Radion Candidate for the LHC Diphoton Resonance

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Abstract

The recent observation of a modest excess in diphoton final states at the LHC, by both the ATLAS and CMS Collaborations, has sparked off the expected race among theorists to find the right explanation for this proto-resonance, assuming that the signal will survive and not prove to be yet another statistical fluctuation. We carry out a general analysis of this 'signal' in the case of a scalar which couples only to pairs of gluons (for production) and photons (for diphoton decay modes), and establish that an explanation of the observed resonance, taken together with the null results of new physics searches in all the other channels, requires a scalar with rather exotic behaviour. We then demonstrate that a fairly simple-minded extension of the minimal Randall-Sundrum model can yield a radion candidate which might reproduce this exotic behaviour.

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The joint announcement last week, by the ATLAS and CMS Collaborations at the CERN LHC [1,2], of a modest excess in the $pp \to \gamma\gamma$ channel, with a clustering of invariant mass around $750 - 760$ GeV, has sparked a great deal of speculation in the literature about the possible origins of this excess. Since the significance level of these signals lies well below the discovery level of 5σ and the excess observed is small, the prime candidate for an explanation must be a statistical fluctuation in the data, as has been the case with so many 'bumps' seen in the past. However, the fact that both the ATLAS and the CMS Collaborations observe excess events in precisely the same invariant mass bin is an unusual happenstance and could well be the harbinger of a momentous discovery, such as the Higgs boson proto-signals in 2011 [3] proved in the next year to be [4]. The situation is ripe, therefore, for theoretical speculation about the possible origins of this 'signal', which cannot be explained within the framework of the Standard Model (SM) of strong and electroweak interactions.

The principal features of the CERN observations $[1,2]$ are as follows.

A. The ATLAS (CMS) Collaboration has seen a modest 'bump' in the invariant mass distribution of $\gamma\gamma$ final states of 14 (10) events clustered around $750\,(760)$ GeV in $3.2\,(2.6)\,\mathrm{fb}^{-1}$ of data at the Run-2 of the LHC at a centre-of-mass energy $\sqrt{s} = 13$ TeV.

B. The statistical significance of these results at the ATLAS (CMS) is $3.9\sigma\;(2.6\sigma)$ when considered for the individual invariant mass bin, but reduces to $2.3\sigma\,(2.0\sigma)$ when one considers the look-elsewhere effect (a width around 45 GeV).

C. The width of this proto-resonance appears to be around 6% of its mass, i.e. around 45 GeV.

D. The tagging efficiency for the diphoton signal, as estimated by the ATLAS (CMS) Collaborations, is $0.4\,(0.6)$.

E. No excess over the SM predictions has been observed in other channels, such as dileptons, dijets, WW, ZZ, jets + MET, etc. as searched by both Collaborations in Run-2 of the LHC.

These observations are consistent with the resonant production, in 13 TeV pp collisions, of a new particle of mass in the range $750 - 760$ GeV. This new particle must decay to $\gamma\gamma$ pairs at a rate large enough to yield the observed signal. At the same time, its possible decays to other channels must be suppressed to the extent of going undetected at the LHC (or elsewhere), at least at the present level of statistics. It is also obvious that such a particle does not belong to the SM, whose particle spectrum was completed by the discovery of

the Higgs boson in 2012, and which does not contain any particle with a mass as high as 750 GeV.

Theoretical speculations about the nature of this new particle start from the observation that it decays into two spin-1 photons, and therefore, must be electrically neutral and have spin 0, or 1, or 2. However, the Landau-Yang theorem [5] forbids a massive spin-1 particle from decaying into two massless spin-1 particles (photons), and hence, the resonance has to be either spin-0 or spin-2. The spin-2 option is easily dismissed, for the only known spin-2 particles in elementary particle models are the gravitons, or rather their Kaluza-Klein excitations in models with large or warped extra dimensions [6]. Such gravitons would have universal couplings, and one cannot reconcile an observed excess in the diphoton channel with the absence of similar excesses in the dilepton, dijet, WW and ZZ channels. There remains the possibility that the resonance is a neutral scalar.

Neutral scalars are ubiquitous in models of physics beyond the SM. Ever since the 1964 discovery by Englert and Brout [7], and by Higgs [8], that such fields can develop a vacuum expectation value (vev) which breaks a local gauge symmetry spontaneously, the same idea has been invoked in diverse models with extra gauge symmetries at high scales which are made to break spontaneously through the vev's of postulated extra neutral scalars. These have been used, among other things, to explain parity violation [9], achieve grand unification [10], solve the strong CP problem [11] and induce inflation in the early Universe [12]. Scalars also play an important role in giving mass to sequential fermions of the SM through their Yukawa interactions [13]. Not surprisingly, therefore, the bulk of theoretical speculations have been attempts to fit in the proto-resonance at 750 GeV with one or the other of these postulated scalars[1].

Some of these theoretical studies have already thrown up interesting results. It is clear, for example, that the 750 GeV resonance *cannot* be

1. one of the heavy scalars H^0 and A^0 postulated in the minimal supersymmetric SM, despite the possibility of varying all the 105 new parameters in the model ([15–18]);

2. any minimal version of the two-Higgs doublet model, i.e. without the addition of new fermion states [15, 16]; however, a more optimistic result is claimed in Refs. [17, 19];

3. a sneutrino $\tilde{\nu}$ in the R-parity-violating version of the above, for its branching ratio to two photons is mediated by a one-loop diagram which is suppressed by a factor not

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[1]An early study can be found in Ref. [14]

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larger than $m_b/750$ GeV $\sim 10^{-5}$, which renders the production of diphoton signals too low to be observed;

4. a massive dilaton arising in a model with an extra dimension [16]; however, [20] claims a positive result with this scenario.

On the other hand, it is claimed that the signals in question *can* be explained by

1. an axion field arising in a model with a broken Peccei-Quinn symmetry [21];

2. models with additional vector-like fermions [15, 16, 22];

3. a radion in a Randall-Sundrum model where the Higgs boson or the entire SM fields live in the five-dimensional bulk [23, 24];

4. a generic singlet scalar or pseudoscalar [25], or specifically, one that may arise in the context of SUSY inspired simplified models [26]

5. a composite scalar coming from strong dynamics [27, 28];

6. dark matter models having a scalar mediator [29]

7. a pseudo-Goldstone boson or a scalar superpartner to the goldstino [30] or to a Dirac bino [31] in a supersymmetric model;

8. a scalar which couples only to photons [32];

9. more imaginative ideas like heavy messenger multiplets, cascade decays, hidden valley theories etc. [33, 34];

Some of these works have discussed model-independent studies of the signal and eventually focussed on specific models [28, 35, 36]. However, we may note that several of the long list of explanations have been devised in haste – not surprisingly under the circumstances – and have not studied the backgrounds very seriously. It is possible, however, to isolate the most serious background to the signal in a very simple-minded construction, which also highlights the difficulty of fitting any of the known models of physics beyond the SM to the observed facts.

In order to be produced in pp collisions at the LHC, a CP-even scalar resonance φ must have a coupling (fundamental or effective) to a pair of partons, and in order to decay to diphoton states it must have a coupling (fundamental or effective) to a pair of photons. These are the

absolutely minimum requirements to see a diphoton resonance at the LHC. These couplings can be parametrised in a gauge-invariant way as

$$\mathcal{L}_{\text{int}} = y_q \varphi \, \bar{q}q + \frac{c_g}{M_\varphi} \sum_{a=1}^{8} \varphi \, G^a_{\mu\nu} G^{\mu\nu,a} + \frac{c_\gamma}{M_\varphi} \varphi \, F_{\mu\nu} F^{\mu\nu} \tag{1}$$

Here q stands for any of the light quarks and could even be summed over all quark flavours, while $G^a_{\mu\nu}$ and $F_{\mu\nu}$ denote the field strength tensors for gluons and photons respectively. Before proceeding further, it should be noted that this is a really minimal construction, as it respects the symmetries $SU(3)_c$ and $U(1)_{em}$, which are known to be unbroken, but not the $SU(2)_L$ of the electroweak theory, which should hold at energy scales above the Higgs vev of 246 GeV. This means that this model assumes an explicit breaking of the $SU(2)_L \times U(1)_Y$ symmetry of the SM by the c_γ term, which would not be observed at lower energies because of the $1/M_\varphi$ suppression.

Once we have fixed the above couplings, we can easily calculate the partial decay widths to a $q\bar{q}$, gg and $\gamma\gamma$ final state. These turn out to be

$$\Gamma(\varphi \to q\bar{q}) = \frac{3}{8\pi} y_q^2 M_\varphi \ , \qquad \Gamma(\varphi \to gg) = \frac{2}{\pi} c_g^2 M_\varphi \ , \qquad \Gamma(\varphi \to \gamma\gamma) = \frac{1}{4\pi} c_\gamma^2 M_\varphi \tag{2}$$

from which it follows that the total decay width of the φ is

$$\Gamma_\varphi = \frac{2M_\varphi}{\pi} \left(c_g^2 + \frac{3}{16} y_q^2 + \frac{1}{8} c_\gamma^2 \right) \tag{3}$$

and the branching ratios to diphotons and dijets are

$$\mathcal{B}_{\gamma\gamma} = \frac{\frac{1}{8} c_\gamma^2}{c_g^2 + \frac{3}{16} y_q^2 + \frac{1}{8} c_\gamma^2} \qquad \mathcal{B}_{JJ} = \frac{c_g^2 + \frac{3}{16} y_q^2}{c_g^2 + \frac{3}{16} y_q^2 + \frac{1}{8} c_\gamma^2} \tag{4}$$

where J denotes a jet arising from a final state quark or a gluon.

We can calculate the production cross-section for the φ as

$$\sigma_\varphi = \frac{y_q^2}{96\pi s} F_q + \frac{c_g^2}{128\pi s} F_g \tag{5}$$

where

$$
\begin{aligned}
F_q &= \int_{r^2}^1 \frac{dx}{x} \left[f_{q/p}(x) f_{\bar{q}/p}\left(\frac{r^2}{x}\right) + f_{\bar{q}/p}(x) f_{q/p}\left(\frac{r^2}{x}\right) \right] \\
F_g &= \int_{r^2}^1 \frac{dx}{x} \left[f_{g/p}(x) f_{g/p}\left(\frac{r^2}{x}\right) \right]
\end{aligned}
\tag{6}
$$

with $r = M_\varphi/\sqrt{s} \simeq 5.77 \times 10^{-2}$ if we take $M_\varphi \simeq 750$ GeV and $\sqrt{s} = 13$ TeV. Using CTEQ-6L structure functions, we then find the following values

$$F_u = 2.177 \times 10^2 \qquad\qquad F_g = 2.914 \times 10^3 \tag{7}$$

with other quarks giving smaller results. Not surprisingly, since r is small, the gluon PDFs dominate all the others.

We are now in a position to put together all the factors and compute the production cross-section for the φ as

$$\sigma_\varphi = 33.36\, c_g^2 + 1.66\, y_u^2 \tag{8}$$

in units of picobarn. Thus, we predict that some tens of thousands of these heavy scalars must have been produced at the LHC Run-2 in order to obtain the signal which has been observed.

It is now a straightforward matter to calculate the cross-sections for diphoton and dijet production at the LHC Run-2. We get

$$\sigma(pp \to \varphi \to \gamma\gamma) = \sigma_\varphi\, \mathcal{B}_{\gamma\gamma} \qquad\qquad \sigma(pp \to \varphi \to JJ) = \sigma_\varphi\, \mathcal{B}_{JJ} \tag{9}$$

where the quantities on the right side can be read off from Eqn. (4) and Eqn. (8). For this part of the analysis, we use the leading- order results. QCD corrections will change the numerics somewhat, but will not affect the qualitative features of the analysis.

This simple-minded model must now be subjected to three experimental constraints, viz.,

    A. The total decay width Γ_φ as given in Eqn. (3) should not exceed about 50 GeV. Any larger value would be invalidated by the best fit width [1] of about 45 GeV.

    B. The diphoton cross-section, as given in Eqn. (9), should lie in the range $5 - 15$ fb, which would make it consistent with both the ATLAS and CMS observations.

    C. The dijet cross-section, as given in Eqn. (9), should not exceed a value around 1.2 pb (at the 1σ level) or 2.5 pb (at the 2σ level). These constraints arise from the fact that the dijet signals observed at the LHC Run-2 are consistent with the SM prediction of around 12.5 ± 1.2 pb (scaled up from the 8 TeV results [37]), leaving no scope for any excess over the experimental errors.

An analysis of the allowed values of c_g and c_γ, for different choices of y_u, is extremely instructive. To illustrate this, we have plotted, in Figure 1, the allowed region in the c_γ–c_g
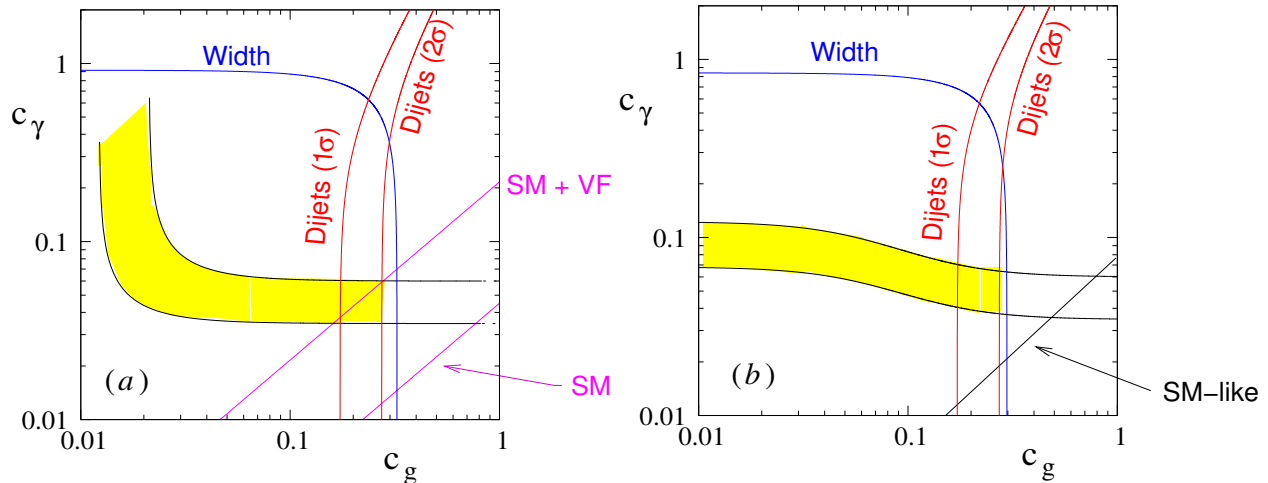
Figure 1: Illustrating regions in the c_γ–c_g plane which can give rise to the signal in question for (a) $y_u = 0$, and (b) $y_u = 0.3$. All points above and to the right of the blue line marked 'Width' are disallowed by the Γ_φ constraint. All points to the right of the red lines marked 'Dijet' would lead to unacceptable dijet rates. The yellow shaded region indicates the permitted region which yields the correct diphoton cross-section. The straight (magenta) lines correspond to a radion scenario as described in this work, with a purely SM-like content (marked 'SM') and with the SM content augmented by one generation of heavy vectorlike fermions (marked 'SM + VF').

plane, for two different values (a) $y_u = 0$, and (b) $y_u = 0.3$ of the Yukawa couplings in Eqn. (1), setting $q = u$.

A glance at Figure 1 shows that only a narrow band of allowed c_γ values can give rise to the observed signal. In the panel marked (a), the graphs curve upward, since c_g is the only source of production and hence cannot be zero. This is no longer the case in the panel marked (b), where some production occurs through the nonvanishing Yukawa coupling. The requirement of a scalar width less than about 50 GeV constrains large values of c_g – as expected – but leaves much of the allowed parameter space unaffected. The dijet constraint is more restrictive at the 1σ level, but at 95% confidence level it is no more constraining than the total width.

On the lower right corner of the panel marked (b), we have plotted a straight line in black, which has been marked 'SM-like'. This corresponds to the case when the scalar has effective couplings to a gluon pair and a photon pair through one loop diagrams with SM particles in the loop. Using the standard computation of the SM partial widths [38] the two parameters will be related by

$$c_\gamma = 0.075 \, c_g \tag{10}$$

which is illustrated by the straight line as shown. The fact that this line is far away from the allowed region only emphasises the difficulty of fitting the observed signal with any of the usual models, as mentioned above. In fact, perhaps the only way in which this line can be shifted towards the allowed region is to include fermions with exotic electromagnetic charges in the loop. In fact,it is not enough to have fermions with charges 5/3, but we also need [15] fermions with charge 8/3 and multiple generations of those to boot. Most of the usual models also predict large WW and ZZ decay modes of the resonant scalar, which may have avoided detection in the current searches, but are sure to be detected in the next LHC run [39, 40]

It is clear, therefore, that any explanation of the observed diphoton excess requires an extra effort of imagination and perhaps a large degree of fine-tuning as well, inasmuch as the observed scalar does not seem to have the usual decay modes other than the diphoton one. As we have remarked already, it is very difficult to invent a scenario in which we have a scalar which couples only to a pair of partons and a pair of photons, and at the same time, obtain values of c_γ which are large enough compared to c_g as illustrated in Figure 1. However, we wish to point out that there exists one new physics scenario where this is a basic feature of the model, albeit in a fine-tuned situation.

The model which, in our view, provides one of the neatest solutions to the enigma of the 750 GeV resonance, is a variant of the Randall-Sundrum model with a warped extra dimension of the form $\mathbb{S}^1/\mathbb{Z}_2$ and a 3-brane at either end [6], one of which (the 'infrared' brane) supports the SM fields. Here the size parameter R_c of the extra dimension is stabilised by the so-called Goldberger-Wise mechanism, where a bulk scalar is introduced into the model and permitted to have $\lambda\phi^4$-type interactions on the two branes [41]. This leads to a very deep and narrow potential for the size parameter with the vev R_c. Its small fluctuations, a.k.a. the radion field φ, mimics a dilatonic excitation of the so-called warped metric. As a result, we have a scalar radion, possibly of electroweak scale mass, which couples to matter through the trace of the energy-momentum tensor. This results in couplings which are very Higgs boson-like, with the SM vev v replaced by the radion vev Λ_φ. However, there exists one major difference, which is that the radion couplings to a $\gamma\gamma$ or a gg pair contain contributions from the trace anomaly, which are absent in the case of a Higgs boson.

Of course, if we consider a radion in isolation, its behaviour is so much like a Higgs boson, that it is precluded from being a solution to the 750 GeV resonance problem by the very same arguments that apply to a heavy Higgs boson [15]. However, there is the very interesting possibility that the radion may *mix* with the Higgs boson of the SM, with the lighter

component being the 125 GeV boson observed at CERN in 2012, and the heavier component being the 750 GeV resonance in question. Such mixings through kinetic terms have been described in Ref. [42], and are controlled by a parameter ξ. A very interesting feature of this kind of mixing is that for a specific choice $\xi = \xi_0 \approx 1/6$, the tree-level couplings of the heavier scalar state to all matter particles vanish, leaving only the one-loop couplings to $\gamma\gamma$ and gg pairs, which are mediated by the trace anomaly. These depend on the beta functions of the gauge theory rather than direct couplings of the radion to matter. Apart from the fact that such radions escape all constraints from precision electroweak tests and heavy Higgs boson searches at the LHC, this scenario is highly conducive to an explanation of the diphoton resonance [23]. Thus, we obtain Eqn. (1) with the specific couplings

$$y_q = 0 \; \forall q \qquad\qquad c_g = \frac{\alpha_s}{16\pi} \frac{M_\varphi}{\Lambda_\varphi} g_\varphi(\xi_0) \, |b_3| \qquad\qquad c_\gamma = \frac{\alpha}{16\pi} \frac{M_\varphi}{\Lambda_\varphi} g_\varphi(\xi_0) \, |b_1 + b_2| \qquad (11)$$

where the b_1, b_2, b_3 correspond to the $U(1)_Y$, $SU(2)_L$ and $SU(3)_c$ gauge groups respectively. The function $g_\varphi(\xi)$ arises from the mixing, but for the choice $\xi = \xi_0$ is approximately unity.

The beta functions in the above couplings are given, as usual, by

$$b_1 = -\frac{20}{9} N_f - \frac{1}{6} N_s \;, \qquad\qquad b_2 = \frac{22}{3} - \frac{4}{3} N_f - \frac{1}{6} N_s \;, \qquad\qquad b_3 = 11 - \frac{4}{3} N_f \qquad (12)$$

where N_f and N_s represent the number of fermion and scalar doublets, respectively, in the model. If the particle content on the 'infrared' brane matches with that of the SM, we will have $N_f = 3$ and $N_s = 1$, and hence obtain the usual values $b_1 = -41/6$, $b_2 = 19/6$ and $b_3 = 7$. In terms of these, we can write

$$c_\gamma \simeq 0.045 c_g \qquad (13)$$

The corresponding curve is plotted in Figure 1, on the panel marked (a), and indicated as 'SM'. It is clear that this is far away from the allowed region and therefore, this version of the model fails to explain the 750 GeV observation. In fact, this version hardly does better than models where the $\gamma\gamma$ and gg couplings are generated from loops containing matter particles (see panel (b) and the discussions following Figure 1).

Though the above result is rather disappointing and belies the optimistic claims made just before, a small addition to the model can provide a scenario which works very nicely. This is the addition, on the 'infrared' brane, of a single family of vectorlike fermions, which are doublets under $SU(2)_L$. The presence of such fermions, so long as their masses lie below that of the resonance, changes N_f from 3 to 5. As a result, we get $b_1 = -203/18$, $b_2 = 1/2$ and $b_3 = 13/3$, and this leads to

$$c_\gamma \simeq 0.216 c_g \qquad (14)$$

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In Figure 1(a), this curve is plotted and marked 'SM + VF'. Obviously, it passes through the allowed region — somewhat marginally if the absence of dijet signals is demanded at 1σ, but much more comfortably, if we relax it to 2σ. Thus, it seems that we can obtain a solution to the 750 GeV resonance by postulating the following:

- A Randall-Sundrum type scenario, with modulus stabilisation through the Goldberger-Wise mechanism;

- Mixing of the scalar radion with the Higgs boson, with a mixing parameter precisely tuned so that the heavier eigenstate decouples from matter fields on the brane;

- Augmentation of the particle content on the 'infrared' brane by one full generation of vectorlike doublet fermions.

An encouraging feature of adding vectorlike fermions is the fact that they are not constrained seriously by electroweak precision tests. However, the story is not completed yet, for we still have to check that the actual values of c_g and c_γ are adequate for our purposes, and do not induce new constraints on the model from, for example, the couplings of the light 125 GeV scalar, which does *not* decouple from matter. This is shown in Figure 2, where we have plotted the diphoton signal as a function of the radion vev Λ_φ – the only free parameter once we set $\xi = \xi_0$. For this part of the analysis, QCD corrections to the production cross-section have been included in the form of a factor $K \approx 2$. The blue curve marked 'SM' shows the cross-section when we consider only SM particles on the brane. Corresponding constraints on the radion vev Λ_φ from the signal strengths (in particular, μ_{WW} at the CMS [43]) of the 125 GeV scalar are shown as the blue shading. Obviously, this scenario fails to produce enough diphoton events. In any case, it is ruled out by the fact that even with this low level of diphoton production, it would lead to an observable dijet excess (see above).

The red curve, marked 'SM + VF', on the other hand, provides very reasonable cross-sections for values of $\Lambda_\varphi > 700$ GeV. This corresponds, as explained before, to the SM augmented by a vectorlike family of doublet fermions. Interestingly, this scenario is less constrained by signal strengths than the previous case. The pink shading shows the bounds on Λ_φ from the Higgs signal strengths. We have already verified (Figure 1) that this model will *not* lead to an observable dijet excess.

To summarise, in this work we have considered a very simple scenario in which the proto-resonance at 750 GeV is a scalar radion of the Randall-Sundrum model, which has a mixing with the Higgs boson, carefully fine-tuned so that the heavier eigenstate decouples from matter. If we identify this with the possible resonance at 750 GeV, we can explain the
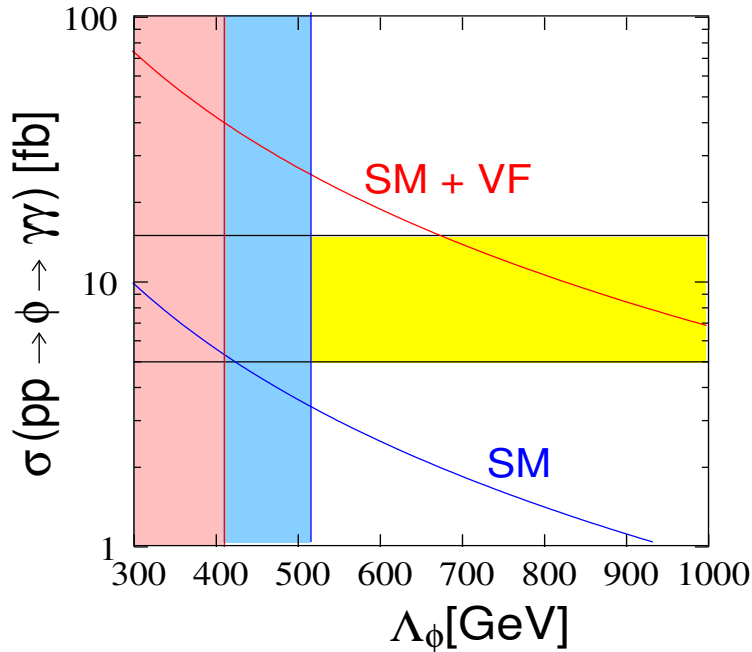
Figure 2: Cross-sections for diphoton production as a function of the radion vev Λ_φ, in the case $\xi = \xi_0$, in two different scenarios. The yellow shading indicates the region of interest for the 750 GeV resonance.

observations, including the lack of a dijet signal, provided the SM stands augmented by a single family of vectorlike fermions. As we include just a single family of such fermions, which live purely on the 'infrared' brane, and that too, with the canonical gauge charges, this appears to be a more economical solution than many of the ones provided in the literature. We may also note, in concluding, that the 750 GeV signal, if confirmed, is sure to prove to be a rather awkward customer for theories which go beyond the SM. Some of the fine-tuned features of our explanation reflect this difficulty, as, in fact, is the case, with most other suggestions in this regard.

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