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Higgs bosons in a left-right–symmetric gauge model

J. A. Grifols*
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
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In the framework of an $SU(2)_L \times SU(2)_R \times U(1)$ gauge model we construct a Higgs sector where some of the scalars have large couplings to the fermions. We discuss the limits on the strength of the couplings imposed by weak-interaction phenomenology. Rough estimates for the decay rates of vector mesons into Higgs particles are given.

In a recent publication Wilczek[1] suggested that an experimentally detectable source of Higgs-particle production and probably the only one, at least in the energy range of the next accelerator facilities, might be through the decay of heavy vector mesons produced in e^+e^- colliding beams. In particular, he estimates for the branching ratio,

$$\frac{\Gamma(\Upsilon(9.5)\to h\gamma)}{\Gamma(\Upsilon(9.5)\to \mu\mu)} \approx 0.007\left(1-\frac{m_h^2}{m_\Upsilon^2}\right)^{1/2}, \qquad (1)$$

which is not a completely hopeless number for future electron-positron machines.

In the same paper, the author points out that Eq. (1) must be regarded as a lower bound since, as he notes, the gauge bosons may acquire the bulk of their mass through Higgs bosons which do not couple to fermions to lowest order and therefore their vacuum expectation values (VEV) are not bound to be of the typical order of magnitude ~300 GeV, thus rendering larger couplings to the fermions.

Given both their theoretical importance for gauge theories and their experimental elusiveness,[2] it seems interesting to explore any possible situation where the Higgs-scalar production signals might be enhanced and to estimate how large an effect one could expect. In the present work we investigate a concrete realization of the above idea and in particular we discuss the rise in ratio (1) that we might hope for.

The recent results of experiments on atomic parity violation,[3] if true, indicate that the original Weinberg-Salam-GIM[4] model has to be abandoned, or at least, extended. This has to be done in a direction that maintains the successes of the model and corrects for its failures. An attractive and elegant solution to this dilemma has recently emerged. It is based on the left-right–symmetric weak gauge group $SU(2)_L\times SU(2)_R\times U(1)$ where the two intermediate neutral bosons $Z_V(Z_A)$ turn out to be pure vector (axial-vector) objects and therefore cure the problems of the standard model. From the many versions of the model,[5] we consider the one studied by Mohapatra and Sidhu.[6] All left- (right-) handed fermions belong to $SU(2)_{L(R)}$ doublets and $SU(2)_{R(L)}$ singlets. The Higgs structure that breaks the symmetry down to electromagnetism is[7,8]

$$\phi(\tfrac{1}{2},\tfrac{1}{2},0),\quad \chi_L(\tfrac{1}{2},0,1),\quad \chi_R(0,\tfrac{1}{2},1),\quad \delta_L(1,0,0)$$

and

$$\delta_R(0,1,0),$$

with VEV

$$\langle\phi\rangle=\begin{pmatrix}k & 0\\ 0 & k'\end{pmatrix},\quad \langle\chi_L\rangle=\langle\chi_R\rangle=\begin{pmatrix}0\\ a\end{pmatrix},\quad \langle\delta_L\rangle=0$$

and

$$\langle\delta_R\rangle=\begin{pmatrix}0\\ b\\ 0\end{pmatrix}. \qquad (2)$$

The latter Higgs field is needed to split the $W_L^\pm$, $W_R^\pm$ masses in order that no phenomenologically unwanted right-handed currents result.

From the representation content of the model we see that fermion masses arise from Yukawa couplings to the ϕ scalars only and therefore by choosing its VEV to be small compared to the VEV of the remaining Higgs bosons one reaches the situation claimed by Wilzcek where $m_f \sim f_\phi\langle\phi\rangle$, and f_ϕ is substantially larger than is usually the case.[9] Since we are interested in exploiting this circumstance to the fullest, we shall in what follows make whatever assumption or ansatz is necessary to obtain a sizable effect (or even to make it possible at all) tolerable both by theory and experiment. From now on we restrict our discussion to the $\phi(\frac{1}{2},\frac{1}{2},0)$ Higgs sector of the model. We also limit our considerations to the quark sector.

As is well known, a major difficulty of left-right–symmetric gauge theories is that the Higgs couplings cannot be made naturally flavor-diagonal.[10] To avoid conflict with low-energy phenomenology at the tree graph level one adopts the prescription of making the Higgs bosons very heavy. This is obviously not going to help us since we want on one hand larger couplings and on the other we require the Higgs bosons to be relatively light ($m_h \gtrsim 4-5$ GeV) to have a chance of detecting them in the next generation of colliding-beam machines (PEP, PETRA).

Although one single Higgs scalar would render interactions flavor-diagonal, the resulting model is phenomenologically unacceptable. In fact, in this case the quark mass matrix is simultaneously diagonal with the Higgs couplings matrix, but since the same matrix transformation diagonalizes up $(u, c, t, \dots)$ and down $(d, s, b, \dots)$ quarks, the Cabibbo angle turns out to be zero (or very small) which is evidently false. In general, one needs more than one Higgs boson to generate fermion masses.

Since more than one Higgs boson is necessary anyway, we ask ourselves if a subset of the Higgs sector can be made flavor diagonal. To this end we decompose the mass matrix of each charge sector in two pieces,

$$M = A + B$$
$$M' = A' + B' . \tag{3}$$

M refers to the $\frac{2}{3}e$-charge quark mass matrix and M' to the $-\frac{1}{3}e$-charge quark mass matrix. A (A') is associated to a single Higgs boson whose couplings are to be made flavor-diagonal. $B(B')$ is associated to the remaining scalars.

In the particular case where B (B') arises also from one single Higgs scalar, we run into the problem stated above. Namely, in this case $A \propto A'$ and $B \propto B'$, and therefore up and down quarks are diagonalized by the same biunitary transformation and consequently the resulting Cabibbo angle is unacceptable.

If B (B') is associated to more than one Higgs boson we meet again the same difficulty, since whatever transformation diagonalizes A(and M, of course) in the up mass sector, it also diagonalizes the proportional matrix A' of the down sector *unless* A (A') is proportional to the identity matrix and left and right transformation matrices are equal (i.e., manifest left-right symmetry).[11] In this case we have;

$$U^{-1}MU = \lambda I + U^{-1}BU ,$$
$$U'^{-1}M'U' = \lambda' I + U'^{-1}B'U' , \tag{4}$$

where $U \neq U'$ and we obtain independent up and down mass matrices and mixing angles. Obviously, this can be generalized to several Higgs with coupling matrices proportional to I.

From the preceding analysis we see that it is possible to have a flavor-diagonal subset of Higgs couplings provided they couple in the Yukawa potential proportionally to the identity matrix. Note that this condition cannot be imposed to the whole Higgs sector since in that case one would obtain degenerate masses $m_u = m_c = m_t = \dots$ and $m_d = m_s = m_b = \dots$. Also, the mimimal number of $(\frac{1}{2}, \frac{1}{2}, 0)$ scalars that are required is three, ϕ, ρ, and ω, where ϕ fulfills the before mentioned condition.

To make such a Higgs structure at least plausible let us construct, for the purpose of illustration, a specific example in the simple four-flavor model. Discrete symmetries have been used lately to obtain relations between masses and mixing angles.[12] Here we define the symmetry K:

$$\psi_{1L} \to \psi_{1R}, \quad \psi_{2L} \to i\psi_{2R}$$
$$\psi_{1R} \to \psi_{1L}, \quad \psi_{2R} \to i\psi_{2L}$$
$$\phi, \tilde{\phi} \to \tilde{\phi}^\dagger, \phi^\dagger, \quad \omega \to i\tilde{\omega}^\dagger$$
$$\rho, \tilde{\rho} \to \rho^\dagger, \tilde{\rho}^\dagger, \quad \tilde{\omega} \to -i\omega^\dagger$$

where

$$\psi_{1,2} \equiv \begin{pmatrix} u, c \\ d, s \end{pmatrix}$$

and

$$(\tilde{\phi}, \tilde{\rho}, \tilde{\omega}) \equiv \tau_2(\phi^*, \rho^*, \omega^*)\tau_2 .$$

The VEV of the additional fields ρ and ω are

$$\langle\rho\rangle = \begin{pmatrix} r & o \\ o & r' \end{pmatrix} \text{ and } \langle\omega\rangle = \begin{pmatrix} w & o \\ o & w \end{pmatrix} \text{ (Ref. 13)}. \tag{6}$$

The most general Yukawa Lagrangian invariant under K is

$$\begin{aligned}\mathcal{L}_Y = {} & \alpha_1(\bar{\psi}_{1L}\phi\psi_{1R} + \bar{\psi}_{1L}\tilde{\phi}\psi_{1R}) + \alpha_2(\bar{\psi}_{2L}\phi\psi_{2R} + \bar{\psi}_{2L}\tilde{\phi}\psi_{2R}) \\ & + \beta_1\bar{\psi}_{1L}\rho\psi_{1R} + \tilde{\beta}_1\bar{\psi}_{1L}\tilde{\rho}\psi_{1R} + \beta_2\bar{\psi}_{2L}\rho\psi_{2R} + \tilde{\beta}_2\bar{\psi}_{2L}\tilde{\rho}\psi_{2R} \\ & + \gamma(\bar{\psi}_{2L}\omega\psi_{1R} + \bar{\psi}_{1L}\tilde{\omega}\psi_{2R}) + \text{H.c.} ,\end{aligned} \tag{7}$$

which is also invariant under the left-right symmetry

$$\begin{aligned}& \psi_{iL} \leftrightarrow \psi_{iR}, \\ & \phi, \tilde{\phi} \leftrightarrow \phi^\dagger, \tilde{\phi}^\dagger, \\ & \rho, \tilde{\rho} \leftrightarrow \rho^\dagger, \tilde{\rho}^\dagger, \\ & \omega \leftrightarrow \tilde{\omega}^\dagger, \\ & i = 1, 2 .\end{aligned} \tag{8}$$

Incidently, since we require left and right unitary transformations to be equal, we cannot implement CP violation at the tree level in this four-quark model.[14] In models with more than four quarks, however, one can have CP violation through the phases appearing in the weak matrix (in the six-flavor model, the Kobayashi and Maskawa phase).[15] Here, for simplicity, we take all VEV and couplings to be real and ignore the problems connected with CP violation.

In Eq. (7) we must make the "unnatural" assumption that $\alpha_1 = \alpha_2$. This must be regarded as an accident of the model. After spontaneous symmetry breakdown a mass matrix of the type

$$M=\begin{pmatrix} x+z_1 & y \\ y & x+z_2 \end{pmatrix} \qquad (9)$$

emerges, where in general $z_1 \neq z_2$ since in general $\beta_1 \neq \beta_2$. An analogous form obtains for the down matrix M' with $x'=x$, $z'_{1,2} \neq z_{1,2}$, and $y'=y$.

Diagonalization of these matrices gives the following approximate relation between the angles θ and θ' (θ' is the actual Cabibbo angle that mixes d and s quarks) and the quark masses

$$\frac{\tan 2\theta}{\tan 2\theta'} \approx \frac{m_s}{m_c}. \qquad (10)$$

This formula, of course, does not determine the Cabibbo angle but rather must be regarded as a relation which is certainly consistent with experiment.

We have therefore divided the $(\frac{1}{2}, \frac{1}{2}, 0)$ Higgs sector into two subsets. In one subset we have Higgs bosons (ϕ) with large flavor-diagonal couplings and relatively small masses, i.e., $m_q < m_h \lesssim M_{W_L}$, and in the other subset we have Higgs scalars (ρ and ω) with small flavor-nondiagonal couplings and very large masses ($m_h \gg M_{W_L}$).[16] Here we are only concerned with the first set.

Next we address the problem of setting an upper limit to the relevant Higgs couplings. This is attained if one considers higher-order strangeness-changing neutral processes. The most stringent limit is imposed by $\Delta S = 2$ processes; i.e., the $K_S - K_L$ mass difference. Since the ϕ-Higgs couplings to the different quarks are all equal, we realize that the GIM mechanism is operative in the box diagrams of Fig. 1. The computation of these amplitudes gives an additional contribution to the mass-difference estimate of Ref. 17. We obtain

$$\frac{\Delta m_K}{m_K} \approx \frac{G_F}{\sqrt{2}} f_K{}^2 \frac{\alpha}{4\pi} \frac{\cos^2\theta_C \sin^2\theta_C}{\sin^2\theta_W} \left(\frac{m_c{}^2}{M_{W_L}{}^2} + \epsilon\right), \qquad (11)$$

where

$$\epsilon = \begin{cases} \dfrac{m_c{}^2}{m_h{}^2}\left(\dfrac{f}{g}\right)^2\left(2\ln\dfrac{m_h{}^2}{m_c{}^2} - 3\right) & \text{for } m_c{}^2 < m_h{}^2 \ll M_{W_L}{}^2, \qquad (12a) \\[2ex] \dfrac{m_c{}^2}{M_{W_L}{}^2}\left(\dfrac{f}{g}\right)^2\left(2\ln\dfrac{M_{W_L}{}^2}{m_c{}^2} - 5\right) & \text{for } m_h{}^2 \approx M_{W_L}{}^2, \qquad (12b) \end{cases}$$

and f and g are the Higgs and weak couplings, respectively. The first term in Eq. (11) is the contribution from double W_L exchange. We neglected the contribution of quarks heavier than the charmed quark c. This is justified if we assume very tiny

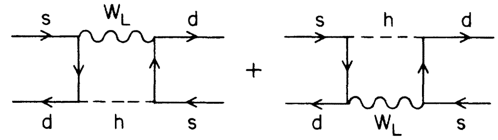

FIG. 1. Diagrams contributing to the K_S^0-K_L^0 mass difference.

mixing angles to the heavy quarks, which we do since we are interested in the maximal allowed Higgs effects. For masses m_h lying between the two limits given above, the corresponding ϵ lies between the two given values.

Even assuming the correctness of this simple quark-model estimate, we certainly can allow for any uncertainty in the value of the charmed quark mass, $m_c \sim 1.5$–2 GeV, which means that the second term in Eq. (11) could be as large as the first one. For the case with the lowest Higgs masses, Eq. (12a), this means that their couplings f could be of the order $g\, m_h/M_{W_L}$. For the process $\Upsilon(9.5) \to h\gamma$, in particular, one might expect a factor $(m_h/m_b)^2$ increase in the rate. On the other mass end, Eq. (12b), the coupling f could reach the value $f \sim 0.3g$. In that case, the estimate of Eq. (1) gets augmented by a rough factor of 20 provided, of course, that the mass of the neutral scalar is much smaller than the mass of the charged scalars. The decay of heavier vector mesons will not improve this figure except for the fact that one reaches more favorable kinematics.

To conclude, let us briefly summarize our results. Our motivation has been to study a model, no matter how exotic, where the couplings of Higgs bosons to fermions were enhanced. For that purpose we investigated a "realistic" model based on the $SU(2)_L \times SU(2)_R \times U(1)$ weak group. We saw that a phenomenologically acceptable $(\frac{1}{2}, \frac{1}{2}, 0)$ Higgs sector consists of three multiplets ϕ, ρ, and ω, where ϕ has large flavor-diagonal couplings and relatively small masses, and ρ and ω have small couplings and very large masses. Depending on the actual value of the charged-Higgs-boson mass the couplings of ϕ to quarks could range from $\sim g(M_h/M_{W_L})$ (for $m_h{}^2 \ll M_{W_L}{}^2$) to about 30% of g for $m_h \approx M_{W_L}$, without conflicting with low-energy weak interactions. In particular, the rate for the process in formula (1) is at most increased by a factor $(m_h/m_b)^2$ for the low-Higgs-boson-mass case and by a factor of about 20 in the other mass limit.

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*On leave from and present address: Departamento de Fisica Teorica, Universidad Autonoma de Barcelona, Bellaterra, Spain.

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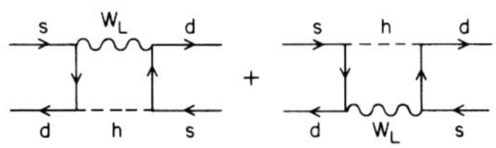

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