Implications for BSM Higgs Bosons of LHC $>$ SM Higgs Hints

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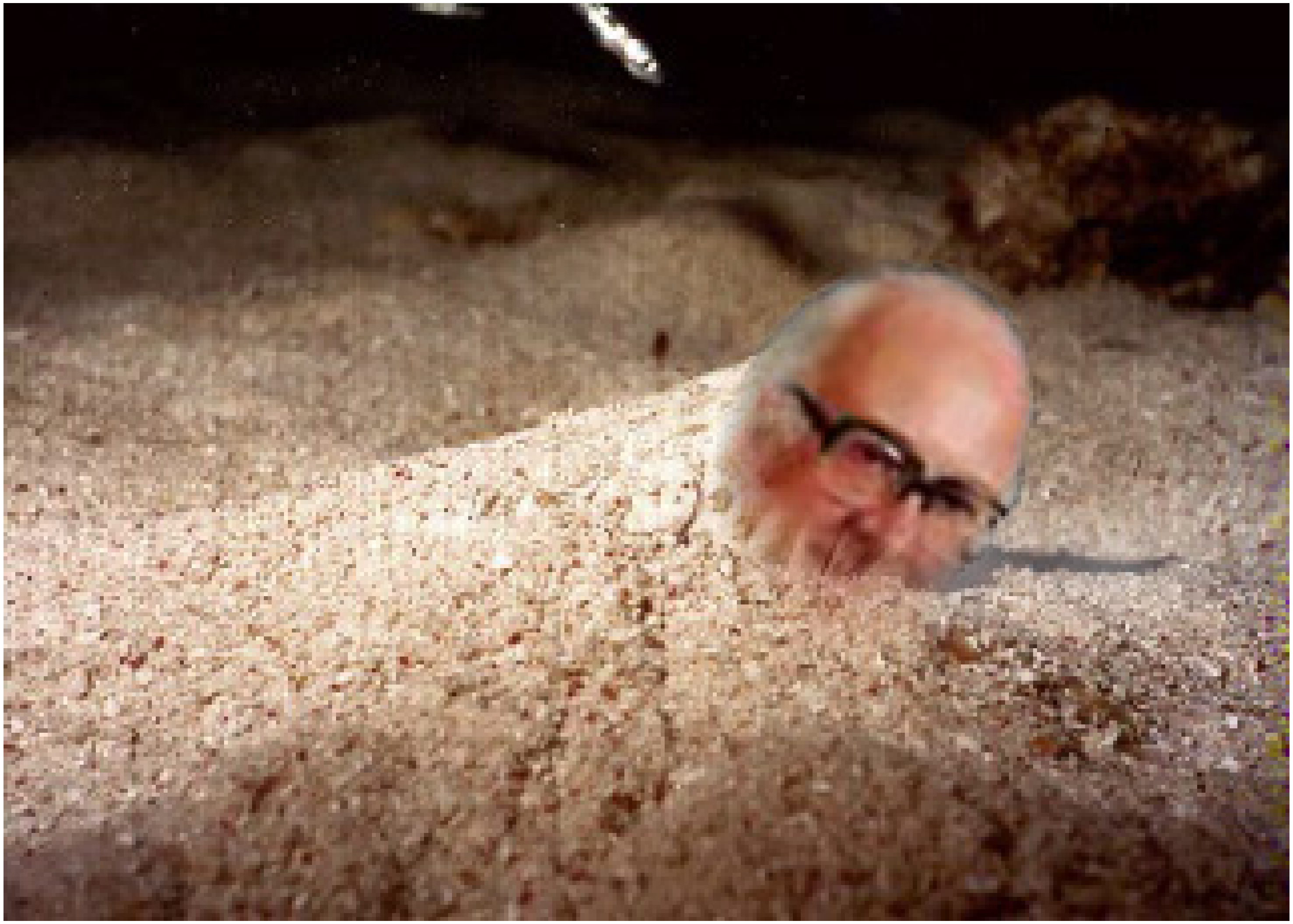
Higgs-like LHC Excesses

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	120 GeV	137 GeV
ATLAS	$R(\gamma\gamma) \sim 2.0^{+0.8}_{-0.8}$, $R(4\ell) \sim 1.5^{+1.5}_{-1.0}$	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	$R(\gamma\gamma) = 1.5^{+0.8}_{-0.8}$, $R(4\ell) < 0.2$

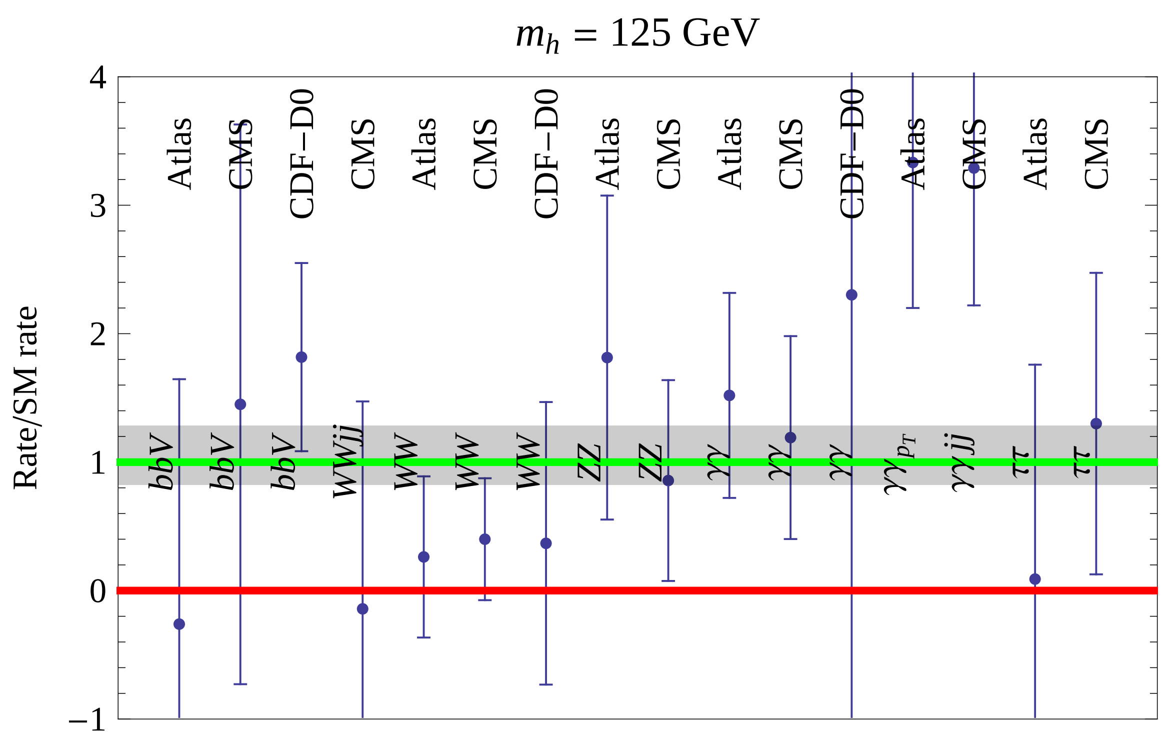
At 125 GeV, CMS separates out gg vs. WW fusion processes, yielding

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

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 at $125~\mathrm{GeV}$ into a SM-like framework, but allowing for rescaling of individual channels, as per arXiv:1203.4254, to obtain



- **Note: $R(WW) < 1$ would imply $gg \to h <$SM, but WW signal is diffuse and I will choose to only pay attention to $R(ZZ)$:**

  $R(ZZ) \gtrsim 1$ **for ATLAS, whereas** $R(ZZ) < 1$ **for CMS.**

- **The big questions:**

  1. **if the deviations from a single SM Higgs survive what is the model?**
  2. **If they do survive, how far beyond our "standard" model set must we go to describe them?**

  Here, I focus on the NMSSM and the Randall-Sundrum models to see what is possible for these "standard" models.

Enhanced Higgs signals in the NMSSM

- NMSSM=MSSM+$\widehat{S}$.
- The extra complex S component of $\widehat{S} \Rightarrow$ the NMSSM has h_1, h_2, h_2, a_1, a_2.
- The new NMSSM parameters of the superpotential (λ and κ) and scalar potential (A_λ and A_κ) appear as:

$$W \ni \lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3 \,, \quad V_{\rm soft} \ni \lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 \tag{4}$$

- $\langle S \rangle \neq 0$ is generated by SUSY breakng and solves μ problem: $\mu_{\rm eff} = \lambda \langle S \rangle$.
- Question: Can the NMSSM give a Higgs mass as large as $125~{\rm GeV}$?

  Answer: it depends on how constrained the model is.

Certainly in general it is possible, especially if $\tan\beta$ is modest and λ is large.

But constrained versions of the NMSSM need not have the necessary freedom to do so while obeying all constraints.

- Various constrained versions have been considered.

1. cNMSSM [41][42]: $m_0 = 0$ and $A_0 \equiv A_t = A_b = A_\tau = A_\lambda = A_\kappa$, $\Rightarrow$
   - $m_{h_1} \lesssim 121~\mathrm{GeV}$ at large $m_{1/2}$.
   - The h_2 can have a mass in the $123 - 128~\mathrm{GeV}$ 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 the LHC data.
2. CNMSSM: universal m_0, A_0: can't give high enough m_{h_1}.
3. universal m_0, A_0, but $A_\lambda = A_\kappa = 0$; can't give high enough m_{h_1}.
4. universal m_0, except for NUHM, universal A_0 except $A_\lambda = A_\kappa = 0$; can get into interesting m_{h_1} range.
5. 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.

- **Can the constrained NMSSM with NUHM relaxation and A_λ, A_κ free from A_0 explain rates in $\gamma\gamma$ and 4ℓ that are $>$SM?**

  Answer: it depends on whether or not we insist on getting good a_μ.

- **The possible mechanism (arXiv:1112.3548, Ellwanger) is to reduce the $b\bar{b}$ width of the mainly SM-like Higgs by giving it some singlet component. The gg and $\gamma\gamma$ couplings are less affected.**

- **Typically, this requires $m_{h_1} \sim m_{h_2}$ (for both singlet-doublet mixing) and large λ (to enhance Higgs mass).**

  Large λ is only possible while retaining perturbativity up to m_{Pl} if $\tan\beta$ is modest in size.

- **The "enhanced" SM-like Higgs can be either h_1 or h_2.**

- **Some illustrative results from JFG, Kraml, Jiang follow. (We focus on gg fusion here.)**

Figure Legend

	LEP/Teva	B-physics	$\Omega h^2 > 0$	$\delta a_\mu (\times 10^{10})$	XENON100	$R^{h_1/h_2}(\gamma\gamma)$
●	$\surd$	$\surd$	$0 - 0.136$	$\times$	$\surd$	$[0.5, 1]$
■	$\surd$	$\surd$	$0 - 0.094$	$\times$	$\surd$	$(1, 1.2]$
▲	$\surd$	$\surd$	$0 - 0.094$	$\times$	$\surd$	> 1.2
■	$\surd$	$\surd$	0.094-0.136	$\times$	$\surd$	$(1, 1.2]$
▲	$\surd$	$\surd$	0.094-0.136	$\times$	$\surd$	> 1.2
◆	$\surd$	$\surd$	$0.094 - 0.136$	4.27-49.1	$\surd$	~ 1

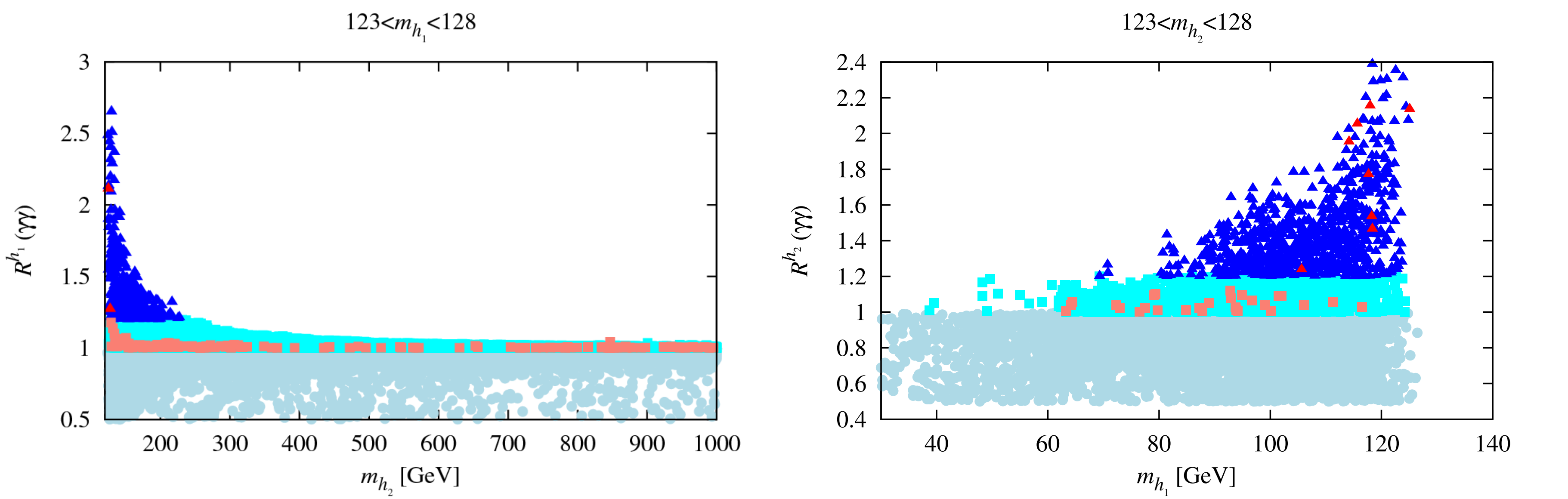


Figure 1: The plot shows $R(\gamma\gamma)$ for the cases of $123 < m_{h_1} < 128$ GeV and $123 < m_{h_2} < 128$ GeV.

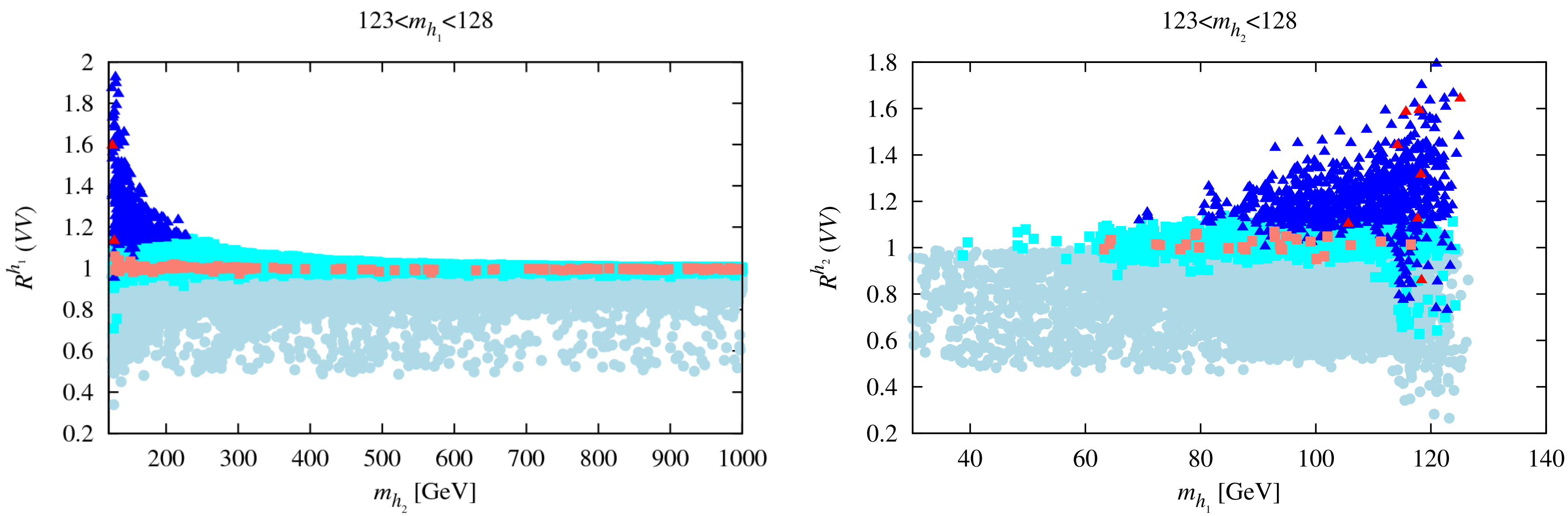


Figure 2: This plot shows that $R(VV)$ values are smaller than $R(\gamma\gamma)$ values but still > 1 for red triangle points with largest $R(\gamma\gamma)$.

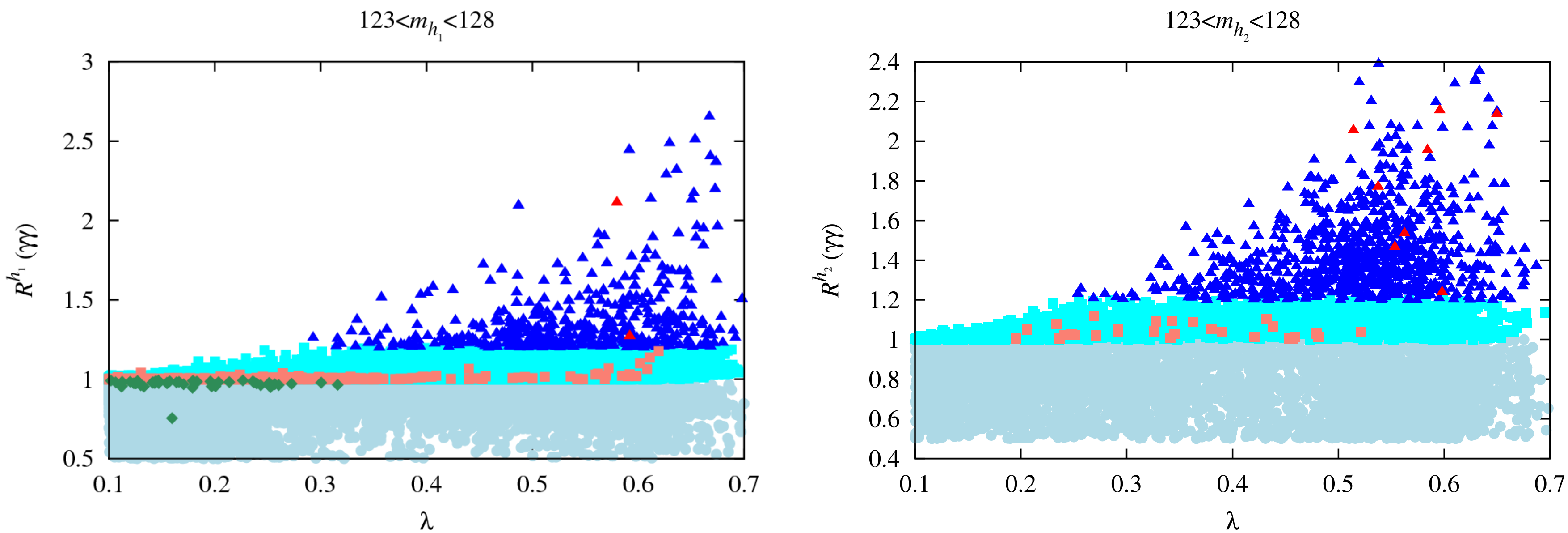


Figure 3: Observe the clear general increase in maximum $R(\gamma\gamma)$ with increasing λ. Green points have good δa_μ and $m_{h_2} > 1$ TeV.

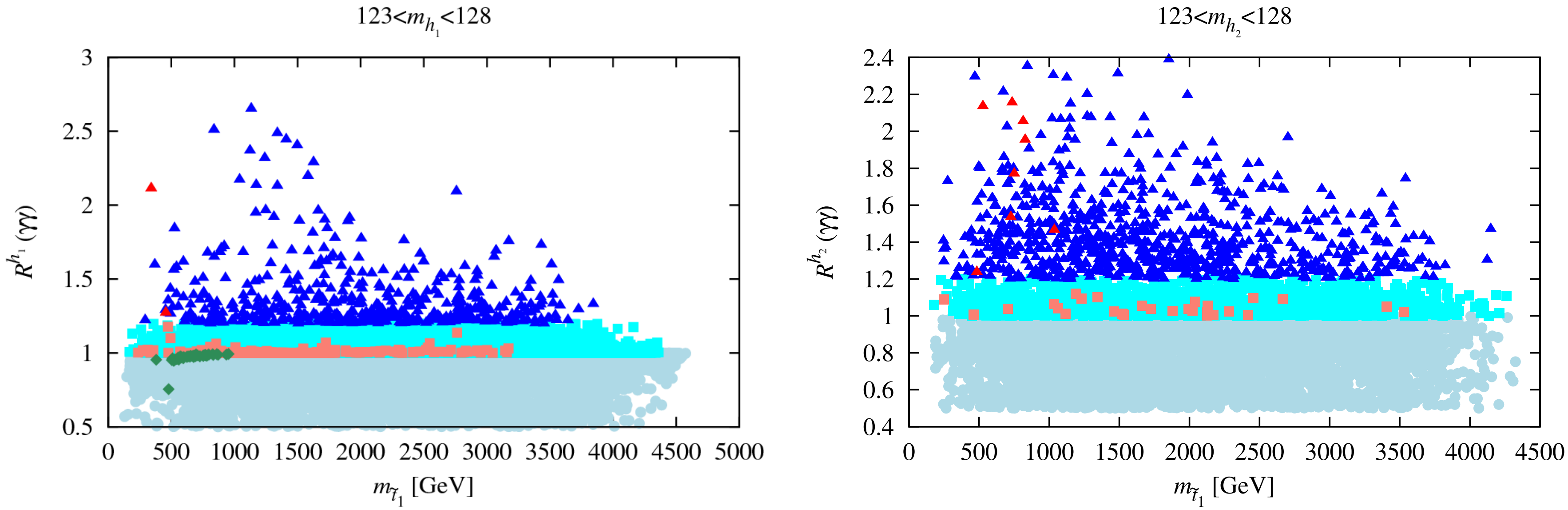


Figure 4: **The lightest stop has mass $\sim 300-700$ GeV for red-triangle points.**

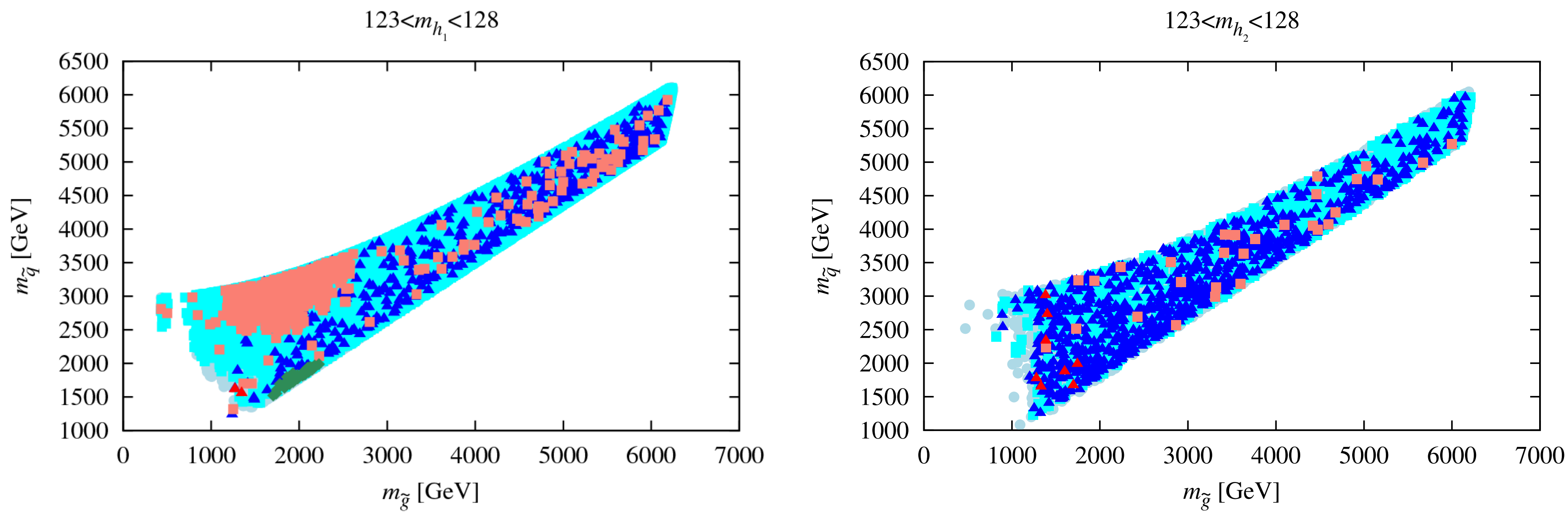


Figure 5: **For red-triangle points, gluino and 1st and 2nd generation squark masses are beyond current LHC limits, but within reach in current run.**

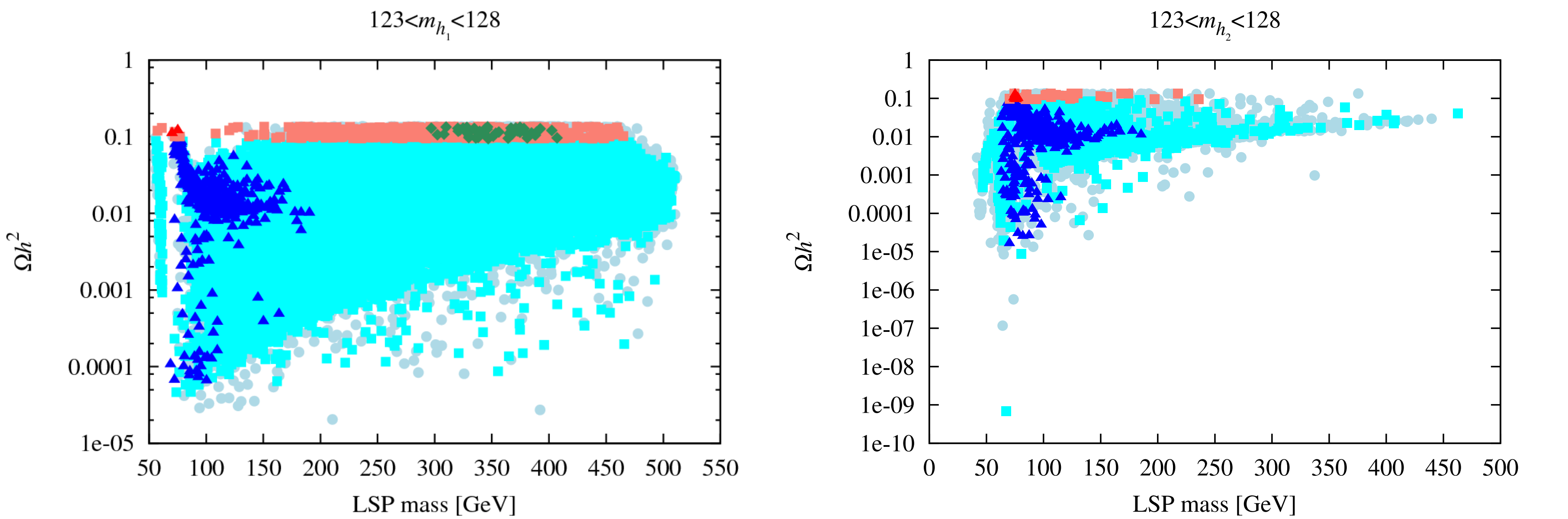


Figure 6: For red-triangle points, LSP mass is low.

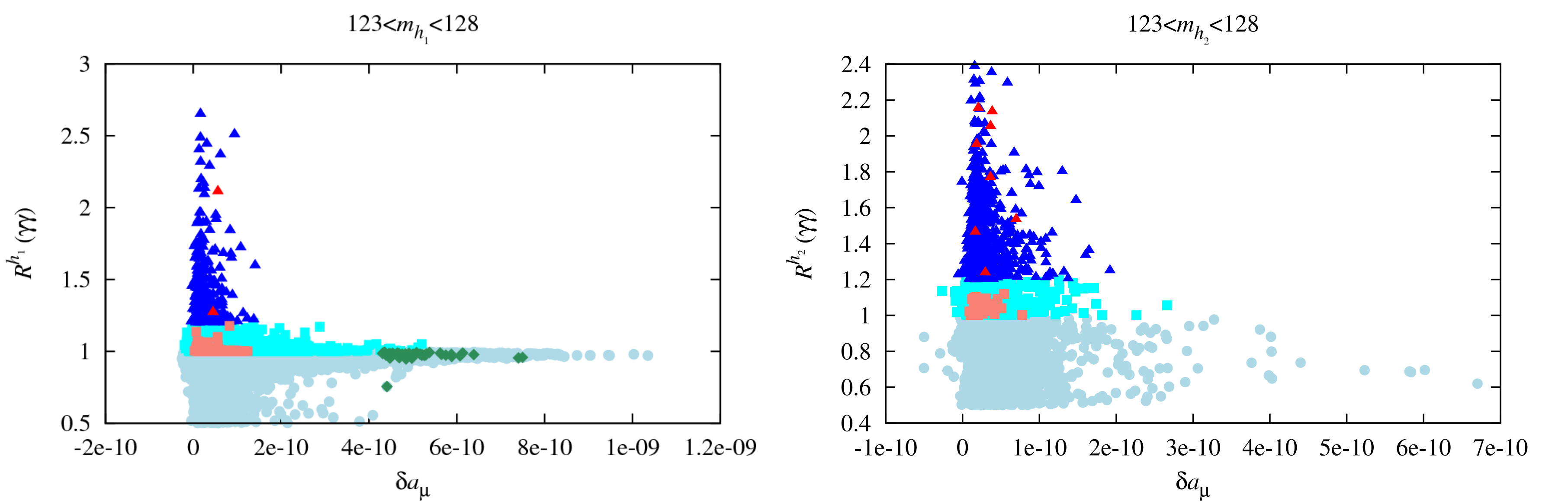


Figure 7: δa_μ is very small for red-triangle points.

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 $125~\mathrm{GeV}$ and $137~\mathrm{GeV}$ excesses.

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

$$ds^2 = e^{-2m_0 b_0 |y|} \eta_{\mu\nu} dx^\mu dx^\nu - b_0^2 dy^2 \tag{5}$$

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:

$$v_0 = \Omega_0 \widehat{v} = e^{-\frac{1}{2} m_0 b_0} \widehat{v} \sim 1 \text{ TeV} \qquad \text{for} \qquad \frac{1}{2} m_0 b_0 \sim 35 \,. \tag{6}$$

- 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 $\Lambda_\phi = \sqrt{6} m_{Pl} \Omega_0 < 5 \text{ TeV}$ or so.

- 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 [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.

- There are various possibilities. No time to outline

- Predictions for bare h_0 couplings are also model-dependent. In particular, the interaction term between the brane Higgs and the up-type fermions can be written as

$$S_Y = \int d^4x dy \sqrt{g_{vis}}\, \delta(y - y_{vis}) \left(H\bar{Q}_L \mathbf{Y_1} U_R + H\bar{Q}_R \mathbf{Y_2} U_L + \mathrm{h.c} \right), \quad (7)$$

where Y_1 and Y_2 are 3×3 complex matrices in flavor space.

The term $\delta(y - y_{vis})H$ represents an $SU(2)$ Higgs doublet field localized on the visible brane, whereas $Q = Q_L + Q_R$ and $U = U_L + U_R$ are 5D fermion fields, transforming as doublet and singlet under $SU(2)$ respectively.

In general, 5D fermions have vectorlike representations, and in order to obtain a chiral low energy theory, one must impose vanishing boundary conditions (Dirichlet boundary conditions) on the field components Q_R and U_L.

Doing so eliminates these components from the lowest Kaluza Klein level, ensuring a chiral theory for the zero-mode fermions (which are therefore understood to be the SM fermions).

The Yukawa operators in Eq. (7) are localized on the visible brane, and are therefore chiral, *i.e.* the left and right handed components of the 5D fermions can be treated differently.

We choose 5D Yukawa couplings and profiles so that there are no corrections to the bare h_0 couplings ($Y_2 = 0$).

Consequences:

1. When $Y2 = 0$, the shift in the top-top-Higgs coupling coming from mixing with KK tops vanishes.
2. There will still be a "gradient" contribution (a suppression), but it is numerically small (less than 2-3% for KK masses of order a few TeV).
3. Also when $Y2 = 0$ KK fermion loop corrections to the ggh_0 coupling, which are proportional to $Y_1^\dagger Y_2$, vanish.
   (In Neubert et.al., Y_1 and Y_2 are taken to be comparable and the ggh_0 coupling is suppressed by the KK fermion loop corrections.)

Net Result: the h_0 will have nearly SM-like couplings. This seems a very reasonable starting point and it will emphasize the importance of the radion for obtaining $>$SM signals due to the anomalous gg and $\gamma\gamma$ couplings of the radion.

- **Since the radion and higgs fields have the same quantum numbers, they can mix. [19]**

$$S_{\xi} = \xi \int d^4x \sqrt{g_{\rm vis}} R(g_{\rm vis}) \widehat{H}^{\dagger} \widehat{H} \,, \tag{8}$$

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

- **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.

- For example, we consider the Agashe et.al model [14] in which there is a lower bound on m_1^g arising from $q\bar{q} \to g^1 \to t\bar{t}$. CMS claims $m_1^g > 1.4$ TeV in this model.

- Then, we must take into account the correlation between Λ_ϕ and m_0/m_{Pl}.

$$\frac{m_0}{m_{Pl}} \simeq \frac{m_1^g}{\Lambda_\phi} \tag{9}$$

If $\Lambda_\phi < 5$ TeV (i.e. we have a solution to the hierarchy problem) this relation requires $m_0/m_{Pl} \gtrsim 0.3$.

If the full data set at the end of the current running pushes to $m_1^g > 5$ TeV in the Agashe model, then $\Lambda_\phi < 5$ TeV implies $m_0/m_{Pl} \gtrsim 1$ is required. The absolute upper limit for consistency of the model is $m_0/m_{Pl} \sim 2-3$.

POSSIBLE SIGNAL SITUATIONS

1. ATLAS: Signal only at 125 GeV

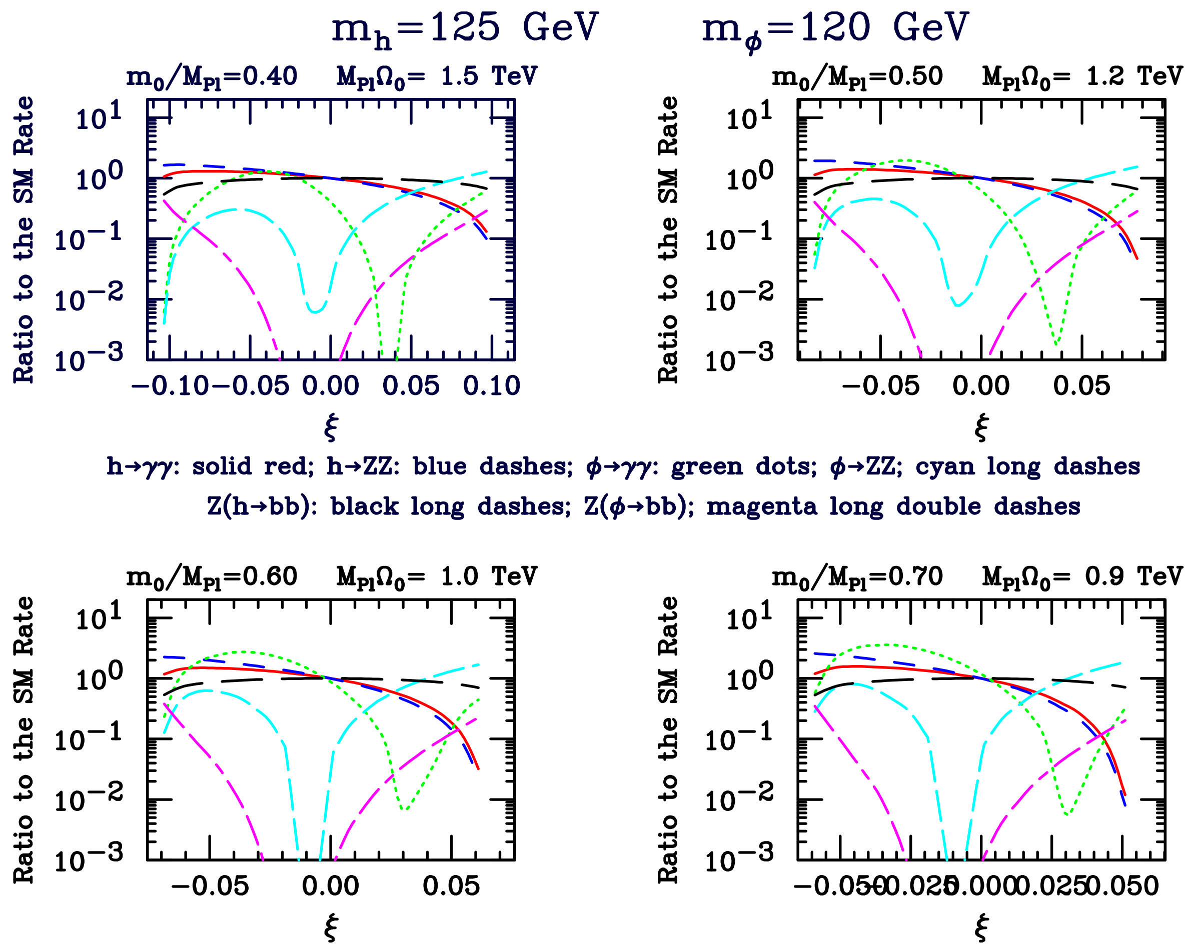


Figure 8: For $m_h = 125$ GeV and $m_\phi = 120$ GeV, we plot $R_h(X)$ and $R_\phi(X)$ for $X = \gamma\gamma$ and $X = ZZ$ (equivalent to $X = 4\ell$) as a function of ξ, assuming $m_1^g = 1.5$ TeV. Also shown are the similarly defined ratios for $Z + h$ production with $h \to b\bar{b}$ and $Z + \phi$ production with $\phi \to b\bar{b}$.

- In Fig. 8 we illustrate some possibilities for $m_h = 125$ GeV and $m_\phi = 120$ GeV taking $m_1^g = 1.5$ TeV.
- 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. **CMSA: Signals at 125 GeV and 120 GeV**

Fig. 8 also exemplifies the fact that with $m_1^g = 1.5$ TeV the Higgs-radion model is unable to describe the CMSA scenario.

For ξ such that appropriate signals are present at 125 GeV from the h, then at 120 GeV the 4ℓ and $\gamma\gamma$ rates are either both suppressed or $R_\phi(\gamma\gamma) > R_\phi(4\ell)$.

3. CMSB: Signals at 125 GeV and 137 GeV

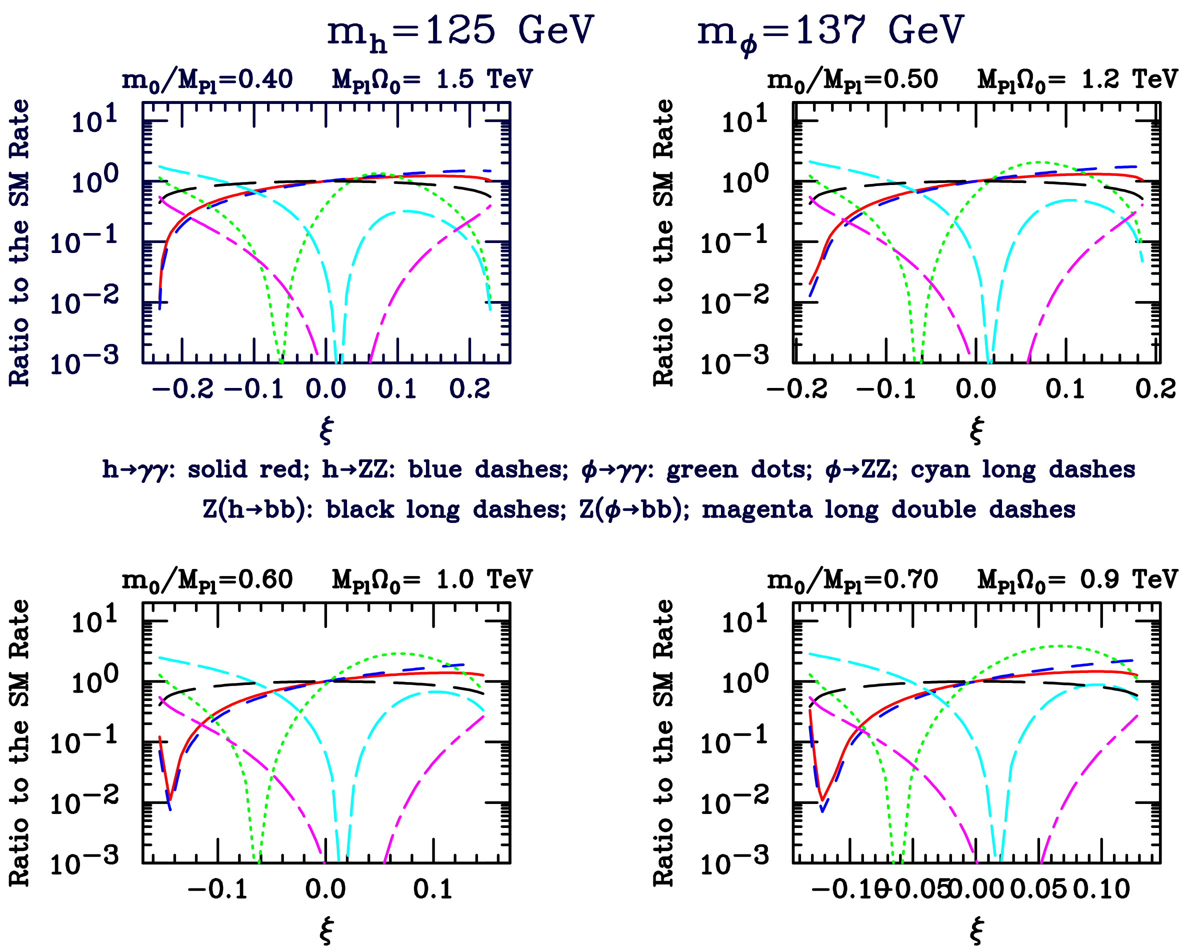


Figure 9: For $m_h = 125$ GeV and $m_\phi = 137$ GeV, we plot $R_h(X)$ and $R_\phi(X)$ for $X = \gamma\gamma$ and $X = ZZ$ vs. ξ, assuming $m_1^g = 1.5$ TeV. Also shown are the similarly defined ratios for $Z + h$ production with $h \to b\bar{b}$ and $Z + \phi$ production with $\phi \to b\bar{b}$.

- In Fig. 9: $m_0/m_{Pl} = 0.5$ and $\xi = 0.12 \Rightarrow$
  125 GeV: $\gamma\gamma \sim 1.3\times$SM; $4\ell \sim 1.5\times$SM; $Z, W + h(\to b\bar{b}) \sim 1\times$SM.
  137 GeV: $\gamma\gamma \sim 1.3\times$SM; $4\ell \sim 0.5\times$SM; $Z, W + \phi(\to b\bar{b}) \sim 0.1\times$SM
  consistent within 1σ with the CMSB observations.
- We note that it is not possible to get enhanced $\gamma\gamma$ and 4ℓ h signals at 125 GeV without having visible 137 GeV ϕ 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, for the $m_h = 125$ GeV and $m_\phi = 137$ GeV mass assignment and $m_1^g = 1.5$ TeV, it is not possible to obtain $R_{WW}(\gamma\gamma)$ significantly above 1. More typically it is slightly below 1.

4. SM signals at 125 GeV and signal at 137 GeV

- This could happen 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.

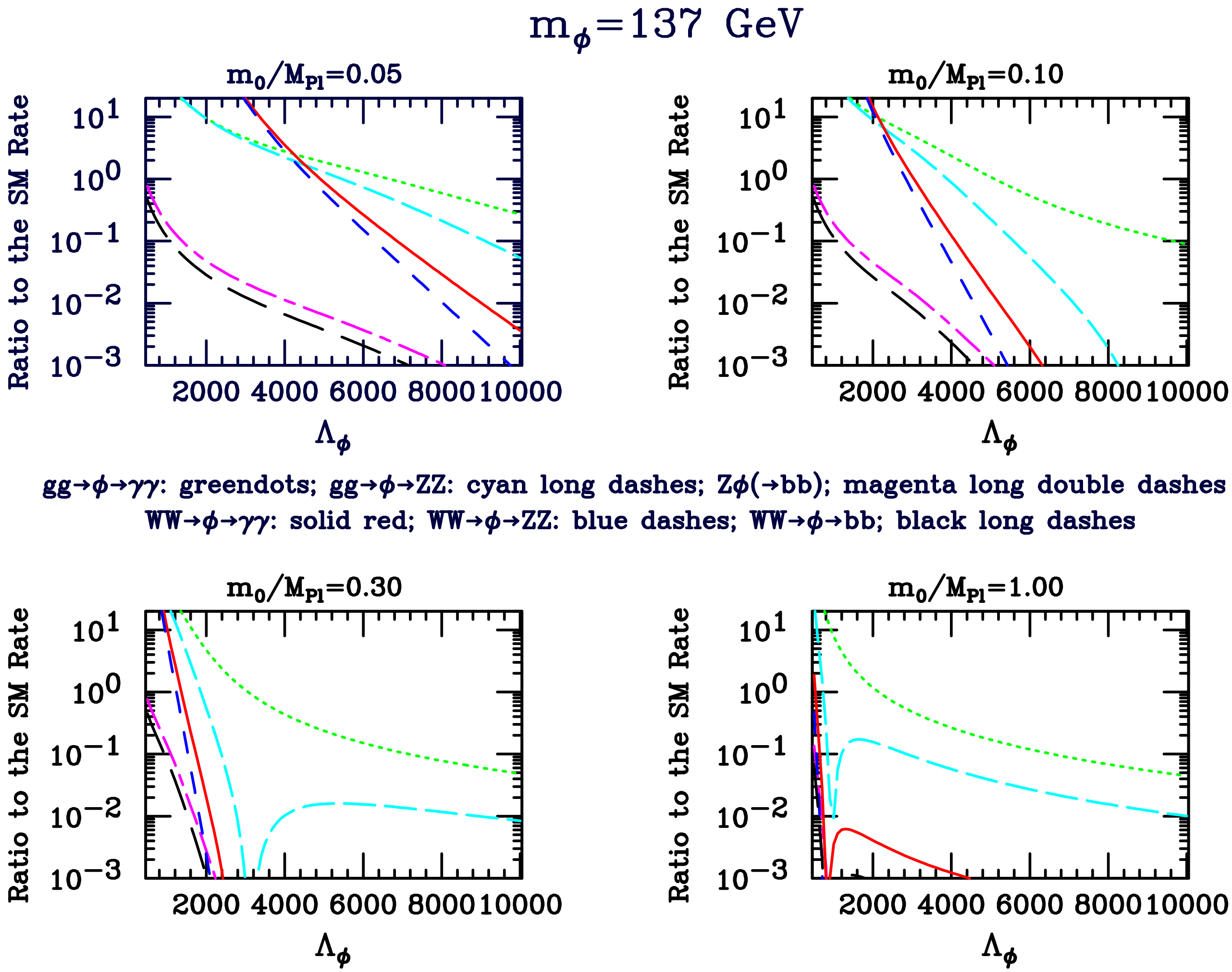


Figure 10: **For $m_\phi = 137$ GeV, we plot $R_\phi(X)$ for $X = \gamma\gamma$ and $X = ZZ$ (equivalent to $X = 4\ell$) as functions of Λ_ϕ taking $\xi = 0$. We also plot ratios to the SM for $Z \to Z\phi$ with $\phi \to b\bar{b}$ and for $WW \to \phi \to X$ for $X = \gamma\gamma$, ZZ and $b\bar{b}$.**

- Fig. 10 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 $137~\mathrm{GeV}$ is achieved for $m_0/m_{Pl} = 0.3$ and $\Lambda_\phi \sim 2.8~\mathrm{TeV}$!
  All other channels are at most $0.1\times$SM.

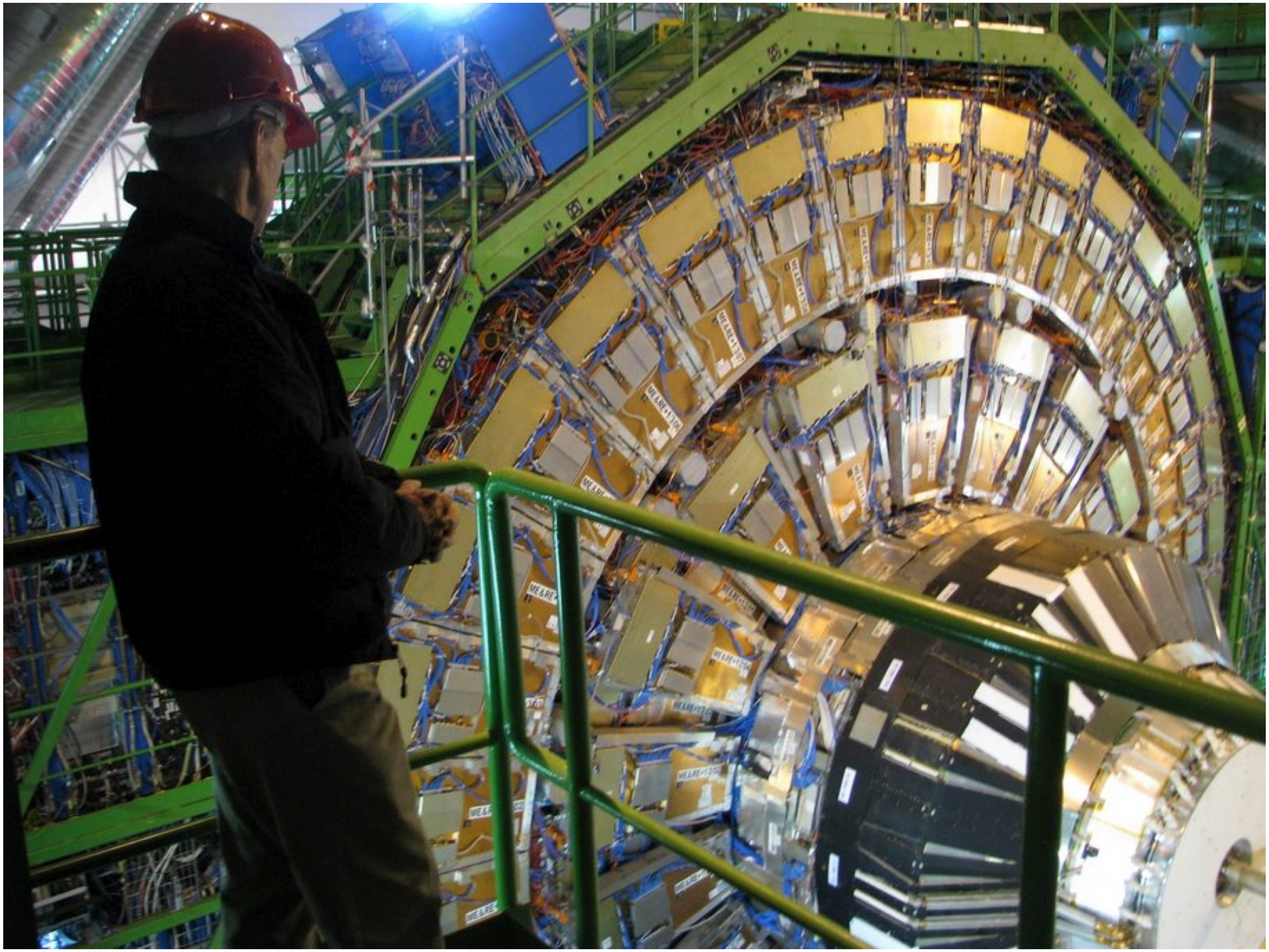
Bottom line: signals from gg fusion in the $\gamma\gamma$ and 4ℓ channels that exceed the SM stress RS models, but do not rule them out so long as Λ_ϕ is modest in size.

Conclusions

- **It seems likely that the Higgs responsible for EWSB is not buried.**
- **Perhaps, other Higgs-like objects are emerging.**
- **Survival of enhanced signals for one or more Higgs boson would be one of the most exciting outcomes of the current LHC run and would guarantee years of theoretical and experimental exploration of BSM models with elementary scalars.**
- $>$**SM signals would appear to guarantee the importance of a linear collider in order to understand fully the responsible BSM physics.**
- **In any case, the current situation illusrates the fact that we must never assume we have un-buried all the Higgs.**

One never knows how much stuff is down there.

Certainly, I will continue watching and waiting



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