CERN-TH.6051/91
UGVA-DPT 1191/03-712

Improved Bounds on Extended Gauge Models from New LEP Data⁺

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Abstract

The LEP results from last year's run are shown to imply a considerable improvement in the bounds on the possible admixture of a new non-standard neutral gauge boson in the observed Z state. One finds that the recent results on lepton asymmetries are particularly important in this respect. The cases of extended gauge models based on E_6 (for arbitrary orientation in group space of the new U(1) generator) and of left-right models are discussed in detail. We also consider a number of more particular models with specified Higgs structure, where limits on m_Z can also be derived.

⁺ Partially supported by the Swiss National Foundation

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CERN-TH.6051/91
UGVA-DPT 1191/03-712
March 1991

1. INTRODUCTION

In this note we shall present an analysis of the most recent LEP data in the framework of extended gauge models. The results of the 1990 runs at LEP have now become available. The implications for extended gauge models of these new data on hadronic and leptonic partial widths and on asymmetries at the peak are very constraining and make an update of previous analyses [1], [2] worthwhile.

The extended gauge models that we shall discuss in detail are the left-right model (LR) [3] and a set of models with an extra $U(1)$ contained in E_6 for arbitrary defining angle θ_2 of the corresponding generator in E_6 space [4]. Most of the results that we derive do not depend on assumptions on the detailed structure of the Higgs sector of the models. However, in some cases, for a number of particular schemes that have been explicitly considered in the literature, we describe additional constraints that follow for the specific structure of the Higgs sector of each model.

In our analysis the standard model radiative corrections to the widths are taken into account at the full one-loop level.

2. WIDTHS AND ASYMMETRIES IN EXTENDED GAUGE MODELS

At LEP1 the existence of an extended gauge sector can only cause departures from the standard predictions to the extent that the observed mass eigenstate Z is in general a mixture of the standard gauge boson Z_S and of a new one Z_N . Given the Z_N couplings as specified in each model (e.g. as functions of θ_2), the effects of such a mixing are completely described in terms of two parameters: the mixing angle ξ_0 and the shift $\Delta\rho_M$ in the ρ parameter due to the mixing. These two parameters are independent unless the Higgs structure of the model is specified. In this case it is possible that the mass of the heavy physical vector boson Z' is fixed as well as the relation between ξ_0 and $\Delta\rho_M$.

In models with an extra $U(1)$, at tree level, before symmetry breaking, Z_S and Z_N are the states which are coupled to the ordinary neutral current $J_{3L} - \sin^2\theta_W J_{em}$ and to the additional current J_N , respectively:

$$L_{NC} = \frac{e}{\sin\theta_W \cos\theta_W} Z_S (J_{3L} - \sin^2\theta_W J_{em}) + g_N Z_N J_N \quad (1)$$

Clearly, Z_S has couplings which are formally identical to the neutral vector boson of the standard model as functions of an angle θ_W whose relation to the basic input parameters of the theory is in general non-standard and will be specified in the following.

After symmetry breaking Z_S and Z_N are mixed. The physical vector bosons Z and Z' :

$$\begin{aligned} Z &= \cos\xi_0 Z_S + \sin\xi_0 Z_N \\ Z' &= -\sin\xi_0 Z_S + \cos\xi_0 Z_N \end{aligned} \quad (2)$$

are mass eigenstates with masses m_Z and $m_{Z'}$. The standard model relation between m_W and m_Z is modified at tree level according to the equation:

$$\frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \rho_0 \quad (3)$$

In Eq. (3) one has:

$$\rho_0 = 1 + \Delta\rho_M + \Delta\rho_{SB} \quad (4)$$

where:

$$\Delta\rho_M = \left[\left(\frac{m_{Z'}}{m_Z}\right)^2 - 1\right] \sin^2\xi_0 > 0 \quad (5)$$

$\Delta\rho_M$ arises because the Z mass in the absence of mixing is always larger than the observed Z mass: $m_{Z_S}^2 = (1 + \Delta\rho_M) m_Z^2$ (the lowest energy level is pushed down by the perturbation) . For LR models there is in general an additional contribution to $\Delta\rho_M$ from the charged sector (which is negligible if the new charged vector bosons are much heavier than the neutral Z'). $\Delta\rho_{SB}$ stands for a possible contribution from the symmetry breaking (SB) sector of the theory. For example, $\Delta\rho_{SB}$ could arise from the presence of non-doublet Higgses. Unless explicitly stated, in the following we shall always assume that $\Delta\rho_{SB} = 0$ at tree level.

Although we have used complete one-loop radiative corrections for the standard model prediction, for simplicity we will refer explicitly to the improved Born approximation [5], which correctly takes into account

large logarithms (i.e., terms of order $\frac{\alpha}{\pi} \log \frac{m_Z^2}{m_{f1}^2}$ where f_1 is a light fermion)

and quadratic terms in the top mass (i.e. terms of order $G_F m_t^2$). Loop effects due to the heavy gauge boson Z' are generally small for the relevant range of parameters and will be neglected here.

In the improved Born approximation the partial widths $\Gamma(Z \rightarrow f\bar{f})$ and the forward-backward asymmetry for the fermion f at $\sqrt{s} = m_Z$ are given by ($f \neq b$) [5]:

$$\Gamma(Z \rightarrow f\bar{f}) = \frac{G_F m_Z^3}{6\pi\sqrt{2}} \rho N_c [(v_{\text{eff}}^f)^2 + (a_{\text{eff}}^f)^2] \quad (6)$$

$$A_{\text{FB}} = 3 \frac{v_{\text{eff}}^e a_{\text{eff}}^e}{(v_{\text{eff}}^e)^2 + (a_{\text{eff}}^e)^2} \frac{v_{\text{eff}}^f a_{\text{eff}}^f}{(v_{\text{eff}}^f)^2 + (a_{\text{eff}}^f)^2} \quad (7)$$

Other asymmetries (e.g., the τ polarisation asymmetry) can similarly be expressed in terms of $v_{\text{eff}}^f/a_{\text{eff}}^f$. Here $N_c = 3(1 + \delta_{\text{QCD}})$ for quarks, $N_c = 1$

for leptons, and ρ also includes the large radiative corrections arising from the top quark loop as well as the logarithmic terms from the Higgs (included in $\Delta\rho_{\text{SB}}$)

$$\rho = 1 + \Delta\rho_M + \Delta\rho_{\text{SB}} + \Delta\rho_t = 1 + \Delta\rho \quad (8)$$

where $\Delta\rho_t \equiv \frac{3G_F m_t^2}{8\pi^2\sqrt{2}} + \dots$. The effective vector and axial vector couplings

v_{eff}^f and a_{eff}^f are given by a superposition of the corresponding Z_S and

Z_N couplings:

$$v_{\text{eff}}^f = \cos\xi_0 v_S^f + \sin\xi_0 v_N^f ; \quad a_{\text{eff}}^f = \cos\xi_0 a_S^f + \sin\xi_0 a_N^f \quad (9)$$

In particular the Z_S couplings are given by:

$$v_S^f = T_{3L}^f - 2 \bar{s}_W^2 Q^f ; \quad a_S^f = -T_{3L}^f \quad (10)$$

where T_{3L}^f and Q^f are the 3rd component of the weak isospin and the electric charge of the fermion f . The quantity $\bar{s}_W^2$ given by the relation:

$$\bar{s}_W^2 \bar{c}_W^2 = \frac{\pi\alpha(m_Z)}{\sqrt{2}G_F m_Z^2 \rho} \quad (11)$$

is the effective $\sin^2\theta_W$ for the on-shell Z couplings. Here $\alpha(m_Z) = \alpha/(1-\Delta\alpha) \approx 1/128.8$. Because of the effect of $\Delta\rho_M$, it differs from the corresponding quantity $\bar{s}_W^2$ in the standard model, for fixed input parameter α , G_F , m_Z , m_f , m_H , according to the relation:

$$\bar{s}_W^2 = \bar{s}_W^2 - \frac{\bar{s}_W^2 \bar{c}_W^2}{[\bar{c}_W^2 - \bar{s}_W^2]} \Delta\rho_M \quad (12)$$

Note that the case $\Gamma(Z \rightarrow b\bar{b})$ is exceptional because, as is well known, there are additional large terms of order $G_F m_t^2$ from vertex diagrams, which are taken into account [5],[6] by replacing $1+\Delta\rho_t$ in ρ by $1-\frac{1}{3}\Delta\rho_t$ and $\bar{s}_W^2$ by $\bar{s}_W^2 (1+\frac{2}{3}\Delta\rho_t)$ in Eqs. (6) and (10). The vector and axial vector couplings v_N^f and a_N^f of the new vector boson Z_N depend on the model.

For the LR and the E_6 models that we consider here, v_N^f and a_N^f are collected in Table 1. The entries in Table 1 correspond to g_N [defined in Eq.(1)] given by $g_N = g' = g \tan\theta_W$. This identification is clearly not necessary, but should be valid as an order of magnitude if grand unification occurs at a large scale.

It is useful to consider the deviations of the predicted Z partial widths and asymmetries from the corresponding standard model values, linearised in ξ_0 and $\Delta\rho_M$. As an example, for $\Gamma(Z \rightarrow f\bar{f})$ one obtains, to first order in ξ_0 :

$$\delta\Gamma_f = \frac{G_F m_Z^3}{24\pi\sqrt{2}} (A_f \Delta\rho_M + B_f \xi_0) \quad (13)$$

In Eq.(13) the coefficients A_f are uniquely determined in terms of the standard model parameters, whereas the B_f also depend on the couplings v_N^f and a_N^f . Their expressions follow immediately from Eqs.(6)-(12) together with Table 1 and can be found in Ref. [1].

We have seen that at the Z peak all effects of extended gauge models are given in terms of $\Delta\rho_M$ and ξ_0 , which are independent if the mass $m_{Z'}$ of the heavy vector boson Z' , which appears in Eq. (5), is not known. We now discuss the constraints imposed by the data on $\Delta\rho_M$ and ξ_0 in E_6 models for all values of θ_2 , and in LR models.

3. THE DATA AND THEIR IMPLICATIONS

The data on the widths and asymmetries that we use in the present analysis of extended gauge models, together with the values of v_{eff}^f and a_{eff}^f as obtained by the LEP experiments, are collected in Table 2 [7]. In the following the Z mass was fixed at the value $m_Z = 91.174$ GeV.

The χ^2 function minimized in the fit is the sum of 4 terms: the total width Γ_Z , the hadronic width Γ_h , the leptonic width Γ_l and the ratio

$(v_{\text{eff}}^e/a_{\text{eff}}^e)^2$. The theoretical expectation for the widths has been defined as the sum of the full one-loop standard model prediction plus the corresponding deviation as given by Eq. (13). For Γ_Z and Γ_h the QCD correction was evaluated for $\alpha_s(m_Z)$ in the range of 0.11-0.13 which is selected by the results of the measurements of α_s at LEP [9].

The resulting constraints on $\Delta\rho_M$ and ξ_0 for E_6 models are plotted in Figs. 1 and 2 for all values of θ_2 .

In Fig.1 the 1.64σ upper and lower limits on $\Delta\rho_M$ are displayed for $m_t = m_H = 100$ GeV and for the two values of $\alpha_s(m_Z)$, 0.11 and 0.13. Varying m_t and m_H , the allowed region is shifted along the vertical direction. It is possible to see that the maximum (with respect to θ_2) of the upper limits varies according to the following relation:

$$\Delta\rho_M < 0.01 - \Delta\rho_{SB} - \Delta\rho_t \quad (14)$$

where $\Delta\rho_{SB}$ and $\Delta\rho_t$ are the standard model Higgs and top contributions to $\Delta\rho$ and we have taken $\alpha_s(m_Z) = 0.11$ so as to obtain the most conservative upper bound. Therefore we can express the above result as an upper limit on $\Delta\rho$ [see Eq. (8)] which is m_t - and m_H -independent: $\Delta\rho < 0.01$. Note that this bound from LEP data is better than the one obtained from m_Z and the recent data from CDF and UA2 on m_W/m_Z , which is $\Delta\rho < 0.014$ [8]. Note that while $\Delta\rho_M > 0$ in models with an extra $U(1)$ [Eq. (5)] we also allowed negative values for $\Delta\rho_M$ in Fig. 1. This is not without interest, because we assumed $\Delta\rho_{SB} = 0$ at tree level and this assumption could be wrong. Thus one can reinterpret Fig. 1 as limits on $\Delta\rho_M + \Delta\rho_{SB}$. Clearly the upper limit on $\Delta\rho_M$ is sensitive to m_t , and there is less space for $\Delta\rho_M$ as m_t increases. The present constraints are powerful enough, and the allowed values of $\Delta\rho_M$ so narrow, that the bounds are also sensitive to sufficiently large variations of m_H . For large m_H the upper bound on $\Delta\rho_M$ is somewhat relaxed.

In Fig.2 the 1.64σ allowed band for ξ_0 is displayed for $m_t = m_H = 100$ GeV, again for $\alpha_s(m_Z) = 0.11$ and 0.13. We have checked that in this case the bounds are very little affected by variations of m_t and m_H . If a comparison is made with the now superseded results in Refs. [1],[2] we see that the limits on ξ_0 have much improved, particularly in the vicinity

of $\theta_2 = 0$, where the separate measurements of v_{eff}^e and a_{eff}^e are very powerful in limiting ξ_0 .

The corresponding results on the LR model are reported in Table 3. The same pattern is found also in this case.

4. SPECIAL MODELS

We now consider the consequences of restricting the scalar structure of the model to a particular choice. We restrict ourselves to a Higgs structure that obeys the physical requirement of vanishing mixing for large $m_{Z'}$, i.e. we demand that, for large $m_{Z'}$:

$$\xi_0 = c \left(\frac{m_Z}{m_{Z'}} \right)^2 \quad (15)$$

with c a constant which depends on the Higgs structure and vacuum expectation values [1]. Once c is given, in a particular model, then either ξ_0 or $\Delta\rho_M$ can be eliminated in favour of $m_{Z'}$. In this case a bound on $m_{Z'}$ is directly obtained from the data. From the following illustrative cases we can appreciate the typical sensitivity of the present LEP data to the heavy vector boson mass.

Figure 3 refers to the so-called minimal left-right model, with Higgs particles transforming as complex $(2,2,0)$, $(3,1,0)$ and $(1,3,0)$ representations of the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. In this case one has [3] $c = \sqrt{\cos 2\theta_W} = 0.73$. Assuming negligible additional mixing from the charged sector and no further exotic contribution to the ρ parameter one finds a lower bound on m_{Z_R} of about 950(800) GeV for a standard Higgs mass of 100 GeV (1 TeV) and a top mass of 90 GeV (in both cases). The lower bound increases with m_t . For example, taking $m_t = 130$ GeV, we find a lower bound of about 1400 (1000) GeV.

The models [10] χ (or B) and η (or A) are illustrated in Figs 4 and 5, respectively. The new gauge generator corresponds to $\theta_2 = 52.24^\circ$ in the χ model and to $\theta_2 = 0$ in the η model. For two Higgs doublets one finds [10] $c_\chi = -0.39$ and $-0.63 < c_\eta < -0.24$. One then obtains a lower bound for m_{Z_χ} of about 540 (500) GeV for $m_H = 100$ GeV (1 TeV) with $m_t = 90$ GeV. For $m_t = 130$ GeV this limit becomes 700 (570) GeV. Less stringent limits are obtained on m_{Z_η} , corresponding to the smaller absolute value allowed for c . For $m_t = 90$ GeV the lower bound is in the range 300-900 GeV

depending on the value of c in the allowed range and on m_H in the interval 0.1-1 TeV.

5. CONCLUSION

By precisely determining the couplings to fermions of the physical Z , the data collected on the Z peak at LEP impose severe constraints on the possible amount of mixing of a non-standard neutral vector boson. The effects of such an admixture are in general described by two parameters ξ_0 and $\Delta\rho_M$. We have studied the bounds on ξ_0 and $\Delta\rho_M$ implied by the whole set of LEP data and shown that they have become very stringent. Actually, the impact of LEP data alone is by now more important in this respect than the totality of all previous data on neutral current processes. However, it must be stressed that a new neutral vector boson could in principle have a negligible mixing to the physical Z . In this case its effect would not be detectable at LEP. Yet the contributions of Z' exchange could be important for all neutral current processes which do not involve an on-shell Z . For example, clearly the Z' could be produced at hadron colliders of sufficiently large centre-of-mass energy. This complementary character results in powerful overall constraints on extended gauge models. As an example, the present new bounds from LEP have been found to give substantial limitations on possible deviations in atomic parity violation experiments as expected within such models [11]. After completion of this paper we received a work [12] where a similar, less complete analysis, is performed.

ACKNOWLEDGEMENT.

We would like to thank W.Hollik for providing us with a programme to compute the full one-loop standard model predictions for the widths.

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FIGURE CAPTIONS

- Fig. 1: Allowed range (90% CL) of $\Delta\rho_M$ versus θ_2 (defining the embedding of the extra U(1) in E_6), for $m_{\text{top}} = m_{\text{Higgs}} = 100$ GeV and $\alpha_s = 0.11$ (solid) or $\alpha_s = 0.13$ (dashed).
- Fig. 2: Allowed range (90% CL) of ξ_0 versus θ_2 (defining the embedding of the U(1) in E_6) for $m_{\text{top}} = m_{\text{Higgs}} = 100$ GeV and $\alpha_s = 0.11$ (solid) or $\alpha_s = 0.13$ (dashed).
- Fig. 3: Lower bound on $m_{Z'}$ (90% CL) for the left-right model as a function of m_{top} , for $m_{\text{Higgs}} = 100$ GeV (full line) and $m_{\text{Higgs}} = 1$ TeV (dotted line). Mixing effects in the charged sector have been neglected.
- Fig. 4: Lower bound on $m_{Z'}$ (90% CL) for the χ model, as a function of m_{top} , for $m_{\text{Higgs}} = 100$ GeV (full line) and $m_{\text{Higgs}} = 1$ TeV (dotted line).
- Fig. 5: Lower bound on $m_{Z'}$ (90% CL) for the η model, as a function of m_{top} , for $m_{\text{Higgs}} = 100$ GeV (full lines) and $m_{\text{Higgs}} = 1$ TeV (dotted lines). For each Higgs mass, the band within the two lines corresponds to the allowed range for the parameter c defining the proportionality between ξ_0 and $(m_Z/m_{Z'})^2$ [Eq. (15)].

Table 1

Vector and axial couplings of fermions to the unmixed new vector boson Z_N in the case of extra U(1) and LR models. For left-right models, we have put in the text $\lambda = g_L/g_R = 1$. As a consequence $y = \sqrt{\cos 2\theta}$.

Extra U(1) Models
$v_N^u = 0,$ $a_N^u = -\frac{2}{3} \sin \theta \cos \theta_2,$ $v_N^d = \frac{1}{2} \sin \theta (\cos \theta_2 + \sqrt{\frac{5}{3}} \sin \theta_2)$ $a_N^d = \sin \theta (-\frac{1}{6} \cos \theta_2 + \frac{1}{2} \sqrt{\frac{5}{3}} \sin \theta_2),$ $v_N^e = -\frac{1}{2} \sin \theta (\cos \theta_2 + \sqrt{\frac{5}{3}} \sin \theta_2),$ $a_N^e = a_N^d,$ $v_N^\nu = -\sin \theta (\frac{1}{6} \cos \theta_2 + \frac{1}{2} \sqrt{\frac{5}{3}} \sin \theta_2)$ $a_N^\nu = -v_N^\nu.$
Left-Right Models
$v_N^f = \left[\frac{\cos^2 \theta}{\lambda y} (T_{3R} - 2\lambda^2 \sin^2 \theta Q_{em}) + \frac{\lambda \sin^2 \theta}{y} (T_{3L} - 2\sin^2 \theta Q_{em}) \right],$ $a_N^f = \left[\frac{\cos^2 \theta}{\lambda y} T_{3R} - \frac{\lambda \sin^2 \theta}{y} T_{3L} \right]$

Table 2

Results of the 1990 LEP run, as presented in Ref. [7]. Note that the reported expressions of g_V^2, g_A^2 follow from the comparison of Eq. (6) with the definitions adopted in Ref. [7] for the vector and axial vector couplings.

Parameter	ALEPH	DELPHI	L3	OPAL	Average
M_Z (GeV)	91.183 ± 0.009	91.175 ± 0.010	91.181 ± 0.010	91.160 ± 0.009	91.174 ± 0.02
Γ_Z (GeV)	2.484 ± 0.017	2.454 ± 0.020	2.501 ± 0.017	2.491 ± 0.017	2.485 ± 0.009
Γ_{had} (GeV)	1.750 ± 0.015	1.718 ± 0.021	1.742 ± 0.019	1.739 ± 0.017	1.740 ± 0.009
Γ_ℓ (MeV)	83.35 ± 0.68	83.4 ± 0.9	83.6 ± 0.8	83.0 ± 0.7	83.31 ± 0.40
$g_a^2 = \rho a_{eff}^2$	0.2489 ± 0.0021	0.250 ± 0.003	0.250 ± 0.003	0.2495 ± 0.0022	0.2495 ± 0.0012
$g_v^2 = \rho v_{eff}^2$	0.0016 ± 0.0006	0.0008 ± 0.0014	0.0021 ± 0.0012	0.0006 ± 0.0007	0.0013 ± 0.0004

Table 3

Combined fit of LEP data for the left-right model, with best values ($\xi_0, \Delta\rho_M$) and lower ($\xi_{low}, \Delta\rho_{M\ low}$) and upper ($\xi_{up}, \Delta\rho_{M\ up}$) bounds (90 % CL).

	$m_t = 100\text{ GeV}$		$m_t = 150\text{ GeV}$	
	$m_H = 100\text{ GeV}$	$m_H = 1000\text{ GeV}$	$m_H = 100\text{ GeV}$	$m_H = 1000\text{ GeV}$
ξ_0	0.0023 ± 0.0044	0.0025 ± 0.0045	0.0026 ± 0.0044	0.0031 ± 0.0045
$\Delta\rho_M$	0.0015 ± 0.0026	0.0038 ± 0.0026	-0.0021 ± 0.0026	0.0004 ± 0.0026
ξ_{low}	-0.0050	-0.0048	-0.0047	-0.0042
ξ_{up}	+0.0096	+ 0.0099	+ 0.0099	+0.0104
$\Delta\rho_{M\ low}$	-0.0029	-0.0006	-0.0064	-0.0040
$\Delta\rho_{M\ up}$	+0.0058	+0.0081	+0.0022	+ 0.0047

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5