Dark Matter and the Diphoton Excess

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1 Introduction

Well over 150 papers have been written on the possible 750 GeV diphoton resonance reported by both ATLAS and CMS. A number of these papers connected the resonance to dark matter.

Assuming the resonance is not just a statistical fluke, we can deduce a few properties of the resonance. First, it must have spin 0 or 2 by the Landau-Yang theorem. The resonance must also be produced by a colour and hypercharge neutral particle, and as a result, additional particles beyond the standard model are necessary to explain its production and decay.

The most thorough statistical analysis of the resonance I have found is [1]. There is tension between the CMS and ATLAS data for both the diphoton cross section and width, and the author finds that the best models are those with either a large width ~ 45 GeV and cross section of 10 fb, or narrow width (less than the experimental resolution of ~ 6 GeV) and a cross section of 4 fb. Using only Run-II data gives a preference for a narrow width, but using both Run-I and Run-II gives a slight preference for a wide resonance

We will first discuss the resonance in terms of effective field theory. Next we discuss the possibility of adding heavy fermions or scalars to explain the coupling between the resonance and the SM gauge bosons. From there we shall survey papers which postulate such models. We will then briefly discuss composite models.

2 Effective Theories

Papers [2] through [9] use effective Lagrangians to describe the coupling of the 750 GeV resonance to SM particles. The resonance ϕ is assumed to be a scalar or pseudoscalar, and is furthermore assumed to couple to a SM singlet which provides the dark matter candidate.

The parameters of interest to these models are contained in the Lagrangian

$$\mathcal{L}_1 = \frac{1}{\Lambda}\left(c_{BB}\phi F_{\mu\nu}F^{\mu\nu} + c_{WW}\phi W^a_{\mu\nu}W_a^{\mu\nu} + c_{GG}\phi G^a_{\mu\nu}G_a^{\mu\nu}\right) + g_\phi \phi\bar{\chi}\chi + m_\chi \bar{\chi}\chi$$

for scalar ϕ, with an analogous Lagrangian existing for pseudoscalar ϕ. It is also possible to couple to the Higgs boson, however the mixing angle is strongly constrained by Higgs coupling measurements ($\sin\alpha \lesssim 0.1$) [19].

Papers [2] to [6] contain general analyses of this effective theory using both data from LHC run 1 and from dark matter searches, whereas [7], [8] and [9] contain more specific analyses. I will start with [3] since it is the most general analysis.

Paper [3] presents a detailed analysis of this theory for Dirac fermion χ. For LHC phenomenology, the rescaling of the photon cross section $\mathcal{R}_{\gamma\gamma}$ from 8 TeV to 13 TeV is important for testing the theory against bounds from Run 1 data. Since this has theoretical uncertainties with the value ranging from between about 2 and 5, the cases of $\mathcal{R}_{\gamma\gamma} = 2$ and 5 are both tested.

Written by members of the CERN Theory division, [2] provides an overview of the different possible models for the resonance. The discussion dark matter is brief, though it does contain a discussion of the DM thermal relic abundance. However the paper provides a good introduction to a variety of theoretical models for the resonance, including both a general discussion of weakly coupled and strongly coupled models.

If $m_\chi \geq m_\phi/2 \approx 375$ GeV, then the scalar field decays only to SM bosons. There are a range of parameters for which the experimental cross section can be reproduced, however Run 1 $Z\gamma$ and jj limits preclude the width from being the ATLAS preferred value of 45 GeV. Both photon fusion and gluon fusion are viable production mechanisms for ϕ, though for photon fusion tension exists with $Z\gamma$ bounds if $\mathcal{R}_{\gamma\gamma} = 2$. The case where $c_{GG} = c_{WW} = 0$ is viable, but it is not possible for $C_{BB} = 0$.

For the case with $m_\chi \leq m_\phi/2 \approx 375$ GeV, a width of 45 GeV can be obtained for g_ϕ of $\mathcal{O}(1)$. Decays to χ then dominate. Restrictions on the SM boson couplings are similar to the previous case.

The effective Lagrangian is analysed to consider whether χ could explain dark matter. For a scalar resonance with photon fusion, a thermal relic is viable for $m_\chi \lesssim m_\phi/2$, and DM coupling with nuclei is below the LZ projected sensitivity. The case of a scalar resonance produced by gluon fusion is strongly constrained by LUX (mono-jets also constrain this case but are strictly dominated by LUX), though it is still possible to choose parameters consistent with both the thermal relic density and the ATLAS preferred width.

For pseudoscalar resonance, indirect searches significantly constrain the parameters, although the results from HESS depend on assumptions about the dark matter density profile. The only viable models are those with gluon fusion and $m_\chi \geq m_\phi/2$ or possible photon fusion with $m_\chi \geq 500$ GeV if the HESS limits are not used.

Paper [4] also presents an analysis of χ as a DM candidate, although rather that using a Dirac fermion, they test Majorana fermions coupled to both scalar and pseudoscalar resonances, and also scalar and vector χ coupled to scalar resonances. Gluon fusion is the only production method discussed in the paper. The authors search through various parameter values to find theories with the correct diphoton cross section and satisfying the Run 1 restrictions, and then use these to find viable values of m_χ and g_ϕ. For scalar and vector χ both direct and indirect dark matter searches restrict the dark matter mass and coupling strength. For Majorana fermions the conclusions are similar to that of the gluon fusion case in [7], with direct detection restricting the scalar ϕ case and indirect detection restricting the pseudoscalar case.

Assuming a scalar resonance, gluon fusion and $g_{WW} = 0$, [5] explores the parameter space of the effective theory to find values of g_ϕ and m_χ which are compatible both with the ATLAS width and with the dark matter relic density. They find that this requires $280 \lesssim m_\chi$, and $g_\phi \approx 1.1$.

The possibility of Higgs mixing is considered in [6], which assumes a pseudoscalar resonance and $g_{WW} = 0$. The authors show that a range of dark matter masses $(88 - 280)$ GeV can give both the correct relic density and total decay width.

In [7] two different parameter sets are discussed, the first of which has $c_{\gamma\gamma} = 0.067$ TeV^{-1}, $c_{GG} = 0.33$ TeV^{-1} and $c_{WW} = 0$. These parameters are however ruled out by dijet results in [3]. The second has $c_{\gamma\gamma} = c_{GG} = 0.04$ TeV^{-1} but with also includes a coupling to the top quark, via an effective interaction

$$0.71\phi\bar{\psi}_t\psi_t$$

though this model is not tested against Run 1 negative results so I'm not sure if it is viable. They should that in the presence of a top coupling and scalar resonance, the prospects of direct detection are low. Otherwise they conclude that direct detection is able to restrict the scalar case, and indirect detection the pseudoscalar case.

Paper [9] discusses the case of pseudoscalar ϕ with $m_\chi \geq 1/2m_\phi$. The authors find that the HESS results place some restrictions on the dark matter mass and coupling, in agreement with [3] and [4].

Finally, [8] gives an analysis of the mono-jet bounds for invisible decays, assuming gluon fusion. In models where χ constitutes dark matter, these bounds are superseded by dark matter searches as shown in [3]. However, the mono-jet bounds still strongly constrain the situation where $m_\chi \leq 1/2m_\phi$, and this is potentially important in more complicated theories.

3 Additional Heavy Particles

To generate the interaction between the scalar resonance and SM gauge bosons, we need to introduce new heavy particles coupling both to the scalar and which transform non-trivially under the SM gauge group. The simplest way to achieve this is to add fermions which must be coupled in a vector-like fashion in order to allow Yukawa couplings with the SM singlet resonance. There are limits on possible masses of the heavy fermions, but I'm not entirely sure how to interpret them. Heavy charged leptons must be heavier than about 100 GeV, and limits on fourth generation coloured fermions are stricter, about 675 GeV for b' and 782 GeV for t'. In general we will have

$$\mathcal{L}_{int} = (m^2 + y\phi)(\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R) + \text{SM singlets involving } \psi_{R,L}$$

The possibility of non-trivial couplings to SM fermions and/or the Higgs boson only occurs for specific representations. Along with the representations used for SM fermions, the representations

$$(1,3)_0, (1,1)_0, (1,2)_{3/2}, (3,3)_{2/3}, (3,2)_{7/6}, (3,2)_{-5/6}$$

also allow non-trivial SM interactions and hence can mixing.

There are many possible combinations of fermions that can achieve the correct cross section. However if we restrict ourselves to the perturbative regime ($y < 1$) it can be difficult to achieve the correct width by adding invisible decays, since these decays decrease the width of the decay to diphotons.

The below table shows the results of different fermion models, setting $y = 1$ and using representation which do not couple to SM fermions.

Rep $(C,T)_Y$	Mass (GeV)	$\gamma\gamma$ cross section (fb)	Invisible Width (GeV)	Width (GeV)
$(1,1)_1$	400	0.0056	0	0.001
$(1,2)_2 \times 2$	400	4.5	0	0.08
$(1,3)_3$	400	2.8	0	0.03
$(3,1)_1$	800	5.2	0	0.004
$(3,2)_2$	600	0.01	44	44
$(3,2)_2 \times 7$	600	4.4	44	45
$(8,1)_2 \times 2$	600	4.4	45	45
$(8,2)_2 \times 2$	600	8.9	45	45

In the first row of the table, we can see that it is difficult to produce the diphoton cross section using fermions charged only under $U(1)_Y$. For a mass of 400 GeV, we have

$$\sigma(pp \to \phi \to \gamma\gamma) = 0.094 N_f Y^2.$$

Taking the cross section to be 4 fb, then

$$N_f Y^2 = 42.6$$

and so we require a large number of fermions or fermions with very large hypercharge. It seems impossible to achieve the correct width without absurdly large numbers of fermions or charges.

Rows two and three demonstrate that it is possible to achieve the $\gamma\gamma$ cross section with a few fermions with nontrivial weak isospin and hypercharge, if there are no invisible decays. On the other hand, it seems impossible to reproduce a wide width with non-coloured fermions in a reasonable model.

Row four shows that once coloured fermions are allowed, it is easy to produce the cross section if the width is assumed to be narrow.

Rows 5-8 show theories where the width is 45 GeV as a result of invisible decays. Without using the adjoint representation of $SU(3)$, it is very difficult to get a theory with the correct diphoton cross-section. If the adjoint representation is used, only a couple of fermions are required.

From the table, we can see that it is very difficult to create a perturbative model with a wide width. From testing I have found it is very difficult to achieve widths above 0.05 GeV. One possible issue with the addition of heavy coloured or weak isospinned particles is that it could destroy the asymptotic freedom of $SU(3)$ or $SU(2)$. While not insurmountable, this could create difficulties in GUT schemes, and in particular for QCD could result in a Landau pole occurring below the GUT scale.

Additional scalar fields can also mediate interactions between the resonance and SM bosons. This situation can be much more complicated than for fermions, since we must consider cubic and quartic interactions involving scalar fields. In particular, each additional scalar field will generically couple to the higgs via the interaction $S^\dagger S H^\dagger H$.

If we just consider

$$\mathcal{L}_{int} = \frac{A}{m}\phi S^\dagger S$$

where A is dimensionless and m is the mass of the scalar S, then the resultant effective interaction is similar to the case of a fermion of the same mass and representation coupling via $A\phi\bar{\psi}\psi$. The ratio is

$$\frac{c_{XX}(\text{scalar})}{c_{XX}(\text{fermion})} = \frac{R(m/M)}{4}$$

where $R(m/M)$ is between $\pi^2/2 - 1$ and 0.5 for $M/2 < m < \infty$. So the case for scalars is worse than fermions, but never more than an eighth of the size.

4 Specific Dark Matter Models

Paper [10] introduces a $(1, 2, -1)$ vector-like fermion ψ to mediate the $\phi \to \gamma\gamma$. It then adds a $(1, 1, 0)$ fermion, which through interaction with the Higgs boson mixes with the neutral part of ψ. The resultant neutral fermions are heavier than $M_\phi/2 \approx 350$ GeV and are able to give correct relic densities whilst avoiding constraints from LUX.

In [11] the 750 GeV resonance is a pseudoscalar incorporated into a ADM model which resolves discrepancies in solar physics through the use of momentum-dependent cross section between dark matter and nuclei. The dark matter mass is around 3 GeV and directly couples to the pseudoscalar, so that the model is compatible with width of 45 GeV. The pseudoscalar also couples directly to quarks in this models, with the production mechanism proceeding through quark annihilation.

Left-right extensions to the standard model are used in papers [12] and [13] to explain the diphoton excess. These models extend the electroweak gauge group to the group $SU(2)_L \times SU(2)_R \times U(1)$. In [12], the resonance is identified with the neutral component of the right-handed Higgs doublet, and right-handed neutrinos provide dark matter candidates, which are stabilized by the inclusion of a global symmetry. The model contains exotic quarks, which enable the production of the scalar through gluon fusion, and scalar decay to photons occurs both through these exotic quarks and also through additional bosons predicted in the model. It can be used to give the correct dark matter relic density if the dark matter mass is 320 GeV. Since the dark matter field does not couple to the scalar resonance, the scalar decays only to SM bosons and hence is narrow. Additionally the model is capable of explaining the muon $(g - 2)$ anomaly and provides neutrinos with mass.

In [13] the left-right model is extended through the inclusion of additional fermions coupled to $SU_R(2)$ and $U(1)$. The resonance is again identified with the neutral component of the right-handed Higgs doublet. The extra fermions couple to the resonance and to photons, allowing the decay of the resonance to diphoton. After right-handed symmetry breaking these fermions provide dark matter candidates which are singlets under SM gauge symmetry and can give the correct DM thermal relic density. Their mass is typically heavier than 1 TeV. Heavy $SU(2)_R$ gauge bosons are able to both explain the 1.9 TeV diboson excess as well as provide a production mechanism for the resonance through a cascade decay.

Unlike the other papers discussed, [18] presents a model where the 750 GeV resonance is spin-2 Kaluza-Klein graviton. The resonance mediates dark matter through gravitational couplings to the dark sector and SM. Scalar, fermionic, and vector dark matter particles can all saturate the DM relic density. DM-Nucleon interaction is too weak to be detected in current direct detection experiments, and indirect detection only constrains the possibility of vector dark matter. Invisible decays of the resonance can be sizable, but in the parameter space compatible with dark matter phenomenology the decays are sub-dominant compared to visible decays.

5 Composite Models for the Resonance

In these models the resonance is not a fundamental particle, but is instead a bound state. There are a range of behaviors that such models allow; [2] explores a number of possibilities. The most well understood models of this kind are those in which is the resonance is a pseudo-Nambu Goldstone boson, where it will behave in a manner analogous to pions in low energy QCD. In these models the effective coupling to SM gauge bosons is via the anomalous coupling

$$\frac{\alpha_X N_{TC} \mathrm{Tr}(T_S T^a T^b) \mathrm{Tr}(T_S T_a T_b)}{2\pi^2 f}.$$

Here f is the technipion constant, and $\mathrm{Tr}(T_S T_a T_b)$ depends on the structure of the technicolour fermions. The number of technicolours is N_{TC}. Here we can see that the coupling to SM gauge bosons is of the same order of magnitude as in the case of weakly coupled heavy fermion models, so again we run into difficulties if we demand that the resonance width is wide.

Composite models for the 750 GeV resonance are discussed in [14]-[17]. These models postulate the existence of heavy fermions coupling to a confining gauge field, along with a coupling to the electroweak force to allow diphoton decay. In [14], [15] and [17] the heavy fermions also couple to the strong force, so that the production of the resonance proceeds through gluon fusion, where as [16] considers a model where production occurs through photon fusion and the Drell-Yan process. None of the models include invisible decay channels for the resonance, and hence all predict narrow widths, $\Gamma_\phi \leq 1$ GeV.

The dark matter candidate in [14], [16] and [17] is the lightest neutral 'baryon'. This is generally multiple times heavier than the 750 GeV resonance, and their properties are model dependent and non-perturbative.

Paper [15] presents two model with a G-parity with the lightest G-odd pion providing the dark matter candidate. This pion must be lighter than 750 GeV and can produce the correct DM thermal abundance whilst LUX constraints on WIMP-nucleon scattering by two orders of magnitude.

6 Conclusion

There are a diverse range of models which can explain both the 750 GeV diphoton resonance and which contain viable dark matter candidates. Direct and indirect detection experiments can constrain the cases where the resonance is scalar and pseudoscalar respectively, and indeed these limits can be stronger than the mono-jet bounds.

Gluon fusion seems to be the most plausible production mechanism; photon fusion is in principle possible, but only in a highly non-perturbative model. While the ATLAS data suggests a broad width of $\sim$ 45 GeV, we have shown that this is impossible to achieve within a perturbative framework, regardless of whether the resonance is taken to be fundamental or is instead composite.

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