $\sqrt{s}$ for $M_{Z'} = 250$ GeV and the same models as in Fig. 1.
- Fig. 3 A_{LR}^h versus $\sqrt{\sigma}$ for $M_{Z'} = 250$ GeV (same models as in Figs. 1 and 2).
- Fig. 4 The ratio R' versus $\sqrt{s}$ for $M_{Z'} = 250$ GeV (same models as in Figs. 1, 2 and 3).
- Fig. 5 The ratio R' at tree level versus $\cos\beta$ at $\sqrt{s} = 200$ GeV for several $M_{Z'}$ values. The dash-dot line is the corresponding MSM prediction.
- Fig. 6 A_{LR}^h (tree level) versus $\cos\beta$ at $\sqrt{s} = 200$ GeV for several $M_{Z'}$ values. The dash-dot line is the corresponding MSM prediction.
- Fig. 7 Combined plot of R' and A_{LR}^h (tree level) for several $M_{Z'}$ values at $\sqrt{s} = 200$ GeV and variable $\cos\beta$. The point in the little circle is the MSM value.
- Fig. 8 The ratio R' (tree level) versus α for several $M_{Z'}$ masses. ($\cdots \equiv$ MSM).
- Fig. 9 A_{LR}^h (tree level) versus α for several $M_{Z'}$ masses ($\cdots \equiv$ MSM).
- Fig. 10 Combined plot of R' versus A_{LR}^h (tree level) for several $M_{Z'}$ values at $\sqrt{s} = 200$ GeV and variable α . ($\odot \equiv$ MSM).
- Fig. 11 R' versus $\cos\beta$ (full line) and versus α (dashed line) at $\sqrt{s} = 200$ GeV for $M_{Z'} = 350$ GeV. ($\cdots \equiv$ MSM).
- Fig. 12 Combined plot of R' and A_{LR}^h versus $\cos\beta$ (closed curves) versus α (open curves) at $\sqrt{s} = 200$ GeV for $M_{Z'} = 350$ and 400 GeV. ($\odot \equiv$ MSM).

Fig. 1a

Fig. 1b

Fig. 2a

Fig. 2b

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12