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Electroweak precision data and right-handed gauge bosons

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Abstract. The implication of recent electroweak precision data for left-right symmetric models is examined. We establish a lower bound on the charged and neutral right-handed gauge bosons independent of the right-handed neutrino mass and of any restrictions or implied symmetries on the right KM matrix.

The establishment of the standard model is one of the major accomplishments in particle physics during the past 30 years. The standard model is mathematically self-consistent and compatible with all known experimental data. But there are questions that cannot be answered satisfactory within the framework of the standard model. For example, which is the origin of CP violation ?, why neutrinos are massless ?

If we belive that the answers to these questions should be given by the model itself rather than having to be put by hand, then we need to seek a more fundamental theory which will reduce to the standard model at present energies. To do so, we construct new theories and models, such as left-right symmetric models [1].

Experimentally, we try also to detect new physical phenomena that might be induced by such underlying new physics. One direct way is to push the center of mass energy higher in experiments, i.e., to built high energy colliders. There is however, a complimentary approach, which is relatively inexpensive and technically feasible. It is based on the observation that the precision of present electroweak experiments will be substantially improved in the next years. If there exist physics beyond the standard model, there might be remnants of that physics at present energies that would cause small deviations of various physical quantities from the standard model values, i.e. precision electroweak measurements test the standard model at the level of its radiative corrections and probe new physics.

This new physics may arise at the tree level, as in the case of an extra Z' bosons or be induced via quantum loop effects, e.g. technicolor scenarios. Whatever the source, we already know that existing experiments allow at most for a few tenth of percent to perhaps a few percent deviations from the standard model. Therefore, cleary discovery of some new physics is unlikely to come simply from improved precision in a single experimental measurement. Instead, one will check various scenarios by global fits to all data. Also, should some new phenomenon be directly observed at high energies, low energy constraints will allow us to sort out its properties.

A nice formalism for studying heavy particle physics effects on gauge bosons self energies was introduced by Peskin and Takeuchi [2], the S, T and U parametrization. In this work we want to review the implementation of that formalism in left-right symmetric models and constrain its parameters by the current experimental limits on the electroweak measurements.

Heavy physics enter in low-energy phenomenology through gauge boson self energies. In the electroweak sector those include vacuum polarization functions $\Pi_{\gamma\gamma}(q^2)$, $\Pi_{\gamma Z}(q^2)$, $\Pi_{ZZ}(q^2)$ and $\Pi_{WW}(q^2)$. Using $\overline{MS}$ sustraction removes heavy particle contributions to the first two by absorbing such effects into the definitions of $\alpha(M_Z)_{\overline{MS}}$ and $\sin\theta_W(M_Z)_{\overline{MS}}$. There are however, residual effects in Π_{ZZ} and Π_{WW} that remain after renormalization and are observable as corrections to the natural relationship [3]

$$\sin^2\theta_W^0 = 1 - \left(\frac{M_W^0}{M_Z^0}\right) \tag{1}$$

These loop effects can be parametrized by tree observables: S_W, S_Z and T defined by [4]

$$\left.\frac{\Pi_{WW}^{new}(M_W^2) - \Pi_{WW}^{new}(0)}{M_W^2}\right|_{\overline{MS}} = \frac{\alpha(M_Z)_{\overline{MS}}}{4\sin^2\theta_W(M_Z)_{\overline{MS}}} S_W = Z_W^{new} - 1 \tag{2}$$

$$\left.\frac{\Pi_{ZZ}^{new}(M_Z^2) - \Pi_{ZZ}^{new}(0)}{M_Z^2}\right|_{\overline{MS}} = \frac{\alpha(M_Z)_{\overline{MS}}}{4\sin^2\theta_W(M_Z)_{\overline{MS}}} S_Z = Z_Z^{new} - 1 \tag{3}$$

$$\frac{\Pi_{WW}^{new}(0)}{M_W^2} - \frac{\Pi_{ZZ}^{new}(0)}{M_Z^2} = \alpha(M_Z)_{\overline{MS}} T = \rho(0)^{new} - 1 \tag{4}$$

where "*new*" means only heavy new particle loops are included, $|_{\overline{MS}}$ means that modified minimal substraction is applied, and $\alpha(M_Z)_{\overline{MS}}$ has been factored out.

In terms of the Peskin-Takeuchi parameters

$$\begin{aligned} S &= S_Z \\ T &= T \\ U &= S_W - S_Z \end{aligned} \tag{5}$$

The T and U correspond to the isospin violating effects, while S is isospin conserving.

It is important to notice that, even without new physics, S, T and U provide a convenient means for approximating deviations from our assumed $m_t = 175$ GeV and $m_H = 300$ GeV values. (However, since the main m_H dependence is only logarithmic, its impact on the bounds we will obtain is very mild)

We will discuss now the determination of S, T and U using the values of weak interaction observables. But lets begin with a general review of the S, T and U parametrization to explain the physics behind the experimental determination of them. In the Peskin-Takeuchi formalism, each observable x depends linearly on S, T and U. Let us write the relation for a general observable as

$$x\,(S,T,U) \;=\; x_{SM}(m_t, m_H) \;+\; a_x\,S \;+\; b_x\,T \;+\; c_x\,U \tag{6}$$

where $x_{SM}(m_t, m_H)$ is the standard model prediction computed at the references value m_t and m_H. In Table 1 we list these formulas for the various observables we will work with. The "nominal" values are calculated for $m_t = 175$ GeV and $m_H = 300$ GeV.

According to (6) a precise experimental determination of x will restrict S, T and U to lie on a surface in the $S-T-U$ space. By intersecting the surfaces correspondings to different observables, we can determine S, T and U. In practice, experimental measurements have associated errors, so that surfaces become volumes in the $S-T-U$ space and we must give a statistical criterion for their overlap.

To make life easier we will assume that the probability distribution which correspond to each measurement is gaussian and we will ignore the correlations between the various measurments believeing that this is a good assumption for the subset of observables we have chosen. Then, the overlap could be quantitatively described by the construction of a likehood function of S, T and U given by

$$\begin{aligned}&\mathcal{L}\,(x_{exp}, S, T, U)\\ &\quad = N \exp\left\{-\frac{1}{2}\sum\left[\frac{x_{exp} - x\,(S,T,U)}{\sigma_x}\right]^2\right\}\end{aligned} \tag{7}$$

where N is a normalization factor such that

$$\int dS\,dT\,dU\;\mathcal{L}\,(x_{exp}, S, T, U) = 1 \tag{8}$$

The point which maximizes $\mathcal{L}\,(x_{exp}, S, T, U)$ is found to be

$$(S, T, U) = (\,-.33,\; -.18,\; -.11) \tag{9}$$

In left-right symmetric models, S, T and U are directly related to each other. This is so, because the departures from the standard model predictions in this type of models can only be caused by the fact that the mass eigenstate observed at LEP, Z_1, is an admixture (through an angle ϕ) of the Z_L (the standard gauge boson) and Z_R (the new one). Once the Z_R couplings are specified, the effects of such a mixing are completely described in terms of two parameters: the mixing angle ϕ and the shift $\delta\rho$ in the ρ parameter (these two parameters are independent unless the Higgs structure of the model is specified). Clearly, Z_L has couplings which are formally identical to the standard model vector boson ones in terms of θ_W, however its relation to the basic input parameters of the theory is not the same as we are going to see later.

For simplicity, we will assume that W_R plays no role in low-energy processes as does not mix with W_L.

As we have stated before, in left-right symmetric models the shifted values of S, T and U can be parametrized in terms of the left right parameters as [14] (actually, they have used the parameters $\epsilon_1 = \alpha T$, $\epsilon_2 = -\frac{\alpha U}{4\overline{s_W}^2}$ and $\epsilon_3 = \frac{\alpha S}{4\overline{s_W}^2}$)

$$\begin{aligned}T &= \frac{1}{\alpha}\left(\delta\rho + 4g'_A \tan\phi\right)\\ S &= \frac{2\tan\phi}{\alpha}\left[\left(1-2\overline{s_W}^2\right)g'_V + \left(1+2\overline{s_W}^2\right)g'_A\right]\\ U &= \frac{4\tan\phi\,\overline{s_W}^2}{\alpha}\left(g'_V - 3g'_A\right)\end{aligned} \tag{10}$$

where $\alpha^{-1} \simeq 128$, $\overline{s_W}^2$ is the effective (on shell) $\sin\theta_W^2$ and g'_V and g'_A are the lepton couplings to the Z_R normalized as in the standard model. They are given by

$$\begin{aligned}g'_V &= \frac{g_V}{\sqrt{\cos 2\theta_W}}\\ g'_A &= \sqrt{\cos 2\theta_W}\,g_A\end{aligned} \tag{11}$$

where we have taken $g_L = g_R$, as dictated by the discrete left-right symmetry, and

$$\begin{aligned}g_V &= T_{3L} - 2\,Q\,\overline{\overline{s_W}}^2\\ g_A &= T_{3L}\end{aligned} \tag{12}$$

where T_{3L} and Q are the weak isospin (third component) and the electric charge of the fermion. The quantity $\overline{\overline{s_W}}^2$ given by the relation

$$\overline{\overline{s_W}}^2 = 1 - \frac{M_W^2}{\rho\,M_{Z_1}^2} \tag{13}$$

is the effective $\sin^2\theta_W$ for the on shell Z_L couplings. Because of the effect of the $\delta\rho$, it differs from the corresponding quantity $\overline{s_W}^2$ in the standard model for fixed input parameters α, G_F, M_Z, m_f and m_H according to the relation

$$\overline{\overline{s_W}}^2 = \overline{s_W}^2 - \frac{\overline{s_W}^2\,\overline{c_W}^2}{\overline{c_W}^2 - \overline{s_W}^2}\,\delta\rho \tag{14}$$

Lets recall the reader that $\delta\rho$ arises because the M_Z, the standard model Z mass in absence of mixing is always larger than the observed mass

$$M_Z^2 = (1+\delta\rho)\,M_{Z_1}^2 \tag{15}$$

Table 1. Here we show the relation between the observable quantities and the S, T and U parameters. These numbers were evaluated with $m_t = 175$ GeV and $m_H = 300$ GeV. The constant terms on the right-hand sides of the third column are the standard model predictions including oblique and direct corrections, and QED and QCD corrections. They are dependent on the values of m_t and m_H while the coefficients of S, T and U are not

quantity	experimental value	theoretical value
M_W	80.26 ± .16 [a)]	80.31 [b)] + .45 T + .34 U - .29 S
Γ_Z	2.4963 ± .0032 [c)]	2.4974 + 2.615 $\cdot 10^{-2}$ T - 9.58 $\cdot 10^{-3}$ S
Γ_{ll^+}	83.94 ± .13 [c)]	83.93 - 1.91 $\cdot 10^{-2}$ S + 7.83 $\cdot 10^{-2}$ T
R	20.788 ± .032 [c)]	20.795 - 5.99 $\cdot 10^{-2}$ S + 4.24 $\cdot 10^{-2}$ T
R_b	.2178 ± .0011 [d)]	.2157 - 4.18 $\cdot 10^{-3}$ S + 8.68 $\cdot 10^{-3}$ T
$\sin^2\theta_{\mathrm{eff}}$	.2325 ± .0013 [e)]	.2320 [f)] + 3.65 $\cdot 10^{-3}$ S - 2.61 $\cdot 10^{-3}$ T
A_{LR}	.1551 ± .0040 [g)]	.1433 - 2.82 $\cdot 10^{-2}$ S + 2 $\cdot 10^{-2}$ T
Q_W(Cs)	-71.04 ± 1.84 [h)]	-72.94 [i)] - .79 S - 5 $\cdot 10^{-3}$ T
Q_W(Tl)	-114.2 ± 3.8 [j)]	-116.8 [k)] - 1.17 S - 6 $\cdot 10^{-2}$ T

[a)] Average of direct measurements and indirect information from neutral/charged current ratio in deep inelastic neutrino scattering [5]
[b)] including perturbative QCD corrections [7]
[c)] LEP averages as for November 1995 [5]
[d)] including ALEPH improved analysis [6]
[e)] from LEP asymmetries [5]
[f)] as calculated in [7]
[g)] from SLD measurement [8]
[h)] weak charge in Cesium [9]
[i)] calculation [4] incorporating atomic physics corrections [10]
[j)] weak charge in Thallium [11]
[k)] calculation [12] incorporating atomic physics corrections [13]

i.e, the lowest energy level is pushed down by the perturbation.

In most models U is much smaller than T and S and can be safely ignored. However, in left-right symmetric models this is not the case. As can be seen from (10), neglecting the small vector couplings, we have

$$\frac{S}{U} \approx \frac{\left(1 + \overline{s_W}^2\right)}{6\,\overline{s_W}^2} \approx -1 \tag{16}$$

i.e, in the context of left-right symmetric model the U parameter cannot be neglected. Even more, it can be taken to be approximately equal to $-S$ and this is precisely what we are going to do in order to simplify the analysis that follows.

Once we have made this simplifying assumption, we have only two parameters that parametrize the deviations from the standard model predictions and just two left-right symmetric parameters to account for them. Then, it is straightforward to constrain the M_{Z_2} and ϕ allowed range by means of the one sigma deviation contour shown in Fig. 1.

To do so, we have to perform the previous fit of experimental data with the theoretical predictions, including its S, T and U dependence but using this time the left-right symmetric constraint $S = -U$. The resulting central points are now

$$(S, T) = (\,-.36,\,-.15) \tag{17}$$

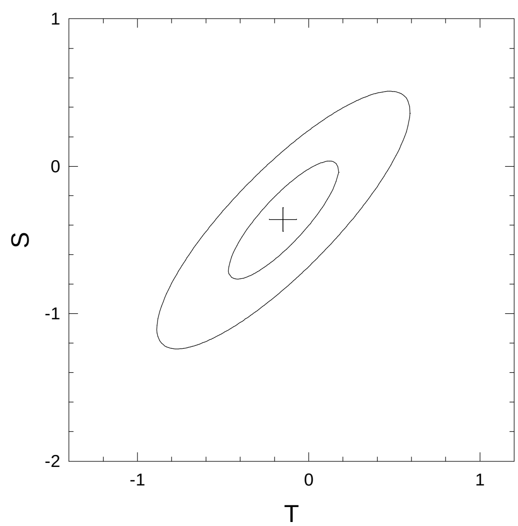

Fig. 1. Allowed ranges of S and T at 68% (*inner ellipse*) and 90% (*outer ellipse*) confidence levels in the left-right symmetric model

Fig. 1 shows this point and the 68% and 90% confidence level contours around it.

As the reader can see, we have gotten esentially the same values as before for S and T. This is not the case for U for which we have imposed $U = -S$, getting then $U = .36$ according to the left-righ symmetric constraint.

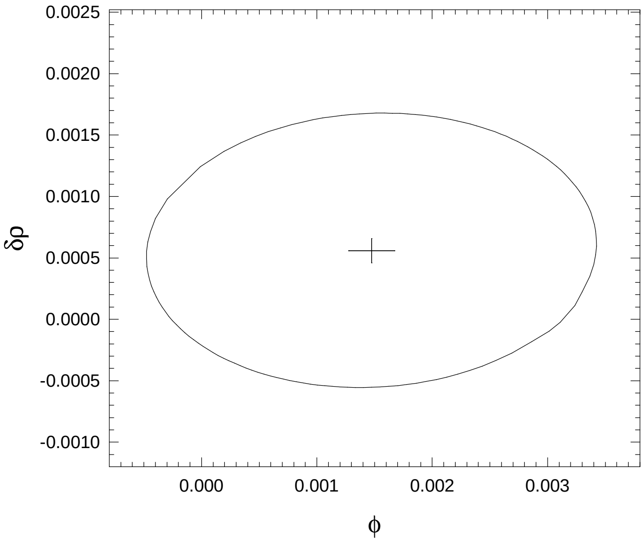

Fig. 2. Allowed ranges of $\delta\rho$ and ϕ corresponding to 68% probability

This is not surprising at all because the unique observable where U enters is M_W, and in this case, the variables S, T and U enter on it on equal footing. But, as S and U coefficients have opposite sign, summing them up M_W is less sensitive to T, so that no dramatic changes could be expected when the left-right symmetric constraint is imposed.

Now, we will try to find out if region exist in the left-right symmetric model's parameters space that allow large, negative S and T, as defined by the leptonic data. The "successful" region of parameter space we find below is meant only to be a *suggestive* as it depend upon the specific values of the input parameters, e.g. m_H, that we employ in this analysis.

The allowed ranges of the mixing angle ϕ and $\delta\rho$ (which is related to the M_{Z_2} permitted space) at the 68% C.L. are shown in Fig. 2. This curve can be easily obtained by inverting (10).

From this one sigma deviation plot we can constrain our ϕ to lie in the range

$$-5.1 \cdot 10^{-4} \;\leq\; \phi \;\leq\; 3.3 \cdot 10^{-3} \tag{18}$$

with a 68% C.L. This limit is in good agreement with theoretical results previously reported [15]. Our result also agrees with experimental estimations of [16], if we take the angle θ_M of that reference as the negative of our ϕ

We can turn our attention now to what we think is the major contribution of this paper, the establishment of a lower bound on the right handed neutral gauge boson mass, M_{Z_2}; and in connection with this bound to settle a lower bound for the mass of the right handed W-boson, M_{W_R}, independent of the right-handed neutrino mass and of any restrictions or implied symmetries on the right Kobayashi-Maskawa (KM) matrix parameters such as manifest ($V_L = V_R$) or pseudomanifest symmetry ($V_L = V_R^*$). Clearly our limits on both M_{Z_2} and M_{W_R} are not always as restrictive as those models which make the above assumptions about the right handed sector, but our work serves to legitimize the hypotesis that the right handed gauge bosons are substantially heavier than their left partners. To our knowledge, no similar limit currently exists.

To get such a bound we have to analize the results depicted in Fig. 2. Only that portion of the graph is meaningful where $\delta\rho \geq 0$, because as we have stated before, the influence or Z_R and the small $Z_L - Z_R$ mixing (through the angle ϕ) has the effect of forming mass eigenstates Z_1 and Z_2 with $M_{Z_1} \leq M_Z$, the standard model Z mass. In such a way that if we use the measured mass (i.e. M_{Z_1}) as an input parameter, the modification of the traditional $W-Z$ mass relation can be parametrized as $\rho = 1 + \delta\rho$ where $\delta\rho$ is always positive and is of order $M_{Z_1}^2/M_{Z_2}^2$. Specifically,

$$\delta\rho = \gamma^2 \frac{M_{Z_1}^2}{M_{Z_2}^2} \tag{19}$$

where

$$\gamma = -\left(1 - \overline{s_W}^2\right)^{\frac{1}{2}} \tag{20}$$

Therefore, we can consider the portion of the graph where $\delta\rho < 0$ to be unacceptable. (It is in order to mention that models allowing a small $W_L - W_R$ mixing can tolerate negative $\delta\rho$ values. But in this case the addition of parameters make the analysis cumbersome and not very enlightening, and as the bounds that can be obtained in this way are almost the same that the ones we have gotten, we are not going to take this possibility into account.)

We find that with 68% C.L.

$$M_{Z_2} \;\geq\; 1.7\,\mathrm{TeV} \tag{21}$$

Right handed gauge bosons in such a range would clearly be beyond the range accesible to the Tevatron and must await discovery at the LHC.

To obtain a limit on M_{W_R}, we have to make use of the well known relation [17]

$$M_{Z_2} \;=\; M_{W_R}\,\frac{\sqrt{y}\;\cos\theta_W}{\sqrt{\cos 2\theta_W}} \tag{22}$$

where $y = 1$ for the case of gauge symmetry breaking to the standard model by a doublet Higgs multiplet (i) and $y = 2$ for the triplet case (ii), which will drive us to the desired bound, yielding

$$M_{W_R} \;\geq\; 1.4\,\mathrm{TeV}\,(i) \quad , \quad 1.1\,\mathrm{TeV}\,(ii) \tag{23}$$

Let us now compare our result to previous ones [18]. To obatin limits on M_{WR} an obvious thing to do is to look for deviations from the predictions from muon decay of the (V-A) theory. However, since right-handed leptonic charged currents involve the right-handed neutrino field, one needs the mass of the right-handed neutrino to carry out the analysis. Assuming that the right-handed neutrinos are light enought to be produced without kinematical suppresion, the most stringent limit at this moment comes from the measurement of the ξ parameter in μ-decay using

100% stopped polarized muons [19] and it is $M_{W_R} \geq 432$ GeV. For values of the right-handed neutrino mass close to or bigger than the mass of the muon, this analysis does not shed light on the strength of the right-handed interactions and one must look at weak processes involving only hadrons.

The most stringent available limits on M_{W_R} then, arise from the $K_L - K_S$ mass diference. As a matter of fact, under the following assumptions:

(a) the left-right symmetry is manifest or pseudomanifest
(b) the hadronic matrix elements are computed in the vacuum saturation approximation.

Beall, Bander and Soni [21] have found that the $K_0 - \overline{K_0}$ mixing strongly constrains the W_R mass, the limit they got is $M_{W_R} \geq 1.7 - 2.5$ TeV depending on the treatement of the short distande QCD corrections [22]. This result was updated in [23] were a bound of $M_{W_R} \geq 1.4$ TeV is obtained. This bounds can be evaded by relaxing the condition (a) above, in this case one is able to get lower limits [24]. In fact lower than the current experimental bound. Another way to lower this bound is to exploit the CP violating phases that might appear in models with spontaneous breakdown of CP [25].

As far as the assumption (b) is concerned, a similar analysis was carried out by evaluating the hadronic matrix elements of the $K_0 - \overline{K_0}$ mixing by three point function QCD sum rules, obtaining $M_{W_R} \geq 700$ GeV [26]. It should be pointed out that all these analysis rely heavily on the KM structure of the model.

We now compare our results with those obtained in the studies [20] and [14]. Langacker and Luo [20] used low energy measurements, LEP measurements and M_W measurements to fit the parameters of the extended models. They found the 95% C.L. bound $\phi = \left(1.8\pm^{6.1}_{6.6}\right) 10^{-3}$ and $M_{Z_2} \geq 857$ GeV in the case of left-right models with $g_L = g_R$. Due to the increased precision of the measurements, the bounds obtained in the present study are considerably tighter.

Altarelli et al. [14] used the LEP measurements and M_W measurements to fit the parameters of the extended models. In the case of left-right symmetric model with $g_L = g_R$ and unespecified scalar sector they found the 1σ ranges $\phi = (.15 \pm 1.58)\, 10^{-3}$ with top mass fixed to m_t =150 GeV. They get a sharper bound for M_{Z_2}, M_{Z_2} $\geq$1.5 TeV for $m_t = 110$ GeV but the price to be paid for it is the imposition of a Higgs structure that obeys the requirement of a mixing ϕ proportional to $(M_{Z_1}/M_{Z_2})^2$.

In conclusion, we have established the results, $-5.1 \cdot 10^{-4} \leq \phi \leq 3.3 \cdot 10^{-3}$, $M_{Z_2} \geq 1.7$ TeV and $M_{W_R} \geq 1.4$ TeV in the doublet case and $M_{W_R} \geq 1.1$ TeV in the triplet case independent of the structure of a particular choice of the KM matrices and of the right-handed neutrino mass.

One way of trying to relax these bounds is by varying λ, the ratio g_L/g_R, which we have taken to be one. However we should keep ourselves in the $.5 \leq \lambda \leq 2$ region, as we expect on general grounds that this ratio should not be too different from unity as suggested by grand unified models and within this region the lower bounds for the right handed gauge bosons that can be obtained are essentially the same as the ones we have gotten (for larger (smaller) values of the ratio g_L/g_R smaller (larger) values of M_{Z_2} are allowed). That is, aside from the very remote possibility of a contrived fine tuning, these limits apply generally to left-right symmetric models.

Experimentally, these results greatly reduce the likelihood of finding M_{Z_2} and M_{W_R} bellow 1.7 and 1.1 TeV respectively, and such a limit will probably keep both out of reach for near future.

Let us conclude with a couple of comments. In the future, individual experiments are expected to reach a better sensitivity for S and T. At that stage, the left-right symmetric model should unveil itself if it is real. In particular, atomic parity violation experiments play a key role in providing information on fundamental parameters in particle physics [27]. Absolute determination of Q_W for one or more atoms to an accuracy of half a percent is a very important goal. This will help to constrain the Peskin-Takeuchi parameter S in a useful manner and could roughly double the present lower limits on extra gauge bosons.

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