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# Implications of a Precise Measurement of the $Z$ Width on the Spontaneous Breaking of Global Symmetries*

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## ABSTRACT

We study global symmetries which are spontaneously broken by Higgs non-singlets. In most cases, there is a significant contribution to the invisible decay width of the $Z$ boson. The recent measurement of this quantity by the MARK II collaboration excludes, in a model independent way, spontaneous breaking due to almost all scalars with hypercharge larger than or equal to 1.

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Scalar particles acquire masses at the highest energy scale which is compatible with the symmetry breaking pattern. It is very likely then that the low energy scalar spectrum consists of a single neutral scalar with properties similar to those of the single Higgs of the minimal Standard Model (SM). If nature is supersymmetric to low enough energies, we may observe five light scalars, with properties similar to those of the scalars in the minimal Supersymmetric SM. If there are light scalars in addition to the above, they are likely to be a signature of symmetries beyond the (SUSY) SM [1].

Spontaneously broken global continuous symmetries imply the existence of massless Goldstone bosons. If the breaking is due to Higgs singlets, then these Goldstone bosons do not interact with any of the known fermions or gauge bosons. If, on the other hand, the breaking is due to Higgs non-singlets, the phenomenological implications are much more exciting: First, there should exist new light scalars, in addition to the Goldstone bosons. Second, the light scalars necessarily couple to the known gauge bosons and may couple to known fermions. Our interest here lies in the case of non-singlets.

The coupling of Higgs non-singlets to gauge bosons depends, of course, on their gauge properties only. If they are light enough, they may affect the widths of the $Z$ and the $W$ bosons. We will argue that this is indeed the case for a large class of such multiplets. Consequently, the recent measurement of the $Z$ width by the MARK II collaboration [2] provides us with a stringent test of this possibility. In this work, we present the results of this test.

We study spontaneously broken global continuous symmetries. For our study we need only the $U(1)$ part of the global symmetry, $U(1)_G$. The symmetry is broken by a non-singlet scalar $\Delta(T, Y, G)$. The relevant quantum numbers are the weak isospin $T$ and hypercharge $Y$. Our normalization is such that the electric charge $Q$ is given by $Q = T_3 + Y$. The only important feature of $G$, the charge under the $U(1)_G$ group, is that $G \neq 0$ so that $\langle | \Delta | \rangle \neq 0$ breaks $U(1)_G$. We note that $G \neq 0$ implies that $\Delta$ is a complex multiplet, even when $Y = 0$.

As $\Delta$ assumes a VEV, it has to have an electrically neutral member (with $T_3 = -Y$). Thus, we are interested only in multiplets with $|Y| \leq T$. We define the components of this neutral field by:

$$\Delta^0 = \sqrt{\frac{1}{2}}(v_G + R_G + iI_G). \tag{1}$$

where the VEV $v_G$ is real. The Goldstone boson is $I_G$:

$$M^2(I_G) = 0. \tag{2}$$

We can use a $U(1)_G$ transformation to rotate from $I_G$ to $R_G$. This implies that in the limit of $U(1)_G$ symmetry the fields $I_G$ and $R_G$ are degenerate. Consequently, $M^2(R_G) - M^2(I_G) = O(v_G^2)$. Together with eq. (2) this gives:

$$M^2(R_G) = O(v_G^2). \tag{3}$$

We conclude that in the case of a global symmetry spontaneously broken by a Higgs non-singlet there are two neutral spin–0 particles (in addition to the SM Higgs): a massless pseudoscalar and a massive scalar whose mass is at the global symmetry breaking scale [3].

How large can $v_G$ be? As $\Delta$ is a non-singlet, $v_G$ cannot be larger than the electroweak breaking scale $v_W$:

$$v_G \lesssim v_W \sim 0.25\ TeV. \tag{4}$$

Much more stringent limits come from the determination of the $\rho$ parameter,

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W}. \tag{5}$$

For an arbitrary number of scalar multiplets, each characterized by its isospin $T_i$

and hypercharge $Y_i$ and carrying a VEV $v_i$, the tree level value of $\rho$ is:

$$\rho_0 = \frac{\sum_i |v_i|^2[T_i(T_i+1) - Y_i^2]}{2\sum_i |v_i|^2 Y_i^2}. \tag{6}$$

If all multiplets with VEVs fulfilled $T(T+1) = 3Y^2$ then $\rho_0 = 1$. This would be the case if we had only Higgs doublets of hypercharge 1/2, as in the minimal SM.

The best determination of $\rho$ comes from low energy experiments: for energies much below $M_W$, the $\rho$ parameter gives the ratio between neutral current and charged current interactions:

$$L_{eff}^{weak} = \frac{G_F}{\sqrt{2}}\left[J_+^\mu J_{-\mu} + \rho J_{NC}^\mu J_{NC\mu}\right]. \tag{7}$$

An overall fit to the data from low energy experiments gives [4]:

$$\rho = 0.998 \pm 0.0086. \tag{8}$$

The value of the $\rho$ parameter is shifted from its tree level value of eq. (6) by radiative corrections. The most important correction comes from the top quark contribution:

$$\rho = \rho_0 + \frac{3\alpha}{16\pi\sin^2\theta_W}\left(\frac{m_t}{M_W}\right)^2. \tag{9}$$

As the top quark contribution always adds to $\rho_0$, eq. (8) gives the following 95% confidence level upper bound on $\delta\rho_0 \equiv \rho_0 - 1$:

$$\delta\rho_0 \leq 0.01. \tag{10}$$

If we assume that the top quark is lighter than 200 $GeV$, as found in ref. [4] and supported by recent measurements of the gauge boson masses, eqs. (8) and (9) give the following 95% confidence level lower bound on $\delta\rho_0$:

$$\delta\rho_0 \geq -0.03. \tag{11}$$

We now assume that the main contribution to the gauge boson masses comes from the VEV of a doublet, $v_W \approx 246\ GeV$. In particular, we assume that $\delta\rho_0 \approx 0$ is not a result of cancellations among various contributions, such as in the model of ref. [5]. The correction to $\rho_0 = 1$ due to the VEV of an additional multiplet is then

$$\delta\rho_0 = \frac{1 + 2(v_i/v_W)^2[T_i(T_i+1) - Y_i^2]}{1 + 4(v_i/v_W)^2[Y_i^2]} - 1 \approx 2\left(\frac{v_i}{v_W}\right)^2 \left[T_i(T_i+1) - 3Y_i^2\right]. \tag{12}$$

There are three possible cases:

(*i*) $3Y_i^2 = T_i(T_i+1)$: These multiplets give $\delta\rho_0 = 0$. There is no constraint on $v_i$ from the $\rho$ measurement [6].

(*ii*) $3Y_i^2 < T_i(T_i+1)$: These multiplets give $\delta\rho_0 > 0$ and we require $\delta\rho_0 \leq 0.01$. We give two specific examples: For non-doublets of hypercharge $\pm 1/2$ carrying a VEV $v_{1/2}$:

$$\delta\rho_0 \geq 6\left(\frac{v_{1/2}^2}{v_W^2}\right) \Longrightarrow \left(\frac{v_{1/2}^2}{v_W^2}\right) \leq \frac{1}{600}; \tag{13}$$

For multiplets of hypercharge 0 carrying a VEV $v_0$:

$$\delta\rho_0 \geq 4\left(\frac{v_0^2}{v_W^2}\right) \Longrightarrow \left(\frac{v_0^2}{v_W^2}\right) \leq \frac{1}{400}. \tag{14}$$

(*iii*) $3Y_i^2 > T_i(T_i+1)$: These multiplets give $\delta\rho_0 < 0$ and we require $|\delta\rho_0| \leq 0.03$. For example, for triplets of hypercharge $\pm 1$ carrying a VEV $v_1$:

$$|\delta\rho_0| = 2\left(\frac{v_1^2}{v_W^2}\right) \Longrightarrow \left(\frac{v_1^2}{v_W^2}\right) \leq \frac{1}{70}. \tag{15}$$

As $T$ and $Y$ are either both integers or both half-integers, the combination $2[T(T+1) - 3Y^2]$ is an even integer. Whenever different from zero, the absolute value of this combination is larger than or equal to 2. We conclude that the bound in eq. (15) is the weakest for all multiplets other than those of group ($i$).

The conclusion is that, for any global symmetry which is spontaneously broken by a Higgs non-singlet with $3Y^2 \neq T(T+1)$, the scale of symmetry breaking has to satisfy

$$v_G^2 \leq v_W^2/70. \tag{16}$$

From eq. (3) we conclude that for these multiplets:

$$M^2(R_G) \lesssim M_Z^2/10. \tag{17}$$

The pseudoscalar $I_G$ and the scalar $R_G$ couple to the $Z$ boson. For any multiplet $\Delta(T,Y,G)$, this coupling depends on the hypercharge $Y$ only. If the scalar $R_G$ is lighter than the $Z$ boson, we have the following contribution to the $Z$ width:

$$\Gamma(Z \to I_G R_G) = \frac{G_F M_Z^3}{6\sqrt{2}\pi}\left[1 - \frac{M^2(R_G)}{M_Z^2}\right]^3 Y^2. \tag{18}$$

In the limit where $M^2(R_G)/M_Z^2$ is small:

$$\Gamma(Z \to I_G R_G) = 2Y^2\Gamma_\nu, \tag{19}$$

where $\Gamma_\nu$ is the contribution of one generation of neutrinos to the $Z$ width. We have just shown that, for any multiplet with $3Y^2 \neq T(T+1)$, this limiting case is indeed relevant (see eq. (17)). As multiplets with $(T,Y) \neq (1/2,1/2)$ do not couple directly to any of the known charged fermions (a $(1,1)$ multiplet may couple to neutrinos), the dominant decay mode for the scalar is $R_G \to I_G I_G$. Thus, the above contribution is to the *invisible* width of the $Z$.

The result in eq. (18) is in agreement with previous results for specific multiplets, with $(T,Y) = (1,1)$ [7,8], (1/2,1/2) [9] and (1,0) [10]. For these specific models (except for the $Y = 0$ case), astrophysical considerations imply that $M(R_G)$ is well below the $MeV$ scale. Thus, the phase space factor is put to 1. Moreover, as in these models $M(R_G) \ll 2m_e$, $R_G$ cannot decay into charged fermions. In our model-independent analysis, $M(R_G)$ could be at the $GeV$ scale. Thus, we have to take into account the phase space factor. Moreover, $R_G \to I_G f\bar{f}$ is allowed for any fermion with $m_f \leq M(R_G)/2$. However, this $Z$–mediated decay is suppressed by a factor of order $(v_G^4/v_W^4)$ relative to the invisible $R_G \to I_G I_G$ mode.

Recently, the MARK II collaboration gave the following 95% confidence level upper bound on the invisible $Z$ width [2]:

$$\Gamma_{inv} \leq 3.9\Gamma_\nu. \tag{20}$$

This puts the following limit on any contributions beyond the three neutrino generations of the SM:

$$\Gamma_{inv}^{NP} \leq 0.9\Gamma_\nu, \tag{21}$$

where NP stands for New Physics. From eq. (19), this excludes contributions from any scalar multiplet with $Y \geq 1$ (unless it belongs to group $(i)$). This is so even for $M^2(R_G)$ close to the limit of eq. (17). *The existence of global symmetries which are spontaneously broken by Higgs multiplets with $Y \geq 1$, $Y \neq T(T+1)/3$, is excluded.* The triplet Majoron model [11, 7] belongs to this class of models and is, therefore, excluded.

Multiplets with $Y = 1/2$ contribute only $\Gamma_\nu/2$ to the $Z$ width. Neutral scalars from doublets may be heavier than the gauge bosons, though in some *specific* models, such as the doublet Majoron model [12], they are much lighter. For non-doublets, the mass of the neutral scalar is $\lesssim 10\ GeV$ (see eq. (13)). Thus, they will be excluded or observed when the $Z$ width is measured to the required accuracy, which is within reach of forthcoming experiments.

Neutral scalars with $Y = 0$ do not couple to the $Z$ boson. Their mass is $\lesssim 12\ GeV$ (see eq. (14)), and we may learn of their existence soon if the charged scalars in the multiplet are light enough:

$$\begin{aligned}\Gamma(Z^0 \to \Delta^+\Delta^-) =& \frac{G_F \cos^2\theta_W M_Z^3}{6\sqrt{2}\pi}\left[1-\frac{4M^2(\Delta^\pm)}{M_Z^2}\right]^{3/2}\\ \Gamma(W^+ \to \Delta^+ R_G) =& \Gamma(W^+ \to \Delta^+ I_G) = \frac{G_F M_W^3 T(T+1)}{24\sqrt{2}\pi}\left[1-\frac{M^2(\Delta^\pm)}{M_W^2}\right]^3 .\end{aligned} \tag{22}$$

Here $\Delta$ is a multiplet of hypercharge zero and we neglected the neutral scalar mass. However, we cannot *exclude* such multiplets on the basis of not observing them in $Z$ or $W$ decays: charged scalars in the multiplet of a Goldstone boson may have their masses at the electroweak breaking scale. A specific example of such a model is the hyperchargeless triplet Majoron model [10].

We emphasize two important points:

First, our analysis is *model independent.* In particular, we have not specified the fermionic couplings of the scalars involved; we have not used any astrophysical constraints. The only assumptions that we make are very mild: that the $Z$ boson is dominantly the gauge boson of the $SU(2)_L \otimes U(1)_Y$ group; that the electroweak gauge bosons acquire their masses dominantly from the VEV of doublets; that a perturbative analysis holds.

Second, the significance of the measurement of the invisible width of the $Z$ resonance lies not only in the improved accuracy over previous results from single-photon production in $e^+e^-$ annihilation. While a scalar at the bound of eq. (17) is light enough to be considered practically massless in the new MARK II measurements, its production would be significantly suppressed in experiments at $\sqrt{s} = 29\ GeV$ [13] or 35–43 $GeV$ [14].

To conclude: in reasonable theoretical frameworks, light scalars (additional to those of the minimal SM or the minimal SUSY SM) are associated with spontaneously broken global symmetries. We are interested in scalar non-singlets. For the *neutral* members of these multiplets, we find the following:

*a*. There may be light scalars ($M \lesssim v_W$) originating from multiplets with $3Y^2 = T(T+1)$, *e.g.* additional scalar doublets, or from various multiplets that combine to give $\rho_0 = 1$. Measurements of $Z$ decays may find them or give lower bounds on their masses.

*b*. There may be *very light* scalars ($M \lesssim 12\ GeV$) with $Y = 0$. They do not couple to the $Z$ boson.

*c*. There may be *very light* scalars ($M \lesssim 10\ GeV$) with $|Y| = 1/2$ (non-doublets). They can be excluded or observed with more accurate measurements of the $Z$ width.

*d*. *There are no light scalars with* $|Y| \geq 1$ *(except for those specified in item a.). Their existence is excluded by the recent measurement of the* $Z$ *width.*

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