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Extended Gauge Models and Precision Electroweak Data⁺

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Abstract

We consider the implications of precision electroweak data on extended gauge models. 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. Fits of the data in terms of these extended gauge models are considered and limits on the mixing parameters are obtained. The relation with the epsilon parameter approach is discussed. We also consider a number of more particular models with specified Higgs structure, where limits on m_Z' can also be derived.

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1. Introduction

In this note we present an analysis of the most recent LEP data in the framework of extended gauge models. The results of the 1991 and, in preliminary form, of the 1992 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 important and make an update of previous works [1,2,3] worthwhile. The present analysis also contains some novel features with respect to previous similar studies where limits on mixing parameters were derived. We consider in detail the question of how the extended gauge models compare with the experimental pattern of results on the small parameters that describe the deviations from the Standard Model plus pure QED corrections (in particular the epsilon parameters, introduced in ref.[4]). We also describe the results of a number of fits of extended gauge models that contain two or three additional parameters with respect to the Standard Model.

The extended gauge models that we shall discuss in detail are the left-right model (LR) [5] 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 [6]. 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, by using the ZFITTER programme [7].

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 in 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:

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

* The present work is based on the latest LEP data presented at the European Physical Society Conference in Marseille, July 1993.

Clearly, Z_S has couplings which are formally identical to the neutral vector boson of the standard model in terms 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:

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

$\Delta\rho_M$ arises because the Z mass in 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.

Beyond the tree level, the complete set of one loop electroweak radiative corrections in the Standard Model have been taken into account, using ZFITTER [7] (the results have also been checked with TOPAZ0 [8]). Loop effects due to the heavy gauge boson Z' are quite small for the relevant range of parameters and will be neglected here. Although we have included the full one loop radiative corrections in the Standard Model, in the following, for the sole purpose of defining, for widths and asymmetries in the extended gauge models, the shifts from the Standard Model limit, it is sufficient to refer to the improved Born approximation [9]. This is because the small corrections from additional radiative effects and from the extended gauge structure can be treated as independent in a linear approximation. In the Standard Model, the improved Born approximation correctly

takes into account large logarithms (i.e. terms of order $\frac{\alpha_f}{\pi} \frac{m_Z^2}{m_f^2}$ where f_l is a light fermion) and quadratic terms in the top mass (i.e. terms of order $G_F m_t^2$).

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

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

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

Other asymmetries (e.g. the τ polarisation asymmetry) can similarly be expressed in terms of $v_{\text{eff}}^f a_{\text{eff}}^f$. Here $N_c = 3(1 + \delta_{\text{QCD}})$ ($1 + \delta_{\text{QED}}$) for quarks, $N_c = (1 + \delta_{\text{QED}})$ for leptons (δ_{QED} is the correction from final state real and virtual photon radiation). The factor ρ also includes the large radiative corrections arising from the top quark loop as well as the logarithmic terms from the Higgs

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

where $\Delta\rho_t \equiv \frac{3G_F m_t^2}{8\pi^2\sqrt{2}} + \dots$, where the dots stand for smaller terms in the large m_t limit.

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:

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

where T_{3L}^f and Q^f are the weak isospin (3rd component) and the electric charge of the fermion f . The quantity s_W^2 is given by the relation:

$$s_W^2 = 1 - \frac{m_W^2}{m_Z^2} \quad (11)$$

is the effective $\sin^2\theta_W$ for the on-shell Z couplings. Because of the effect of $\Delta\rho_M$, it differs from the corresponding quantity s_W^2 in the standard model, for fixed input parameter α ,

G_F , m_Z , m_f , m_H , according to the relation:

$$s_W^2 = s_W^2 - \frac{s_W^2}{[c_W^2 - s_W^2]} \frac{\Delta\rho_M}{c_W^2} \quad (12)$$

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 [9,10] by replacing $1 + \Delta\rho_t$ in ρ by $1 - \frac{1}{3}\Delta\rho_t$ and s_W^2 by $s_W^2 (1 + \frac{2}{3}\Delta\rho_t)$ 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. For a different choice of $1 = g_N/g'$, with not too large a value, the consequence would be a rescaling of the results on ξ_0 by a factor $1/r$, while, in our approach, where m_Z is not specified, the limits and the best fit values obtained for $\Delta\rho_M$ are not affected.

It is useful to consider the deviations from the corresponding standard model values of the predicted observables, m_W/m_Z , the Z partial widths and asymmetries, linearised in ξ_0 and $\Delta\rho_M$, expressed in the following form:

$$\frac{\delta O}{O} = (A_O \Delta\rho_M + B_O \xi_0) \quad (13)$$

In eq.13 the coefficients A_0 are uniquely determined in terms of the standard model parameters, whereas B_0 also depend on the couplings v_N^f and a_N^f [11]. Their expressions immediately follow from eqs.(6-12) and their numerical values are given in table 2, for all the relevant measured quantities.

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 m_W/m_Z and of v_{eff}^f and a_{eff}^f as obtained by the LEP experiments are collected in table 3. The Z mass was fixed at the value $m_Z = 91.187$ GeV.

The χ^2 function minimized in the fit is the sum of 6 terms: m_W/m_Z , the total width Γ_Z , the ratio of the hadronic and leptonic widths $R_h = \Gamma_h/\Gamma_l$, the hadronic cross section at the peak $\sigma_h = 12\pi/m_Z^2 \Gamma_e \Gamma_h/\Gamma_Z^2$, the ratio $R_{bb} = \Gamma_b/\Gamma_h$ of $\Gamma_b = \Gamma(Z \rightarrow b\bar{b})$ and the total hadronic width Γ_h and the ratio v_{eff}^e/a_{eff}^e . We have taken into account the main entries of the correlation matrix, which, in the basis Γ_Z , σ_h and R_h , are $c_{12} = -0.07$, $c_{23} = 0.13$ and $c_{13} = 0.00$. 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.

Rather than deriving bounds on ξ_0 and $\Delta\rho_M$ it is more convenient to use ξ_0 and $\Delta\rho$ (given by eq.8, or, more precisely by $\Delta\rho = \epsilon_{N1} + \Delta\rho_M$, with ϵ_{N1} defined in ref.11). The bounds on $\Delta\rho$ are in fact almost independent on m_t , contrary to those on $\Delta\rho_M$. The resulting constraints on $\Delta\rho$ and ξ_0 for E_6 models are plotted in figs.1 and 2 for all values of θ_2 .

In figs.1 and 2 the 90% c.l. upper and lower limits on $\Delta\rho$ and ξ_0 , respectively, are displayed for $m_H = 100$ GeV, $\alpha_s = 0.118$ and $m_t = 100$ and 200 GeV. As anticipated, for $\Delta\rho$, there is little dependence on m_t . The residual dependence arises from logarithmic terms and also from the residual quadratic terms in the $Z \rightarrow b\bar{b}$ vertex (which is of only moderate importance for the fit because the error on Γ_b is still relatively large). With increasing m_t less and less space is left for $\Delta\rho_M$ because the standard term $\Delta\rho_t$ is positive and increases quadratically. A typical value for the upper bound on $\Delta\rho$ (at $\alpha_s = 0.118$) of about 0.006 is already saturated by the contribution from $\Delta\rho_t$ with $m_t \sim 175$ GeV. The dependence on m_t of the limits on ξ_0 is also very moderate, except in the region near $\theta_2 = 0$. We have also studied the dependence on α_s in the range $0.111 < \alpha_s < 0.125$. It turns out that, for $m_H = 100$

GeV, $m_t = 150$ GeV, by increasing α_s of 0.01 the allowed region for $\Delta\rho_M$ is shifted down by about 0.0015. As for ξ_0 the corresponding shift of the allowed region is at most of about 0.004. The change is upward for $\theta_2 > 0$ and downward for $\theta_2 < 0$.

The corresponding results on the LR model are reported in table 4. The same pattern is found also in this case.

The data set is by now sufficiently rich that we can attempt a fit of the 6 experimental entries in terms of the parameters of the Standard Model, plus those of the extended gauge models. First we fix $m_H = 100$ GeV, $m_t = 100$ or 150 GeV and $\alpha_s = 0.118$ and we fit ξ_0 and $\Delta\rho$ (in E_6 models we do the fit for a number of points on the θ_2 axis). The results are reported in table 5. Since the Standard Model fit, for the chosen values of the parameters, is already good, it is not too impressive that the extended gauge model fit, with 2 more parameters, is quite good for all values of θ_2 , also for $m_t = 100$ GeV. One can obtain a pictorial impression of the quality of the fit and a comparison with the Standard Model by using the epsilon variables of ref.[11]. As discussed in ref.[4], in extended gauge models ϵ_{N1} , ϵ_{N2} and ϵ_{N3} receive the additional contributions (with respect to the Standard Model) given by:

$$\begin{aligned}\Delta\epsilon_{N1} &= \Delta\rho_M + 4 \frac{1}{a_N} \text{tg}\xi_0 \\ \Delta\epsilon_{N2} &= -\text{tg}\xi_0 \left(\frac{1}{v_N} - 3 \frac{1}{a_N} \right) \\ \Delta\epsilon_{N3} &= \frac{\text{tg}\xi_0}{2} \left[\frac{1}{s_W^2} \left((1-2 \frac{s_W^2}{s_W^2}) v_N^2 + (1+2 \frac{s_W^2}{s_W^2}) a_N^2 \right) \right]\end{aligned}\quad (14)$$

Note that, with respect to ref.[4], there is a sign change in front of the $\frac{1}{a_N}$ terms. This is simply due to the fact that the opposite sign definition for $\frac{1}{a_N}$ was adopted here, following eq.(10) for the axial couplings in the Standard Model. The variable ϵ_0 is not particularly relevant in the present context because, in all extended gauge models we consider, all the couplings are family independent. Thus, whatever correction to the $Z \rightarrow b\bar{b}$ vertex would also affect all down quark vertices by the same amount. Since the accuracy of the data on Γ_b is relatively modest, we cannot adjust the value of Γ_b without at the same time spoil the agreement with the other hadronic observables.

In figs. 3a and 3b, for $m_t = 100$ or 150 GeV, respectively, and $m_H = 100$ GeV, $\alpha_s = 0.118$ we plot a set of dots in the plane ϵ_{N3} vs ϵ_{N1} that correspond to the best fit for each θ_2 value obtained by considering the whole set of data given in table 3. The solid lines, for each dot, show the 1σ variation due to $\Delta\rho$, while the dashed lines span 1σ in ξ_0 . The result for the LR model also appears in the figures, marked by a box symbol. The corresponding Standard Model point is also shown, together with the ellipse of the experimental data (with 1σ projections on both axes). The data correspond to a fit to the defining variables for ϵ_{N1} , ϵ_{N2} and ϵ_{N3} , i.e. m_W/m_Z , Γ_l and the ratio v_{eff}^e/a_{eff}^e obtained by

combining all the asymmetries. This corresponds to the fit in column 2 of table 4 of ref.[11]. We recall that other observables cannot be used to further constrain ϵ_{N1} , ϵ_{N2} and ϵ_{N3} because the extended gauge models preserve lepton universality but add different vertex corrections to leptons, down and up quarks. Thus, as explained in ref.11, the mentioned set of data is the largest that can be used for ϵ_{N1} , ϵ_{N2} and ϵ_{N3} in the present context. Similarly in figs 4a and 4b we present the analogous plot in the plane ϵ_{N2} vs ϵ_{N3} . In general, for small values of m_t there is a substantial improvement in going from the Standard Model to the extended gauge models, mostly due to the presence of 2 additional parameters and the fact that $\Delta\rho_M$ increases $\Delta\rho$. This is seen, for example, from figs 3a and 4a, which refer to $m_t=100$ GeV. For $m_t=150$ GeV and $m_H=100$ GeV, we see from figs. 3b and 4b that the Standard Model by itself provides a particularly good fit to the data. This is also confirmed by looking at the results of the fits displayed in table 5. We see that the best fit at all values of θ_2 is very close to $\xi_0=0$ and $\Delta\rho=0.0035$ which is the Standard Model value for $m_t=150$ GeV.

Leaving θ_2 also free the results of the fit are, for $m_t=100$ GeV:

$$\xi_0=(-1.5^{+5.2}_{-6.2}) 10^{-3}, \Delta\rho=(3.1 \pm 1.6) 10^{-3}, \theta_2(\text{deg})=49^{+41}_{-139} \quad (15)$$

The minimum in θ_2 is very flat so that the fit is not much sensitive to the physical structure of the new $U(1)$ (see also table 5). The same situation also applies for $m_t=150$ GeV, where we find:

$$\xi_0=(-0.9 \pm 5.6) 10^{-3}, \Delta\rho=(3.6 \pm 1.6) 10^{-3}, \theta_2(\text{deg})=8^{+89.2}_{-90.8} \quad (16)$$

The corresponding χ^2 values are given by 1.08 and 2.41, respectively, (for 3 degrees of freedom). For comparison, the χ^2 of the Standard Model fit, for the same values of m_t and α_s , is given by $\chi^2=7.26$ for $m_t=100$ GeV and $\chi^2=2.41$ for $m_t=150$ GeV (for 6 degrees of freedom).

Similarly, for LR models, we obtain:

$$\begin{aligned} m_t=100 \text{ GeV:} \quad & \xi_0=(-0.84 \pm 1.58) 10^{-3}, \Delta\rho=(3.37 \pm 1.39) 10^{-3} \\ m_t=150 \text{ GeV:} \quad & \xi_0=(0.15 \pm 1.58) 10^{-3}, \Delta\rho=(3.48 \pm 1.39) 10^{-3} \end{aligned} \quad (17)$$

with χ^2 values given by 1.42 and 2.43, respectively, (for 4 degrees of freedom). We then let also m_t and α_s to vary. The results are

$$\begin{aligned} \xi_0 &=(-1.2 \pm 3.1) 10^{-3}, \Delta\rho=(3.2^{+2.6}_{-2.4}) 10^{-3}, \theta_2(\text{deg})=90^{+180}_{-0.0} \\ \alpha_s &=0.118 \pm 0.017, \quad m_t < 153.8 \text{ GeV (at } 1\sigma) \end{aligned} \quad (18)$$

with a χ^2 , for 1 degree of freedom, given by $\chi^2=1.06$. Again, for comparison, the Standard Model fit, for the same values of m_H and α_s gives $m_t=143 \pm 18$ GeV with $\chi^2=2.27$ (for 5 degrees of freedom). Leaving α_s also free we obtain practically the same value of m_t together with $\alpha_s=0.120 \pm 0.006$ with $\chi^2=2.19$ (for 4 degrees of freedom). The same fitting procedure for LR models leads to the result:

$$\begin{aligned} \xi_0 &=(-0.1 \pm 2.5) 10^{-3}, \Delta\rho=(3.9^{+2.0}_{-1.8}) 10^{-3} \\ \alpha_s &=0.113 \pm 0.012, m_t < 147.1 \text{ GeV (at } 1\sigma) \end{aligned} \quad (19)$$

with a χ^2 , for 2 degrees of freedom, given by $\chi^2=1.22$. We recall that our fitting procedure is not sensitive to the strong m_t dependence contained in the $\Delta\rho$ parameter, so that the upper bound on m_t that we obtain is a consequence of the quadratic m_t dependence of the $Z \rightarrow b\bar{b}$ vertex and of residual logarithmic behaviour. Indeed, as shown by the χ^2 values, the extended gauge model fit prefers low values of m_t mainly to find agreement with the ratio $R_{b\ell}$.

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 :

$$\xi_0 = c \left(\frac{m_Z}{m_t} \right)^2 \quad (20)$$

with c a constant which depends on the Higgs structure and vacuum expectation values. 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.

We have considered 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 [5] $c = \sqrt{\cos 2\theta_W} = 0.73$. 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 of about 1.5 TeV for a standard Higgs mass of 100 GeV and a top mass of 110 GeV. The lower bound increases with m_t as is seen from fig.5, (all bounds are given for $\alpha_s=0.118$).

Models χ [12] (or B [13]) and η [12] (or A [13]) are also illustrated in fig.5. 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 [13] $c_\chi=0.39$ and $0.24 < c_\eta < 0.63$. One then obtains a lower bound for m_Z of about 900 GeV for $m_t=100$ GeV increasing with m_t . Less stringent limits are obtained on m_Z , corresponding to the smaller value allowed for c . For

$m_t=110$ GeV the lower bound is in the range 500–1000 GeV depending on the value of c in the allowed range.

5. Conclusion

The data collected at LEP on the Z peak were shown to impose very severe constraints on the mixings of a non standard Z' , described by two parameters ξ_0 and $\Delta\rho_M$, which in general are not related by the gauge structure of the model but only by the detailed structure of the Higgs sector. At present, the Standard Model is in such good agreement with the data that no indication for additional corrections is found, at least for unspecified m_t . In fact, only a very small amount of mixing is allowed, with ξ_0 always less than 1%. The fit of the data in terms of extended gauge models is of comparable quality than that of the Standard Model, once that the existence of more parameters is properly taken into account.

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TABLE CAPTIONS

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. Here $\theta = \theta_W$. For left-right models, we have put in the text $\lambda = g_L/g_R = 1$. As a consequence $y = \sqrt{\cos 2\theta}$.

Table 2 - Coefficients A and B defined in eq. 13.

Table 3 - Experimental values from LEP and CDF/UA2 for the observables used for the fit.

Table 4 - LR Model. Best Fit with 1σ errors +90% C.L. bounds.

Table 5 - Best Fit values for ξ_0 and $\Delta\rho$ with 1σ errors for the various models and corresponding values for the observables.

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FIGURE CAPTIONS

[1] Allowed range (90% c.l.) for $\Delta\rho$ versus θ_2 , for $m_H = 100$ GeV, $\alpha_s = 0.118$.

[2] Allowed range (90% c.l.) for ξ_0 versus θ_2 , for $m_H = 100$ GeV, $\alpha_s = 0.118$.

[3] In the ϵ_{N1} , ϵ_{N3} plane the 1σ ellipse corresponding to the experimental data on m_W/m_Z , Γ_1 and the ratio v_{eff}^e/a_{eff}^e obtained by combining all the asymmetries is shown together with the Standard Model point. The set of dots correspond to the best fit for the θ_2 values listed in table 5. The box symbol corresponds to the LR model. The solid lines, for each dot, show the 1σ variation due to $\Delta\rho$, while the dashed lines span 1σ in ξ_0 . Here we have assumed $m_H = 100$ GeV, $\alpha_s = 0.118$, with $m_t = 100$ GeV (a) or 150 GeV (b).

[4] Same as fig.3 for the ϵ_{N2} , ϵ_{N3} plane. Note the absence of the solid lines through the dots, due to the independence of ϵ_{N2} and ϵ_{N3} from $\Delta\rho_M$.

[5] Lower bounds on m_Z (90% c.l.) as functions of m_t obtained for $m_H = 100$ GeV, $\alpha_s = 0.118$ for LR models (dotted line), for the χ model (dashed-dotted), for the η model with $c = 0.24$ (dashed) and $c = 0.63$ (solid).

extra $U(1)$ models

$$\begin{aligned} v_N^u &= 0 \\ a_N^u &= -\frac{2}{3} \sin \theta \cos \theta_2 \\ v_N^d &= \frac{1}{2} \sin \theta (\cos \theta_2 + \sqrt{\frac{5}{3}} \sin \theta_2) \\ a_N^d &= \sin \theta (-\frac{1}{6} \cos \theta_2 + \frac{1}{2} \sqrt{\frac{5}{3}} \sin \theta_2) \\ v_N^e &= -\frac{1}{2} \sin \theta (\cos \theta_2 + \sqrt{\frac{5}{3}} \sin \theta_2) \\ a_N^e &= a_N^d \\ v_N^f &= -\sin \theta (\frac{1}{6} \cos \theta_2 + \frac{1}{2} \sqrt{\frac{5}{3}} \sin \theta_2) \\ a_N^f &= -v_N^f \end{aligned}$$

left-right models

$$\begin{aligned} v_N^f &= \frac{\cos^2 \theta}{\lambda y} (T_{3R} - 2\lambda^2 \sin^2 \theta Q_{em}) + \frac{\lambda \sin^2 \theta}{y} (T_{3R} - 2 \sin^2 \theta Q_{em}) \\ a_N^f &= \frac{\cos^2 \theta}{\lambda y} T_{3R} - \frac{\lambda \sin^2 \theta}{y} T_{3L} \end{aligned}$$

Table 1

	A	B for extra-U(1) models	B for LR model
Γ_Z	1.350	$-0.130 \cos \theta_2 + 0.0044 \sin \theta_2$	-0.290
R	0.275	$0.189 \cos \theta_2 - 1.158 \sin \theta_2$	1.056
σ_h	-0.030	$-0.045 \cos \theta_2 + 1.489 \sin \theta_2$	-1.250
R_{bh}	-0.060	$-0.614 \cos \theta_2 + 0.087 \sin \theta_2$	0.280
g_v/g_a	-17.556	$-6.547 \cos \theta_2 - 7.623 \sin \theta_2$	-2.098
M_W/M_Z	0.715	0	0

Table 2

Γ_Z (MeV)	$R = \Gamma_h/\Gamma_l$	σ_h (nb)	R_{bh}	g_v/g_a	M_W/M_Z
2489 ± 7	20.77 ± 0.05	41.55 ± 0.14	0.220 ± 0.0027	0.0712 ± 0.0028	0.8798 ± 0.0028

Table 3

	$m_t = 100 \text{ GeV}$			$m_t = 200 \text{ GeV}$		
	$\alpha_s = 0.111$	$\alpha_s = 0.118$	$\alpha_s = 0.125$	$\alpha_s = 0.111$	$\alpha_s = 0.118$	$\alpha_s = 0.125$
$\xi_0 \times 10^3$	0.4 ± 1.6	-0.8 ± 1.6	-2.1 ± 1.6	2.7 ± 1.6	1.5 ± 1.6	0.2 ± 1.6
$\Delta\rho \times 10^3$	4.1 ± 1.4	3.4 ± 1.4	2.7 ± 1.4	4.4 ± 1.4	3.7 ± 1.4	3.1 ± 1.4
$(\xi_0)_{low} \times 10^3$	-2.2	-3.5	-4.8	0.1	-1.1	-2.4
$(\xi_0)_{up} \times 10^3$	3.0	1.8	0.5	5.3	4.1	2.8
$(\Delta\rho)_{low} \times 10^3$	1.8	1.1	0.4	2.1	1.4	0.8
$(\Delta\rho)_{up} \times 10^3$	6.4	5.7	5.0	6.7	6.0	5.4

Table 4

Fig. 1

θ_2	$(\xi_0) \times 10^3$	$(\Delta\rho) \times 10^3$	χ^2	Γ_Z	R_h	σ_h	R_{bh}	g_v/g_a	M_W/M_Z
$\alpha_s = 0.118 \quad m_{top} = 100 \quad m_h = 100$									
-90.00	-1.1 ± 1.4	3.2 ± 1.4	1.1127	2.4917	20.7522	41.5047	0.2178	0.0707	0.8790
-70.00	-1.1 ± 1.4	3.3 ± 1.4	1.1403	2.4920	20.7522	41.5025	0.2179	0.0706	0.8791
-50.00	-1.2 ± 1.7	3.4 ± 1.4	1.1852	2.4924	20.7527	41.4986	0.2179	0.0704	0.8791
-30.00	-1.6 ± 2.4	3.4 ± 1.4	1.2806	2.4929	20.7549	41.4895	0.2180	0.0701	0.8792
-10.00	-1.6 ± 4.2	3.5 ± 1.5	1.5598	2.4932	20.7663	41.4594	0.2180	0.0698	0.8792
0.00	0.2 ± 5.5	3.3 ± 1.6	1.7053	2.4919	20.7790	41.4388	0.2178	0.0703	0.8791
10.00	2.6 ± 5.0	2.9 ± 1.6	1.4366	2.4899	20.7753	41.4626	0.2175	0.0712	0.8788
30.00	2.1 ± 2.7	3.0 ± 1.5	1.1104	2.4903	20.7584	41.5004	0.2176	0.0712	0.8789
50.00	1.4 ± 1.8	3.1 ± 1.4	1.0830	2.4910	20.7541	41.5056	0.2177	0.0710	0.8789
70.00	1.2 ± 1.5	3.2 ± 1.4	1.0933	2.4914	20.7527	41.5058	0.2178	0.0708	0.8790
90.00	-1.1 ± 1.4	3.2 ± 1.4	1.1127	2.4917	20.7522	41.5047	0.2178	0.0707	0.8790
LR	-0.8 ± 1.6	3.4 ± 1.4	1.4222	2.4928	20.7600	41.4828	0.2177	0.0701	0.8791
$\alpha_s = 0.118 \quad m_{top} = 150 \quad m_h = 100$									
-90.00	0.0 ± 1.4	3.5 ± 1.4	2.4384	2.4897	20.7425	41.4710	0.2163	0.0711	0.8801
-70.00	0.0 ± 1.4	3.5 ± 1.4	2.4377	2.4897	20.7420	41.4721	0.2163	0.0711	0.8801
-50.00	-0.1 ± 1.7	3.5 ± 1.4	2.4364	2.4898	20.7414	41.4735	0.2163	0.0711	0.8801
-30.00	-0.2 ± 2.4	3.5 ± 1.4	2.4331	2.4898	20.7404	41.4753	0.2163	0.0711	0.8801
-10.00	-0.6 ± 4.2	3.5 ± 1.5	2.4218	2.4901	20.7390	41.4763	0.2164	0.0710	0.8801
0.00	-0.9 ± 5.5	3.5 ± 1.6	2.4135	2.4904	20.7404	41.4710	0.2164	0.0708	0.8802
10.00	-0.6 ± 5.0	3.5 ± 1.6	2.4217	2.4903	20.7439	41.4636	0.2164	0.0709	0.8802
30.00	-0.1 ± 2.7	3.5 ± 1.5	2.4363	2.4898	20.7444	41.4655	0.2163	0.0710	0.8801
50.00	0.0 ± 1.8	3.5 ± 1.4	2.4385	2.4898	20.7436	41.4682	0.2163	0.0711	0.8801
70.00	0.0 ± 1.5	3.5 ± 1.4	2.4387	2.4897	20.7430	41.4798	0.2163	0.0711	0.8801
90.00	0.0 ± 1.4	3.5 ± 1.4	2.4384	2.4897	20.7425	41.4710	0.2163	0.0711	0.8801
LR	0.1 ± 1.6	3.5 ± 1.4	2.4300	2.4896	20.7463	41.4618	0.2163	0.0711	0.8801

Table 5

Fig. 2

Fig. 3a

Fig. 3b

Fig. 4a

Fig. 5

Fig. 4b