Higgs-Radion mixing and the LHC Higgs-like excesses

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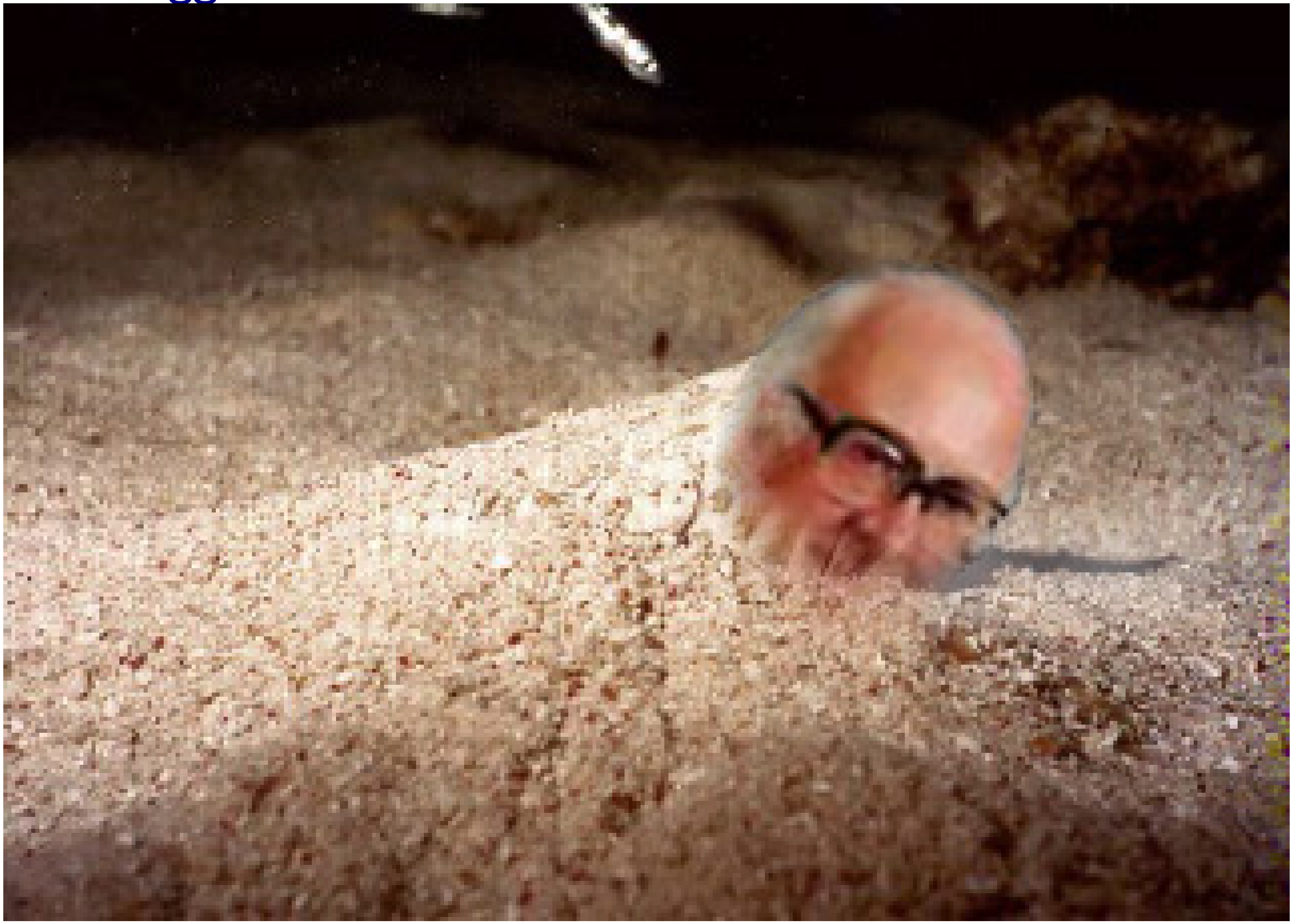
Higgs-like LHC Excesses

Is what we are seeing a Higgs-like chameleon?

Higgs-like LHC Excesses

Or is it THE Higgs?



- **Given that the mass(es) is(are) of order $125\ \mathrm{GeV}$, the MSSM or the much more attractive NMSSM extension thereof is a natural candidate theory.**

  After all, SUSY solves the hierarchy problem, predicts gauge coupling unification at the GUT scale and so forth.

  However:

  - **A SM-like Higgs with mass as large as $125\ \mathrm{GeV}$ is a bit of a stretch. Even in the NMSSM $125\ \mathrm{GeV}$ is "on the edge" for semi-universal (NUHM) GUT boundary conditions (and not possible for full CNMSSM b.c.).**
  - **This is aggravated if the signal is $>$ SM.**
  - **And, even more problematically, there may be more than one 'excess' in the data (cf. CMS data).**

- **The only other really attractive alternate solution to the hierarchy problem that provides a self-contained ultraviolet complete framework is to allow extra dimensions.**

  One particular implementation is the Randall Sundrum model in which there is a warped 5th dimension.

The Randall Sundrum Model

- **The background RS metric that solves Einstein's equations takes the form[1]**

$$ds^2 = e^{-2m_0 b_0 |y|}\eta_{\mu\nu}dx^\mu dx^\nu - b_0^2 dy^2 \tag{1}$$

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 $\eta_{\mu\nu}$ and b_0, respectively.**

- **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**

$$\mathcal{L}_{\rm int} = -\frac{1}{\widehat{\Lambda}_W}\sum_{n\neq 0} h^n_{\mu\nu}T^{\mu\nu} - \frac{\phi_0}{\Lambda_\phi}T^\mu_\mu \tag{2}$$

where $h^n_{\mu\nu}(x)$ are the Kaluza-Klein (KK) modes (with mass m_n) of the graviton field $h_{\mu\nu}(x,y)$.

- Λ_ϕ is the vacuum expectation value of the radion field and is related to $\widehat\Lambda_W$ and m_{Pl} as follows.

$$\widehat\Lambda_W \simeq \sqrt{2} m_{Pl} \Omega_0, \quad \text{where} \quad \Omega_0 = e^{-\frac{1}{2} m_0 b_0}, \quad \Lambda_\phi = \sqrt{3}\,\widehat\Lambda_W\,. \qquad (3)$$

- If matter propagates in the bulk then the interactions of gravitons and radion with matter are controlled by the overlap of appropriate extra-dimensional profiles and corrections to (2) appear.

- Besides 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, $\widehat{v}$, by:

$$v_0 = \Omega_0 \widehat{v} = e^{-\frac{1}{2}m_0 b_0} \widehat{v} \sim 1 \text{ TeV} \quad \text{for} \quad \frac{1}{2} m_0 b_0 \sim 35 \,. \tag{4}$$

To solve the hierarchy problem, $\Lambda_\phi = \sqrt{6} m_{Pl} \Omega_0 \lesssim 1 - 10$ TeV needed.

- m_0/m_{Pl} is a particularly crucial parameter that characterizes the 5-dimensional curvature.

  $m_0/m_{Pl} \gtrsim 0.5$ is favored for fitting the LHC Higgs excesses and by bounds on FCNC and PEW constraints.

  Views on m_0/m_{Pl} are changing:

  – Original: $R_5/M_5^2 < 1$ (M_5 being the 5D Planck scale and $R_5 = 20 m_0^2$ the size of the 5D curvature) is needed to suppress higher curvature terms in the 5D action: $\Rightarrow m_0/m_{Pl} \lesssim 0.15$.
  – New: [9] argues that R_5/Λ^2 ($\Lambda =$ energy scale at which the 5D gravity theory becomes strongly coupled, with NDA estimate of $\Lambda \sim 2\sqrt{3}\pi M_5$), is the appropriate measure,
  $\Rightarrow m_0/m_{Pl} < \sqrt{3\pi^3/(5\sqrt{5})} \sim 3$ acceptable.

- Note: the mass of 1st KK graviton excitation (G^1) is related to m_0/m_{Pl} and Λ_ϕ by

$$m_1^{\rm KK} = \frac{(m_0/m_{Pl})x_1^{\rm KK}}{\sqrt{6}}\Lambda_\phi\,, \quad (5)$$

where $x_1^{\rm KK} \sim 3.83$.

$\Rightarrow$ large m_0/m_{Pl} if the lower bound on $m_1^{\rm KK}$ is large and $\Lambda_\phi \sim 1~{\rm TeV}$.

- In the simplest RS scenario, the SM fermions and gauge bosons are confined to the brane.

  Now regarded as highly problematical:

  – Higher-dimensional operators in the 5D effective field theory are suppressed only by ${\rm TeV}^{-1}$, $\Rightarrow$ FCNC processes and PEW observable corrections are predicted to be much too large.
  $\Rightarrow$ no explanation of the flavor hierarchies.

- Must move fermions and gauge bosons (but not Higgs) off the brane [2][3][4][5][6][7][8][9]

The SM particles = zero-modes of the 5D fields and the profile of a SM fermion in the extra dimension can be adjusted using a mass parameter.

Two possibilities:

1. **If 1st and 2nd generation fermion profiles peak near the Planck brane then FCNC operators and PEW corrections will be suppressed by scales** $\gg \text{ TeV}$**.**
   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]).**
2. **Use fairly flat profiles for the 1st and 2nd generation fermions in the 5th dimension.**
   $\Rightarrow$ **the coupling of light quarks to** g^1, W^1, Z^1**, proportional to the integral of the square of the fermion profile multiplied by the gauge boson profile, will be very small, implying small FCNC.**
   PEW constraints would still be very problematical unless a special 5D GIM mechanism is employed [11] and/or there is a custodial symmetry in the bulk and there is a discrete $L \leftrightarrow R$ **symmetry to suppress** $Z \to b\bar{b}$ **corrections.**

In either case, the interactions of Eq. (2) are greatly modified when gauge bosons and fermions are allowed to propagate in the bulk.

- If the gauge bosons and fermions do not propagate in the bulk, then the strongest limits on Λ_ϕ come, via Eq. (5), from the lower bound placed by the LHC on the first graviton KK excitation (see, for example, [13] and [14] 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.

- First approach: In the model of [12], in which light fermion profiles peak near the Planck brane, there is a universal component to the light quark coupling $q\overline{q}g^1$ that is roughly equal to the SM coupling g times a factor of ζ^{-1}, where $\zeta \sim \sqrt{\frac{1}{2}m_0 b_0} \sim 5-6$.

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, the $t_R\bar{t}_R g^1$ coupling is large since the t_R profile peaks near the TeV brane – the prediction of [12] is $g_{t_R\bar{t}_R g^1} \sim \zeta g$.

$\Rightarrow g^1 \to t\bar{t}$ decays dominant.

$\Rightarrow$ lower bound of $m_1^g \gtrsim 1.5~\mathrm{TeV}$ [15] using an update of the analysis of [12]. ([16] gives a weaker bound of $m_1^g > 0.84~\mathrm{TeV}$.) .

- In terms of Λ_ϕ, we have the following relations:

$$\frac{m_0}{m_{Pl}} = \frac{\sqrt{6}}{x_1^g}\frac{m_1^g}{\Lambda_\phi} \simeq \frac{m_1^g}{\Lambda_\phi}, \quad \text{and} \quad \frac{1}{2}m_0 b_0 = -\log\left(\frac{\Lambda_\phi}{\sqrt{6}m_{Pl}}\right) \tag{6}$$

where $x_1^g = 2.45$ is the 1st zero of an appropriate Bessel function.

If the model really solves the hierarchy problem then $\widehat{\Lambda}_W$ in Eq. (2) cannot be much larger than $1~\mathrm{TeV}$. Let us take $\widehat{\Lambda}_W \lesssim 5.5~\mathrm{TeV}$ as an extreme possibility, which implies $\Lambda_\phi = \sqrt{3}\widehat{\Lambda}_W \lesssim 10~\mathrm{TeV}$.

If we adopt the CMS limit of $m_1^g > 1.5~\mathrm{TeV}$ then (6) implies a lower limit on the 5-dimensional curvature of $m_0/m_{Pl} \gtrsim 0.15$.

Thus, a significant lower bound on m_1^g implies that only relatively large values for m_0/m_{Pl} are allowed. $\Rightarrow$ probably ok given latest ideas.

- Alternate approach: Take light fermion profiles to be flat in 5th dimension. $\Rightarrow q\bar{q}g^1, \ldots$ couplings are small (fix precision data as noted earlier)

  $\Rightarrow$ no direct experimental bound on m_1^g.

  Λ_ϕ?

  if $\Lambda_\phi = 1~\mathrm{TeV}$, for $m_0/m_{Pl} = 0.01, 0.1$ Eq. (6) implies $m_1^g = 10, 100~\mathrm{GeV}$.

  Could the g^1 really have escaped discovery for such low masses?

  If there is no firm bound on $m_1^g \Rightarrow$ discuss the phenomenology for fixed Λ_ϕ. We will consider $\Lambda_\phi = 1~\mathrm{TeV}$ and $1.5~\mathrm{TeV}$.

Higgs-Radion Mixing

- **Since the radion and higgs fields have the same quantum numbers, they can mix. [17]**

$$S_\xi = \xi \int d^4x \sqrt{g_{\rm vis}} R(g_{\rm vis}) \widehat{H}^\dagger \widehat{H}\,, \tag{7}$$

The physical mass eigenstates, h and ϕ, are obtained by diagonalizing and canonically normalizing the kinetic energy terms.

The diagonalization procedures and results for the h and ϕ using our notation can be found in [10] (see also [17][18]).

In the end, one finds

$$h_0 \;=\; dh + c\phi \quad -\phi_0 = a\phi + bh\,. \tag{8}$$

where a, b, c, d are functions of the eigenstate masses, m_h and m_ϕ, ξ and $\gamma \equiv v_0/\Lambda_\phi$ ($v_0 = 246~{\rm GeV}$). For $\xi = 0$, $d = 1, a = -1, c = b = 0$. Radion couplings to SM $\propto \gamma$.

Consistency of the diagonalization $\Rightarrow$ strong restrictions on the ξ range as a function of the final eigenstate masses m_h and m_ϕ

- For the full Feynman rules for the h and ϕ when fermions and gauge bosons propagate in the bulk see [19].

  Of particular note are the anomaly terms associated with the ϕ_0 interactions before mixing. Defining

$$g_h = (d+\gamma b) \quad g_\phi = (c+\gamma a) \quad g_h^r = \gamma b \quad g_\phi^r = \gamma a\,. \tag{9}$$

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

$$c_\gamma^{h,\phi} = -\frac{\alpha}{2\pi v}\left[g_{h,\phi}\sum_i e_i^2 N_c^i F_i(\tau_i) - (b_2 + b_Y + \frac{2\pi}{\alpha \frac{1}{2} m_0 b_0})g_{h,\phi}^r\right] \tag{10}$$

  New relative to old on-the-brane results are the $2\pi\ldots$ corrections to the g^r terms. They can be significant in the c_γ case.

- There are also modifications to the WW and ZZ couplings of the h and ϕ relative to old on-the-brane results.

  These bring in $W^\dagger_{\mu\nu}W^{\mu\nu}$ terms in $\mathcal{L}$ in addition to the usual $W^\dagger_\mu W^\nu$ terms.

LHC Excesses

- **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 a few cases. Errors quoted for the excesses are $\pm 1\sigma$.

1. ATLAS:

   125 GeV: $\gamma\gamma$ excess of $2^{+0.8}_{-0.8}\times$SM

   125 GeV: 4ℓ excess of $1.5^{+1.5}_{-1}\times$ SM

2. CMSA:

   124 GeV: $\gamma\gamma$ excess of $1.7^{+0.8}_{-0.7}\times$ SM

   124 GeV: 4ℓ excess of $0.5^{+1.1}_{-0.7}\times$SM

   120 GeV: 4ℓ excess of $\sim 2^{+1.5}_{-1}\times$SM but $\gamma\gamma$ rate $< 0.5\times$SM.

3. CMSB:

   124 GeV: as above

   137 GeV: $\gamma\gamma$ excess of $1.5^{+0.8}_{-0.8}\times$SM

   137 GeV: $4\ell < 0.2\times$SM

Notes:

- For plots use 125 GeV always: no change if 125 GeV $\rightarrow 124$ GeV.

- As discussed, consider two different kinds of models:

1. lower bound on m_1^g of 1.5 TeV
2. fixed Λ_ϕ

Lower bound of $m_1^g = 1.5$ TeV

- Recall that Λ_ϕ will be correlated with m_0/m_{Pl}.

$$\frac{m_0}{m_{Pl}} \simeq \frac{m_1^g}{\Lambda_\phi} \tag{11}$$

$\Rightarrow$

For small m_0/m_{Pl}, Λ_ϕ is too large, so only solve hierarchy if m_0/m_{Pl} is $\gtrsim 0.2$.

- Only have time for a limited selection of situations.

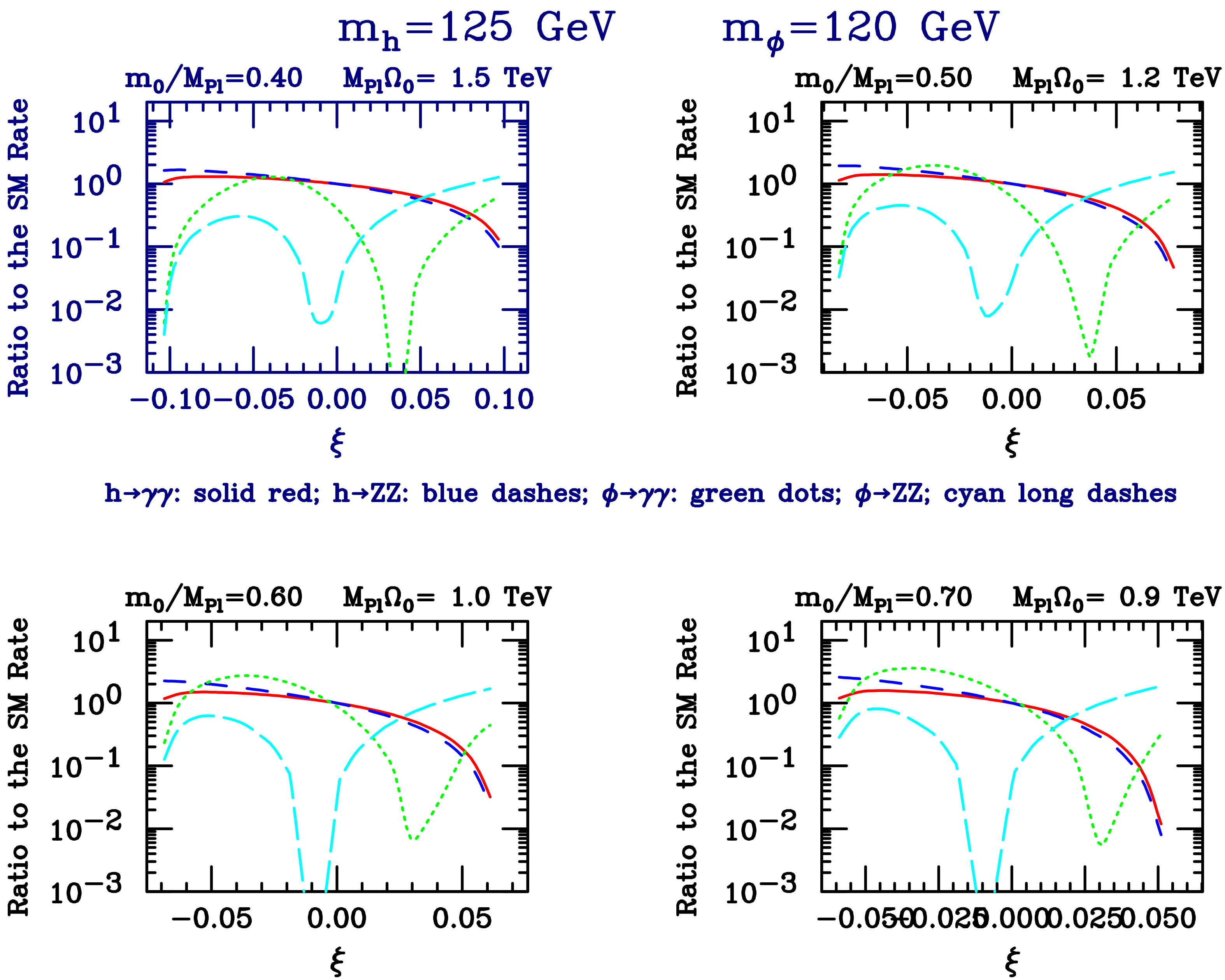


Figure 1: We plot $\gamma\gamma$ and ZZ relative to SM vs ξ.

Only 125 GeV excess

- If want no excesses at ~ 120 GeV, but $\gamma\gamma$ excess at 125 GeV of order $\gtrsim 1.5\times$SM, then $m_0/m_{Pl} = 0.4$ and $\xi \sim -0.09$ are good choices.

  4ℓ signal at 125 GeV is $> \gamma\gamma$ but still within error.

- For the reversed assignments of $m_h = 120$ GeV and $m_\phi = 125$ GeV, no decent description of the ATLAS 125 GeV excesses with signals at 120 GeV being sufficiently suppressed.

Excesses at 125 GeV and 120 GeV

- Higgs-radion scenario fails.

  In the regions of ξ for which appropriate signals are present at 125 GeV from the h, the 4ℓ and $\gamma\gamma$ rates at 120 GeV are either both suppressed or it is the $\gamma\gamma$ rate that is enhanced more than the 4ℓ rate at 120 GeV. This phenomenon persists at higher m_0/m_{Pl} values.

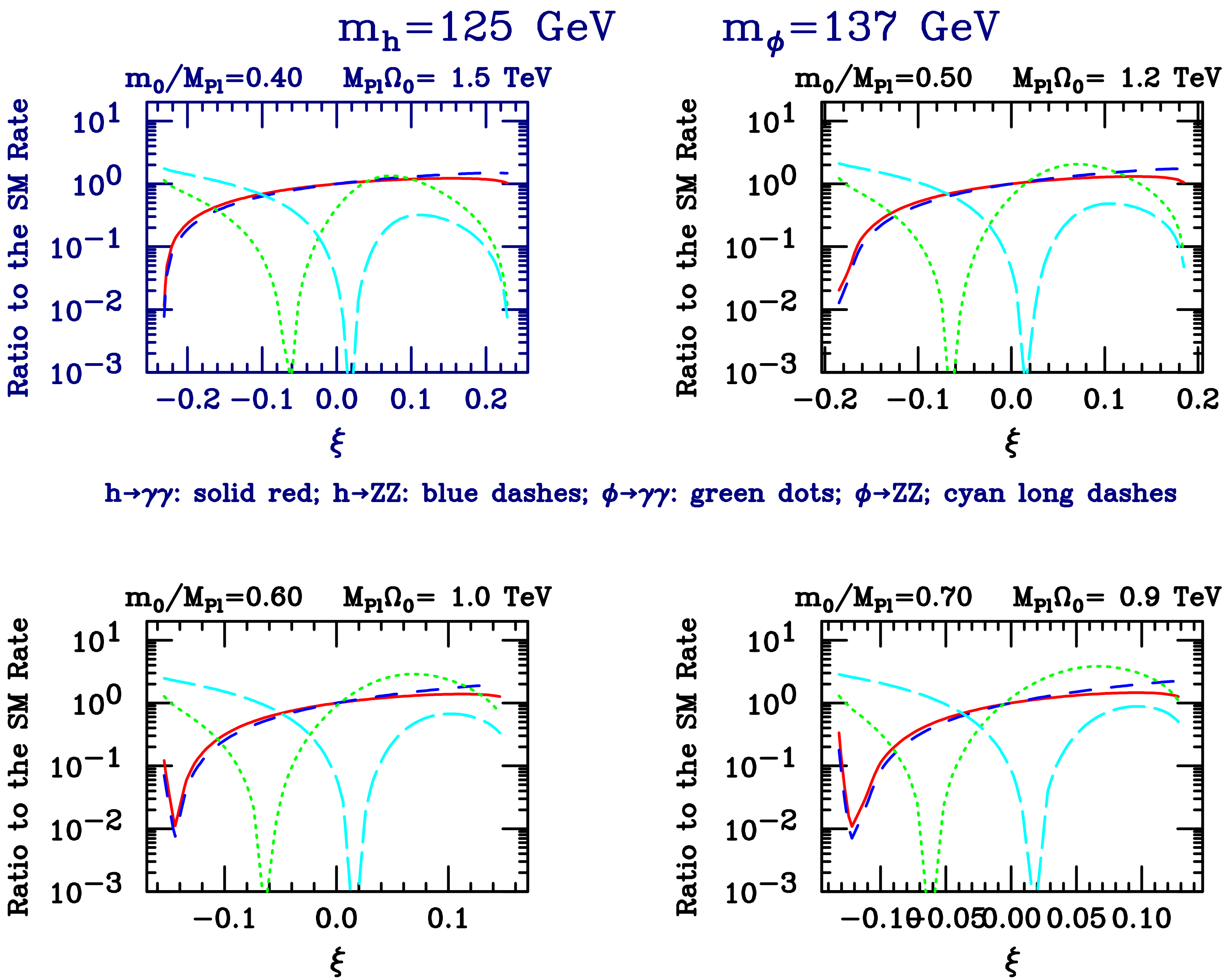


Figure 2: $\gamma\gamma$ **and** ZZ **relative to SM vs** ξ**.**

Signals at $\mathbf{125}$ GeV and $\mathbf{137}$ GeV

- **In Fig. 2 (previous page):** $m_0/m_{Pl} = 0.5$ **and** $\xi = 0 \Rightarrow$

  $\mathbf{125}$ GeV: $\gamma\gamma \sim 1\times$**SM and** $4\ell \sim 1\times$**SM**

  $\mathbf{137}$ GeV: $\gamma\gamma \sim 1\times$**SM and** 4ℓ **very small**

  These rates are consistent within 1σ **with the CMS observations.**

m_h=500 GeV m_ϕ=125 GeV

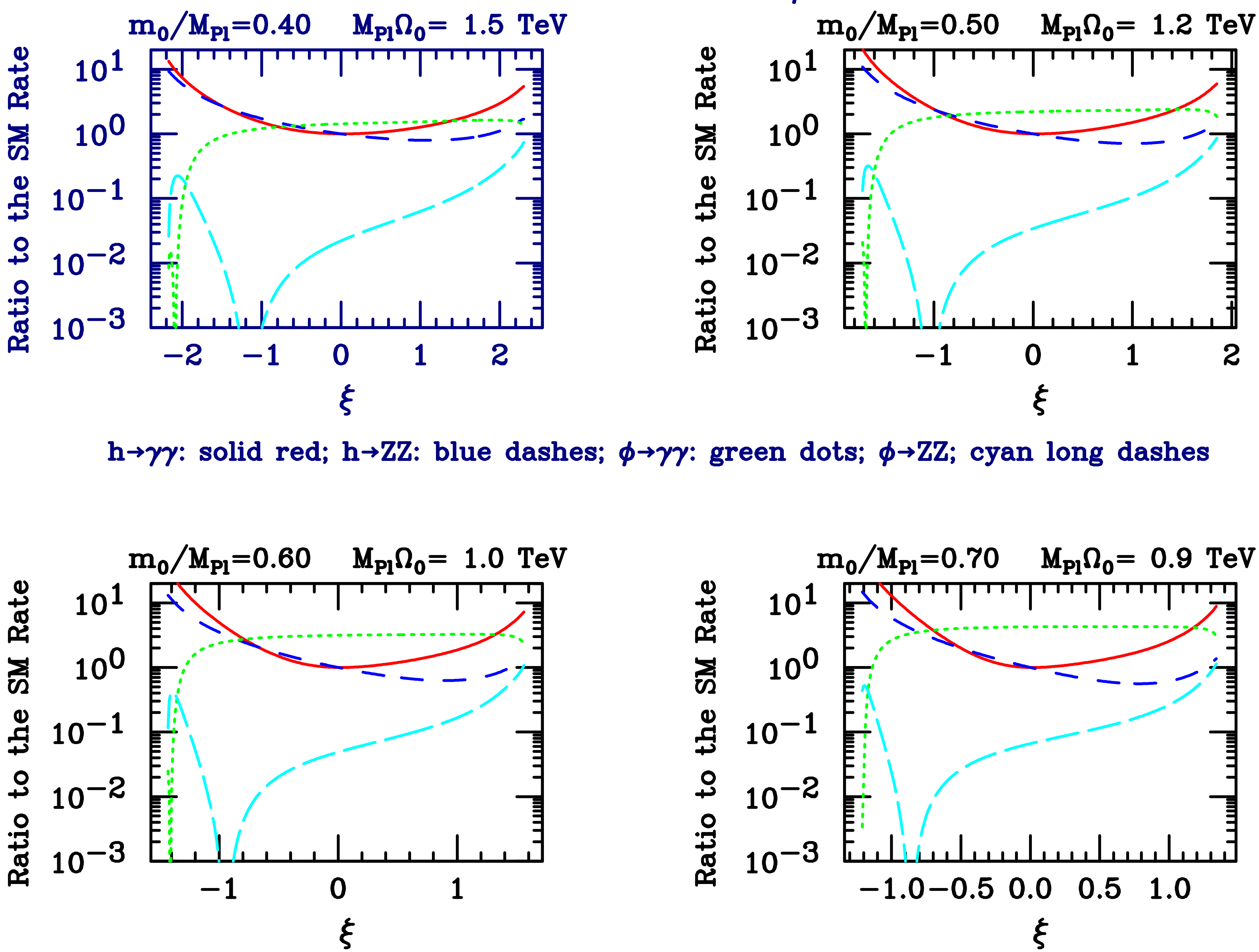


Figure 3: We plot $\gamma\gamma$ and ZZ relative to SM vs ξ.

Signals at 125 GeV and 500 GeV

- There are two choices, $m_h = 125$ GeV with $m_\phi = 500$ GeV or reverse. Let us discuss the reverse. Fig. 3.

- $\xi \sim \xi^{\max} \Rightarrow \gamma\gamma \sim 2\times$SM and $4\ell \sim 1\times$SM at $m_\phi = 125$ GeV for $m_0/m_{Pl} = 0.4$ and 0.5.

- $h \to 4\ell$ signal at 500 GeV $\sim$SM.

- $\gamma\gamma$ signal at 500 GeV enhanced, but SM rate small, and thus almost surely unobservable.

- 4ℓ rates at 500 GeV? ATLAS and CMS disagree.

  Probably, the heavy h in this scenario would have to be placed beyond LHC reach (for which the $m_\phi = 125$ GeV signals shown would be unchanged).

Fixed Λ_ϕ

- If fermionic profiles are quite flat, couplings of light quarks to the gauge excitations are very small. $\Rightarrow$ no bounds on m_1^g or Λ_ϕ.

  We choose to examine the phenomenology for (low) values of $\Lambda_\phi = 1$ TeV and $\Lambda_\phi = 1.5$ TeV.

- When fermions and, in particular, gauge bosons propagate in the bulk the phenomenology does not depend on Λ_ϕ alone — at fixed Λ_ϕ there is strong dependence on m_0/m_{Pl} when m_0/m_{Pl} is small.

- Only for large $m_0/m_{Pl} \gtrsim 0.5$ is the phenomenology determined almost entirely by Λ_ϕ.

  But, not the same as when 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 4ℓ channels.

Single resonance at 125 GeV

- The choice of $\Lambda_\phi = 1$ TeV with $m_\phi = 125$ GeV and $m_h = 120$ 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 4ℓ channels. (figure not shown)

  A good choice of parameters is $m_0/m_{Pl} = 1$ and $\xi = -0.015$.

- In contrast, for $\Lambda_\phi = 1.5$ TeV the 125 GeV predicted $\gamma\gamma$ and 4ℓ excesses are below $1\times$SM and thus would not provide a good description of the ATLAS excesses.

- For the reversed assignments of $m_h = 125$ GeV and $m_\phi = 120$ GeV, any choice of parameters that gives a good description of the 125 GeV signals yields a highly observable 120 GeV signal, not appropriate for ATLAS.

Signals at 125 GeV and 120 GeV

- There is a marginal solution for $m_h = 125$ GeV, $m_\phi = 120$ GeV, $\xi = \xi^{\max}$ and $m_0/m_{Pl} = 1.1$.

- With the reversed assignments of $m_h = 120$ GeV and $m_\phi = 125$ GeV a satisfactory description of the two CMS excesses is not possible.

Signals at 125 GeV and 137 GeV

- **CMS data want:**

  125 GeV: $\gamma\gamma \sim 1.7\times$SM and $4\ell < 1.6\times$SM.

  137 GeV: $\gamma\gamma \sim 1.5\times$SM and $4\ell \sim small$.

- **For $\Lambda_\phi = 1$ TeV, $m_h = 125$ GeV, $m_\phi = 137$ GeV get rough description at $m_0/m_{Pl} = 0.6$ and $\xi = -0.05$**

- **For $\Lambda_\phi = 1.5$ TeV, can do better.**

  Fig. 4 (next page) shows results for $m_h = 125$ GeV and $m_\phi = 137$ GeV.

  For $m_0/m_{Pl} = 0.25$ and $\xi \sim -0.1 \Rightarrow$

  125 GeV: $\gamma\gamma \sim 2\times$SM and $4\ell \sim 1.5\times$SM.

  137 GeV: $\gamma\gamma \sim 2\times$SM and 4ℓ very suppressed.

- **For $\Lambda_\phi = 1$ TeV or 1.5 TeV, the reverse configuration of $m_h = 137$ GeV and $m_\phi = 125$ GeV is not good.**

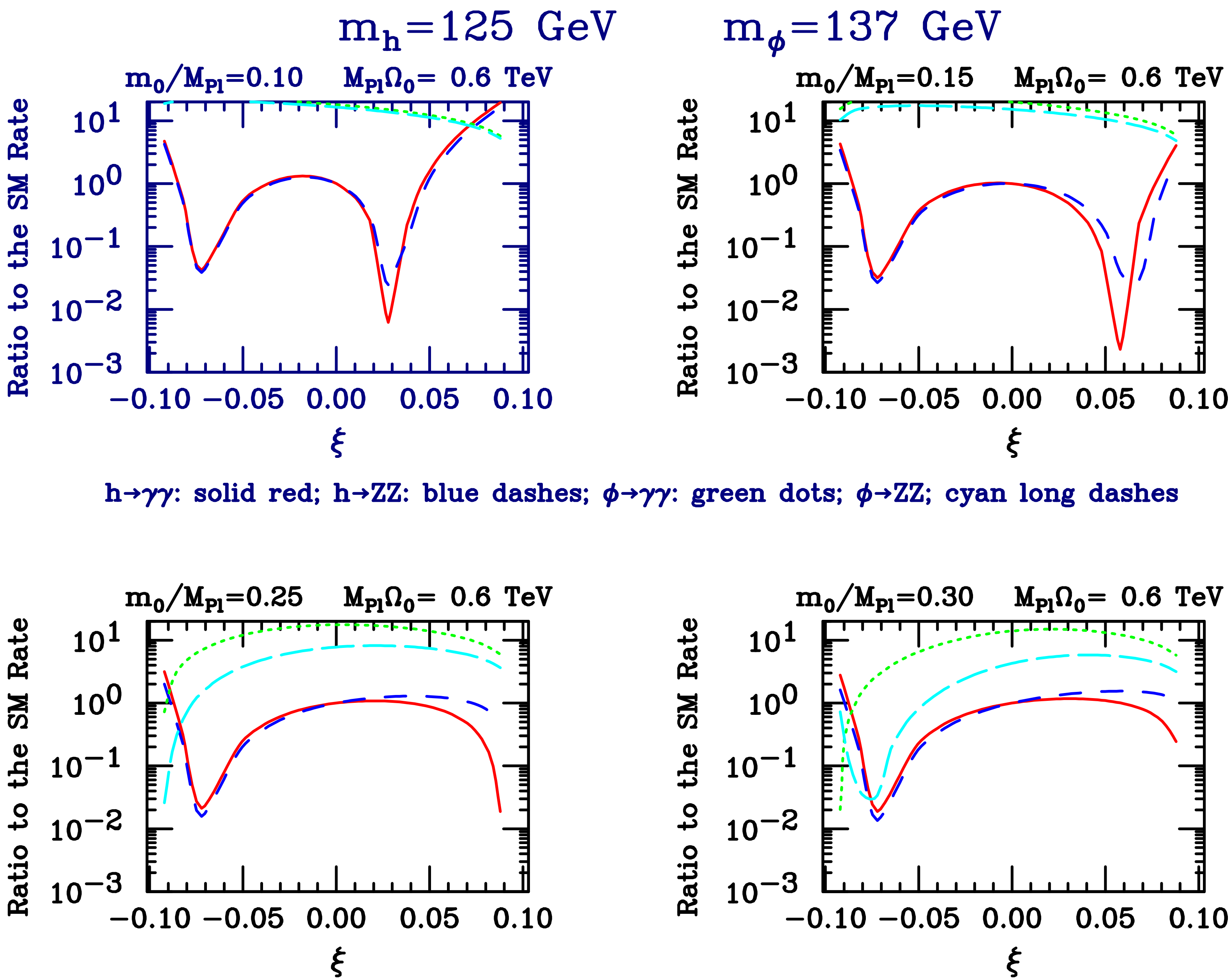


Figure 4: $\gamma\gamma$ and ZZ rates relative to SM vs ξ taking Λ_ϕ fixed at 1.5 TeV.

Signals at $\mathbf{125}$ GeV and $\mathbf{500}$ GeV

- Generally speaking, it is easy to find $\Lambda_\phi = 1$ TeV or 1.5 TeV choices for ξ and m_0/m_{Pl} which give a good description of the 125 GeV signal either for $m_h = 125$ GeV and $m_\phi = 500$ GeV or $m_h = 500$ GeV and $m_\phi = 125$ GeV.

- However, it is typically the case that the 4ℓ signal at 500 GeV is at least as large as the SM value.

  This is not in disagreement with CMS observation in this mass region, but ATLAS has a deficit.

- Thus, it may be preferred to take either the h or the ϕ to have mass $\gtrsim 1$ TeV with the other located at 125 GeV. It is then possible to describe the 125 GeV excesses while avoiding any possible conflict with the 500 GeV region data.

SM 125 GeV signal, with varying Λ_ϕ

- Perhaps the signal at 125 GeV will look very precisely SM-like after more L is accumulated.

  Then, one should probably take $\xi = 0$ (no mixing) and ask what the constraints are if there is a radion at some nearby mass. We consider $m_\phi = 137$ GeV, a signal that might survive.

- Fig. 5 shows $\gamma\gamma > 4\ell$ at m_ϕ is always the case. The unmixed radion cannot describe a $4\ell > \gamma\gamma$ excess.

- A decent fit to the current CMS $\gamma\gamma$ excess at 137 GeV is achieved for quite modest $m_0/m_{Pl} = 0.05$ and $\Lambda_\phi \sim 5.5$ TeV!

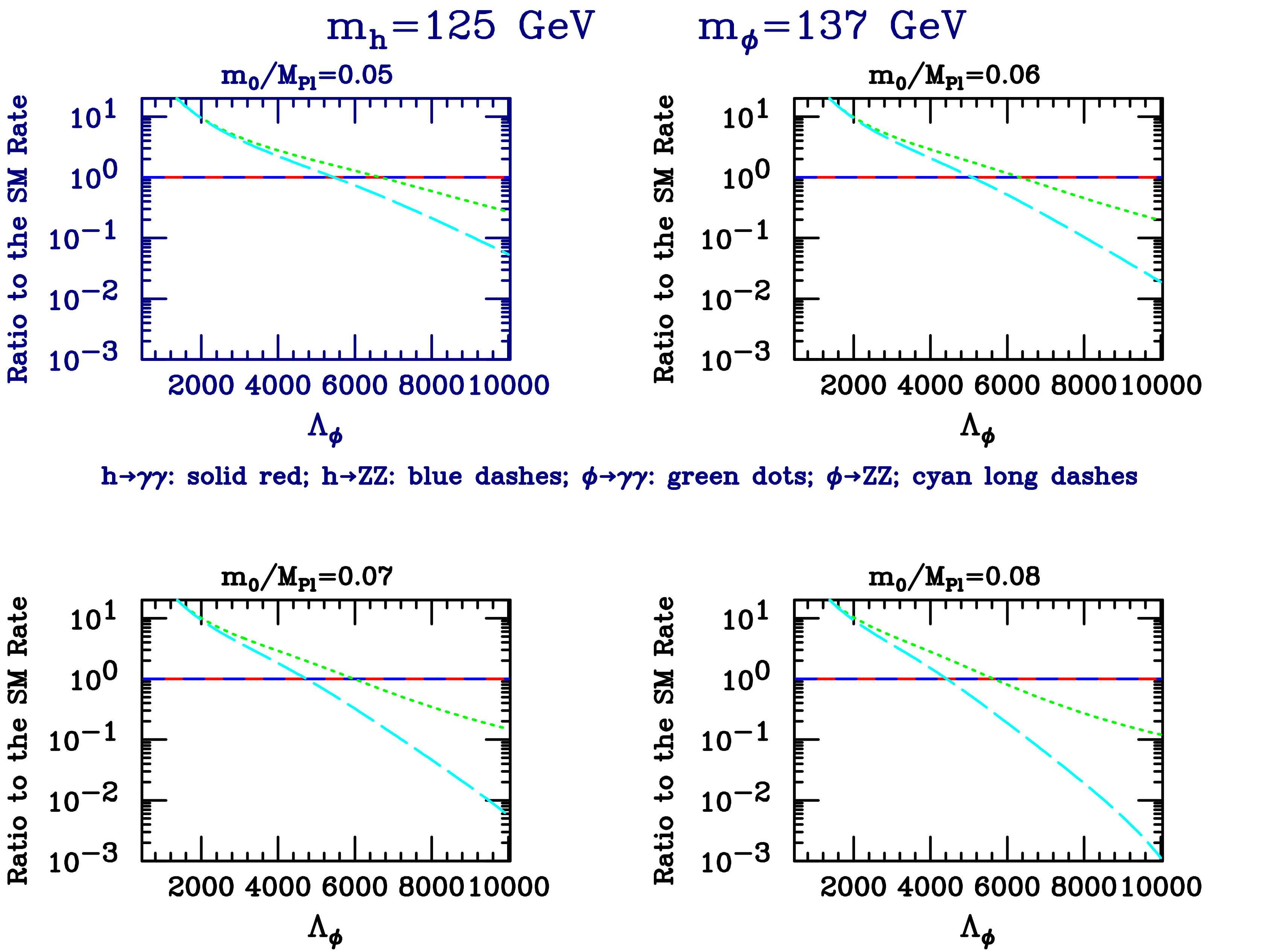


Figure 5: $\gamma\gamma$ and ZZ rates relative to SM vs Λ_ϕ taking $\xi = 0$.

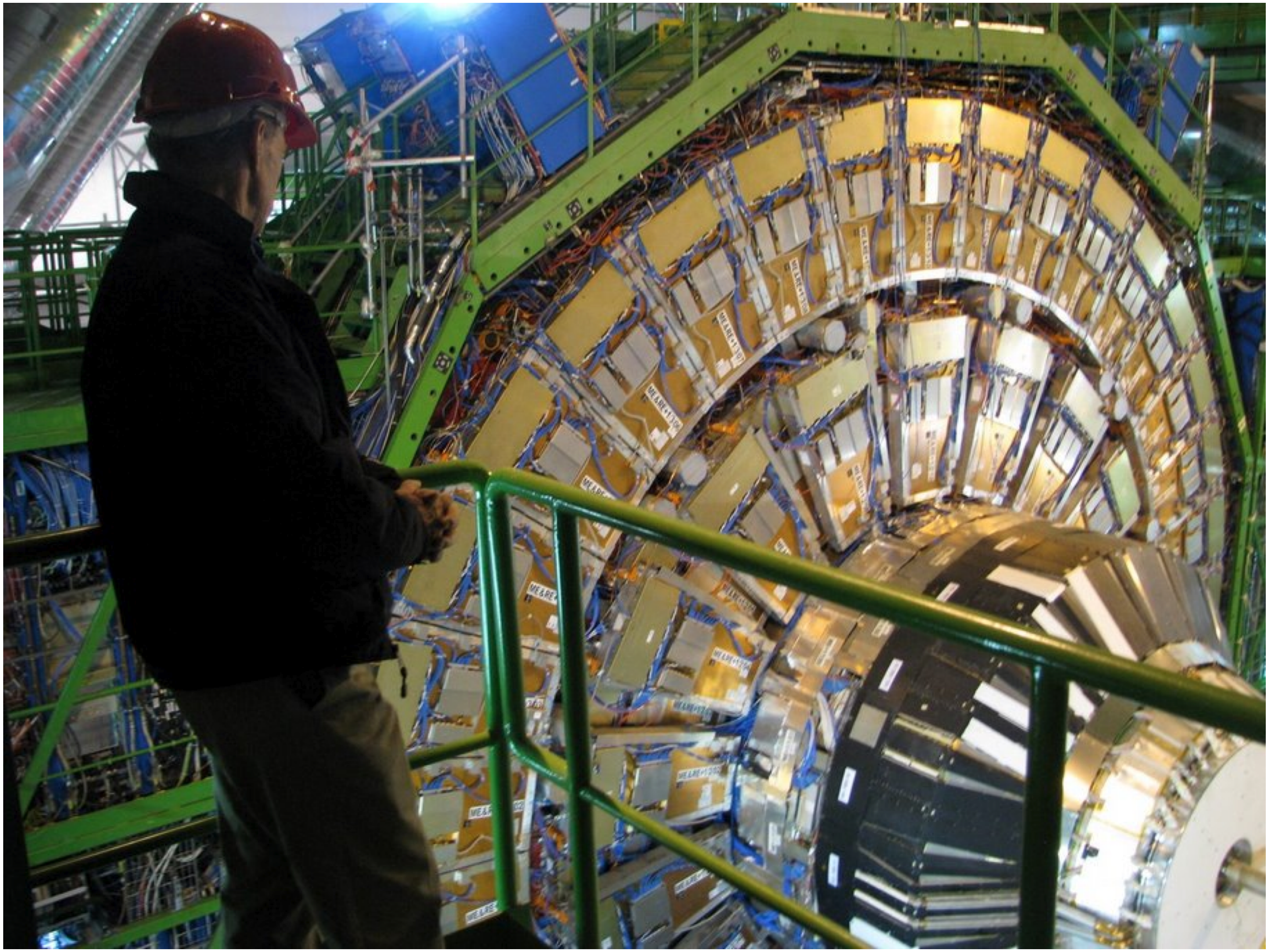
Conclusions

It seems likely that the Higgs responsible for EWSB is not buried

Perhaps, other Higgs-like objects are emerging.

But, we must never assume we have un-buried all the Higgs.

Certainly, I will continue watching and waiting



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