Diphoton excess at 750 GeV in an extended scalar sector

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We discuss an extended scalar model which explains the recent results of diphoton excess at 750 GeV at LHC Run II experiments. An additional singlet scalar boson with the mass of 750 GeV, which couples to top quarks via a dimension five operator, is produced via gluon fusion and decays into two photons via loop contributions of a number of (multiply) charged scalar bosons. Origin of such a dimension five operator would be, for example, in the context of composite Higgs models. The excess can be explained without contradicting the data from LHC Run I and also theoretical consistencies such as perturbative unitarity and charge non-breaking.

I. INTRODUCTION

Since the discovery of the Higgs boson at LHC Run I ¹, the main target of high energy collider experiments has turned to detect new direct evidence of physics beyond the standard model (SM). Recently both ATLAS Collaboration and CMS Collaboration reported a new excess in the diphoton data at 750 GeV with the width about 45 GeV at LHC Run II ² 3, which might be the resonance of a new particle beyond the SM. Many physicists have been trying to understand the new excess based on various ideas, and quite a few papers have already been submitted until now for a short time ⁴ ⁵. In a large number of the proposed models, vector-like fermions as well as several (multiply) charged scalar bosons (pNGBs). They become components of one additional real singlet scalar field

St

L

R

, and also couples to charged scalars via trilinear interactions of the singlet field

S

φ

±

as

|φ|

. We here introduce a simple extension of the SM with an additional real singlet scalar field

S

and several (multiply) charged scalar bosons. We can assume that the singlet does not have a vacuum expectation value (VEV).



S

Φ

0

where

Φ

is the Higgs doublet field, and the cause of strongly first order phase transition and CP violation required for electroweak baryogenesis. In addition, new paradigms beyond the SM also require a specific Higgs sector in each model.

We here introduce a simple extension of the SM with an additional real singlet scalar field

S

and several (multiply) charged scalar bosons. We can assume that the singlet does not have a vacuum expectation value (VEV). The singlet couples to top quarks

(StL)T

R

, whose coupling originally comes from a dimension five operator

St

Φ

T

R

, and also couples to charged scalars via trilinear scalar couplings with dimensionful parameters. At LHC, the singlet field

S

can then be produced via the gluon fusion process. The produced

S

fields mainly decay into

γγ

but some do into diphoton. The observed data ² ³ suggest that the signal at

Mγγ

≈

750 GeV should satisfy

ATLAS : \( \sigma(pp \to SX \to \gamma\gamma X) \approx 5 \pm 4 \, fb \) (95%CL) ,

CMS : \( \sigma(pp \to SX \to \gamma\gamma X) \approx 9 \pm 7 \, fb \) (95%CL) .

(1)

We show that by our simple setup the observed signal cross section and the observed total width \( \Gamma_\gamma \approx 45 \, GeV \) ² can be explained without contradicting the data from LHC Run I ² ³ and also constraints from theoretical consistencies such as perturbative unitarity ⁹ and charge non-breaking vacuum ⁹.

II. MODEL

We consider the following effective Lagrangian for interactions of the singlet field

S

as

L_{eff} = -\frac{S}{\Lambda} \left( \overline{q}_L \Phi q_R \right) - \sum_q n_q \sum_{i,j} \mu_{iq} \Phi \phi_i^{\pm} \phi_j^{-q},

(2)

where \( \Phi \) is the Higgs doublet field, \( \phi_i^{\pm} \) are scalar bosons with the electric charge of \( \pm q \), and \( n_q \) is the number of \( q \)-charged scalar bosons. We can assume that the singlet

S

does not have a VEV while the Higgs doublet field

Φ

does have the VEV \( \langle \Phi^0 \rangle = v/\sqrt{2} \), where \( v \approx 246 \, GeV \). Therefore, only \( v \) gives the mass to the quarks and leptons.

The origin of the dimension five operator in Eq. (2) would be in the context of composite Higgs models ¹⁰. For example, in the SO(6)/SO(5) model where the global symmetry SO(6) is spontaneously broken to SO(5) at the composite scale, there are 5 pseudo Nambu-Goldstone bosons (pNGBs). They become components of one Higgs doublet and one neutral real scalar singlet filed in the Higgs sector ¹¹. This singlet couples to charged fermions as

L_{int} = im_f \sqrt{\frac{\xi}{\xi - 1}} \cot \theta_f \overline{S}_L f_R \Phi^T ,

(3)

where \( m_f \) is the mass of the fermion, and \( \xi \) is the compositeness parameter, and the mixing angle \( \cot \theta_f \) is the
FIG. 1: The hadronic production cross section $pp \to S + X$ as a function of $y$ at the LHC for the centre-of-mass energy to be 13 TeV (red) and 8 TeV (blue).

$Z_2$ breaking parameter which vanishes at $\theta_f = \pi/2$ where the exact $Z_2$ symmetry ($S \to -S$) recovers.

The existence of charged singlet scalars would also be realized in the context of composite Higgs models. In the composite Higgs models, the number of light scalar degrees of freedom in the low energy effective theory is determined by the symmetry breaking structure $G/H$. A part of the list for various $G/H$ and corresponding extended Higgs sectors is presented in Ref. 12. For example, in the $(SO(6))^2/SO(6)$ model, where the global symmetry $(SO(6))^2$ is spontaneously broken to $SO(6)$, it appear 15 pNGBs which are decomposed as one real singlet, two doublets and two real triplet fields [13]. In such a model, we have the singlet real scalar field $S$ which couples to both $t_t \bar{t}_R$ and a number of (singly) charged scalar bosons.

In the following, however, we do not specify the fundamental model which predicts the Lagrangian in Eq. (2). Instead, we consider models with extended scalar sectors with the interaction in Eq. (2) in a general framework and try to explain the excess at 750 GeV in the recent LHC data.

For simplicity, we here consider the case where the trilinear scalar couplings $\mu^{ij}_S$ in Eq. (2) are diagonal and universal, and all charged scalars are degenerate in mass,

$$\mu^{ij}_S = \mu \delta^{ij}, \quad (4)$$

$$m_{\phi^3} = m_{\phi^\pm}, \quad \forall q, \quad (5)$$

so that there are only two coupling parameters $\mu$ and $m_S$ as well as the common mass of charged scalars $m_S$.

The basic idea of our scenario is the following. We assume that the excess is the result of the production and decay of $S$ with the mass of 750 GeV. The production cross section $pp \to S + X$ is dominated by gluon fusion of top-quark loop mediation. The main decay mode of $S$ is $t\bar{t}$, so that the production cross section of $\sigma(pp \to SX)$ and the total width $\Gamma_S$ are correlated and controlled by the coupling $\mu$. From the observed value of $\Gamma_S$, the magnitude of $\mu$ is determined. On the other hand, the decay rate of $S \to \gamma\gamma$ is determined by the top-loop contribution and also by the charged-scalar loop effect. If the number of charged scalars is not small, scalar loop contributions dominate the top-loop effect. In such a case, the decay rate is determined by the trilinear scalar coupling $\Gamma_S$. In the following, we show that the data of the excess can be explained by tuning these parameters under the constraint from the 8 TeV data.

### III. NUMERICAL EVALUATION

The partonic production cross section $gg \to S$ is given by

$$\hat{\sigma}(gg \to S) = \frac{G_F m_S^2}{288 \sqrt{2\pi}} \left| \frac{3}{4} F_f(\tau_t) \right|^2 \frac{y \mu^2}{\sqrt{2m_f \Lambda}}, \quad (6)$$

where $\hat{s}$ is the centre-of-mass energy of this subprocess and $\tau_t = 4m_t^2/\hat{s}$. The hadronic cross section is evaluated by

$$\sigma(pp \to SX) = K \int_{\tau_s = m_S^2/\hat{s}}^1 d\tau \frac{d\mathcal{L}_{gg}}{d\tau} \times \hat{\sigma}(gg \to S), \quad (7)$$

where $d\mathcal{L}_{gg}/d\tau$ is the luminosity function. We here use MSTW2008 LO [14], and the $K$ factor is taken to be 2.5 in our calculation [13]. When we take $\Lambda = v$, we obtain

$$\sigma(pp \to S) \sim 0.3y^2 \text{ pb}. \quad (8)$$

for $\sqrt{s} = 13$ TeV. In Fig. 1 the production cross section of $pp \to S + X$ is shown at the leading order as a function of $y$ for $\sqrt{s} = 13$ TeV (red) and 8 TeV (blue).

We next consider the decay branching ratios of the produced $S$. We here assume that $m_S < 2m_t$ so that the charged scalars affect the total width $\Gamma_S$ only via the quantum loop contributions in $S \to \gamma\gamma$. The decay rates of the singlet $S$ are calculated by

$$\Gamma(S \to t\bar{t}) = \frac{N_c g^2 m^2_t}{32\pi m_W^2} m_S |\kappa_{stt}|^2 \left(1 - \frac{4m_t^2}{m_S^2}\right)^{\frac{3}{2}}, \quad (9)$$

$$\Gamma(S \to \gamma\gamma) = \frac{\alpha^2 g^2}{1024 \pi^2} \frac{m_3^4}{m_W^2}$$

$$\times \left| \kappa_{\gamma\gamma} \frac{4}{3} F_f \left(\frac{4m_t^2}{m_S^2}\right) + r \kappa_{st} F_0 \left(\frac{4m_t^2}{m_S^2}\right) \right|^2, \quad (10)$$

$$\Gamma(S \to Z\gamma) = \frac{\alpha^2 m_3^4}{128 \pi v^2} \left(1 - \frac{m_Z^2}{m_S^2}\right)^3$$

$$\times \left| 2\kappa_{stt} J_f + \sum_i \frac{q_i q_i}{c_W} (I_3 - s_W q_i) \frac{m_W^2}{v} J_S \right|^2, \quad (11)$$

where $r = \sum_q q^2 n_q$, and

$$\kappa_{stt} = \frac{y \mu^2}{\sqrt{2m_t}}, \quad \kappa_{st} = \frac{m_W}{g m_t \mu}. \quad (12)$$
FIG. 2: Contour plots of the signal cross section \( \sigma(pp \to SX) \times Br(S \to \gamma\gamma) \) [fb] on the \( y-\mu \) plane for \( m_\pm = 400 \) GeV. The regions which satisfy the 13 TeV data (red) [2] and 8 TeV data (grey) [6] within the 95 \% CL are shown. The regions where the total width of \( S \) is in 40 GeV < \( \Gamma_S < 50 \) GeV (blue band) and the curve of \( \Gamma_S = 5.3 \) GeV (blue dashed), the energy resolution of the diphoton system, are also indicated. From top-left to bottom-right, the results are shown in the models wish \( r = 1, 10, 16, 25, 50 \) and 65.

The loop integral functions are defined by

\[
F_t(\tau) = -2\tau [1 + (1 - \tau)f(\tau)],
\]

\[
F_0(\tau) = \tau(1 - \tau) f(\tau),
\]

and

\[
f(\tau) = \begin{cases} 
\left[ \sin^{-1} \left( \frac{1}{\sqrt{\tau}} \right) \right]^2 & \text{for } \tau \geq 1, \\
-\frac{1}{4} \left[ \log \left( \frac{1 + \sqrt{1 - \tau}}{1 - \sqrt{1 - \tau}} \right) - i\pi \right]^2 & \text{for } \tau < 1.
\end{cases}
\]

(13)

(14)

(15)

\( J_f \) is written by \( A_{1/2}^H \) in Ref. [17] as

\[
J_f = \frac{v_f}{s_{WCW}} A_{1/2}^H.
\]

(16)

The loop contribution \( J_S \) is given in Ref. [18]. Our model can be classified by the parameter \( r \), and characterized by the parameters of \( y, \mu \) and \( m_\pm \) with \( m_S \) being set to be 750 GeV.

The signal cross section of \( pp \to S + X \to \gamma\gamma + X \) is then given by

\[
\sigma(pp \to SX \to \gamma\gamma X) = \sigma(pp \to SX) \cdot Br(S \to \gamma\gamma),
\]

(17)

where we employ the narrow width approximation, because the ratio \( \Gamma_S/m_S \) is smaller than 0.1.

Now we survey the parameter region where the data of the excess at 750 GeV is explained without contradiction with the Run I data for the process \( pp \to S + X \to \gamma\gamma + X \) at 8 TeV [6, 7],

ATLAS : \( \sigma(pp \to SX \to \gamma\gamma X) \approx 1.6 \pm 1.3 \) fb (95\%CL) ,

CMS : \( \sigma(pp \to SX \to \gamma\gamma X) \approx 0.9 \pm 0.6 \) fb (95\%CL) .

(18)

If the model contains doubly charged scalar bosons, we have to take into account the constraint on the mass from the LHC data. In particular, if the doubly charged scalars from isospin singlets (triplets) decay into dilepton, the current lower bound is about 430 GeV (550 GeV) [19]. On the other hand, if they are of the complex triplet scalar fields, it can mainly decay into diboson (\( W^\pm W^\pm \)) when the VEV for the triplet is larger than 0.1 MeV. In
such a case, the current mass lower limit is about 90 GeV [20], which is much relaxed as compared to the case of dilepton decays. If we consider \( n_q > 1 \) of doubly charged Higgs bosons, these bounds should become stronger. We here do not specify the isospin of charged scalar bosons and also their main decay mode for a while, and we come back to this issue later.

In Fig. 2, contour plots of the regions satisfying the data from the 13 TeV Run (red) [2] and those at 8 TeV (grey) [6] are shown (in the 95% CL) on the \( y-\mu \) plane for the six models with \( r = 1, 10, 16, 25, 50, \) and 65. The region where the width of \( S \) is in \( 40 \text{ GeV} < \Gamma_S < 50 \text{ GeV} \) (blue band) and the curve of \( \Gamma_S = 5.3 \text{ GeV} \) (blue dashed), the energy resolution of the diphoton system, are also indicated. From top-left to bottom-right, the results are shown in the models wish \( r = 1, 10, 16, 25, 50 \) and 65.

In Fig. 3, the similar figures for the results with the mass of the universal charged scalar mass \( m_\pm \) to be 600 GeV are shown with the same fashion. We see that the required values of \( \mu \) for each model are larger than the cases with \( m_\pm = 400 \text{ GeV} \).

IV. DISCUSSION

We here discuss theoretical constraints which limit parameter regions, and then give some comments on the relation of our model to the new physics phenomena.

First, in order to obtain enough enhancement in the diphoton decay rate of the singlet \( S \), a larger value of \( \mu \) is required for a smaller values of \( r \). However, taking a too large value of \( \mu \) compared to \( m_S \) and \( m_\pm \) possibly causes dangerous charge breaking minima. For the case of \( m_S = 750 \text{ GeV} \) and \( m_\pm = 400–600 \text{ GeV} \), the value of \( \mu \) larger than about 10 TeV is not favored at all by the similar analysis to the case of large trilinear coupling in the minimal supersymmetric standard model (MSSM)[21].

Second, the perturbative unitarity bound for scattering processes such as \( \phi^+\phi^- \rightarrow \phi^0\phi^0 \) should also be
taken into account in the case with a large $\mu$. It is known that in the MSSM, constraints from perturbative unitarity for the trilinear coupling are similar in strength to bounds from color and charge breaking minima \cite{22}. The unitarity bound on $\mu$ in our model is also expected to lead to a similar constraint from charge non-breaking vacuum.

Therefore, from these theoretical constraints, the models with a small $r$ and a large $m_{\pm}$ are not favored even though there are regions which satisfy the data of the excess. As seen in Fig. 2, for though there are regions which satisfy the data of the $m$ bounds, while for $m = 600$ GeV only those with $r = 65$ can be allowed (see Fig. 3).

In order to have a relatively large values of $r$, introduction of a scalar field with a higher isospin representation would be helpful. For example, in the model with an isospin septet scalar field, there are many multiply charged scalar bosons $\phi^{\pm 5}$, $\phi^{\pm 4}$, $\phi^{\pm 3}$, $\phi^{\pm 2}$, $\phi^{\pm}$ and $\phi^{\mp 1}$, which give $r = 56$. The phenomenology of the septet field is discussed in Ref. \cite{24}. We note that models with a higher representation scalar field than the septet are not realistic from viewpoint of perturbative unitarity \cite{25}.

In our analysis, we only have considered the models with only one real singlet field $S$. However, it would also be possible to consider the cases with more real singlets $S_i$ ($i = 1, \cdots N$). If they have the common mass and the universal couplings with $t_L t_R$ and with charged scalars, then the signal cross section becomes $N^2$ larger than the case with $N = 1$. In such a case, the magnitude of the trilinear coupling can be smaller so that the constraint from perturbative unitarity and charge non-breaking would be milder. In this case, the excess at 750 GeV can be explained with smaller values of $r$.

In our scenario, many (multiply) charged scalar fields are introduced. Such introduction of many scalars can also be seen in the models for quantum generation of tiny neutrino masses (so called radiative seesaw scenarios), where neutrino masses are deduced from the extended scalar sectors at one-loop \cite{25, 26}, two-loop \cite{27} and three-loop levels \cite{28, 30}. Therefore, the excess at 750 GeV would be indirect evidence for such radiative seesaw scenarios with $S$ which couples to $t_L t_R$. In addition, introduction of many scalars can cause strongly first order phase transition at electroweak symmetry breaking \cite{31}, which is required for a successful scenario of electroweak baryogenesis \cite{32}.

For $m_S = 750$ GeV and the observed value of $\Gamma_S \sim 45$ GeV, the branching ratio of $S \rightarrow 4 \gamma$ is required to take values between about 0.6 $\%$ and about 3.5 $\%$ to satisfy all the diphoton data for all cases of $r$ and $m_{\pm}$. The data can be consistent with similar values of the branching ratio even if the value of the width is smaller than 45 GeV. The main decay mode of $S$ is always $t \bar{t}$, whose branching ratio is larger than 95 $\%$. Produced number of $t \bar{t}$ via the $S$ decay is much smaller than the uncertainty in the data of the $t \bar{t}$ production cross section at the 8 TeV \cite{33} and the 13 TeV \cite{34}.

In the following, we mention some phenomenological features with speculation. Detailed study is beyond the scope of this letter. If our scenario is true, the second phenomenological signature would be the discovery of charged Higgs bosons with the mass to be 400-600 GeV. In particular, if some of them have double electric charge, the final state would be dilepton or diboson, depending on their isospin charges and the other parameters. If they decay into dilepton, the signature is expected to be observed very soon at LHC Run II, otherwise the model is ruled out. If doubly charged scalars have isospin, the main decay mode can be same sign diboson. In such a case, the current lower limit is about 90 GeV \cite{20}. In order to detect the signal around 400-600 GeV, considerable amount of luminosity has to be accumulated. Finally if the model contains higher order isospin representation scalar fields, their charged scalar components also enhance the $Z\gamma$ decay rate by the loop effect, whose branching ratio can be a few times 1 $\%$. In such a case, the signal of $S \rightarrow Z\gamma$ would be discovered in the near future at LHC Run II.

V. CONCLUSION

We have discussed extended scalar models which can explain the recent results of diphoton excess at 750 GeV at LHC Run II. An additional singlet scalar boson with the mass of 750 GeV, which couples to top quarks via dimension five operator, is produced via gluon fusion and decays into two photons via loop contributions of a number of (multiply) charged scalar bosons. The excess can be explained without contradicting the data from LHC Run I. From theoretical consistencies such as perturbative unitarity and charge non-breaking, the number of charged particles can be constrained.

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