Higgs-Radion interpretation of the LHC data?

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We explore the parameter choices in the five-dimensional Randall-Sundrum model with the inclusion of Higgs-radion mixing that can describe current LHC hints for one or more Higgs boson signals.

I. INTRODUCTION

The two simplest ways of reconciling the weak energy scale $\mathcal{O}(1 \text{ TeV})$ and the much higher GUT or reduced Planck mass scale $\mathcal{O}(10^{18} \text{ GeV})$ in a consistent theory are (i) to employ supersymmetry or (ii) to introduce one or more warped extra dimensions. In this letter, we pursue the 5D version of the latter introduced by Randall and Sundrum (RS) [1], but modified in that all fields other than the Higgs reside in the bulk. Having the gauge and fermion fields in the bulk is needed to adequately suppress flavor changing neutral current (FCNC) operators and operators contributing to precision electroweak (PEW) corrections [2–9].

In the notation of [10], the background RS metric that solves Einstein’s equations takes the form

$$ds^2 = e^{-2m_y|y|}g_{\mu\nu}dx^\mu dx^\nu - b_0^2dy^2$$  \hspace{1cm} (1)

where $y$ is the coordinate for the 5th dimension with $|y| \leq 1/2$. The graviton and radion fields, $h_{\mu\nu}(x,y)$ and $\phi_0(x)$, are the quantum fluctuations relative to the background metric $g_{\mu\nu}$ and $b_0$, respectively. In particular, $\phi_0(x)$ is the quantum degree of freedom associated with fluctuations of the distance between the branes. In the simplest case, only gravity propagates in the bulk while the SM is located on the infrared (or TeV) brane at $y = 1/2$ and the interactions of Kaluza-Klein (KK) gravitons and the radion with the SM are described by

$$\mathcal{L}_{\text{int}} = -\frac{1}{\Lambda_W} \sum_{n \neq 0} h_n^{\mu\nu} T^{\mu\nu} - \frac{\phi_0}{\Lambda_\phi} T^{\mu}_\mu$$  \hspace{1cm} (2)

where $h_n^{\mu\nu}(x)$ are the KK modes (with mass $m_n$) of the graviton field $h_{\mu\nu}(x,y)$. In the above, $\Lambda_W = \sqrt{2m_{Pl}}\Omega_0$, where $\Omega_0 = e^{-\frac{1}{2}m_yb_0}$, and $\Lambda_\phi = \sqrt{3}\Lambda_W$ is the vacuum expectation value of the radion field. Note from Eq. (2) that the radion couples to matter with coupling strength $1/\Lambda_\phi$. If matter and gauge fields propagate in the bulk then the interactions of gravitons and the radion with the matter and gauge fields are controlled by the overlap of appropriate 5th-dimensional profiles and corrections to Eq. (2) appear.

In addition to the radion, the model contains a conventional Higgs boson, $h_0$. The RS model provides a simple solution to the hierarchy problem if the Higgs is placed on the TeV brane at $y = 1/2$ by virtue of the fact that the 4D electro-weak scale $v_0$ is given in terms of the $\mathcal{O}(m_{Pl})$ 5D Higgs vev, $\hat{v}$, by: $v_0 = \Omega_0 \hat{v} = e^{-\frac{1}{2}m_yb_0}\hat{v} \sim 1 \text{ TeV}$ for $\frac{1}{2}m_yb_0 \sim 35$. As a result, to solve the hierarchy problem, $\Lambda_\phi = \sqrt{6m_{Pl}}\Omega_0$ should not exceed a few TeV [1].

The ratio $m_0/m_{Pl}$ is a particularly crucial parameter that characterizes the 5-dimensional curvature. As discussed shortly, large curvature values $m_0/m_{Pl} \gtrsim 0.5$ are favored for fitting the LHC Higgs excesses and by bounds on FCNC and PEW constraints. In early discussions of the RS model it was argued that $R_5/M_5^2 < 1$ ($M_5$ being the 5D Planck scale and $R_5 = 20m_0^2$ the size of the 5D curvature) is needed to suppress higher curvature terms in the 5D action, which leads to $m_0/m_{Pl} \lesssim 0.15$ being preferred. However [11] argues that $R_5/\Lambda^2$ (with $\Lambda$ being the energy scale at which the 5D gravity theory becomes strongly coupled, estimated by naive dimensional analysis to be $\Lambda \sim 2\sqrt{3}\pi M_5$) is the appropriate measure, implying that values as large as $m_0/m_{Pl} < \sqrt{3\pi^3/(5\sqrt{5})} \sim 3$ are acceptable. In this
regard, the relation between the mass of the 1st KK graviton excitation \((G^1)\), \(m_0/m_{Pl}\) and \(\Lambda_{\phi}\),

\[
m^1_{KK} = \frac{(m_0/m_{Pl}) x_1^{KK}}{\sqrt{6}} \Lambda_{\phi},
\]

where \(x_1^{KK} \sim 3.83\) is the 1st zero of the Bessel function \(J_1\), will require large \(m_0/m_{Pl}\) if the lower bound on \(m^1_{KK}\) is large and \(\Lambda_{\phi} \sim 1\) TeV.

In the simplest RS scenario, the SM fermions and gauge bosons are confined to the brane. However, this is now regarded as highly problematical because the higher-dimensional operators in the 5D effective field theory are suppressed only by \(\text{TeV}^{-1}\) and then FCNC processes and PEW observable corrections are predicted to be much too large. This arrangement also provides no explanation of the flavor hierarchies. It is therefore now regarded as necessary \([2–9]\) to allow all the SM fields (except the Higgs) to propagate in the extra dimension. The SM particles are then the zero-modes of the 5D fields and the profile of a SM fermion in the extra dimension can be adjusted using a mass parameter. If 1st and 2nd generation fermion profiles peak near the Planck brane then FCNC operators and PEW corrections will be suppressed by scales \(\gg\) TeV. Even with this arrangement it is estimated that the \(g^1, W^1\) and \(Z^1\) masses must be larger than about 3 TeV (see the summary in \([9]\)).

If the gauge bosons and fermions do not propagate in the bulk, then the strongest limits on \(\Lambda_{\phi}\) come, via Eq. (3), from the lower bound placed by the LHC on the first graviton KK excitation (see, for example, \([11]\) and \([12]\) for the ATLAS and CMS limits). However, when the fermions propagate in the bulk, the couplings of light fermion pairs to \(G^1\) are greatly reduced and these limits do not apply. When gauge bosons propagate in the bulk, a potentially important experimental limit on the model comes from lower bounds on the 1st excitation of the gluon, \(g^1\). In the model of \([13]\), in which light fermion profiles peak near the Planck brane, there is a universal component to the light quark coupling \(q \bar{q} g^1\) that is roughly equal to the SM \(SU(2)\) gauge coupling \(g\) times a factor of \(\zeta^{-1}\), where \(\zeta \sim \sqrt{2} m_0 b_0 \sim 5 - 6\). The suppression is due to the fact that the light quarks are localized near the Planck brane whereas the KK gluon is localized near the TeV brane. Even with such suppression, the LHC \(g^1\) production rate due to \(u\bar{u}\) and \(d\bar{d}\) collisions is large. Further, whatever the model, the \(t_R^{-1} g^1\) coupling is large since the \(t_R\) profile peaks near the TeV brane – the prediction of \([13]\) is \(g_{t_R} g^1 \sim \zeta g\). As a result, the dominant decay of the \(g^1\) is to \(t\bar{t}\). ATLAS and CMS search for \(t\bar{t}\) resonances at high mass. Using \(g_{t\bar{t}} g^1 \sim g\zeta^{-1}\), \(q = u, d\), one finds a lower bound of \(m^q_{t\bar{t}} \gtrsim 1.5\) TeV \([14]\) using an update of the analysis of \([13]\). (\([15]\) gives a weaker bound of \(m^q_{t\bar{t}} > 0.84\) TeV.)

In terms of \(\Lambda_{\phi}\), we have the following relations:

\[
\frac{m_0}{m_{Pl}} = \frac{\sqrt{6}}{x_1^{KK}} \frac{m^q_{t\bar{t}}}{\Lambda_{\phi}} \approx \frac{m^q_{t\bar{t}}}{\Lambda_{\phi}}, \quad \text{and} \quad \frac{1}{2} m_0 b_0 = - \log \left( \frac{\Lambda_{\phi}}{\sqrt{6} m_{Pl}} \right)
\]

where \(x_1^q \sim 2.45\) is the 1st zero of an appropriate Bessel function. If the model really solves the hierarchy problem then \(\Lambda_{\phi} \lesssim 10\) TeV is required. If we adopt the CMS limit of \(m^q_{t\bar{t}} > 1.5\) TeV then Eq. (4) implies a lower limit on the 5-dimensional curvature of \(m_0/m_{Pl} \gtrsim 0.15\). Thus, a significant lower bound on \(m^q_{t\bar{t}}\) implies that only relatively large values for \(m_0/m_{Pl}\) are allowed. As discussed above, \(m_0/m_{Pl}\) values up to \(\sim 2 - 3\) are probably consistent with curvature corrections to the RS scenario being small. Still, tension between the lower bound on \(m^q_{t\bar{t}}\) and keeping acceptably small \(m_0/m_{Pl}\) could increase to an unacceptable point as the LHC data set increases. We will discuss the phenomenology that applies if the value of \(\Lambda_{\phi}\) for any given \((m_0/m_{Pl})\) is tied to the lower bound of \(m^q_{t\bar{t}} = 1.5\) TeV using Eq. (4). Alterations to the phenomenology using \(m^q_{t\bar{t}} = 3\) TeV, as perhaps preferred by PEW constraints, will also be illustrated.

However, there are alternative approaches in which a lower bound on \(m^q_{t\bar{t}}\) from the LHC implies a less tight bound on \(\Lambda_{\phi}\). For example, including brane kinetic terms localized on the visible brane for gauge fields and gravity will modify the Kaluza-Klein spectrum and the couplings of the fields \([10–15]\). In particular, the relation between \(m_0/m_{Pl}\), \(m^q_{t\bar{t}}\) and \(\Lambda_{\phi}\) will be modified in such a way that a large lower bound on \(m^q_{t\bar{t}}\) can still allow \(\Lambda_{\phi}\) sufficiently low that the radion will have phenomenological impact. In this paper, we thus also examine a non-minimal model in which no \(m_0/m_{Pl}\)-dependent tie between \(m^q_{t\bar{t}}\) and \(\Lambda_{\phi}\) is assumed, implying that direct and indirect bounds on \(m^q_{t\bar{t}}\) do not exclude the relatively low values of \(\Lambda_{\phi} = 1.5\) TeV and 1 TeV for even relatively low values of \(m_0/m_{Pl}\).

Since the radion and Higgs fields have the same quantum numbers, it is generically possible to introduce some amount of mixing between them. When the Higgs is localized on the TeV brane, this mixing can be introduced through an action operator that can be written in the form \([19]\):

\[
S_{\xi} = \xi \int d^4 x \sqrt{g_{vis}} R(g_{vis}) \tilde{H}^\dagger \tilde{H},
\]
where $R(g_{\text{vis}})$ is the Ricci scalar for the metric induced on the visible brane, and $\hat{H}$ is the Higgs field in the 5-D context before rescaling to canonical normalization. The physical mass eigenstates, $h$ and $\phi$, are obtained by diagonalizing and canonically normalizing the kinetic (and mass) terms in the Higgs-radion Lagrangian. The diagonalization procedures and results for the $h$ and $\phi$ using our notation can be found in [10] (see also [10] [20]). One finds

$$h_0 = dh + c\phi - \phi_0 = a\phi + bh, \quad \text{where} \quad d = \cos \theta - t \sin \theta, \quad c = \sin \theta + t \cos \theta, \quad a = -\frac{\cos \theta}{Z}, \quad b = \frac{\sin \theta}{Z}, \quad (6)$$

with $t = 6\xi/|Z|$, $Z^2 = 1 + 6\xi^2(1 - 6\xi)$ and $\tan \theta = 12\xi|Z|m^2_{h,\phi}/(m^2_{h,\phi} - m^2_{h,\phi} |Z^2 - 36\xi^2\gamma^2|)$. Here $m^2_{h,\phi}$ and $m^2_{\phi,\phi}$ are the Higgs and radion masses before mixing. Consistency of the diagonalization imposes strong restrictions on the possible $\xi$ values as a function of the final eigenstate masses $m_h$ and $m_\phi$, which restrictions depend strongly on the ratio $\gamma \equiv v_0/\Lambda_{\phi}$ ($v_0 = 246$ GeV).

The full Feynman rules after mixing for the $h$ and $\phi$ interactions with gauge bosons and fermions located in the bulk were derived in [21]. Of particular note are the anomaly terms associated with the $\phi_0$ interactions before mixing. To be precise, we give a few details of these important couplings and their implications. Let us begin by defining

$$g_h = (d + \gamma b) \quad g_\phi = (c + \gamma a) \quad g^r_h = \gamma b \quad g^r_\phi = \gamma a. \quad (7)$$

Relative to the Feynman rules of Fig. 29 of [10], the following modifications of the $gg$ and $\gamma\gamma$ couplings are required when the gauge bosons propagate in the bulk:

$$\epsilon^g_{h,\phi} = -\frac{\alpha_s}{4\pi v} \left[ g_{h,\phi} \sum F_{1/2}(\tau_i) - 2(b_3 + \frac{2\pi}{\alpha_s \frac{1}{2} m_0 b_0}) g^r_{h,\phi} \right]$$

$$\epsilon^g_{h,\phi} = -\frac{\alpha}{2\pi v} \left[ g_{h,\phi} \sum e^2_{\gamma} N_{i}^2 F_{1}(\tau_i) - (b_2 + b_3 + \frac{2\pi}{\alpha_s \frac{1}{2} m_0 b_0}) g^r_{h,\phi} \right] \quad (8)$$

(In Fig. 29 of [10] we used the notation $g_{IV}$ for what we here call $g_{h,\phi}$. Also $g_r$ from [10] is replaced here by $g^r_{h,\phi}$ which incorporates the bulk propagation effects by the virtue of the second term in the parentheses above). Since $b_3 = 7$ and $b_2 + b_3 = -11/3$, the new $g^r_{h,\phi}$ corrections can be significant.

There are also modifications to the $WW$ and $ZZ$ couplings of the $h$ and $\phi$ relative to Fig. 29 of [10]. Without bulk propagation, these couplings were simply given by SM couplings (proportional to the metric tensor $\eta^{\mu\nu}$) times $g_h$ or $g_\phi$. For the bulk propagation case, there are additional terms in the interaction Lagrangian that lead to Feynman rules that have terms not proportional to $\eta^{\mu\nu}$, see [21]. For example, for the $W$ we have (before mixing)

$$\mathcal{L} \ni h_0 \frac{2m^2_W}{v} W^\mu W^\mu + \phi_0 \frac{2m^2_W}{\Lambda_{\phi}} \left[ W^\mu_{\mu} (1 - \kappa_W) + W^\mu_{\mu} W^{\mu\nu} \frac{1}{4m^2_W (\frac{1}{2} m_0 b_0)} \right] \quad (9)$$

where $\kappa_V = \left( \frac{3m^2_W (\frac{1}{2} m_0 b_0)}{\Lambda_{\phi}^2 (m_0/2m_W)^2} \right)$ for $V = W, Z$. After mixing, this becomes, for example for the $h$ interaction

$$\mathcal{L} \ni h \frac{2m^2_W}{v} \left[ g^V_{h,\phi} W^\mu W^\mu + g^r_{h,\phi} \frac{1}{4m^2_W (\frac{1}{2} m_0 b_0)} W_{\mu\nu} W^{\mu\nu} \right] \equiv h \frac{2m^2_W}{v} g^V_{h,\phi} W^\mu W^\mu + g^r_{h,\phi} \frac{1}{4m^2_W (\frac{1}{2} m_0 b_0)} W_{\mu\nu} W^{\mu\nu} \quad (10)$$

with a similar result for the $\phi$. Here we have defined

$$g^V_{h,\phi} \equiv g_{h,\phi} - g^r_{h,\phi} \kappa_V, \quad \eta^V_{h,\phi} = \frac{g^r_{h,\phi}}{g^V_{h,\phi}} \frac{1}{4m^2_W (\frac{1}{2} m_0 b_0)}. \quad (11)$$

Substituting one $m_W = \frac{1}{2} g v$ this gives the Feynman rule for the $hWW$ coupling as

$$igm_W g^V_h \left[ \eta_{\mu\nu} (1 - 2k^+ \cdot k^- \eta^W_{h,k^+}) + 2\eta^W_{h,k^+} k^+ \eta^W_{h,k^-} \right] \quad (12)$$

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Note however that in the case of a Higgs leaking into the bulk, the 5D Higgs potential itself will induce some mixing with the radion, which should be added to that coming from Eq. (3). For simplicity we will restrict ourselves to the case of a brane localized Higgs.

In the current paper we change the sign of our convention for $\phi_0$. We also note that in [19] [20] the coefficients in the $h_0$ decomposition are denoted by $a, b$ and those in the $\phi_0$ decomposition are denoted $c, d$, i.e. the reverse of our conventions.
where \(k^+, k^-\) are the momenta of the \(W^+, W^-\), respectively. The notations and results for the \(\phi\) and for \(V = Z\) are obtained by corresponding modifications. Now, defining \(R^V = 2n_{h_\phi} m_V^2(1 - 2k^+ \cdot k^- \eta_{h_\phi})\) and \(x_V^{h_\phi} \equiv 4m_V^2/m_{h_\phi}^2\), one finds that the matrix-element-squared for \(h, \phi \rightarrow V V\) is proportional to

\[
(g_{h_\phi})^2(1 - 2k^+ \cdot k^- \eta_{h_\phi}) \left\{ \left[ 1 - x_V^{h_\phi} + \frac{3}{4}(x_V^{h_\phi})^2 \right] + R^V \left[ -6 + \frac{4}{x_V} + 2x_V^{h_\phi} \right] + (R^V)^2 \left[ 4 + \frac{4}{(x_V)^2} - \frac{8}{x_V} \right] \right\},
\]

where \(k^+ \cdot k^- = (2m_V^2/x_V^{h_\phi})(1 - \frac{1}{2}x_V^{h_\phi})\). The SM result would be obtained by setting \(g_{h_\phi} = 1\) and \(x_V^{h_\phi} = 0\).

In the case of fermions propagating in the bulk, both the radion and the Higgs couplings to SM fermions can be slightly modified. The couplings of the radion to the TeV-brane-localized top quark will receive no corrections with respect to the original setup. However, for quarks that are localized near the UV brane (including the right-handed bottom), the modifications to the radion quark couplings can be of order \(\sim 10\% - 20\% \) \cite{21}. Moreover, these coupling modifications are not universal and so will also produce some amount of flavor violation into the couplings of the radion with fermions \cite{22}.

Even though we neglect bulk effects in Yukawa couplings, it is worth commenting further on the possible consequences of fermions propagating in the bulk. As an illustration, we briefly discuss the case of the unmixed Higgs-radion system in the context of LHC data. We will show in particular that an approximate fit to the most prominent “excesses” in the Higgs search data can be explained in the context of the model. Earlier papers on this topic include \cite{28}, \cite{29} (see also \cite{30}) and \cite{31}.

II. LHC EXCESSES

The Large Hadron Collider (LHC) data from the ATLAS \cite{32} and CMS \cite{33} collaborations suggests the possibility of a fairly Standard Model (SM) like Higgs boson with mass of order 123 – 128 GeV. In particular, promising hints

\footnote{In order to reduce tensions from PEW constraints one could consider extending the gauge symmetry group in order to add some built-in custodial symmetry protection (see e.g. \cite{3}).}

\footnote{The corrections (either enhancement or suppression) to Yukawa couplings and Higgs production cross sections arising if fully general situations are considered, i.e. by employing moderate to large entries in both matrices \(Y_1\) and \(Y_2\), can be of order tens of percent \cite{28, 29}.}
appear of a narrow excess over background in the $\gamma\gamma$ and $ZZ \to 4\ell$ final states with strong supporting evidence from the $WW \to b\bar{b}\ell\bar{\ell}$ mode. The ATLAS results suggest that the $\gamma\gamma$ and $4\ell$ rates may be significantly enhanced with respect to the SM expectation at a mass near 125 GeV. The CMS $\gamma\gamma$ rate is maximal for $M_{\gamma\gamma} \sim 124$ GeV and also appears to be somewhat enhanced with respect to the SM expectation. At this mass the CMS signals in other channels, including $b\bar{b}\ell\bar{\ell}$ and $4\ell$ are roughly consistent with the expectation for a SM Higgs. In addition, CMS data shows excesses in the $4\ell$ rate near 120 GeV (at which mass they do not see a $\gamma\gamma$ excess) and in the $\gamma\gamma$ rates near 137 GeV (at which mass there is no $\ell\nu\ell\nu$ excess), but neither is confirmed in the ATLAS data.

One important point regards the $W^+W^- \to b\bar{b}\ell\bar{\ell}$ final state. The signal for a scalar state of any given mass will be spread out into many bins of a variable such as the transverse mass, $m_T$, as a result of the missing energy carried by the neutrinos. Thus, if there are two scalar states that have equal production cross section times $WW$ branching ratio both may contribute but their contribution will depend upon the analysis cuts applied. This contrasts with the $ZZ \to 4\ell$ channel (the only $ZZ$ channel analyzed for scalar masses below 200 GeV) and the $\gamma\gamma$ channel both of which have excellent mass resolution so that excesses should appear centered on the scalar state masses. For this reason, we focus on these latter channels.

In the context of the Higgs-radion model, positive signals can only arise for two masses. If more than two excesses were to ultimately emerge, then a more complicated Higgs sector will be required than the single $h_0$ case we study here. Certainly, one can consider including extra Higgs singlets or doublets. For the moment, we presume that there are at most two excesses. In this case, it is sufficient to pursue the single Higgs plus radion model.

We will consider three cases, labelled as ATLAS, CMSA and CMSB. We quantify the excesses in terms of the best fit value for $R(X) \equiv \sigma(X)/\sigma_{SM}(X)$ for a given final state $X$. Errors quoted for the excesses are those for $\pm 1\sigma$. The mass locations and excesses in the $\gamma\gamma$ and $4\ell$ channels in these three cases, tabulated in Table I, are taken from Figs. 8a and 8b of [32] in the ATLAS case and from the appropriate windows of Fig. 14 of [33] in the case of CMSA and CMSB. To an excellent approximation, only the $gg$ initial state is relevant for inclusive $h$ and $\phi$ production followed by decay to $\gamma\gamma$ or $ZZ \to 4\ell$ and so we will be comparing the ratios

$$R_h(X) = \frac{\Gamma_h(gg)\text{BR}(h \to X)}{\Gamma_{h_{SM}}(gg)\text{BR}(h_{SM} \to X)}, \quad R_\phi(X) = \frac{\Gamma_\phi(gg)\text{BR}(\phi \to X)}{\Gamma_{h_{SM}}(gg)\text{BR}(h_{SM} \to X)},$$

where numerator and denominator are computed for the same mass, to the ATLAS, CMSA and CMSB $R(X)$ values quoted above. We also note that CMS gives results for $W, Z + b\bar{b}$ relative to $W, Z + h_{SM}$ with $h_{SM} \to b\bar{b}$ in the SM at 120 GeV and 124 GeV of $1_{-1.1}^{+1.9}$ and $0.5_{-1.5}^{+1.1}$, respectively. No measurement for the $b\bar{b}$ final state is quoted for 137 GeV. Finally, CMS has recently given results at 125 GeV for the $\gamma\gamma$ final state in which the $WW$ fusion induced rate is separated from the $gg$ fusion induced rate [34]. They find a ratio relative to the SM prediction for $WW \to h_{SM} \to \gamma\gamma$ of $R_{WW}(\gamma\gamma) = 3.7_{-1.8}^{+2.1}$ at 125 GeV. Removing this $WW$ fusion component from the inclusive $\gamma\gamma$ final state gives a $gg$ fusion ratio of $R_{gg}(\gamma\gamma) = 1.62 \pm 0.69$. Were the $R_{WW}(\gamma\gamma)$ and $R_{gg}(\gamma\gamma)$ enhancements to both persist with increased statistics, it will be a huge challenge to the Higgs-radion approach (as we shall discuss) as well as to other models.

We note that the error bars on the SM multipliers for the ATLAS, CMSA and CMSB scenarios are large and we regard it as likely that the central values will surely change with more integrated luminosity at the LHC. Increased integrated luminosity will hopefully increase the agreement between the ATLAS and CMS excesses, but could also worsen the consistency, or perhaps even lead to the disappearance of the excesses. Thus, the comparisons below should only be taken as illustrative of the possibilities. (Note that our plots are always done with either $m_h$ or $m_\phi$ equal to 125 GeV as appropriate for the ATLAS excess. However, there is no change in the plots if we use 124 GeV, as more precisely appropriate to the central value of the CMSA and CMSB excesses.)

As discussed above, it is appropriate to consider two different kinds of models: a basic model in which a strong lower bound on the mass of the first excited gluon implies a significant lower bound on $\Lambda_\phi$ as a function of $m_0/m_{P1}$ and a model with non-minimal extensions such that a fixed (low) value of $\Lambda_\phi$ can be considered for the full range of $m_0/m_{P1}$ even if there is a significant lower bound on $m_0^\phi$. We consider these two alternatives in turn.

| Mass (GeV) | ATLAS | CMSA | CMSB |
|-----------|-------|------|------|
| 125       | $R(\gamma\gamma) \sim 2.0_{-0.8}^{+0.8}$, $R(4\ell) \sim 1.5_{-0.8}^{+1.5}$ | $R(4\ell) = 2.0_{-1.0}^{+1.5}$, $R(\gamma\gamma) < 0.5$ | $R(\gamma\gamma) = 1.5_{-0.8}^{+0.8}$, $R(4\ell) < 0.2$ |
| 124       | no excesses | no excesses | no excesses |
A. Lower bound on $m_1^0$

In this section, we consider a model along the lines of [13] in which FCNC and PEW constraints are satisfied by virtue of the fermionic profiles being peaked fairly close to the Planck brane leading to fairly definitive couplings of the fermions to the excited gauge bosons. As described earlier, a lower bound of $m_1^0 \sim 1.5$ TeV can be obtained from LHC data while FCNC and PEW constraints suggest a still higher bound of $\sim 3$ TeV. We will show some results for both choices as we step through various possible mass locations for the Higgs and radion that are motivated by the LHC excesses in the $\gamma\gamma$ and/or $4\ell$ channels. In what follows, each plot will be labelled by the value of $m_0/m_{Pl}$ chosen and the corresponding $m_{Pl}\Omega_0$ value as calculated for the fixed $m_1^0$ using Eq. (4).

![Graphs showing the ratio of the SM rate to the Higgs-radion model rate for different choices of $m_0/m_{Pl}$ and $m_{Pl}\Omega_0$.](graph.png)

**FIG. 1.** For $m_h = 125$ GeV and $m_\phi = 120$ GeV, we plot $R_h(X)$ and $R_\phi(X)$ for $X = \gamma\gamma$ and $X = ZZ$ (equivalent to $X = 4\ell$) as a function of $\xi$, assuming $m_1^0 = 1.5$ TeV. Also shown are the similarly defined ratios for $Z + h$ production with $h \to b\bar{b}$ and $Z + \phi$ production with $\phi \to b\bar{b}$.

1. Signal at only 125 GeV

In Fig. 1 we illustrate some possibilities for $m_h = 125$ GeV and $m_\phi = 120$ GeV taking $m_1^0 = 1.5$ TeV. First, we note that to get an enhanced $\gamma\gamma$ rate at 125 GeV, it is necessary to have $m_0/m_{Pl} \gtrsim 0.4$ and $\xi < 0$. In order to have small $R_\phi(\gamma\gamma)$ and $R_\phi(4\ell)$ at 120 GeV while at the same time $R_h(\gamma\gamma) \gtrsim 1.5$ at 125 GeV, for consistency with the ATLAS scenario, then $m_0/m_{Pl} = 0.4$ and $\xi \sim -0.09$ are good choices. The somewhat larger associated value of $R_h(4\ell)$ is still consistent within errors with the ATLAS observation at 125 GeV. We note that for the reversed assignments of $m_h = 120$ GeV and $m_\phi = 125$ GeV, we cannot find parameter choices that yield a decent description of the ATLAS 125 GeV excesses with $R_h(\gamma\gamma)$ and $R_h(4\ell)$ being sufficiently suppressed at 120 GeV.

2. Signals at 125 GeV and 120 GeV

Fig. 1 also exemplifies the fact that with $m_1^0 = 1.5$ TeV the Higgs-radion model is unable to describe the CMSA scenario. In the regions of $\xi$ for which appropriate signals are present at 125 GeV from the $h$, then at 120 GeV the
4ℓ and γγ rates are either both suppressed or \( R_\phi(\gamma\gamma) > R_\phi(4\ell) \). This phenomenon persists at higher \( m_0/m_{Pl} \) values as well as higher \( m_1^\phi \).

3. Signals at 125 GeV and 137 GeV

Let us next consider the CMSB scenario, i.e. neglecting the 4ℓ excess at 120 GeV in the CMS data. Taking \( m_h = 125 \) GeV and \( m_\phi = 137 \) GeV with \( m_1^\phi = 1.5 \) TeV, Fig. 2 shows that the choices \( m_0/m_{Pl} = 0.5 \) and \( \xi = 0.12 \) give \( R_h(\gamma\gamma) \sim 1.3 \) and \( R_h(4\ell) \sim 1.5 \) at 125 GeV and \( R_\phi(\gamma\gamma) \sim 1.3 \) at 137 GeV, fairly consistent with the CMSB observations. However, \( R_\phi(4\ell) \sim 0.5 \) at 137 GeV is a bit too large. Also shown in the figure are the rates for \( Z,W+h \) with \( h \to b\bar{b} \) and \( Z,W+\phi \) with \( \phi \to b\bar{b} \) relative to their SM counterparts. For the above choices, the \( Z,W+h(\to b\bar{b}) \) rate at 125 GeV is only slightly below the SM value, whereas the \( Z,W+\phi(\to b\bar{b}) \) rate is about 10% of the SM level predicted at 137 GeV. The former is consistent with the poorly measured \( b\bar{b} \) rate at 124 GeV while confirmation of the latter would require much more integrated luminosity.

We note that it is not possible to get enhanced \( \gamma\gamma \) and 4ℓ \( h \) signals at 125 GeV without having visible 137 GeV \( \phi \) signals, i.e. the ATLAS scenario of no observable excesses other than those at 125 GeV cannot be realized for \( m_\phi = 137 \) GeV. In addition, we note that for the \( m_h = 125 \) GeV and \( m_\phi = 137 \) GeV mass assignment and \( m_1^\phi = 1.5 \) TeV, it is not possible to obtain \( R_{WW}(\gamma\gamma) \) significantly above 1. More typically it is slightly below 1.

For this case, it is also interesting to consider results for \( m_h = 125 \) GeV and \( m_\phi = 137 \) GeV for the higher value of \( m_1^\phi = 3 \) TeV. Results for this choice are plotted in Fig. 3. We observe that \( R_h(\gamma\gamma) \) and \( R_h(4\ell) \) are both \( \lesssim 1 \) (or less) except for \( m_0/m_{Pl} = 0.7 \) and large \( \xi \) for which \( R_\phi(\gamma\gamma) \ll 1 \). Thus, a reasonable description of the CMSB scenario requires relatively small \( m_1^\phi \).

Next, one can also consider the reversed mass assignments of \( m_h = 137 \) GeV and \( m_\phi = 125 \) GeV. One finds that there is no choice of \( m_0/m_{Pl} \) at \( m_1^\phi = 1.5 \) TeV for which the CMSB enhancements are approximately described. For \( \xi \) choices for which there is an enhanced \( \gamma\gamma \) signal at 137 GeV, the 4ℓ signal is even more enhanced. One can find \( \xi \) and \( m_0/m_{Pl} \) values such that the \( \gamma\gamma \) and 4ℓ signals are suppressed at 137 GeV (i.e. we seek a description of the ATLAS case) but for such choices there is no \( \gamma\gamma \) enhancement at 125 GeV. As above, for \( m_1^\phi = 3 \) TeV significant enhancements are not possible.

4. Signals at 125 GeV and high mass

A general question is whether one could explain the ATLAS 125 GeV excesses as being due to the \( h \) or \( \phi \) with the other being at high mass. As shown in Fig. 4, if \( m_h = 125 \) GeV and \( m_\phi \sim 500 \) GeV, at \( m_0/m_{Pl} \sim 1.1 \) one finds \( R_h(\gamma\gamma) \sim 1.18 \) and \( R_h(4\ell) \sim 1.45 \) for \( \xi \sim 0.79 \). As usual, the 4ℓ signal is more enhanced (relative to the SM) than the \( \gamma\gamma \) signal, but the above numbers are still consistent with the CMS 125 GeV ratios within errors. For these same choices, the \( m_\phi = 500 \) GeV signal in the 4ℓ final state would be of order that expected for a SM Higgs at the same mass. CMS results in the 4ℓ channel show a broad deficit in this same mass region that is inconsistent with the Higgs-radion prediction at the 2σ level. For the above parameter choices, the \( \gamma\gamma \) signal at \( m_\phi = 500 \) GeV would be of order 8 times that for a SM Higgs at the same mass.

Of course, it could happen that the CMS signals at 125 GeV drop to SM-level after more data is accumulated. SM-like signals are obtained for \( m_h = 125 \) GeV and \( m_\phi = 500 \) GeV at moderate \( \xi \) values. In this same parameter region, the heavy \( \phi \) has a 4ℓ rate that is suppressed relative to the SM, while the \( \gamma\gamma \) rate is most typically highly enhanced, for example by a factor of \( \sim 5000 \) if \( \xi \sim 0.1 \) and \( m_0/m_{Pl} = 1.1 \). If the \( \gamma\gamma \) rate is this large then the diphoton events at large invariant masses are likely to be observable.

Finally, we note that if \( |\xi| \) is not modest in size when \( m_\phi \) is large, the \( \phiVV \) (\( V = W,Z \)) couplings become of SM strength or larger, thus adding more pressure on the general setup coming from precision electroweak constraints. For more discussion see [35].

If the mass assignments are reversed, \( m_h = 500 \) GeV and \( m_\phi = 125 \) GeV, then the 4ℓ and/or \( \gamma\gamma \) signals at 125 GeV are suppressed relative to the SM. In addition, this case is under tension from precision electroweak constraints since for all \( \xi \) the \( h \) alone has \( hhV \) couplings that are at least SM-like. Much larger \( \Lambda_\phi \) would be needed to have a hope of achieving PEW consistency from the Higgs-radion system [36]. In addition, the \( h \to 4\ell \) signal at high mass would be at least as large as predicted for a high-mass SM-like Higgs and therefore quite observable if \( m_\phi < 500 \) GeV, as seemingly inconsistent with ATLAS and CMS data. If \( m_h \sim 1 \) TeV, then the 4ℓ signal would be beyond current LHC reach but PEW inconsistency would be much worse.
FIG. 2. For $m_h = 125$ GeV and $m_\phi = 137$ GeV, we plot $R_h(X)$ and $R_\phi(X)$ for $X = \gamma\gamma$ and $X = ZZ$ (equivalent to $X = 4\ell$) as a function of $\xi$, assuming $m_1^q = 1.5$ TeV. Also shown are the similarly defined ratios for $Z + h$ production with $h \rightarrow b\bar{b}$ and $Z + \phi$ production with $\phi \rightarrow b\bar{b}$.

FIG. 3. For $m_h = 125$ GeV and $m_\phi = 137$ GeV, we plot $R_h(X)$ and $R_\phi(X)$ for $X = \gamma\gamma$ and $X = ZZ$ (equivalent to $X = 4\ell$) as a function of $\xi$, assuming $m_1^q = 3$ TeV. Also shown are the similarly defined ratios for $Z + h$ production with $h \rightarrow b\bar{b}$ and $Z + \phi$ production with $\phi \rightarrow b\bar{b}$. 
FIG. 4. For \( m_h = 125 \text{ GeV} \) and \( m_{\phi} = 500 \text{ GeV} \), we plot \( R_h(X) \) and \( R_{\phi}(X) \) for \( X = \gamma\gamma \) and \( X = ZZ \) (equivalent to \( X = 4\ell \)) as a function of \( \xi \), assuming \( m_g^1 = 1.5 \text{ TeV} \). Also shown are the similarly defined ratios for \( Z + h \) production with \( h \rightarrow b\bar{b} \) and \( Z + \phi \) production with \( \phi \rightarrow b\bar{b} \).

B. Fixed \( \Lambda_{\phi} \)

In this section, we consider relaxing the tight relationship between \( m_g^1 \) and \( \Lambda_{\phi} \), which can occur in non-minimal scenarios as explained in the introduction. The relaxation of this relationship opens up additional phenomenological possibilities as a result of the fact that one is then free to consider rather low values of \( \Lambda_{\phi} \) independent of \( m_0/m_{Pl} \) — we will study \( \Lambda_{\phi} = 1 \text{ TeV} \) and \( \Lambda_{\phi} = 1.5 \text{ TeV} \), for which the Higgs-radion model can yield LHC rates in the \( \gamma\gamma \) and \( 4\ell \) channels that exceed those that are predicted for a SM Higgs. We note that when the gauge bosons propagate in the bulk, the phenomenology does not depend on \( \Lambda_{\phi} \) alone — at fixed \( \Lambda_{\phi} \) explicit plots not given here show that there is strong dependence on \( m_0/m_{Pl} \) when \( m_0/m_{Pl} \) is small. However, for large \( m_0/m_{Pl} \gtrsim 0.5 \) the phenomenology is determined almost entirely by \( \Lambda_{\phi} \), but is still not the same as found in the case where all fields are on the TeV brane. Once again, we step through the various possible mass locations for the Higgs and radion that are motivated by the LHC excesses in the \( \gamma\gamma \) and/or \( 4\ell \) channels.

1. Signal only at 125 GeV

As shown in Fig. 5, the choice of \( \Lambda_{\phi} = 1 \text{ TeV} \) with \( m_{\phi} = 125 \text{ GeV} \) and \( m_h = 120 \text{ GeV} \) gives a reasonable description of the ATLAS excesses at 125 GeV with no visible signals at 120 GeV in either the \( \gamma\gamma \) or \( 4\ell \) channels when one chooses \( m_0/m_{Pl} = 1 \) and \( \xi = -0.016 \). In contrast, for \( \Lambda_{\phi} = 1.5 \text{ TeV} \) the 125 GeV predicted excesses are below \( 1 \times \text{SM} \) and thus would not provide a good description of the ATLAS data. As exemplified in Fig. 6 for the reversed assignments of \( m_h = 125 \text{ GeV} \) and \( m_{\phi} = 120 \text{ GeV} \) any choice of parameters that gives a good description of the 125 GeV signals always yields a highly observable 120 GeV signal.
FIG. 5. For $m_h = 120$ GeV and $m_\phi = 125$ GeV, we plot $R_h(X)$ and $R_\phi(X)$ for $X = \gamma\gamma$ and $X = ZZ$ (equivalent to $X = 4\ell$) as a function of $\xi$ taking $\Lambda_\phi$ fixed at 1 TeV.

2. Signals at 125 GeV and 120 GeV

We can also consider Fig. 6 to see if there is a choice of $\xi$ for which consistency with the CMSA scenario is achieved. We observe that if $\xi$ is at its maximum value and $m_0/m_{Pl} = 1.1$ then the $\gamma\gamma$ and $4\ell$ signals at $m_h = 125$ GeV are still within $1\sigma$ of the CMS data while at $m_\phi = 120$ GeV one finds $R_\phi(4\ell) \sim 2.5$ while $R_\phi(\gamma\gamma) \sim 0.3$, which values are roughly consistent with the CMSA situation. For the reversed assignments of $m_h = 120$ GeV and $m_\phi = 125$ GeV, Fig 5 illustrates the fact that a satisfactory description of the two CMSA excesses is not possible — for $\xi$ such that appropriate $125$ GeV excesses are present, $R_h(\gamma\gamma)$ and $R_h(4\ell)$ at 120 GeV are always small so that the $4\ell$ excess at 120 GeV is not explained.

3. Signals at 125 GeV and 137 GeV

Let us now consider the CMSB scenario. For $\Lambda_\phi = 1$ TeV, one finds $m_h = 125$ GeV and $m_\phi = 137$ GeV with the choices $m_0/m_{Pl} = 0.6$ and $\xi = -0.05$ give $R_h(\gamma\gamma) \sim 2$ and $R_h(4\ell) \sim 1$ at 125 GeV, while $R_\phi(\gamma\gamma) \sim 2$ and $R_\phi(4\ell) \sim 0.4$ at 137 GeV, an ok description of the CMSB excesses. An equally rough description of this same situation is also possible for $\Lambda_\phi = 1$ TeV with $m_0/m_{Pl} = 0.8$ and $\xi = 0.05$.

For $\Lambda_\phi = 1.5$ TeV a somewhat better simultaneous description of these excesses is possible. Fig. 7 shows some results for $m_h = 125$ GeV and $m_\phi = 137$ GeV. For $m_0/m_{Pl} = 0.25$ and $\xi = -0.1$ one finds $R_h(\gamma\gamma) \sim 2$ and $R_h(4\ell) \sim 1.5$ at $m_h = 125$ GeV, while $R_\phi(\gamma\gamma) \sim 2$ and $R_\phi(4\ell) \ll 1$ at $m_\phi = 137$ GeV, in pretty good agreement with the CMSB scenario.

If we reverse the configuration to $m_h = 137$ GeV and $m_\phi = 125$ GeV, only $\Lambda_\phi = 1$ TeV with $m_0/m_{Pl} = 0.8$ and $\xi = 0.05$ comes close to describing the two excess; one finds that the $m_\phi = 125$ GeV $\gamma\gamma$ and $4\ell$ signals and the $m_h = 137$ GeV $\gamma\gamma$ signal are all at the level of $\sim 1.4\times$SM. However, the $m_h = 137$ GeV $4\ell$ signal is at the level of $\sim 0.6\times$SM which is $4\sigma$ away from the CMS central value at this mass. For these mass assignments and the higher $\Lambda_\phi = 1.5$ TeV value, $m_0/m_{Pl}$ and $\xi$ choices that approximately describe the CMS excesses cannot be found — the
For $m_h = 125$ GeV and $m_\phi = 120$ GeV, we plot $R_h(X)$ and $R_\phi(X)$ for $X = \gamma\gamma$ and $X = ZZ$ (equivalent to $X = 4\ell$) as a function of $\xi$ taking $\Lambda_\phi$ fixed at 1 TeV.

$m_\phi = 125$ GeV signals are never simultaneously sufficiently large to fit the observed signals.

4. Signals at 125 GeV and higher mass

We choose not to show any specific plots for this situation. For $\Lambda_\phi = 1$ TeV or 1.5 TeV, it is possible to choose one of either the $h$ or $\phi$ to have a mass of 125 GeV and find $m_0/m_{Pl}$ and $\xi$ values that result in a decent description of the 125 GeV ATLAS excesses. When the $\phi$ is heavy, the scenario can be viable but the $\phi$ might be hard to discover due to suppressed couplings to ZZ. When the $h$ is heavy there would be tensions coming PEW constraints and, if the higher mass is chosen below 500 GeV, a highly observable $4\ell$ signal that would be inconsistent with ATLAS and CMS observations in that region of mass.

5. SM Higgs at 125 GeV and Signal at 137 GeV

It is still quite conceivable that, after accumulating more data, the excesses at $\sim 125$ GeV will converge to those appropriate for a SM Higgs boson. Such a situation would correspond to taking $\xi = 0$ in the Higgs-radion model. In this case, one can ask whether or not there could be a radion at some nearby mass and what its experimental signature would be. To exemplify, let us suppose that the signal at 137 GeV of the CMSB scenario survives. In Fig. 8 we plot $R_\phi(X)$ for $X = \gamma\gamma$ and $X = ZZ$ as a function of $\xi$ taking $\Lambda_\phi$ fixed at 1 TeV. Also shown are ratios to the SM for $Z \rightarrow Z\phi$ with $\phi \rightarrow b\bar{b}$ and for $WW \rightarrow \phi \rightarrow X$ for $X = \gamma\gamma$, $ZZ$ and $b\bar{b}$. One observes that a nice description of the $R(\gamma\gamma) \sim 2$ excess at 137 GeV is possible, for example, for $m_0/m_{Pl} = 0.3$ at $\Lambda_\phi \sim 2.8$ TeV with the $4\ell$ signal (and all other signals) being very suppressed. As also apparent, other choices of the $m_0/m_{Pl}$ and $\Lambda_\phi$ will also yield $R_\phi(\gamma\gamma) \sim 2$ with varying levels of $4\ell$ and other signals. (However, to suppress $R_\phi(4\ell)$ below 0.2 while achieving $R_\phi(\gamma\gamma) \sim 2$ requires $m_0/m_{Pl} \geq 0.3$.) We also note that for $\xi = 0$ the $Z, W + \phi(\rightarrow b\bar{b})$ rates are greatly suppressed relative to their SM counterparts.
FIG. 7. For $m_h = 125$ GeV and $m_\phi = 137$ GeV, we plot $R_h(X)$ and $R_\phi(X)$ for $X = \gamma\gamma$ and $X = ZZ$ (equivalent to $X = 4\ell$) as a function of $\xi$ taking $\Lambda_\phi$ fixed at 1.5 TeV.

Plots for the case of a SM Higgs at 125 GeV and $m_\phi = 120$ GeV look very similar and, in particular, it is not possible to find parameters for which the 4$\ell$ signal substantially exceeds the $\gamma\gamma$ signal — the reverse always applies, as one anticipates from the enhanced anomalous $\gamma\gamma$ coupling of the (unmixed) $\phi$.

III. SUMMARY AND CONCLUSIONS

The Randall Sundrum model solution to the hierarchy problem yields interesting phenomenology for the Higgs-radion sector, especially when Higgs-radion mixing is allowed for, and can be made consistent with FCNC and PEW constraints if fermions and gauge bosons propagate in the 5th dimension. At the moment, there are interesting hints at the LHC of narrow excesses above SM backgrounds in the $\gamma\gamma$ and $ZZ \to 4\ell$ channels, as well as a broad excess in the $WW \to \ell\nu\ell\nu$ channel. ATLAS sees excesses in the $\gamma\gamma$ and $4\ell$ channels at a mass of $\sim 125$ GeV of order $2 \times$ SM and $1.5 \times$ SM respectively. CMS sees a $\gamma\gamma$ excess of order $1.5 \times$ SM at $\sim 124$ GeV and constrains the $4\ell$ channel at this mass to be less than $\sim 1.5 \times$ SM. Additional excesses at 120 GeV (in the $4\ell$ channel) and at 137 GeV (in the $\gamma\gamma$ channel) are present in the CMS data.

In this paper, we explored a wide range of possibilities within the Randall Sundrum model context. In a first set of plots, we assumed the standard relation between $\Lambda_\phi$ (the radion field vacuum expectation value), the curvature ratio $m_0/m_{Pl}$ and $m_1^g$ (the mass of the 1st excited gluon state) that applies in the class of scenarios in which the 5th dimension profiles for light fermions need to be peaked near the Planck brane in order to avoid corrections to FCNC and PEW constraints that are too large. We considered lower bounds on the latter of $m_1^g > 1.5$ TeV or 3 TeV, as estimated using LHC data. Our second set of plots are done holding $\Lambda_\phi$ fixed at either 1 TeV or 1.5 TeV, using the fact that the lower bounds (as a function of $m_0/m_{Pl}$) on $\Lambda_\phi$ resulting from a lower bound on the mass of the $g^1$ can be loosened in non-minimal extensions of the setup. Our studies are done assuming that the Yukawa coupling of the brane Higgs to the 5D fermionic fields proportional to $H\bar{Q}YU_L + h.c.$ is small. Such a choice is consistent with FCNC and PEW constraints. In this case, the unmixed $h_0$ couplings, in particular to $gg$ and $\gamma\gamma$, are not modified with respect to those of a SM Higgs boson. In this way, we sample an interesting range of phenomenological possibilities. For fully general $Y_2$, corrections to the $h_0$ couplings due to 5D effects can be large and can either suppress or enhance
For $m_\phi = 137$ GeV, we plot $R_\phi(X)$ for $X = \gamma\gamma$ and $X = ZZ$ (equivalent to $X = 4\ell$) as functions of $\Lambda_\phi$ taking $\xi = 0$. We also plot ratios to the SM for $Z \rightarrow Z\phi$ with $\phi \rightarrow b\bar{b}$ and for $WW \rightarrow \phi \rightarrow X$ for $X = \gamma\gamma$, $ZZ$ and $b\bar{b}$.

Since the single Higgs plus radion model can describe at most two Higgs-like excesses, we considered three scenarios labelled as: ATLAS, with $\gamma\gamma$ and $4\ell$ excesses at 125 GeV larger than SM and no other significant excesses; CMSA, with $\gamma\gamma$ and $4\ell$ excesses at 124 GeV above SM level and a $4\ell$ excess at 120 GeV; and, CMSB, with $\gamma\gamma$ and $4\ell$ excesses at 124 GeV above those predicted for a SM Higgs boson of this same mass along with a $\gamma\gamma$ excess at 137 GeV that is also larger than would have been predicted for $m_{h_{SM}} = 137$ GeV. In both the fixed $m_{g_1} = 1.5$ TeV and the fixed $\Lambda_\phi = 1$ TeV model possibilities, the signal levels of the ATLAS and CMSB scenarios could be nicely described, whereas the enhancements relative to the SM were too small for $m_{g_1} = 3$ TeV and $\Lambda_\phi = 1.5$ TeV, respectively. A satisfactory description of the CMSA scenario was also found in the case of fixed $\Lambda_\phi = 1$ TeV, but not in the case where fixed $m_{g_1} = 1.5$ TeV was used to determine $\Lambda_\phi$ as a function of $m_0/m_{Pl}$. In general, successful fitting of the ATLAS and CMSB excesses required a modest value for the radion vacuum expectation value, mostly $\Lambda_\phi \lesssim 3$ TeV, and typically $m_0/m_{Pl} \gtrsim 0.5$, a range that the most recent discussion suggests is still consistent with higher curvature corrections to the RS scenario being small.

We also considered expectations for the radion signal in the case where the Higgs signal was assumed to ultimately converge to precisely that for a SM Higgs of mass 125 GeV. This situation would arise if there is no Higgs-radion mixing. We found that interesting excesses at the radion mass would be present for low enough $\Lambda_\phi$, namely $\Lambda_\phi \lesssim 3$ TeV, but would always be characterized by a $\gamma\gamma$ signal that substantially exceeds the $4\ell$ signal (as appropriate for the CMS $\gamma\gamma$ excess at 137 GeV but in definite contradiction with the CMS $4\ell$ excess at 120 GeV). Finally, we noted that a larger-than-SM signal in $WW \rightarrow h$ or $\phi \rightarrow \gamma\gamma$, as possibly seen by CMS at 125 GeV, cannot be achieved (at least in the model employed here where the unmixed $h_0$ couplings are SM-like).

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