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Composite models for the 750 GeV diphoton excess

Keisuke Harigaya [a,b,*], Yasunori Nomura [a,b]

[a] Berkeley Center for Theoretical Physics, Department of Physics, University of California, Berkeley, CA 94720, United States
[b] Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States

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ABSTRACT

We present composite models explaining the diphoton excess of mass around 750 GeV recently reported by the LHC experiments.

1. Introduction

Recently, the existence of a diphoton excess of mass around 750 GeV has been reported by both the ATLAS [1] and CMS [2] experiments at the LHC. The signals are still only 3.6 σ and 2.6 σ in the respective experiments, but if confirmed, this would indicate the long awaited discovery of new physics at the TeV scale.

Because of the Landau–Yang theorem [3], a particle decaying into two photons must have spin either 0, 2, or higher. Assuming spin 0, it is natural to postulate that the particle is a composite state of some strong dynamics around the TeV scale, since it would then not introduce any new hierarchy problem beyond that of the standard model Higgs boson, which may have an environmental understanding [4].

In fact, the relevance of strong dynamics is also suggested by the data. Suppose the diphoton resonance is a scalar field S of mass $m_S \simeq 750$ GeV, whose couplings to the gluon and photon are induced by the following interaction

$$\mathcal{L} = \lambda S Q \bar{Q}, \tag{1}$$

where λ is a coupling constant, and $(Q, \bar{Q})$ is a heavy vector-like fermion of mass m_Q charged under the standard model gauge group, $SU(3)_C \times SU(2)_L \times U(1)_Y$. Assuming that $(Q, \bar{Q})$ is an $SU(3)_C$ triplet and has charge q, its loop generates

$$\mathcal{L} \sim \frac{1}{24\pi^2}\frac{\lambda S}{m_Q}\left(\frac{1}{2}g_3^2 G^{a\mu\nu}G^a_{\mu\nu} + 3(qe)^2 F^{\mu\nu}F_{\mu\nu}\right), \tag{2}$$

where g_3 and e are the QCD and QED gauge couplings, respectively, and $G^a_{\mu\nu}$ and $F_{\mu\nu}$ are the corresponding field strengths. The production cross section of S through gluon fusion times the branching ratio into diphoton is then given by

$$\sigma_{pp\to S} B_{S\to AA} \simeq 0.2\ \text{fb} \times \lambda^2 \left(\frac{q}{2/3}\right)^4 \left(\frac{600\ \text{GeV}}{m_Q}\right)^2. \tag{3}$$

Here, we have normalized m_Q by its experimental lower bound [5]. (Note also that the decay of S into $Q\bar{Q}$ must be kinematically forbidden in order not to suppress the diphoton signal, giving $m_Q > m_S/2 \simeq 375$ GeV.) We find that to reproduce the observed excess, which requires $\sigma_{pp\to S} B_{S\to AA} \sim 10$ fb, the coupling λ must be rather large. This suggests the existence of strong dynamics behind the physics generating couplings between the resonance of interest and standard model gauge bosons.

Motivated by these considerations, in this paper we present models in which the observed diphoton excess arises from a composite particle of some hidden strong gauge interactions. We present a scenario in which the particle is a state around the dynamical scale (a hidden glueball or a hidden eta prime) as well as a scenario in which it is lighter (a hidden pion). We see that some of the models have possible tensions with diboson searches at 8 TeV, but others do not. In particular, we find that the model having the charge assignment consistent with $SU(5)$ grand unification has a parameter region in which the observed diphoton excess is reproduced without contradicting the other data. In general, the models described here yield multiple resonances in the TeV region, which may be observed in the future LHC data.

In the appendix, we present a general analysis of constraints from the 8 TeV data in the case that the scalar resonance is coupled to the standard model gauge fields only through dimension-5 operators.

* Corresponding author at: Berkeley Center for Theoretical Physics, Department of Physics, University of California, Berkeley, CA 94720, United States.
E-mail address: keisukeharigaya@berkeley.edu (K. Harigaya).

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Table 1
Charge assignment of a hidden "heavy" quark. Here, $a \neq 0$, and Q and $\bar{Q}$ are left-handed Weyl spinors.

	G_H	$SU(3)_C$	$U(1)_Y$
Q	$\square$	$\bar{\square}$	a
$\bar{Q}$	$\bar{\square}$	$\square$	$-a$

2. Hidden glueball: minimal model

Consider a hidden gauge group G_H, with the dynamical scale (the mass scale of generic resonances) Λ. For simplicity, we take G_H to be $SU(N)$. We also introduce a vector-like hidden quark $(Q, \bar{Q})$ of mass m, whose charges under G_H and the standard model $SU(3)_C$ and $U(1)_Y$ are given in Table 1. Here, Q and $\bar{Q}$ represent left-handed Weyl spinors.

For $m \gtrsim \Lambda$, the hidden quark can be regarded as a "heavy" quark (with respect to Λ), and the lightest hidden hadron will be a glueball s consisting of hidden sector gauge fields, of mass

$$m_s \sim \Lambda. \tag{4}$$

Due to the existence of $(Q, \bar{Q})$, we expect that this state couples to the standard model gauge fields as

$$\mathcal{L} \sim -\frac{\Lambda^3}{4\pi m^4} s \left(\frac{g_3^2}{2} G^{a\mu\nu} G^a_{\mu\nu} + \frac{9a^2 g_1^2}{5} B^{\mu\nu} B_{\mu\nu} \right), \tag{5}$$

where $a = 1, \cdots, 8$ is the $SU(3)_C$ adjoint index, and g_3 and g_1 are the $SU(3)_C$ and $U(1)_Y$ gauge couplings, respectively.[1] Here and below, we count possible factors of 4π using naive dimensional analysis [6].

The hidden glueball state s can be produced by gluon fusion (among others) and decay into diphoton with the branching ratio

$$B_{s\to\gamma\gamma} = \frac{81a^4}{50} \frac{\cos^4\theta_W g_1^4}{8g_3^4} \simeq 0.033\, a^4, \tag{6}$$

where θ_W is the Weinberg angle. The production cross section of s through Eq. (5) at 13 TeV pp collisions can be estimated (after multiplying the diphoton branching ratio) as

$$\sigma_{pp\to s} B_{s\to\gamma\gamma} \sim 10 \text{ fb} \times a^4 \left(\frac{3.5 \text{ TeV}}{m^4/\Lambda^3} \right)^2, \tag{7}$$

where we have used NNPDF 3.0 [7] for the parton distribution function. We thus find that

$$\Lambda \sim 700 \text{ GeV}, \qquad m \sim 1 \text{ TeV} \tag{8}$$

give m_s and $\sigma_{pp\to s} B_{s\to\gamma\gamma}$ roughly consistent with the excess in the 13 TeV data.

The model is subject to constraints from analogous high-mass diboson resonance searches in the 8 TeV data. Assuming that the production occurs through interactions in Eq. (5), the ratio of the s production cross sections at 8 TeV and 13 TeV is

$$\frac{\sigma_{pp\to s}|_{8\text{ TeV}}}{\sigma_{pp\to s}|_{13\text{ TeV}}} \simeq 0.21, \tag{9}$$

for $m_s = 750$ GeV. This gives $\sigma_{pp\to s} B_{s\to\gamma\gamma}$ close to the upper limit from the 8 TeV data [8]. The model also gives definite predictions for the relative branching ratios between $s \to \gamma\gamma, ZZ,$ and $Z\gamma$

$$\frac{B_{s\to ZZ}}{B_{s\to\gamma\gamma}} = \tan^4\theta_W \simeq 0.09, \tag{10}$$

$$\frac{B_{s\to Z\gamma}}{B_{s\to\gamma\gamma}} = 2\tan^2\theta_W \simeq 0.6, \tag{11}$$

where we have ignored the phase space factors. With Eq. (9), we thus obtain

$$\sigma \times B|_{Z\gamma,\,8\text{ TeV}} \simeq 1.3 \text{ fb} \left(\frac{\sigma \times B|_{\gamma\gamma,\,13\text{ TeV}}}{10 \text{ fb}} \right). \tag{12}$$

This is consistent with the upper limit from the 8 TeV data [9].

We note that the precise value of $\sigma \times B|_{8\text{ TeV}}$ depends on the details of s production, which we have assumed here to occur only through Eq. (5). (For an analysis of constraints from the 8 TeV data for general dimension-5 couplings between s and the standard model gauge fields, see the appendix.) The assumption of gluon fusion dominated production, however, may not be valid in some cases. For example, depending on the values of m and Λ, production of heavy resonances that are composed of Q and $\bar{Q}$ and decay into s may give comparable contributions to the production of single s through the gluon fusion. With this production mechanism, the production rates of s in 8 TeV and 13 TeV pp collisions will differ more, relaxing the constraints from the 8 TeV data. The production mechanisms can be differentiated experimentally, e.g., through the transverse momentum distribution of photons. Detailed analyses of this issue are warranted.

Limits from other diboson decays of s, i.e. to gg and ZZ, are weaker.

Table 2
Charge assignment of hidden "light" quarks. Here, $a^2 \neq b^2$, and $Q_{1,2}$ and $\bar{Q}_{1,2}$ are left-handed Weyl spinors.

	G_H	$SU(3)_C$	$U(1)_Y$	$U(1)_A$
Q_1	$\square$	$\bar{\square}$	a	1/3
Q_2	$\square$	**1**	b	−1
$\bar{Q}_1$	$\bar{\square}$	$\square$	$-a$	1/3
$\bar{Q}_2$	$\bar{\square}$	**1**	$-b$	−1

3. Hidden pion: minimal model

We now consider a model in which the 750 GeV resonance is a hidden "pion," instead of the hidden glueball. A virtue of this model is that we need to rely less on the dynamical assumption about the hidden sector. As before, we take the hidden gauge group G_H to be $SU(N)$, but now we take the hidden quarks to have charges in Table 2 and mass terms

$$\mathcal{L} = -m_1 Q_1 \bar{Q}_1 - m_2 Q_2 \bar{Q}_2 + \text{h.c.}, \tag{13}$$

where we take $m_{1,2} > 0$ without loss of generality. We assume that these masses are sufficiently smaller than the dynamical scale, $m_{1,2} \ll \Lambda$, so that $Q_{1,2}$ and $\bar{Q}_{1,2}$ can be regarded as hidden "light" quarks.

3.1. Hidden pion dynamics

The strong G_H dynamics makes the hidden quarks condensate

$$\langle Q_1 \bar{Q}_1 \rangle \approx \langle Q_2 \bar{Q}_2 \rangle \equiv \langle Q \bar{Q} \rangle \approx \frac{1}{16\pi^2} \Lambda^3. \tag{14}$$

These condensations do not break the standard model $SU(3)_C$ or $U(1)_Y$, since the hidden quark quantum numbers under these gauge groups are vector-like with respect to G_H [10]. The spectrum below Λ then consists of hidden pions, arising from spontaneous breaking of approximate $SU(4)_A$ axial flavor symmetry:

[1] Throughout the paper, we adopt the hypercharge normalization such that the standard model fermions have $(q, \bar{u}, \bar{d}, l, \bar{e}) = (1/6, -2/3, 1/3, -1/2, 1)$, and g_1 is in the $SU(5)$ normalization.