LHC hints and Higgs bosons beyond the (MS)SM

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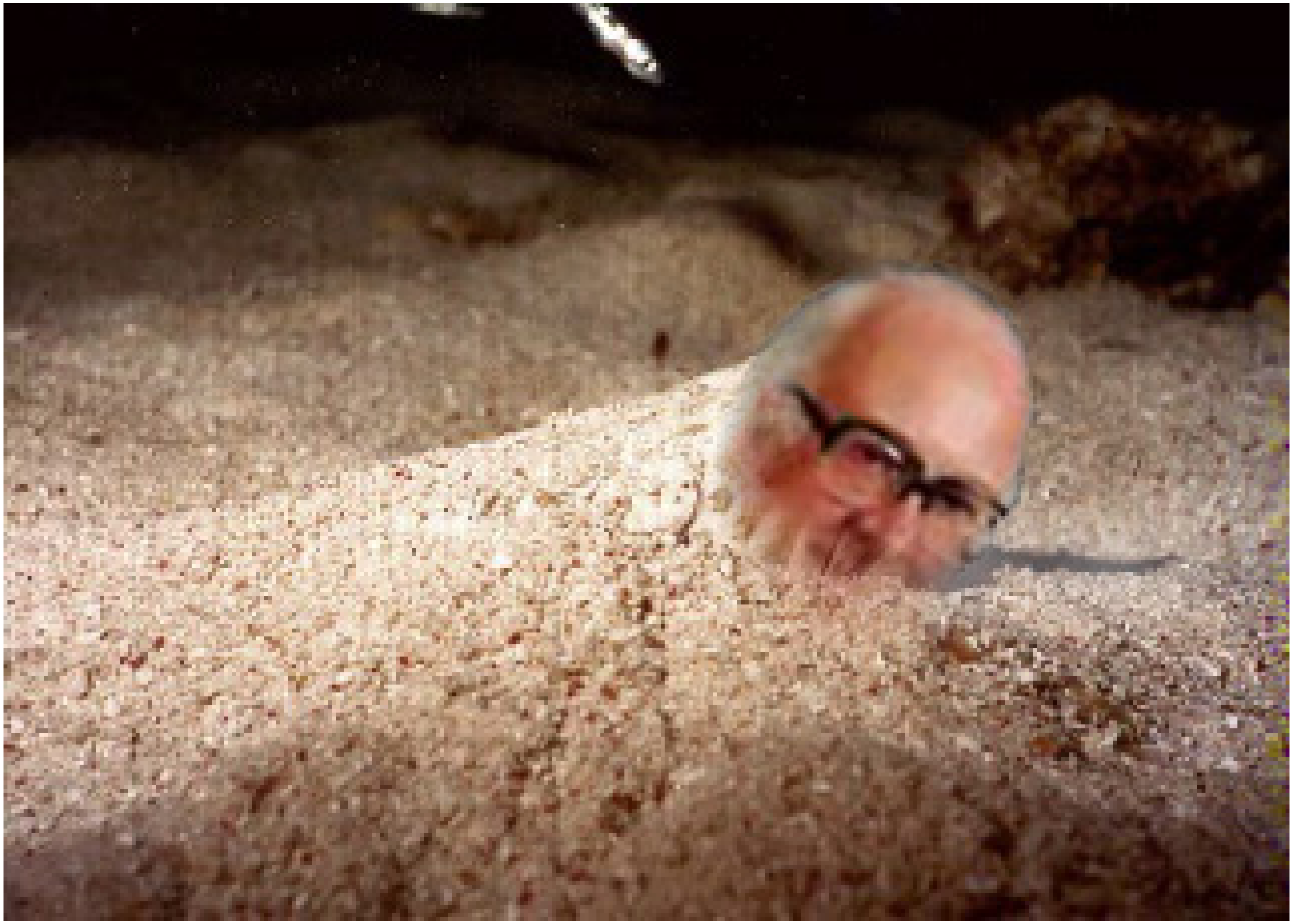
Higgs-like LHC Excesses

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.

	$125~\mathrm{GeV}$	$120~\mathrm{GeV}$	$137~\mathrm{GeV}$
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	$R(\gamma\gamma) \sim 1.7^{+0.8}_{-0.7}$, $R(4\ell) \sim 0.6^{+0.9}_{-0.6}$	$R(4l) = 2.0^{+1.5}_{-1.0}$, $R(\gamma\gamma) < 0.5$	no excesses
CMSB	$R(\gamma\gamma) \sim 1.7^{+0.8}_{-0.7}$, $R(4\ell) \sim 0.6^{+0.9}_{-0.6}$	no excesses	$R(\gamma\gamma) = 1.5^{+0.8}_{-0.8}$, $R(4\ell) < 0.2$

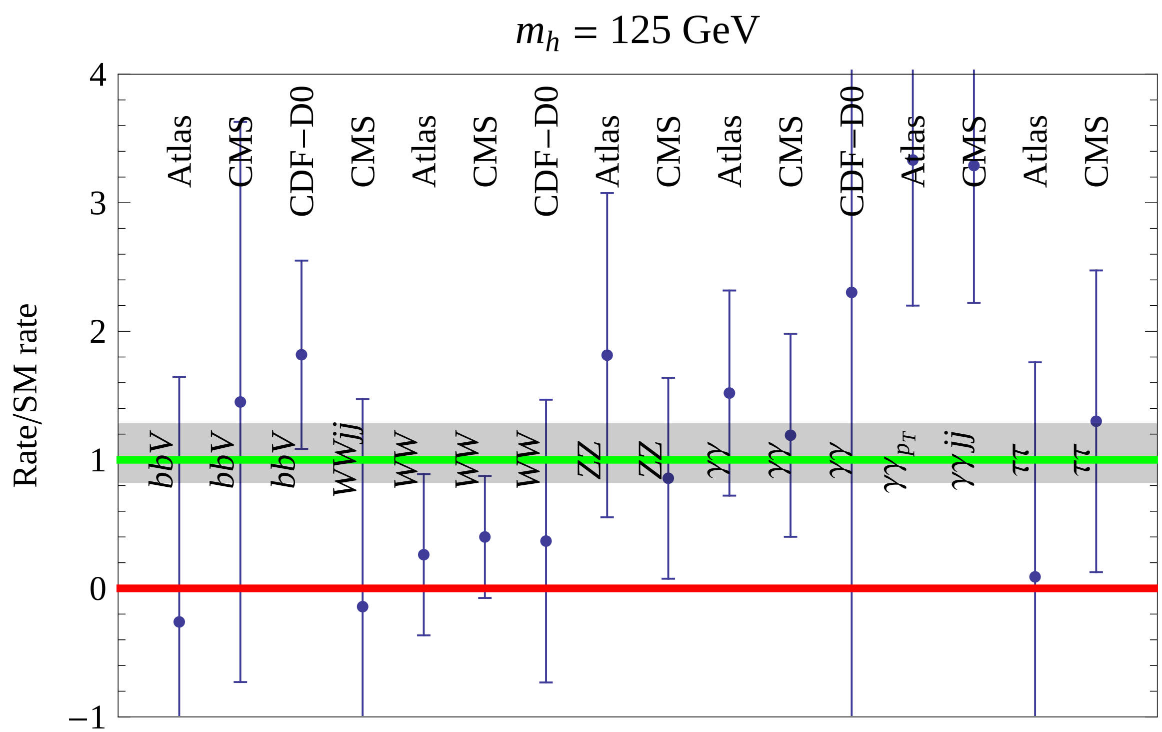
At $125~\mathrm{GeV}$, CMS separates out gg vs. WW fusion processes, yielding

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

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

$$R_{Vh}^{\mathrm{CMS}}(b\bar{b}) = 1.2^{+1.5}_{-1.8}\,, \quad R_{Vh}^{\mathrm{ATLAS}}(b\bar{b}) \sim -0.8 \pm 1.5\,, \quad R_{Vh}^{\mathrm{Tev}}(b\bar{b}) \sim 2 \pm 0.7\,(morion \tag{3}$$

One can also force all the observations into a SM-like framework, but allowing for rescaling of individual channels, as per (Giardino et.al. [62]) to obtain



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

SM + singlets and/or doublets: non-SUSY

Add only singlets (Espinosa, Gunion [63])(vanderBij [64])

- All signals reduced relative to SM by common mixing factor, $\sin\theta_i$, which parameterizes the amount of doublet contained in the ith mass eigenstate., $h_i = \sin\theta_i h_{SM} +$ singlet stuff. Some SM final state branchiing ratios can be reduced even further if $h_i \to h_j h_k, a_j a_k$ decays are present.

Add a second doublet

- Simplest two models: Type I and Type II. Focus on Type II as an example.

- Higgs bosons are h, H, A, $H^\pm$.

  CP even mixing angle $= \alpha$.

  WW coupling of $h, H = \sin(\beta - \alpha), \cos(\beta - \alpha)$.

  $hb\overline{b}, Hb\overline{b}$ coupling $= \frac{-\sin\alpha}{\cos\beta}, \frac{\cos\alpha}{\cos\beta}$. $ht\bar{t}, Ht\bar{t}$ coupling$=\frac{\cos\alpha}{\sin\beta}, \frac{\sin\alpha}{\sin\beta}$.

- **Can you fit the enhanced $\gamma\gamma$ rate?**

  The trick is to suppress the $b\bar{b}$ rate for either h or H while keeping $t\bar{t}$ coupling of h or H large —- easily done. e.g. for h take $\sin\alpha$ small and $\cos\beta$ at least moderate in size.

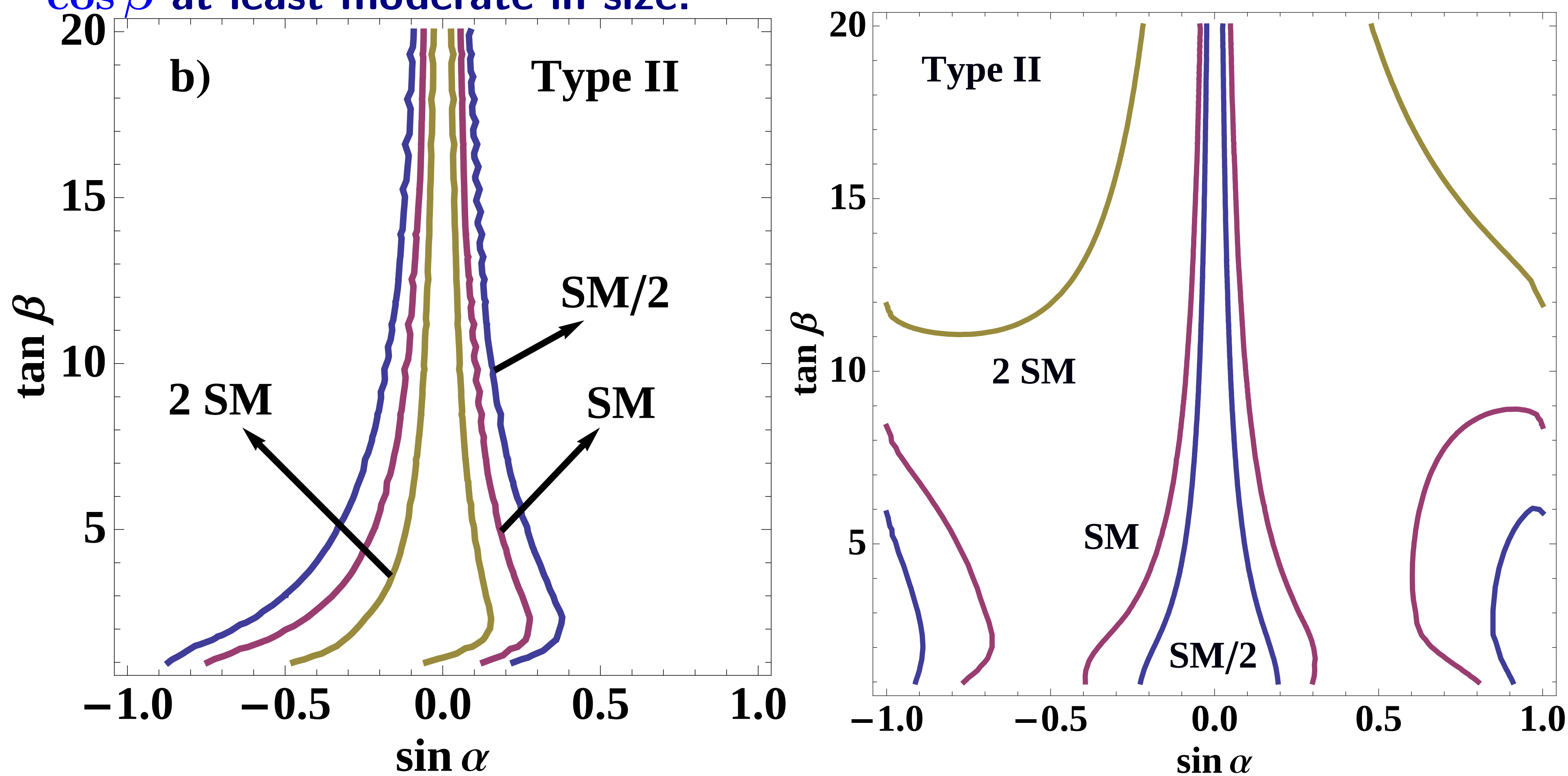


Figure 1: Left: Contours of $R^h_{gg}(\gamma\gamma)$ for fixed $m_h = 125~\mathrm{GeV}$; Right: Contours of $R^h_{Vh}(b\bar{b})$ — from (Ferreira et.al [61]). The $b\bar{b}$ reduction is awkward for CMS, Tevatron data.

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

  However, sometimes this is expanded to include dimensionful parameters as in (Hall et.al. [1])where $\widehat{W} \ni \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \widehat{\mu}\widehat{H}_u\widehat{H}_d + \frac{1}{2}M_S\widehat{S}^2$.

- In the NMSSM it is definitely easier to get largish Higgs mass.

$$
\begin{aligned}
m_h^2 &= m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2\beta + \delta_t^2, \\
\delta_t^2 &= \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\widetilde{t}}^2}{m_t^4} + \frac{X_t^2}{m_{\widetilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\widetilde{t}}^2}\right)\right]
\end{aligned}
\tag{4}
$$

where $\lambda = \lambda_{\rm SUSY}$, $m_{\widetilde{t}}^2 = \sqrt{m_{\widetilde{t}_1}^2 m_{\widetilde{t}_2}^2}$ and $X_t = A_t - \mu\cot\beta$. Even at $X_t = 0$, the NMSSM gives $m_h = 125~\mathrm{GeV}$ for $\tan\beta \sim 1$ and $\lambda \sim 0.6 - 0.7$, the latter needing only $m_{\tilde t} \sim 500~\mathrm{GeV}$.

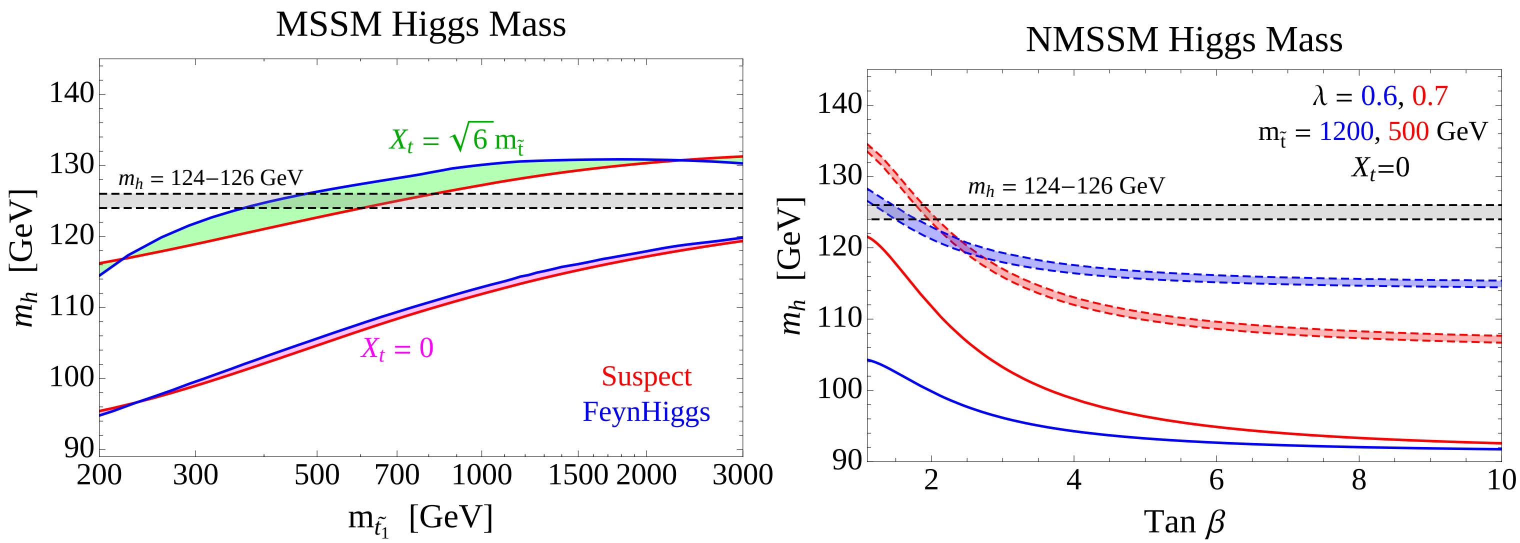


Figure 2: MSSM Higgs vs. NMSSM Higgs from (Hall et.al [1]
)

In the (simplified) NMSSM, $m_h = 125~\mathrm{GeV}$ can be achieved with rather modest fine-tuning and $m_{\tilde t}$.

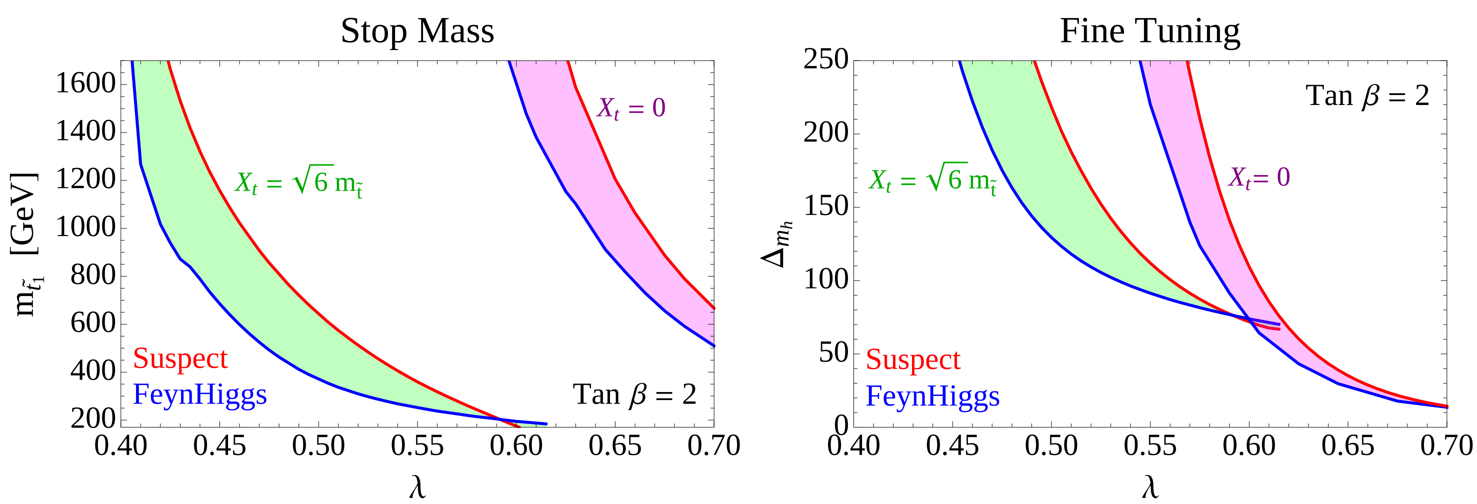


Figure 3: **Mean stop mass and associated fine-tuning needed to achieve $m_h = 125$ GeV.**

NMSSM with GUT-scale unification/constraints

- **Various constrained versions of the NMSSM have been considered. Here, we discuss only the strict NMSSM (no dimensionful parameters in $\widehat{W}$). For all models, $m_{1/2} = M_1 = M_2 = M_3$ is assumed. If not stated otherwise, for stated results we impose LEP constraints, B-physics constraints, $\Omega h^2 < 0.136$ (or perhaps WMAP window), but not necessarily δa_μ.**

1. **strict-CNMSSM**

But, strict universality using $m_0^2 = m_{H_u}^2 = m_{H_d}^2 = m_S^2 = ...$ and $A_0 = A_t = A_\kappa = A_\lambda = \ldots$ plus varying λ and κ is not consistent with observed m_Z while simultaneously obeying minimization equations for $\langle H_u \rangle$, $\langle H_d \rangle$ and $\langle S \rangle$. $\Rightarrow$

2. semi-CNMSSM (Belanger et.al [2]): Input $m_0^2 = m_{H_u}^2 = m_{H_d}^2 = \ldots \neq m_S^2$ and $A_0 = A_t = A_\lambda = \ldots \neq A_\kappa$ with m_S^2 and κ determined from minimization equations (i.e. ok to break universality for singlet-related parameters). $\Rightarrow m_{h_1} \lesssim 115~\mathrm{GeV}$.
3. cNMSSM (Djouadi et.al. [3][4]): $m_0^2 = m_{H_u}^2 = m_{H_d}^2 = \ldots = 0$, $|m_S^2 - m_0^2|$=small (which determines $\tan\beta$) and $A_0 \equiv A_t = A_b = A_\tau = A_\lambda = A_\kappa$ (i.e. approximately a very special case of strict-CNMSSM), $\Rightarrow$
   - $m_{h_1} \lesssim 121~\mathrm{GeV}$ 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 LHC data.
4. Model I (Gunion, Kraml, Yun [5]): universal m_0^2, except m_S^2, universal A_0 except $A_\lambda = A_\kappa = 0$ (natural in $U(1)_R$ symmetry limit). m_S^2 and κ are determined by scalar potential V minimization equations; yields too

low m_{h_1}.

Models achieving $m_{h_1} \sim 125$ GeV with $\lambda_{\rm GUT} < 1$

5. Model II [5];: universal m_0^2, except for NUHM ($m^2_{H_u}$, $m^2_{H_d}$ independent of m_0^2), m_S^2 and κ from V minimization, universal A_0 except $A_\lambda = A_\kappa = 0$. One finds m_{h_1} can be ok, but $\gamma\gamma$ rate is not enhanced.

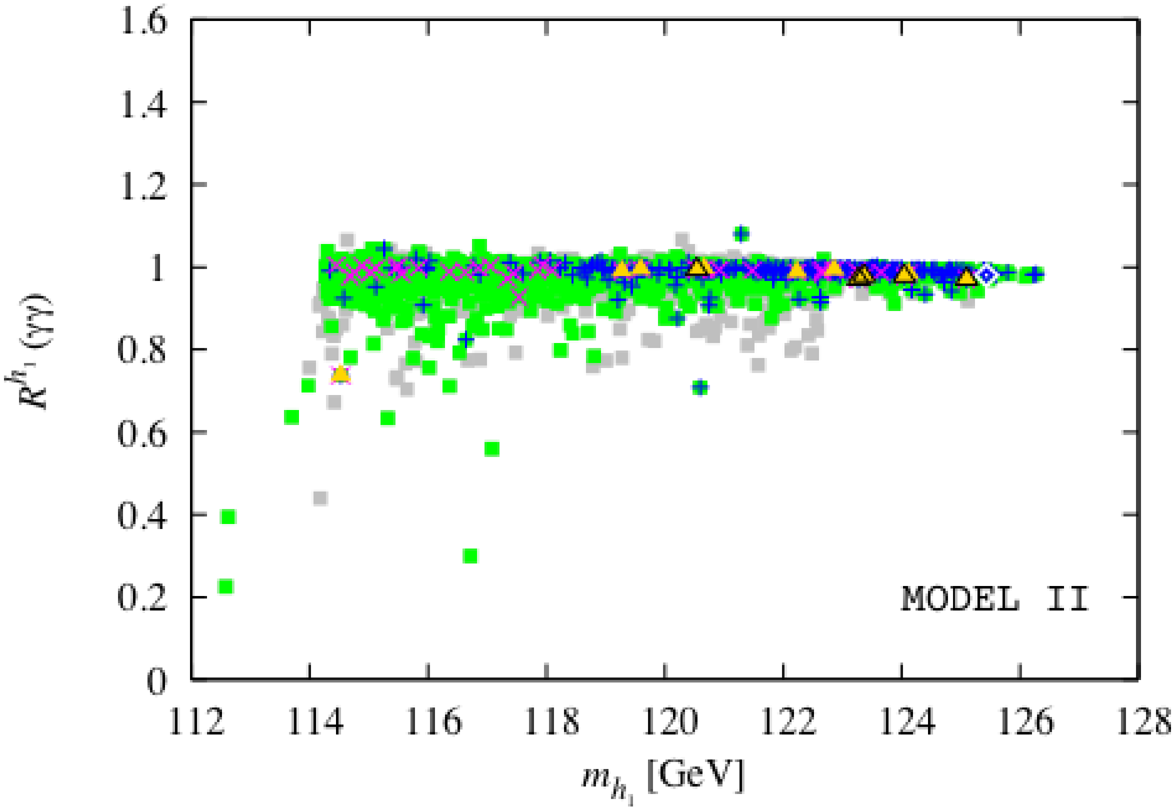


Figure 4: Black triangle = *perfect*, satisfies all constraints including δa_μ; white diamond = *almost perfect*, δa_μ relaxed by $\frac{1}{2}\sigma$.

6. **Model III: universal m_0^2, except for NUHM, universal A_0 except A_λ and A_κ allowed to vary freely [5]: gives further expansion of interesting scenarios, but harder to find** *perfect* **points with $m_{h_1} \sim 125$ GeV.**

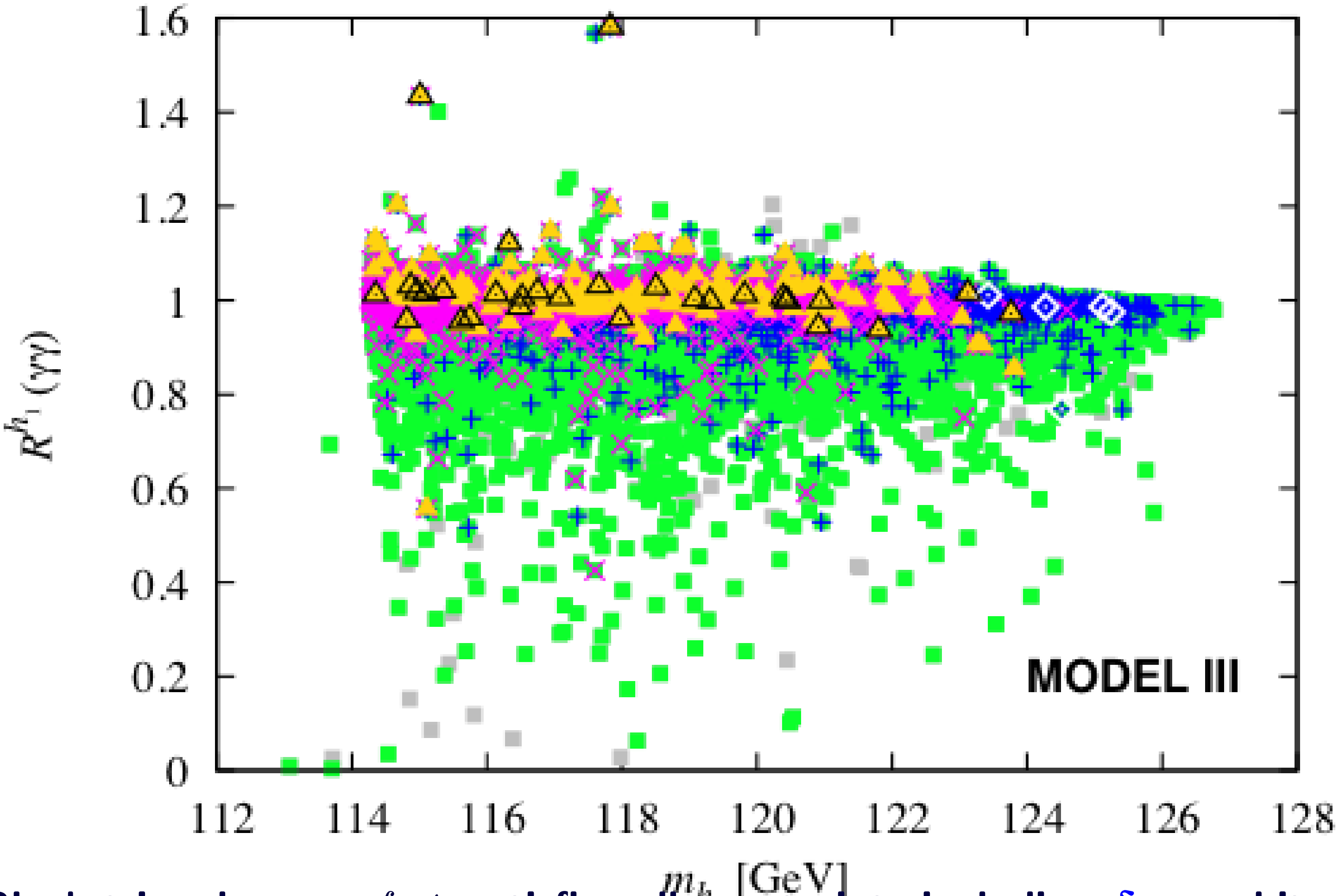


Figure 5: **Black triangle =** *perfect*, **satisfies all constraints including δa_μ; white diamond =** *almost perfect*, **δa_μ relaxed by $\frac{1}{2}\sigma$.**

SUSY implications of Models II and III?

- **Nothing really forces small $m_{\widetilde{t}_1}$ until $m_{h_1} \sim 125$ GeV is required.**

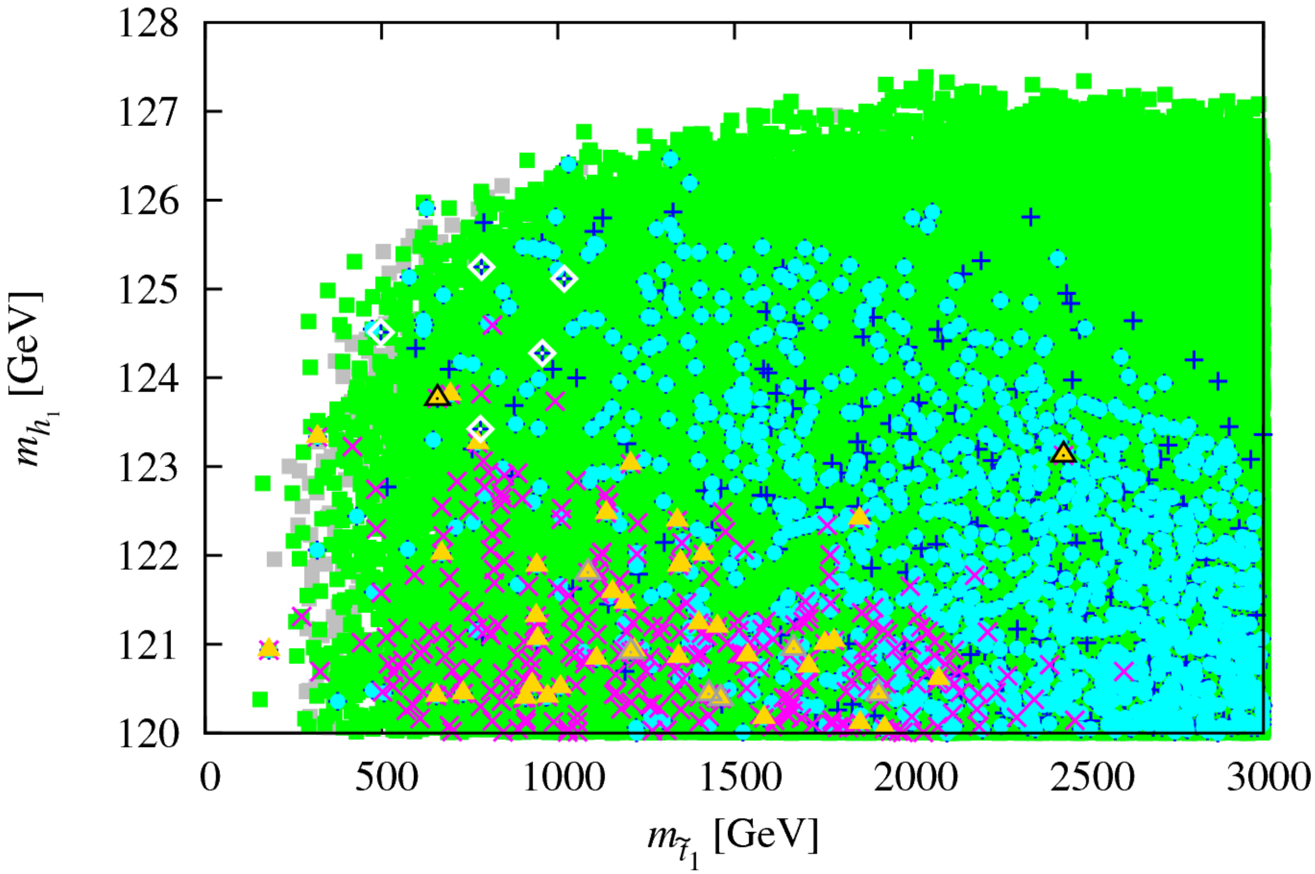


Figure 6: **Model III: Black triangle =** *perfect*, **satisfies all constraints including δa_μ; white diamond =** *almost perfect*, **δa_μ relaxed by $\frac{1}{2}\sigma$. Green squares=LEP ok + B-physics ok; blue pluses = $\Omega h^2 < 0.136$; cyan circles = Ωh^2 in WMAP window; magenta X's = δa_μ good.**

- **Upper bounds on gluino and squark masses arise just from Ωh^2, but these are large. The upper bounds are lower (but somewhat beyond current LHC reach) if $m_{h_1} \sim 125$ GeV is required and all other constraints are satisfied.**

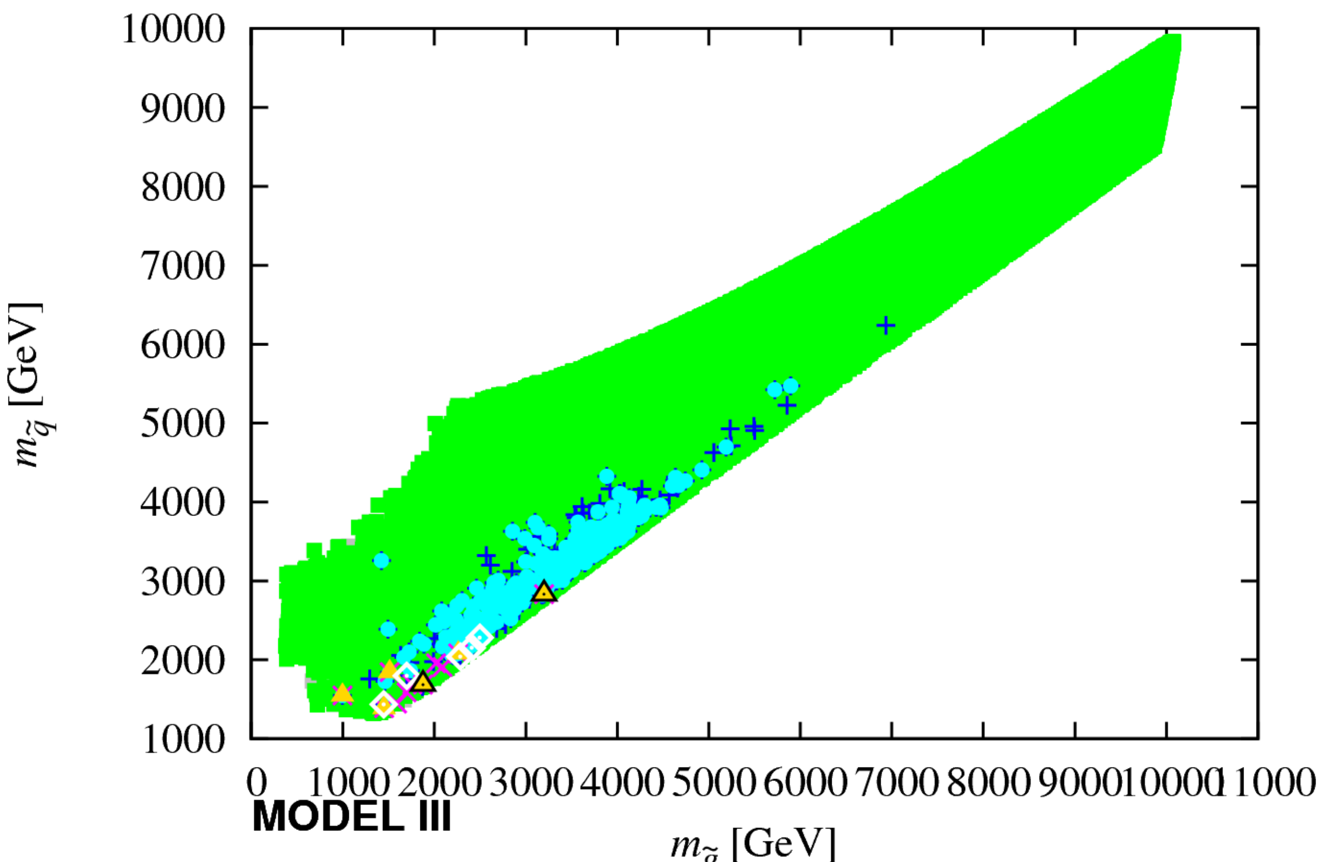


Figure 7: $m_{h_1} > 123$ GeV required. Black triangle = *perfect*, **satisfies all constraints including δa_μ; white diamond =** *almost perfect*, **δa_μ relaxed by $\frac{1}{2}\sigma$. Green squares=LEP ok + B-physics ok; blue pluses = $\Omega h^2 < 0.136$; cyan circles = Ωh^2 in WMAP window; magenta X's = δa_μ good.**

- **An upper bound on the LSP mass also arises just from Ωh^2. $m_{LSP} \lesssim 700$ GeV (most points $\lesssim 500$ GeV) if $m_{h_1} \sim 125$ GeV and all other constraints are satisfied.**

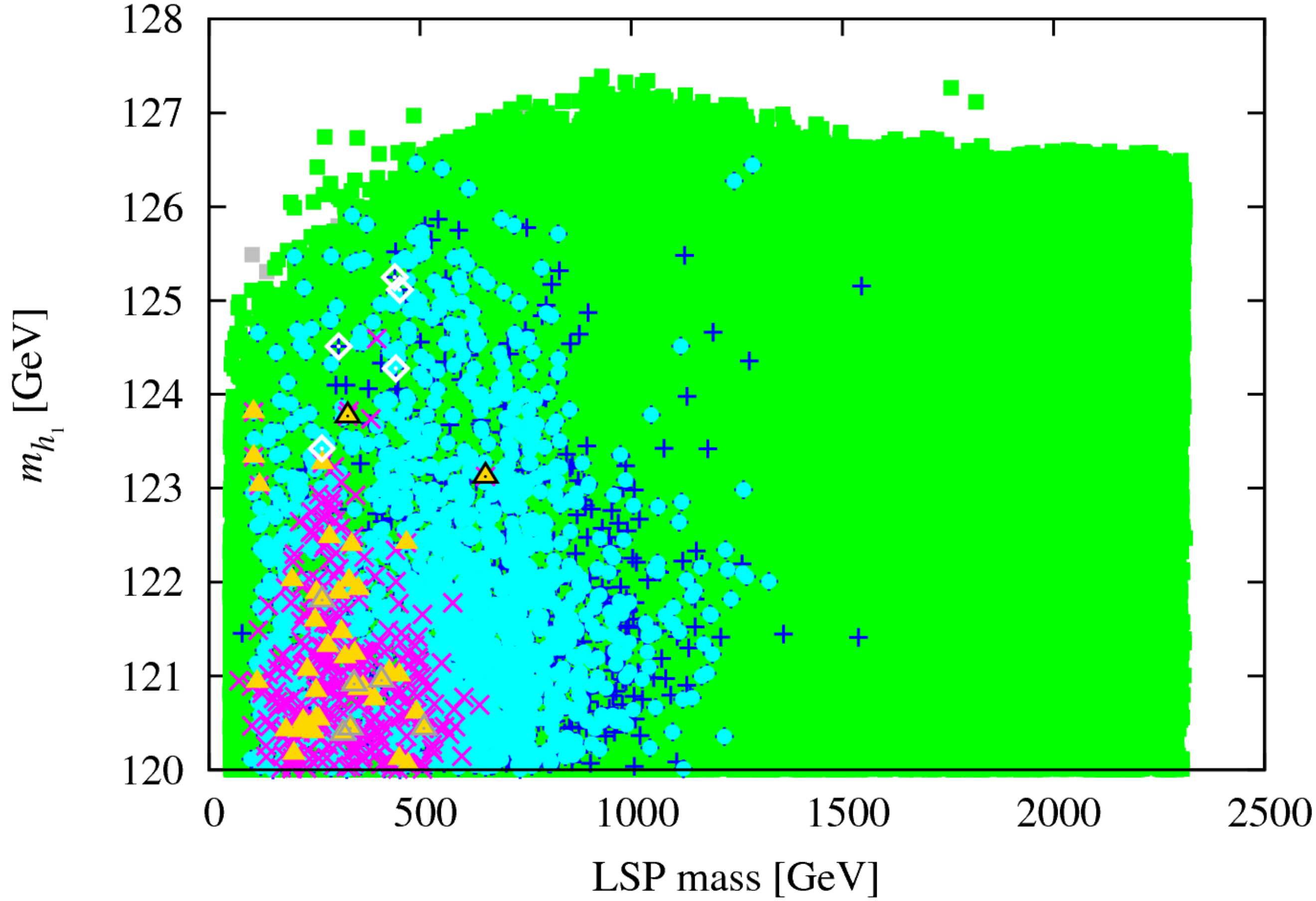


Figure 8: $m_{h_1} > 123$ GeV **required. Black triangle =** *perfect*, **satisfies all constraints including** δa_μ**; white diamond =** *almost perfect*, δa_μ **relaxed by** $\frac{1}{2}\sigma$**. Green squares=LEP ok + B-physics ok; blue pluses =** $\Omega h^2 < 0.136$**; cyan circles =** Ωh^2 **in WMAP window; magenta X's =** δa_μ **good.**

Model III with $\lambda_{\rm GUT} > 1$

- Can expand to large values the range of λ at the GUT scale that can be handled by NMSSMTools (Ellwanger, Hugonie [43]).

- Slightly different but equivalent input parameter set

$$\lambda, \quad \kappa, \quad \tan\beta, \quad \mu_{\rm eff}(=\lambda s), \quad A_\lambda, \quad A_\kappa, \quad A_0, \quad ,m_{1/2}, \quad m_0 \qquad (5)$$

where they have traded κ and $\mu_{\rm eff}$ for $m^2_{H_u}$ and $m^2_{H_d}$.

- They impose LEP, B-physics, WMAP, no direct detection, but not δa_μ.

- They find $m_{h_2} \sim 125~{\rm GeV}$ and highly enhanced $h_2 \to \gamma\gamma$ rate, but not for h_1. $R^{h_2}_{gg}(\gamma\gamma) > 1$ because of enhanced ${\rm BR}(h_2 \to \gamma\gamma)$ due to small $\Gamma(h_2 \to b\overline{b})$ arising from large singlet-doublet mixing. Also, $R^{h_2}_{gg}(ZZ) > 1$.

  Parameter region with $m_{h_2} \in [124, 127]~{\rm GeV}$ and $R^{h_2}_{gg}(\gamma\gamma) > 1$ is

$$0.41 < \lambda < 0.69, \quad 0.21 < \kappa < 0.46, \quad 1.7 < \tan\beta < 6\,. \qquad (6)$$

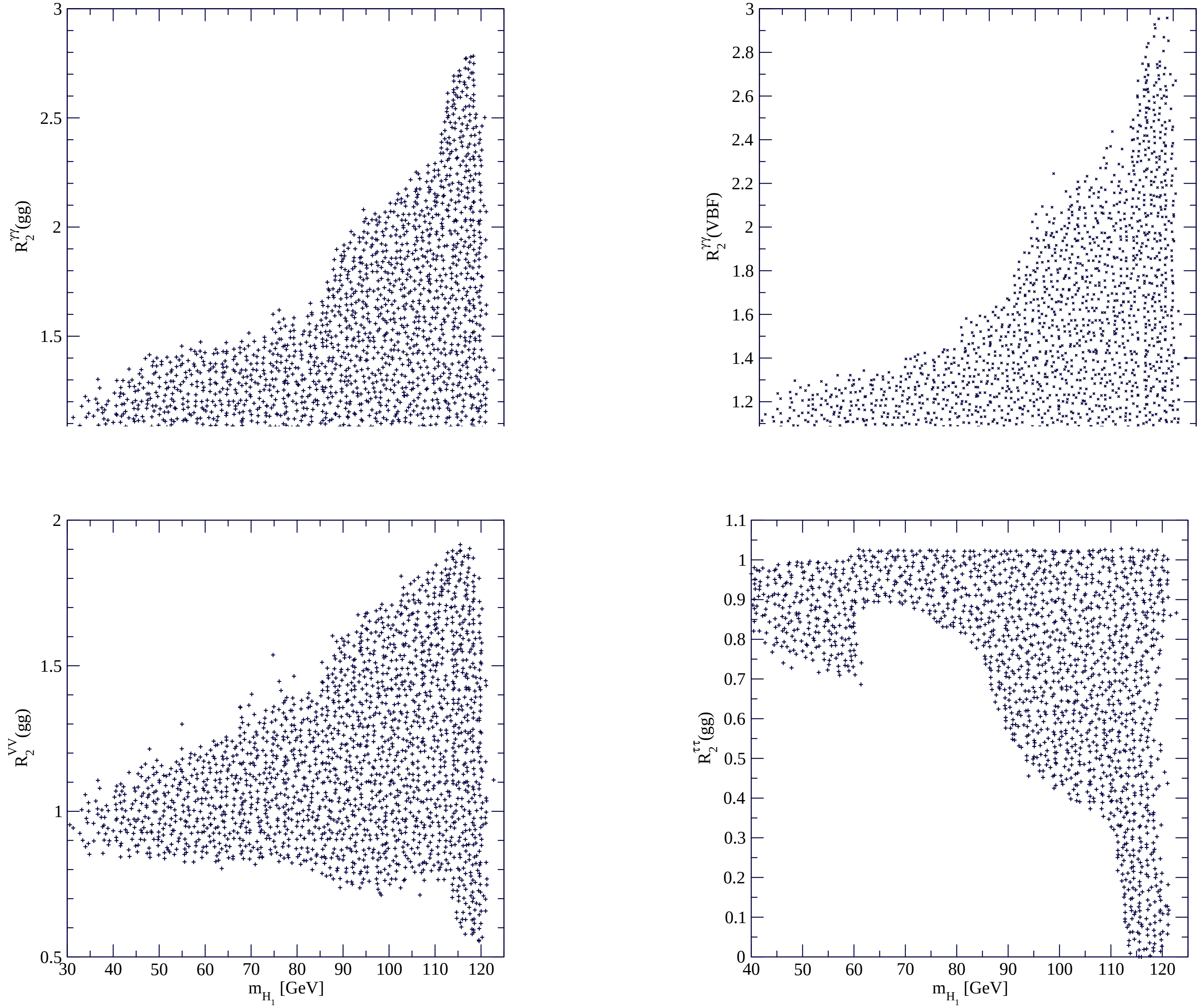


Figure 9: **Reduced signal cross sections R_2 for H_2 with a mass in the $124-127$ GeV range, as a function of M_{H_1} for a representative sample of viable points in parameter space. Upper left: $R_2^{\gamma\gamma}(gg)$ (diphoton channel, H_2 production via gluon fusion), upper right: $R_2^{\gamma\gamma}(VBF)$ (diphoton channel, H_2 production via VBF), lower left: $R_2^{VV}(gg)$ (ZZ, WW channels, H_2 production via gluon fusion), lower right: $R_2^{\tau\tau}(VBF)$ ($\tau\,\tau$ channel, H_2 production via VBF).**

- **Associated production VH_2 with H_2 can be significant as required by Tevatron data. $R_2^{b\bar b}(VH) > .7$ requires $R_2^{\gamma\gamma}(gg) < 2$.**

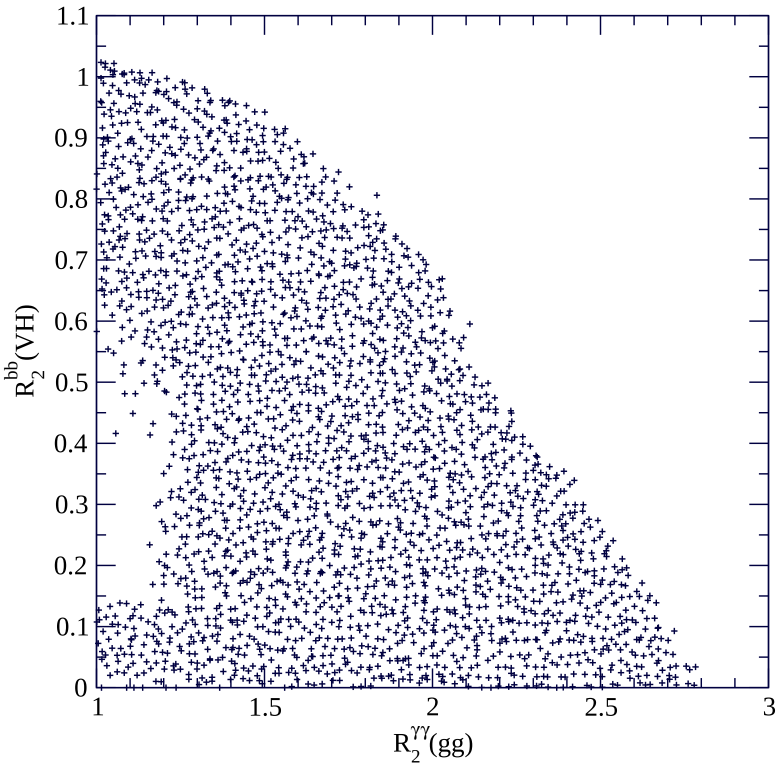


Figure 10: $R_2^{b\bar b}(VH)$ ($W/Z + H_2$ with $H_2 \to b\bar b$) as a function of $R_2^{\gamma\gamma}(gg)$.

- **Strong couplings at the GUT scale is probably a generic way in which to get enhancements, see, e.g., $\lambda - SUSY$ and perhaps other models. What should we trust? Ultimately, experiment may dictate.**

- **SUSY masses can be smaller than cases with $\lambda_{\rm GUT} < 1$.**

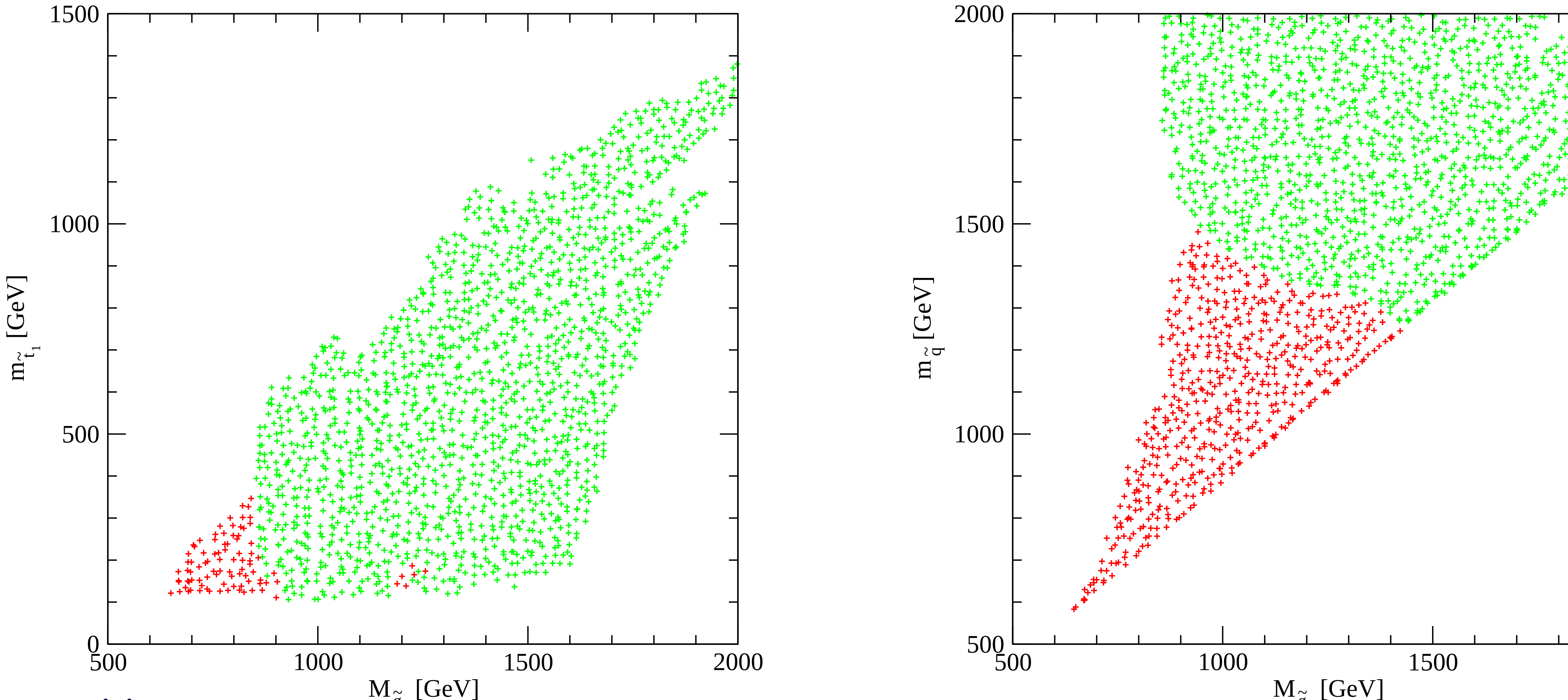


Figure 11: $m_{\tilde{t}_1}$ **(left panel) and** $m_{\tilde{q}}$ **(right panel) as a function of** $M_{\tilde{g}}$**. Points in red (darker points) satisfy the LEP/Tevatron bounds, but not the CMSSM type LHC bounds, while points in green (brighter) satisfy both constraints.**

In addition, $m_{LSP} \in [60, 80]$ GeV and is typically mainly higgsino-like but has reduced σ^{si} due to sizable singlino component.

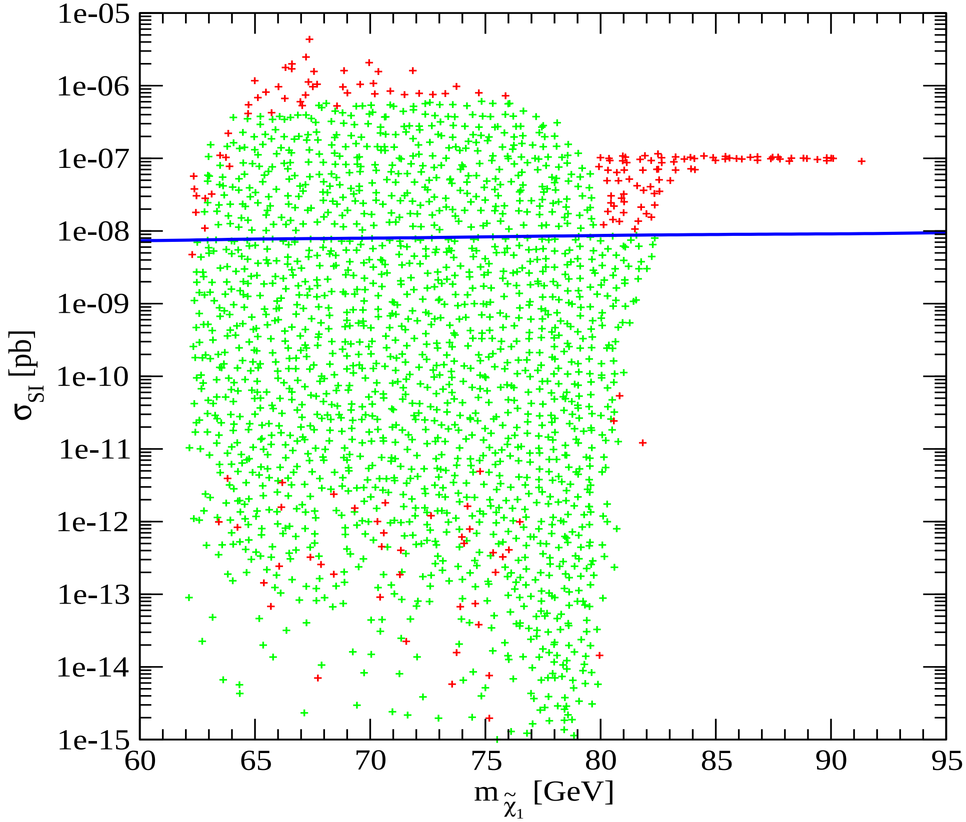


Figure 12: **The spin-independent neutralino-proton scattering cross section $\sigma^{si}(p)$ as a function of $M_{\chi_1^0}$. The blue line indicates the bound from XENON100, and we have added points violating this bound (but respecting all the others). The color code is as in Figs. 11.**

pNMSSM

- **Like the pMSSM, this the model in which all (independent) GUT scale parameters are allowed to very freely.**
- **No time for details, but just some highlights.**
  1. **Can once again get enhanced $\gamma\gamma$ signal for the h_2 (Ellwanger [6]):**
     This occurs at large λ and arises due to the suppression of the $\mathrm{BR}(h_2 \to b\bar{b})$ which is in turn due to singlet-doublet Higgs mixing (which also aids in getting m_{h_2} into the LHC mass region via level-crossing "repulsion") while keeping the $h_2 t\bar{t}$ coupling sufficient for the t loop contribution to $gg \to h_2$ not very suppressed.
  2. **Sparticle masses can be very modest in the pNMSSM.**
     In particular, parameters can be chosen so that the LSP is very light (usually singlino, but bino possible), in particular in the CoGENT/DAMA type mass region with the required σ_{SI}. However, the $m_{LSP} < 15~\mathrm{GeV}$ constraint makes it impossible to achieve the observed enhancement

$R_{gg}^{h_1,h_2}(\gamma\gamma) > 1$ for either the h_1 or h_2 (Vasquez, Belanger et.al.[58]).

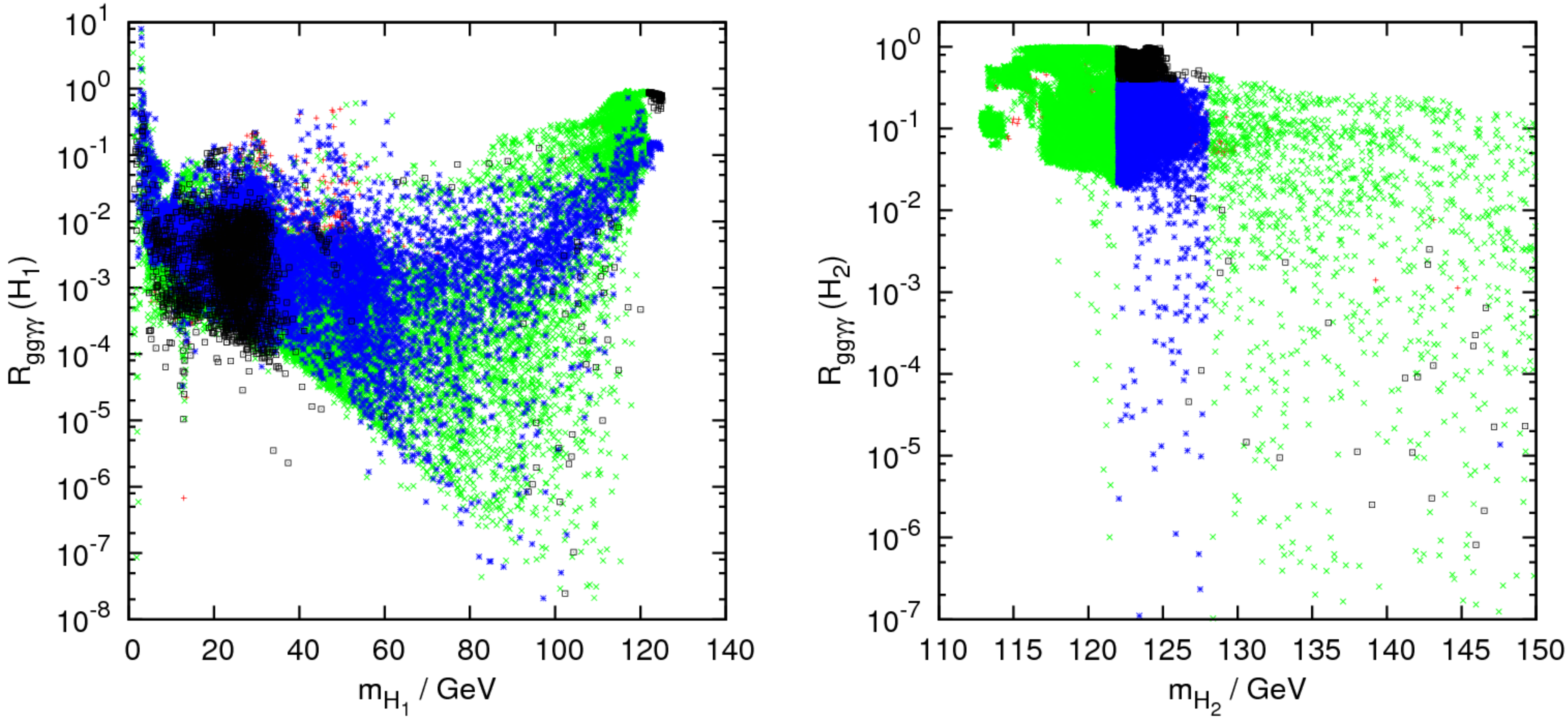


Figure 13: $R_{gg\gamma\gamma}$ as a function of the mass of H_1 (left panel) and of H_2 (the more usual candidate; right panel) in the light neutralino LSP model. Red points are ruled out either by 'HiggsBounds' constraints or the ATLAS $1~\text{fb}^{-1}$ jets and missing E_T SUSY search. Green points have no Higgs with a mass in $122-128$ GeV, blue points have a Higgs (H_1 and/or H_2) within this mass range, and black points have such a Higgs with $R_{gg\gamma\gamma} > 0.4$.

In the light LSP scenario, relic abundance is often achieved via pole annihilation using h_1 or a_1.

3. To get $R^{h_1}_{gg}(\gamma\gamma) > 1$ or $R^{h_2}_{gg}(\gamma\gamma) > 1$, it seems that it is necessary to have substantial LSP mass.

Extra dimensions and Higgs-radion Mixing

- **Aside from SUSY, 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 $\mathbf{2}$ or more scalar eigenstates, as might end up being required, e.g. to fit $\mathbf{125}$ GeV and $\mathbf{137}$ GeV excesses.**

- **The background RS metric that solves Einstein's equations takes the form (Randall, Sundrum [7])**

$$ds^2 = e^{-2m_0 b_0 |y|} \eta_{\mu\nu} dx^\mu dx^\nu - b_0^2 dy^2 \tag{7}$$

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:

$$v_0 = \Omega_0 \widehat{v} = e^{-\frac{1}{2} m_0 b_0} \widehat{v} \sim 1 \text{ TeV} \quad \text{for} \quad \frac{1}{2} m_0 b_0 \sim 35 \,. \tag{8}$$

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

- 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. m_0/m_{Pl} up to ~ 2 is now viewed as ok. (Agashe et.al. [14][15])

- 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 [8][9][10][11][12][13][14][15].

  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 (Goertz, Neubert et.al. [50]) for alternative.

- Since the radion and Higgs fields have the same quantum numbers, they can mix.(Giudice, Wells [23])

$$S_{\xi} = \xi \int d^4x \sqrt{g_{\rm vis}} R(g_{\rm vis}) \widehat{H}^{\dagger} \widehat{H} \,, \tag{9}$$

  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 (Dominici et.al [16]) (see also (Giudice et.al [23]) (Hewett et.al [24])).

- 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 $1.5\ \mathrm{TeV}$ from CMS data.

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

$$\frac{m_0}{m_{Pl}} \simeq \frac{m_1^g}{\Lambda_\phi} \tag{10}$$

$\Rightarrow$ For small m_0/m_{Pl}, Λ_ϕ is large, i.e. only solve hierarchy for $m_0/m_{Pl} \gtrsim 0.2$.

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

- In Fig. 14: $m_0/m_{Pl} = 0.5$ and $\xi = 0.12 \Rightarrow$

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

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

consistent within 1σ with the CMS observations.

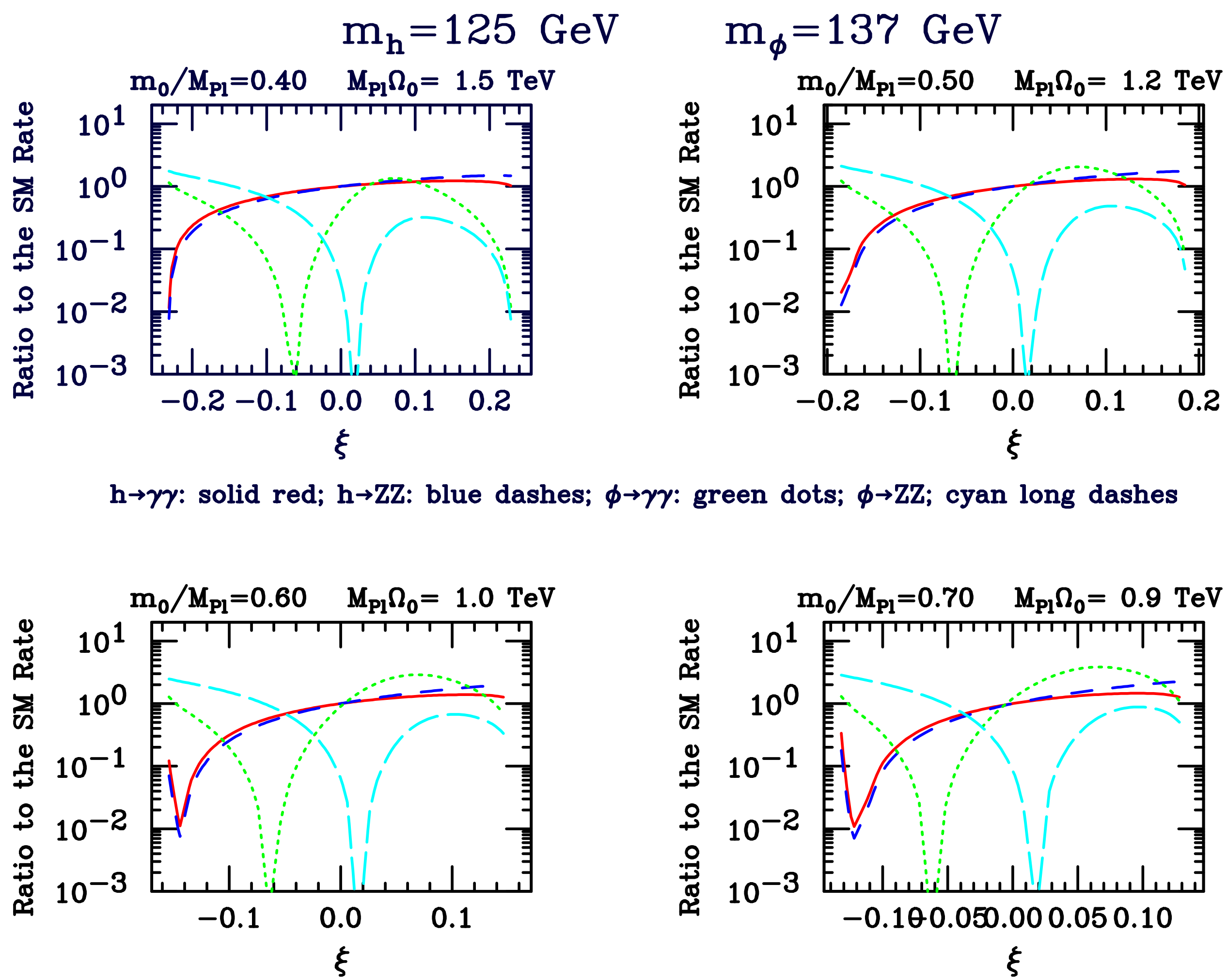


Figure 14: **We plot $\gamma\gamma$ and ZZ relative to SM vs ξ taking $m_1^g = 1.5$ TeV.**

- **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.**

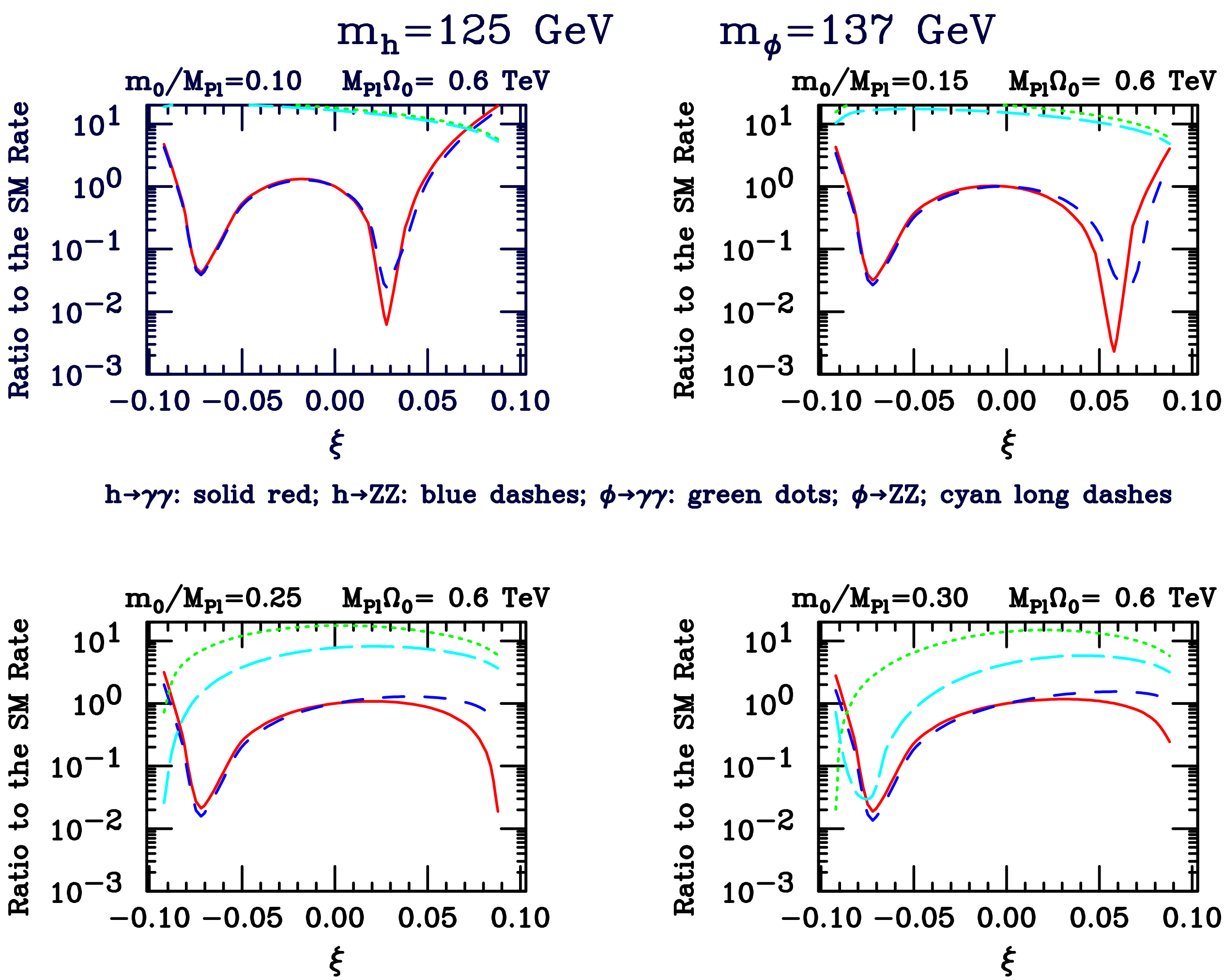


Figure 15: **We plot $\gamma\gamma$ and ZZ rates relative to SM vs ξ taking Λ_ϕ fixed at 1.5 TeV.**

- **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. 16 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 modest $m_0/m_{Pl} = 0.3$ and $\Lambda_\phi \sim 2.8$ TeV — all other channels have very small signals.**

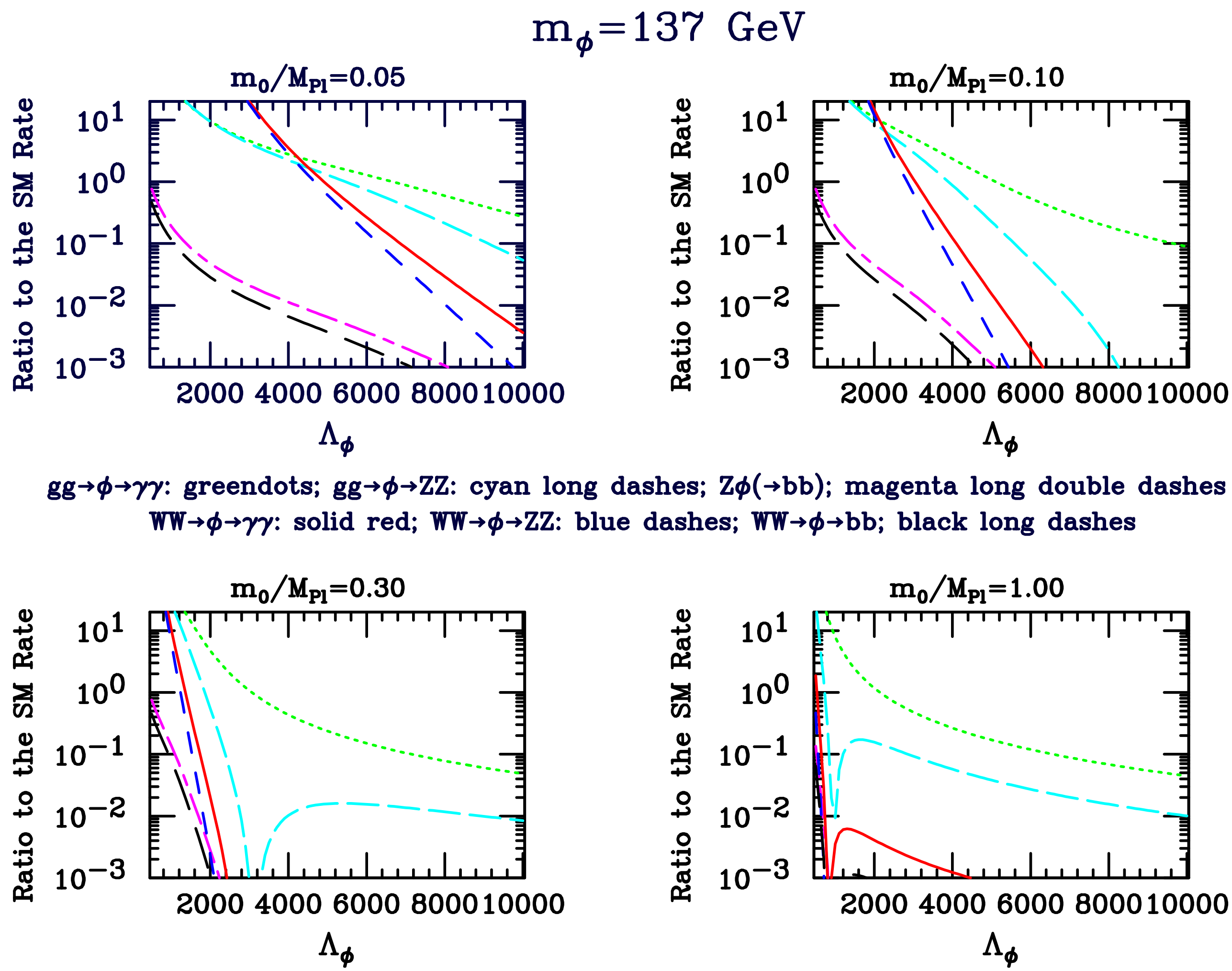


Figure 16: We plot $gg \to \phi \to \gamma\gamma$ and ZZ rates relative to SM vs Λ_ϕ taking $\xi = 0$. Also shown: $Z\phi$ with $\phi \to b\bar{b}$ and WW fusion rates of $\gamma\gamma$, ZZ and $b\bar{b}$.

- (Goertz, Neubert et.al. [50]) give h_0 results for "democratic" Yukawas.

  This differs from previous $Y_2 \ll Y_1$ model in that quark KK excitations can contribute in the $gg \to h_0$ and $h_0 \to \gamma\gamma$ loops

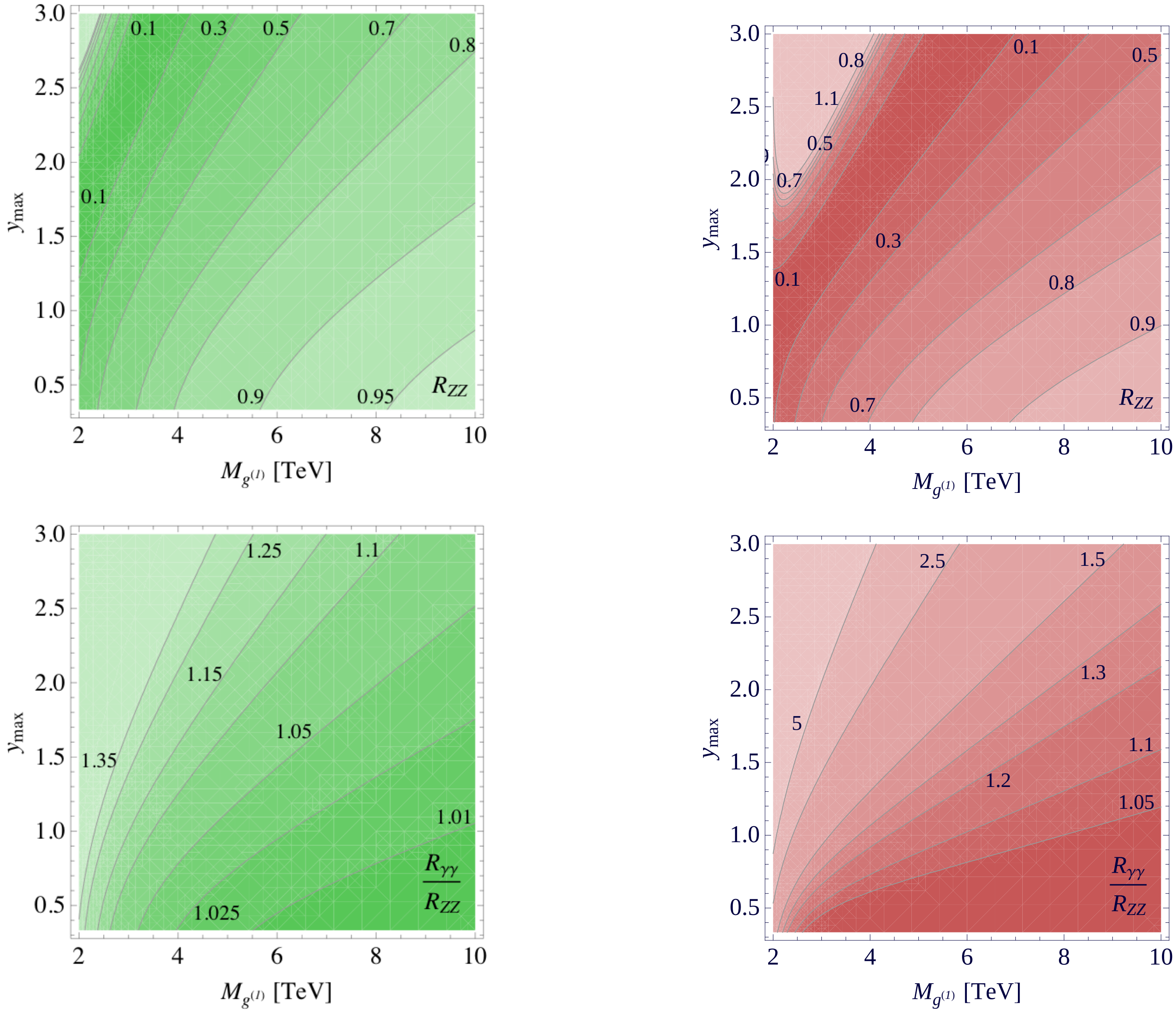
  They consider two models:

  the minimal $SU(2)_L \times U(1)_Y$ RS model: mRS;

  the custodial RS model with $SU(2)_L \times SU(2)_R \times U(1)_X \times P_{LR}$ symmetry in the bulk: cRS.

  Results: plot in space of m_1^g and $y^{\max}$ (mass of 1st gluon excitation and size of "typical" bulk Yukawa coupling).

Figure 17: Minimal RS vs. Custodial RS.



1. **At 125 GeV, mRS always gives suppressed $gg \to h_0 \to ZZ$ signal except in limit of large m_1^g; this is also true for the cRS model except that there is an enhanced region at high $y^{\max}$ and small m_1^g.**
2. **For $gg \to h_0 \to \gamma\gamma$ (the product of upper times lower plot) one finds mostly suppression for mRS and for cRS on finds at best modest enhancement — only at high $y^{\max}$ and small m_1^g is large enhancement predicted.**

Randall Sundrum + SUSY

Why both?, see (Gherghetta et.al. [52]).

- As noted earlier, the approach of avoiding hierarchies in the Yukawas by using fermion profiles, to get fermion masses and good PEW, FCNC etc. is called anarchic or democratic couplings for the Yukawas in the 5D space.

- However, with anarchic couplings, CP-violating processes mediated by Kaluza-Klein (KK) modes are in excess of experimental bounds unless the IR scale is at least $\mathcal{O}(10~\mathrm{TeV})$, see e.g. (Agashe et.al [53]).

- Although this bound can be avoided with additional structure (such as flavour symmetries, see e.g. (flavor symmetries references [56])), electroweak precision tests still require an IR scale larger than the electroweak scale.

- To obtain the correct Z-boson mass, some tuning is needed. This is a manifestation of the little hierarchy problem that also plagues other solutions to the gauge hierarchy problem.

- A well-known way to protect the Higgs from radiative corrections is supersymmetry (SUSY).

  Usually, it is supposed to stabilize the entire hierarchy between the electroweak and the Planck scale.

  In RS+SUSY the idea is that SUSY protects the Higgs only up to $\mathcal{O}(10\,\mathrm{TeV})$ and that warping (or compositeness in the dual picture) is responsible for the remaining hierarchy up to the Planck scale.

- For this purpose, a reduced form of SUSY is sufficient.

  Since the Higgs in warped models is localized near the IR brane, loops are cut off at a warped-down scale Λ_{IR}.

  The one-loop correction to the Higgs mass due to a quark is

$$\Delta m_H^2 = -\frac{3}{8\pi^2}\, y_q^2\, \Lambda_{\mathrm{IR}}^2 \sim -(10\, m_q)^2, \tag{11}$$

where y_q is the Yukawa coupling and m_q the mass of the quark. In the last step, we have assumed that $\Lambda_{\rm IR} = \mathcal{O}(10~\mathrm{TeV})$ and $\tan\beta = \mathcal{O}(1)$.

In this case, only the top loop correction is in excess of the electroweak scale and stops are the only light superpartners required to protect the Higgs from the quark sector.

Similarly, no lepton superpartners have to be light (or even present at all).

Gauge bosons and the Higgs itself, on the other hand, lead to sizeable corrections whose cancellation requires light gauginos and Higgsinos.

This reduced spectrum of superpartners is all that is needed to protect the Higgs up to $\mathcal{O}(10~\mathrm{TeV})$.

This is similar in spirit to Little Higgs models except that this warped model provides a UV completion for energies above $10~\mathrm{TeV}$.

- The end result is that you have the Higg+radion phenomenology (appropriate to anarchic Yukawas) but with reduced warping factor, plus a minimal form of SUSY.

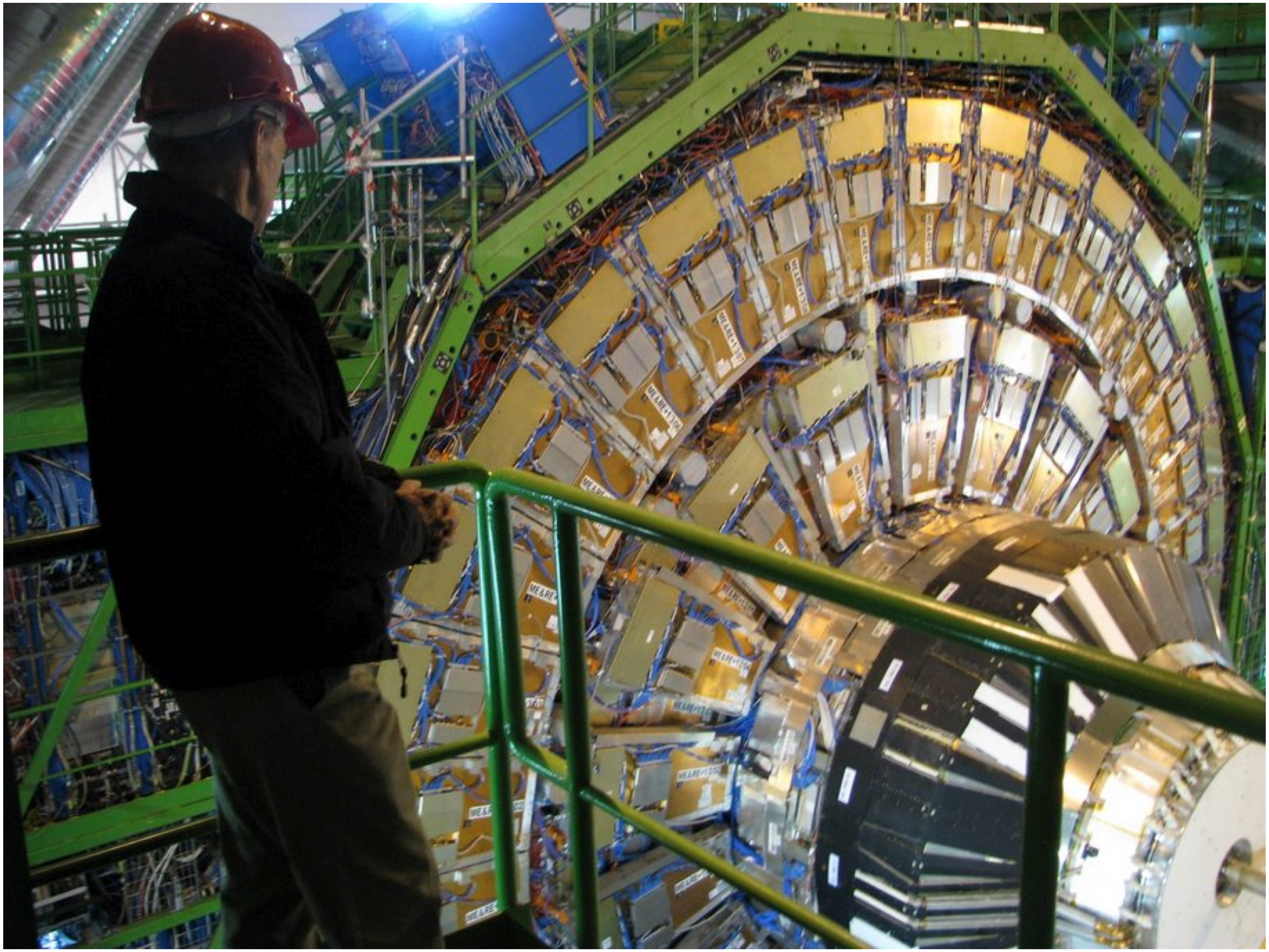
Conclusions

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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