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New bound on right-handed charged gauge boson mass

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Using our previous bounds on $\Delta\rho$ and the Z-Z' mixing angle ξ_N in the $SU(2)_L \otimes SU(2)_R \otimes U(1)_{(B-L)}$ model from the Z line shape and energy-dependent forward-backward asymmetries of the 1990 data from CERN LEP, we obtain a strong lower bound $\simeq 439$ GeV at 90% C.L. on the right-handed charged gauge boson mass for $m_t = 200$ GeV using commonly chosen Higgs triplets, which becomes stronger for doublet Higgs fields. It is independent of the neutrino mass or of assumptions about the right-handed quark mixing matrix. Consequences of more exotic Higgs multiplets are also discussed.

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In spite of the successes of the standard electroweak model (SM), there are appealing reasons to believe that there is new physics beyond it. One such extension stems from the fact that the SM does not *explain* the $(V-A)$ character of the weak interactions; it is put in by hand. The natural solution is to assume left-right (LR) symmetry $[SU(2)_L \otimes SU(2)_R \otimes U(1)_{(B-L)}$ gauge symmetry] at higher energies [1], and the $(V-A)$ nature emerges through a spontaneous breaking of $SU(2)_R \otimes U(1)_{(B-L)} \rightarrow U(1)_Y$. A crucial question is what are the masses of the right-handed (RH) $SU(2)_R$ gauge bosons?

The low energy neutral current data were not very restrictive in this context, particularly since the standard model parameters were not that well known. One could find consistency of low energy (~ 100 GeV) LR symmetry with all neutral current data with the weak mixing angle $\sin^2\theta_W$ as high as 0.29 [2]. These ideas were subsequently tested in the light of much more precise data and stronger constraints, in particular for the neutral current sector, were obtained [3].

The strongest low energy constraint on the mass of the RH charged gauge boson, M_{W_R}, comes from the $K_L - K_S$ mass difference; from the box diagram with both W_L and W_R exchanges a lower bound of 1.6 TeV is obtained [4]. For this one has to assume the so-called manifest LR symmetry; i.e., the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrices of the left- and right-handed sectors (V_L and V_R) are the same. We wish to emphasize that this *symmetry* is rather artificial since a departure from it can be obtained even with the minimal choice of the Higgs fields if one writes the most general Higgs potential. If manifest LR symmetry is not assumed [5,6] the bound on M_{W_R} is relaxed; even with restrictions on fine-tunings, it can be as low as 300 GeV [7]. A stringent bound on M_{W_R} comes from the direct search by the Collider Detector at Fermilab (CDF) Collaboration [8]. Assuming that the new charged gauge bosons decay into leptons and stable neutrinos of negligible mass, events with high p_T electrons and/or muons and large missing energy are looked for. Their lower bound $M_{W_R} > 520$ GeV will, however, not apply in many popular versions of LR symmetry where the W_R couples only to heavy neutrinos which can decay within the detector.

The situation has changed with the precision measurements at the Z pole. The experiments at the CERN e^+e^- collider at LEP are in very good agreement with the SM [9] restricting any new physics beyond it severely. Although the parameter space is squeezed, the data alone cannot put constraints on M_{W_R}. If in addition one wants to embed LR symmetry in a grand unified theory (GUT) model then the present value of $\sin^2\theta_W \simeq 0.234$ does not allow any simple GUT's or partially unified theories to have LR symmetry at energies below 10^{10} GeV [10]. However, since there is no clear evidence in favor of GUT's, the issue of a relatively low RH scale should also be addressed from a purely phenomenological approach using the available data. This is important since these RH gauge bosons form an important item in the menu of new particle searches at the CERN Large Hadron Collider (LHC) and Superconducting Supercollider (SSC).

The current phase of LEP, with a catch of around 550 000 Z events until the end of the 1990 run, has already enriched the information about the neutral current sector on and around the Z pole [11–13]. In one of our previous analyses the cross sections and leptonic asymmetries in the region $\sqrt{s} \approx M_Z$ have been fitted in the LR-symmetric model [11] where additional neutral and charged gauge bosons appear. $\Delta\rho$, the tree level change of the ρ parameter from unity and ξ_N, the Z-Z' mixing angle, were treated as free parameters. The analysis was carried out without appealing to any particular Higgs structure. Here we consider two popular LR-symmetric models with given Higgs representations [14,15] and utilize the information on $\Delta\rho$ and ξ_N to bound the RH mass scale. A lower bound on the heavier W-boson mass follows. Towards the end of the paper we shall comment on more complicated Higgs structures. Lower bounds on the heavier *neutral* gauge boson mass have been considered earlier (see, e.g., [13]) though not from an energy-dependent line-shape analysis.

In the following we briefly describe the steps of our analysis. We require that $\rho \simeq 1$ should result without any fine-tuning or accidental cancellation between the contributions of different Higgs multiplets. This restricts the choice to the multiplets $(\frac{1}{2},\frac{1}{2},0)$, $(\frac{1}{2},\frac{1}{2},\pm 2)$, $(0,I,Y)$ and, because of LR symmetry, $(I,0,Y)$ [16], where (I_L, I_R, Y_I) are the $SU(2)_L$, $SU(2)_R$, and $Y=(B-L)$ quantum numbers, respectively. Since $(I,0,Y_I)$ must contain a neutral component, $|Y_I| \leq 2I$. We assume all vacuum expectation values (VEV's) to be real, keeping aside the possibility of a small *CP* violation. Following the spirit of LR symmetry we set $g_L = g_R = g = e/\sin\theta_W$, where $g_{L(R)}$ is the coupling constant of $SU(2)_{L(R)}$ and $\sin^2\theta_W = s^2 = 1 - c^2$. The $U(1)_{(B-L)}$ gauge coupling constants is $g' = e/y$, where $y = \sqrt{c^2 - s^2}$.

In the neutral gauge boson sector it is convenient to choose the basis (Z, Z', A) in which the photon is decoupled. It can be realized from the weak basis by a standard orthogonal transformation. Z is the gauge boson coupled to $(J_L^3 - s^2 J_{\rm em})$ and in this model is not a mass eigenstate. The gauge boson mass matrices, in the Z-Z' $(W_L$-$W_R)$ basis for the neutral (charged) sector, are

$$M_i^2 = (g_i^2/2) \begin{bmatrix} A_i & B_i \\ B_i & D_i \end{bmatrix} , \tag{1}$$

where $i = N$ or C, $g_N^2 = g_C^2/c^2 = e^2/s^2c^2$, and

$$A_N = K^2 + K'^2 + U^2 + 2V_{LN}^2 , \tag{2}$$

$$B_N = -y(K^2 + K'^2) + U^2/y + \frac{2s^2}{y} V_{LN}^2 , \tag{3}$$

$$D_N = y^2(K^2 + K'^2) + U^2/y^2 + \frac{2s^4}{y^2} V_{LN}^2 + \frac{2c^4}{y^2} V_{RN}^2$$

$$= D_N' + \alpha_N V_{RN}^2 , \tag{4}$$

$$A_C = K^2 + K'^2 + U^2 + V_{LC}^2 , \tag{5}$$

$$B_C = 2KK' , \tag{6}$$

$$D_c = K^2 + K'^2 + U^2 + V_{RC}^2$$

$$= D_C' + \alpha_C V_{RC}^2 . \tag{7}$$

We denote the VEV's of the neutral components of $(\frac{1}{2},\frac{1}{2},0)$, $(\frac{1}{2},\frac{1}{2},\pm 2)$, $(I,0,Y_I)$, and $(0,I,Y_I)$ by (k,k'), $u_\pm$, $v_{(L)IY_I}$, and $v_{(R)IY_I}$, respectively. Then

$$(K^2, K'^2) = \sum_j (k_j^2, k_j'^2); \quad KK' = \sum_j k_j k_j'; \quad U^2 = \sum_j u_{+j}^2 + \sum_j u_{-j}^2 , \tag{8}$$

$$V_{(L,R)N}^2 = 2 \sum_I \sum_{Y_I} \left[\frac{Y_I^2}{4} \right] \sum_j v_{j(L,R)IY_I}^2 , \tag{9}$$

$$V_{(L,R)C}^2 = 2 \sum_I \sum_{Y_I} \left[I(I+1) - \left[\frac{Y_I^2}{4} \right] \right] \sum_j v_{j(L,R)IY_I}^2 , \tag{10}$$

where the subscript j distinguishes Higgs multiplets with the same transformation properties under the gauge group.

The lighter and heavier eigenvalues of the mass matrices are, respectively, given by

$$M_{1i}^2 \approx (g_i^2/2) \left[A_i - \frac{B_i^2}{\alpha_i V_{Ri}^2} \right] , \quad M_{2i}^2 \approx (g_i^2/2) \left[D_i + \frac{B_i^2}{\alpha_i V_{Ri}^2} \right] . \tag{11}$$

Henceforth we shall identify W_1 and Z_1 as the charged and neutral gauge bosons with masses 80.14 and 91.18 GeV, respectively. The mixing angles relating the eigenstates to the gauge bases are given by

$$\tan 2\xi_i = -\frac{2B_i}{\alpha_i V_{Ri}^2} - \frac{2B_i(A_i - D_i')}{\alpha_i^2 V_{Ri}^4} + O\left[\frac{1}{V_{Ri}^6}\right] . \qquad (12)$$

Using the above formulas one finds the two key relations:

$$\tan 2\xi_N = \frac{y^3}{c^4}\frac{A_C}{V_{RN}^2} - \frac{2y}{c^2}\frac{U^2}{V_{RN}^2} , \qquad (13)$$

$$\rho - 1 \equiv \frac{M_{1C}^2}{c^2 M_{1N}^2} - 1$$
$$\simeq \frac{y^4}{2c^4}\frac{A_C}{V_{RN}^2} - \frac{V_{RC}^2 \tan^2 2\xi_C}{4A_C} - \frac{2V_{LN}^2 - V_{LC}^2}{A_C}$$
$$- \frac{2y^2}{c^2}\frac{U^2}{V_{RN}^2} + \frac{2U^4}{V_{RN}^2 A_C} , \qquad (14)$$

where A_C is defined in Eq. (5) and is the dominant contribution to $M_{W_1}^2$ [see Eq. (11)]. Demanding the absence of fine-tuning or accidental cancellation, it is natural to require that each term on the RH side (RHS) of Eqs. (13) and (14) must be bounded from above by the experimental upper limits on $\tan 2\xi_N$ and $|\Delta\rho|$, respectively. It is clear that the constraint on $\Delta\rho$ will limit (V_L^2/A_C) to be very small. We have, therefore, dropped its higher powers and terms $O(V_L^2/V_R^2)$.

We now utilize the values of $\Delta\rho$ and ξ_N obtained in our previous analysis [11]. First, a few words on the description of the fits. The experimental inputs are the energy-dependent leptonic and hadronic cross sections and the leptonic forward-backward asymmetries in the region $\sqrt{s} \approx M_Z$. It has been assumed that the loop effects arise from the standard model and only the tree level modifications due to the presence of an additional neutral gauge boson have been incorporated. The change in ρ is described by $\Delta\rho + \Delta\rho_t$ where $\Delta\rho_t$ originates from the top-mediated oblique corrections. The effective weak angle in the presence of Z-Z' mixing is

$$\sin^2\bar{\bar{\theta}}_W \simeq \sin^2\bar{\theta}_W - \frac{c^2 s^2}{c^2 - s^2}\Delta\rho , \qquad (15)$$

where $\sin^2\bar{\theta}_W$ is the effective weak angle taking into consideration the standard model loop contribution arising from γ-Z mixing at the Z pole. For given values of m_t, m_H, and α_s, $\Delta\rho_t$ and $\sin^2\bar{\theta}_W$ have been evaluated analytically using the program package ZFITTER. The effective vector and axial vector couplings of the physically observed Z boson to the fermions can be parametrized in terms of $\Delta\rho$ and ξ_N. The theoretical predictions of cross sections and asymmetries in terms of these effective couplings are compared to the corresponding precision measurements with $\Delta\rho$ and ξ_N as fitted parameters. For $m_t = 150$ GeV, $m_H = 100$ GeV and $\alpha_s = 0.118$, the fitted values are

$$\Delta\rho = -0.0015 \pm 0.0028, \quad \xi_N = 0.0048 \pm 0.0033 \text{ (rad)} . \qquad (16)$$

We now consider the consequences of the above results for two popular versions of the LR-symmetric model.

(i) Using $(\frac{1}{2},\frac{1}{2},0)$, $(\frac{1}{2},0,1)$, and $(0,\frac{1}{2},1)$ Higgs multiplets [15] (i.e., $V_{(L,R)C}^2 = 2V_{(L,R)N}^2 = 2v_{(L,R)}^2$, $U^2 = 0$, $K^2 + K'^2 = k^2 + k'^2$), we obtain, from the first term on the RHS in Eq. (14),

$$M_{W_2} \geq \frac{y^2 M_{W_1}}{c^2\sqrt{|\Delta\rho|_{\max}}} \geq 713 \text{ GeV} , \qquad (17)$$

where the first inequality above is derived from Eq. (11) dropping small terms proportional to A_C/V_{RC}^2 and B_C^2/V_{RC}^4, while the second inequality follows from the experimental limit. We have used the 90% C.L. upper limit of $|\Delta\rho|$ in extracting the above bound. For this specific choice of Higgs field, only the first two terms in the RHS of Eq. (14) are nonzero. Further, $|\xi_C|$ has been shown to be ≤ 0.0025 even if manifest or pseudomanifest symmetry is not assumed, provided certain *CP*-violating phases are not large [7]. Thus the second term is expected to be very small. Since the first term is positive, we can exploit the negative sign of the central value of $\Delta\rho$ to get the tighter bound $M_{W_2} \geq 1000$ GeV at 90% C.L. Alternatively, choosing $v_L = 0$, which is not an unreasonable approximation [2], and fixing the remaining three VEV's in terms of M_{W_1}, M_{Z_1}, and an input M_{W_2}, $\Delta\rho$ can be determined. Equation (16) then sets a more definitive bound on M_{W_2} of 1012 GeV at 90% C.L. In general, however, there is the possibility of cancellation between different terms on the RHS of Eq. (14) each having the same order of magnitude leading to a sum of the same order and conservatively we have used $|\Delta\rho|$ in extracting the bounds below. Similarly from the fitted value of ξ_N we obtain, at 90% C.L.,

$$M_{W_2} \geq 645 \text{ GeV} . \qquad (18)$$

Note that this bound, though weaker, remains valid even if the one from $\Delta\rho$ is evaded by a fine-tuning of V_L or KK'. Further, this choice of the Higgs fields necessarily leads to light neutrinos and the direct search limit from CDF applies. It is, therefore, gratifying to note that the above constraints are already somewhat stronger and are expected to improve in the future.

(ii) Using $(\frac{1}{2},\frac{1}{2},0)$, $(1,0,2)$, and $(0,1,2)$ representations (i.e., $V_{(L,R)N}^2 = V_{(L,R)C}^2$, $U^2 = 0$, $K^2 + K'^2 = k^2 + k'^2$), one obtains

$$M_{W_2} \geq 504 \text{ GeV from } |\Delta\rho|_{\max} \text{ at 90\% C.L.} , \qquad (19)$$

$$M_{W_2} \geq 456 \text{ GeV from } |\xi_N|_{\max} \text{ at 90\% C.L.} \qquad (20)$$

It should be emphasized that the main motivation for this scenario was to naturally lead to light neutrinos via the seesaw mechanism [17], which in turn implies that the W_2 is coupled to heavy neutrinos and *the CDF limit does not apply.* The power of the precision measurements reveals itself through the above bounds which are already comparable to those from direct searches and are very likely to improve with the accumulation of data and with better control over the systematic errors.

For $m_t=100$ (200) GeV and with the same choice of m_H and α_s as before, the fitted values of $\Delta\rho$ and ξ_N are [11] $\Delta\rho=0.0014(-0.0053)\pm0.0028$ and $\xi_N=0.0043(0.0056)\pm0.0033$ (rad). From $|\Delta\rho|$ one finds $M_{W_2}\geq 508$ (396) GeV while from $|\xi_N|$, $M_{W_2}\geq 468$ (439) GeV for the case of a Higgs triplet. For a Higgs doublet, the bounds are raised by a factor of $\sqrt{2}$.

There is no pressing physical motivation for extending the Higgs sector beyond the above two. Still one may speculatively toy with exotic representations. Since the bound from $|\Delta\rho|$ or ξ_N applies to V_{RN}^2 while V_{RC}^2 determines M_{W_2}, the strengthening or weakening of a bound for a fixed Y depends on the interplay between I and Y via Eqs. (9) and (10). The weakest bound for any Y arises for $I=Y/2$, the minimum I for a neutral field to be present in the multiplet. For example, if parity is predominantly broken by a (0,2,4) multiplet then the bounds become weaker by a factor of 2 than in case (i). $I>2$, with $Y=4$, will yield stronger bounds.

With $(\frac{1}{2},\frac{1}{2},\pm2)$ scalars present, the choice $K^2+K'^2=U^2/y^2$ can eliminate both bounds. But this requires a conspiracy between the gauge coupling constants and the parameters in the Higgs potential which, though allowed in principle, is not very aesthetic. It can also be envisaged that the electroweak symmetry is broken predominantly by the VEV U. In that case the bounds from ξ_N will be strengthened by a factor of $1/y\simeq\sqrt{2}$. It should, however, be borne in mind that fermion masses are generated through the VEV's of the $(\frac{1}{2},\frac{1}{2},0)$ multiplets. Especially in the light of the rather heavy top quark it is unlikely that these VEV's are small.

Crucial tests of a low RH scale and departures from manifest LR symmetry can only come from an analysis of the K_L-K_S mass difference in conjunction with heavy flavor decays [5]. This issue has recently been revived [18]. It has been shown that with M_{W_2} in the vicinity of 300 GeV [7] existing phenomenology can all be explained with a purely RH b-quark coupling. Our strengthening of this lower bound from a new angle, independent of the assumptions usually made [4,8], will put these ideas to closer scrutiny.

In summary, we have exploited for the first time the precision measurements at LEP to set bounds on M_{W_2} in the LR-symmetric model. For the commonly chosen scalar multiplets, these are more stringent than existing ones and are likely to improve as more data accumulate.

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