Physics Letters B 786 (2018) 268–271

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Models with higher weak-isospin Higgs multiplets

Cheng-Wei Chiang [a,b,c], Kei Yagyu [d,*]

[a] Department of Physics, National Taiwan University, Taipei, 10617, Taiwan, ROC
[b] Institute of Physics, Academia Sinica, Taipei, 11529, Taiwan, ROC
[c] Kavli IPMU, University of Tokyo, Kashiwa, 277-8583, Japan
[d] Seikei University, Musashino, Tokyo 180-8633, Japan

ARTICLE INFO

Article history:
Received 13 September 2018
Accepted 25 September 2018
Available online 28 September 2018
Editor: J. Hisano

ABSTRACT

In order for scale factors κ_V $(V = W, Z)$ of the 125-GeV Higgs boson couplings to have the possibilities of being greater than unity and $\kappa_W \neq \kappa_Z$ while keeping the electroweak ρ parameter unity at tree level, the Higgs sector must be extended with at least two exotic $SU(2)_L$ multiplets in addition to the doublet Higgs field in the Standard Model. By the requirements of perturbative unitarity, no Landau pole in gauge couplings, and no accidental global $U(1)$ symmetry, we exhaust all the possible combinations of two exotic Higgs fields and derive general formulas for κ_V. We find that the current central values $\kappa_W = 1.12$ and $\kappa_Z = 0.99$ reported by CMS can be accommodated in the model with a complex and a real Higgs triplets as the simplest example.

1. Introduction

In the pursue of models with an extended Higgs sector, an important empirical constraint is the electroweak ρ parameter. Its experimental value has been known to be quite close to unity, *i.e.*, 1.00039 ± 0.00019 [1]. This fact suggests that the extended Higgs sector should naturally be constructed so as to have $\rho = 1$ at tree level.

In addition to the ρ parameter, measurements of 125-GeV Higgs boson (h) couplings to a pair of Standard Model (SM) particles X are important to further narrow down the structure of the Higgs sector. To discuss the compatibility, the scale factor κ_X defined as the hXX coupling normalized to its SM prediction is often introduced. If deviations in the h couplings, *i.e.*, $\kappa_X \neq 1$ are established in future experiments, they will be indirect evidence of physics beyond the SM, particularly the existence of an extended Higgs sector.

Currently, measured values of κ_W and κ_Z at the CERN Large Hadron Collider (LHC) are summarized in Table 1. It is interesting to note that the central values are "non-standard," suggesting that not only could they be greater than unity, there is also a possibility that they differ from each other by $\sim 10\%$ according to the CMS result. Even though these possibilities are far from conclusive due to the large uncertainties on both quantities at the moment, it is anticipated that the errors will reduce to 2−4% at the high-luminosity LHC [2] or even down to the sub-percent level at the International Linear Collider [3]. Moreover, recently a new method has been proposed to determine κ_W/κ_Z, including its sign, at lepton colliders [4]. Therefore, differences between κ_W and κ_Z and/or from unity at $\mathcal{O}(10\%)$ level can become significant then. If such non-standard κ_W and κ_Z are established in the future experiments, a natural question is what kind of models features such properties.

Table 1
Best-fit values and $\pm 1\sigma$ uncertainties of κ_W and κ_Z reported by ATLAS and CMS Collaborations [5,6] using 13-TeV collision data and with 79.8 fb^{-1} and 35.9 fb^{-1} integrated luminosities, respectively. Numbers shown here are based on the assumption of no beyond the SM decay channels for h. The last column gives the weighted averages of the two quantities, where the errors have been symmetrized.

Parameter	ATLAS	CMS	Average
κ_W	1.07 ± 0.10	$1.12^{+0.13}_{-0.19}$	1.08 ± 0.08
κ_Z	1.07 ± 0.10	0.99 ± 0.11	1.03 ± 0.07

It has been known that $\kappa_V > 1$ $(V = W, Z)$ cannot be realized in a Higgs sector constructed with only isospin doublets and/or singlets, but is possible in models having triplets or higher multiplets [7,8]. The Georgi–Machacek (GM) model [9] constructed by adding additional real and complex triplet fields is known as one

* Corresponding author at: Seikei University, Musashino, Tokyo 180-8633, Japan.
E-mail addresses: chengwei@phys.ntu.edu.tw (C.-W. Chiang), yagyu@st.seikei.ac.jp (K. Yagyu).

https://doi.org/10.1016/j.physletb.2018.09.050

of the simplest realizations to allow $\kappa_V > 1$ with $\rho = 1$ at tree level. However, if we impose the custodial symmetry in the Higgs potential, $\kappa_W = \kappa_Z$ is also predicted at tree level. Interestingly, requiring $\rho = 1$ at tree level does not necessarily result in $\kappa_W = \kappa_Z$ and a sizable difference between κ_W and κ_Z can be accommodated in the case without the custodial symmetry. In this Letter, we would like to clarify models with an extended Higgs sector that has $\rho = 1$ and κ_V possibly greater than 1 as well as $\kappa_W \neq \kappa_Z$ at tree level.

2. Scenarios

Let us consider a renormalizable extended Higgs sector composed of a Higgs doublet Φ as in the SM and N extra Higgs multiplets X_a $(a = 1, \cdots, N)$ whose $SU(2)_L$ and $U(1)_Y$ quantum numbers are (T_a, Y_a). The electric charge of a particular component field in X_a is given by $Q_a = T_a^3 + Y_a$ with T_a^3 denoting the third component of weak isospin. In order for each of X_a to participate in electroweak symmetry breaking, it must have a neutral component and, therefore, Y_a must be an integer (half integer) for integer (half integer) T_a. The vacuum expectation value (VEV) of the neutral component of X_a is denoted as $v_a/\sqrt{2}$ (v_a) if it is a complex (real) scalar. For simplicity, we do not consider either explicit or spontaneous CP violation in the Higgs potential.

It is known that introduction of a Higgs multiplet with too large T_a breaks perturbative unitarity of tree-level scattering amplitudes, *e.g.*, the Scalar–Scalar → Gauge–Gauge type of processes [10] due to the enhancement in Scalar–Scalar–Gauge couplings. According to Ref. [10], the maximum size of T_a is given by 7/2 (4) for a complex (real) scalar in the $N = 1$ case. We thus impose the same upper limits on T_a, although more severe conditions would be obtained for larger N because of additional contributions to the scattering processes.

In such a model, the electroweak ρ parameter, defined by $\rho \equiv m_W^2/(m_Z^2 \cos^2\theta_W)$ with m_W (m_Z) and θ_W denoting respectively the W (Z) boson mass and the weak mixing angle, at tree level is given by

$$\rho_{\rm tree} = \frac{v_\Phi^2 + 2\sum_{b=1}^N v_b^2[T_b(T_b+1) - Y_b^2]}{v_\Phi^2 + 4\sum_{a=1}^N v_a^2 Y_a^2} , \qquad (1)$$

where $v_\Phi = \sqrt{2}\langle\Phi^0\rangle$. The condition $\rho_{\rm tree} = 1$ gives

$$\sum_{a=1}^N v_a^2[T_a(T_a+1) - 3Y_a^2] = 0 . \qquad (2)$$

In the case of $N = 1$, we have the well-known solutions:

$$(T_1, Y_1) = (0, 0), \;\; (1/2, 1/2), \;\; (3, 2). \qquad (3)$$

As already mentioned above, the first two solutions always have $\kappa_V \leq 1$, while the last one allows the possibility $\kappa_V > 1$ [7,11]. However, all of these solutions predict $\kappa_W = \kappa_Z$ at tree level, which is expected to be violated at $\mathcal{O}(1\%)$ level or smaller when radiative corrections are included (see, for example, Ref. [12]).

We therefore consider the next simplest case of $N = 2$. Without loss of generality, we assume that $T_1 \geq T_2$. Moreover, neither multiplets have the quantum numbers shown in Eq. (3); otherwise, it reduces to a model with $\kappa_W = \kappa_Z$ at tree level. With Eq. (2), the two VEVs satisfy the following relation:

$$r \equiv \frac{v_2^2}{v_1^2} = -\frac{T_1(T_1+1) - 3Y_1^2}{T_2(T_2+1) - 3Y_2^2} . \qquad (4)$$

Besides, we have a sum rule about the VEVs:

$$v^2 = v_\Phi^2 + \xi^2 v_1^2 \quad \text{with } \xi^2 \equiv 4\left(Y_1^2 + rY_2^2\right) , \qquad (5)$$

where $v \simeq 246$ GeV. For later convenience, we define a mixing angle β through

$$\tan\beta = \frac{v_\Phi}{\xi v_1} \qquad (6)$$

in a way consistent with that in two-Higgs doublet models [13]. More explicitly, β is the mixing angle appearing in the rotation matrix to separate the Nambu–Goldstone (NG) bosons to be absorbed into the weak gauge bosons from the physical Higgs states such as CP-odd and singly-charged Higgs bosons.

Even if models with $N = 2$ satisfy the condition given in Eq. (2), some of them should be excluded because of the existence of accidental global $U(1)$ symmetries associated with phase rotations of X_1 and X_2 as they would give rise to at least one phenomenologically unacceptable massless NG boson after the electroweak symmetry breaking. To avoid such NG bosons, we require that there be no accidental global $U(1)$ symmetry in the Higgs potential. The following are general situations where such a $U(1)$ symmetry can be broken explicitly by renormalizable terms. First, introducing a multiplet of $(T_a, Y_a) = (1, 0)$, $(1, 1)$, $(3/2, 1/2)$ and $(3/2, 3/2)$ is safe because they can couple with an appropriate number of Φ fields and/or their conjugates. Also, having a real multiplet $(Y = 0)$ is all right because its bilinear and higher power terms can be constructed. Finally, for a multiplet other than the above-mentioned ones, one needs to check if at least one renormalizable term involving this multiplet and the other scalars can be constructed.

We then find all possible scenarios, as listed in Table 2. Some of them would result in a Landau pole in the $SU(2)_L$ gauge coupling below the Planck scale. The scale at which the Landau pole appears, denoted by $\Lambda_{\rm LP}$, is calculated by using one-loop renormalization group equations and given in the table. We note that the Landau pole sometimes also appears in the $U(1)_Y$ gauge coupling. But its scale is always higher than that of the $SU(2)_L$ gauge coupling. In addition, we also show the upper limit on v_1, denoted by $v_1^{\rm max}$, by requiring that the top Yukawa coupling y_t remains perturbative, *i.e.*, $y_t \leq \sqrt{4\pi}$ at the electroweak scale. It is also worth mentioning here that the first and fourth scenarios listed in Table 2 can have the custodial symmetry in the Higgs potential as discussed in Ref. [14]. In this case, however, $\kappa_W = \kappa_Z$ is predicted at tree level as alluded to before. We do not impose such custodial symmetry in this Letter.

In order to obtain the expressions for the Higgs boson couplings, let us denote the three CP-even scalars associated with (Φ, X_1, X_2) as $(h_\Phi, h_{X_1}, h_{X_2})$ and the three physical states as (h, H_1, H_2). The two sets of fields are related by

$$\begin{pmatrix} h_\Phi \\ h_{X_1} \\ h_{X_2} \end{pmatrix} = R \begin{pmatrix} h \\ H_1 \\ H_2 \end{pmatrix} , \qquad (7)$$

where R is a 3×3 orthogonal rotation matrix. In general, R involves three independent mixing angles.

We then obtain the general expressions for κ_W and κ_Z as

$$\begin{aligned} \kappa_W &= s_\beta R_{11} + c_\beta \frac{2[T_1(T_1+1) - Y_1^2]R'}{\xi} c_\theta \\ &\quad + c_\beta\sqrt{r}\frac{2[T_2(T_2+1) - Y_2^2]R'}{\xi} s_\theta , \qquad (8) \\ \kappa_Z &= s_\beta R_{11} + c_\beta \frac{4Y_1^2 R'}{\xi} c_\theta + c_\beta\sqrt{r}\frac{4Y_2^2 R'}{\xi} s_\theta , \end{aligned}$$