

# Multiple Higgs models and the 125 GeV state: an NMSSM perspective

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36th Johns Hopkins Workshop, GGI, Oct. 16-19, 2012

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1. “*Higgs Bosons at 98 and 125 GeV at LEP and the LHC*” G. Belanger, U. Ellwanger, J. F. Gunion, Y. Jiang, S. Kraml and J. H. Schwarz. arXiv:1210.1976 [hep-ph]
2. “*Two Higgs Bosons at the Tevatron and the LHC?*” G. Belanger, U. Ellwanger, J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1208.4952 [hep-ph]
3. “*Diagnosing Degenerate Higgs Bosons at 125 GeV*” J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1208.1817 [hep-ph]
4. “*Could two NMSSM Higgs bosons be present near 125 GeV?*” J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1207.1545 [hep-ph]
5. “*The Constrained NMSSM and Higgs near 125 GeV*” J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1201.0982 [hep-ph] Phys. Lett. B **710**, 454 (2012)

# Higgs-like LHC Excesses at 125 GeV

- **Experimental Higgs-like excesses: define**

$$R_Y^h(X) = \frac{\sigma(pp \rightarrow Y \rightarrow h) \text{BR}(h \rightarrow X)}{\sigma(pp \rightarrow Y \rightarrow h_{SM}) \text{BR}(h_{SM} \rightarrow X)}, \quad R^h(X) = \sum_Y R_Y^h, \quad (1)$$

where  $Y = gg$  or  $WW$ .

**Table 1: Summary of status for 125 GeV as of a few months ago — not important to get exact**

$R(X), X =$	$\gamma\gamma$	$4\ell$	$l\nu l\nu$	$b\bar{b}$	$\tau^+\tau^-$
<b>ATLAS</b>	$\sim 1.9 \pm 0.5$	$\sim 1.1 \pm 0.6$	$0.5 \pm 0.6$	$0.5 \pm 2.3$	$0.4 \pm 2.0$
<b>CMS</b>	$\sim 1.6 \pm 0.6$	$\sim 0.7 \pm 0.3$	$0.6 \pm 0.5$	$0.1 \pm 0.7$	$\sim 0 \pm 0.8$

In addition, we have

$$R_{WW}^{\text{ATLAS}}(\gamma\gamma) = 2.5 \pm 1.2 \quad R_{WW}^{\text{CMS}}(\gamma\gamma) = 2.3 \pm 1.3 \quad (2)$$

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

$$R_{Vh}^{\text{CMS}}(b\bar{b}) = 0.5 \pm 0.6, \quad R_{Vh}^{\text{ATLAS}}(b\bar{b}) \sim 0.5 \pm 2.0, \quad R_{Vh}^{\text{Tev}}(b\bar{b}) \sim 1.8 \pm 1, \quad (3)$$

all being very crude estimates.

Note:  $R(WW) < 1$  would imply  $gg \rightarrow h < \text{SM}$ , but  $WW$  signal is diffuse and I will choose to mainly 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 a number of amusing possibilities in the NMSSM.

# 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 ( $\lambda$  and  $\kappa$ ) and scalar potential ( $A_\lambda$  and  $A_\kappa$ ) appear as:

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

- $\langle S \rangle \neq 0$  is generated by SUSY breaking and solves  $\mu$  problem:  $\mu_{\text{eff}} = \lambda \langle S \rangle$ .
- First question: Can the NMSSM give a Higgs mass as large as 125 GeV?

Answer: **Yes**, so long as it is not a highly unified model. For our studies, we employed universal  $m_0$ , except for NUHM ( $m_{H_u}^2, m_{H_d}^2, m_S^2$  free), universal  $A_t = A_b = A_\tau = A_0$  but allow  $A_\lambda$  and  $A_\kappa$  to vary freely. Of course,  $\lambda > 0$  and  $\kappa$  are scanned demanding perturbativity up to the GUT scale.

- Can this model achieve rates in  $\gamma\gamma$  and  $4\ell$  that are  $>SM$ ?

Answer: it depends on whether or not we insist on getting good  $a_\mu$ .

- 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  $m_{h_1}$  and  $m_{h_2}$  to have similar masses (for singlet-doublet mixing) and large  $\lambda$  (to enhance Higgs mass).

Large  $\lambda$  (by which we mean  $\lambda > 0.1$ ) is only possible while retaining perturbativity up to  $m_{Pl}$  if  $\tan\beta$  is modest in size.

In the semi-unified model we employ, enhanced rates and/or large  $\lambda$  cannot be made consistent with decent  $\delta a_\mu$ . (J. F. Gunion, Y. Jiang and S. Kraml.arXiv:1201.0982 [hep-ph])

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

$$R_{gg}^{h_i}(X) \equiv (C_{gg}^{h_i})^2 \frac{\text{BR}(h_i \rightarrow X)}{\text{BR}(h_{SM} \rightarrow X)}, \quad R_{\text{VBF}}^{h_i}(X) \equiv (C_{WW}^{h_i})^2 \frac{\text{BR}(h_i \rightarrow X)}{\text{BR}(h_{SM} \rightarrow X)}, \quad (5)$$

where  $h_i$  is the  $i^{\text{th}}$  NMSSM scalar Higgs, and  $h_{SM}$  is the SM Higgs boson. The  $C_Y^{h_i}$  is the ratio of the  $Y \rightarrow h_i$  coupling relative to the  $Y \rightarrow h_{SM}$  coupling.

Note that the corresponding ratio for  $V^* \rightarrow Vh_i$  ( $V = W, Z$ ) with  $h_i \rightarrow X$  is equal to  $R_{\text{VBF}}^{h_i}(X)$  in doublets + singlets models.

Some illustrative  $R_{gg}$  results from (J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1207.1545):

Figure Legend

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

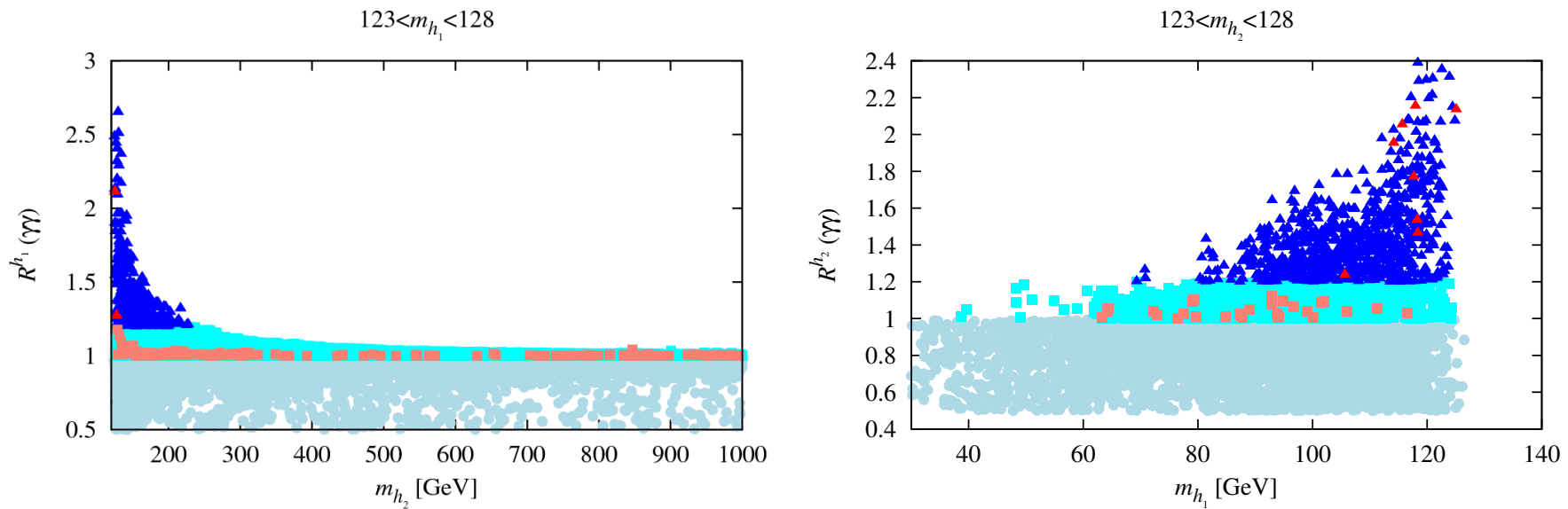
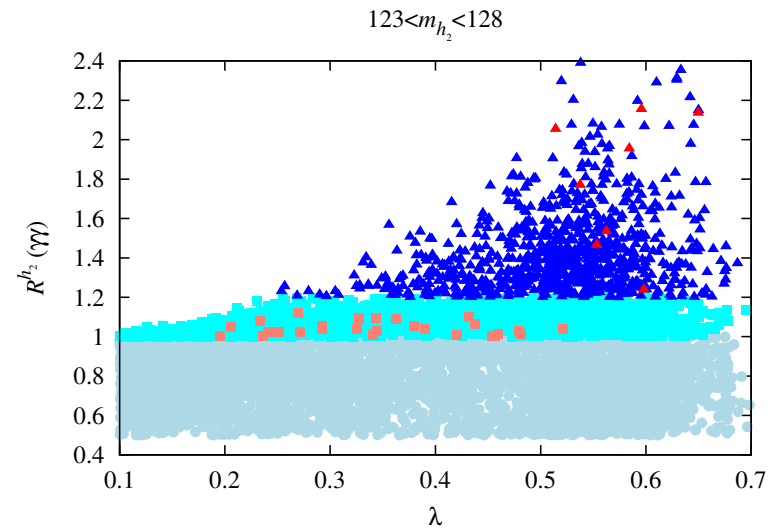
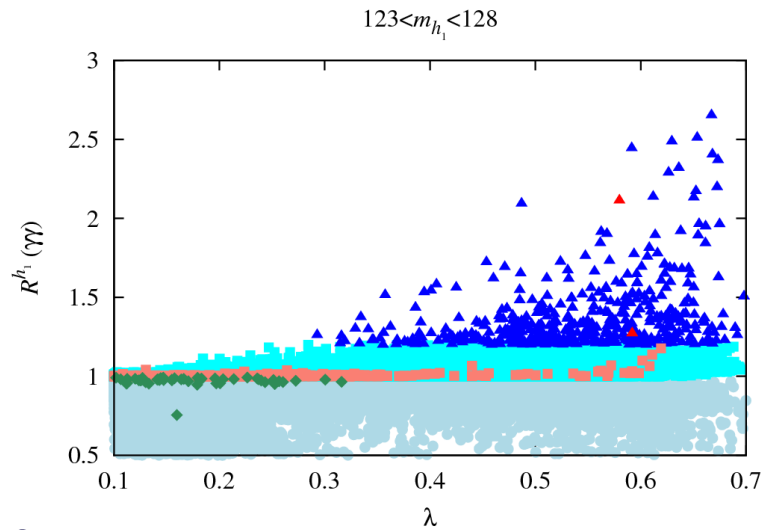
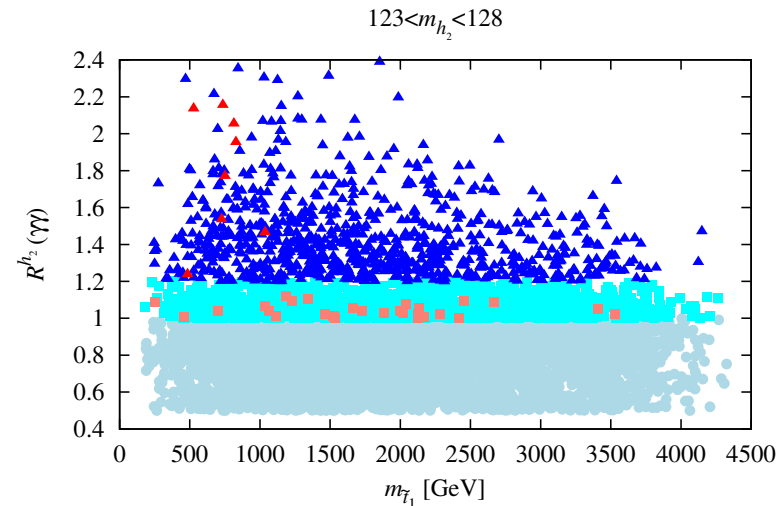
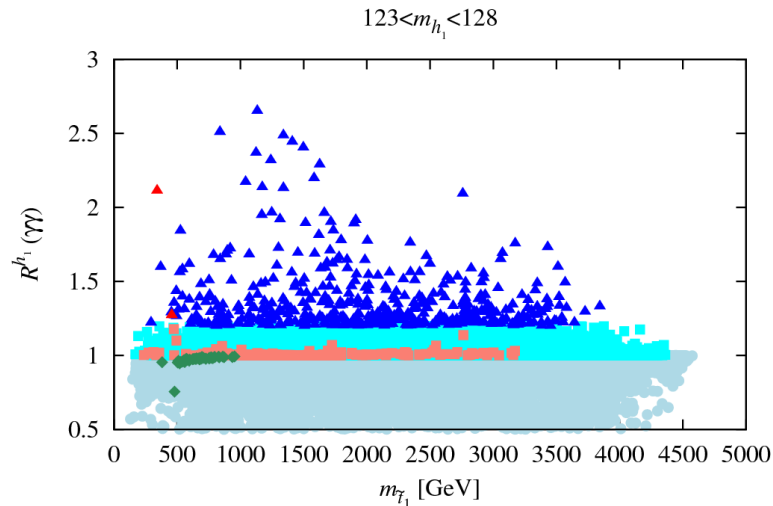


Figure 1: The plot shows  $R_{gg}(\gamma\gamma)$  for the cases of  $123 < m_{h_1} < 128$  GeV and  $123 < m_{h_2} < 128$  GeV.



**Figure 2:** Observe the clear general increase in maximum  $R_{gg}(\gamma\gamma)$  with increasing  $\lambda$ . Green points have good  $\delta a_\mu$ ,  $m_{h_2} > 1$  TeV BUT  $R_{gg}(\gamma\gamma) \sim 1$ .



**Figure 3:** The lightest stop has mass  $\sim 300 - 700$  GeV for red-triangle points.

- If we ignore  $\delta a_\mu$ , then  $R_{gg}(\gamma\gamma) > 1.2$  (even  $> 2$ ) is possible while satisfying all other constraints provided  $h_1$  and  $h_2$  are close in mass, especially in the case where  $m_{h_2} \in [123, 128]$  GeV window.
  - This raises the issue of scenarios in which *both*  $m_{h_1}$  and  $m_{h_2}$  are in the  $[123, 128]$  GeV window where the experiments see the Higgs signal.
  - If  $h_1$  and  $h_2$  are sufficiently degenerate, the experimentalists might not have resolved the two distinct peaks, even in the  $\gamma\gamma$  channel.
  - The rates for the  $h_1$  and  $h_2$  could then add together to give an enhanced  $\gamma\gamma$ , for example, signal.
  - The apparent width or shape of the  $\gamma\gamma$  mass distribution could be altered.
  - There is more room for an apparent mismatch between the  $\gamma\gamma$  channel and other channels, such as  $b\bar{b}$  or  $4\ell$ , than in non-degenerate situation.
- In particular, the  $h_1$  and  $h_2$  will generally have different  $gg$  and  $WW$  production rates and branching ratios.



# Degenerate NMSSM Higgs Scenarios:

(arXiv:1207.1545, JFG, Jiang, Kraml)

- For the numerical analysis, we use NMSSMTools version 3.2.0, which has improved convergence of RGEs in the case of large Yukawa couplings.
- The precise constraints imposed are the following.
  1. Basic constraints: proper RGE solution, no Landau pole, neutralino LSP, Higgs and SUSY mass limits as implemented in NMSSMTools-3.2.0.
  2.  $B$  physics:  $\text{BR}(B_s \rightarrow X_s \gamma)$ ,  $\Delta M_s$ ,  $\Delta M_d$ ,  $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ ,  $\text{BR}(B^+ \rightarrow \tau^+ \nu_\tau)$  and  $\text{BR}(B \rightarrow X_s \mu^+ \mu^-)$  at  $2\sigma$  as encoded in NMSSMTools-3.2.0, plus updates.
  3. Dark Matter:  $\Omega h^2 < 0.136$ , thus allowing for scenarios in which the relic density arises at least in part from some other source.  
However, we single out points with  $0.094 \leq \Omega h^2 \leq 0.136$ , which is the ‘WMAP window’ defined in NMSSMTools-3.2.0.

4. 2011 XENON 100: spin-independent LSP–proton scattering cross section bounds implied by the neutralino-mass-dependent XENON100 bound. (For points with  $\Omega h^2 < 0.094$ , we rescale these bounds by a factor of  $0.11/\Omega h^2$ .) (2012 XENON 100 has little additional impact.)
5.  $\delta a_\mu$  ignored: impossible to satisfy for scenarios we study here.

- Compute the effective Higgs mass in given production and final decay channels  $Y$  and  $X$ , respectively, and  $R_{gg}^h$  as

$$m_h^Y(X) \equiv \frac{R_Y^{h_1}(X)m_{h_1} + R_Y^{h_2}(X)m_{h_2}}{R_Y^{h_1}(X) + R_Y^{h_2}(X)} \quad R_Y^h(X) = R_Y^{h_1}(X) + R_Y^{h_2}(X). \quad (6)$$

- The extent to which it is appropriate to combine the rates from the  $h_1$  and  $h_2$  depends upon the degree of degeneracy and the experimental resolution.

Very roughly, one should probably think of  $\sigma_{\text{res}} \sim 1.5$  GeV or larger. **The widths of the  $h_1$  and  $h_2$  are very much smaller than this resolution.**

- We perform scans covering the following parameter ranges:

$$\begin{aligned}
0 \leq m_0 \leq 3000; & \quad 100 \leq m_{1/2} \leq 3000; & \quad 1 \leq \tan \beta \leq 40; \\
-6000 \leq A_0 \leq 6000; & \quad 0.1 \leq \lambda \leq 0.7; & \quad 0.05 \leq \kappa \leq 0.5; \\
-1000 \leq A_\lambda \leq 1000; & \quad -1000 \leq A_\kappa \leq 1000; & \quad 100 \leq \mu_{eff} \leq 500.
\end{aligned} \quad (7)$$

We only display points which pass the basic constraints, satisfy  $B$ -physics constraints, have  $\Omega h^2 < 0.136$ , obey the 2011 XENON100 limit on the LSP scattering cross-section off protons *and* have both  $h_1$  and  $h_2$  in the desired mass range:  $123 \text{ GeV} < m_{h_1}, m_{h_2} < 128 \text{ GeV}$ .

- In Fig. 4, points are color coded according to  $m_{h_2} - m_{h_1}$ .

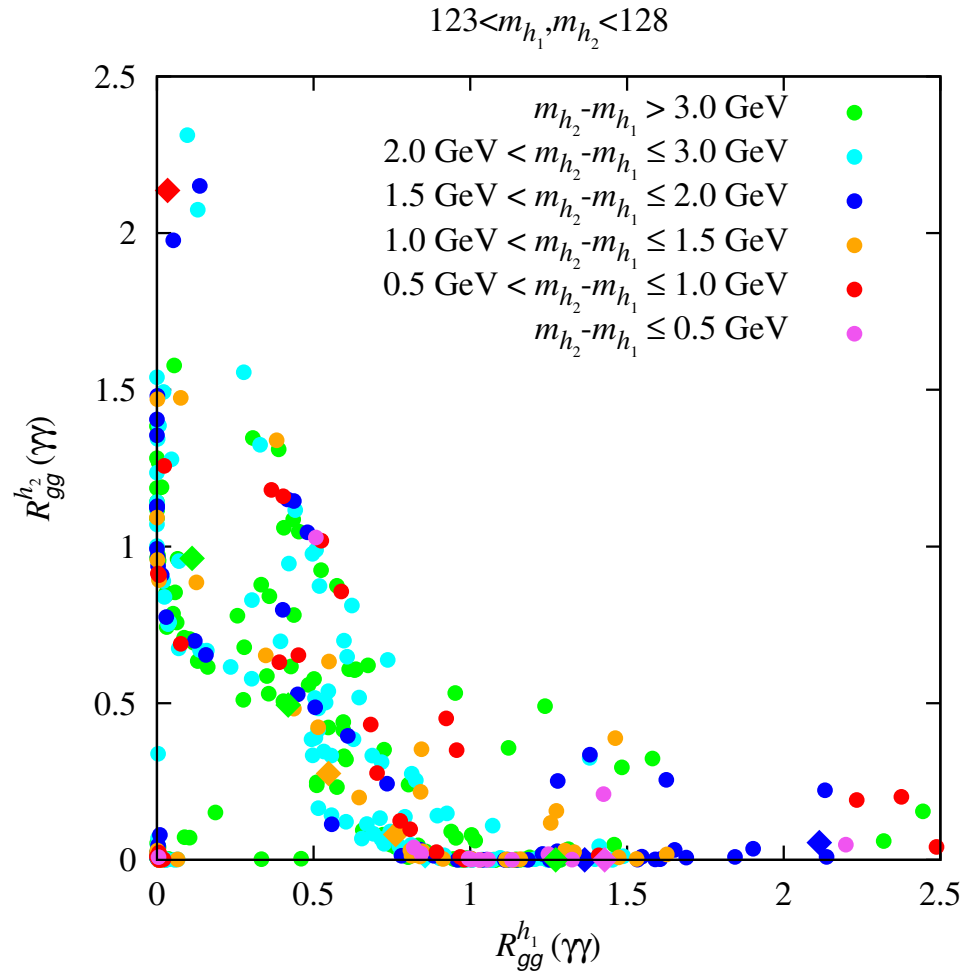
Circular points have  $\Omega h^2 < 0.094$ , while diamond points have  $0.094 \leq \Omega h^2 \leq 0.136$  (*i.e.* lie within the WMAP window).

- Many of the displayed points are such that  $R_{gg}^{h_1}(\gamma\gamma) + R_{gg}^{h_2}(\gamma\gamma) > 1$ .

- A few such points have  $\Omega h^2$  in the WMAP window.

These points are such that either  $R_{gg}^{h_1}(\gamma\gamma) > 2$  or  $R_{gg}^{h_2}(\gamma\gamma) > 2$ , with the  $R$  for the other Higgs being small. Scanning is continuing.

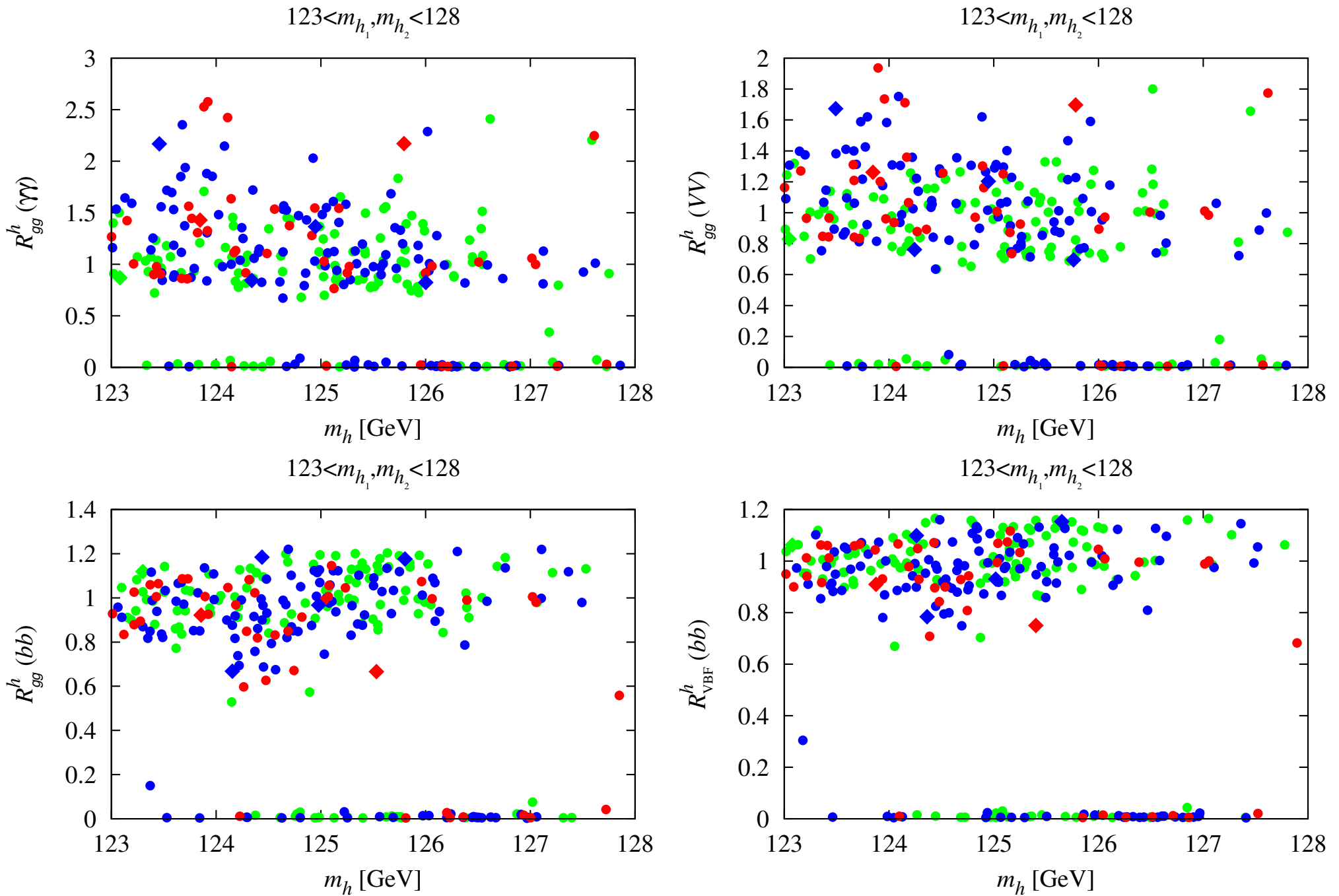
- However, the majority of the points with  $R_{gg}^{h_1}(\gamma\gamma) + R_{gg}^{h_2}(\gamma\gamma) > 1$  have  $\Omega h^2 < 0.094$  and the  $\gamma\gamma$  signal is often shared between the  $h_1$  and the  $h_2$ .



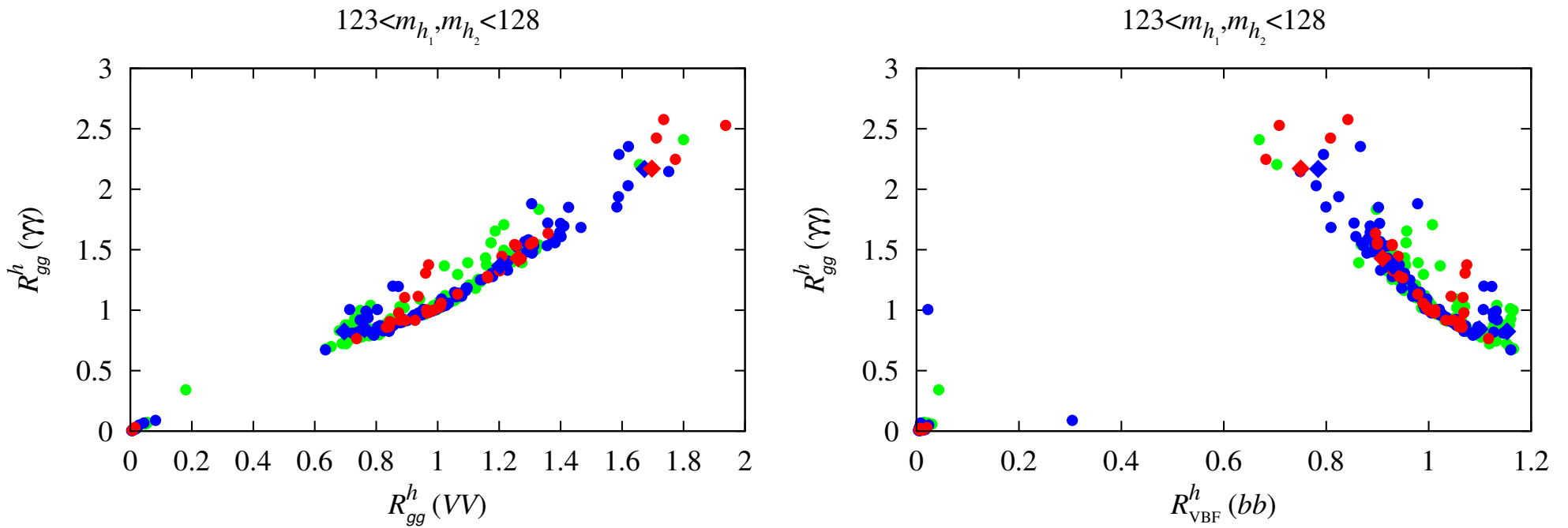
**Figure 4:** Correlation of  $gg \rightarrow (h_1, h_2) \rightarrow \gamma\gamma$  signal strengths when both  $h_1$  and  $h_2$  lie in the 123–128 GeV mass range. The circular points have  $\Omega h^2 < 0.094$ , while diamond points have  $0.094 \leq \Omega h^2 \leq 0.136$ . Points are color coded according to  $m_{h_2} - m_{h_1}$ .

Now combine the  $h_1$  and  $h_2$  signals as described above. Recall: circular (diamond) points have  $\Omega h^2 < 0.094$  ( $0.094 \leq \Omega h^2 \leq 0.136$ ). Color code:

1. red for  $m_{h_2} - m_{h_1} \leq 1$  GeV;
  2. blue for  $1 \text{ GeV} < m_{h_2} - m_{h_1} \leq 2$  GeV;
  3. green for  $2 \text{ GeV} < m_{h_2} - m_{h_1} \leq 3$  GeV.
- For current statistics and  $\sigma_{\text{res}} \gtrsim 1.5$  GeV we estimate that the  $h_1$  and  $h_2$  signals will not be seen separately for  $m_{h_2} - m_{h_1} \leq 2$  GeV.
  - In Fig. 5, we show results for  $R_{gg}^h(X)$  for  $X = \gamma\gamma, VV, b\bar{b}$ . Enhanced  $\gamma\gamma$  and  $VV$  rates from gluon fusion are very common.
  - The bottom-right plot shows that enhancement in the  $Wh$  with  $h \rightarrow b\bar{b}$  rate is also natural, though not as large as the best fit value suggested by the new Tevatron analysis.
  - Diamond points (*i.e.* those in the WMAP window) are rare, but typically show enhanced rates.



**Figure 5:**  $R_{gg}^h(X)$  for  $X = \gamma\gamma, VV, b\bar{b}$ , and  $R_{VBF}^h(b\bar{b})$  versus  $m_h$ . For application to the Tevatron, note that  $R_{VBF}^h(b\bar{b}) = R_{W^* \rightarrow Wh}^h(b\bar{b})$ .



**Figure 6:** Left: correlation between the gluon fusion induced  $\gamma\gamma$  and  $VV$  rates relative to the SM. Right: correlation between the gluon fusion induced  $\gamma\gamma$  rate and the  $WW$  fusion induced  $b\bar{b}$  rates relative to the SM; the relative rate for  $W^* \rightarrow Wh$  with  $h \rightarrow b\bar{b}$  (relevant for the Tevatron) is equal to the latter.

- **Comments on Fig. 6:**

1. Left-hand plot shows the strong correlation between  $R_{gg}^h(\gamma\gamma)$  and  $R_{gg}^h(VV)$ .

Note that if  $R_{gg}^h(\gamma\gamma) \sim 1.5$ , as suggested by current experimental results, then in this model  $R_{gg}^h(VV) \geq 1.2$ .

2. The right-hand plot shows the (anti) correlation between  $R_{gg}^h(\gamma\gamma)$  and  $R_{W^* \rightarrow Wh}^h(b\bar{b}) = R_{VBF}^h(b\bar{b})$ .

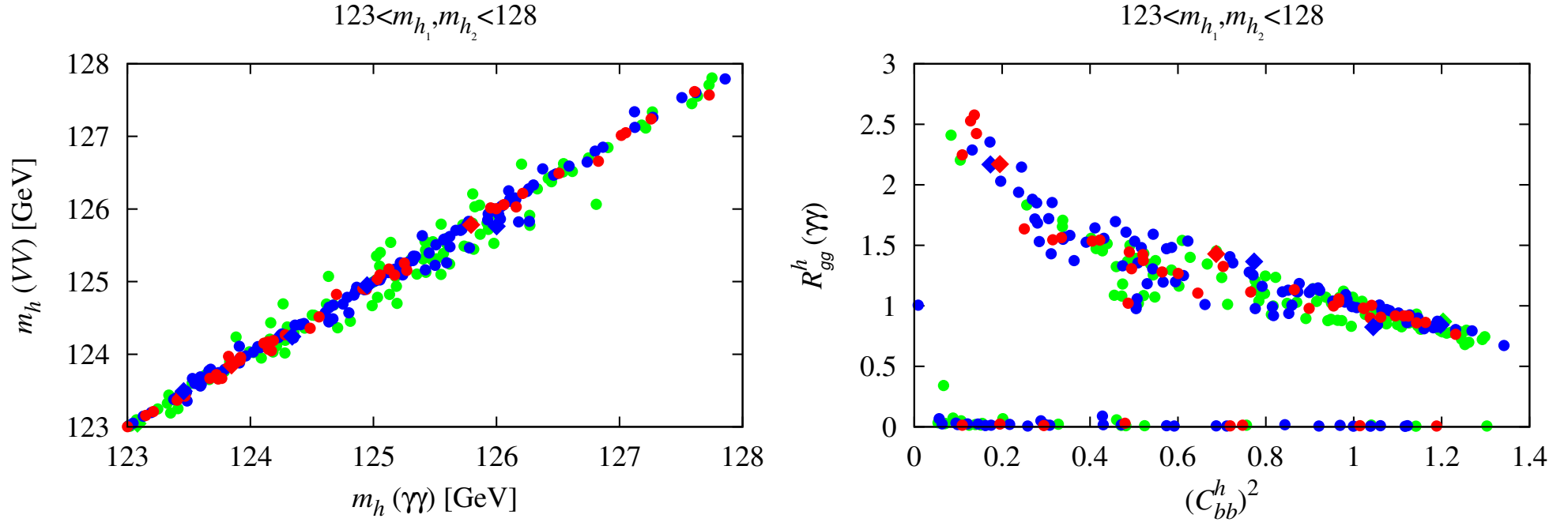
In general, the larger  $R_{gg}^h(\gamma\gamma)$  is, the smaller the value of  $R_{W^* \rightarrow Wh}^h(b\bar{b})$ . However, this latter plot shows that there *are* parameter choices for which both the  $\gamma\gamma$  rate at the LHC and the  $W^* \rightarrow Wh(\rightarrow b\bar{b})$  rate at the Tevatron (and LHC) can be enhanced relative to the SM as a result of there being contributions to these rates from both the  $h_1$  and  $h_2$ .

3. It is often the case that one of the  $h_1$  or  $h_2$  dominates  $R_{gg}^h(\gamma\gamma)$  while the other dominates  $R_{W^* \rightarrow Wh}^h(b\bar{b})$ . This is typical of the diamond WMAP-window points.

However, a significant number of the circular  $\Omega h^2 < 0.094$  points are such that either the  $\gamma\gamma$  or the  $b\bar{b}$  signal receives substantial contributions from both the  $h_1$  and the  $h_2$ .

We did not find points where the  $\gamma\gamma$  and  $b\bar{b}$  final states *both* receive substantial contributions from *both* the  $h_1$  and  $h_2$ .





**Figure 7:** Left: effective Higgs masses obtained from different channels:  $m_h^{gg}(\gamma\gamma)$  versus  $m_h^{gg}(VV)$ . Right:  $\gamma\gamma$  signal strength  $R_{gg}^h(\gamma\gamma)$  versus effective coupling to  $b\bar{b}$  quarks  $(C_{bb}^h)^2$ . Here,  $C_{bb}^h{}^2 \equiv [R_{gg}^{h_1}(\gamma\gamma)C_{bb}^{h_1}{}^2 + R_{gg}^{h_2}(\gamma\gamma)C_{bb}^{h_2}{}^2] / [R_{gg}^{h_1}(\gamma\gamma) + R_{gg}^{h_2}(\gamma\gamma)]$ .

### Comments on Fig. 7

1. The  $m_h$  values for the gluon fusion induced  $\gamma\gamma$  and  $VV$  cases are also strongly correlated — in fact, they differ by no more than a fraction of a

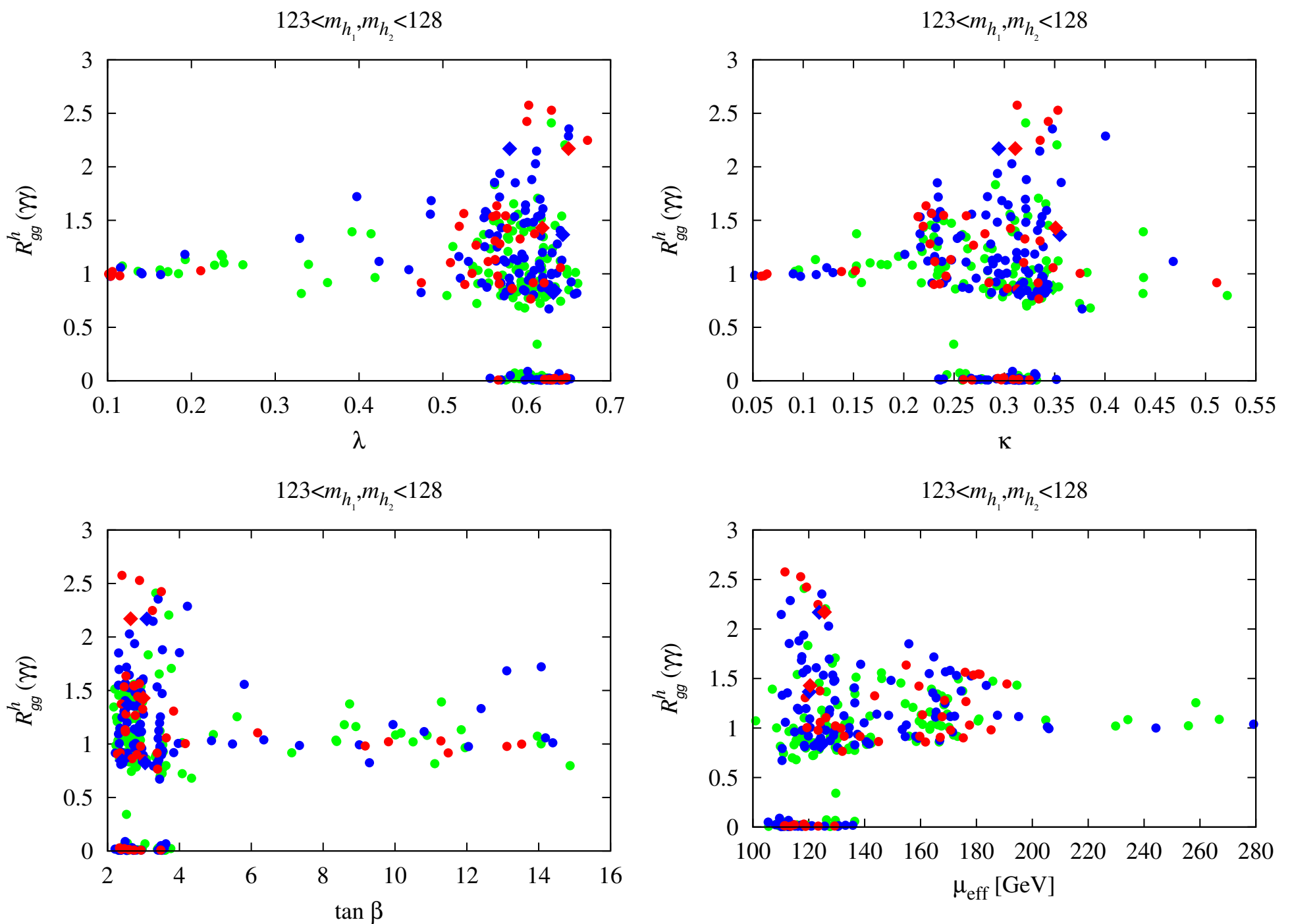
GeV and are most often much closer, see the left plot of Fig. 7.

2. The right plot of Fig. 7 illustrates the mechanism behind enhanced rates, namely that large net  $\gamma\gamma$  branching ratio is achieved by reducing the average total width by reducing the average  $b\bar{b}$  coupling strength.

- The dependence of  $R_{gg}^h(\gamma\gamma)$  on  $\lambda$ ,  $\kappa$ ,  $\tan\beta$  and  $\mu_{\text{eff}}$  is illustrated in Fig. 8.

We observe that the largest  $R_{gg}^h(\gamma\gamma)$  values arise at large  $\lambda$ , moderate  $\kappa$ , small  $\tan\beta < 5$  (but note that  $R_{gg}^h(\gamma\gamma) > 1.5$  is possible even for  $\tan\beta = 15$ ) and small  $\mu_{\text{eff}} < 150$  GeV.

Such low values of  $\mu_{\text{eff}}$  are very favorable in point of view of fine-tuning, in particular if stops are also light.



**Figure 8:** Dependence of  $R_{gg}^h(\gamma\gamma)$  on  $\lambda$ ,  $\kappa$ ,  $\tan \beta$  and  $\mu_{\text{eff}}$ .

Fig. 9 shows that the stop mixing is typically large in these cases,  $(A_t - \mu_{\text{eff}} \cot \beta) / M_{\text{SUSY}} \approx 1.5\text{--}2$ . Moreover, the few points which we found in the WMAP window always have  $m_{\tilde{t}_1} < 700$  GeV.

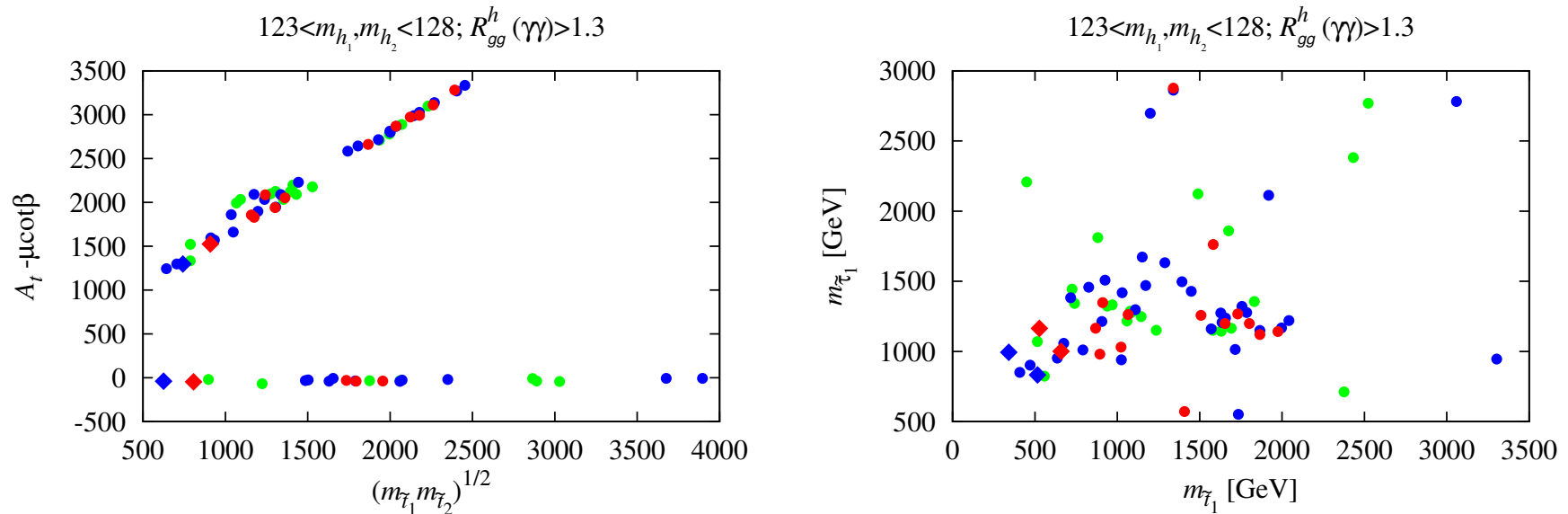
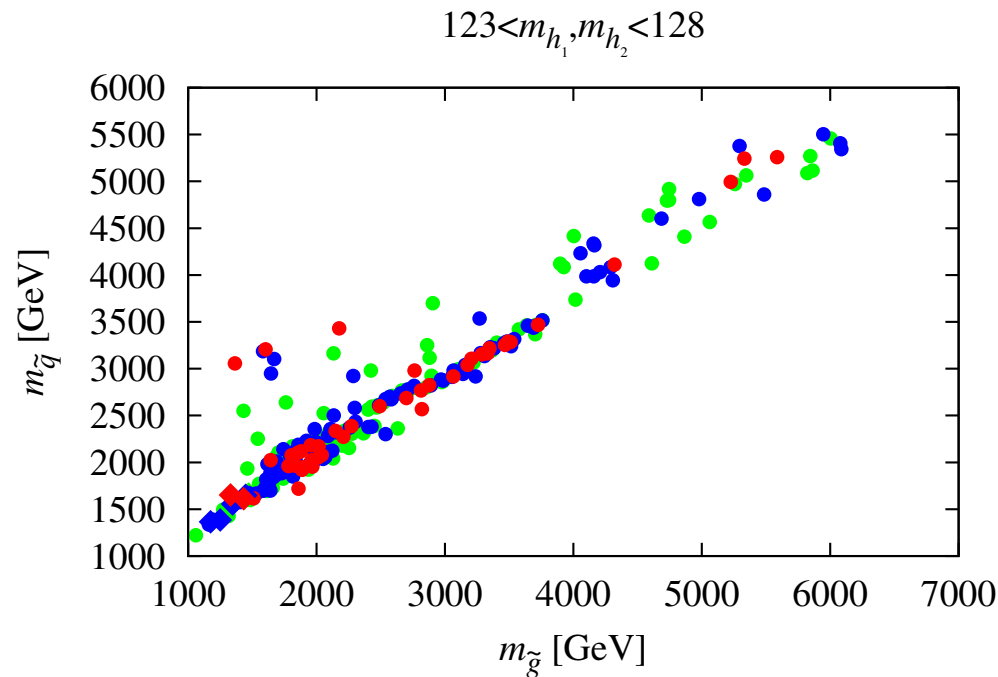


Figure 9: Left: Stop mixing parameter vs.  $M_{\text{SUSY}} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ . Right:  $m_{\tilde{\tau}_1}$  vs.  $m_{\tilde{t}_1}$ . Points plotted have  $R_{gg}^h(\gamma\gamma) > 1.3$ .

- Implications of the enhanced  $\gamma\gamma$  rate scenarios for other observables are also quite interesting.

First, let us observe from Fig. 10 that these scenarios have squark and gluino masses that are above about 1.25 TeV ranging up to as high as 6 TeV (where our scanning more or less ended).

The WMAP-window points with large  $R_{gg}^h(\gamma\gamma)$  are located at low masses of  $m_{\tilde{g}} \sim 1.3$  TeV and  $m_{\tilde{q}} \sim 1.6$  TeV.



**Figure 10:** Average light-flavor squark mass,  $m_{\tilde{q}}$ , versus gluino mass,  $m_{\tilde{g}}$ , for the points plotted in the previous figures.

- The value of  $R_{gg}^h(\gamma\gamma)$  as a function of the masses of the other Higgs bosons is illustrated in Fig. 11.

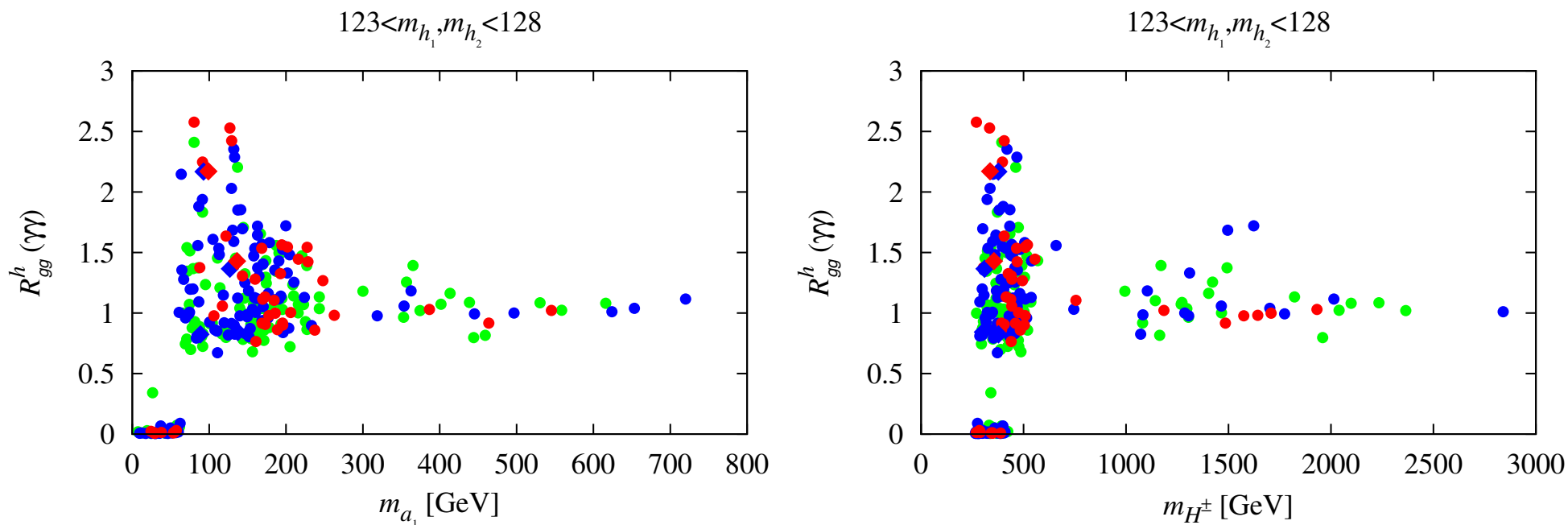


Figure 11:  $R_{gg}^h(\gamma\gamma)$  versus the masses of  $m_{a_1}$  and  $m_{H^\pm}$  (note that  $m_{H^\pm} \simeq m_{a_2} \simeq m_{h_3}$ ).

### Comments on Fig. 11:

1. We see that values above of  $R^h(\gamma\gamma) > 1.7$  are associated with masses

for the  $a_2$ ,  $h_3$  and  $H^\pm$  of order  $\lesssim 500$  GeV and for the  $a_1$  of order  $\lesssim 150$  GeV.

(Note that  $m_{a_2} \simeq m_{h_3} \simeq m_{H^\pm}$ )

While modest in size, detectability of these states at such masses requires further study.

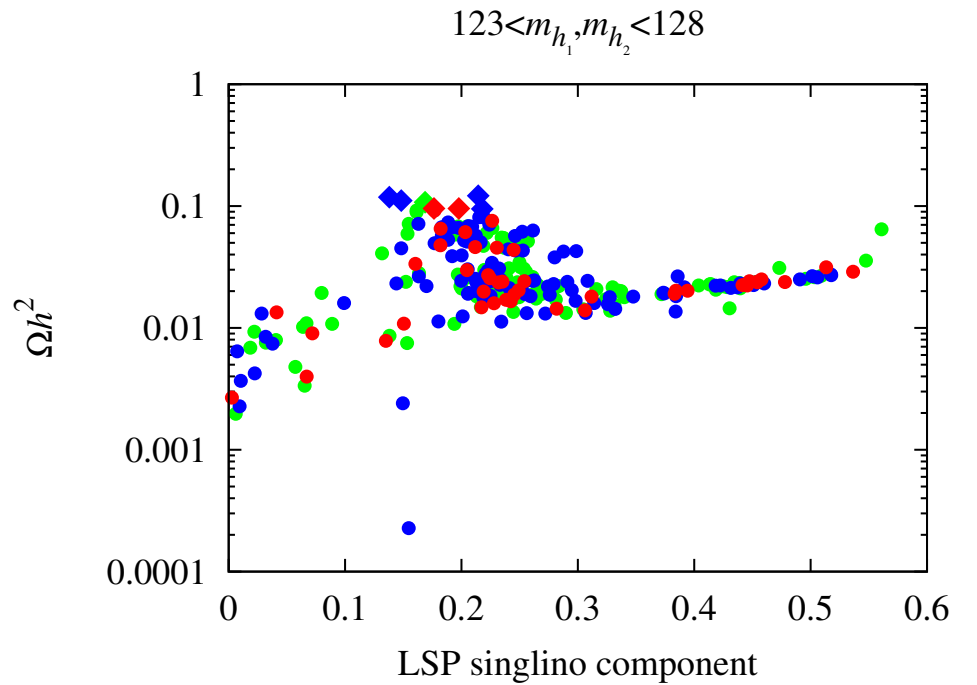
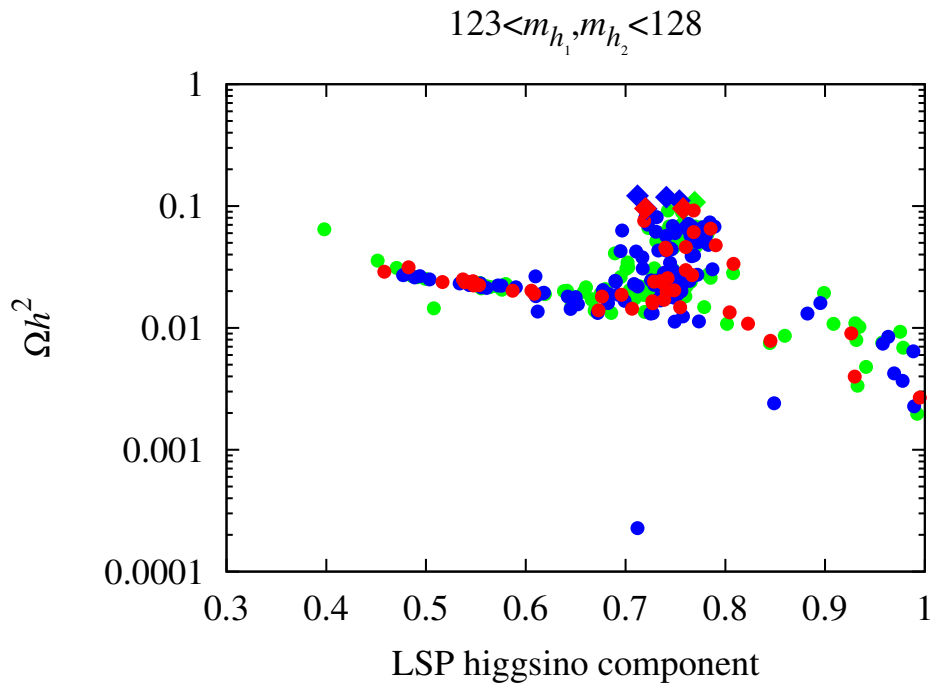
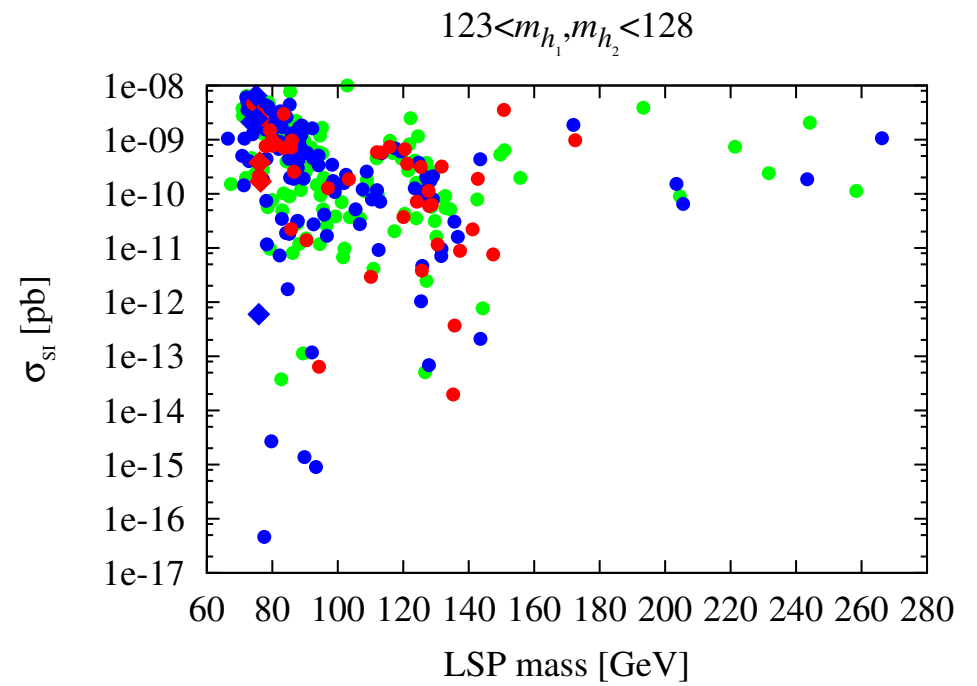
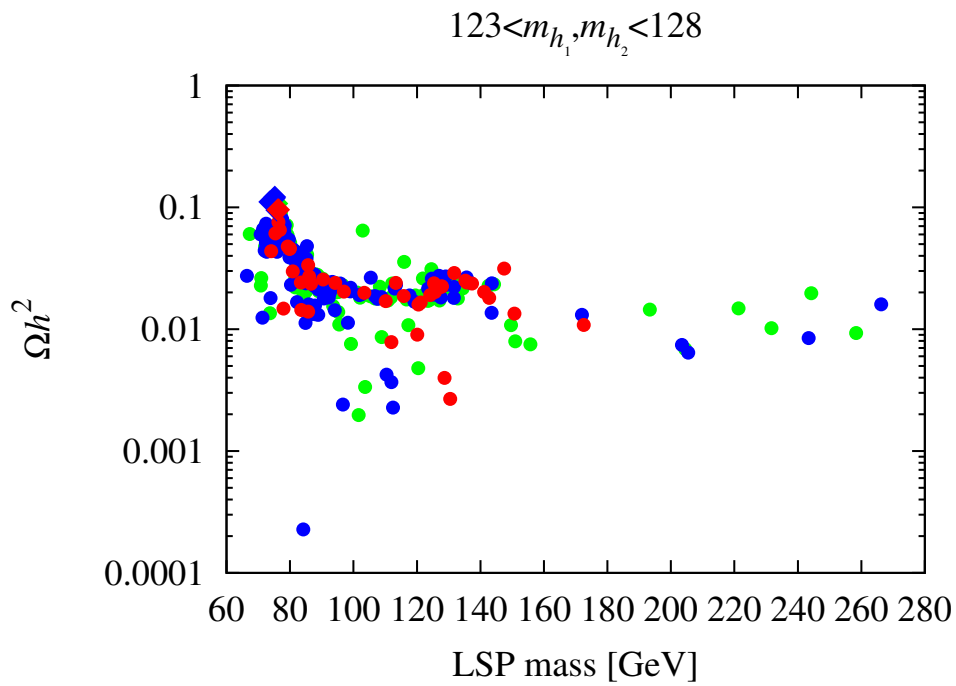
2. One interesting point is that  $m_{a_1} \sim 125$  GeV is common for points with  $R_{gg}^h(\gamma\gamma) > 1$  points.

We have checked that  $R_{gg}^{a_1}(\gamma\gamma)$  is quite small for such points — typically  $\lesssim 0.01$ .

- In Fig. 12, we display  $\Omega h^2$  and the spin-independent cross section for LSP scattering on protons,  $\sigma_{SI}$ , for the points plotted in previous figures.

Comments on Fig. 12:

1. Very limited range of LSP masses consistent with the WMAP window, roughly  $m_{\tilde{\chi}_1^0} \in [60, 80]$  GeV.
2. Corresponding  $\sigma_{SI}$  values range from *few*  $\times 10^{-9}$  pb to as low as *few*  $\times 10^{-11}$  pb.



**Figure 12:** Top row:  $\Omega h^2$  and spin-independent cross section on protons versus LSP mass for the points plotted in previous figures. Bottom row:  $\Omega h^2$  versus LSP higgsino (left) and singlino (right) components.



3. Owing to the small  $\mu_{\text{eff}}$ , the LSP is dominantly higgsino, which is also the reason for  $\Omega h^2$  typically being too low.

The points with  $\Omega h^2$  within the WMAP window are mixed higgsino–singlino, with a singlino component of the order of 20%, see the bottom-row plots of Fig. 12.

- It is interesting to note a few points regarding the parameters associated with the points plotted in previous figures.
  1. For the WMAP-window diamond points,  $\lambda \in [0.58, 0.65]$ ,  $\kappa \in [0.28, 0.35]$ , and  $\tan \beta \in [2.5, 3.5]$ .
  2. Points with  $R_{gg}^h(\gamma\gamma) > 1.3$  have  $\lambda \in [0.33, 0.67]$ ,  $\kappa \in [0.22, 0.36]$ , and  $\tan \beta \in [2, 14]$ .
- Can't find scenarios of this degenerate/enhanced type such that  $\delta a_\mu$  is consistent with that needed to explain the current discrepancy.

In particular, the very largest value of  $\delta a_\mu$  achieved is of order  $1.8 \times 10^{-10}$  and, further, the WMAP-window points with large  $R_{gg}^h(\gamma\gamma, VV)$  have  $\delta a_\mu < 6 \times 10^{-11}$ .

# Diagnosing the presence of degenerate Higgses

(J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1208.1817)

- Given that enhanced  $R_{gg}^h$  is very natural if there are degenerate Higgs mass eigenstates, **how do we detect degeneracy?** Must look at correlations among different  $R^h$ 's.
- In the context of any doublets plus singlets model not all the  $R^{h_i}$ 's are independent; a complete independent set of  $R^h$ 's can be taken to be:

$$R_{gg}^h(WW), \quad R_{gg}^h(bb), \quad R_{gg}^h(\gamma\gamma), \quad R_{VBF}^h(WW), \quad R_{VBF}^h(bb), \quad R_{VBF}^h(\gamma\gamma). \quad (8)$$

Let us now look in more detail at a given  $R_Y^h(X)$ . It takes the form

$$R_Y^h(X) = \sum_{i=1,2} \frac{(C_Y^{h_i})^2 (C_X^{h_i})^2}{C_\Gamma^{h_i}} \quad (9)$$

where  $C_X^{h_i}$  for  $X = \gamma\gamma, WW, ZZ, \dots$  is the ratio of the  $h_i X$  to  $h_{SM} X$  coupling and  $C_\Gamma^{h_i}$  is the ratio of the total width of the  $h_i$  to the SM Higgs

total width. The diagnostic tools that can reveal the existence of a second, quasi-degenerate (but non-interfering in the small width approximation) Higgs state are the double ratios:

$$\text{I): } \frac{R_{VBF}^h(\gamma\gamma)/R_{gg}^h(\gamma\gamma)}{R_{VBF}^h(bb)/R_{gg}^h(bb)}, \quad \text{II): } \frac{R_{VBF}^h(\gamma\gamma)/R_{gg}^h(\gamma\gamma)}{R_{VBF}^h(WW)/R_{gg}^h(WW)}, \quad \text{III): } \frac{R_{VBF}^h(WW)/R_{gg}^h(WW)}{R_{VBF}^h(bb)/R_{gg}^h(bb)}, \quad (10)$$

each of which should be unity if only a single Higgs boson is present but, due to the non-factorizing nature of the sum in Eq. (9), are generally expected to deviate from 1 if two (or more) Higgs bosons are contributing to the net  $h$  signals.

In a doublets+singlets model all other double ratios that are equal to unity for single Higgs exchange are not independent of the above three.

Of course, the above three double ratios are not all independent.

Which will be most useful depends upon the precision with which the  $R^h$ 's for different initial/final states can be measured.

E.g measurements of  $R^h$  for the  $bb$  final state may continue to be somewhat imprecise and it is then double ratio II) that might prove most discriminating.

Or, it could be that one of the double ratios deviates from unity by a much larger amount than the others, in which case it might be most discriminating even if the  $R^h$ 's involved are not measured with great precision.

- In Fig. 16, we plot the numerator versus the denominator of the double ratios I) and II), III) being very like I) due to the correlation between the  $R_{gg}^h(\gamma\gamma)$  and  $R_{gg}^h(WW)$  values discussed earlier.
- We observe that any one of these double ratios will often, but not always, deviate from unity (the diagonal dashed line in the figure).
- The probability of such deviation increases dramatically if we require (as apparently preferred by LHC data)  $R_{gg}^h(\gamma\gamma) > 1$ , see the solid (vs. open) symbols of Fig. 16.

This is further elucidated in Fig. 17 where we display the double ratios I) and II) as functions of  $R_{gg}^h(\gamma\gamma)$  (left plots).

For the NMSSM, it seems that the double ratio I) provides the greatest discrimination between degenerate vs. non-degenerate scenarios with values

very substantially different from unity (the dashed line) for the majority of the degenerate NMSSM scenarios explored in the earlier section of this talk that have enhanced  $\gamma\gamma$  rates.

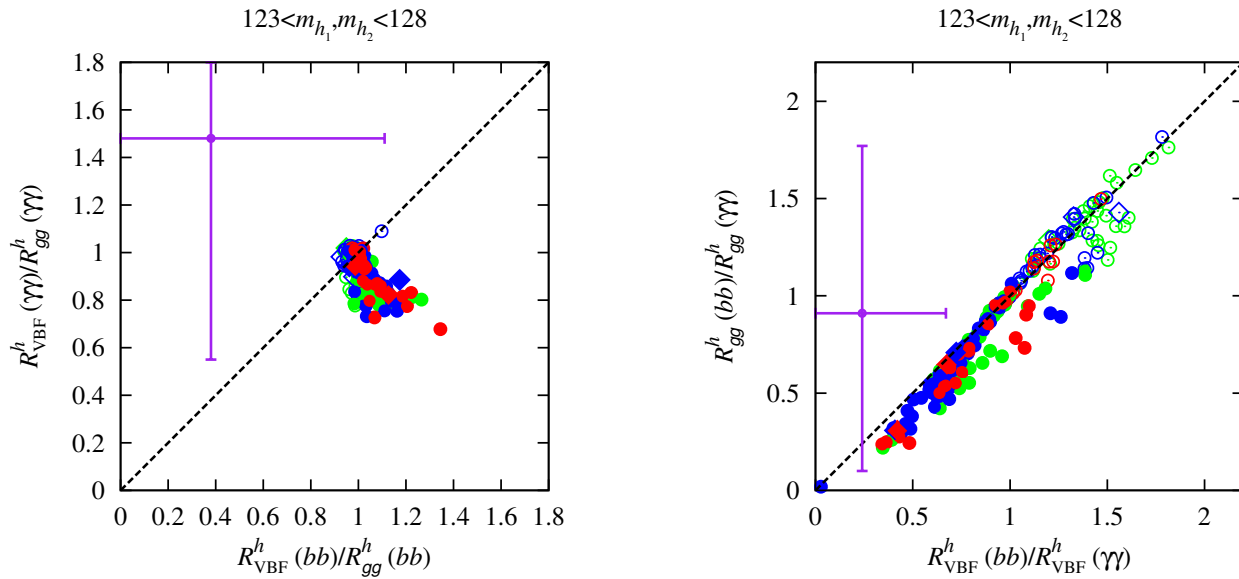
Note in particular that I), being sensitive to the  $b\bar{b}$  final state, singles out degenerate Higgs scenarios even when one or the other of  $h_1$  or  $h_2$  dominates the  $gg \rightarrow \gamma\gamma$  rate, see the top right plot of Fig. 17.

In comparison, double ratio II) is most useful for scenarios with  $R_{gg}^h(\gamma\gamma) \sim 1$ , as illustrated by the bottom left plot of Fig. 17.

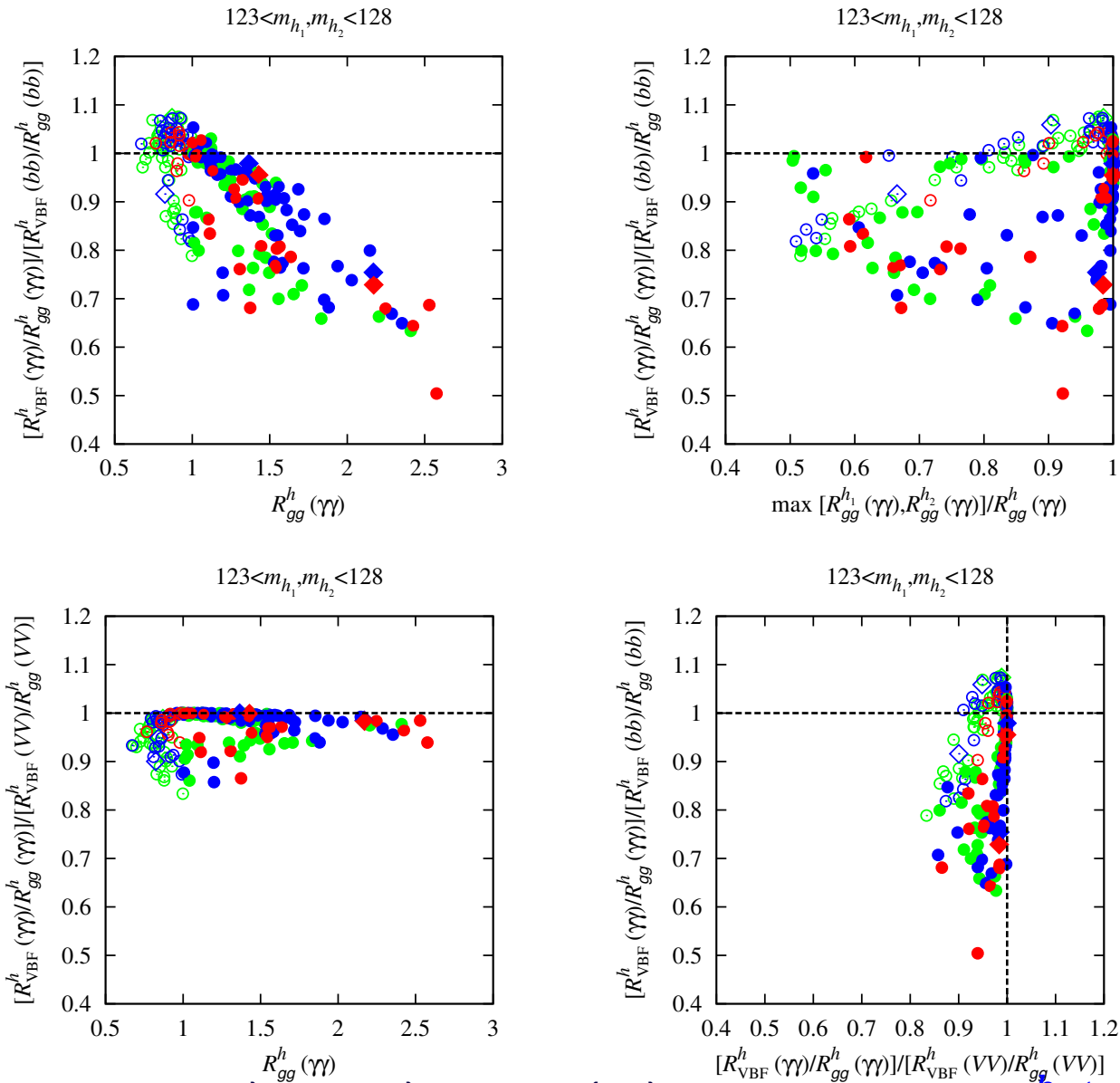
- Thus, as illustrated by the bottom right plot of Fig. 17, the greatest discriminating power is clearly obtained by measuring both double ratios.

In fact, a close examination reveals that there are no points for which *both* double ratios are exactly 1!

Of course, experimental errors may lead to a region containing a certain number of points in which both double ratios are merely consistent with 1 within the errors.



**Figure 13:** Comparisons of pairs of event rate ratios that should be equal if only a single Higgs boson is present. The color code is green for points with  $2 \text{ GeV} < m_{h_2} - m_{h_1} \leq 3 \text{ GeV}$ , blue for  $1 \text{ GeV} < m_{h_2} - m_{h_1} \leq 2 \text{ GeV}$ , and red for  $m_{h_2} - m_{h_1} \leq 1 \text{ GeV}$ . Large diamond points have  $\Omega h^2$  in the WMAP window of  $[0.094, 0.136]$ , while circular points have  $\Omega h^2 < 0.094$ . Solid points are those with  $R_{gg}^h(\gamma\gamma) > 1$  and open symbols have  $R_{gg}^h(\gamma\gamma) \leq 1$ . Current experimental values for the ratios from CMS data along with their  $1\sigma$  error bars are also shown.



**Figure 14:** Double ratios I) and II) of Eq. (10) as functions of  $R_{\text{gg}}^h(\gamma\gamma)$  (on the left). On the right we show (top) double ratio I) vs.  $\max[R_{\text{gg}}^{h_1}(\gamma\gamma), R_{\text{gg}}^{h_2}(\gamma\gamma)]/R_{\text{gg}}^h(\gamma\gamma)$  and (bottom) double ratio I) vs. double ratio II) for the points displayed in Fig. 16. Colors and symbols are the same as in Fig. 16.

- What does current LHC data say about these various double ratios?

The central values and  $1\sigma$  error bars for the numerator and denominator of double ratios I) and II) obtained from CMS data [?] are also shown in Fig. 16.

Obviously, current statistics are inadequate to discriminate whether or not the double ratios deviate from unity.

About 100 times increased statistics will be needed. This will not be achieved until the  $\sqrt{s} = 14$  TeV run with  $\geq 100 \text{ fb}^{-1}$  of accumulated luminosity.

Nonetheless, it is clear that the double-ratio diagnostic tools will ultimately prove viable and perhaps crucial for determining if the  $\sim 125$  GeV Higgs signal is really only due to a single Higgs-like resonance or if two resonances are contributing.

Degeneracy has significant probability in model contexts if enhanced  $\gamma\gamma$  rates are indeed confirmed at higher statistics.



# Higgs at 125 GeV for LHC and 136 GeV for the Tevatron (and LHC?):

(G. Belanger, U. Ellwanger, J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1208.4952)

## 1) A Higgs boson $H_1$ at 125–126 GeV

- Combining ATLAS and CMS:

$$R_1^{\gamma\gamma}(ggF) \simeq 1.66 \pm 0.36 . \quad (11)$$

At CMS, combining the 7 TeV dijet tag and 8 TeV dijet tight results, yields  $R_1^{\gamma\gamma}(VBF) \sim 2.6 \pm 1.3$ ; note that here the  $VBF$  category contains roughly 25%  $ggF$  production.

For ATLAS, we obtain  $R_1^{\gamma\gamma}(VBF) \sim 2.7 \pm 1.5$  (with unspecified  $ggF$  contamination).

Subsequently we merely assume  $R_1^{\gamma\gamma}(VBF) > 1$ .

- The  $ggF$  process also dominates the Higgs signal in the  $ZZ$  channel. The best fits to  $R_1^{ZZ^{(*)}}(ggF)$  from the ATLAS and CMS collaborations are both consistent with 1:  $R_1^{ZZ^{(*)}}(ggF) \simeq 1.4 \pm 0.6$  (ATLAS),  $R_1^{ZZ^{(*)}}(ggF) \simeq 0.75 \pm 0.5$  (CMS).

Combining, we estimate

$$R_1^{ZZ^{(*)}}(ggF) \simeq 1.02 \pm 0.38 . \quad (12)$$

## 2) A Higgs boson $H_2$ at 135–136 GeV

- In the  $\gamma\gamma$  mode, CMS has observed an excess of events of about two standard deviations around 136 GeV, the excess being a bit larger for the 7 TeV data than for the 8 TeV data.

Combining the two data sets, the corresponding reduced signal rate can be estimated as  $R_2^{\gamma\gamma}(ggF) \simeq 0.9 \pm 0.4$  (CMS).

However, no excess of events at this mass was observed by ATLAS.

We estimate  $R_2^{\gamma\gamma}(ggF) \simeq 0.0 + 0.4$  (ATLAS).

Taken together, one obtains

$$R_2^{\gamma\gamma}(ggF) \simeq 0.45 \pm 0.3. \quad (13)$$

The above is a crude estimate, which could be improved by more detailed analyses and/or more data; here we consider it as a first hint for the existence of a second state near 136 GeV in the Higgs sector.

- In the  $ZZ^{(*)}$  mode, no excess has been observed by the ATLAS and CMS collaborations for  $M_H \sim 136$  GeV.

Combining both upper bounds on the reduced signal rate, we estimate

$$R_2^{ZZ^{(*)}}(ggF) \lesssim 0.2 \quad (14)$$

at the level of one standard deviation.

### 3) Low mass resolution channels.

- In the  $\tau\tau$  channel and tagging two jets (sensitive mostly to the  $VBF$  production mode), CMS observes a deficit with respect to the background-only hypothesis assuming  $M_H \sim 125$  GeV.

Hence  $R_1^{\tau\tau}(VBF)$  should be as small as possible.

- Assuming  $M_H \gtrsim 132$  GeV, CMS observes an excess of events of about half a standard deviation; the upper limit (for  $M_{H_2} \sim 135$  GeV) is given as

$$R_2^{\tau\tau}(VBF) < 1.81. \quad (15)$$

In the presence of two Higgs states these values have to be reinterpreted to account for overlapping signals — will not give details.

- In the  $bb$  channel, the CDF and D0 collaborations at the Tevatron (where the dominant production mode is  $VH$ ) have observed large values of  $R^{bb}(VH)$ :  $R_{125}^{bb}(VH) \simeq 1.97 + 0.74 - 0.68$  assuming  $M_{H_{SM}} = 125$  GeV, and

$$R_{135}^{bb}(VH) \simeq 3.53 + 1.26 - 1.16 \quad (16)$$

assuming  $M_{H_{\text{SM}}} = 135 \text{ GeV}$ .

CMS has also observed excesses in this channel, but below the expectations for a SM Higgs boson at 125 GeV.

Assuming larger values of  $M_{H_{\text{SM}}}$ , the excesses observed by CMS are larger (with a peak around  $M_{H_{\text{SM}}} \sim 130 \text{ GeV}$ ), but have large error bars.

It is clear that the central value of (16) is difficult to explain: the  $VH$  production cross section  $\propto c_V^2$  cannot be enhanced with respect to the SM, and the SM Higgs branching fraction of  $\sim 40\%$  for  $M_{H_{\text{SM}}} = 135 \text{ GeV}$  can be enhanced at most by a factor of 2.5 in the unphysical limit  $c_D \rightarrow \infty$ .

- Using the same reduced couplings for Higgs bosons to  $b$ -quarks and  $\tau$ -leptons, one finds

$$R^{bb}(VH) = R^{\tau\tau}(VBF) \quad (17)$$

for all Higgs states.

If  $R_1^{\tau\tau}(VBF)$  is as small as observed by CMS, the values for  $R^{bb}(VH)$  measured at the Tevatron should originate primarily from  $H_2$  with  $M_{H_2} \sim 135\text{--}136 \text{ GeV}$ ;

**This possibility is one of the main advantages of the present proposal.**

However, the contribution of  $H_1$  to the signal rate  $R^{bb}(VH)$  obtained assuming  $M_{H_{\text{SM}}} \sim 135$  GeV can still be sizable, since the production cross section of  $H_1$  is  $\sim 30\%$  larger.

Assuming a mass resolution worse than 10 GeV,  $R_{135}^{bb}(VH)$  in (16) would correspond to

$$R_{\text{eff}}^{bb}(VH) \simeq R_2^{bb}(VH) + 1.3 \times R_1^{bb}(VH) . \quad (18)$$

(In addition, the contribution from  $H_2$  to the signal rate  $R_{125}^{bb}(VH)$  should be as large as possible.)

## NMSSM Model that does a good job

$\lambda$	0.617	$\mu_{\text{eff}}$	143
$\kappa$	0.253	$A_\lambda$	164
$\tan \beta$	1.77	$A_\kappa$	337
$M_{H_1}$	125	$M_{A_1}$	95
$M_{H_2}$	136	$M_{A_2}$	282
$M_{H_3}$	289	$M_{H^\pm}$	272

**Table 2:** NMSSM-specific parameters and Higgs masses of a point with desired properties. (The dimensionful parameters are given in GeV.)

- The Higgs states are strongly mixed, both  $H_1$  and  $H_2$  having large SU(2) doublet and singlet components.
- $H_1$  has the smallest  $c_D$  component, which leads to an increase of the reduced branching fraction into  $\gamma\gamma$  as discussed above.

However, the partial width  $\Gamma(H_1 \rightarrow \gamma\gamma)$  also receives an additional NMSSM-specific contribution of  $\sim 20\%$  from higgsino-like charginos with

$m_{\tilde{\chi}_1^\pm} = 126$  GeV in the loop.

- The reduced branching fractions for the CP-even Higgs bosons are given in Table 3, and their signal rates relative to SM expectations in Table 4.

Higgs	$\frac{BR(H_i \rightarrow bb)}{BR(H_{SM} \rightarrow bb)}$	$\frac{BR(H_i \rightarrow VV^{(*)})}{BR(H_{SM} \rightarrow VV^{(*)})}$	$\frac{BR(H_i \rightarrow \gamma\gamma)}{BR(H_{SM} \rightarrow \gamma\gamma)}$
$H_1$	0.73	1.52	2.21
$H_2$	1.46	0.62	0.54
$H_3$	43.45	0.08	1.37

**Table 3:** Reduced branching fractions for the three CP-even Higgs states. Note that we have  $\frac{BR(H_i \rightarrow \tau\tau)}{BR(H_{SM} \rightarrow \tau\tau)} \sim \frac{BR(H_i \rightarrow bb)}{BR(H_{SM} \rightarrow bb)}$ , and

$$\frac{BR(H_i \rightarrow WW^{(*)})}{BR(H_{SM} \rightarrow WW^{(*)})} = \frac{BR(H_i \rightarrow ZZ^{(*)})}{BR(H_{SM} \rightarrow ZZ^{(*)})} \equiv \frac{BR(H_i \rightarrow VV^{(*)})}{BR(H_{SM} \rightarrow VV^{(*)})}.$$



Higgs	$R^{\gamma\gamma}(ggF)$	$R^{\gamma\gamma}(VBF)$	$R^{VV^{(*)}}(ggF)$	$R^{VV^{(*)}}(VH)$	$R^{bb}(VH)$	$R^{\tau\tau}(ggF)$
$H_1$	1.30	1.09	0.90	0.75	0.36	0.42
$H_2$	0.16	0.27	0.18	0.31	0.74	0.43
$H_3$	0.58	0.01	0.04	0.004	0.23	19.6

**Table 4:** Reduced signal rates for the three CP-even Higgs states. Note that  $R^{VV^{(*)}}(VBF) = R^{VV^{(*)}}(VH)$ , and  $R^{\tau\tau}(VBF) \sim R^{bb}(VH)$ .

Do these signal rates have the desired properties listed earlier.

- We observe that  $R_1^{\gamma\gamma}(ggF)$ ,  $R_1^{ZZ^{(*)}}(ggF)$ ,  $R_2^{\gamma\gamma}(ggF)$  and  $R_2^{ZZ^{(*)}}(ggF)$  satisfy Eqs. (11), (12), (13) and (14), respectively.
- Note that  $R_1^{\gamma\gamma}(VBF)$  is also enhanced, in agreement with the observations.
- In the  $\tau\tau$  channel,  $R_1^{\tau\tau}(VBF) = R_1^{bb}(VH)$  is indeed suppressed, as is  $R_1^{\tau\tau}(ggF)$ .
- $R_2^{\tau\tau}(VBF)$  is not enhanced but, as discussed earlier,  $R_2^{\tau\tau}$  (like  $R_2^{bb}(VH)$ ) can receive a considerable contribution from  $R_1^{\tau\tau}$ .

Indeed, for  $R_{\text{eff}}^{bb}(VH)$ , defined by

$$R_{\text{eff}}^{bb}(VH) \simeq R_2^{bb}(VH) + 1.3 \times R_1^{bb}(VH) , \quad (19)$$

we obtain  $R_{\text{eff}}^{bb}(VH) \sim 1.20$ , with the dominant contribution from  $R_2^{bb}(VH)$ .

This value coincides with the large excess given in (16) (assuming a single Higgs state at 135 GeV) only within about two standard deviations, but at least exceeds the SM value.

- Finally, the signal rates in the  $WW^{(*)}$  channel via  $VH$  are consistent with the present limits.

### Semi-Constrained NMSSM GUT scenarios?

- One can find scenarios where  $H_1$  and  $H_2$  have masses of about 125 and 136 GeV, respectively.
- However, we did not find any points where the constraints (11) to (14) are all satisfied simultaneously —

at least one of the conditions on  $R_1^{\gamma\gamma}(ggF)$ ,  $R_2^{\gamma\gamma}(ggF)$  or  $R_2^{ZZ^{(*)}}(ggF)$  has to be relaxed to find valid points.

For example, we can satisfy Eqs. (11), (12), (14) (and (15)), but then  $R_2^{\gamma\gamma}(ggF)$  turns out too low,  $R_2^{\gamma\gamma}(ggF) \lesssim 0.06$ . **Maybe a good thing in the end?**

Or we can satisfy (12)–(15), but then  $R_1^{\gamma\gamma}(ggF) \lesssim 1.3$ . Moreover,  $R_2^{bb}(VH)$  is never large, making it difficult to explain the Tevatron result in this channel.

## Higgses at 98 GeV for LEP and 125 GeV for LHC:

( G. Belanger, U. Ellwanger, J. F. Gunion, Y. Jiang, S. Kraml and J. H. Schwarz.  
arXiv:1210.1976)

- We demonstrate that the two lightest CP-even Higgs bosons,  $h_1$  and  $h_2$ , of the NMSSM could have properties such that the  $h_1$  fits the LEP excess at  $\sim 98$  GeV while the  $h_2$  is reasonably consistent with the Higgs-like LHC signals at  $\sim 125$  GeV, including in particular the larger-than-SM signal in the  $\gamma\gamma$  channel.

To describe the LEP and LHC data the  $h_1$  must be largely singlet and the  $h_2$  primarily doublet (mainly  $H_u$  for the scenarios we consider).

An  $h_2$  with  $m_{h_2} \sim 125$  GeV and enhanced  $\gamma\gamma$  rate is obtained, as in previous cases, at large  $\lambda$  and moderate  $\tan\beta$ .

- In order to display the ability of the NMSSM to simultaneously explain the LEP and LHC Higgs-like signals, we (once again) turn to NMSSM scenarios with semi-unified GUT scale soft-SUSY-breaking.

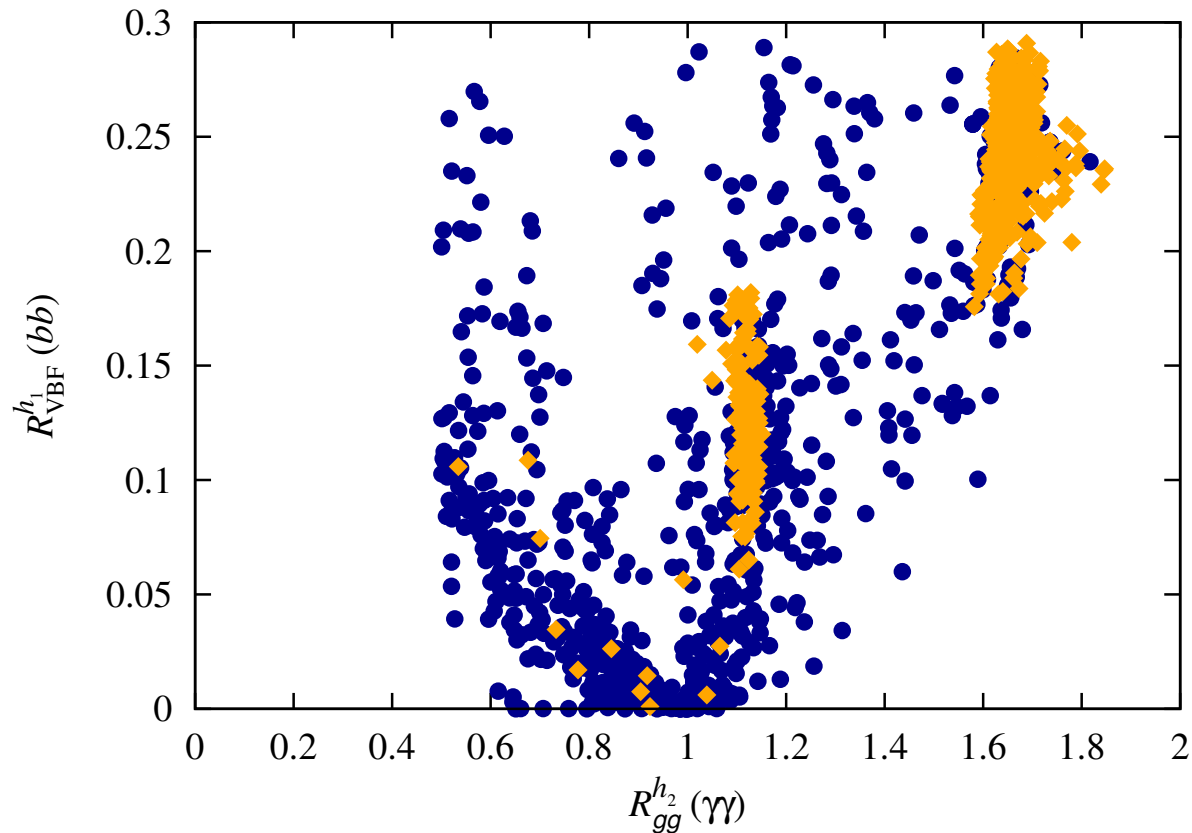
- All the accepted points correspond to scenarios that obey all experimental constraints (mass limits and flavor constraints as implemented in NMSSMTools,  $\Omega h^2 < 0.136$  and 2011 XENON100 constraints on the spin-independent scattering cross section) except that the SUSY contribution to the anomalous magnetic moment of the muon,  $\delta a_\mu$ , is too small to explain the discrepancy between the observed value of  $a_\mu$  and the SM prediction.
- Fig. 15, the crucial plot, shows  $R_{VBF}^{h_1}(bb)$  (which =  $R_{Z^* \rightarrow Zh_1}^{h_1}(bb)$  as for LEP) versus  $R_{gg}^{h_2}(\gamma\gamma)$  when  $m_{h_1} \in [96, 100]$  GeV and  $m_{h_2} \in [123, 128]$  GeV are imposed in addition to the above mentioned experimental constraints.<sup>1</sup>

(In this and all subsequent plots, points with  $\Omega h^2 < 0.094$  are represented by blue circles and points with  $\Omega h^2 \in [0.094, 0.136]$  (the "WMAP window") are represented by orange diamonds.)

Note that  $R_{VBF}^{h_1}(bb)$  values are required to be smaller than 0.3 by virtue of the fact that the LEP constraint on the  $e^+e^- \rightarrow Zb\bar{b}$  channel with  $M_{b\bar{b}} \sim 98$  GeV is included in the NMSSMTools program.

<sup>1</sup>Here the Higgs mass windows are designed to allow for theoretical errors in the computation of the Higgs masses.

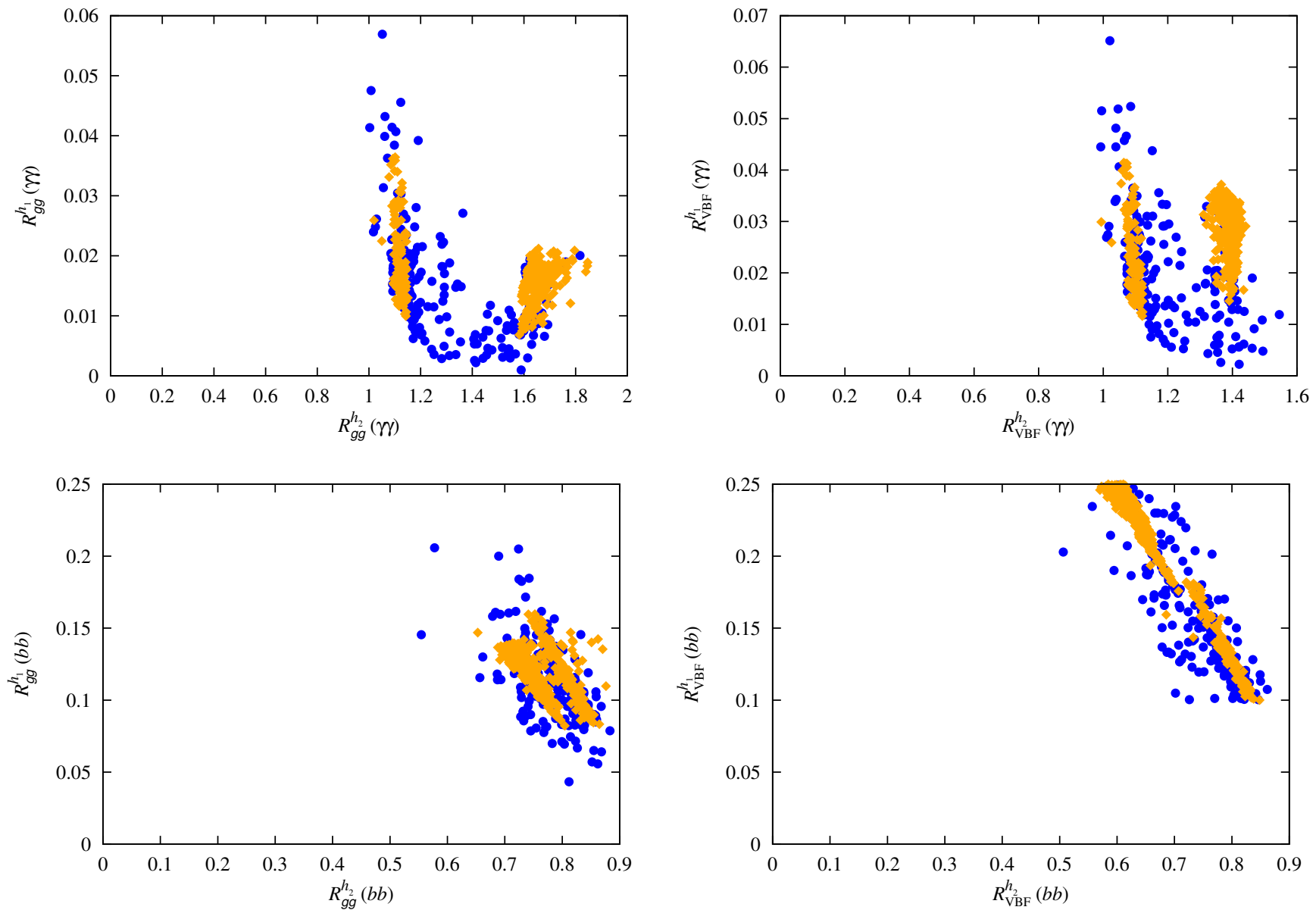
Those points with  $R_{VBF}^{h_1}(bb)$  between about 0.1 and 0.25 would provide the best fit to the LEP excess.



**Figure 15:** Signal strengths (relative to SM)  $R_{VBF}^{h_1}(bb)$  versus  $R_{gg}^{h_2}(\gamma\gamma)$  for  $m_{h_1} \in [96, 100]$  GeV and  $m_{h_2} \in [123, 128]$  GeV. In this and all subsequent plots, points with  $\Omega h^2 < 0.094$  are represented by blue circles and points with  $\Omega h^2 \in [0.094, 0.136]$  (the "WMAP window") are represented by orange diamonds.

To focus on scenarios for which the  $h_2$  signal (at  $\sim 125$  GeV) in  $\gamma\gamma$  is enhanced and the LEP 98 GeV excess is well fit, in all the remaining plots we will impose the additional requirements:  $R_{gg}^{h_2}(\gamma\gamma) > 1$  and  $0.1 \leq R_{VBF}^{h_1}(bb) \leq 0.25$ .

In the following, we will refer to these NMSSM scenarios as the “98 + 125 GeV Higgs scenarios” or “LEP-LHC scenarios”.



**Figure 16:** For  $h = h_1$  and  $h = h_2$ , we plot (top)  $R_{gg}^h(\gamma\gamma)$  and  $R_{VBF}^h(\gamma\gamma)$  and (bottom)  $R_{gg}^h(bb)$  and  $R_{VBF}^h(bb)$  we show only points satisfying all the basic constraints as well as  $m_{h_1} \in [96, 100]$  GeV,  $m_{h_2} \in [123, 128]$  GeV,  $R_{gg}^{h_2}(\gamma\gamma) > 1$  and  $R_{VBF}^{h_1}(bb) \in [0.1, 0.25]$ , *i.e.* the “98 + 125 GeV Higgs scenarios”.



- In Fig. 16, the upper plots show that the  $h_2$  can easily have an enhanced  $\gamma\gamma$  signal for both  $gg$  and VBF production whereas the  $\gamma\gamma$  signal arising from the  $h_1$  for both production mechanisms is quite small and unlikely to be observable.

Note the two different  $R_{gg}^{h_2}(\gamma\gamma)$  regions with orange diamonds (for which  $\Omega h^2$  lies in the WMAP window), one with  $R_{gg}^{h_2}(\gamma\gamma) \sim 1.1$  and the other with  $R_{gg}^{h_2}(\gamma\gamma) \sim 1.6$ .

The first region corresponds to  $m_{\tilde{\chi}_1^0} > 93$  GeV and  $m_{\tilde{t}_1} > 1.8$  TeV while the second region corresponds to  $m_{\tilde{\chi}_1^0} \sim 77$  GeV and  $m_{\tilde{t}_1}$  between 197 GeV and 1 TeV.

These same two regions emerge in many subsequent figures.

If  $R_{gg}^{h_2}(\gamma\gamma)$  ends up converging to a large value, then masses for all strongly interacting SUSY particles would be close to current limits if the present  $m_{h_1} \sim 98$  GeV- $m_{h_2} \sim 125$  GeV scenario applies.

The bottom row of the figure focuses on the  $b\bar{b}$  final state. We observe the reduced  $R_{gg}^{h_2}(bb)$  and  $R_{VBF}^{h_2}(bb)$  values that are associated with reduced

$b\bar{b}$  width (relative to the SM) needed to have enhanced  $R_{gg}^{h_2}(\gamma\gamma)$  and  $R_{VBF}^{h_2}(\gamma\gamma)$ .

Meanwhile, the  $R_{gg}^{h_1}(bb)$  and  $R_{VBF}^{h_1}(bb)$  values are such that the  $h_1$  could not yet have been seen at the Tevatron or LHC. Sensitivity to  $R_{gg}^{h_1}(bb)$  ( $R_{VBF}^{h_1}(bb)$ ) values from 0.05 to 0.2 (0.1 to 0.25) will be needed at the LHC.

This compares to expected sensitivities after the  $\sqrt{s} = 8$  TeV run in these channels to  $R$  values of at best 0.8.<sup>2</sup>

Statistically, a factor of 4 to 10 improvement requires integrated luminosity of order 16 to 100 times the current  $L = 10 \text{ fb}^{-1}$ . Such large  $L$  values will only be achieved after the LHC is upgraded to 14 TeV.

Finally, note that for WMAP-window points the largest  $R_{VBF}^{h_1}(bb)$  values occur for the light- $m_{\tilde{\chi}_1^0}$  point group described above for which supersymmetric particle masses are as small as possible.

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<sup>2</sup>Here, we have used Fig. 12 of cmshiggs extrapolated to a Higgs mass near 98 GeV and assumed  $L = 20 \text{ fb}^{-1}$  each for ATLAS and CMS.

- Other NMSSM particles, properties and parameters, including  $\tilde{\chi}_1^0$  and  $\tilde{\chi}_1^\pm$  compositions

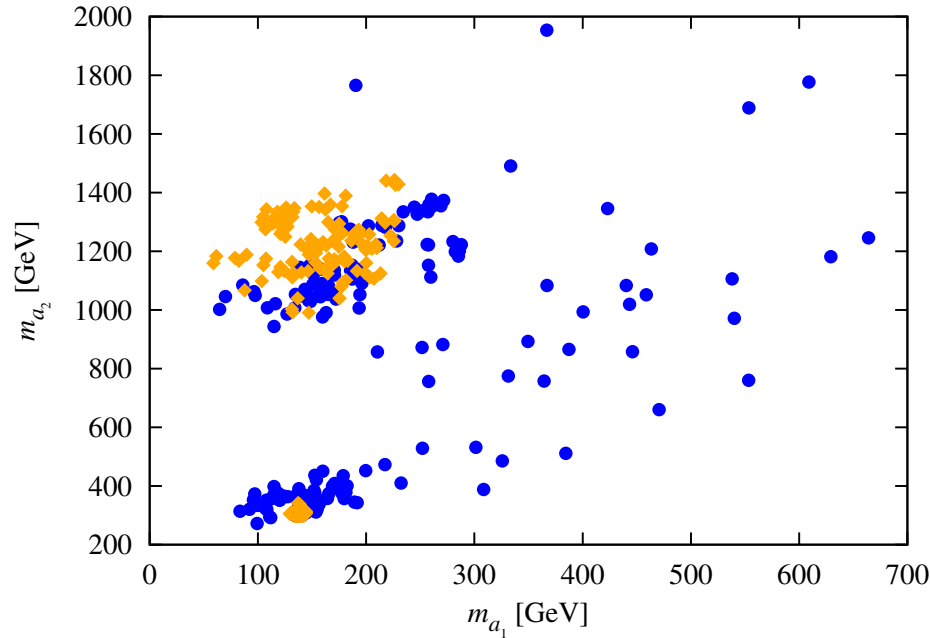
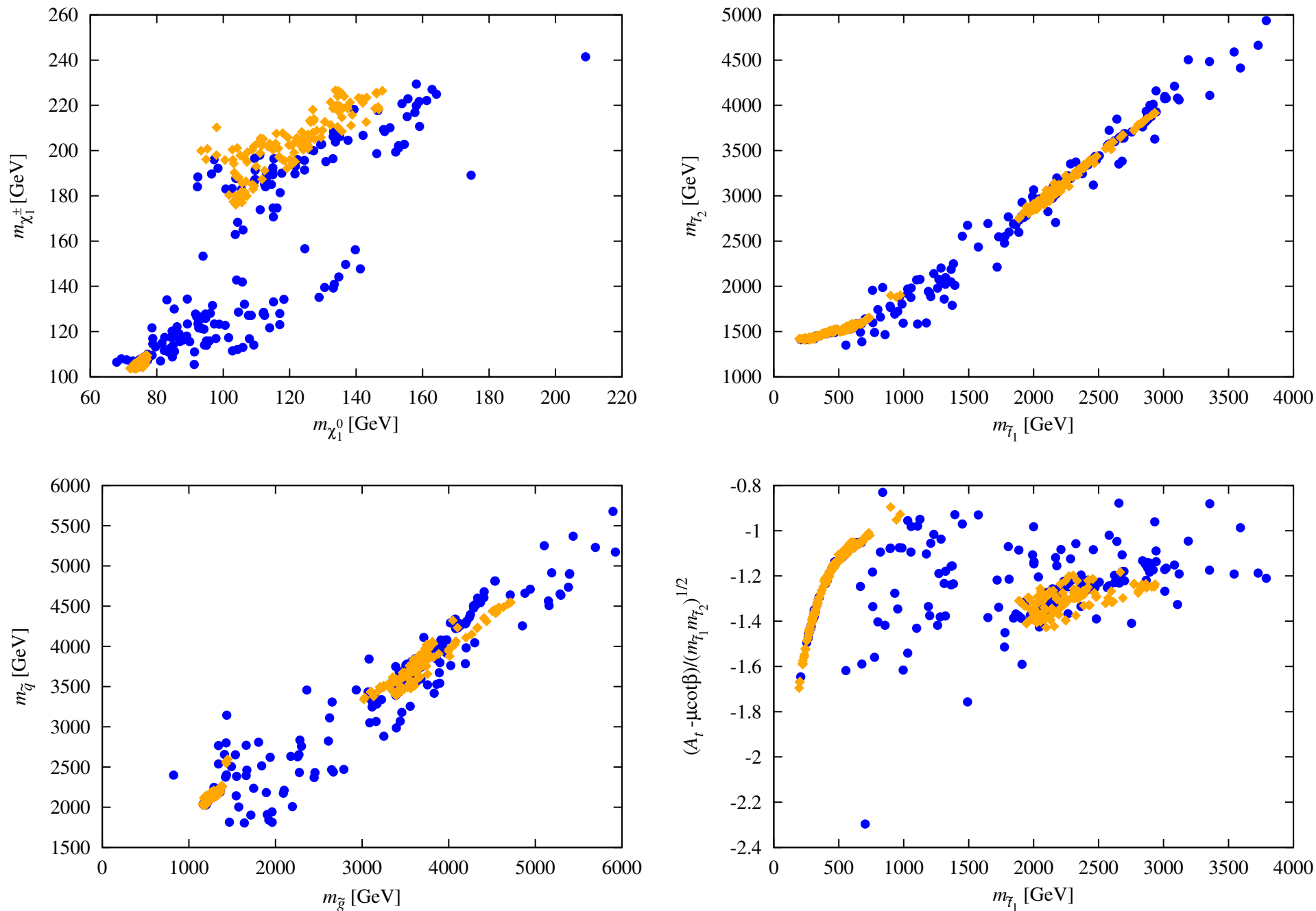
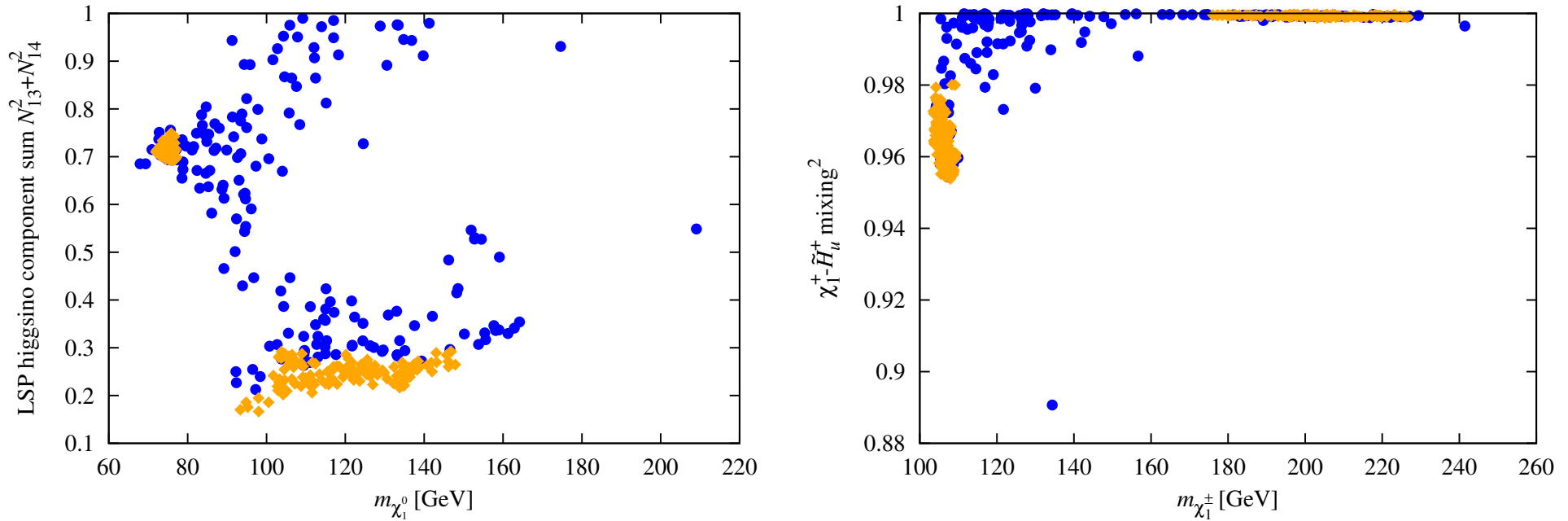


Figure 17: Scatter plot of  $m_{a_2}$  versus  $m_{a_1}$  for the 98+125 GeV scenario; note that  $m_{a_2} \simeq m_{h_3} \simeq m_{H^\pm}$ . Note that in this figure there is a dense region, located at  $(m_{a_1}, m_{a_2}) \sim (130, 330)$  GeV, of strongly overlapping orange diamond points. These are the points associated with the low- $m_{\tilde{\chi}_1^0}$  WMAP-window region of parameter space. Corresponding dense regions appear in other figures.

We note without a plot that the good  $\Omega h^2$  points all have  $m_{\tilde{\ell}_R}$ ,  $m_{\tilde{\nu}_\ell}$ ,  $m_{\tilde{\tau}_1}$  and  $m_{\tilde{\nu}_\tau}$  larger than 1.5 TeV.



**Figure 18:** Plots showing  $m_{\tilde{\chi}_1^0}$ ,  $m_{\tilde{\chi}_1^\pm}$ ,  $m_{\tilde{\tau}_1}$ ,  $m_{\tilde{\tau}_2}$ ,  $m_{\tilde{q}}$ ,  $m_{\tilde{g}}$ , and the mixing parameter  $(A_t - \mu \cot \beta) / \sqrt{m_{\tilde{\tau}_1} m_{\tilde{\tau}_2}}$ .

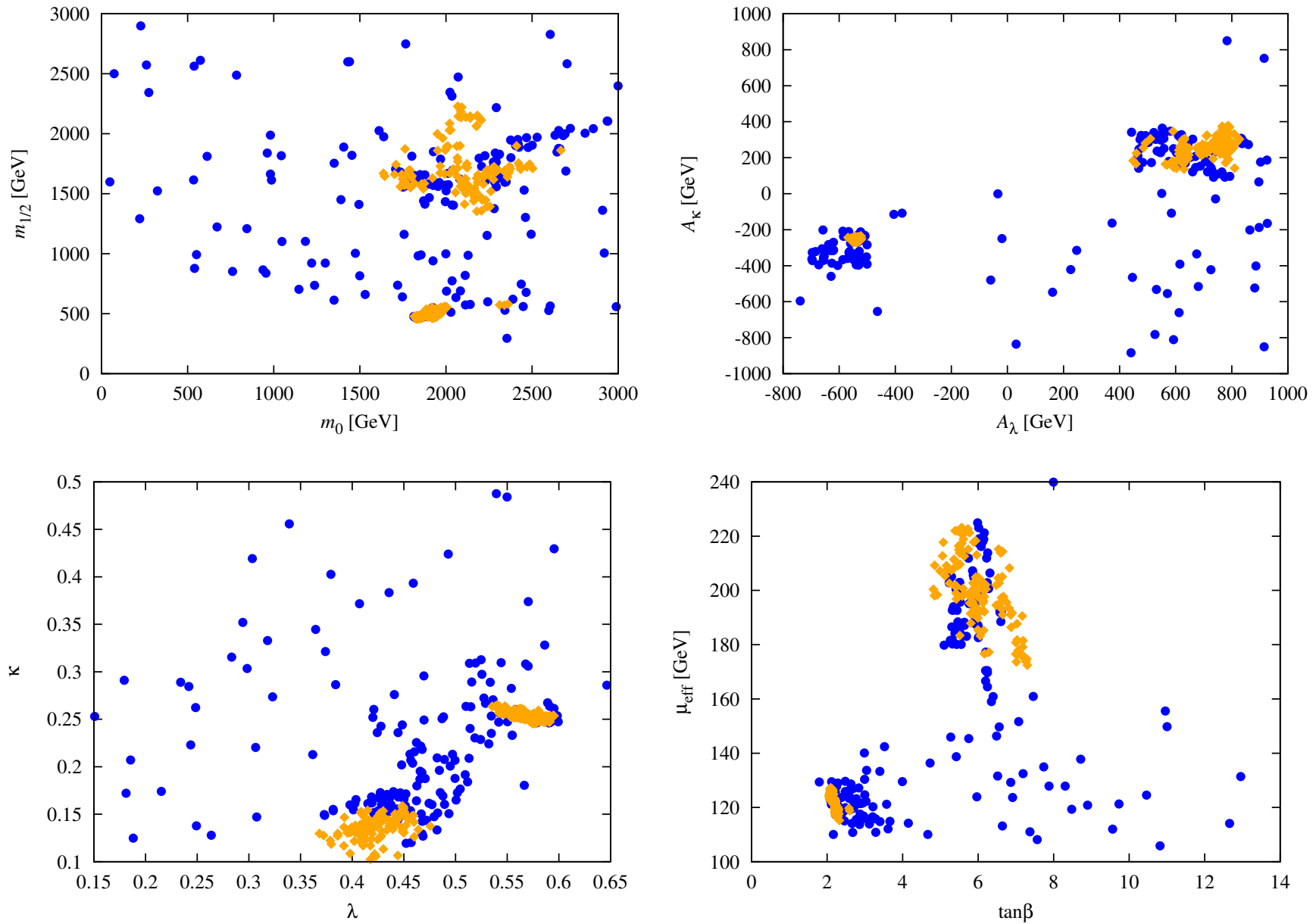


**Figure 19:** Neutralino and chargino compositions for the LEP–LHC scenarios.

Note that the  $\tilde{\chi}_1^0$  is very singlino in the low- $m_{\tilde{\chi}_1^0}$  WMAP-window scenarios.

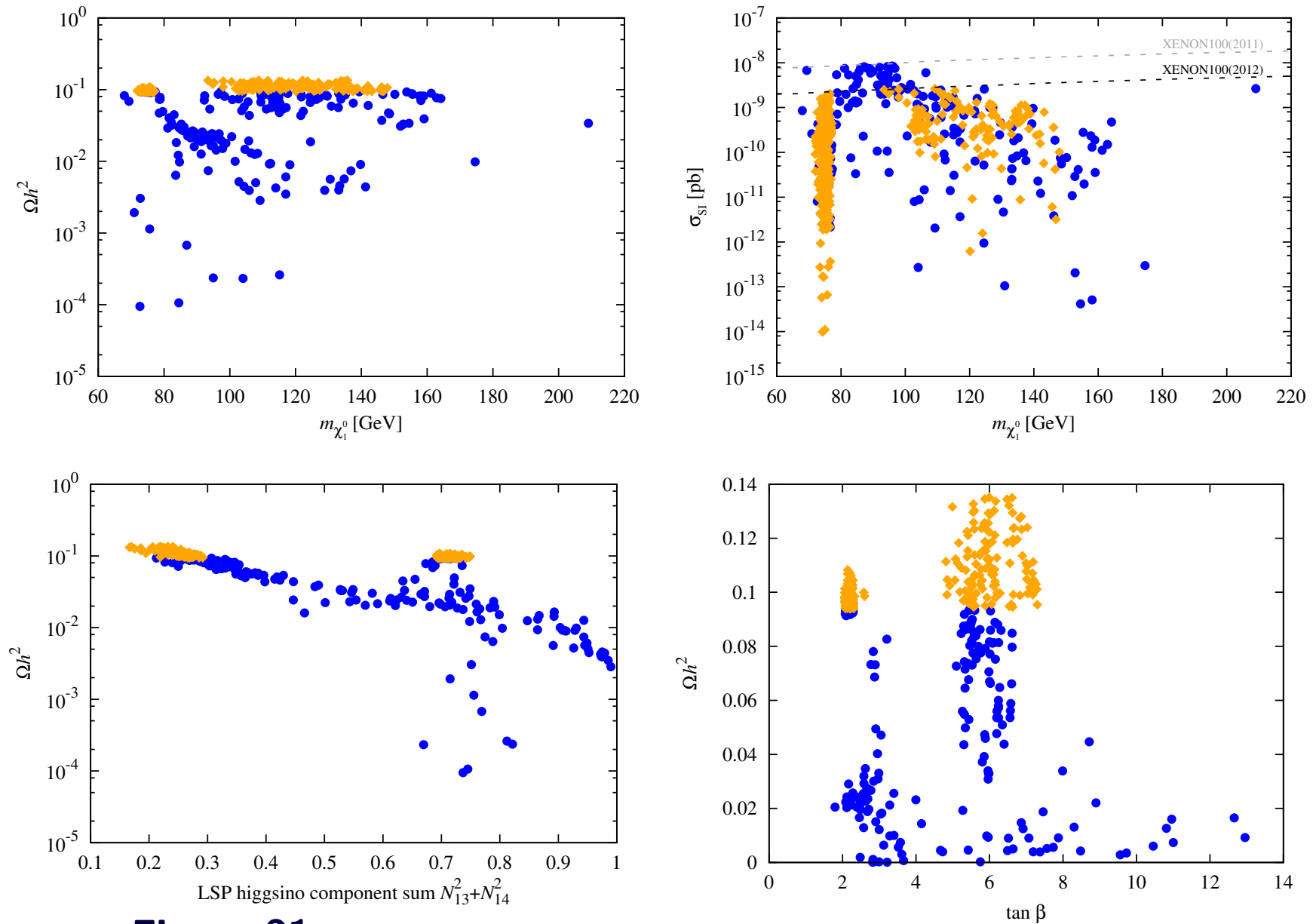
- **Input parameters**

The most important thing to note in the following figure is that the low- $m_{\tilde{\chi}_1^0}$  WMAP-window scenarios have not only low  $m_{\tilde{t}_1}$  but also low  $\mu_{\text{eff}}$ , implying not much fine-tuning.



**Figure 20: GUT scale and SUSY scale parameters leading to the LEP–LHC scenarios.**

# ● Dark Matter Issues



**Figure 21: Dark matter properties for the LEP-LHC scenarios.**

The composition of the  $\tilde{\chi}_1^0$  and the  $\tilde{\chi}_1^\pm$  are crucial when it comes to the relic density of the  $\tilde{\chi}_1^0$ .

For those points in the WMAP window with low  $m_{\tilde{\chi}_1^0}$ , the  $\tilde{\chi}_1^0$  can have a large Higgsino fraction since the  $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow W^+W^-$  annihilation mode (mainly via  $t$ -channel exchange of the light Higgsino-like — see second plot of Fig. 19 — chargino) is below threshold.

In contrast, the group of points with  $m_{\tilde{\chi}_1^0} > 93$  GeV can lie in the WMAP window only if the  $\tilde{\chi}_1^0$  does not have a large Higgsino fraction.

This division is clearly seen in Fig. 19. (We note that to a reasonable approximation the singlino fraction of the  $\tilde{\chi}_1^0$  is given by 1 minus the higgsino fraction plotted in the left-hand window of the figure.)

Dark matter (DM) properties for the surviving NMSSM parameter points are summarized in Fig. 21. Referring to the figure, we see a mixture of blue circle points (those with  $\Omega h^2 < 0.094$ ) and orange diamond points (those with  $0.094 \leq \Omega h^2 \leq 0.136$ , *i.e.* in the WMAP window).

The main mechanism at work to make  $\Omega h^2$  too small for many points is



rapid  $\tilde{\chi}_1^0 \tilde{\chi}_1^0$  annihilation to  $W^+W^-$  due to a substantial higgsino component of the  $\tilde{\chi}_1^0$  (see third plot of Fig. 21). Indeed, the relic density of a higgsino LSP is typically of order  $\Omega h^2 \approx 10^{-3} - 10^{-2}$ .

As the higgsino component declines  $\Omega h^2$  increases and (except for the strongly overlapping points with  $m_{\tilde{\chi}_1^0} < m_W$ , for which  $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow W^+W^-$  is below threshold) it is the points for which the LSP is dominantly singlino that have large enough  $\Omega h^2$  to fall in the WMAP window.

Also plotted in Fig. 21 is the spin-independent direct detection cross section,  $\sigma_{SI}$ , as a function of  $m_{\tilde{\chi}_1^0}$ . We see that experiments probing the spin-independent cross section will reach sensitivities that will probe some of the predicted  $\sigma_{SI}$  values relatively soon, especially the  $m_{\tilde{\chi}_1^0} > 93$  GeV points that are in the WMAP window.

However, it is also noteworthy that the  $m_{\tilde{\chi}_1^0} \sim 75$  GeV WMAP-window points can have very small  $\sigma_{SI}$ .

The fourth plot of Fig. 21 and fifth plot of Fig 20 illustrate clearly the two categories of WMAP-window points.

The first category of points is that for which  $m_{\tilde{\chi}_1^0} > 93$  GeV,  $\tan\beta \in [5, 7]$  and  $\lambda \in [0.37, 0.48]$ ; the second category is that for which the  $\tilde{\chi}_1^0$  has low mass and large higgsino component with  $\tan\beta \in [2, 2.6]$  and  $\lambda \in [0.53, 0.6]$ .

- **Direct Higgs production and decay at the LHC**

We have already noted in the discussion of Fig. 16 that  $gg$  and VBF production of the  $h_1$  with  $h_1 \rightarrow b\bar{b}$  provide event rates that might eventually be observable at the LHC once much higher integrated luminosity is attained. Other possibilities include production and decay of the  $a_1$ ,  $a_2$ , and  $h_3$ .

Decay branching ratios and LHC cross sections in the  $gg$  fusion mode for  $a_2$  and  $h_3$  are shown in Fig. 22.

Since the  $a_1$  is dominantly singlet in nature, its production rates at the LHC are rather small.

The  $a_2$  is dominantly doublet and provides better discovery prospects.

- If  $m_{a_2} > 2m_t$ , the  $t\bar{t}$  final state has  $\sigma(gg \rightarrow a_2)\text{BR}(a_2 \rightarrow t\bar{t}) > 0.01$  pb for  $m_{a_2} < 550$  GeV, implying  $> 200$  events for  $L = 20 \text{ fb}^{-1}$ .

A study is needed to determine if this would be observable in the presence of the  $t\bar{t}$  continuum background.

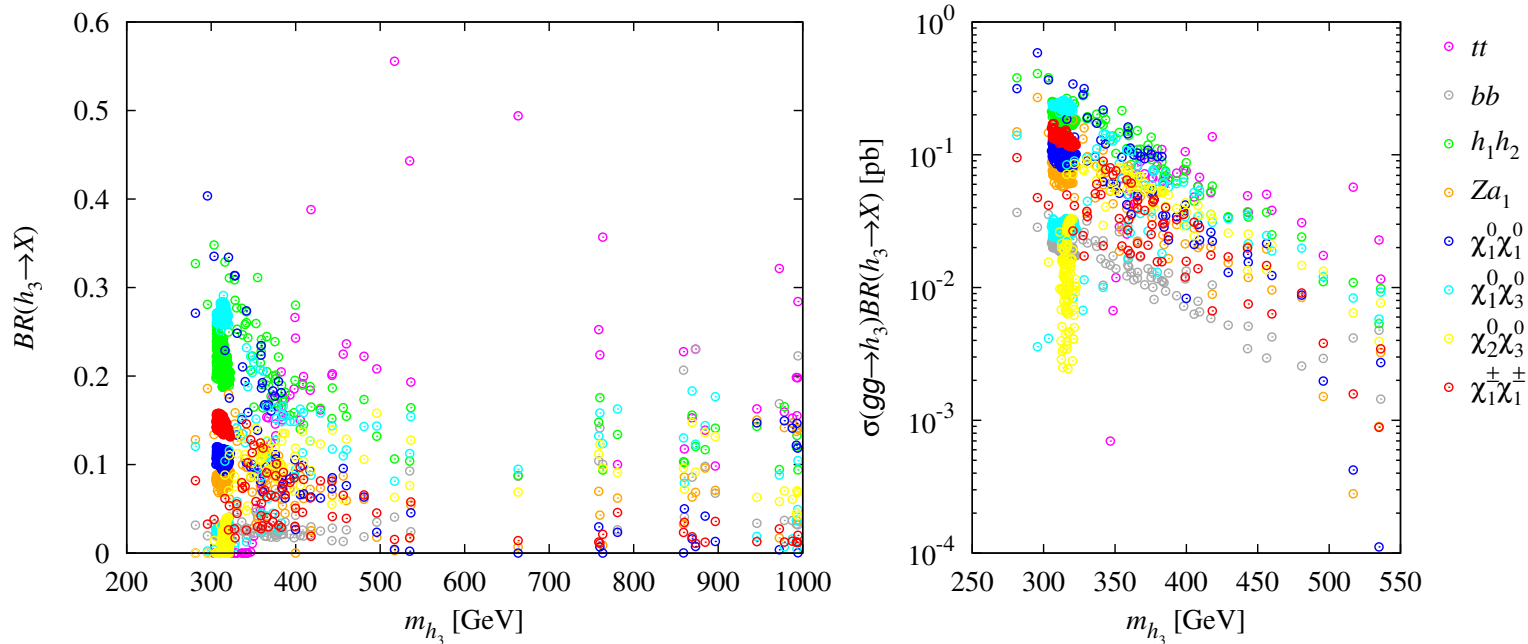
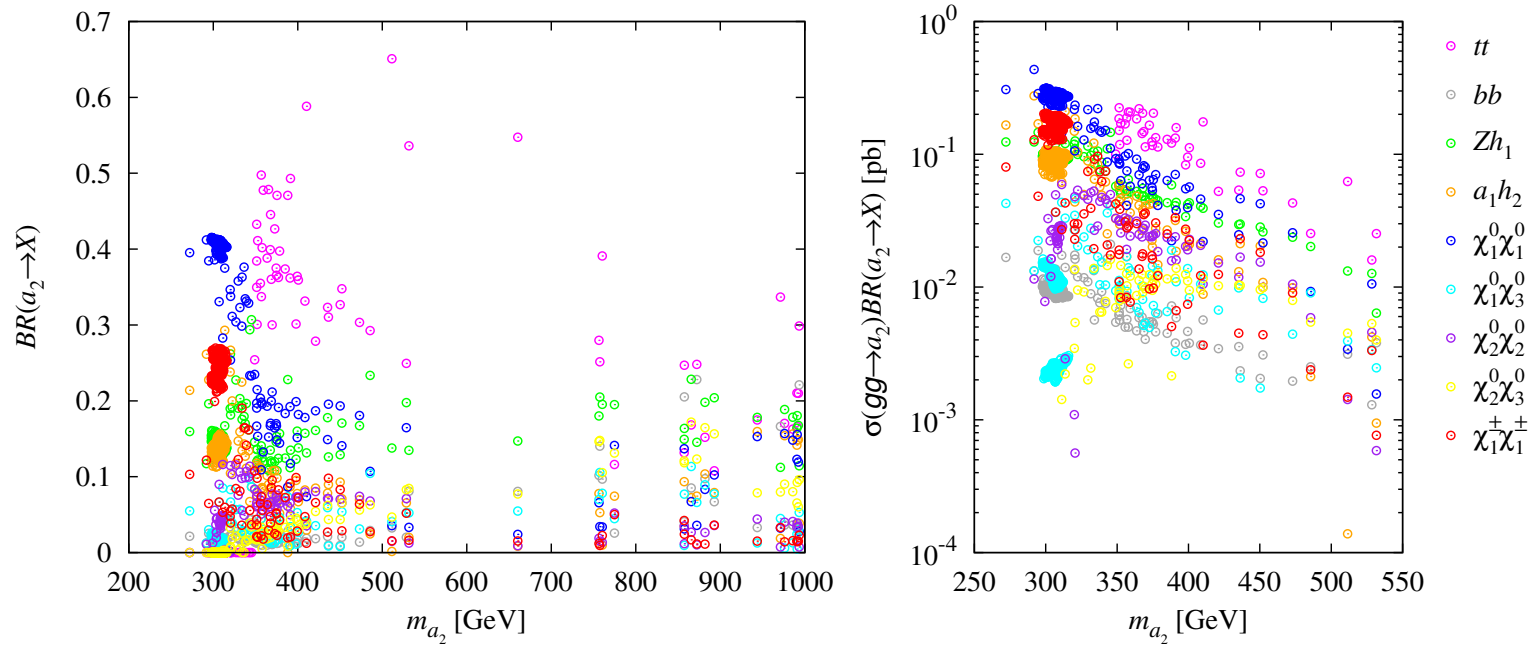
No doubt, efficient  $b$  tagging and reconstruction of the  $t\bar{t}$  invariant mass in, say, the single lepton final state would be needed.

- For  $m_{a_2} < 2m_t$ , the  $X = a_1 h_2$  final state with both  $a_1$  and  $h_2$  decaying to  $b\bar{b}$  might be visible above backgrounds.

However, a dedicated study of this particular decay mode is still lacking.

Similar remarks apply in the case of the  $h_3$  where the possibly visible final states are  $t\bar{t}$  for  $m_{h_3} > 2m_t$  and  $h_1 h_2$  for  $m_{h_3} < 2m_t$ .

For both the  $a_2$  and  $h_3$ ,  $\sigma\text{BR}(X)$  is substantial for  $X = \tilde{\chi}_1^0 \tilde{\chi}_1^0$ , but to isolate this invisible final state would require an additional photon or jet tag which would reduce the cross section from the level shown.



**Figure 22:** Decay branching ratios and LHC cross sections in the  $gg$  fusion mode (at  $\sqrt{s} = 8$  TeV) for  $a_2$  and  $h_3$

Well, the story goes, with complicated decays of neutralinos and charginos to the various lighter Higgs bosons.

No time to go into it all here.

We do think this scenario is an intriguing one and hope experimentalists will educate themselves about some of its peculiarities.

It is possible, but far from guaranteed (in the low- $m_{\tilde{\chi}_1^0}$  region), that  $\sigma_{SI}$  is large enough to be detectable soon.

## Conclusions

- It seems likely that the Higgs responsible for EWSB has emerged.
- 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 or LEP3 or muon collider in order to understand fully the responsible BSM physics.
- In any case, the current situation illustrates the fact that we must never assume we have uncovered all the Higgs.

**Certainly, I will continue watching and waiting**

