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BOUNDS ON EXTENDED GAUGE MODELS

FROM LEP DATA ^{*)}

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ABSTRACT

We perform fits to a number of extended gauge models on the basis of the published LEP data. We find that these data already allow for a sharp improvement of the present bounds on the $Z - Z'$ mixing angle ξ_0 . In the left-right model the present lower bound on ξ_0 is cut by a large factor; in the extra U(1) model χ (or B) a similar reduction is obtained for the upper bound; in the models called ψ and C the lower bounds on ξ_0 are again reduced by large factors. For a general extra U(1) in E_6 a gratifying complementarity appears with respect to neutral current data fits, the allowed intervals for ξ_0 being mainly of opposite signs, thus leading to very significant overall improvements of the bounds. An exception to the general trend is provided by the model η (or A), which is much less severely constrained by both the neutral current data and the LEP measurements.

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1. Introduction

In this note we shall present an analysis of the recent LEP data in the framework of the extended gauge models. The interesting conclusion will be that the existing LEP data already allow for an extraordinary sharpening of the existing limits on the $Z - Z'$ mixing angle. This result is in part due to the fact that, for a large class of models, the allowed regions in parameter space obtained from fitting the LEP data have only small overlap with the corresponding regions from previous neutral current experiments, so that little room for the parameters is left after all data are taken into account.

Before performing the fits to extended gauge models we shall preliminarily carry out a model independent fit to an improved Breit-Wigner shape and a radiatively corrected standard model (SM) fit (with due attention to the dependence on m_t and α_s). These fits are both based on the hadronic LEP data.

The extended gauge models we shall consider are the left-right model (LR) and the extra- $U(1)$ models. To be definite we take the extra $U(1)$ as contained in E_6 for arbitrary defining angle θ_1 . From the viewpoint of full E_6 this is like assuming negligible mixing with additional E_6 fermions. In fitting these models all existing LEP data [1-6] are used, including both hadronic and leptonic channels. The analysis for extended gauge models is based on the work done in ref. [7,8].

A new neutral heavier vector state leads to a modification of the couplings of the physical Z . The corresponding current is a mixture determined by the angle ξ_0 of the currents coupled to the standard Z and to the new vector boson. The tree level SM $W - Z$ mass relation is modified by a variation of the ρ parameter, $\rho = 1 + \Delta\rho$, where $\Delta\rho$, in addition to possible contributions from $SU(2)_L$ non doublet Higgs bosons, will now also contain a term from the vector mixing (for the LR model there is also a term from the charged sector). Electroweak radiative corrections give an additional $\Delta\rho_T$ term increasing as m_t^2 . The variation $\Delta\rho$ affects the overall Z coupling strength and also the expression for the effective angle of the ordinary neutral current as a function

of $M_{Z'}$. All these features, as well as the folding of initial state radiation, are duly incorporated in our fits. The Z fermionic widths are in first approximation modified by terms proportional to $\Delta\rho$ and ξ_0 , whose coefficients were tabulated in ref. [8] for the various models. The parameters for the fits are thus $M_{Z'}$, ξ_0 and $\Delta\rho$. For models with only $SU(2)_L$ doublet and singlet Higgs bosons, $M_{Z'}$ can be employed in place of $\Delta\rho$.

We shall first present our treatment of the data, then perform the model independent and the SM fits. The quantitative analysis of the extended gauge models will be the main object of this work, with discussion of the LR model, of special extra- $U(1)$ models, and of the general extra- $U(1)$ model from E_6 .

2. Treatment of the data

The input for our fits are the hadronic and the leptonic data published by the four LEP collaborations in the measurement of the Z line shape [1-6]. The hadronic data are the measured cross-sections at several beam energies around the Z peak, divided into five samples, each characterized by a different systematic error. One sample refers to the ALEPH collaboration (table 1 of ref.[1]) and it is affected by a systematic error of 1.5%. Another sample refers to the DELPHI collaboration (table 3 of ref.[2]) with 2.6% as systematic error. Two samples concern the L3 collaboration. They refer to two independent runs. The data of the first run (table 2 of ref.[3]) have a systematic error of 6.0%. The beam energies of this sample have been corrected by +43 MeV to take into account a better energy calibration [4]. The data of the second run (table 3 of ref.[4]) are affected by a systematic error of 2.0%. A final sample refers to the OPAL collaboration (table 2 of ref.[5]). Its systematic error amounts to 2.3%. The overall number of data points is 49. The systematic errors given by the different collaborations include mainly the luminosity and the data selection uncertainties. We have neglected the systematic error due to a possible point to point uncertainty in the beam energy calibration.

In all fits the systematic errors on hadronic data have been accounted for by the

following terms in χ^2 function:

$$\chi^2 = \sum_i \sum_j \frac{[\sigma_{exp}^i(E_j) - S_i \sigma_{th}(E_j)]^2}{\delta\sigma_{stat}^2} + \sum_i \frac{(1.0 - S_i)^2}{\delta\sigma_{syst}^2} \quad (2.1)$$

where $\sigma_{exp}(E)$ and $\sigma_{th}(E)$ are the measured and theoretical cross-sections at the energy E , $\delta\sigma_{stat}$ and $\delta\sigma_{syst}$ are the statistical and systematic errors, the indices i and j refer to the data samples and the individual energy points respectively. S_i ($i = 1, \dots, 5$) are independent overall scale factors, one for each data sample, to which we have assigned a measured value equal to one and an error given by the corresponding systematic error $\delta\sigma_{syst}^i$.

As far as the leptonic data are concerned, we have directly taken as input the results of the global, model independent fits performed separately by each LEP collaboration, assuming lepton universality. The ALEPH collaboration finds $\Gamma_l = 83.0 \pm 2.2$ MeV [1], DELPHI obtains $\Gamma_l = 85.1 \pm 2.9$ MeV [2], L3 gives $\Gamma_l = 82.8 \pm 2.4$ MeV [6] and OPAL has $\Gamma_l = 81.9 \pm 2.0$ MeV [5].

3. Model independent fit

Our first fit, based on the hadronic data alone, is a model independent fit to an improved Breit-Wigner line shape [10]:

$$\sigma_0(s) = \sigma_p^A \frac{M_Z^2 \Gamma_T^2}{|D(s)|^2} \left[\frac{s}{M_Z^2} + R \frac{(s - M_Z^2)}{M_Z^2} + \dots \right] \quad (3.1)$$

where

$$D(s) \approx s - M_Z^2 + i M_Z \Gamma_T \frac{s}{M_Z^2} \quad (3.2)$$

The line shape $\sigma_0(s)$ has a maximum for:

$$\sqrt{s} \approx M_Z - \frac{(1-R)}{4} \frac{\Gamma_T^2}{M_Z} \approx M_Z - (1-R)(17 \text{ MeV}) \quad (3.3)$$

Eq. (3.1) has to be corrected for the initial state radiation [9,10]. The analytic formula of ref. [10] was actually used in the fit. As independent parameters we have taken the

Z mass M_Z , its total width Γ_T and the (deconvoluted) peak cross section σ_p^A . One finds that the results of all fits are not sensitive to R. By changing R from zero to 10% we do not observe significant modifications of our results.

The result of the model independent fit to the hadronic data is:

$$\begin{aligned} M_Z &= 91.163 \pm .013(stat) \pm .030(syst) \text{ GeV} \\ \Gamma_T &= 2.532 \pm .027 \text{ GeV} \\ \sigma_p^A &= 41.1 \pm .5 \text{ nb} \end{aligned} \quad (3.4)$$

with a $\chi_{min}^2 = 36.0$ for 46 independent degrees of freedom (dof). The error $\pm .030$ GeV is due to the overall uncertainty on the beam energy calibration.

4. Standard Model fit

The second fit, again based on the hadronic data only, is performed within the SM. The same procedure of correction for initial state radiation is applied as for the previous fit.

SM predictions have been implemented via an improved Born approximation [11-13]. The accuracy is completely satisfying at the level of the present fit, the fitted value of M_Z being insensitive to further improvements in the evaluation of the line-shape parameters.

In this case, for given values of m_t , m_H and α_s , all predictions depends on M_Z . For $m_t = 100$ GeV, $m_H = 100$ GeV and $\alpha_s = .12$ we find:

$$M_Z = 91.160 \pm .012(stat) \pm .030(syst) \quad (4.1)$$

with a $\chi_{min}^2 = 38.6$ for 48 independent dof. Varying m_t from 100 to 200 GeV and α_s from .12 to .14, M_Z varies by a few MeVs only.

5. Fit to extended gauge models. General formulation.

In the analysis of extended gauge models we used both hadronic and leptonic data. We have based our analysis on a formulation of the extended gauge models explicitly tailored for the LEP physics [7,8] and in the following we will refer to it. In the present letter we focus on the LR model [14] and on the class of extra $U(1)$ models whose new abelian factor is contained in E_6 [15].

At LEP1 the presence of a new massive, neutral vector boson will show up through two general mechanisms.

First, one has a modification of the couplings of the ordinary Z . Denoting by Z_0 and Z'_0 the states which are coupled to the ordinary neutral current $J_{3L} - \sin^2 \theta J_{em}$ (with an appropriate effective angle θ) and to the additional current J_Y , the mass eigenstates Z and Z' will be coupled to the admixtures $\cos \xi_0 (J_{3L} - \sin^2 \theta J_{em}) + \sin \xi_0 J_Y$ and $-\sin \xi_0 (J_{3L} - \sin^2 \theta J_{em}) + \cos \xi_0 J_Y$ respectively, ξ_0 being the $Z - Z'$ mixing angle.

Second, one has a modification of the SM relation between M_W and M_Z according to the equation, valid at tree-level:

$$\frac{M_W^2}{M_Z^2 \cos^2 \theta} = \rho \quad (5.1)$$

In eq. (5.1) one has:

$$\rho = 1 + \Delta\rho_M + \Delta\rho_{SB} = 1 + \Delta\rho \quad (5.2)$$

where:

$$\Delta\rho_M = \left[\left(\frac{M_{Z'}}{M_Z} \right)^2 - 1 \right] \tan^2 \xi_0 \geq 0 \quad (5.3)$$

$\Delta\rho_M$ arises because the Z_0 mass in absence of the mixing is always larger than the observed Z mass: $M_{Z_0}^2 = (1 + \Delta\rho_M) M_Z^2$. For LR models there is in general an additional contribution to $\Delta\rho_M$ from the charged sector. $\Delta\rho_{SB}$ stands for a possible contribution from the symmetry breaking (SB) sector of the theory, such as that given by non-vanishing vacuum expectation values of scalar representations which are not $SU(2)_L$

doublets or singlets. Eq. (5.1) has in turn the effect of modifying the relation with M_Z of the effective angle θ entering the expression of the ordinary neutral current. One has at tree level:

$$\sin^2 \theta = \left(\frac{1}{2} - \sqrt{\frac{1}{4} - \frac{\mu^2}{\rho M_Z^2}} \right) \quad (5.4)$$

where $\mu^2 = (\pi\alpha/\sqrt{2}G_F) = (37.280 \text{ GeV})^2$.

For the sake of computing deviations from the SM predictions, one can take into account the electroweak radiative corrections in an improved Born approximation [11-13]. In such a scheme a fermion antifermion pair $f\bar{f}$ contributes to the ordinary neutral current through the following term:

$$J_{eff,\mu}^f = (4\sqrt{2}G_F M_Z^2 \rho_f)^{\frac{1}{2}} \bar{f} \gamma_\mu \left[T_{3L}^f (1 - \gamma_5) - 2Q_{em} \sin^2 \theta_f \right] f \quad (5.5)$$

When f is different from the bottom quark, this simply amounts to add to the ρ parameter defined in eq. (5.2) the following approximate term:

$$\Delta\rho_T \approx 3 \frac{G_F m_t^2}{8\pi^2 \sqrt{2}} \quad (5.6)$$

so that:

$$\rho_f = 1 + \Delta\rho + \Delta\rho_T \quad (5.7)$$

and renormalize the fine structure constant α by the multiplicative factor $1/(1 - \Delta\alpha)$ with $\Delta\alpha$ given by:

$$\Delta\alpha = 0.0601 \pm 0.0009 \quad (5.8)$$

Having done this, one finds for the effective angle $\sin^2 \theta_f$ ($f \neq b$) the following expression:

$$\sin^2 \theta_f = \left(\frac{1}{2} - \sqrt{\frac{1}{4} - \frac{\mu^2}{\rho M_Z^2 (1 - \Delta r)}} \right) \quad (5.9)$$

with $\Delta r = \Delta\alpha - \Delta\rho_T$ and ρ given by eq. (5.2). The case of the bottom quark can easily be treated separately [11,12].

As illustrated in ref [7,8], any deviation of a Z line shape parameter from the SM predictions is given, to first order in the $Z - Z'$ mixing angle ξ_0 , by a linear combination

of $\Delta\rho$ and ξ_0 . In particular, the deviation for the partial width of Z into a fermion antifermion pair $f\bar{f}$ is given by:

$$\delta\Gamma_f = \frac{G_F M_Z^2}{24\pi\sqrt{2}} [A_f \Delta\rho + B_f \xi_0] \quad (5.10)$$

where

$$A_f = 4N_c^f \bar{p}_f \left[\left(T_{3L}^f - 2\sin^2\theta_f Q_{em}^f \right)^2 + \left(T_{3L}^f \right)^2 + 4 \frac{\sin^2\theta_f \cos^2\theta_f}{\cos 2\theta_f} Q_{em}^f \left(T_{3L}^f - 2\sin^2\theta_f Q_{em}^f \right) \right] \quad (5.11)$$

and

$$B_f = 8N_c^f \bar{p}_f \left[\left(T_{3L}^f - 2\sin^2\theta_f Q_{em}^f \right) g_V^f - T_{3L}^f g_A^f \right] \quad (5.12)$$

In eqs. (5.11) and (5.12) $N_c^f = 1$ for leptons and $N_c^f = 3(1 + \alpha_s/\pi) \sim 3.12$ for quarks; $\bar{p}_f$ indicates the top contribution and is given by $\rho_f - \Delta\rho$; g_V^f and g_A^f are the vector and axial-vector coupling constants of the unmixed gauge boson Z_0' . For the total, the hadronic and the leptonic widths, which are those relevant to our analysis, one has (see also tables 1,2,3 of ref [8]): $A_T = 40.5(41.0)$, $A_b = 31.0(31.2)$, $A_t = 1.18(1.23)$, for $m_t = 100(200)$ GeV. The B coefficients are model dependent. In the LR model one has: $B_T = -8.71(-8.84)$, $B_b = -8.21(-8.24)$, $B_t = -1.45(-1.47)$, for $m_t = 100(200)$ GeV. In the general case of extra $U(1) \subset E_6$ one finds: $B_T = -3.92(-3.89) \cos\theta_2 + 0.140(0.133) \sin\theta_2$, $B_b = -1.19(-1.21) \cos\theta_2 + 3.66(3.60) \sin\theta_2$, $B_t = -0.261(-0.246) \cos\theta_2 + 1.33(1.35) \sin\theta_2$, for $m_t = 100(200)$ GeV.

If the extended gauge model has only $SU(2)_L$ doublets and singlets in its scalar content (and if one neglects other possible contributions to the ρ parameter), then $\Delta\rho$ is totally due to the $Z - Z'$ mixing and we have already called it $\Delta\rho_M$. $\Delta\rho_M$ is related to ξ_0 through the relation (5.3), so that in this case one can take as independent parameters ξ_0 and $M_{Z'}$ or any combination of them [7,8]. In the present analysis we do not make any assumption on the symmetry breaking sector of the models we deal with, and therefore here $\Delta\rho$ includes all possible contributions to the ρ parameter of whatever origin (except the top contribution which is accounted for separately). The natural independent parameters of the fits are in this case M_Z , ξ_0 and $\Delta\rho$.

From the measured value of M_W/M_Z and the knowledge of M_Z from LEP a direct model independent bound on $\Delta\rho$ is obtained (at 1 σ) [7]:

$$\Delta\rho < 0.020 - 0.002 \left[\frac{m_t}{80 \text{ GeV}} \right]^2 \quad (5.13)$$

from $\frac{M_W^2}{M_Z^2} = 0.779 \pm 0.010$, obtained by combining a preliminary result from CDF [16] and the published UA2 [17] value. Eq. (5.13) corresponds to $1 + \Delta\rho + \Delta\rho_T = 1.010 \pm 0.010$. The limit in eq.(5.13) is a generous one. One could improve on it significantly by reanalyzing the whole of neutral current data including the effect of Z' .

The line-shape parameters relevant to the present fits have been evaluated by adding the deviations obtained with the procedure outlined above to the SM prediction. The latter has been worked out in the framework of the improved Born approximation as described in ref. [11-13]. We have explicitly gauged the accuracy reached in evaluating Γ_T , σ_p^A and Γ_1 , which directly enter the χ^2 expression we use. By comparing our results to the more precise computation of ref. [18] where the full 1-loop radiative corrections were taken into account, we assign, as a conservative estimate of the possible error involved in the SM quantities we adopt, the following values:

$$\delta(\Gamma_T)_{SM} = \pm 5 \text{ MeV} \quad \delta(\sigma_p^A)_{SM} = \pm 0.1 \text{ nb} \quad \delta(\Gamma_1)_{SM} = \pm 0.4 \text{ MeV} \quad (5.14)$$

The comparison refers to $m_H = 100$ GeV and values of m_t ranging from 90 to 200 GeV. For m_H ranging from 25 to 1000 GeV, and m_t varying from 90 to 200 GeV, $\delta(\sigma_p^A)_{SM}$ and $\delta(\Gamma_1)_{SM}$ are still those quoted in eq. (5.14). For an increasing Higgs mass $(\Gamma_T)_{SM}$ decreases. For a Higgs mass of 1000 GeV an excess of up to +14 MeV affects our value of $(\Gamma_T)_{SM}$. We will separately comment on this case of large m_H . It is important to check how much the results we obtain (fitted values of ξ_0 and $\Delta\rho$ and corresponding upper and lower limits) depend on the accuracies listed in eq (5.14). This issue will be addressed specifically in the following sections for each of the models considered.

The expression of the improved Breit-Wigner line shape obtained for the extended gauge models by including the deviations defined in eq. (5.10) has been folded with the initial state radiation spectrum as done for the two previous fits.

6. Fit to the left-right model

The results for the LR model are displayed in table 1 and in fig. 1. We consider LR models under the same assumptions as in ref [8], that is for $g_L = g_R$ and supposing that the right-handed neutrino is heavy. In general, there is in this case an additional contribution to $\Delta\rho_M$ from the charged sector of the theory. This contribution, as well as the mixing angle ξ of the charged sector, are presumably negligible if the right-handed $W_R^\pm$ have masses of a few TeV as demanded by the data for the simplest version of the LR model. Here however we consider the general case where values of M_{W_R} and ξ are still allowed, as long as they are not in conflict with existing experimental bounds. Fixed values of m_t , m_H and α_s were taken in minimizing the χ^2 function, and $g_R = g_L$ was assumed. The value of M_Z is insensitive to both m_t and α_s , and does not change appreciably whether the leptonic data are included in the fit or not. We find:

$$M_Z = 91.163 \pm .013(stat) \pm .030(syst) \quad (6.1)$$

The upper part of table 1 contains the best fit values of ξ_0 and $\Delta\rho$ and their 1σ errors. Four illustrative values of (m_t, α_s) are considered. The results for ξ_0 are not much sensitive to the actual values of m_t and α_s in the range considered. Including the leptonic data has the effect of shifting the central values of ξ_0 upwards and of reducing slightly the errors. $\Delta\rho$ is much more sensitive to variations of m_t and α_s . By increasing m_t and α_s , the hadronic width Γ_h and Γ_T increase. Since the data favour central values of Γ_h and Γ_T which are moderately larger with respect to the average SM prediction, for small values of m_t and α_s , the fit attributes this excess to $\Delta\rho$, whereas for large values of m_t and α_s , a smaller $\Delta\rho$ is preferred.

The lower part of table 1 reproduces the 90% CL bounds on ξ_0 and $\Delta\rho$, here called $\xi_{0low,wp}$ and $\Delta\rho_{low,wp}$. The correlation between them is shown in fig 1 where the 90% CL region in the plane $(\xi_0, \Delta\rho)$ is plotted for $m_t = 100 \text{ GeV}$ and $\alpha_s = .12$. The bounds on ξ_0 are impressive. They are mainly due to the hadronic data alone and they should be compared with the results of ref. [19]. For the LR model, the angle θ of ref. [19]

coincides with our ξ_0 . From fig. 9(a) of ref. [19] we read the following 90%CL bounds: $\theta_{low} \sim -0.05$ rad and $\theta_{wp} \sim +0.02$ rad. (We warn the reader that these values are only approximate since they are read from a 90% CL allowed region in the two dimensional plane (ξ_0, M_Z) obtained by contouring the value $\chi_{min}^2 + 4.61$, whereas the 90% CL bounds on a single parameter is obtained by going from χ_{min}^2 to $\chi_{min}^2 + 2.7$ allowing for the other variables to freely find their minima.) Our analysis shows that ξ_{0wp} is of the same order of magnitude of θ_{wp} , but $|\xi_{0low}|$ is about one order of magnitude smaller than $|\theta_{low}|$. For $m_t = 100 \text{ GeV}$ and $\alpha_s = .12$, by including the leptonic data, we find $\xi_{0low} = -.004$ rad and $\xi_{0wp} = +.024$ rad. In the minimal LR model with $g_R = g_L$, the relation $\xi_0 \sim \sqrt{\cos 2\theta_W} (M_Z/M_{Z'})^2$ holds, θ_W being the Weinberg angle, and ξ_{0wp} translates into a lower bound on $M_{Z'}$ of about 500 GeV . On the other hand the bounds on $\Delta\rho$ are comparable to those derived by combining the measurement of the ratio $M_{W'}/M_Z$ at UA2 and CDF and the measurement of M_Z at LEP [7], given in eq. (5.13).

We have also checked the dependence of our results on the accuracy reached in evaluating the SM quantities. An uncertainty $\delta(\sigma_p^b)_{SM} = \pm 0.1 \text{ nb}$ produces an uncertainty $\delta\xi_0 \sim \pm 0.002$ on the central value ξ_0 of our fit, whereas $\Delta\rho$ remains unchanged. The accuracy $\delta(\Gamma_T)_{SM} = \pm 5 \text{ MeV}$ reflects in an error $\delta\Delta\rho \sim \pm 0.0015$ on the central value of $\Delta\rho$, but does not affect ξ_0 . Finally, in the fit including the leptonic data, the precision $\delta(\Gamma_l)_{SM} = \pm 0.4 \text{ MeV}$ induces an uncertainty $\delta\xi_0 \sim \pm 0.001$ leaving $\Delta\rho$ untouched. For a large value of $m_H = 1000 \text{ GeV}$ the central value of $\Delta\rho$ is shifted by $+0.004$. This remark applies as well to the fits of all the models considered. The errors on ξ_0 and $\Delta\rho$ are not modified.

7. Fits to the extra U(1) models in E_6 (special models).

The results for the extra U(1) models are illustrated in tables 2-5 and in fig. 2-4. For a more detailed presentation, out of the allowed possibilities we have selected four particular cases obtained by specifying the value of the angle θ_2 [20] which parametrize the choice of the new abelian factor among the two extra neutral generators of E_6 . They

are: $\theta_2 = 0^\circ, +52.24^\circ, -52.24^\circ, -82.76^\circ$. In all cases we find:

$$M_Z = 91.163 \pm .013(stat) \pm .030(syst) \quad (7.1)$$

not depending on α_s and m_t , for both fits with and without the leptonic data.

The model with $\theta_2 = 0^\circ$ is also known as model A [20] or η [19,21] in the literature. In various respects this case is rather peculiar, as shown in table 2 and fig. 2. It is evident that the model is very poorly constrained from the first LEP measurements. In ref. [7,8] we showed that models whose θ_2 angle is close to zero are not able to produce sizeable deviations in measurements of the peak cross sections σ_p^h and σ_p^l , and small maximal deviations are expected for the leptonic width Γ_l . Indeed in our fit the inclusion of the leptonic data tightens somewhat the bounds obtained with the hadronic data alone, but the limits that we finally obtain are still very loose. Nevertheless fig. 2 shows that a strong correlation between $\Delta\rho$ and ξ_0 exists. Therefore large values of the mixing angle ξ_0 are allowed only for corresponding large values of the $\Delta\rho$ parameter. The reason for this correlation is that, for $\theta_2 = 0$ the coefficients which multiply $\Delta\rho$ and ξ_0 in the expression of the deviation for σ_p^h are both very small. Therefore the measurement of σ_p^h provides no strong constraint on either $\Delta\rho$ or ξ_0 . A similar situation occurs for Γ_l so that the relevant constraint comes mainly from Γ_T . At first approximation, Γ_T limits only a linear combination of $\Delta\rho$ and ξ_0 with coefficients of opposite signs ($A_T \sim 41, B_T(\theta_2 = 0) \sim -3.9$), which explains at the same time the weakness of the bound and the strong positive correlation exhibited in fig. 2. We observe however that, by including the knowledge of $\Delta\rho$ from the measurement of vector boson masses (see eq. (5.13)), one can further cut by a factor of about two the upper bound on ξ_0 . By combining the various sectors (neutral current (NC) data, vector boson masses and LEP data) one expects a substantial improvement of the limits which concern this model.

The adopted precision in the SM predictions affects also the results for the model with $\theta_2 = 0^\circ$. The major source of uncertainty is $\delta(\sigma_p^h)_{SM} = \pm 0.1$ nb which causes shifts of the central values ξ_0 and $\Delta\rho$ according to $\delta\xi_0 \sim \pm 0.04$ and $\delta\Delta\rho \sim \pm 0.004$.

Although these values are larger than in the LR case, they are always a small fraction of the allowed region of the two parameters.

Results for the model with $\theta_2 = 52.24^\circ$, also denoted B [20] or χ [19,22,23], are given in table 3 and fig. 3. As pointed out in ref. [21] this model is anomaly free even if no new fermions exist beyond the standard quarks and leptons and a right-handed neutrino. Concerning the dependence on m_t and α_s of the results and the differences in including or not the leptonic data, the same comments done for the LR model apply here as well as in the subsequent cases. Bounds on $\Delta\rho$ are comparable with those obtained from the knowledge of vector boson masses, given in eq (5.13). Fig. 3 shows the correlation between $\Delta\rho$ and ξ_0 . Interesting in this case is the comparison with the analysis of the NC data. For extra $U(1)$ models our angle ξ_0 has to be identified with the angle θ_3 of reference [20] (and with the angle $-\theta$ of ref [19]). Allowed regions for ξ_0 from LEP data and from NC data go in opposite directions. NC data leave more room for positive mixing angles (see fig. 9(b) of ref [19], fig. 4 of ref [20]), while LEP data tends to prefer a negative ξ_0 . For instance, at $m_t = 100$ GeV and $\alpha_s = .12$, we find $\xi_{0,low} = -.027$ rad and $\xi_{0,up} = +.005$ rad, while ref. [20] gives, in the unconstrained Higgs case, $\theta_{3,low} = -.015$ rad and $\theta_{3,up} = +.052$ rad. The authors of ref. [22] have also performed a fit of NC data for the model χ with the additional constraint coming from the LEP M_Z measurement. However, they derive their bounds by demanding the realization of a specific Higgs structure. In this way they are able to limit the mass of the new Z' , which is taken as the only free parameter of the fit.

The case $\theta_2 = -52.24^\circ$ (model C of ref [20]) is considered in table 4 and fig. 3. Bounds on $\Delta\rho$ are very similar to those discussed for the LR model. Bounds on ξ_0 can be compared to those obtained in ref. [20]. Assuming $m_t = 100$ GeV and $\alpha_s = .12$ we find $\xi_{0,low} = -.005$ rad to be compared to $\theta_{3,low} = -.046$ rad and $\xi_{0,up} = +.025$ rad against $\theta_{3,up} = +.052$ rad of ref. [20] for an unconstrained Higgs. The correlation between $\Delta\rho$ and ξ_0 is illustrated in fig. 3.

Finally table 5 and fig. 3 refer to the case $\theta_2 = -82.76^\circ$, which corresponds to the model ψ of ref [19]. The limits on $\Delta\rho$ are again similar to those discussed for the LR model. For $m_t = 100$ GeV and $\alpha_s = .12$ we find $\xi_{0\text{low}} = -.004$ rad and $\xi_{0\text{up}} = +.021$ rad. Fig 5 gives the 90% CL allowed region in the $(\Delta\rho, \xi_0)$ plane.

For the three models $\theta_2 = +52.24^\circ, -52.24^\circ, -82.76^\circ$ we have found that the accuracies given in eq. (5.14) for the prediction of the SM quantities produce uncertainties on ξ_0 and $\Delta\rho$ of the same order or even smaller than those described for the LR model, at the end of section 6.

8. The general extra $U(1)$ in E_6 .

Fig. 4 summarizes our results by showing the 90% CL bounds on ξ_0 and $\Delta\rho$ as a function of θ_2 . The full curve refer to ξ_0 for the fit which include the leptonic data. For comparison, we have also plotted the analogous bound obtained from NC data, taken from ref [17] (their β is related to θ_2 through $\beta = \theta_2 - 52.24^\circ$). Here we have considered their unconstrained case, which means that no particular assumption is made about the scalar content of the model. The region around $\theta_2 = 0^\circ$ is not much constrained from LEP data. However, for θ_2 ranging from -90° to -30° and from 30° to 90° the improvement with respect the NC data is evident. The size of the allowed interval for the mixing angle ξ_0 easily decreases by a factor two or more. Particularly significant is the superposition of our bounds with those of ref [19]. Very little room remains to ξ_0 for θ_2 outside the central range $-30^\circ \leq \theta_2 \leq 30^\circ$, if one takes the intersection of the allowed regions. LEP and NC play a complementary role in cutting the physical region for ξ_0 . Fig. 4 also shows that, with the exception of a narrow region close to $\theta_2 = 0^\circ$, LEP data provide also a significant bound on $\Delta\rho$, which is comparable with that given in eq (5.13), derived in ref [7] from the measurement of the ratio M_W/M_Z together with the precise knowledge of M_Z from LEP.

All bounds derived concern the case $\lambda = g_T/g' = 1$, q_T and g' being the gauge coupling constant associated to the extra $U(1)$ and to the weak hypercharge, respectively.

Varying λ , the bounds on ξ_0 simply scale with $1/\lambda$, while the bounds on $\Delta\rho$ remain unaffected.

We have also checked the stability of our results against possible small uncertainties in the adopted values for the SM predictions. Allowing for variations of $(\Gamma_T)_{SM}$, $(\sigma_p^h)_{SM}$ and $(\Gamma_t)_{SM}$ according to the amounts conservatively quantified in eq. (5.14), we find that small shifts of the central values of ξ_0 and $\Delta\rho$ are indeed possible. For θ_2 outside the range $-30^\circ \leq \theta_2 \leq 30^\circ$, these shifts are comparable or even smaller than those discussed in the LR section. For θ_2 closer to 0° they can be larger, nevertheless remaining a small fraction of the allowed region of the parameters analyzed. In any case the errors on ξ_0 and $\Delta\rho$ do not change.

9. Conclusion

The treatment of the data, in particular of their systematic errors, has been explained in section 2. The model independent fit of the hadronic data by an improved Breit-Wigner, corrected for initial state radiation, leads to $M_Z = 91.163 \pm .013(stat) \pm .030(syst)$ GeV, $\Gamma_T = 2.532 \pm .027$ GeV and $\sigma_p^h = 41.1 \pm .5$ nb. The SM fit of the hadronic data gives $M_Z = 91.160 \pm .012(stat) \pm .030(syst)$ GeV, for typical values $m_t = 100$ GeV, $m_H = 100$ GeV and $\alpha_s = .12$.

The main purpose of our work was to extract limitations from the LEP data on extended gauge models (LR models and models with an extra $U(1)$). For the LR model (details are in section 6) LEP data typically give, for $m_t = 100$ GeV, $\alpha_s = .12$, lower and upper bounds for the mixing angle ξ_0 of -0.004 rad and $+0.024$ rad, to be compared with corresponding previous bounds of the order of -0.05 rad and $+0.02$ rad. LEP data alone thus imply an allowed interval for ξ_0 about twice smaller than before, cutting away most of the negative range.

The extra $U(1)$ models considered depend continuously on an angle θ_2 fixing the chosen mixture of extra E_6 generators. Models for $\theta_2 = 0^\circ$ (η or A), $\theta_2 = 52.24^\circ$ (χ

or B), $\theta_2 = -52.24^\circ$ (C) and $\theta_2 = -82.76^\circ$ (ψ) occur in the literature. Details of the fits are in section 7. Model η (A) is poorly constrained from present LEP data, except for the existence of a strong correlation allowing for large ξ_0 only in correspondence of large $\Delta\rho$, which in turn is suppressed by non-LEP data. In model χ (B) LEP data already limits $\Delta\rho$ comparably as from the data on vector boson masses. Comparison with neutral current data is particularly effective: LEP data sharply cut the upper bound on ξ_0 from previous $+0.052$ rad to $+0.005$ rad ($m_t = 100$ GeV, $\alpha_s = .12$). In model C the lower bound on ξ_0 is also sharply cut from LEP data down to -0.005 rad as compared to the previous value -0.046 rad. In model ψ LEP data again sharply reduce the negative interval for ξ_0 , similarly as in C. Fig. 4 illustrates the bounds for general values of θ_2 , (details in section 8). The complementary, almost orthogonal, role of LEP data with respect to NC data in producing allowed regions in the parameter space is evident from fig. 4. For negative θ_2 the NC data mainly allow negative ξ_0 , while LEP data favor positive ξ_0 . For positive θ_2 NC data allow for practically only positive ξ_0 and the LEP data do the opposite.

We also stress that, although in some cases a sizeable improvement on the derived bounds comes from including the leptonic data, most of the results are mainly due to consideration of the hadronic data only, due to the larger statistics accumulated.

We conclude with some speculative comments. It is interesting to note that all four LEP experiments find a central value for the total Z width which is above the standard model. This effect reflects itself in a corresponding increase of the value of the hadronic width (when averaged over the four experiments). Within the experimental errors and the remaining theoretical ambiguities in the standard model predictions, at the moment there is full consistency with the standard model. However one could entertain the following question. Assuming that really there will be an excess of a few tens of MeV in Γ_T and Γ_A with the leptonic partial widths more or less coincident with the expected values, could such an effect be accommodated by an extended gauge model satisfying all existing constraints? We have already shown in ref. [7,8] that an increase of Γ_T and Γ_A

up to $50-60$ MeV can be reproduced in extended gauge models, at least for a relatively light top with $m_t = 100$ GeV. We can provide explicit examples of models where Γ_T and Γ_A are sizably increased but Γ_l and Γ_{inv} are not affected. For instance in the η model with $\theta_2 = 0$, for $\xi_0 = 0.036$, $\Delta\rho_M = 0.0168$ (with $m_t = 100$ GeV) one would obtain $\delta\Gamma_T \sim +45$ MeV, $\delta\Gamma_A \sim +40$ MeV, $\delta\Gamma_l \sim +0.9$ MeV, $\delta\Gamma_{inv} \sim +2.7$ MeV and $\delta\sigma_p^A \sim -0.1$ nb.

We are sure that, with the ongoing accumulation of LEP data, additional very important constraints will be added very soon to the standard model and the extended gauge models.

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Table 1 - Combined fit to leptonic and hadronic LEP data for the left-right model. The corresponding result from the hadronic data alone is given in parenthesis for comparison.
 $\chi^2 = 37/50$ (36/46)

	$m_t = 100 \text{ GeV}$		$m_t = 200 \text{ GeV}$	
	$\alpha_s = 0.12$	$\alpha_s = 0.14$	$\alpha_s = 0.12$	$\alpha_s = .14$
ξ_0	0.010 ± 0.009 (0.007 $\pm$ 0.010)	0.007 ± 0.009 (0.005 $\pm$ 0.010)	0.011 ± 0.009 (0.008 $\pm$ 0.010)	0.009 ± 0.009 (0.006 $\pm$ 0.010)
$\Delta\rho$	0.013 ± 0.009 (0.014 $\pm$ 0.009)	0.009 ± 0.009 (0.010 $\pm$ 0.009)	0.006 ± 0.009 (0.007 $\pm$ 0.009)	0.002 ± 0.009 (0.003 $\pm$ 0.009)
ξ_{low}	-0.004 (-0.009)	-0.007 (-0.011)	-0.003 (-0.008)	-0.006 (-0.010)
ξ_{up}	$+0.024$ (+0.023)	$+0.022$ (+0.021)	$+0.025$ (+0.024)	$+0.023$ (+0.022)
$\Delta\rho_{low}$	-0.001 (0.000)	-0.005 (-0.004)	-0.009 (-0.008)	-0.013 (-0.012)
$\Delta\rho_{up}$	$+0.028$ (+0.029)	$+0.024$ (+0.025)	$+0.021$ (+0.022)	$+0.017$ (+0.018)

Table 2 - Combined fit to leptonic and hadronic LEP data for the extra U(1) model $\theta_2 = 0^\circ$. The corresponding result from the hadronic data alone is given in parenthesis for comparison.
 $\chi^2 = 37/50$ (36/46)

	$m_t = 100 \text{ GeV}$		$m_t = 200 \text{ GeV}$	
	$\alpha_s = 0.12$	$\alpha_s = 0.14$	$\alpha_s = 0.12$	$\alpha_s = 0.14$
ξ_0	0.15 ± 0.11 ($0.16^{+0.19}_{-0.32}$)	0.12 ± 0.11 ($0.11^{+0.20}_{-0.33}$)	0.17 ± 0.11 ($0.18^{+0.19}_{-0.33}$)	0.14 ± 0.11 ($0.14^{+0.20}_{-0.33}$)
$\Delta\rho$	0.028 ± 0.017 ($0.028^{+0.024}_{-0.026}$)	0.021 ± 0.017 ($0.020^{+0.024}_{-0.026}$)	0.022 ± 0.017 ($0.023^{+0.024}_{-0.026}$)	0.015 ± 0.017 ($0.015^{+0.024}_{-0.026}$)
ξ_{low}	-0.04 (-0.23)	-0.07 (-0.28)	-0.02 (-0.21)	-0.05 (-0.25)
ξ_{up}	$+0.33$ ($+0.46$)	$+0.30$ ($+0.42$)	$+0.35$ ($+0.47$)	$+0.32$ ($+0.44$)
$\Delta\rho_{low}$	-0.001 (-0.016)	-0.007 (-0.024)	-0.007 (-0.021)	-0.014 (-0.030)
$\Delta\rho_{up}$	$+0.056$ ($+0.068$)	$+0.049$ ($+0.060$)	$+0.050$ ($+0.062$)	$+0.043$ ($+0.054$)

Table 3 - Combined fit to leptonic and hadronic LEP data for the extra U(1) model $\theta_2 = 52.24^\circ$. The corresponding result from the hadronic data alone is given in parenthesis for comparison.
 $\chi^2 = 37/50$ (36/46)

	$m_t = 100 \text{ GeV}$		$m_t = 200 \text{ GeV}$	
	$\alpha_s = 0.12$	$\alpha_s = 0.14$	$\alpha_s = 0.12$	$\alpha_s = 0.14$
ξ_0	-0.011 ± 0.010 (-0.008 ± 0.011)	-0.008 ± 0.010 (-0.005 ± 0.011)	-0.012 ± 0.010 (-0.009 ± 0.011)	-0.009 ± 0.010 (-0.006 ± 0.011)
$\Delta\rho$	0.010 ± 0.007 (0.012 ± 0.008)	0.007 ± 0.007 (0.009 ± 0.008)	0.002 ± 0.007 (0.005 ± 0.008)	-0.001 ± 0.007 (0.001 ± 0.008)
ξ_{low}	-0.027 (-0.025)	-0.024 (-0.023)	-0.028 (-0.026)	-0.025 (-0.024)
ξ_{up}	$+0.005$ ($+0.010$)	$+0.008$ ($+0.012$)	$+0.004$ ($+0.009$)	$+0.007$ ($+0.011$)
$\Delta\rho_{low}$	-0.002 (0.000)	-0.005 (-0.004)	-0.009 (-0.008)	-0.013 (-0.011)
$\Delta\rho_{up}$	$+0.022$ ($+0.025$)	$+0.019$ ($+0.022$)	$+0.014$ ($+0.018$)	$+0.011$ ($+0.014$)

Table 4 - Combined fit to leptonic and hadronic LEP data for the extra $U(1)$ model $\theta_2 = -52.24^\circ$. The corresponding result from the hadronic data alone is given in parenthesis for comparison.
 $\chi^2 = 37/50$ (36/46)

	$m_t = 100 \text{ GeV}$			$m_t = 200 \text{ GeV}$		
	$\alpha_s = 0.12$	$\alpha_s = 0.14$	$\alpha_s = 0.12$	$\alpha_s = 0.14$	$\alpha_s = 0.12$	$\alpha_s = 0.14$
ξ_0	0.010 ± 0.009 (0.007 ± 0.010)	0.008 ± 0.009 (0.005 ± 0.010)	0.011 ± 0.009 (0.008 ± 0.010)	0.009 ± 0.009 (0.006 ± 0.010)		
$\Delta\rho$	0.012 ± 0.008 (0.013 ± 0.008)	0.008 ± 0.008 (0.010 ± 0.008)	0.004 ± 0.008 (0.006 ± 0.008)	0.001 ± 0.008 (0.002 ± 0.008)		
ξ_{low}	-0.005 (-0.009)	-0.007 (-0.012)	-0.003 (-0.008)	-0.006 (-0.011)		
ξ_{up}	$+0.025$ ($+0.023$)	$+0.023$ ($+0.022$)	$+0.026$ ($+0.025$)	$+0.024$ ($+0.023$)		
$\Delta\rho_{low}$	-0.001 (0.000)	-0.005 (-0.004)	-0.009 (-0.008)	-0.012 (-0.012)		
$\Delta\rho_{up}$	$+0.025$ ($+0.027$)	$+0.022$ ($+0.023$)	$+0.017$ ($+0.019$)	$+0.014$ ($+0.016$)		

Table 5 - Combined fit to leptonic and hadronic LEP data for the extra $U(1)$ model $\theta_2 = -82.76^\circ$. The corresponding result from the hadronic data alone is given in parenthesis for comparison.
 $\chi^2 = 37/50$

	$m_t = 100 \text{ GeV}$			$m_t = 200 \text{ GeV}$		
	$\alpha_s = 0.12$	$\alpha_s = 0.14$	$\alpha_s = 0.12$	$\alpha_s = 0.14$	$\alpha_s = 0.12$	$\alpha_s = 0.14$
ξ_0	0.008 ± 0.007 (0.006 ± 0.008)	0.006 ± 0.007 (0.004 ± 0.008)	0.009 ± 0.007 (0.007 ± 0.008)	0.007 ± 0.007 (0.005 ± 0.008)		
$\Delta\rho$	0.011 ± 0.008 (0.013 ± 0.008)	0.008 ± 0.008 (0.009 ± 0.008)	0.003 ± 0.008 (0.005 ± 0.008)	0.001 ± 0.008 (0.002 ± 0.008)		
ξ_{low}	-0.004 (-0.008)	-0.006 (-0.009)	-0.003 (-0.007)	-0.005 (-0.009)		
ξ_{up}	$+0.021$ ($+0.019$)	$+0.019$ ($+0.018$)	$+0.022$ ($+0.020$)	$+0.019$ ($+0.018$)		
$\Delta\rho_{low}$	-0.001 (0.000)	-0.005 (-0.003)	-0.009 (-0.008)	-0.012 (-0.011)		
$\Delta\rho_{up}$	$+0.024$ ($+0.026$)	$+0.021$ ($+0.023$)	$+0.016$ ($+0.019$)	$+0.013$ ($+0.015$)		

FIGURE CAPTIONS

Fig. 1: 90% CL contour in the plane $(\xi_0, \Delta\rho)$ for the LR model, from the fit including leptonic and hadronic data.

Fig. 2: 90% CL contour in the plane $(\xi_0, \Delta\rho)$ for the extra- $U(1)$ model at $\theta_2 = 0^\circ$, from the fit including leptonic and hadronic data.

Fig. 3: 90% CL contour in the plane $(\xi_0, \Delta\rho)$ for the extra- $U(1)$ models at $\theta_2 = +52.24^\circ$ (full), $\theta_2 = -52.24^\circ$ (dashed) and $\theta_2 = -82.76^\circ$ (dot-dashed), from the fit including leptonic and hadronic data.

Fig. 4: 90% CL upper and lower bounds on ξ_0 (full) and $\Delta\rho$ (thin-dashed) from LEP data, for $m_t = 100 \text{ GeV}$ and $\alpha_s = .12$; 90% CL upper and lower bounds on ξ_0 (thick-dashed) from NC data, taken from ref [19]. Additional constraints on $\Delta\rho$ arise from NC data [19,20] and from the recent measurement of M_W/M_Z . In particular we recall the bound on $\Delta\rho$ from M_W/M_Z given by eq. (5.13). This bound directly restricts the allowed region for $\Delta\rho$ (thin-dashed line). Also, through the correlation between $\Delta\rho$ and ξ_0 shown for the $\theta_2 = 0^\circ$ model in fig. 2, it sizably reduces the ξ_0 range.

Fig. 1

Fig. 2

Fig. 3

Fig. 4