Diphoton excess at 750 GeV: Singlet scalars confront triviality

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Abstract

We suggest that the recently observed diphoton excess at 750 GeV comes from a quasi-degenerate bunch of gauge singlet scalars produced and decaying through one or more vector-like fermions. This explains the broad nature of the resonance, even though the decay is loop-mediated. At the same time, the model keeps the new Yukawa couplings in the perturbative region, which is necessary for the stability of the potential.

1 Introduction

Recently, the ATLAS and the CMS Collaborations at the Large Hadron Collider (LHC) announced the hint of a resonance seen at around $\sqrt{s} = 750$ GeV, and decaying into two photons [1, 2]. The local significance of this event is 3.6σ for ATLAS, and 2.6σ for CMS; the global significance, taking into account the look-elsewhere effect, is somewhat smaller. The combined local significance of such a diphoton excess is above 4σ. While it is too early to definitely predict any new physics beyond the Standard Model (SM) right now, the result has led to a flurry of different interpretations. The two-photon decay channel excludes spin-1 nature of the resonance, leaving open spin-0 or spin-2 options (theoretically, higher spins too). Even these options are highly constrained from the apparent significance of the signal even with such a low integrated luminosity, which points to rather strong couplings, and also from non-observation of excesses in certain channels, like dilepton or $t\bar{t}$.

In this paper, we will focus on one of the simplest and most economical explanations of the excess, that caused by a gauge singlet scalar (or a bunch of such scalars, degenerate in mass). For production through gluon fusion and subsequent decay to two photons, this new particle must couple with some vectorlike fermions (VF). Such a model has been discussed in Refs. [3, 4, 5]; there have been other proposals using one or more VFs [6]. Examples of models with such vectorlike fermions can be found, *e.g.*, in Refs. [7].

While being economical, the model also raises a few questions. First, the new Yukawa couplings of the VFs with the scalar have to be very large to explain the signal. Such couplings are not only nonperturbative but also make the scalar potential unstable because of the strong negative pull on the singlet quartic coupling, which must be positive for stability of the potential. At the same time, it is hard to predict why the width of such a loop-mediated decay be broad. One must mention that attempts to explain this signal are aplenty in the literature [8] [1]. Even when one takes the weighted average of 8 TeV and 13 TeV data, the Yukawa couplings remain nonperturbative.

We would like to ask the question: assuming that the model is renormalizable, how does one make the scalar potential stable? In other words, how does one make the Yukawa couplings small and still be consistent with the data? One answer, of course, is to introduce more VFs; the number of VFs depend on their quantum numbers as well as what is considered to be the perturbative limit. The production cross-section goes as the square of the VF Yukawa coupling, while the negative pull on the scalar quartic coupling goes as the fourth power of the same (the expressions are shown later), so obviously introduction of more VFs will help. An alternative option, which we would like to explore, is to introduce more than one gauge singlet scalars. While such a plethora of scalars may appear bizarre at the first sight, it is perhaps not more bizarre than an equally imposing plethora of VFs.

The simplest version of such a model with N singlet scalars may have a degeneracy or quasi-degeneracy among them. This may also be motivated by some $O(N)$ symmetry of the potential, whose soft breaking possibly gives

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[1] This is reminiscent of the initial Higgs boson results, where the diphoton decay width was slightly anomalous [9, 10], and which gave rise to a lot of possible new physics interpretations.

rise to a quasi-degeneracy of mass. If these scalars are quasi-degenerate, it explains why the resonance looks broad; this is actually a bunch of closely-spaced narrow resonances, seen through experiments whose energy resolution is not that fine. Such a fake broad resonance is hard to resolve at the LHC unless there are two distinct bumps at least 20 GeV apart. Multiple resonances also mean that the Yukawa couplings can be small, the effect being the sum of all these resonances. This makes the model stable with respect to a renormalization group running until the couplings blow up at the Landau pole.

In Section II, we briefly discuss the model, and show our results in Section III. In Section IV, we summarize and conclude.

2 The model

As this is a short paper, we will not go through the salient features of the model but refer the reader to Ref. [11] for details. The scalar potential is

$$V(\Phi, S_i) = -\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2 + M^2 \sum_i S_i^2 + \lambda_S \left(\sum_i S_i^2 \right)^2 + a(\Phi^\dagger \Phi) \sum_i S_i^2 \,. \tag{1}$$

where, apart from the SM doublet Φ, we have taken N number of gauge singlet scalars, $i = 1 \cdots N$. There is an explicit Z_2 symmetry, $S_i \to -S_i$, preventing the odd terms in S_i. We will take $\mu^2, M^2 > 0$ so that the S-fields do not have a nonzero vacuum expectation value (VEV) and hence do not mix with Φ. At this simplest level, all singlets are degenerate and have the same quartic coupling λ_S. This, however, is not a strict requirement. One can also remove the ad hoc Z_2 symmetry. That will allow terms like $\Phi^\dagger \Phi S_i$ in the potential and may lead to S_i decaying into two Higgs bosons. Without the Z_2 symmetry, the potential is also far richer and may involve multiple minima of different depth.

For the time being, we will consider only one vector quark Q, singlet under $SU(2)_L$ and with electric charge e_Q , which can be $+\frac{2}{3}$ or $-\frac{1}{3}$ for conventional vector fermion models. This brings in two further terms in the potential:

$$\mathcal{L}_Q \supset -M_Q \overline{Q} Q - \zeta_{iQ} \overline{Q} Q S_i \,, \tag{2}$$

where ζ_Q, the new Yukawa coupling, plays the crucial role in production and decay of the singlets. For simplicity, we take all the ζ_{iQ}s to be the same and denote it by ζ_Q.

Knowledge of the potential parameters like λ_S, a, or ζ_Q will help us narrowing down the features of the potential [12]. However, only ζ_Q can be accessed through the diphoton channel and the quartic couplings a and λ_S remain free parameters of the theory.

There are no constraints from oblique parameters if the VFs are degenerate and the singlet scalars do not mix with Φ. The stability of the potential imposes the following conditions for stability:

$$\lambda > 0 \,, \quad \lambda_S > 0 \,, \quad a + 2\sqrt{\lambda \lambda_S} > 0 \,. \tag{3}$$

Next, we would like to see how the couplings evolve with energy. We will limit our discussions within one-loop effects only The one-loop β-functions are [11]

$$
\begin{aligned}
16\pi^2\beta_\lambda &= 12\lambda^2 + 6g_t^2\lambda + Na^2 - \frac{3}{2}\lambda(g_1^2+3g_2^2) - 3g_t^4 + \frac{3}{16}(g_1^4 + 2g_1^2g_2^2 + 3g_2^4)\,, \\
16\pi^2\beta_{\lambda_S} &= (32+4N){\lambda_S}^2 + a^2 + 4\lambda_S Z^2 - N_c\zeta_Q^4\,, \\
16\pi^2\beta_a &= \left[6\lambda + 12\lambda_S + 4a + 6g_t^2 + 4Z^2 - \frac{3}{2}g_1^2 - \frac{9}{2}g_2^2\right]a\,, \\
16\pi^2\beta_{g_t} &= \left[\frac{9}{4}g_t^2 - \frac{17}{24}g_1^2 - \frac{9}{8}g_2^2 - 4g_3^2\right]g_t\,, \\
16\pi^2\beta_{g_3} &= -\frac{17}{6}g_3^3\theta(q^2-m_Q^2) - \frac{19}{6}g_3^3\theta(m_Q^2-q^2)\,, \\
16\pi^2\beta_{\zeta_U} &= \left[\frac{3}{2}\zeta_U^2 + Z^2 - \frac{4}{3}\left(\frac{1}{12}\right)g_1^2 - 0\left(\frac{9}{4}\right)g_2^2 - 4g_3^2\right]\zeta_U\,, \\
16\pi^2\beta_{\zeta_D} &= \left[\frac{3}{2}\zeta_U^2 + Z^2 - \frac{1}{3}\left(\frac{1}{12}\right)g_1^2 - 0\left(\frac{9}{4}\right)g_2^2 - 4g_3^2\right]\zeta_D\,,
\end{aligned}
\tag{4}
$$

where $\beta_h \equiv dh/dt$, and $t \equiv \ln(q^2/\mu^2)$, and we have taken all VFs to be heavier than the top. If there are more than one such VFs, the last term in the second β-function, $N_c\zeta_Q^4$, should be replaced by $\sum_i N_c^i\zeta_i^4$, where $N_c^i = 3(1)$ for quarks (leptons). Note that our definition of t differs by a factor of 2 from that used by some authors. For the new fermions, the β-functions are given for the singlet (doublet) type VFs. For simplicity, we have put all the SM Yukawa couplings equal to zero except for that of the top quark. This hardly changes our conclusions. Note that a large value of ζ_Q quickly makes λ_S negative because of the ζ_Q^4 term, thus rendering the potential unstable.

If the vectorlike quark Q is much heavier than 750 GeV, we can integrate it out to write the effective interaction vertices

$$
\mathcal{L}_{\rm eff} = C_\gamma F_{\mu\nu}F^{\mu\nu}S + C_g G^a_{\mu\nu}G^{a\mu\nu}S\,, \tag{5}
$$

where

$$
\begin{aligned}
C_\gamma &= \frac{\alpha}{2\pi}N_c e_Q^2\frac{\zeta_Q}{M_Q}A_{1/2}(x)\,, \\
C_g &= \frac{\alpha_s}{4\pi}\frac{\zeta_Q}{M_Q}A_{1/2}(x)\,,
\end{aligned}
\tag{6}
$$

with

$$
A_{1/2}(x) = 2x\left[1+(1-x)f(x)\right]\,,\quad f(x) = \left[\sin^{-1}(1/\sqrt{x})\right]^2\,. \tag{7}
$$

Here $x = 4M_Q^2/M_S^2$ and in the limit $x \gg 1$, $A_{1/2}(x) \to \frac{4}{3}$. The decay widths in this limit are given by

$$
\Gamma(S\to\gamma\gamma) = \frac{\alpha^2}{16\pi^3}e_Q^4\zeta_Q^2\frac{M_S^3}{M_Q^2}\,,\quad \Gamma(S\to gg) = \frac{\alpha_s^2}{72\pi^3}\zeta_Q^2\frac{M_S^3}{M_Q^2}\,. \tag{8}
$$

The cross-section for $pp\to\gamma\gamma$, mediated by all the scalars, is proportional to

$$
\sigma(pp\to\gamma\gamma) \propto \frac{N}{M_S}\left(\frac{\Gamma(S\to\gamma\gamma)\Gamma(S\to gg)}{\Gamma(S\to\gamma\gamma)+\Gamma(S\to gg)}\right)\,. \tag{9}
$$

3 Analysis

We will not go into a detailed analysis of the signal here. The 13 TeV data, in a narrow-width approximation, gives $\sigma(pp\to\gamma\gamma) \in [3:9]$ fb at 68% CL, taking both ATLAS and CMS numbers [4], for $M_S = 750$ GeV. This gives a range of ζ_Q, as a function of the number of singlets N, the mass of the fermion, and the electric charge of the fermion. Taking both 8 TeV and 13 TeV data, the range for the cross-section, at 68% CL, changes to $[1.3:4.2]$ fb. We will work only with the 13 TeV data.

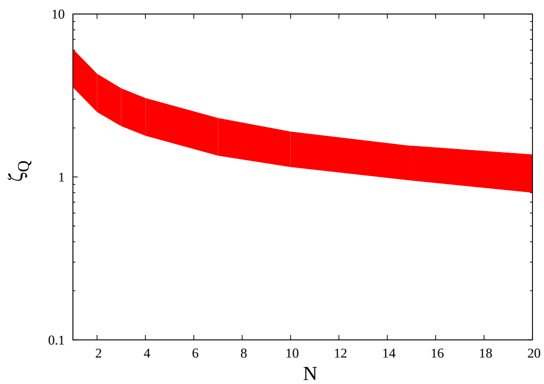

Figure 1: *Upper and lower ranges of the Yukawa coupling ζ_Q, as a function of the number of singlet scalars N, assuming a diphoton cross section of* $[3:9]$ *fb.*

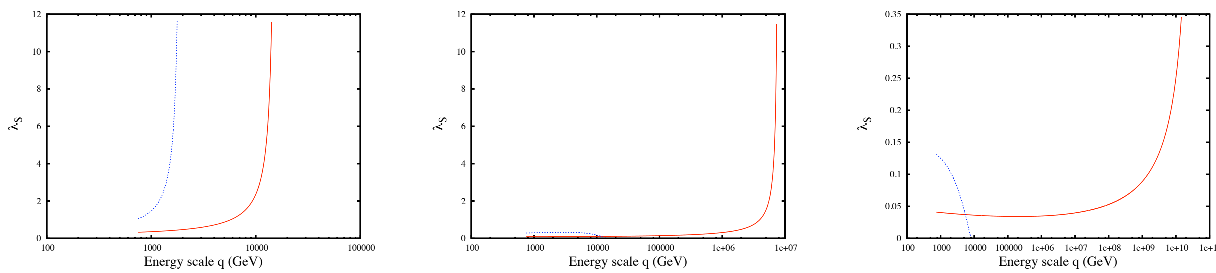

Figure 2: *The running of λ_S with energy as a function of N, for $N = 10$ (left), 20 (centre) and 30 (right). The solid (red) line is for the lower range of the diphoton cross-section, and the dashed (blue) line is for the upper range. We have taken only one charge $+\frac{2}{3}$ isosinglet vector-like quark at $M_Q = 1$ TeV.*

In Fig. 1, we show the range of the Yukawa coupling ζ_Q that is needed to generate the signal, as a function of the number of singlet scalars. The range is highly nonperturbative for a small number of scalars. The plot is drawn for $M_Q = 1$ TeV and $e_Q = +\frac{2}{3}$, it gets even worse for heavier fermions (only the ratio ζ_Q/M_Q is bounded from the data), and down-type quarks, for which the branching fraction to $\gamma\gamma$ goes down, needing an even higher ζ_Q to compensate it. One may add a full vectorial generation, including leptons, to add a further channel that helps in $S \to \gamma\gamma$ decay but does not affect the production [3], but a single VF generation with one singlet scalar still needs uncomfortably large ζ_Q. This is only to be expected, as we are trying to reproduce a signal, whose strength is more indicative of a strong dynamics, through weak dynamics only. With a single scalar, it is also impossible to reproduce a large decay width with perturbative Yukawa couplings.

Interesting but expected results appear when we look at the renormalization group evolution of the couplings, as shown in Fig. 2, for which we use the one-loop β-functions given in Eq. (4). We use the following values for the scalar quartic couplings, λ being already fixed by the Higgs boson mass.

$$\begin{aligned} N = 10 \quad &\Rightarrow \quad a = 0.42\,, \quad \lambda_S = 0.33(1.05)\,, \\ N = 20 \quad &\Rightarrow \quad a = 0.21\,, \quad \lambda_S = 0.09(0.29)\,, \\ N = 30 \quad &\Rightarrow \quad a = 0.14\,, \quad \lambda_S = 0.04(0.13)\,. \end{aligned} \tag{10}$$

These numbers might be taken as some sample benchmark values, the lower (higher) value of λ_S being chosen for the lower (higher) range of the diphoton cross-section, ~ 3 fb (~ 9 fb). The value of ζ_Q is fixed by N, e_Q, the cross-section, and the mass of Q, which we take to be 1 TeV. However, one can also check that these benchmark values make the coefficients of the quadratic divergences of the scalars to vanish at the energy scale of 750 GeV, whatever might be read into that.

Obviously, higher values of the couplings make the model unstable more quickly. For $N = 10$, the upper value of λ_S hits the Landau pole at 1.8 TeV, which is very much accessible at the LHC; for the lower value, the range is a bit higher, at about 14 TeV. Thus, even with 10 such singlets, the model is superseded by some ultraviolet complete theory at a few TeV at the most, and the situation is much worse for smaller values of N. One may postpone this fate till a higher energy scale with smaller values of a to start with. On the other hand, smaller values of λ_S will make the theory unstable even faster, because of the negative pull of the Yukawa coupling ζ_Q.

The problem is easy to identify: the large value of ζ_Q needed to satisfy the data. One may make the model work till the Planck scale with enough singlet scalars (the exact number depends on the values of a and λ_S), also leading to a first-order electroweak phase transition. However, the situation improves considerably if the diphoton cross-section settles down to the lower range, something like the average of 8 and 13 TeV data.

4 Summary

In this paper, we have tried to take a critical look at one of the simplest models to explain the recently observed diphoton excess at the LHC, namely, a singlet scalar associated with a vectorlike fermion. The immediate hurdle is the large number of events, which means a large production cross-section, and hence a Yukawa coupling ζ_Q which is nonperturbative. This also means that a renormalizable theory has very limited validity, thus indicating the possible presence of more scalars and fermions.

With one singlet scalar, both ζ_Q and λ_S are strongly nonperturbative. While one cannot apply the perturbative β-functions to evaluate the running of the couplings, one may surmise that the model is quite unstable because of the strong negative pull of ζ_Q on λ_S. This forces us to consider a scenario where there are more than one such singlet scalars. They better be quasi-degenerate, all contributing to the signal, and explaining the broad resonance as a sum of unresolved narrow resonances. In the simplest scenario, the singlets do not mix with the SM doublet field. This removes the constraint coming from $t\bar{t}$ production at the resonance, and keeps the Higgs boson partial decay widths consistent with the SM expectation.

With $N \gg 1$, the couplings are brought back in the perturbative region, and a study of the renormalization group equations indicate that the model remains valid beyond the LHC range, the validity depending strongly on N and rapidly increasing with it.

One may fine-tune or extend the model further, by adding more vectorlike fermions. Even the simplest model with one isosinglet quark is not realistic without a tiny admixture with the chiral quarks. One may have $SU(2)$ doublets or triplets of such vectorlike quarks, and also vectorlike leptons. If a dijet excess is not seen at 750 GeV, vectorlike leptons with stronger Yukawa couplings than the quarks may be a solution. There may be more than one generation of such fermions. The $O(N)$ symmetry of the scalars may be softly broken. The next step would be to confirm this signal, look for the dijet excess, followed by a search for exotic fermions. Unfortunately, if the singlet scalars are quasi-degenerate, the resolution of LHC may not be enough to split the individual peaks. Another interesting possibility is to study the model in a photon-photon collider [13].

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