B(SM and MSSM) Higgs bosons consistent with LHC Hints

Jack Gunion
U.C. Davis

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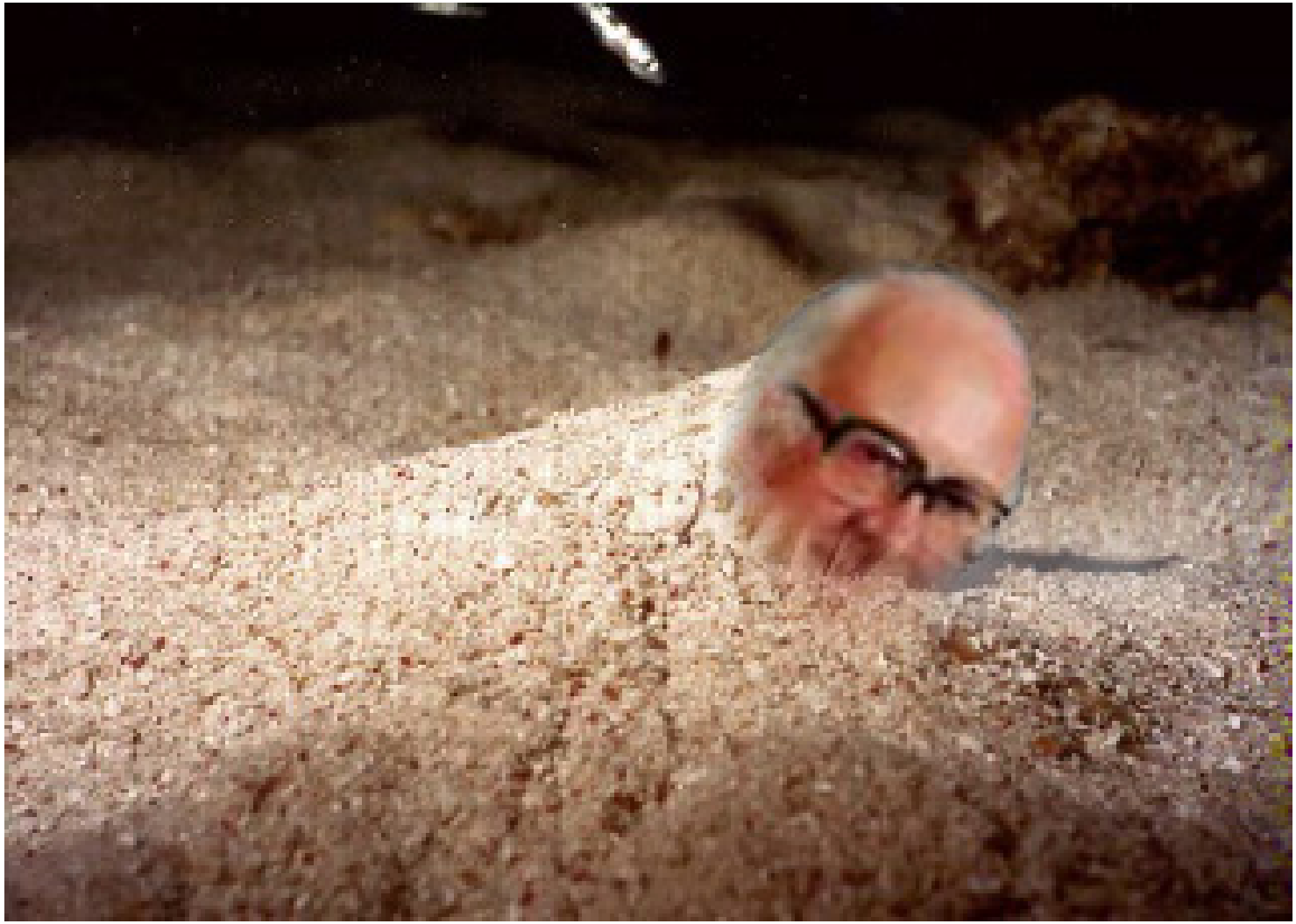
Contributing collaborators: B. Grzadkowski, S. Kraml, M. Toharia, Y. Jiang

Higgs-like LHC Excesses

Are we seeing THE Higgs, or only A Higgs or Higgs-like Scalar?



Experimental Higgs-like excesses: define

$$R(X) = \frac{\sigma(pp \to h)\mathrm{BR}(h \to X)}{\sigma(pp \to h_{SM})\mathrm{BR}(h_{SM} \to X)}\,, \quad R_i(X) = \frac{\sigma(pp \to i \to h)\mathrm{BR}(h \to X)}{\sigma(pp \to i \to h_{SM})\mathrm{BR}(h_{SM} \to X)} \tag{1}$$

where $i = gg$ or WW.

Table 1: Three scenarios for LHC excesses in the $\gamma\gamma$ and 4ℓ final states.

	125 GeV	137 GeV	120 GeV
ATLAS	$R(\gamma\gamma) \sim 2.0^{+0.8}_{-0.8}$, $R(4\ell) \sim 0.5^{+1.5}_{-1.0}$	no excesses	no excesses
CMSA	$R(\gamma\gamma) \sim 1.7^{+0.8}_{-0.7}$, $R(4\ell) \sim 0.5^{+1.1}_{-0.7}$	$R(4l) = 2.0^{+1.5}_{-1.0}$, $R(\gamma\gamma) < 0.5$	no excesses
CMSB	$R(\gamma\gamma) \sim 1.7^{+0.8}_{-0.7}$, $R(4\ell) \sim 0.5^{+1.1}_{-0.7}$	no excesses	$R(\gamma\gamma) = 1.5^{+0.8}_{-0.8}$, $R(4\ell) < 0.2$

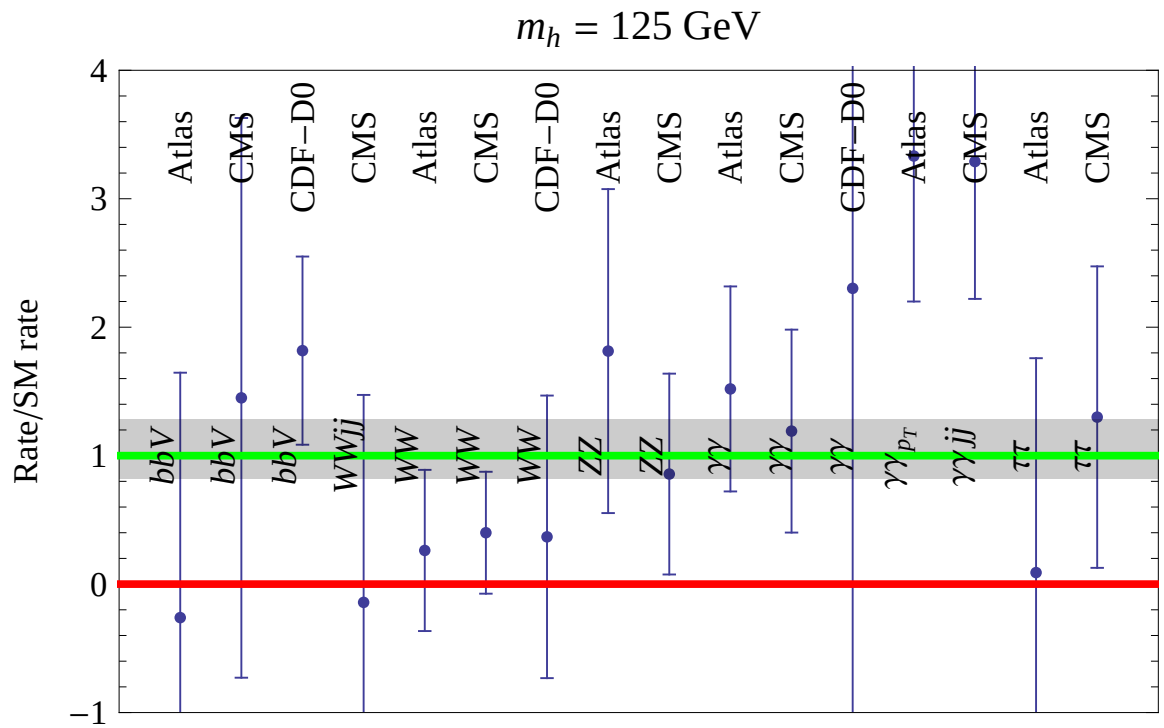
At 125 GeV, CMS separates out gg vs. WW fusion processes, yielding

$$R^{\mathrm{CMS}}_{gg}(\gamma\gamma) = 1.6 \pm 0.7\,, \quad R^{\mathrm{CMS}}_{WW}(\gamma\gamma) = 3.7^{+2.1}_{-1.8} \tag{2}$$

and also there are CMS, ATLAS and D0+CDF=Tevatron measurements of Vh production with $h \to b\bar{b}$ giving at 125 GeV

$$R^{\mathrm{CMS}}_{Vh}(b\bar{b}) = 0.5^{+1.3}_{-1.5}\,, \quad R^{\mathrm{ATLAS}}_{Vh}(b\bar{b}) \sim 0 \pm 1.5\,, \quad R^{\mathrm{Tev}}_{Vh}(b\bar{b}) \sim 1.8 \pm 1\,, \tag{3}$$

the latter two being very crude estimates as the collaborations do not directly quote these numbers. One can also force all the observations into a SM-like framework, but allowing for rescaling of individual channels, as per arXiv:1203.4254, to obtain



So, it could be a very SM-like Higgs boson once statistics increase, or some of the enhancement/suppressions could survive. Note: $R(WW) < 1$ could imply $gg \to h <$SM, but $R(ZZ) \gtrsim 1$ suggests not.

NMSSM

- Extra singlet superfield solves μ problem and gives more Higgs states than MSSM: h_1, h_2, h_3, a_1 and a_2 (and $H^{\pm}$).

  New parameters: λ, κ in $W \ni \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$, A_κ and A_λ in $V_{soft} \ni \lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3$

- Various constrained versions have been considered.

  1. cNMSSM [?][?]: $m_0 = 0$ and $A_0 \equiv A_t = A_b = A_\tau = A_\lambda = A_\kappa$, $\Rightarrow$
     - $m_{h_1} \lesssim 121$ GeV at large $m_{1/2}$.
     - The h_2 can have a mass in the $123 - 128$ GeV range for not too large $m_{1/2}$, but $R^{h_2}(\gamma\gamma)$ is of order $0.5 - 0.6$.

  Doesn't look like LHC data.

- CNMSSM: universal m_0, A_0: can't give high enough m_{h_1}.

- universal m_0, A_0, but $A_\lambda = A_\kappa = 0$; can't give high enough m_{h_1}.

- universal m_0, except for NUHM, universal A_0 except $A_\lambda = A_\kappa = 0$; can get into interesting m_{h_1} range.

- universal m_0, except for NUHM, universal A_0 except A_λ and A_κ allowed to vary freely: gives further expansion of interesting scenarios.

Extra dimensions and Higgs-radion Mixing

- **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, as might end up being required, e.g. to fit 125 GeV and 137 GeV excesses.**

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

$$ds^2 = e^{-2m_0 b_0 |y|} \eta_{\mu\nu} dx^\mu dx^\nu - b_0^2 dy^2 \tag{4}$$

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:

$$v_0 = \Omega_0 \widehat{v} = e^{-\frac{1}{2} m_0 b_0} \widehat{v} \sim 1 \text{ TeV} \quad \text{for} \quad \frac{1}{2} m_0 b_0 \sim 35 \,. \tag{5}$$

- 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.

- 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 $\Lambda_\phi = \sqrt{6} m_{Pl} \Omega_0 \lesssim 1 - 10 \text{ TeV}$.

- 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.

  Now viewed as ok.

- **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 [?][?][?][?][?][?][?][?].**

  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.

- **There are various possibilities. No time to outline. We choose 5D Yukawa couplings and profiles so that there are no corrections to the bare h_0 couplings ($Y_2 \ll Y_1$), but see Neubert et.al. for alternative.**

- **Since the radion and higgs fields have the same quantum numbers, they**

can mix. [?]

$$S_\xi = \xi \int d^4x \sqrt{g_{\rm vis}} R(g_{\rm vis}) \widehat{H}^\dagger \widehat{H} \,, \tag{6}$$

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 mass eignestates h and ϕ using our notation can be found in [?] (see also [?][?]).

- 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.

- **Let us use the CMSB scenario as an example.**

- **Let us use a model in which there is a lower bound on m_1^g of 1.5 TeV from CMS data.**

- **Then, Λ_ϕ will be correlated with m_0/m_{Pl}.**

$$\frac{m_0}{m_{Pl}} \simeq \frac{m_1^g}{\Lambda_\phi} \tag{7}$$

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

Signals at 125 GeV and 137 GeV

- **In Fig. ??: $m_0/m_{Pl} = 0.5$ 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.

consistent within 1σ with the CMS observations.

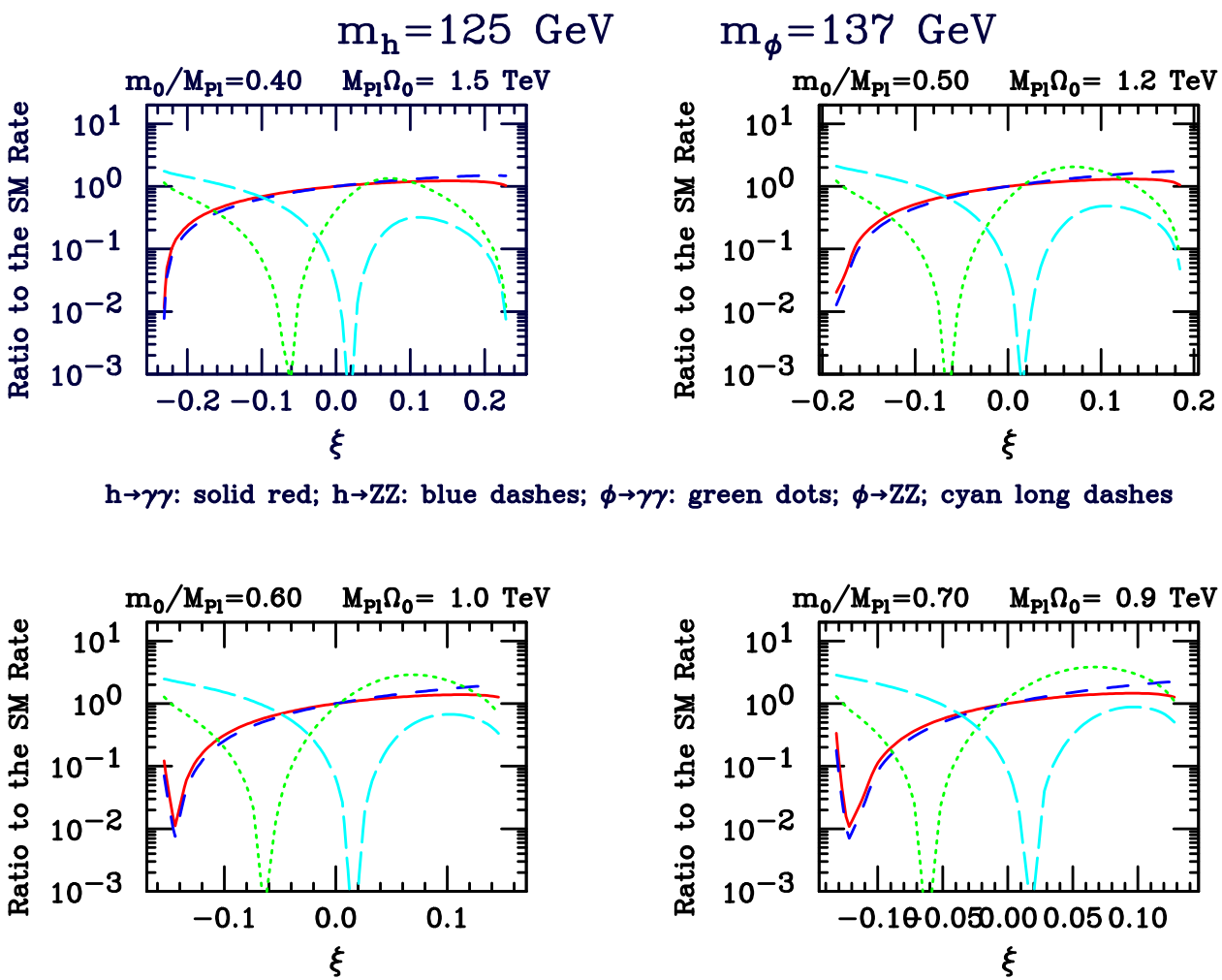


Figure 1: We plot $\gamma\gamma$ and ZZ relative to SM vs ξ taking $m_1^g = 1.5$ TeV.

- **For other 5D fermion Yukawa and profile choices, there are no reliable lower bounds on KK excitations, so can consider holding Λ_ϕ fixed as m_0/m_{Pl} is varied. $\Rightarrow$ fit for $m_0/m_{Pl} = 0.25$, $\xi = -0.1$ if $\Lambda_\phi = 1$ TeV.**

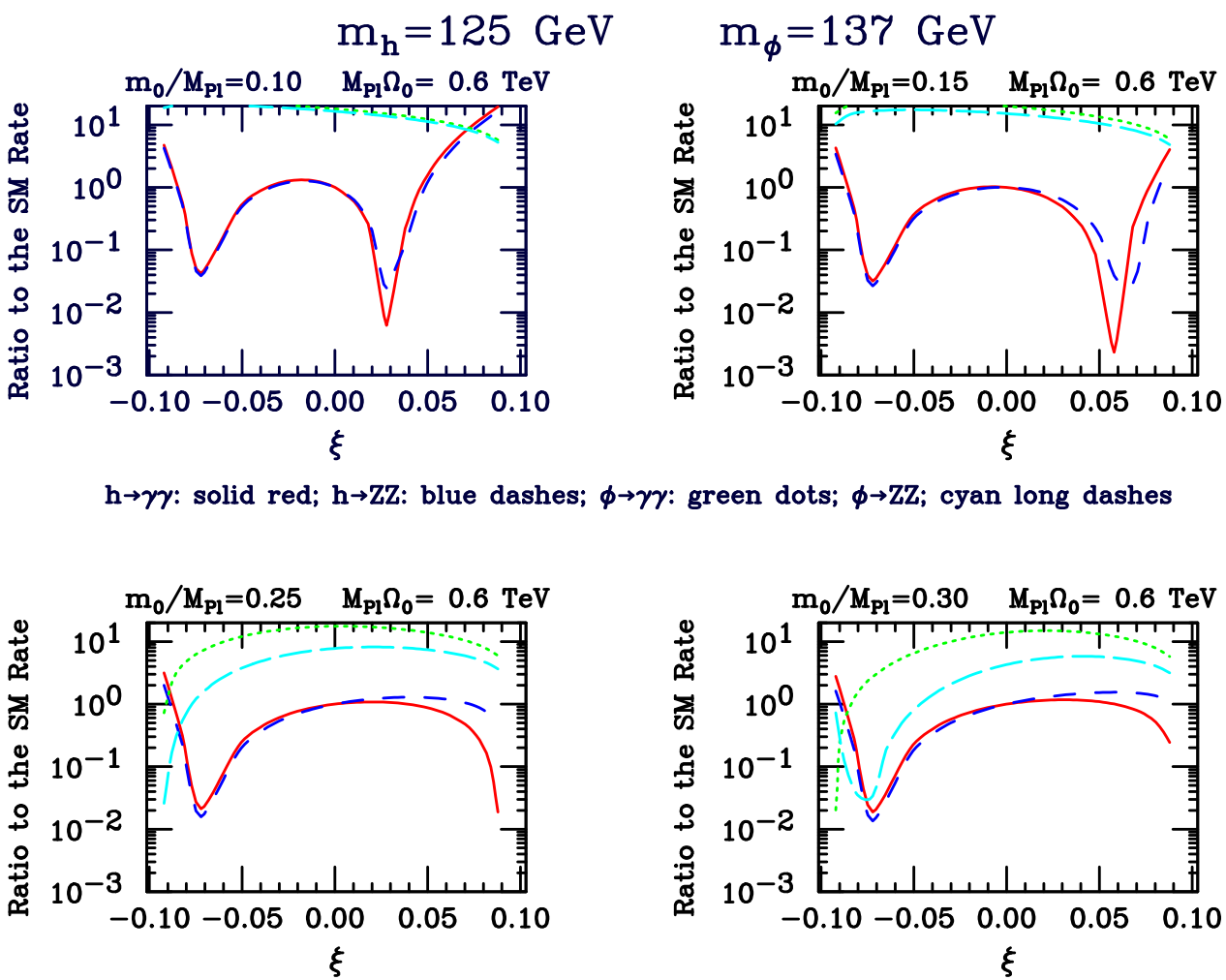


Figure 2: We plot $\gamma\gamma$ and ZZ rates relative to SM vs ξ taking Λ_ϕ fixed at 1.5 TeV.

- **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. ?? 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!**

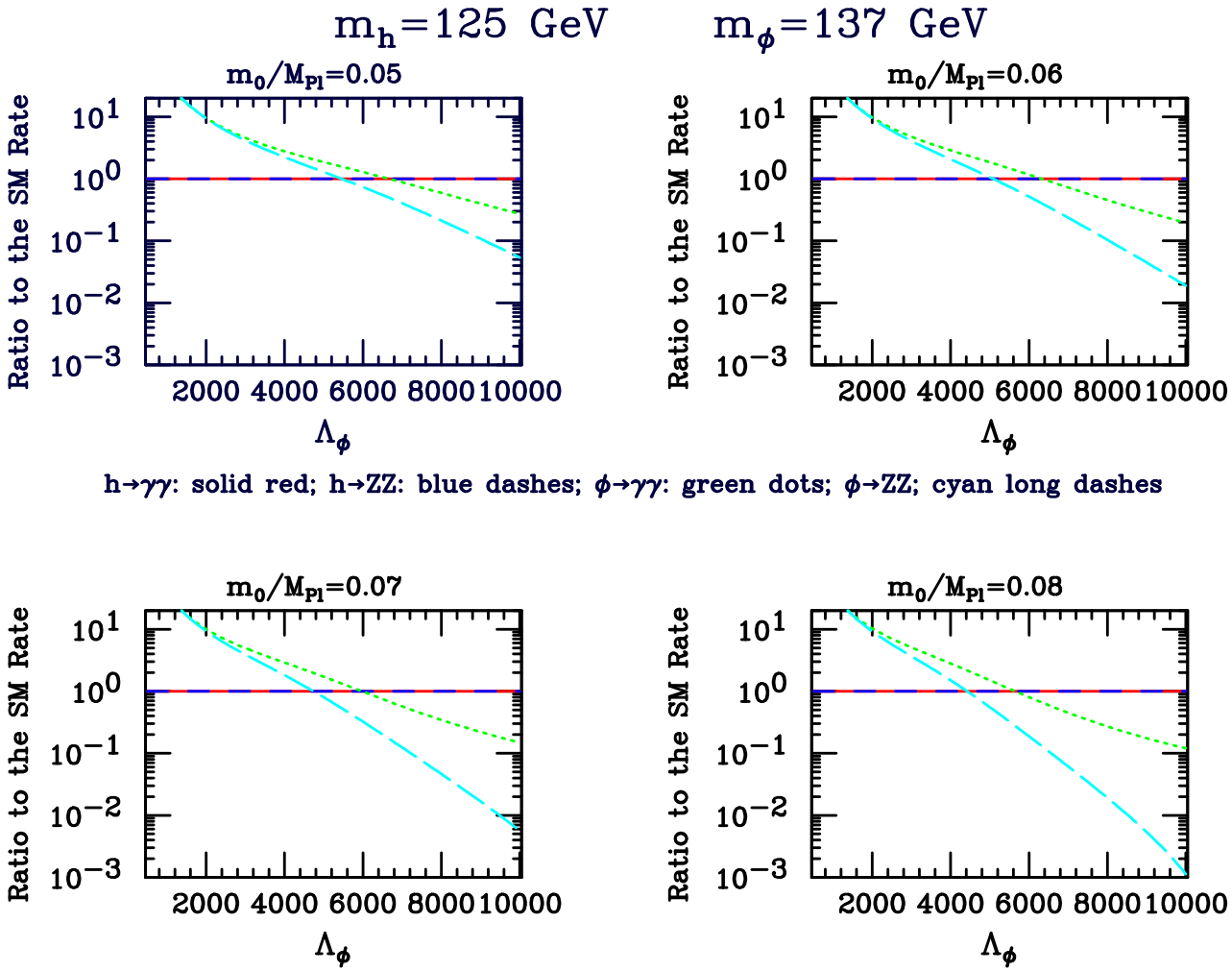


Figure 3: We plot $\gamma\gamma$ and ZZ rates relative to SM vs Λ_ϕ taking $\xi = 0$.

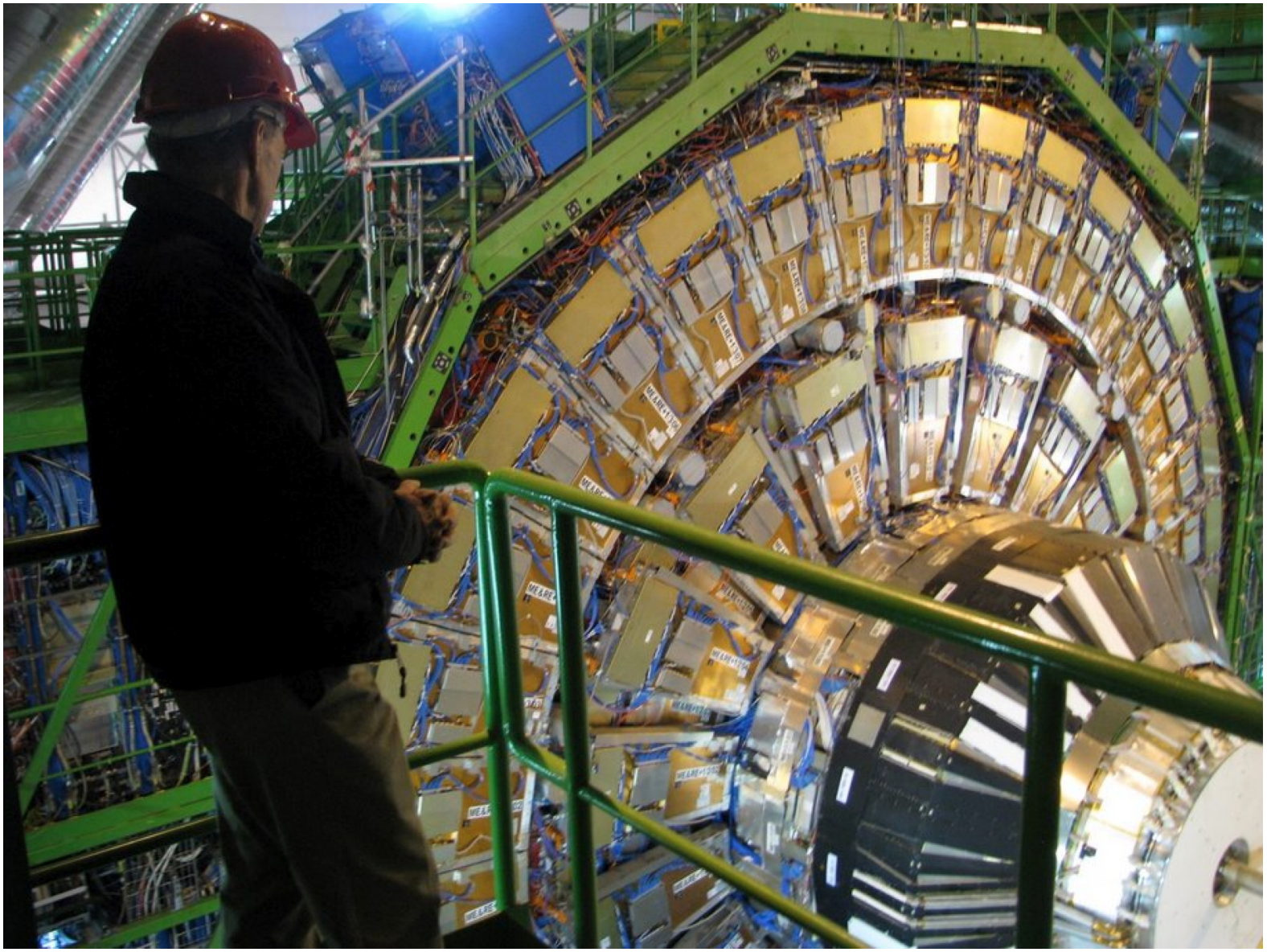
Conclusions

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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