Symmetries behind the 750 GeV diphoton excess

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Symmetry Behind the 750 GeV Diphoton Excess

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Abstract

A 750 GeV resonance has been observed at the Run 2 LHC in the diphoton channel. In this paper, we explain this resonance as a CP-even scalar, $\mathbb{S}$, that triggers the spontaneous breaking of local $U(1)_B$ or $U(1)_{B+L}$ gauge symmetries. $\mathbb{S}$ couples to gluon and photon pairs at the one-loop level, where particles running in the loop are introduced to cancel anomalies. And the gluon fusion is the dominate production channel of $\mathbb{S}$ at the LHC. The model contains a scalar dark matter candidate, stabilized by the new gauge symmetry. Our study shows that both the observed production cross section at the LHC and the best fit decay width of $\mathbb{S}$ can be explained in this model without conflicting with any other experimental data. Constraints on couplings associated with $\mathbb{S}$ are studied, which show that $\mathbb{S}$ has a negligible mixing with the standard model Higgs boson but sizable coupling with the dark matter.

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I. INTRODUCTION

Both the ATLAS [1] and CMS [2] collaborations have observed a resonance about 750 GeV in the diphoton channel. It may be just a statistical fluctuation, but absolutely deserves a systematic study of new physics explanations. According to the Landau-Yang theorem [3, 4], which uses the general principle of invariance under rotation and inversion to derive selection rules governing decays of a particle into diphoton, this new resonance can only be colorless spin-0 or spin-2 bosonic states, whose signal at the LHC is

$$\sigma(pp \to \mathbb{S} \to \gamma\gamma) = \frac{2J+1}{s}\frac{\Gamma^{\mathbb{S}}_{tot}}{M}\left[C_{gg}\text{BR}(\mathbb{S} \to gg) + \sum_q C_{q\bar{q}}\text{BR}(\mathbb{S} \to q\bar{q})\right]\text{BR}(\mathbb{S} \to \gamma\gamma)\ , \quad (1)$$

where $\sqrt{s}$ is the centre-of-mass energy, J and M are the spin and mass of $\mathbb{S}$ respectively, C_{gg} and $C_{q\bar{q}}$ are dimensionless partonic integrals, $\text{BR}(\mathbb{S} \to XX)$ and $\Gamma^{\mathbb{S}}_{\text{tot}}$ are the branching ratio and total decay rate of $\mathbb{S}$. A first glance of Eq. (1) shows many possible interactions of the new resonance could explain this anomaly. But one needs to explain why the Run-I LHC only saw little excesses [5, 6] in the meanwhile. From this point of view heavy flavors and/or gluon fusion production of the resonance are favored, since the luminosity ratio, $r = \sigma_{13\text{TeV}}/\sigma_{8\text{TeV}}$, ranges from $2.5 \sim 4.1$ for light flavors to $4.8 \sim 5.4$ for heavy flavors and gluon [7]. Considering $C_{gg}/C_{x\bar{x}} \sim \mathcal{O}(20 \sim 100)$, where x represents heavy flavors, as well as constraints arising from searches of dijet at the Run-1 LHC, it turns out the resonance is more likely produced at the LHC via the gluon fusion.

In this paper we assume the resonance is a scalar $\mathbb{S}$. To explain the 750 GeV diphoton excess, $\mathbb{S}$ is likely coupled to both photon and gluon pairs. The effective interactions of $\mathbb{S}$ with the gluon and photon can be written as

$$\delta\mathcal{L} \ni \mathbf{\Theta}_{\gamma\gamma}\mathbb{S}\text{F}_{\mu\nu}\text{F}^{\mu\nu} + \tilde{\mathbf{\Theta}}_{\gamma\gamma}\mathbb{S}\text{F}_{\mu\nu}\tilde{\text{F}}^{\mu\nu} + \mathbf{\Theta}_{gg}\mathbb{S}\text{G}^{a\mu\nu}\text{G}^a_{\mu\nu} + \tilde{\mathbf{\Theta}}_{gg}\mathbb{S}\text{G}^{a\mu\nu}\tilde{\text{G}}^a_{\mu\nu} \quad (2)$$

where $\mathbf{\Theta}_{aa}$ and $\tilde{\mathbf{\Theta}}_{aa}$ are CP-conserving and CP-violating effective couplings respectively, which have inverse energy scale. Since CP-violating effective couplings is constrained by the non-observation of the permanent electric dipole moments, CP-conserving effective couplings are more convenient and less constrained explanation. There are already many explanations of the excess [7–46][1], some of which start from Eq. (2) using the bottom-up strategy while others start with concrete models using the top-down strategy.

[1] For studies of new physics in the diphoton channel, see, Refs. [47, 48].

Although many models can explain this excess, one is still not clear with the physics behind this resonance. Is this scalar a fundamental particle? Does it have anything to do with the symmetry breaking? Why this neutral colorless scalar couples to gluon and photon? How does it interact with the standard model (SM) Higgs boson? In this paper we will provide a concrete explanation to these questions. We work in the framework of the SM extended with a local $U(1)_X$ gauge symmetry, where X can be local baryon number B or $B+L$ symmetry, that is spontaneously broken as $\mathbb{S}$ gets nonzero vacuum expectation value (VEV). New vector-like quarks are introduced to cancel anomalies, which have Yukawa interactions with $\mathbb{S}$ that generate nonzero fermion masses as the $U(1)_X$ symmetry is broken. The same Yukawa interactions induce effecive interactions of $\mathbb{S}$ with gluon-gluon and diphoton at the one-loop level. A scalar dark matter, stabilized by the new U(1) symmetry, should be introduced to avoid the problem of long lived charged/colored particles. We find this model can efficiently explain the 750 GeV diphoton excess without conflicting with any other experimental data. $\mathbb{S}$ can mixies with the SM Higgs boson, but the mixing angle is constrained to be very much small, $\mathcal{O}(10^{-2})$, which means this resonance is not able to trigger the strongly first order electroweak phase transition required by the electroweak baryogenesis mechanism. Commendably, all particles relevant to the explanation of the resonance has their own duty in this model. We take it as a prototype of the complete theory behind the 750 GeV diphoton excess.

The remaining of this paper is organized as follows: We briefly describe the model in section II and study its constraints in section III. Section IV is devoted to investigate the 750 GeV diphoton excess. The last part is concluding remarks.

II. THE MODEL

In the SM, both the baryon number and the lepton number are accidental global symmetries. According to Sakharov [49], the baryon number (B) must be broken to have a matter-antimatter asymmetric Universe. Lepton number (L) is expected to be broken to have Majorana neutrino masses. In this paper we take B or $B+L$ as a spontaneously broken gauge symmetry. We start with the construction of a general local $U(1)_X$ gauge symmetry then get back to the gauged B or $B+L$ symmetry as a special case. Particle contents and their representations under the $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$ are listed in the

SM particles	G_{SM}	$U(1)_X$	BSM particles	G_{SM}	$U(1)_X$
$(u,\ d)_L$	$(3,\ 2,\ 1/6)$	m	$\psi_L^{\rm D}$	$(3,\ 2,\ 7/6)$	b
u_R	$(3,\ 1,\ 2/3)$	m	$\psi_R^{\rm D}$	$(3,\ 2,\ 7/6)$	-b
d_R	$(3,\ 1,\ -1/3)$	m	ψ_{1R}^r	$(3,\ 1,\ 5/3)$	b
$(\nu,\ e)_L$	$(1,\ 2,\ 1/2)$	k	ψ_{2R}^r	$(3,\ 1,\ 2/3)$	b
e_R	$(1,\ 1,\ -1)$	k	ψ_{1L}^l	$(3,\ 1,\ 5/3)$	-b
ν_R	$(1,\ 1,\ 0)$	k	ψ_{2L}^l	$(3,\ 1,\ 2/3)$	-b
H	$(1,\ 2,\ 1/2)$	0	$\mathbb{S}$	$(1,\ 1,\ 0)$	-2b

TABLE I: Quantum numbers of fields under the local gauge symmetries $G_{SM} \times U(1)_X$, where $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$. Notice that extra quarks are not VL with respect to the $U(1)_X$ because pure VL fermions would not create anomalies.

Table. I[2]. Note that new fermions are VL only with respect to the SM gauge group, not VL with respect to the $U(1)_X$, because pure VL fermions would not create any anomalies. The global $SU(2)_L$ anomaly [50] requires the even number of fermion doublets, which is automatically satisfied. The absence of axial-vector anomalies [51–53] and the gravitational-gauge anomaly [54–56] requires that certain sums of the $U(1)'$ charges vanish. These anomaly-free conditions finally turns to be

$$3m + k + 2xb = 0 \ , \tag{3}$$

where x is the number of families of new fermions. The eq. (3) is the master equation of anomaly cancellations. The weak hypercharge of newly introduced fermions are totally free. One has following four interesting scenarios arising from eq. (3) by setting $x = 1$:

- $b = 0$, $k = -1$ and $m = 1/3$ corresponds to the famous $U(1)_{B-L}$ symmetry.
- $k = 0$, $m = 1/3$ and $b = -1/2$ corresponds to the $U(1)_B$ gauge symmetry.
- $m = 0$, $k = 1$ and $b = -1/2$ corresponds to the $U(1)_L$ gauge symmetry.
- $m = 1/3$, $k = 1$ and $b = -1$ corresponds to the $U(1)_{B+L}$ gauge symmetry.

[2] Our particle contents are similar to these Refs [58–60] but charges of fields are different, because we study anomaly cancellations of the $U(1)_{xL+yB}$ gauge symmetry.

$U(1)_{B-L}$ gauge symmetry was well-studied, while the phenomenology of $U(1)_{B+L}$ gauge symmetry is not studied before. Anomaly cancellations of a $U(1)_{xB+yL}$ gauge symmetry was first proposed in Ref. [57]. $U(1)_L \times U(1)_B$ gauge symmetries were studied in Refs. [58–60]. In the following we take the $U(1)_X$ as $U(1)_B$ or $U(1)_{B+L}$ gauge symmetry, and study its possible explanation of the 750 GeV diphoton excess.

New fermions have following Yukawa interactions:

$$\mathcal{L}_{\rm Y} \supset \sum_{i=1}^{2} y_\psi^i \overline{\psi_{iL}^l} \mathbb{S} \psi_{iR}^r + y_\psi^3 \overline{\psi_L^{\rm D}} \mathbb{S} \psi_R^{\rm D} + y_H^1 \overline{\psi_L^{\rm D}} H \psi_{2R}^r + y_H^2 \overline{\psi_L^{\rm D}} \tilde{H} \psi_{1R}^r$$
$$+ y_H^3 \overline{\psi_{1L}^l} H^T \psi_R^{\rm D} + y_H^4 \overline{\psi_{2L}^l} H^\dagger \psi_R^{\rm D} + \text{h.c.} \tag{4}$$

which give rise to masses of new fermions as the $U(1)_X$ symmetry is spontaneously broken. Yukawa couplings of new fermions with the SM Higgs are constrained by the electroweak precision measurements (EWPM), which was studied in Ref. [72]. In this paper we assume these Yukawa couplings(y_H^2, y_H^3 and y_H^4) are negligible for simplicity. In this case there is no constraint of the EWPM and no extra contribution to effective couplings of hgg and $h\gamma\gamma$ vertices[3], where h is the SM Higgs. The Yukawa interaction between the SM quarks and new fermions is forbidden by the $U(1)_X$ symmetry. Thus there is no mixing between the new colored states and SM quarks. To avoid the problem of the long lived charged/colored particle, one needs to introduce a flavored scalar dark matter χ, whose $U(1)_X$ charge is 2/3. χ couples to ψ_{2L}^l and the right-handed top quark:

$$\mathcal{L}_{\rm DM} \supset c_\chi \overline{\psi_{2L}^l} \chi t_R + \text{h.c.}. \tag{5}$$

The decay chain of charged fermions is then $\psi_{Q=5/3} \to \psi'_{Q=2/3} + W^+ \to \chi + t + W^+$. In this way, constraints from searching new color states at the LHC can be greatly loosed, which is somehow similar to the case of the stealth supersymmetry [71]. Notice that χ is automatically stabilized by the $U(1)_X$ symmetry in this case. We refer the reader to Ref. [72] for the detail of the dark matter phenomenology in the gauged B+L symmetry.

The gauge interaction of $\mathbb{S}$ as well as the scalar potential can be written as

$$\mathcal{L} \ni (D_\mu \mathbf{S})^\dagger (D^\mu \mathbf{S}) - \left\{ -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 - \mu_1^2 \mathbf{S}^\dagger \mathbf{S} + \lambda_1 (\mathbf{S}^\dagger \mathbf{S})^2 + \tilde{\lambda} (\mathbf{S}^\dagger \mathbf{S})(H^\dagger H) \right\} \tag{6}$$

[3] We refer the reader to Ref. [64] for the study of BR($h \to \gamma\gamma$) arising from VL fermions, which is similar to our case. The contribution of VL fermions is negligible for the small Yukawa coupling scenario.

where $D_\mu = \partial_\mu - iY_X g_X Z'_\mu$ with Z'_μ the gauge field of the $U(1)_X$, $\mathbf{S} = (\mathbb{S} + v_\mathbb{S} + iA_\mathbb{S})/\sqrt{2}$. The potential contains no CP violation but results in the $\mathbb{S} - H$ mixing through the term: $\tilde{\lambda}(\mathbb{S}^\dagger\mathbb{S})(H^\dagger H)$. According to the minimization conditions one has

$$v^2 = \frac{4\lambda_1\mu^2 - 2\tilde{\lambda}\mu_1^2}{4\lambda\lambda_1 - \tilde{\lambda}^2}\ , \qquad v_\mathbb{S}^2 = \frac{4\lambda\mu_1^2 - 2\tilde{\lambda}\mu^2}{4\lambda\lambda_1 - \tilde{\lambda}^2}\ , \tag{7}$$

where v and $v_\mathbb{S}$ are the VEVs of the SM Higgs and $\mathbf{S}$ respectively. As $\mathbf{S}$ gets non-zero VEV the $U(1)_X$ gauge symmetry is spontaneously broken. The mass eigenvalue of Z' is then $M_{Z'} \approx 2bg_X v_\mathbb{S}$. Notice that $\mathbb{S}$ might also interact with the dark matter χ, whose effect will be discussed in section IV.

III. CONSTRAINTS

After the spontaneous breaking of the electroweak and the $U(1)_X$ symmetries, the CP-even scalar mass matrix in the basis $(h,\ \mathbb{S})$ can be written as

$$M^2_{\text{CP even}} = \begin{pmatrix} 2\lambda v^2 & \tilde{\lambda} v v_S \\ \tilde{\lambda} v v_S & 2\lambda_1 v_S^2 \end{pmatrix}\ , \tag{8}$$

which can be diagonalized by the 2×2 unitary transformation. Physical parameters of this model are then m_h, $m_\mathbb{S}$, θ, $v_\mathbb{S}$, y_ψ^i (i=1,2,3) and $m_{Z'}$, where θ is the mixing angle of $\mathbb{S}$ with the SM Higgs. Mass eigenvalues of new fermions can be roughly written as $m_\psi^i = y_\psi^i v_\mathbb{S}$, and parameters in the potential can be reconstructed from the squared mass matrix (Eq. (8)) in terms of mass eigenvalues, mixing angle θ and VEVs:

$$\tilde{\lambda} = (m_\mathbb{S}^2 - m_h^2) cs \frac{1}{v v_\mathbb{S}}\ , \tag{9}$$

$$\lambda = \frac{1}{2v^2}\left[m_h^2 c^2 + m_\mathbb{S}^2 s^2\right]\ , \tag{10}$$

$$\lambda_1 = \frac{1}{2v_s^2}\left[m_h^2 s^2 + m_\mathbb{S}^2 c^2\right]\ , \tag{11}$$

where $c = \cos\theta$ and $s = \sin\theta$. μ^2 and μ_1^2 can be determined by tadpole conditions. The decay rate of $\mathbb{S}$ can be written as

$$\Gamma(\mathbb{S} \to 2\psi) = \frac{c^2 n_C m_\psi^2 (m_\mathbb{S}^2 - 4m_\psi^2)^{3/2}}{8\pi m_\mathbb{S}^2 v_\mathbb{S}^2}\theta(m_R - 2m_\psi)\ , \tag{12}$$

$$\Gamma(\mathbb{S} \to 2V) = \frac{s^2\sqrt{m_\mathbb{S}^2 - 4m_V^2}}{(1+\delta_V)4\pi v^2 m_\mathbb{S}^2}\left(3m_V^4 - m_\mathbb{S}^2 m_V^2 + \frac{1}{4}m_\mathbb{S}^4\right) \quad (V = W, Z)\ , \tag{13}$$

$$\Gamma(\mathbb{S}\to t\bar{t}) \;=\; \frac{s^2 n_C m_t^2 (m_{\mathbb{S}}^2-4m_t^2)^{3/2}}{8\pi m_{\mathbb{S}}^2 v^2}\,, \tag{14}$$

$$\Gamma(\mathbb{S}\to hh) \;\approx\; \frac{\sqrt{m_{\mathbb{S}}^2-4m_h^2}}{32\pi m_{\mathbb{S}}^2}\left|\tilde{\lambda} v_s c^3 + 6cs^2(\lambda_1 v_{\mathbb{S}} - \lambda v)\right|^2 . \tag{15}$$

where n_C is the color number, $\delta_W = 0$ and $\delta_Z = 1$[4], m_V ($V = W/Z$) represents the mass of W or Z gauge boson, m_ψ is the mass of new colored fermion. In our model $\mathbb{S}$ couples to the SM fermions via its mixing with the SM Higgs. Such that its decay rates to the SM fermions equal to these of the SM-like Higgs multiplied by the factor $\sin^2\theta$. The decay rate of $\mathbb{S}\to\bar{u}u$ is then suppressed by both the mixing angle and the tiny Yukawa coupling of the u quark with the SM Higgs. As a result, the rate of $\mathbb{S}\to\bar{u}u$ can be safely neglected. For interactions with vector bosons, $\mathbb{S}$ couples to WW and ZZ through the mixing with SM Higgs and couples to the $Z'Z'$ directly due to its nonzero $U(1)_X$ charge, which is the typical feature of our model compared with the case of CP-odd scalar, etc.. Notice that the value of $\sin\theta$ plays very important rule in the decay of $\mathbb{S}$, however it is constrained by the Higgs measurements. Performing a universal Higgs fit [61] to the current data given by the ATLAS and CMS collaborations, one gets the bound on the mixing angle, which has $c > 0.865$ [62] at the 95% confidence level. For the constraint of the oblique parameters [63], restrictions from the S and T parameters are negligible because of the near degeneracy of the vector-like fermions, as can be seen from Eq. (4).

In our model $\mathbb{S}$ couples to photon and gluon pairs at the one-loop level, with new colored fermions running in the loop. Decay rates of $\mathbb{S}$ to gg and $\gamma\gamma$ can be written as

$$\Gamma(\mathbb{S}\to\gamma\gamma) \;\approx\; \frac{\alpha^2 m_{\mathbb{S}}^3}{1024\pi^3 v_{\mathbb{S}}^2}\left|\sum_\psi 2n_C Q_\psi^2 A_{1/2}(\tau_\psi)\right|^2 , \tag{16}$$

$$\Gamma(\mathbb{S}\to gg) \;\approx\; \frac{\alpha_s^2 m_{\mathbb{S}}^3}{128\pi^3 v_{\mathbb{S}}^2}\left|\sum_\psi A_{1/2}(\tau_\psi)\right|^2 . \tag{17}$$

where $\tau_\psi = 4m_\psi^2/m_{\mathbb{S}}^2$. the expression of the loop function $A_{1/2}(x)$ can be found in Refs. [34, 64].

Assuming $m_{\mathbb{S}} < 2m_{Z',\psi}$, $\mathbb{S}$ might mainly decay into the SM final states though its mixing with the SM-like Higgs or through the triangle loop. We show in the left panel of Fig. 1

[4] The reason we define $\delta_Z = 1$ and $\delta_W = 0$ is that there are two identical particles in the ZZ channel, such that $\Gamma(\mathbb{S}\to ZZ)$ is phase space suppressed compared with $\Gamma(\mathbb{S}\to WW)$.

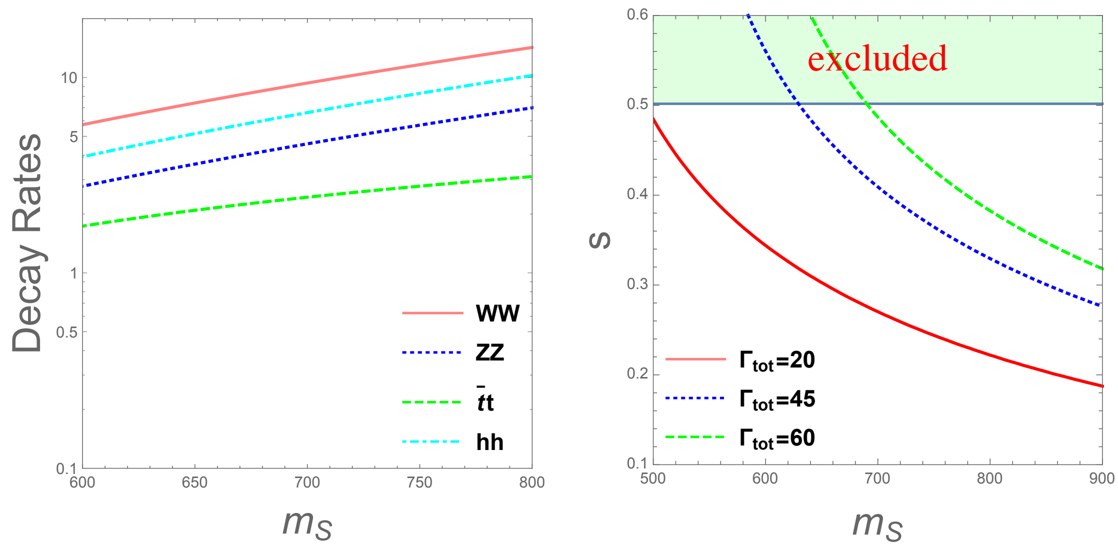

FIG. 1: Left panel: Decay rates of $\mathbb{S}$ as the function of $m_\mathbb{S}$ by setting $s = 0.4$; Right panel: Contours of the total decay rate in the $m_\mathbb{S} - s$ plane, where the green region is excluded by the Higgs measurements.

the decay rates of $\mathbb{S}$ as the function of $m_\mathbb{S}$ in WW, $ZZ, \bar{t}t$ and hh channels, by setting $v_\mathbb{S} = 400$ GeV and $s = 0.4$. It shows that WW and hh channels dominate the decay of $\mathbb{S}$. The decay rate of $\mathbb{S}$ in the hh channel will overtake the decay rate of $\mathbb{S}$ in the WW channel as $v_\mathbb{S} < 300$ GeV. We show in the right panel of Fig. 1 contours of the total decay rate in the $m_\mathbb{S} - s$ plane, where the solid, dotted and dashed lines correspond to $\Gamma_{\rm tot} = 20,\ 45,\ 60$ GeV respectively and the green region is excluded by the Higgs measurements. Taking $m_\mathbb{S} = 750$ GeV, one gets $\Gamma_{\rm tot} = 45$ GeV for $s = 0.365$ which is consistent with all current bounds. Since decays of $\mathbb{S}$ into diphoton and gluon-gluon final states can only happen at the one-loop level, their rates are small compared with the tree-level processes, and are sensitive to the electric charges and colors of the particle in the triangle loop. We show in the left panel of Fig. 2 decay rates of $\mathbb{S}$ as the function of vector-like quark mass in the gg and $\gamma\gamma$ channels, by setting $v_\mathbb{S} = 400$ GeV, $m_\mathbb{S} = 750$ GeV and assuming a degenerate vector-like quark masses for simplicity. In this case, the ratio $r = \Gamma(\mathbb{S} \to gg)/\Gamma(\mathbb{S} \to \gamma\gamma) \sim 11.5$, which is the typical feature of this model. Actually, the diphoton decay rate can be greatly enhanced by choosing a relatively larger weak hypercharge or adding new vector like quark pairs which cancel anomalies automatically and might have Yukawa interactions with the $\mathbb{S}$. We plot in the right panel of Fig. 2, decay rates of $\mathbb{S}$ for the case where there is two more

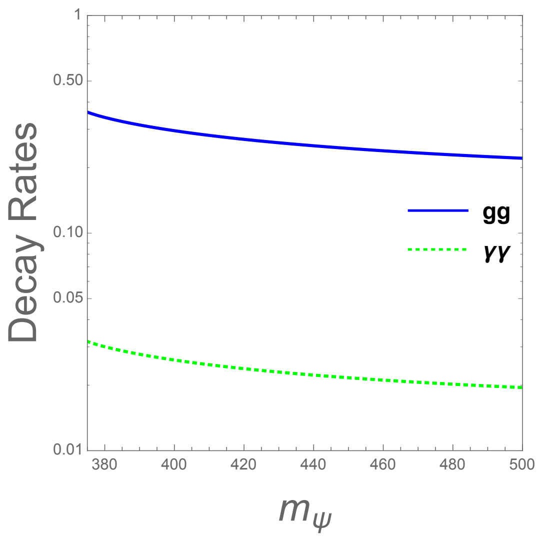

FIG. 2: Decay rate as the function of new fermion masses the gg and $\gamma\gamma$ channels, by setting $v_{\mathbb{S}} = 400$ GeV and $m_{\mathbb{S}} = 750$ GeV. Left panel corresponds to the minimal particle contents showed in the Table. I, while right panel corresponds to the case of adding two extra vector like quarks.

vector-like fermions $\psi_{(3L,3R)}$ and $\psi_{(4L,4R)}$, where quantum numbers of $\psi_{(3L,3R)}$ are the same as $\psi^{(l,r)}_{(1L,1R)}$ while $\psi_{(4L,4R)}$ have opposite $U(1)_X$ charges compared with that of $\psi_{(3L,3R)}$[5], and extra fermions have the same Yukawa coupling with $\mathbb{S}$. Decay rates are greatly enhanced in this case. $\mathbb{S}$ might also decay into dark matter pair, whose rate is proportional to the coupling of $\mathbb{S}$ to the dark matter, which is a little bit arbitrary and whose effect will be studied in the next section. The phenomenology of the dark matter arising from this model, which is interesting but beyond the reach of this paper, will be shown in a future study [72].

IV. DIPHOTON EXCESS

Both the CMS and ATLAS collaborations have observed the diphoton excess at $m_{\gamma\gamma} =$ 750 GeV, whose cross section can be roughly estimated as $\sigma(pp \to \mathbb{S} \to \gamma\gamma) \approx 5 \sim 10$ fb. The best fit width of the resonance is about 45 GeV. It is interesting to interpret this result as a signal of new physics. But it is not trivial to find the new physics that can reasonably fit with the observed data. The production cross section of the resonance at the LHC is given in Eq. (1), with the numerical value of partonic integral evaluated at

[5] In this scenario the Eq. (3) does not change.

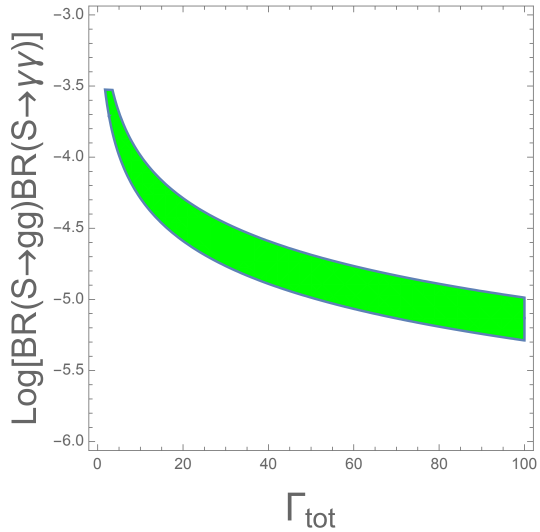

FIG. 3: Region in the $\Gamma^{\mathbb{S}}_{\rm tot} - {\rm Log}[{\rm BR}(\mathbb{S}\to gg)\times {\rm BR}(\mathbb{S}\to\gamma\gamma)]$ plane, that has $\sigma(pp\to\mathbb{S}\to\gamma\gamma)\approx 5\sim 10$ fb.

$M = 750$ GeV and $\sqrt{s} = 13$ TeV as $C_{gg}\approx 3163$ [7]. We plot in Fig. 3 the region in the $\Gamma^{\mathbb{S}}_{\rm tot} - {\rm Log}[{\rm BR}(\mathbb{S}\to gg)\times {\rm BR}(\mathbb{S}\to\gamma\gamma)]$ plane that might give rise to the observed cross section. For our model, we take the following two group benchmark inputs of $\Gamma(\mathbb{S}\to gg)$ and $\Gamma(\mathbb{S}\to\gamma\gamma)$, based on the numerical simulations shown in the left and right panels of Fig. 2 by setting $v_{\mathbb{S}} = m_\psi = 400$ GeV[6],

$$(\textbf{Benchmark I}) \quad \Gamma(\mathbb{S}\to gg) = 0.296 \text{ GeV} , \quad \Gamma(\mathbb{S}\to\gamma\gamma) = 0.026 \text{ GeV} ; \tag{18}$$

$$(\textbf{Benchmark II}) \quad \Gamma(\mathbb{S}\to gg) = 0.665 \text{ GeV} , \quad \Gamma(\mathbb{S}\to\gamma\gamma) = 0.054 \text{ GeV} . \tag{19}$$

We derive the benchmark I using the particle contents given in Table. I, while the benchmark II corresponds to the case of extending the particle contents of the benchmark I with two extra vector-like fermions $\psi_{(3L,3R)}$ and $\psi_{(4L,4R)}$ without introducing any further anomalies.

Using these two benchmark inputs we plot the production cross section of $\mathbb{S}$ as the function of $\Gamma^{\mathbb{S}}_{\rm tot}$ in Fig. 4. The solid and dotted lines correspond to the prediction of benchmark I and benchmark II respectively, the vertical dot-dashed is the best fit value of the total decay rate, while the light green band between the grey horizontal lines is the observed cross section.

[6] The collider signature of ψ in our model is $pp\to\psi\bar\psi\to jj+\chi\chi$(missing energy). For the case ψ being only slightly heavier than χ, the dijet will be very soft and $m_\psi = 400$ GeV will be compatible with the LHC direct searches of VL quarks, which is similar to the case of the stealth supersymmetry [71] and stealth top model [34].

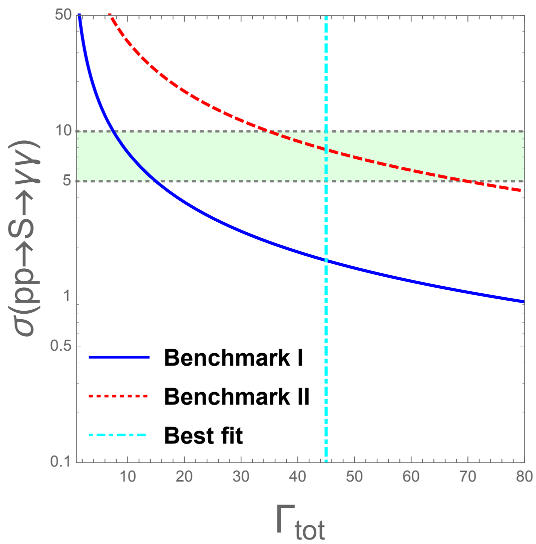

FIG. 4: Production cross section as the function of $\Gamma^{\mathbb{S}}_{\rm tot}$ for the benchmark (I) and (II).

It shows that $\Gamma^{\mathbb{S}}_{\rm tot} \in (7.5,\ 15)$ for benchmark I and $\Gamma^{\mathbb{S}}_{\rm tot} \in (35, 70)$ for benchmark II. Taking $\Gamma^{\mathbb{S}}_{\rm tot}$ as its best fit value (45 GeV from the ATLAS), one has $\sigma(pp \to \mathbb{S} \to \gamma\gamma) = 1.7,\ 7.8$ fb for benchmark I and benchmark II respectively. Benchmark II provides better explanation to the data, but benchmark I is still available up to upon a more precise measurement of the total rate.

As was discussed in the last section, $\mathbb{S}$ might decay into SM final states through its mixing with the SM Higgs boson, or dark matter pair through the interaction $\lambda_{\rm DM}(\mathbf{S}^\dagger \mathbf{S})\chi^\dagger\chi$. The $\Gamma(\mathbb{S} \to \text{invisible})$ can be written as

$$\Gamma(\mathbb{S} \to \text{invisible}) \approx \frac{(\lambda_{\rm DM} v_{\mathbb{S}})^2}{16\pi m_{\mathbb{S}}^2} \sqrt{m_{\mathbb{S}}^2 - 4m_\chi^2}\ . \tag{20}$$

This rate depends on a new parameter $\lambda_{\rm DM}$, which is somehow arbitrary in this model. If this rate is negligible, one might get the bound on the mixing angle θ from the observed cross section: $\sin\theta \in [0.15,\ 0.21]$ for benchmark I and $\sin\theta \in [0.32,\ 0.50]$ for benchmark II. These constraint are still consistent with the constraint of Higgs measurements. On the other hand, the Run-1 LHC at the 8 TeV has searched for the diHiggs, WW, ZZ and $\bar{t}t$ final states, and the non-observation any signal puts upper bound on these cross sections: $\sigma \cdot {\rm BR(ZZ)} < 12$ fb [65], $\sigma \cdot {\rm BR(WW)} < 40$ fb [66], $\sigma \cdot {\rm BR(hh)} < 39$ fb [67] and $\sigma \cdot {\rm BR(\bar{t}t)} < 550$ fb [68]. Each channel puts a upper bound on the $\sin\theta$, it turns out the strongest constraint comes from the ZZ channel, which has $\sin\theta < 6 \times 10^{-3}$. In this case $\Gamma(\mathbb{S} \to \text{SM final states})$ is negligible and the $\mathbb{S} \to \chi\chi$ channel dominates the contribution to the total width. One has $\lambda_{\rm DM} \in (1.3,\ 1.9)$ for the benchmark I and $\lambda_{\rm DM} \in (2.8,\ 4.0)$ for the benchmark II. It should be mentioned that $\mathbb{S}$ may decay into the new fermion final states when $m_{\mathbb{S}} > 2m_\psi$.

Finally let us consider the constraint of the Z'. A heavy Z', whose couplings with SM fermions are the same as these of Z boson, was searched at the LHC in the dilepton channel, which is excluded at the 95% CL for $M_{Z'} < 2.9$ TeV [69] and for $M_{Z'} < 2.79$ TeV [70]. To be consistent with this constriant, one extra scalar singlet with the same quantum number as $\mathbb{S}$ should be introduced, whose VEV, $v_{\rm new}$, breaks the new gauge symmetry spontaneously and contributes to the mass of Z'. It is similar to the case of two Higgs doublet model of Type-I, where the second Higgs doublet contributes to the electroweak symmetry breaking but has no effect in generating fermion masses. In our case $v_{\rm new}$ should be roughly larger than 5.6 TeV to satisfy the current collider constraint. The scenario of breaking a local $U(1)_{B/(B+L)}$ symmetry with multi-singlets, which is brand new but beyond the reach of this paper, will be investigated in another project.

V. CONCLUSION

Both the ATLAS and CMS collaborations have observed excesses in the $(pp \to \gamma\gamma)$ channel at the $\sqrt{s} = 13$ TeV. If confirmed, it would be very interesting and important to investigate the new physics behind this excess since no SM process could generate this excess. We provide a complete theoretical explanation to the excess, which is a CP-even scalar, $\mathbb{S}$, that triggers the spontaneous breaking of a local $U(1)_B$ or $U(1)_{B+L}$ symmetry. $\mathbb{S}$ couples to gluon and photon pairs at the one-loop level with vector like quarks running in the loop, which are introduced to cancel anomalies of this new $U(1)_X$ gauge symmetry. The model also include a scalar dark matter candidate, stabilized by the $U(1)_{B/B+L}$ symmetry, which couples to new fermions so as to avoid the problem of long lived charged/colored particles. Our study shows that this model can naturally explain the diphoton excess without conflicting with other observables. Notably it (benchmark II) also favor the best fit width given by the ATLAS. Constraints on couplings of $\mathbb{S}$ were studied, which showed that $\mathbb{S}$ has a negligible mixing with the standard model Higgs boson, but sizable coupling with the dark matter. We expect the run-2 LHC at high luminosity could shed light on the total width of this new resonance. We just simply assume a very much heavy Z', the phenomenology of which, although important but beyond the reach of this paper, will be given in a future study.

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