Higgs-Radion mixing in the Randall Sundrum model and the LHC Higgs-like excesses

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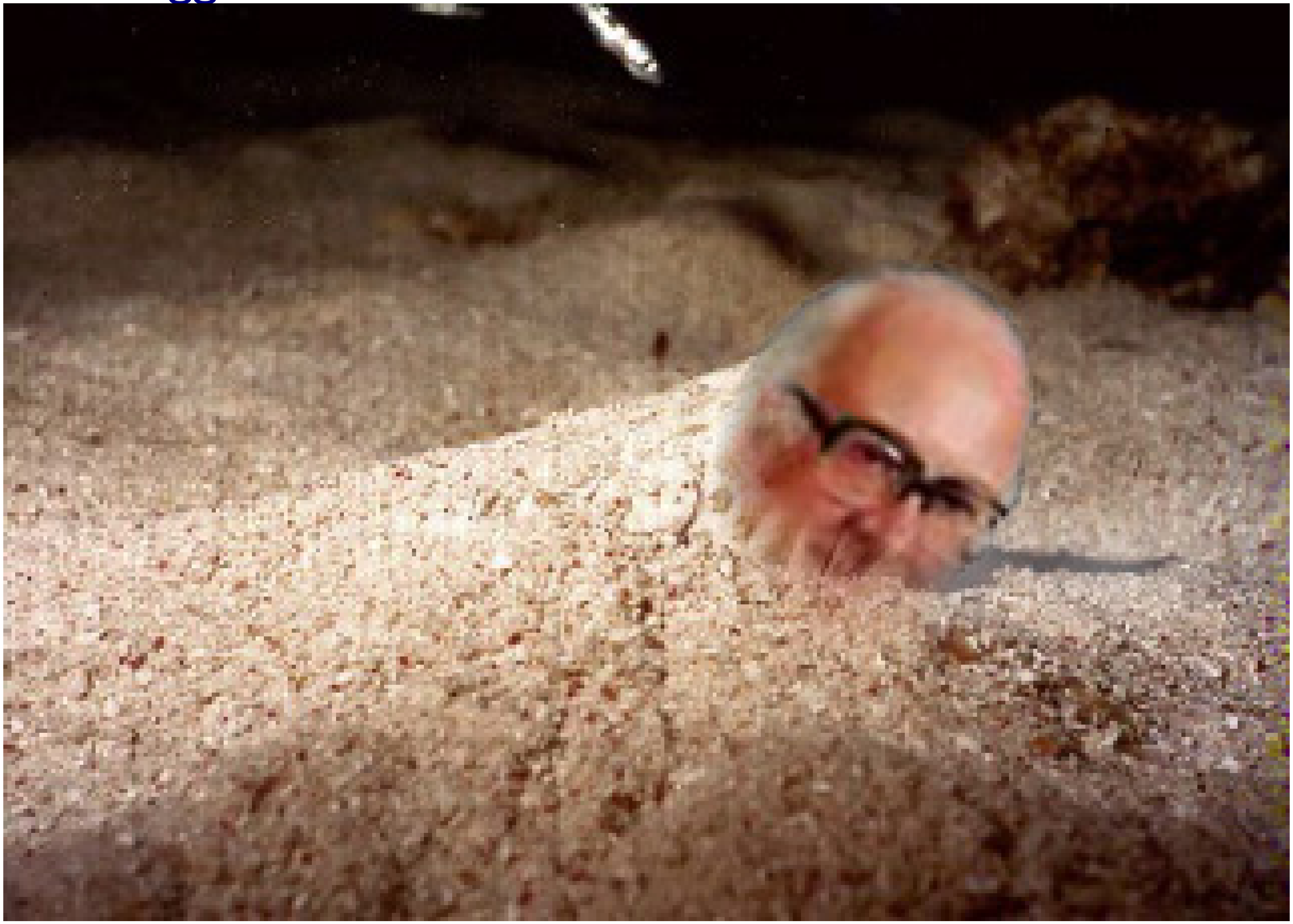
Higgs-like LHC Excesses

Is what we are seeing a Higgs-like chameleon?

Higgs-like LHC Excesses

Or is it THE Higgs?



Why think of alternatives to the SM and SUSY

Given that the mass(es) of the excess(es) are of order $\mathbf{125}~\mathrm{GeV}$,

- **The SM is on the edge of being inconsistent as a complete model up to the GUT scale. Need to make use of metastability etc.**

- **SUSY, especially the MSSM and even more especially the CMSSM and related, is being pushed to the limit of very high stop masses and/or mixing.**

  Even the NMSSM is stretched to the limit.

  – **Masses for the SM-like Higgs as high as $\mathbf{125}~\mathrm{GeV}$ are possible after imposing all constraints (including Ωh^2 and δa_μ) in constrained versions of the NMSSM but again squark and gluino masses must be very large. See, for example, [1].**

  – **Getting an enhanced value for**

$$R_h(X) \equiv \frac{\Gamma(h \to gg)\mathrm{BR}(h \to X)}{\Gamma(h_{SM} \to gg)\mathrm{BR}(h_{SM} \to X)} \tag{1}$$

for $X = \gamma\gamma$ requires using $h = h_2$ and appropriate low-scale values for NMSSM input parameters [2].

- There may be excesses at more than one mass with substantial $R_h(X)$ values in one or more channels.

  This would require going well beyond the NMSSM. Not even clear if it is possible at all within a two-doublet + singlets (for gauge coupling unification) SUSY model.

- 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.

  Depending on the Higgs representation employed, can get 2 or more scalar eigenstates.

The Randall Sundrum Model

- The background RS metric that solves Einstein's equations takes the form[3]

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

where y is the coordinate for the 5th dimension with $|y| \leq 1/2$.

- 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:

$$v_0 = \Omega_0 \widehat{v} = e^{-\frac{1}{2}m_0 b_0}\widehat{v} \sim 1 \text{ TeV} \quad \text{for} \quad \frac{1}{2}m_0 b_0 \sim 35\,. \tag{3}$$

- 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.

- Critical parameters are Λ_ϕ, the vacuum expectation value of the radion field, and m_0/m_{Pl} where m_0 characterizes the 5-dimensional curvature.

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

- Besides the radion, the model contains a conventional Higgs boson, h_0.

- $m_0/m_{Pl} \gtrsim 0.5$ 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: [11] 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.

- 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 TeV^{-1}, $\Rightarrow$ FCNC processes and PEW observable corrections are predicted to be much too large.

- Must move fermions and gauge bosons (but not necessarily the Higgs — we keep it on the brane) off the brane [4][5][6][7][8][9][10][11].

  The SM gauge bosons $=$ 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 $\gg \mathrm{TeV}$.

Even with this arrangement it is estimated that the g^1, W^1 and Z^1 masses must be larger than about $3~\mathrm{TeV}$ (see the summary in [11]).

There is also a direct experimental limit on m_1^g from LHC of $m_1^g \gtrsim 1.5~\mathrm{TeV}$.

– In the model of [14], 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 $t_R\bar{t}_Rg^1$ coupling is large since the t_R profile peaks near the TeV brane – the prediction of [14] is $g_{t_R\bar{t}_Rg^1} \sim \zeta g$.

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

– $\Rightarrow$ lower bound of $m_1^g \gtrsim 1.5~\mathrm{TeV}$ [17] using an update of the analysis of [14]. ([18] gives a weaker bound of $m_1^g > 0.84~\mathrm{TeV}$.) .

In terms of Λ_ϕ, we have the following relations:

$$\frac{m_0}{m_{Pl}} = \frac{\sqrt{6}}{x_1^g}\frac{m_1^g}{\Lambda_\phi} \simeq \frac{m_1^g}{\Lambda_\phi}, \quad \text{and} \quad \frac{1}{2}m_0 b_0 = -\log\left(\frac{\Lambda_\phi}{\sqrt{6}m_{Pl}}\right) \qquad (4)$$

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

If we require $\Lambda_\phi < 10\ \mathrm{TeV}$ for acceptable hierarchy and adopt the CMS limit of $m_1^g > 1.5\ \mathrm{TeV}$ then (4) implies a lower limit on the 5-dimensional curvature of $m_0/m_{Pl} \gtrsim 0.15$.

2. Use $\approx$ flat profiles for the 1st and 2nd generation fermions in the 5th dimension.

   $\Rightarrow$ the coupling of light quarks to G^1, 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.

   $\Rightarrow$ small FCNC. PEW and $Z \to b\bar{b}$ consraints can be satisfied using a combination of custodial group structures, a 5D GIM mechanism and a $L \leftrightarrow R$ discrete symmetry.

   Since $u\overline{u}, d\overline{d} \to g^1, G^1$ couplings are greatly suppressed there are no direct experimental limits on their masses.

Λ_ϕ?

If $\Lambda_\phi = 1~\mathrm{TeV}$, for $m_0/m_{Pl} = 0.01, 0.1$ Eq. (4) implies $m_1^g = 10, 100~\mathrm{GeV}$. Seems kind of crazy, but maybe ok. If you want larger m_1^g and yet low $\Lambda_\phi \Rightarrow$ large m_0/m_{Pl}.

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. [19]

$$S_\xi = \xi \int d^4x \sqrt{g_{\rm vis}} R(g_{\rm vis}) \widehat{H}^\dagger \widehat{H}\,, \tag{5}$$

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 [12] (see also [19][20]).

In the end, one finds

$$\begin{aligned} h_0 &= dh + c\phi \quad -\phi_0 = a\phi + bh\,, \quad \text{where} \\ d &= \cos\theta - t\sin\theta,\ c = \sin\theta + t\cos\theta,\ a = -\frac{\cos\theta}{Z},\ b = \frac{\sin\theta}{Z}\,, \end{aligned} \tag{6}$$

with

$$t = 6\xi\gamma/Z, \quad Z^2 = 1 + 6\xi\gamma^2(1-6\xi), \quad \tan 2\theta = \frac{12\gamma\xi Z m_{h_0}^2}{m_{\phi_0}^2 - m_{h_0}^2[Z^2 - 36\xi^2\gamma^2]}. \tag{7}$$

Here $m_{h_0}^2$ and $m_{\phi_0}^2$ are the Higgs and radion masses before mixing.

Consistency of the diagonalization imposes strong restrictions on the possible ξ values as a function of the final eigenstate masses m_h and m_ϕ, which restrictions depend strongly on the ratio $\gamma \equiv v_0/\Lambda_\phi$ ($v_0 = 246\ \mathrm{GeV}$).

- The full Feynman rules after mixing for the h and ϕ interactions with gauge bosons and fermions located in the bulk were derived in [21].

  Of particular note are the anomaly terms associated with the ϕ_0 interactions before mixing. After mixing we find

$$g_h = (d + \gamma b) \quad g_\phi = (c + \gamma a) \quad g_h^r = \gamma b \quad g_\phi^r = \gamma a\,. \tag{8}$$

$$\begin{aligned} c_g^{h,\phi} &= -\frac{\alpha_s}{4\pi v}\left[g_{h,\phi}\sum_i F_{1/2}(\tau_i) - 2(b_3 + \frac{2\pi}{\alpha_s \frac{1}{2} m_0 b_0})g_{h,\phi}^r\right] \\ c_\gamma^{h,\phi} &= -\frac{\alpha}{2\pi v}\left[g_{h,\phi}\sum_i e_i^2 N_c^i F_i(\tau_i) - (b_2 + b_Y + \frac{2\pi}{\alpha \frac{1}{2} m_0 b_0})g_{h,\phi}^r\right] \end{aligned} \tag{9}$$

New relative to old on-the-brane results are the $2\pi\ldots$ correctons to the g^r terms. By comparing, the c_g and c_γ results with and without the extra off-the-brane corrections one finds very significant changes.

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

  Without bulk propagation, these couplings were simply given by SM couplings (proportional to the metric tensor $\eta^{\mu\nu}$) times g_h or g_ϕ.

  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)

$$\mathcal{L} \ni h_0 \frac{2m_W^2}{v} W_\mu^\dagger W^\mu - \phi_0 \frac{2m_W^2}{\Lambda_\phi} \left[W_\mu^\dagger W^\mu \left(1-\kappa_W\right) + W_{\mu\nu}^\dagger W^{\mu\nu} \frac{1}{4m_W^2 (\frac{1}{2} m_0 b_0)} \right] \tag{10}$$

After mixing, this becomes, for example for the h interaction

$$\mathcal{L} \ni \equiv h\frac{2m_W^2}{v}g_h^W\left[W_\mu^\dagger W^\mu + \eta_h^W W_{\mu\nu}^\dagger W^{\mu\nu}\right] \tag{11}$$

with a similar result for the ϕ.

Here,

$$g_{h,\phi}^V \equiv g_{h,\phi} - g_{h,\phi}^r \kappa_V\,, \quad \eta_{h,\phi}^V \equiv \frac{g_{h,\phi}^r}{g_{h,\phi}^V}\frac{1}{4m_V^2(\frac{1}{2}m_0 b_0)}\,, \tag{12}$$

where $\kappa_V = \left(\frac{3m_V^2(\frac{1}{2}m_0 b_0)}{\Lambda_\phi^2(m_0/m_{Pl})^2}\right)$ for $V = W, Z$.

The full Feynman rule for the hWW vertex is:

$$igm_W g_h^W\left[\eta_{\mu\nu}(1 - 2k^+\cdot k^-\eta_h^W) + 2\eta_h^W k_\mu^+ k_\nu^-\right] \tag{13}$$

where k^+, k^- are the momenta of the W^+, W^-, respectively.

- For the fermions, we assume profiles such that there are no corrections to the h_0 and ϕ_0 couplings due to propagation in the bulk.

This is a very good approximation for the top quark quark which must be localized near the TeV brane.

Also for the bottom quark the approximation is better than 20%, see [21].

Even though the approximation is not necessarily good for light quarks, it is only the heavy quarks that impact the phenomenology of the higgs-radion system.

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 $\to$ 124 GeV.**

- **As discussed, consider two different kinds of models:**

1. lower bound on m_1^g of 1.5 TeV or 3 TeV (one case)
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}.

$$\frac{m_0}{m_{Pl}} \simeq \frac{m_1^g}{\Lambda_\phi} \tag{14}$$

$\Rightarrow$ 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.

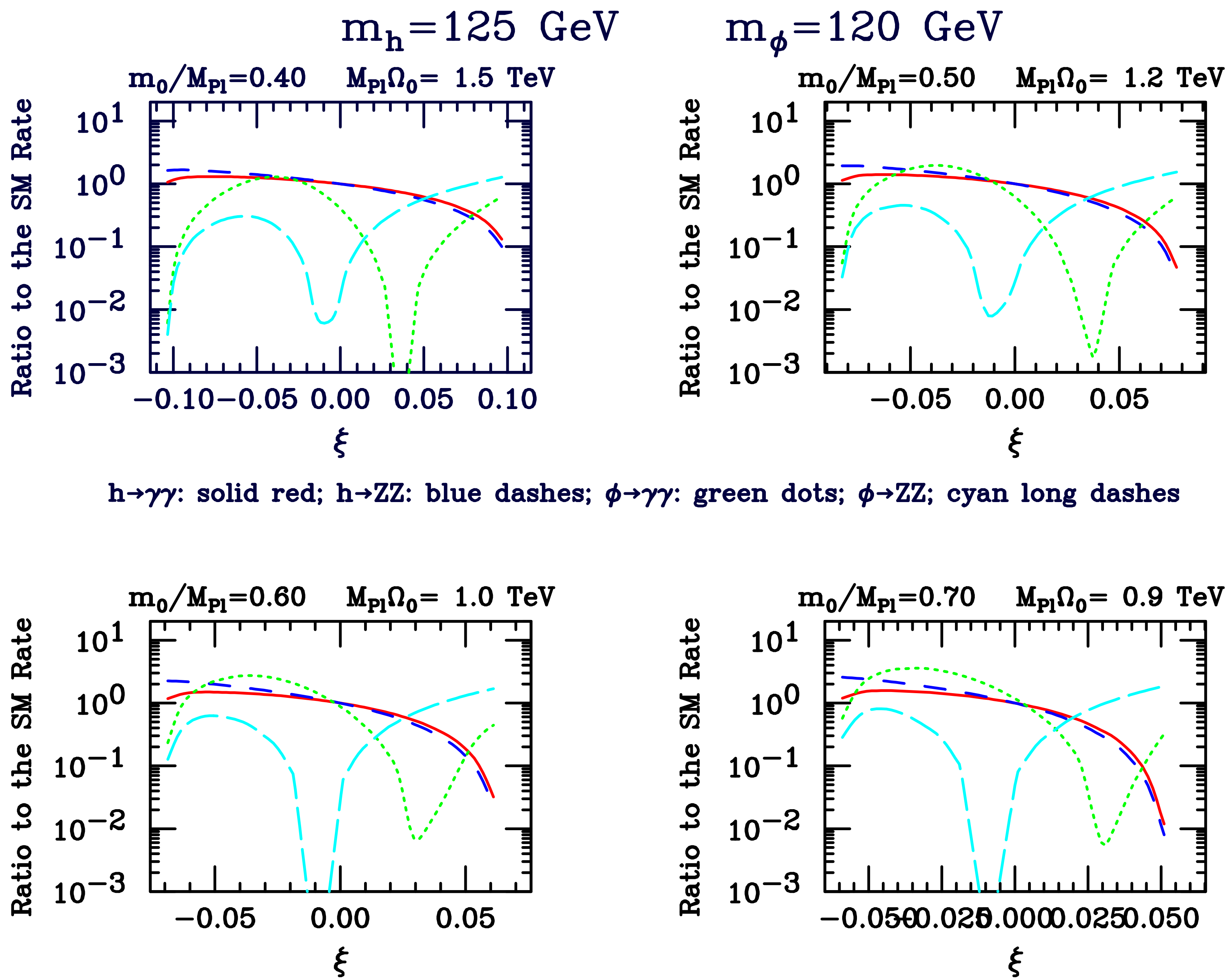


Figure 1: We plot $\gamma\gamma$ and ZZ relative to SM vs ξ taking $m_1^g = 1.5~\mathrm{TeV}$.

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. $\gamma\gamma > 4\ell$ if 120 GeV signals are visible.

Signals at 125 GeV and 137 GeV

- In Fig. 2 (next page): $m_0/m_{Pl} = 0.5$ and $\xi = 0.12 \Rightarrow$

  125 GeV: $\gamma\gamma \sim 1.3\times$SM and $4\ell \sim 1.5\times$SM

137 GeV: $\gamma\gamma \sim 1.3\times$SM and $4\ell \sim 0.5\times$SM.

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

The following figure, Fig. 3, shows that if $m_1^g = 3$ TeV enhanced excesses are much harder to achieve.

- Not possible to get enhanced $\gamma\gamma$ (and 4ℓ) h signals at 125 GeV without having visible 137 GeV ϕ signals.

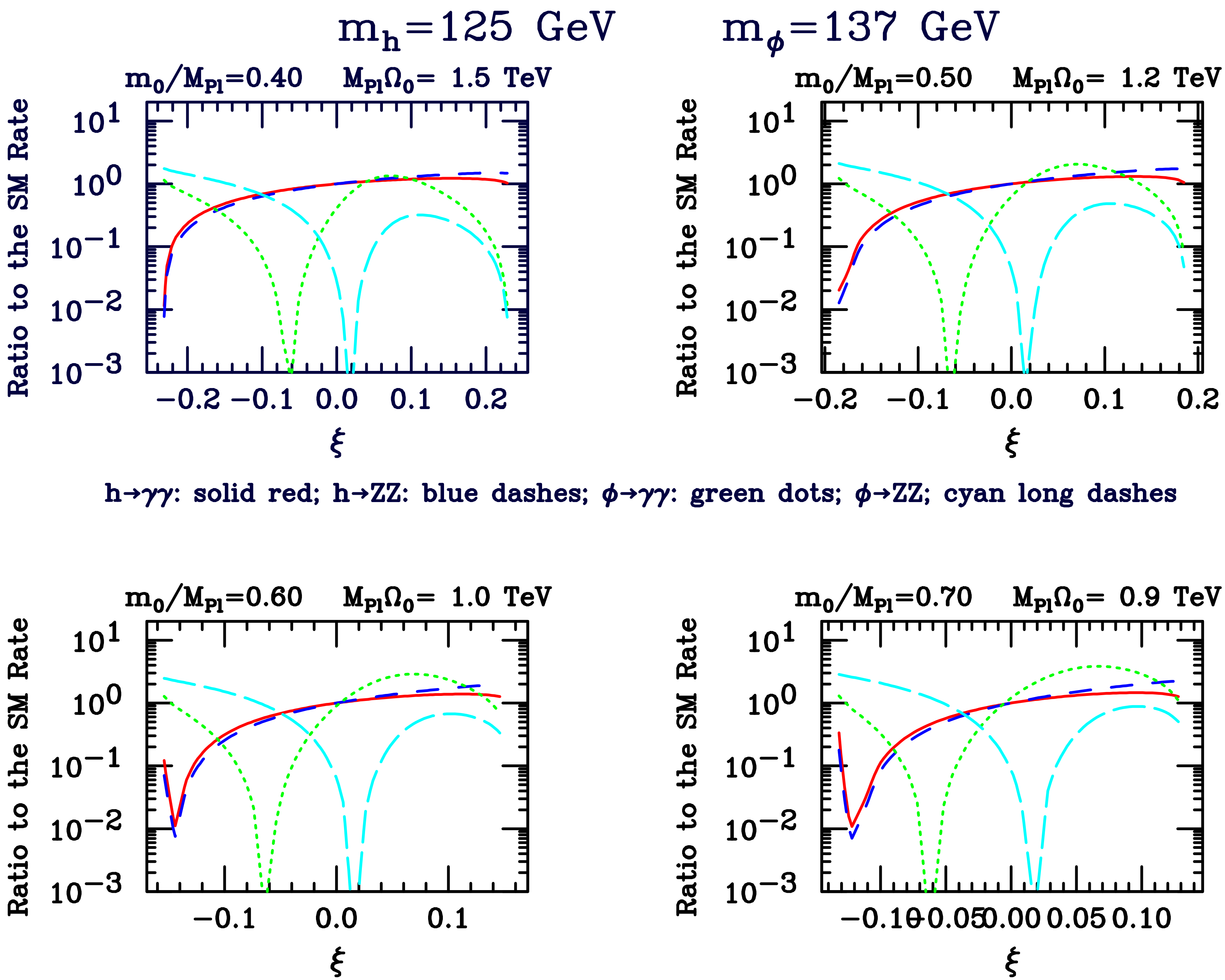


Figure 2: We plot $\gamma\gamma$ and ZZ relative to SM vs ξ taking $m_1^g = 1.5$ TeV.

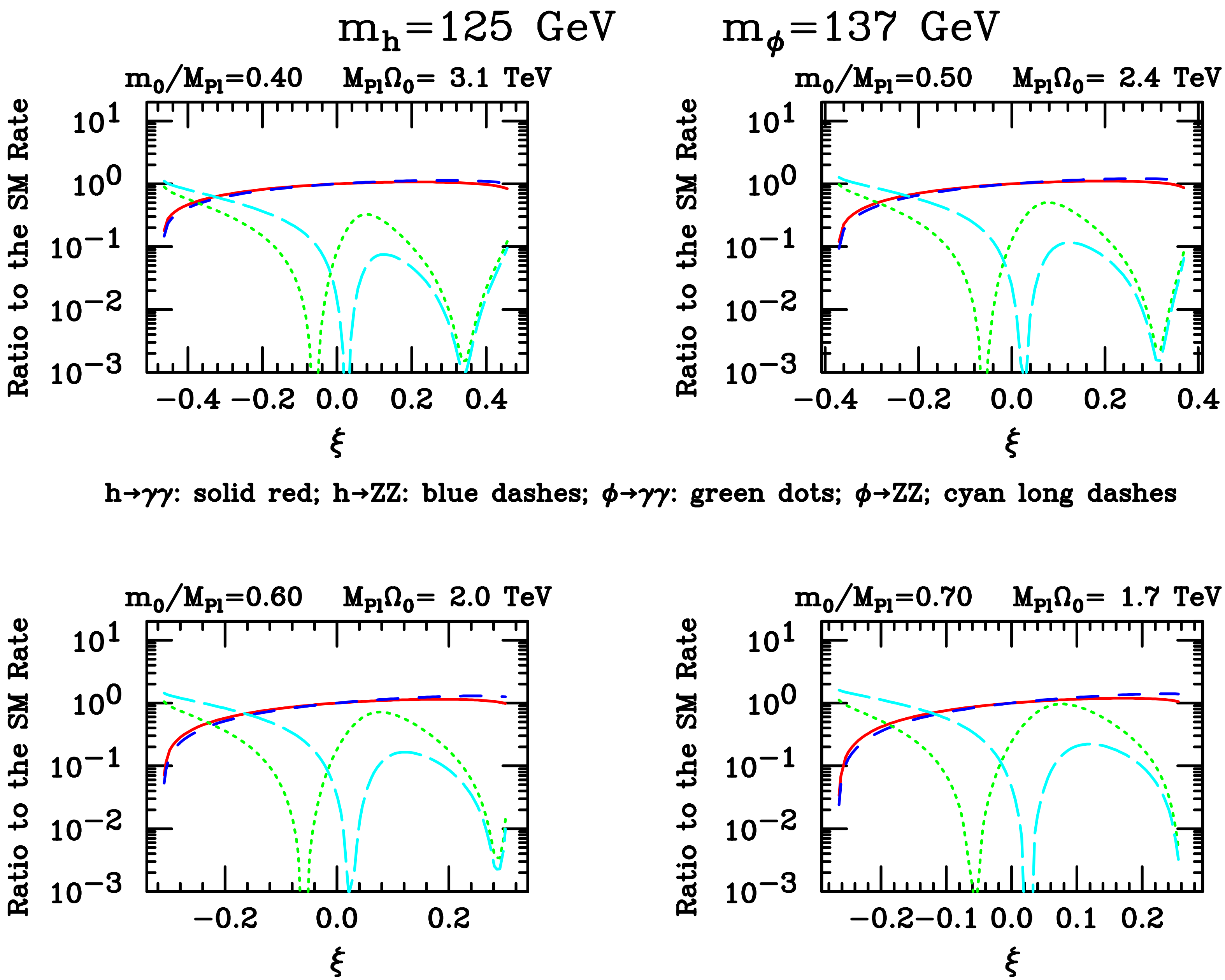


Figure 3: We plot $\gamma\gamma$ and ZZ relative to SM vs ξ taking $m_1^g = 3$ TeV.

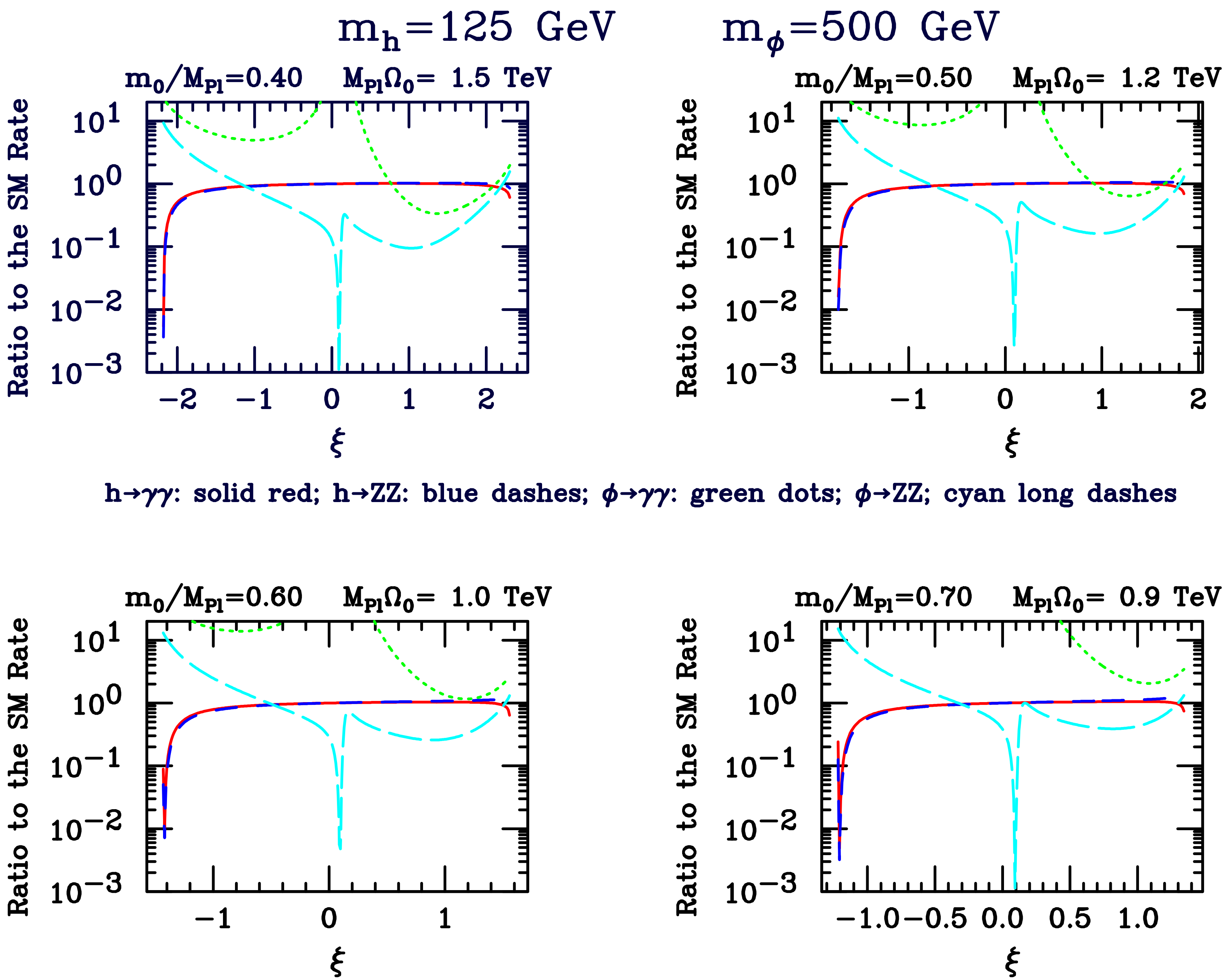


Figure 4: For $m_h = 125$ GeV and $m_\phi = 500$ GeV, we plot $\gamma\gamma$ and ZZ relative to the SM vs ξ taking $m_1^g = 1.5$ TeV.

Signals at 125 GeV and 500 GeV

This case is illustrated in Fig. 4 for the same range of m_0/m_{Pl} values as considered in Fig. 1.

- If m_ϕ is taken to be much larger than m_h then it is typically the case that the largest 125 GeV signals are at most SM-like and excesses of order $1.5\times$SM are not achieved.

- The largest 125 GeV signals arise for ξ close to its upper limit and are very SM-like.

- At large $\xi > 0$ the 500 GeV signals in the $\gamma\gamma$ channel are only somewhat enhanced relative to the SM (and thus not detectable) but the 4ℓ signals are also quite SM-like and thus easily detectable.

- The ATLAS data in the 4ℓ channel shows an excess of order $1 \times SM$ for masses above 450 GeV [28], but the breadth of the excess in $M_{4\ell}$ is greater than the expected ϕ width.

CMS data [29] actually shows a deficit in the 4ℓ channel at large mass.

- **Thus, if ξ is large and the h is light and SM-like and the ϕ is heavy then the ϕ must be placed beyond the mass range to which current LHC data is sensitive.**

  The alternative of $\xi \sim 0$ is also a possibility if Λ_ϕ is large (i.e. not tied to m_1^g as in this plot).

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.

  Now some possibilities.

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 $\xi = -0.015$.

- 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 as per CMSA

- It is not possible to describe the CMSA $m_h = 120$ GeV excess in the 4ℓ channel at the same time as the 125 GeV excess.

  The model always predicts that the $\gamma\gamma$ excess should exceed the 4ℓ excess, contrary to the CMSA scenario.

Signals at 125 GeV and 137 GeV as per CMSB

- CMSB 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 $4\ell \sim \mathit{small}$.

- For $\Lambda_\phi = 1.5$ TeV, Fig. 5 (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.

  $\Rightarrow$ good fit to CMS numbers.

- 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.

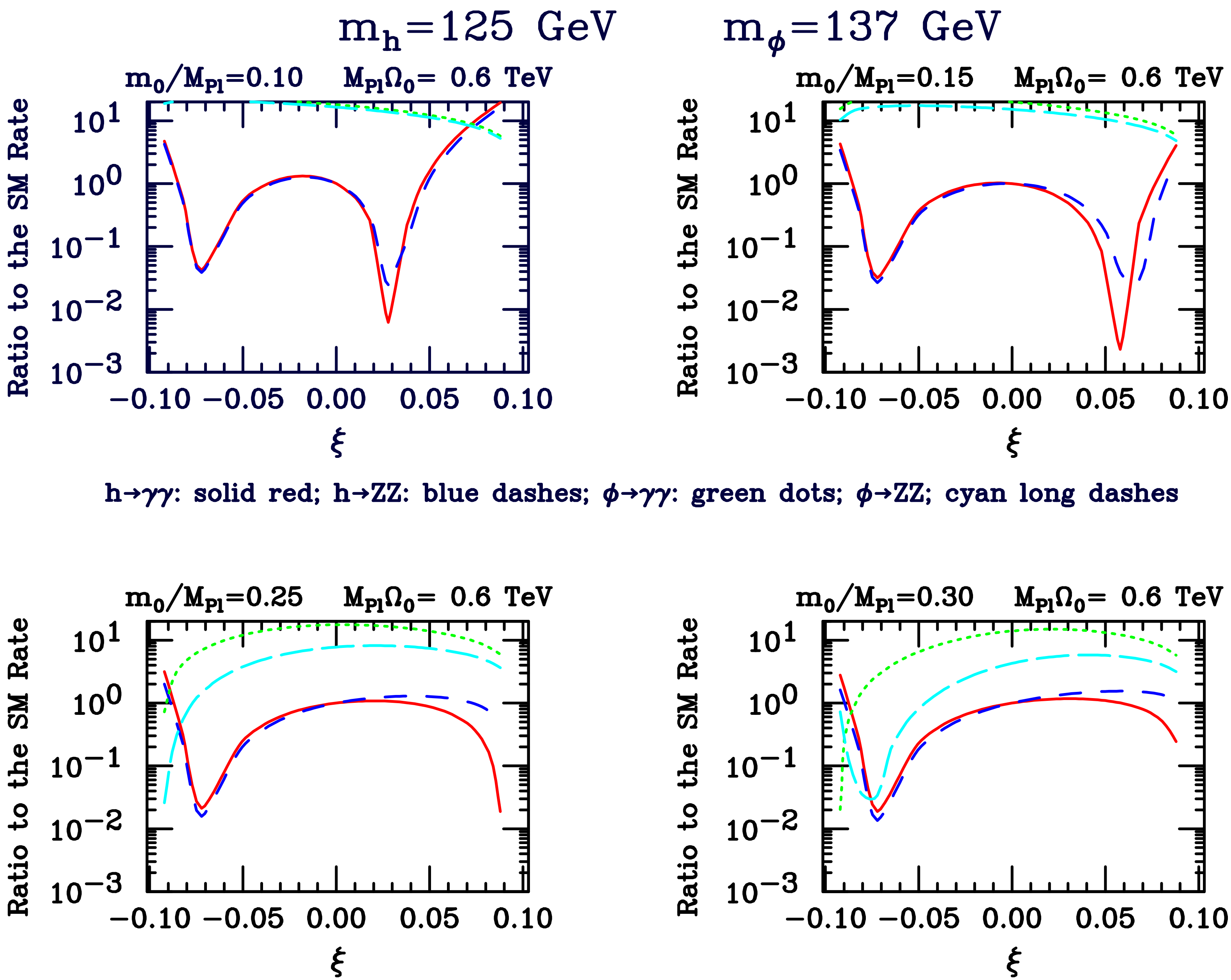


Figure 5: We plot $\gamma\gamma$ and ZZ rates relative to SM vs ξ taking Λ_ϕ fixed at 1.5 TeV.

SM $\mathbf{125}$ GeV signal, with varying $\boldsymbol{\Lambda_\phi}$

- **Perhaps the signal at $\mathbf{125}$ GeV will look very precisely SM-like after more $\boldsymbol{L}$ is accumulated.**

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

- **Fig. 6 shows $\boldsymbol{\gamma\gamma > 4\ell}$ at $\boldsymbol{m_\phi}$ is always the case. The unmixed radion cannot describe a $\boldsymbol{4\ell > \gamma\gamma}$ excess.**

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

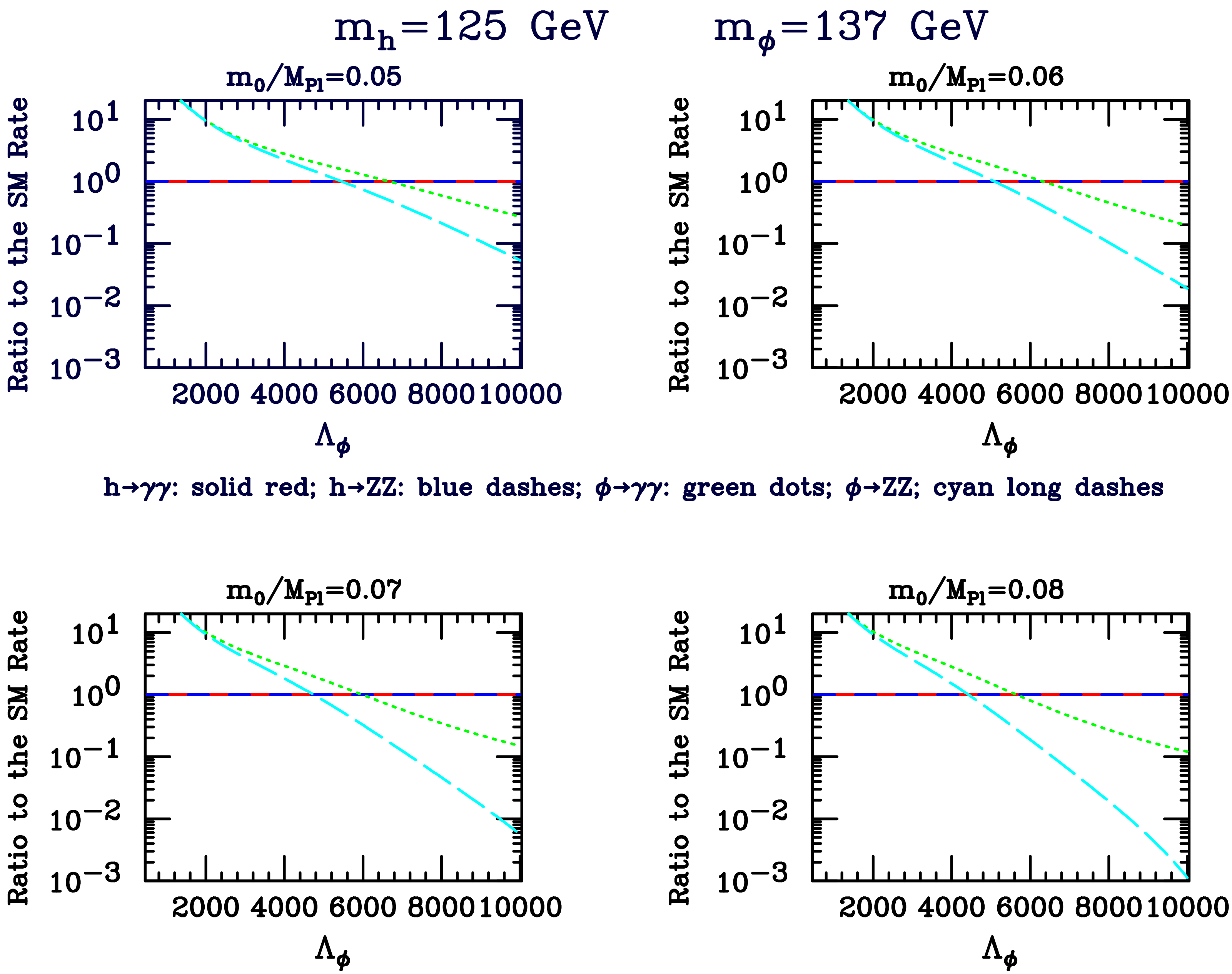


Figure 6: We plot $\gamma\gamma$ and ZZ rates relative to SM vs Λ_ϕ taking $\xi = 0$.

Implications for the Linear Collider

- There are many situations where a precision measurement of some ratio of branching ratios could determine important parameters of the model.

  Would want multiple channel analysis, esp. ability to see $\gamma\gamma$ final state.

  The small branching ratio to $\gamma\gamma$ and the often reduced $ZZ\phi$ coupling might make this challenging at a linear collider without high luminosity.

- Indeed, if $\xi = 0$ then the $ZZ\phi$ coupling is very small for typical $\Lambda_\phi > 1~\mathrm{TeV}$ and radion production at the ILC from $Z^* \to Z\phi$ will be very small. Probably could not study the ϕ at $\xi = 0$.

  Of course, a $\gamma\gamma$ collider would be excellent, making using of the anomalous $\phi\gamma\gamma$ coupling for production.

- There are however many $\xi \neq 0$ situations where the LHC sensitivity is too small to see a signal that is suppressed relative to the SM Higgs, but the ILC might do the job.

- The radion-related signals at the LHC and a linear collider decline as m_1^g or Λ_ϕ increase.

  But, they are probably still visible as long as Λ_ϕ is in the $\lesssim 10~\mathrm{TeV}$ range needed for the RS model to really solve the hierarchy problem and provided ξ is substantial.

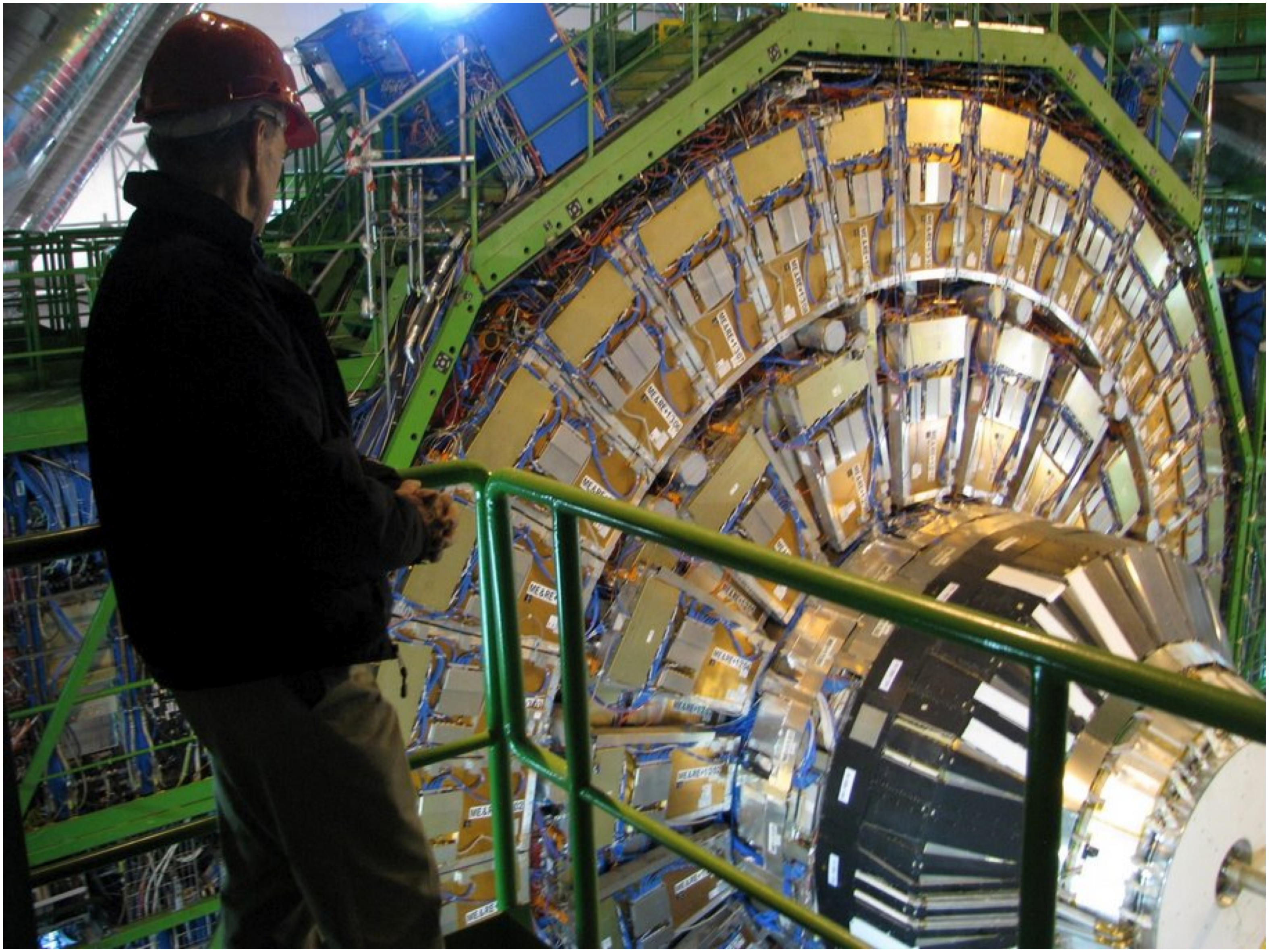
Conclusions

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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