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750 GeV diphoton resonance in a top and bottom seesaw model

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ABSTRACT

The top and bottom seesaw model, which extends the top seesaw in order to accommodate a 125 GeV Higgs boson, predicts vector-like top/bottom partners and these partners can be bounded to form several neutral and charged singlet composite scalars by some new strong dynamics. In this letter, we use such a singlet scalar to interpret the 750 GeV diphoton resonance. This singlet scalar is dominantly produced through the gluon fusion process induced by the partners and its diphoton decay is induced by both the partners and the charged singlet scalars. We show that this scenario can readily account for the observed 750 GeV diphoton signal under the current LHC constraints. Further, this scenario predicts some other phenomenology, such as a strong correlation between the decays to $\gamma\gamma$, $Z\gamma$ and ZZ, a three-photon signal from the associate production of a singlet scalar and a photon, as well as some signals from the partner cascade decays. These signals may jointly allow for a test of this framework in future 100 TeV hadron collider and ILC experiments.

1. Introduction

The observation of a 125 GeV Higgs boson at the LHC Run-1 [1,2] is a great triumph of the Standard Model (SM). The current experimental measurements of its production cross sections and decay rates are consistent with the predictions of the SM Higgs boson. However, without a symmetry protection, the SM Higgs mass is quadratically sensitive to the cutoff scale via quantum corrections. This renders the SM rather unnatural and widely motivates new theories beyond the SM. Among many extensions of the SM, the Higgs sector is usually enlarged or modified. So any evidence of non-SM Higgs bosons would indicate the existence of new physics and can be used to elucidate the electroweak symmetry breaking (EWSB) mechanism.

Very recently, the ATLAS and CMS collaborations have reported their first results at 13 TeV LHC and found a resonance-like excess in the diphoton invariant mass spectrum around 750 GeV [3,4]. The significances of the signals are still only 3.6σ and 2.6σ in the respective experiments, but if confirmed with more data, this would open the window of new physics at the TeV scale. Several explanations have been proposed for such an excess [5–7]. When interpreting the excess in terms of the production rate of the resonance X, based on the expected and observed exclusion limits, the CMS and ATLAS experiments at 13 TeV LHC approximately give [6]

$$\sigma^{750}_{\gamma\gamma}(\text{CMS}) = \sigma(pp \to X) \times Br(X \to \gamma\gamma) = 5.6^{+2.4}_{-2.4}\ \text{fb}, \quad (1)$$

$$\sigma^{750}_{\gamma\gamma}(\text{ATLAS}) = \sigma(pp \to X) \times Br(X \to \gamma\gamma) = 6.0^{+2.4}_{-2.0}\ \text{fb}. \quad (2)$$

Combined with the 8 TeV data [8,9], the diphoton excess contributing to the combined production rate is given by [6]

$$\sigma^{750}_{\gamma\gamma} = (4.4 \pm 1.1)\ \text{fb}. \quad (3)$$

Because of the Landau–Yang theorem [10], the 750 GeV resonance X can only be a spin-2 or spin-0 particle. However, a graviton-like spin-2 particle with an universal coupling is disfavored by the searches for the jj [11], ZZ [12,13] and $t\bar{t}$ [14,15] resonances. Besides, to enhance the diphoton rate, other SM decay modes of the heavy resonance have to be suppressed. So, the most economic way is to construct a theory with a spin-0 SM-singlet scalar S. Such a singlet naturally has no tree level couplings with the SM particles. While the large loop couplings Sgg and $S\gamma\gamma$ can be achieved by introducing new vector-like fermions and/or new charged scalars, which can be found in some composite models and strong dynamics.

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In this paper our aim is not to construct a full ultraviolet complete model, but instead work directly with an effective framework inspired by the extension of the top seesaw with the bottom seesaw (namely top and bottom seesaw) [16,17] to explain the 750 GeV diphoton resonance without conflicting with other LHC data.[1] Because of the heavy mass ($m_t \sim 175$ GeV), top quark could potentially be associated with the EWSB. The idea of top quark condensation was proposed to explain the EWSB, where a SM Higgs-like $t\bar{t}$ bound state (called the top-Higgs boson) with a mass $\sim 2m_t$ is predicted [18]. Obviously, the minimal top condensation model [19] can hardly be consistent with the recent measurements of the Higgs boson at the LHC. To accommodate 125 GeV Higgs boson, some extensions of top quark condensation with seesaw mechanism [20–27,16,28,17] have been widely investigated. Among them, top and bottom seesaw is a feasible way [16,17]. Such models naturally predict the vector-like top and bottom partners, which can be bounded to form several neutral and charged composite scalars by some new strong dynamics. In our work we use such a neutral singlet scalar (composed of bottom partners) to interpret the 750 GeV resonance. This singlet scalar is dominantly produced through the gluon fusion process induced by the partners and its diphoton decay is induced by both the partners and the charged singlet scalars. Under the current experimental constraints, we find that the 750 GeV diphoton excess can be explained in this top and bottom seesaw scenario.

This paper is organized as follows. In Sec. 2, we describe the interactions relevant for the 750 GeV diphoton resonance and discuss the current experimental constraints. In Sec. 3 we present the numerical results. The conclusion is given in Sec. 4.

2. The relevant interactions and constraints

We focus on the relevant interactions for the 750 GeV diphoton resonance within the framework of top and bottom seesaw model [17]. Here we will concern only with the weak isospin singlet sector of the model and decouple it from the electroweak breaking sector that is assumed to correctly reproduce the observed Higgs mass. We start from the effective four-fermion interactions (which are assumed to be generated by some strong dynamics at energy scale Λ) given by

$$\begin{aligned}\mathcal{L}_\Lambda \supseteq\ & [m_{0\chi}\bar{\chi}_L\chi_R + m_{0\omega}\bar{\omega}_L\omega_R + h.c.] + G_\chi(\bar{\chi}_L\chi_R)(\bar{\chi}_R\chi_L) \\ & + G_\omega(\bar{\omega}_L\omega_R)(\bar{\omega}_R\omega_L) + G_{\chi\omega}(\bar{\omega}_L\chi_R)(\bar{\chi}_R\omega_L) \\ & + G_{\omega\chi}(\bar{\chi}_L\omega_R)(\bar{\omega}_R\chi_L), \end{aligned} \tag{4}$$

where $\chi_{L,R}$ and $\omega_{L,R}$ are the vector-like top and bottom partners, transforming as singlets under the electroweak $SU(2)_L$ gauge symmetry. Their SM quantum numbers are given by

$$\chi_L, \chi_R : (3,\ 1,\ 2/3), \quad \omega_L, \omega_R : (3,\ 1,\ -1/3). \tag{5}$$

At low energy scale $\mu(<\Lambda)$, the theory is described in terms of composite fields corresponding to the bounded fermion pairs in Eq. (5). There are six composite scalars relevant for our study, i.e., two neutral singlets S_{N_i} and four charged singlets $S^{\pm}_{C_i}$ $(i = 1, 2)$[2]:

$$\begin{aligned} & S_{N_1} \sim \bar{\chi}_L\chi_R, \quad S_{N_2} \sim \bar{\omega}_L\omega_R, \\ & S^+_{C_1} \sim \bar{\omega}_L\chi_R, \quad S^+_{C_2} \sim \bar{\omega}_R\chi_L, \quad S^-_{C_1} \sim \bar{\chi}_L\omega_R, \quad S^-_{C_2} \sim \bar{\chi}_R\omega_L. \end{aligned} \tag{6}$$

Then, the effective Lagrangian describing the interactions between vector-like quarks and the scalars as well as the self-interactions of the scalars can be written as

$$\begin{aligned}\mathcal{L}_{\mu<\Lambda} \supseteq\ & y_{N_1}S_{N_1}\bar{\chi}_L\chi_R + y_{N_2}S_{N_2}\bar{\omega}_L\omega_R + y_{C_1}S^+_{C_1}\bar{\omega}_L\chi_R \\ & + y_{C_2}S^+_{C_2}\bar{\omega}_R\chi_L + m_{0\chi}\bar{\chi}_L\chi_R + m_{0\omega}\bar{\omega}_L\omega_R + h.c. \\ & + V(S_{N_i}, S^{\pm}_{C_i}), \end{aligned} \tag{7}$$

where the bare mass terms $m_{0\chi}$ and $m_{0\omega}$ are allowed by the SM gauge symmetry. Using large N_c fermion loop approximation [19], the Yukawa couplings y_{N_i} at leading order can be estimated as

$$y_{N_i} \simeq \frac{4\pi}{\sqrt{N_c \ln(\Lambda^2/\mu^2)}}. \tag{8}$$

These couplings tend to infinity at the compositeness scale Λ due to the compositeness condition. For example, when $\Lambda = 10$ TeV, $\mu = 1$ TeV and $N_c = 3$, Yukawa couplings $y_{N_i} \simeq 3.4$ are predicted. To obtain smaller y_{N_i}, the cut-off scale Λ should be higher, (in this case, the theory will suffer from the fine tuning, but which is not the focus of this work.), e.g. $\Lambda = 10^{12}$ TeV, $\mu = 1$ TeV, then $y_{N_i} \simeq 1$. However, it is noted that for $\Lambda \gg \mu$, the fermion bubble approximation may not be accurate enough and the full one-loop RG equations are needed to be solved [19]. The potentially large anomalous dimensions can drive large y_{N_i} values at the compositeness scale down to substantially lower values at low energies [29]. Depending on the details of the full theory, one may in principle end up with hierarchically different Yukawa couplings y_{N_i} as well. The exact numerical results can be worked out in the full theory, but this is beyond the scope of this paper. After spontaneous symmetry breaking, the vector-like quark masses are $m_\chi = y_{N_1}\langle S_{N_1}\rangle + m_{0\chi}$ and $m_\omega = y_{N_2}\langle S_{N_2}\rangle + m_{0\omega}$. Since the couplings of vector-like quarks to the neutral composite scalars are not proportional to their masses, we can separate the vector-like quark masses from the strength of the interaction y_{N_i}. This feature can potentially enhance the effective couplings of $S_{N_i}gg$ and $S_{N_i}\gamma\gamma$.

Besides the vector-like quarks, these new charged scalars can contribute to the diphoton decay of S_{N_i}. The relevant terms of the effective potential $V(S_{N_i}, S^{\pm}_{C_i})$ in Eq. (7) are given by[3]

$$\begin{aligned} V(S_{N_i}, S^{\pm}_{C_i}) \supseteq\ & \sum_{i=1}^{2}\frac{1}{2}m^2_{S_{N_i}}S^2_{N_i} + \sum_{i=1}^{2}\frac{1}{2}m^2_{S^{\pm}_{C_i}}S^+_{C_i}S^-_{C_i} \\ & + \sum_{i,j=1}^{2}\lambda_{C_{ij}}\mu' S_{N_i}S^+_{C_j}S^-_{C_j}, \end{aligned} \tag{9}$$

where $m_{S_{N_i}}$ and $m_{S^{\pm}_{C_i}}$ are the masses of the neutral and charged singlets, respectively. μ' is the dimensional parameter and assumed to be 1 TeV. Similarly to Yukawa couplings y_{N_i}, the trilinear coupling $\lambda_{C_{ij}}$ can be estimated at leading order through the fermion bubble approximation,

$$\lambda_{C_{ij}} \simeq \frac{32\pi^2}{N_c \ln(\Lambda^2/\mu^2)}. \tag{10}$$

[1] The original top seesaw model can hardly explain the 750 GeV diphoton excess since the mixing between top quark and top partner usually leads to a sizable branching ratio of the resonance decay to $t\bar{t}$.

[2] The masses of these composite singlets can be independent of each other since the global symmetry that protects the Higgs boson to be light, is imposed on the electroweak breaking sector [16,17] and may be broken in the isospin singlet sector.

[3] In a full theory, the singlets S_{N_i} may mix with the neutral components of the electroweak doublets. This mixing can be small because the vacuum expectation values $\langle S_{N_i}\rangle$ can be small and even vanishing. Similarly, $S_{N_1}H^\dagger H$ and $S_{N_2}H^\dagger H$ interactions that are respectively induced by t–χ and b–ω loops can be further suppressed by the large cut-off scale Λ due to the twice transition of t–χ and b–ω. In this case, the contribution of $S_{N_i} \to hh$ channel to the total decay width of S_{N_i} can be negligibly small. We also require $m_{S^{\pm}_{C_i}} > m_{S_{N_i}}/2$ to kinematically forbid the decay channel $S_{N_i} \to S^{\pm}_{C_i}S^{\mp}_{C_i}$.