A resonance without resonance: scrutinizing the diphoton excess at 750 GeV

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Abstract: Motivated by the recent diphoton excesses reported by both ATLAS and CMS collaborations, we suggest that a new heavy spinless particle is produced in gluon fusion at the LHC and decays to a couple of lighter pseudoscalars which then decay to photons. The new resonances could arise from a new strongly interacting sector and couple to Standard Model gauge bosons only via the corresponding Wess-Zumino-Witten anomaly. We present a detailed recast of the newest 13 TeV data from ATLAS and CMS together with the 8 TeV data to scan the consistency of the parameter space for those resonances.

Keywords: BSM Phenomenology, Hadronic Colliders

Contents

1 Introduction

After analyzing the first 13 TeV data, the ATLAS and CMS collaborations have reported an excess with respect to the background predictions in the diphoton channel search [1, 2]. ATLAS has found the most significant deviation for a mass of about 750 GeV, corresponding to a local significance of $3.64\,\sigma$ using 3.3 fb^{-1} accumulated data, whereas CMS has a significance of $2.6\,\sigma$ for a mass about the same as ATLAS using 2.7 fb^{-1} data.

A simple explanation of such an excess could be through a resonance of a spin-0 or spin-2 particle with mass $\sim$ 750 GeV that decays to photons [3–40], while spin-1 is excluded by the Yang-Landau theorem [41, 42]. However, resonant production via the s-channel might be in tension with bounds imposed by run-I data [43–45].

Motivated by this fact, we propose an alternative scenario to explain the excess via a non-resonant process. We demonstrate our idea within the framework of strong dynamics around the TeV scale. The basis of the theoretical model are outlined in [46] (some of these ideas have also been mentioned in [3]) with the addition of two composite singlet scalar (or pseudoscalar) particles which couple to Standard Model (SM) gauge bosons via the Wess-Zumino-Witten anomaly [47, 48], and to each other via a trilinear coupling. Here, we assume that the lighter 750 GeV pseudoscalar has no effective coupling to the gluons and thus cannot be directly produced. Therefore, the lighter pseudoscalar has to be produced in the decay of the heavy one which can be produced via gluon fusion. In contrast to e.g. [3] we do not try to embed this into a complete model, but concentrate on the minimal simplified model that resembles a "composite sector toy model" including two resonances to describe the LHC results from the 8 and 13 TeV data sets.

The parameter space of the model then consists of the masses of the two (pseudo)scalar states, their decay constants, and their three anomaly coefficients to the field strengths of the three gauge groups of the SM. In this work we search for solutions that explain the excess, and to determine the best fit to the data by means of a numerical analysis.

This work is structured as follows. In Section 2 we present a general description of our model assumptions, whereas in Section 3 we describe the numerical procedure used to fit the data and show the results, and finally in Section 4 the conclusions are outlined.

2 Model assumptions

In this section, we describe in detail the assumptions for our simplified model setup to explain the ATLAS and CMS data. We discuss the most important phenomenological aspects of the simplified model below. Detailed information about the underlying assumptions on strongly interacting sectors for such a setup can be found e.g. in Ref. [3, 46].

In our simplified model, we consider the SM particle spectrum extended by possible weak scale singlet spin 0 resonances. We assume that these new resonances (and possibly also the SM-like Higgs boson) are composite objects. However, the details of the electroweak symmetry breaking will not affect our numerical analysis and its results and thus we do not discuss it any further. We assume a hidden strongly interacting (confining) gauge group G_N. Two pseudoscalar resonances σ and η emerge as the Nambu Goldstone bosons of the broken gauge group G_N. [1] The kinetic terms of the weak singlet pseudoscalars are given by

$$\mathcal{L}_{\text{kin}} = \partial_\mu \eta \partial^\mu \eta + \partial_\mu \sigma \partial^\mu \sigma - m_\eta^2 \eta^2 - m_\sigma^2 \sigma^2. \tag{2.1}$$

Here, m_η and m_σ are the mass terms of the real pseudoscalar fields η and σ. We assume the following parity violating trilinear σ-η-η interaction term,[2]

$$\mathcal{L}_{\text{trilinear}} = \lambda\, \sigma \eta \eta, \tag{2.2}$$

where λ is a real parameter of mass dimension one. In a more general framework, all interaction terms up to mass dimension 4 consistent with our model should be included. However, since the diphoton excess can be explained with the trilinear interaction term only, we will omit these terms in the remainder of the letter.

The new resonances only couple to the SM gauge bosons via the Wess-Zumino-Witten (WZW) anomaly [47, 48] ,

$$\mathcal{L}_{\eta gg} = \kappa_g^\eta \frac{g_3^2}{32\pi^2} \frac{1}{F_\eta} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} \eta, \tag{2.3}$$

$$\mathcal{L}_{\eta WW} = \kappa_W^\eta \frac{g_2^2}{32\pi^2} \frac{1}{F_\eta} \epsilon^{\mu\nu\rho\sigma} W^i_{\mu\nu} W^i_{\rho\sigma} \eta, \tag{2.4}$$

$$\mathcal{L}_{\eta BB} = \kappa_B^\eta \frac{g_Y^2}{32\pi^2} \frac{1}{F_\eta} \epsilon^{\mu\nu\rho\sigma} B_{\mu\nu} B_{\rho\sigma} \eta, \tag{2.5}$$

[1] There are possibly more resonances, but they do not play a role for the moment as no further signals have been observed yet.

[2] We assume that parity is explicitly violated via a nonzero θ term in the gauge group G_N.

and

$$\mathcal{L}_{\sigma gg} = \kappa_g^\sigma \frac{g_3^2}{32\pi^2}\frac{1}{F_\sigma}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}\sigma, \tag{2.6}$$

$$\mathcal{L}_{\sigma WW} = \kappa_W^\sigma \frac{g_2^2}{32\pi^2}\frac{1}{F_\sigma}\epsilon^{\mu\nu\rho\sigma}W^i_{\mu\nu}W^i_{\rho\sigma}\sigma, \tag{2.7}$$

$$\mathcal{L}_{\sigma BB} = \kappa_B^\sigma \frac{g_Y^2}{32\pi^2}\frac{1}{F_\sigma}\epsilon^{\mu\nu\rho\sigma}B_{\mu\nu}B_{\rho\sigma}\sigma, \tag{2.8}$$

respectively. Here, κ_i^η, κ_i^σ and F_η, F_σ denote arbitrary real coefficients and pseudoscalar decay constants, respectively. $G_{\mu\nu}$, $W_{\mu\nu}$ and $B_{\mu\nu}$ are the color, weak isospin and abelian hypercharge field strength fields, and g_3, g_2 and g_Y denote the corresponding dimensionless SM gauge couplings. The prefactors κ_i^η and κ_i^σ can be explicitly calculated in a complete model, i.e. if the particle content (fermions in the composite sector and their exact quantum numbers) in the triangle loop is known [3, 46]. However, in this work we do not consider a particular model and assume that the coefficients κ_i^η and κ_i^σ are free parameters of our effective Lagrangian. In the following, we will assume that the coefficients are independent and determine their values in a numerical analysis without referring to a specific model.

Since the direct production of a 750 GeV resonance via s channel is in tension with constraints from Run 1 data, we assume that it cannot be directly produced, i.e. we set the corresponding anomaly coefficient to zero, $\kappa_g^\eta = 0$. So its production must occur via the heavy resonance σ assuming that σ has anomaly induced couplings to the gluons. Thus, we consider a hierarchical scenario in order to evade the 8 TeV limits. We focus on resonant production of the heavy singlet pseudoscalar σ via gluon fusion with subsequent on-shell decay into a pair of ηs. The light pseudoscalar η is allowed to decay into all electroweak SM gauge bosons via the WZW mechanism and thus we expect the following signature

$$pp \to \sigma \to \eta\eta \to \gamma\gamma + X, \tag{2.9}$$

where X denotes the rest of the event. Both experiments, ATLAS and CMS do not veto on X. We have listed the selection cuts from ATLAS and CMS in Table 1. Hence, this signature can explain the diphoton excess. The anomaly coefficients for the weak and hypercharge group have been partially set to zero as they are phenomenologically not relevant for the numerical analysis (in the case of the heavy resonance), or are not allowed in order not to give a too small branching fraction into photons (for the light resonance). Note that there is a certain redundancy of parameters in the simplified model, as changes to the decay constant can within a certain range of parameters always be emulated by changes in the anomaly coefficient. Once a specific composite model is investigated, this has to be carefully disentangled from each other.

ATLAS	CMS
$p_T(\gamma) \geq$25 GeV	$p_T(\gamma) \geq$75 GeV
$\lvert\eta^\gamma\rvert \leq 2.37$	$\lvert\eta^\gamma\rvert \leq 1.44$ or $1.57 \leq \lvert\eta^\gamma\rvert \leq 2.5$ at least one γ with $\lvert\eta^\gamma\rvert \leq 1.44$
$E_T^{\gamma_1}/m_{\gamma\gamma} \geq 0.4$, $E_T^{\gamma_2}/m_{\gamma\gamma} \geq 0.3$	$m_{\gamma\gamma} \geq 230$ GeV

Table 1. Selection cuts of the 13 TeV ATLAS/CMS diphoton searches [1, 2].

3 Numerical results

In the following, we first briefly discuss the numerical tools and then describe our numerical framework. Finally, we will discuss our results.

3.1 Numerical tools

We have implemented the model with the program `FeynRules 2.3.13` [49] and created a `UFO` output [50] for the numerical studies. Parton level events were generated with `Madgraph 2.3.3` [51] interfaced with `Pythia 6.4` [52] for the parton shower and hadronization. Branching ratios and cross sections have been cross-checked with an independent numerical implementation of the simplified model into `WHIZARD 2.2.8` [53–55]. We have implemented the 8 and 13 TeV diphoton searches from ATLAS and CMS [1, 2] into the `CheckMATE 1.2.2` framework [56] with its `AnalysisManager` [57]. `CheckMATE 1.2.2` is based on the fast detector simulation `Delphes 3.10` [58] with heavily modified detector tunes and it determines the number of expected signal events passing the selection cuts of the particular analysis. The selection cuts for both ATLAS and CMS analyses are shown in Table 1.

3.2 Scan procedure

In order to find values of parameters that provide a good description of data we performed a scan in λ and κ_g^σ in the ranges displayed in Table 2. We simulated pair production of η states via resonant s-channel σ exchange. [3] All decay modes of η were included in the simulation. For each point the number of events passing experimental selections in our simulation is compared to the number of events reported by the LHC collaborations, see Table 3. The expected number of background events is extracted from the respective publication. Because the experiments did not clearly define signal regions, we performed a fit in the invariant mass window $700 < m_{\gamma\gamma} < 800$ GeV. For the CMS search we split the events into the barrel and end-cap regions, following the collaboration's procedure. Finally,

[3] This neglects possible box diagram contributions to η pair production which, however, are equally zero if the QCD WZW anomaly of the η current vanishes.

Parameter	Description	Value or range
m_σ	mass of heavier resonance	2 TeV
m_η	mass of lighter resonance	750 GeV
λ	dimensionfull $\eta\sigma\sigma$	[0. TeV, 1.5 TeV]
F_η	η decay constant	1 TeV
F_σ	σ decay constant	1 TeV
κ_g^η	anomaly coefficient	0
κ_W^η	anomaly coefficient	0
κ_B^η	anomaly coefficient	1
κ_g^σ	anomaly coefficient	[0, 15]
κ_W^σ	anomaly coefficient	0
κ_B^σ	anomaly coefficient	0

Table 2. Variable input parameters of our pseudoscalar scenario and the range over which these parameters are scanned and the best fit point solution.

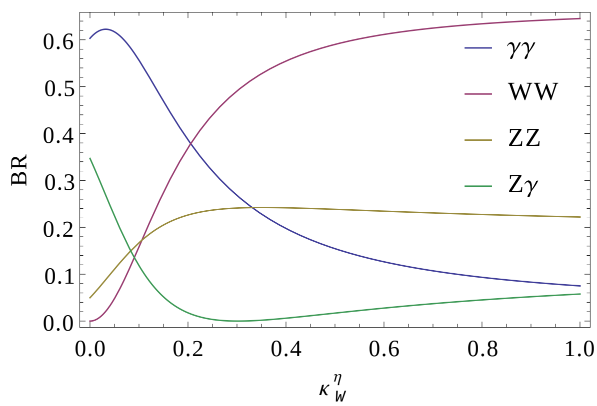

Figure 1. The branching ratios for the decays of η as a function of κ_W^η with $\kappa_B^\eta = 1$.

the 8 TeV searches are used solely as a consistency check in order to see if the parameter points were not excluded during the previous run.

Clearly, the pseudoscalar sector is parametrized by many *a priori* free parameters, as can be seen in Table 2. For simplicity, in the current analysis we set some of them to zero, therefore our heavy pseudoscalar couples only to gluons through the anomaly while the light one only to B. The light pseudoscalar will still have other decay modes to ZZ and $Z\gamma$. Once the κ_W^η coupling is allowed, additional decay modes to WW pairs will be open. We show the decay pattern of η in Figure 1. This will provide a distinctive feature at the colliders: the diphoton pairs will be often accompanied by jets, leptons or missing transverse energy. Along with an expected significant transverse momentum of the $\gamma\gamma$ pairs, this can serve as a way to probe this type of models

The fit was performed with the χ^2 test statistics. Namely,

$$\chi_i^2 = \frac{(n_i - \mu_i)^2}{\sigma_{i,\text{stat}}^2 + \sigma_{i,b}^2} \,, \tag{3.1}$$

where

$$\mu_i = \mu_{i,b} + \mu_{i,s} \,. \tag{3.2}$$

Here, n_i is the number of observed events, $\mu_{i,b}$ is the expected number of background events, $\mu_{i,s}$ is the expected number of signal events, $\sigma_{i,\text{stat}}$ and $\sigma_{i,b}$ are the statistical and systematic uncertainty on the expected number of background events for each signal region, i. We assume that all errors are uncorrelated. The signal regions are defined as $700 < m_{\gamma\gamma} < 800$ GeV.

3.3 Discussion

As explained above, we have performed a scan as a function of the couplings λ and κ_g^σ while keeping the other parameters fixed as it is shown in Table 2. This has been done with the ATLAS and CMS searches and in the following we combine the data of both experiments.

Figure 2 shows the $\log \chi^2$ as a function of λ and κ_g^σ (left panel for ATLAS data alone and right panel for CMS data alone). Figure 3 shows the combination of both experiments. The black contours have a $\chi^2 = 6$ above minimum that correspond to 2σ once the extra degrees of freedom in the fit are considered. It is interesting to notice that the χ^2 follows a hyperbolic-type of curve in the λ, κ_g^σ plane since as it is expected there is a clear degeneracy among the two couplings. Namely an increase in the κ_g^σ coupling enhances the production rate of the σ field via gluon-fusion which is compensated by a decrease of the λ coupling which affects the decay branching fraction of σ decaying to a pair of ηs.

The combined analysis gives the best fit point:

$$\begin{aligned} \lambda &= 0.41 \text{ TeV} \,, \\ \kappa_g^\sigma &= 4.9 \,, \\ \chi^2 &= 2.15 \,. \end{aligned} \tag{3.3}$$

This χ^2 value at the minimum should be compared to the SM-only hypothesis which yields $\chi^2_{\text{SM}} = 8.8$. Finally, we provide the expected and observed numbers of events for each signal region in Table 3.

4 Conclusions

In this work we present a model based on composite states that fits well the diphoton excess observed by the ATLAS and CMS collaborations which points to the existence of a resonance of mass of about 750 GeV.

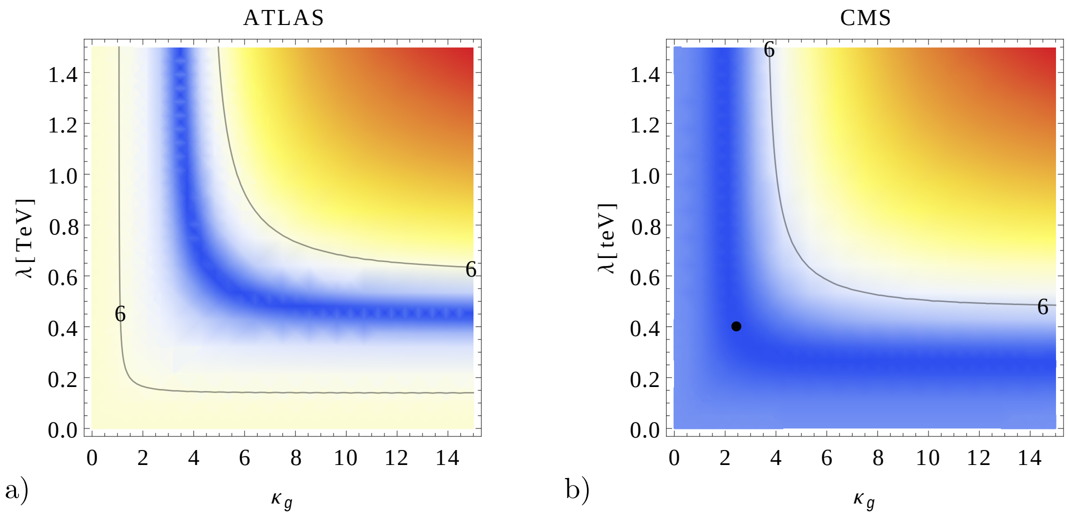

Figure 2. The distribution of the $\log\chi^2$ test as a function of the dimensionful coupling λ and κ_g^σ a) ATLAS [1] b) CMS [2]. The black line denotes $\Delta\chi^2 = 6$ above minimum and the black dot the 'best fit' point using CMS data only.

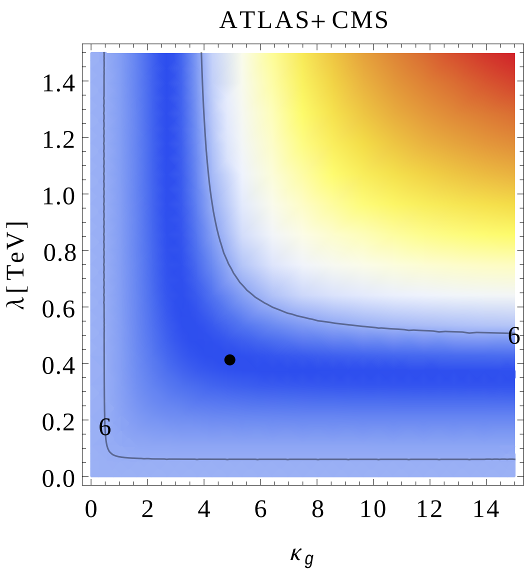

Figure 3. The distribution of the χ^2 test as a function of the dimensionful coupling λ and κ_g^σ for the combined ATLAS and CMS results. The black line denotes $\chi^2 = 6$ above minimum and the black dot the 'best fit' point as specified in Eq. (3.3).

The mechanism consists in the production of a heavy pseudoscalar via gluon fusion with a mass about 2 TeV, which decays to a pair of lighter pseudoscalars with a mass of about 750 GeV that finally decay to photons. While both pseudoscalars couple to the SM gauge bosons via the WZW anomaly, the heavy pseudoscalar couples with the light ones via a dimensionful trilinear coupling which is allowed by the theory.

Our best fit point from the combined analysis of the ATLAS and CMS data is given by

signal region	observed	background	best fit	$\Delta\chi^2$
ATLAS	28	11.4 ± 3	10.4	1.0
CMS EBEB	14	9.5 ± 1.9	7.8	0.62
CMS EBEE	16	18.5 ± 3.7	1.3	0.49

Table 3. The number of events for each of the signal regions: observed, SM background, our 'best fit' according to the simulation results and the $\Delta\chi^2$ contribution. 'EBEB' denotes the signal region with both photons in the barrel while 'EBEE' the signal region with one photon in the end-cap.

$\lambda = 0.41$ TeV and $\kappa_g^\sigma = 4.9$. the χ^2 value at the minimum is 2.15 and the models markedly improves the SM-only value of 8.8. It is also consistent with the 8 TeV searches. It is distinctive feature in the collider experiments compared to the direct s-channel resonance would be non-trivial p_T spectrum of the diphoton pairs and the presence of additional jets, leptons or missing energy, depending on the decays of gauge bosons produced in the opposite decay chain.

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