Degenerate Higgs bosons at 126 GeV?

Jack Gunion
U.C. Davis

Grenoble Higgs Workshop, March 19, 2013

1. *"Diagnosing Degenerate Higgs Bosons at 125 GeV"* J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1208.1817 [hep-ph]
2. *"Could two NMSSM Higgs bosons be present near 125 GeV?"* J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1207.1545 [hep-ph]
3. *"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)
4. *"Two-Higgs-Doublet Models and Enhanced Rates for a 125 GeV Higgs"* A. Drozd, B. Grzadkowski, J. F. Gunion and Y. Jiang. arXiv:1211.3580 [hep-ph]

Higgs-like LHC Signal

- Fits with MVA CMS suggest we are heading towards the SM, but it could simply be a "decoupling" limit of a more complicated model.
- Still, there are discrepancies between ATLAS and CMS that are reduced if CiC CMS is right — both ATLAS and CMS agree on enhanced $\gamma\gamma$ rate relative to SM.
- Further, both experiments have enhanced $\gamma\gamma$ rate in VBF.
- ZZ and WW rates are quite SM-like in CMS, but enhanced in ATLAS data.
- ATLAS has a Higgs mass discrepancy between the ZZ and the $\gamma\gamma$ final state.

- **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 the "standard" model must we go to describe them?**
3. **If they don't survive, must it be the SM or the decoupling limit of an extended Higgs sector or could considerable complexity underlie an apparently SM-like signal?**
4. **It seems that whether or not the signal appears to be a single**

SM-like Higgs boson, it could nonetheless come from several overlapping Higgs bosons.

The Models

1. 2HDM
   There are certainly parameter choices, especially in Type I model for which all signal strengths are SM-like despite being from both $h + A$, but also enhancements are possible.
2. NMSSM
   Same story: $h_1 + h_2$ can combine to give either SM-like net signal or enhancement relative to SM.
3. Higgs-radion
   The $\gamma\gamma$ and gg couplings of the radion are anomalous and this opens up non-2HDM situations when the Higgs and radion physical eigenstates are degenerate.

How to decide?

Double ratios are one very important tool.

NMSSM

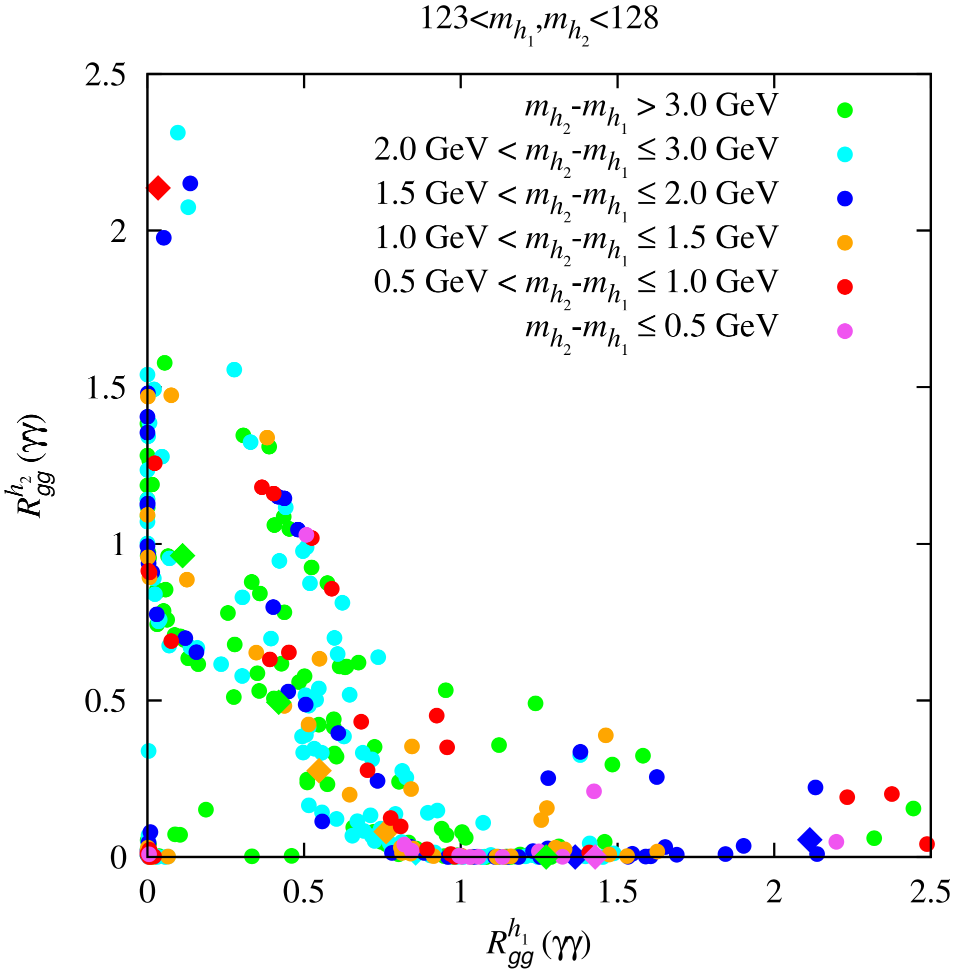

Figure 1: **Correlation of $gg \to (h_1, h_2) \to \gamma\gamma$ signal strengths when both h_1 and h_2 lie in the 123–128 GeV mass range. The circular points have $\Omega h^2 < 0.094$, while diamond points have $0.094 \leq \Omega h^2 \leq 0.136$. Points are color coded according to $m_{h_2} - m_{h_1}$. Probably green and cyan points can be resolved in mass.**

- In plot above, 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, but not all, of the displayed points have $R^{h_1}_{gg}(\gamma\gamma) + R^{h_2}_{gg}(\gamma\gamma) > 1$.
- The majority of the points with $R^{h_1}_{gg}(\gamma\gamma) + R^{h_2}_{gg}(\gamma\gamma) > 1$ have $\Omega h^2 < 0.094$ and the $\gamma\gamma$ signal is often shared between the h_1 and the h_2.

Now combine the h_1 and h_2 signals.

1. red for $m_{h_2} - m_{h_1} \leq 1~\mathrm{GeV}$;
2. blue for $1~\mathrm{GeV} < m_{h_2} - m_{h_1} \leq 2~\mathrm{GeV}$;
3. green for $2~\mathrm{GeV} < m_{h_2} - m_{h_1} \leq 3~\mathrm{GeV}$.

- For current statistics and $\sigma_{\rm res} \gtrsim 1.5~\mathrm{GeV}$ we estimate that the h_1 and h_2 signals will not be seen separately for $m_{h_2} - m_{h_1} \leq 2~\mathrm{GeV}$.
- In Fig. 2, we show results for $R^h_{gg}(X)$ for $X = \gamma\gamma, VV, b\bar{b}$. Enhanced $\gamma\gamma$ and VV rates from gluon fusion are very common, but so are points with SM-like rates in all channels.

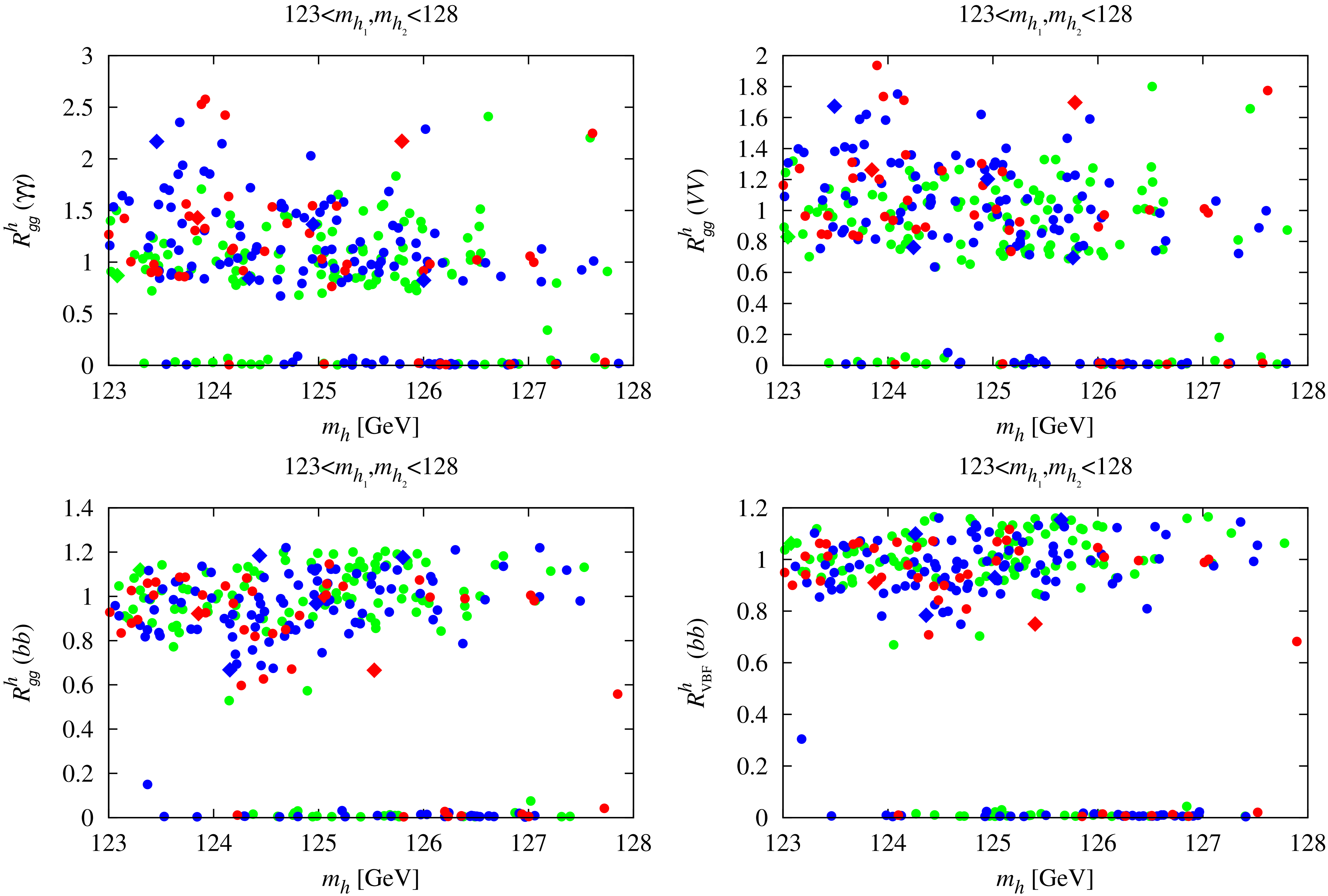

Figure 2: $R^h_{gg}(X)$ for $X = \gamma\gamma, VV, b\bar{b}$, and $R^h_{\rm VBF}(b\bar{b})$ versus m_h. For application to the Tevatron, note that $R^h_{\rm VBF}(b\bar{b}) = R^h_{V*\to Vh}(b\bar{b})$.

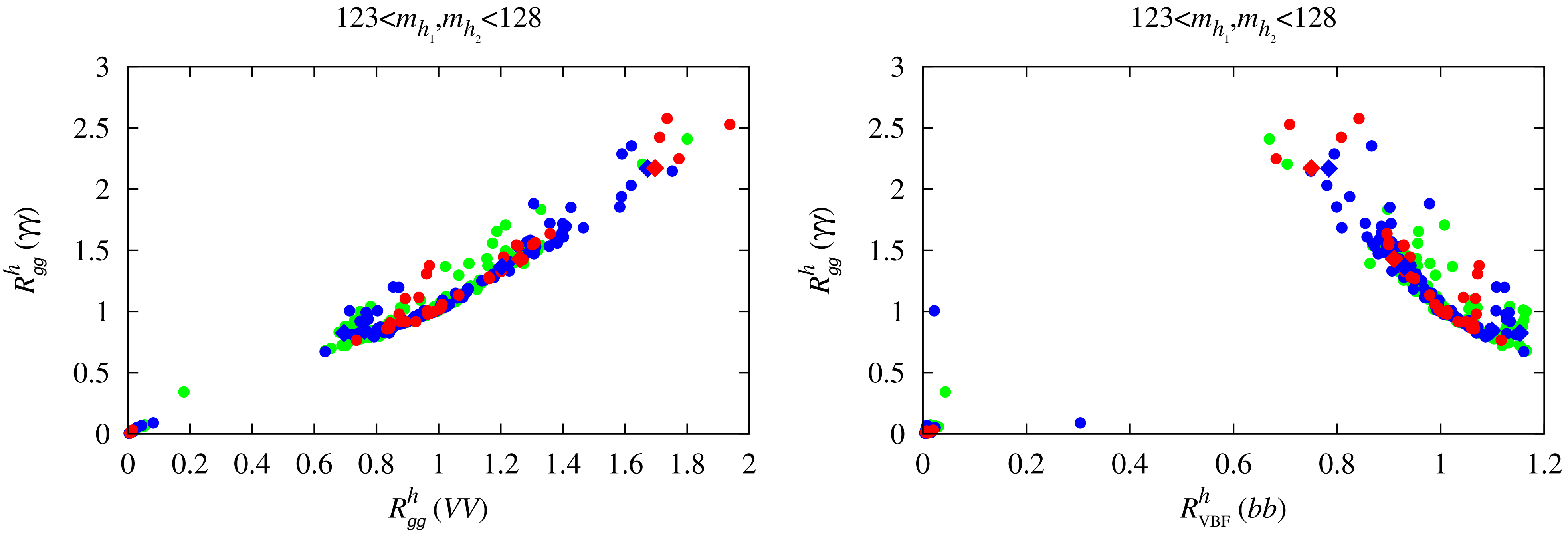

Figure 3: **Left: correlation between the gluon fusion induced $\gamma\gamma$ and VV rates relative to the SM. Right: correlation between the gluon fusion induced $\gamma\gamma$ rate and the VV fusion induced $b\overline{b}$ rates relative to the SM; the relative rate for $V^* \to Vh$ with $h \to b\overline{b}$ (relevant for the Tevatron) is equal to the latter.**

- **Comments on Fig. 3:**
  1. **Left-hand plot shows the strong correlation between $R^h_{gg}(\gamma\gamma)$ and $R^h_{gg}(VV)$. Note that if $R^h_{gg}(\gamma\gamma) \sim 1.5$, then in this model $R^h_{gg}(VV) \geq 1.2$.**
  2. **The right-hand plot shows the (anti) correlation between $R^h_{gg}(\gamma\gamma)$ and $R^h_{V^*\to Vh}(b\overline{b}) = R^h_{\rm VBF}(b\overline{b})$.**

In general, the larger $R^h_{gg}(\gamma\gamma)$ is, the smaller the value of $R^h_{V^*\to Vh}(b\overline{b})$.
However, this latter plot shows that there *are* parameter choices for which both the $\gamma\gamma$ rate at the LHC and the $V^* \to Vh(\to b\overline{b})$ 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 $R^h_{gg}(\gamma\gamma)$ while the other dominates $R^h_{V^*\to Vh}(b\overline{b})$. 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 $b\overline{b}$ signal receives substantial contributions from both the h_1 and the h_2.
   We did not find points where the $\gamma\gamma$ and $b\overline{b}$ final states *both* receive substantial contributions from *both* the h_1 and h_2.

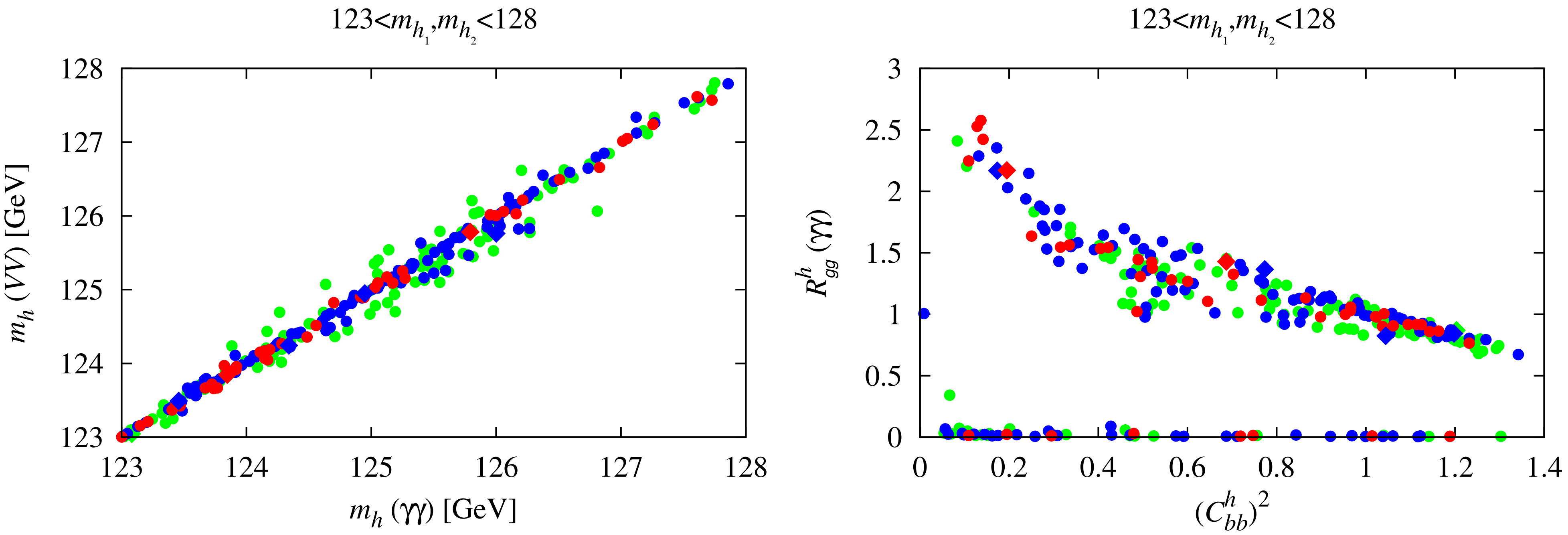

Figure 4: **Left: effective Higgs masses obtained from different channels: $m_h^{gg}(\gamma\gamma)$ versus $m_h^{gg}(VV)$. Right: $\gamma\gamma$ signal strength $R^h_{gg}(\gamma\gamma)$ versus effective coupling to $b\bar b$ quarks $(C^h_{b\bar b})^2$. Here, ${C^h_{b\bar b}}^2 \equiv \left[R^{h_1}_{gg}(\gamma\gamma){C^{h_1}_{b\bar b}}^2 + R^{h_2}_{gg}(\gamma\gamma){C^{h_2}_{b\bar b}}^2\right] / \left[R^{h_1}_{gg}(\gamma\gamma) + R^{h_2}_{gg}(\gamma\gamma)\right]$.**

Comments on Fig. 4

1. **The m_h values for the gluon fusion induced $\gamma\gamma$ and VV cases are also strongly correlated — see the left plot of Fig. 4.**

Separate Mass Peaks for ZZ vs. $\gamma\gamma$

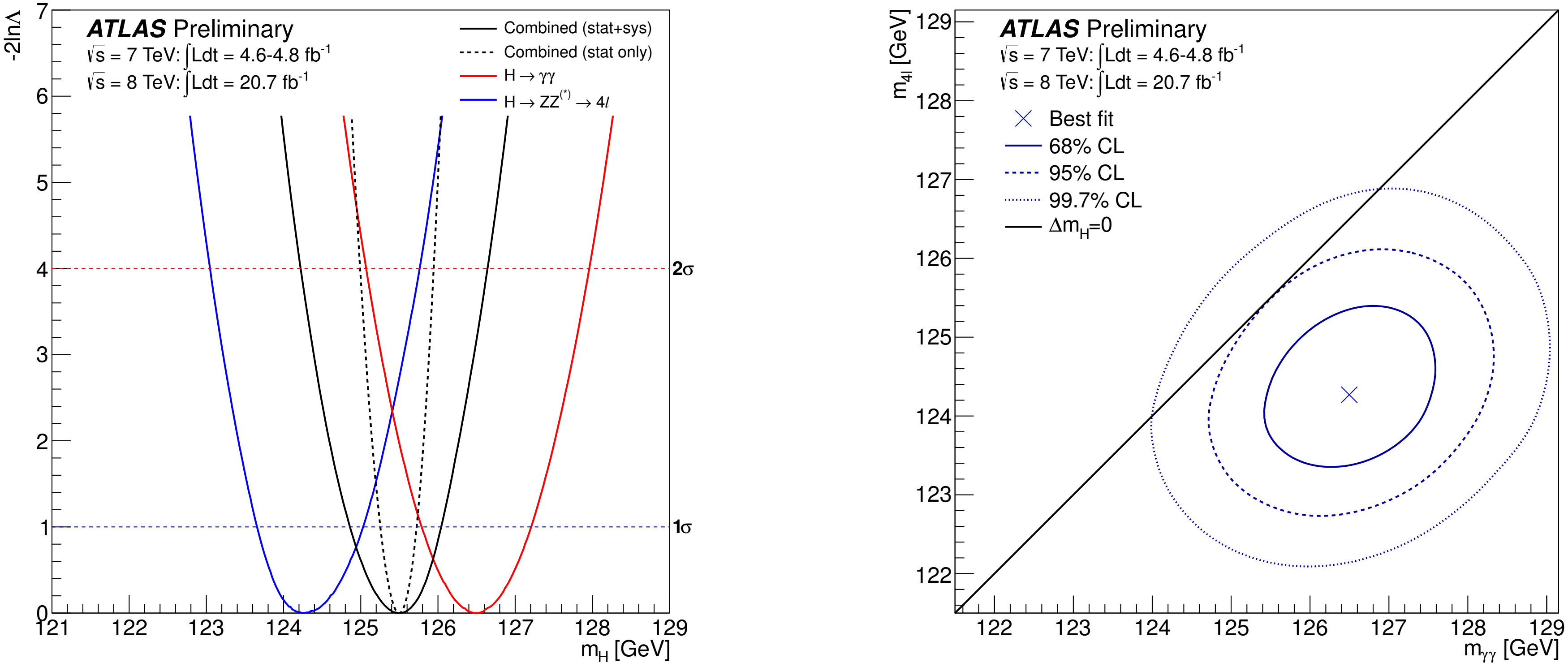

Figure 5: Mass plots for ZZ and $\gamma\gamma$ final states.

In the above plot of combined m_H, it is assumed that there is just one Higgs boson, $i.e.$ multiply two probability distributions. How should you consider such results if there are actually two Higgs bosons.

- h_1 should have $m_{h_1} \sim 124.3~\mathrm{GeV}$ and ZZ rate not too much smaller than SM-like rate, but suppressed $\gamma\gamma$ rate.

- h_2 should have $m_{h_2} \sim 126.5~\mathrm{GeV}$ and enhanced $\gamma\gamma$ and somewhat suppressed ZZ rate.

- The kind of extreme apparently seen by ATLAS is hard to arrange in the NMSSM.

  This is because the mechanism for getting enhanced $\gamma\gamma$ (suppression of bb partial width through mixing) automatically also enhances ZZ. Recall the correlation plot given earlier

- To assess a bit more quantitatively, we compute $m_h(VV)$ vs. $m_h(\gamma\gamma)$ using previous formula involving weighting by $R_{gg}^{h_1,h_2}(ZZ)$ and $R_{gg}^{h_1,h_2}(\gamma\gamma)$ and accepting points with $121~\mathrm{GeV} \leq m_{h_1}, , m_{h_2} \leq 128~\mathrm{GeV}$.

  Or, selecting points with $122~\mathrm{GeV} < m_{h_1} < 124~\mathrm{GeV}$ (for pre-Moriond data set) and $125~\mathrm{GeV} < m_{h_2} < 127~\mathrm{GeV}$.

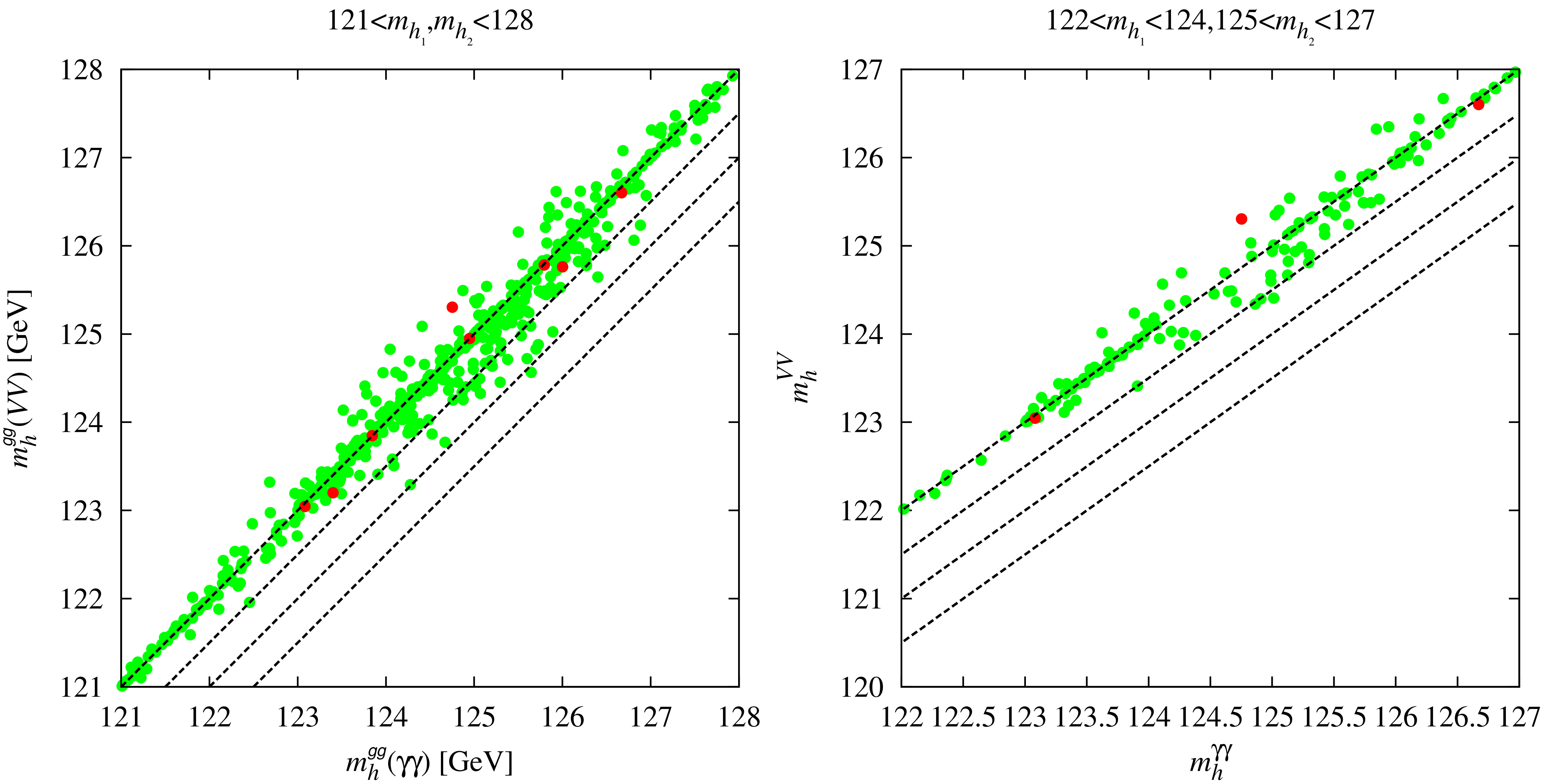

Figure 6: m_h **obtained in** ZZ **vs.** $\gamma\gamma$ **final state when scanning and requiring:** $121~\mathrm{GeV} \leq m_{h_1}, m_{h_2} \leq 128~\mathrm{GeV}$ **(Left) or** $122~\mathrm{GeV} < m_{h_1} < 124~\mathrm{GeV}$, $125~\mathrm{GeV} < m_{h_2} < 127~\mathrm{GeV}$ **(Right). Dashed lines show** $m_h(ZZ) = m_h(\gamma\gamma) - (0, 0.5, 1, 1.5)$. **Red dots are in WMAP window. Hard to get a mass shift of more than** $1~\mathrm{GeV}$.

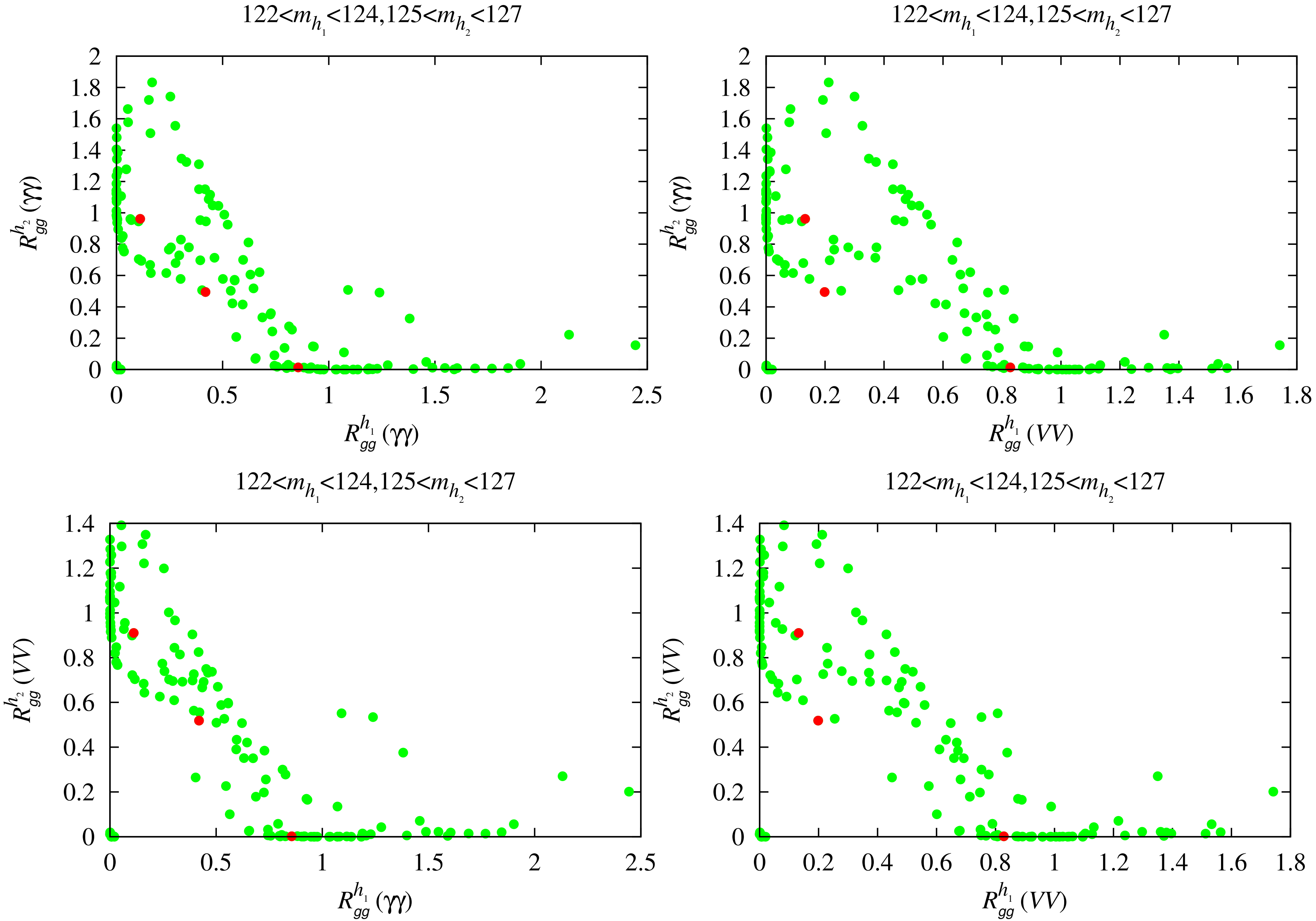

Figure 7: Too much correlation between VV and $\gamma\gamma$ channels for the h_1 and h_2 separately.

- **Note: if $\gamma\gamma$ rate is large for h_2 then VV rate for h_1 is small — *i.e.* the opposite of what we want.**

Diagnosing the presence of degenerate Higgses

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

- Given that enhanced (and non-enhanced) $R^h_{gg}(\gamma\gamma)$ is very natural if there are degenerate Higgs mass eigenstates, how do we detect degeneracy if closely degenerate? 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:

$$R^h_{gg}(VV), \quad R^h_{gg}(bb), \quad R^h_{gg}(\gamma\gamma), \quad R^h_{VBF}(VV), \quad R^h_{VBF}(bb), \quad R^h_{VBF}(\gamma\gamma)\,. \tag{1}$$

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

$$R^h_Y(X) = \sum_{i=1,2} \frac{(C^{h_i}_Y)^2 (C^{h_i}_X)^2}{C^{h_i}_\Gamma} \tag{2}$$

  where $C^{h_i}_X$ for $X = \gamma\gamma, WW, ZZ, \ldots$ is the ratio of the $h_i X$ to $h_{SM} X$ coupling and $C^{h_i}_\Gamma$ 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:

$$\text{I):}\ \frac{R^h_{VBF}(\gamma\gamma)/R^h_{gg}(\gamma\gamma)}{R^h_{VBF}(bb)/R^h_{gg}(bb)}, \quad \text{II):}\ \frac{R^h_{VBF}(\gamma\gamma)/R^h_{gg}(\gamma\gamma)}{R^h_{VBF}(VV)/R^h_{gg}(VV)}, \quad \text{III):}\ \frac{R^h_{VBF}(VV)/R^h_{gg}(VV)}{R^h_{VBF}(bb)/R^h_{gg}(bb)}, \tag{3}$$

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. (2), 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. 8, 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 $R^h_{gg}(\gamma\gamma)$ and $R^h_{gg}(VV)$ 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 preferred by ATLAS data) $R^h_{gg}(\gamma\gamma) > 1$, see the solid (vs. open) symbols of Fig. 8.
- This is further elucidated in Fig. 9 where we display the double ratios I) and II) as functions of $R^h_{gg}(\gamma\gamma)$ (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 $gg \to \gamma\gamma$ rate, see the top right plot of Fig. 9.

In comparison, double ratio II) is most useful for scenarios with $R^h_{gg}(\gamma\gamma) \sim 1$, as illustrated by the bottom left plot of Fig. 9.

- **Thus, as illustrated by the bottom right plot of Fig. 9, 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, there are experimental errors.

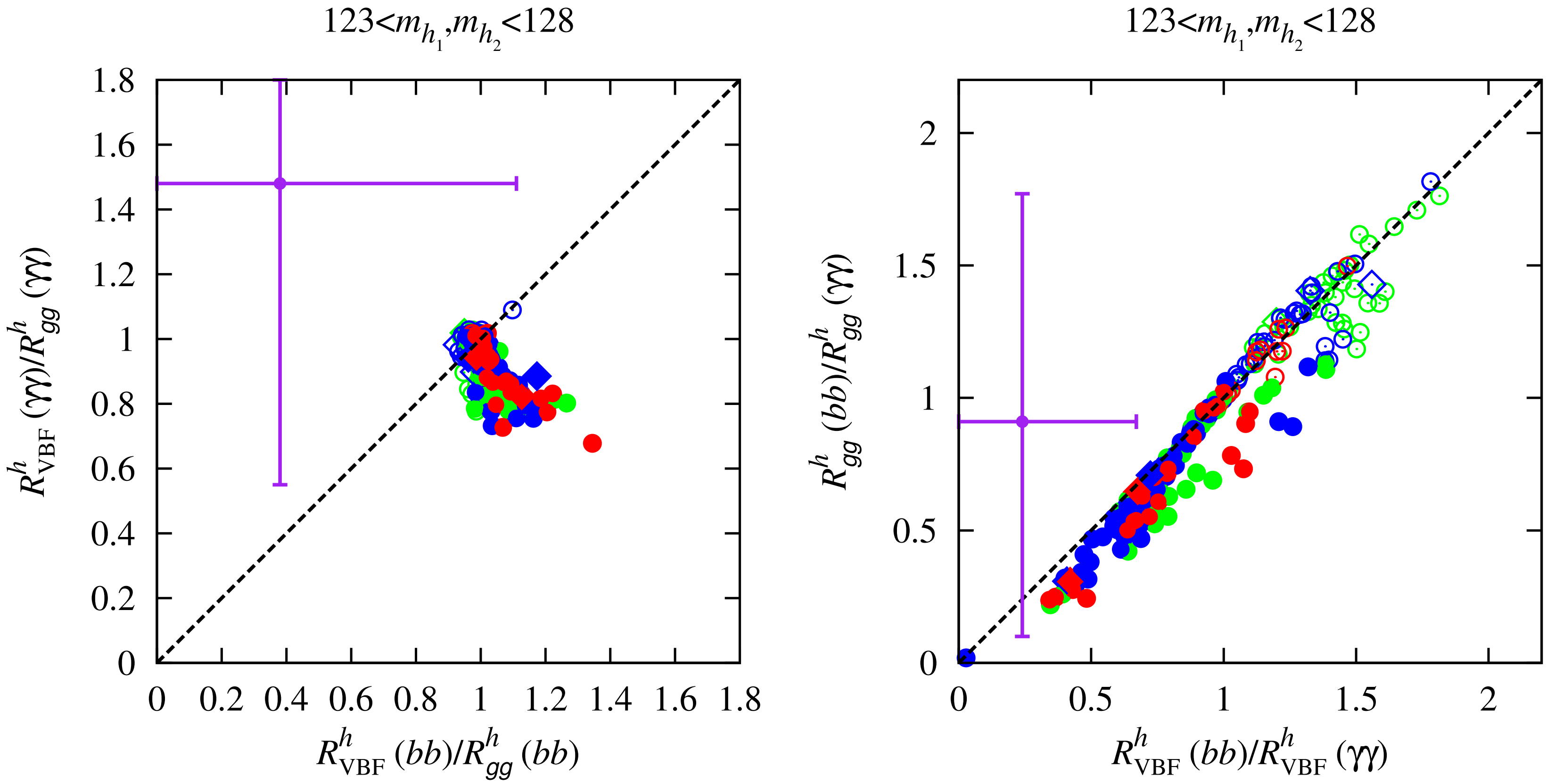

Figure 8: **Comparisons of pairs of event rate ratios that should be equal if only a single Higgs boson is present. The color code is green for points with $2~\mathrm{GeV} < m_{h_2} - m_{h_1} \leq 3~\mathrm{GeV}$, blue for $1~\mathrm{GeV} < m_{h_2} - m_{h_1} \leq 2~\mathrm{GeV}$, and red for $m_{h_2} - m_{h_1} \leq 1~\mathrm{GeV}$. Large diamond points have Ωh^2 in the WMAP window of $[0.094, 0.136]$, while circular points have $\Omega h^2 < 0.094$. Solid points are those with $R^h_{gg}(\gamma\gamma) > 1$ and open symbols have $R^h_{gg}(\gamma\gamma) \leq 1$. Current experimental values for the ratios from CMS data along with their 1σ error bars are also shown.**

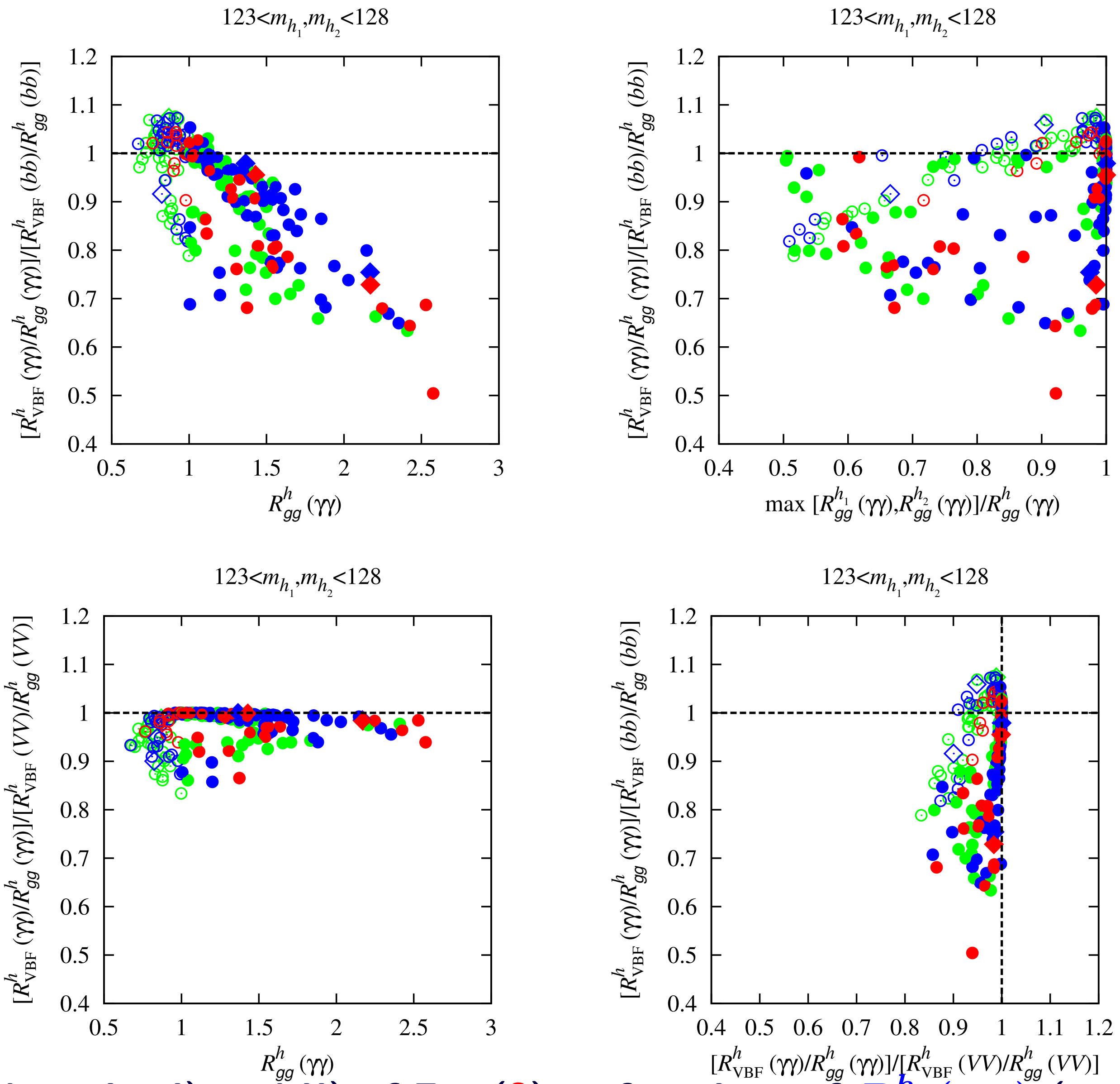

Figure 9: **Double ratios I) and II) of Eq. (3) as functions of $R^h_{gg}(\gamma\gamma)$ (on the left). On the right we show (top) double ratio I) vs. $\max\left[R^{h_1}_{gg}(\gamma\gamma), R^{h_2}_{gg}(\gamma\gamma)\right]/R^h_{gg}(\gamma\gamma)$ and (bottom) double ratio I) vs. double ratio II) for the points displayed in Fig. 8. Colors and symbols are the same as in Fig. 8.**

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

  The central values and 1σ error bars for the numerator and denominator of double ratios I) and II) obtained from CMS data (CMS-PAS-HIG-12-020) are also shown in Fig. 8.

  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 $\sqrt{s} = 14~\mathrm{TeV}$ run with $\geq 100~\mathrm{fb}^{-1}$ of accumulated luminosity.

  Nonetheless, it is clear that the double-ratio diagnostic tools will ultimately prove viable and perhaps crucial for determining if the $\sim 125~\mathrm{GeV}$ 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-radion case

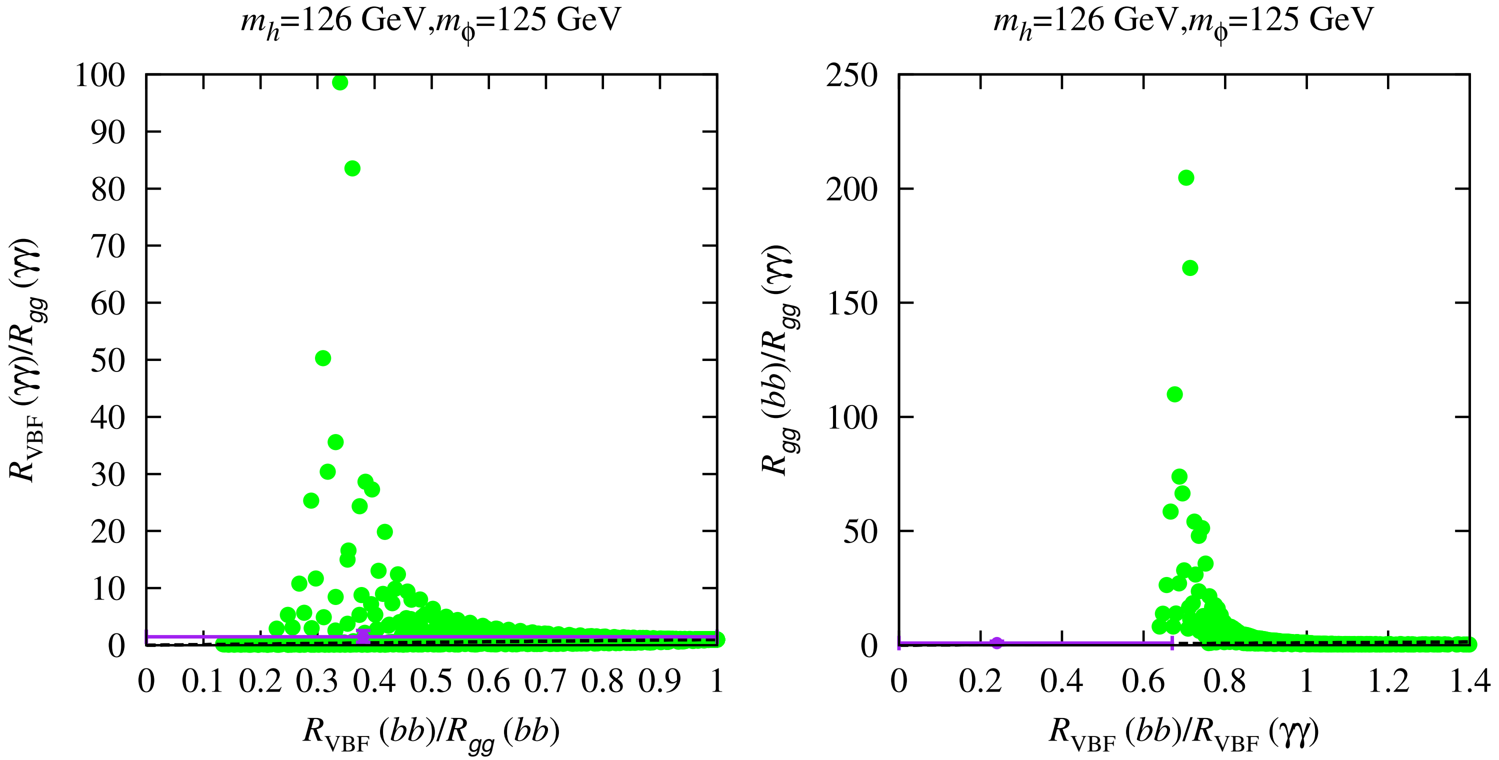

Figure 10: **Equal double ratio line is hardly visible at bottom.**

- **Much bigger deviations of double ratios from being equal, related to anomalous gg and $\gamma\gamma$ couplings of the radion. (Compare to first NMSSM plot of preceding section)**

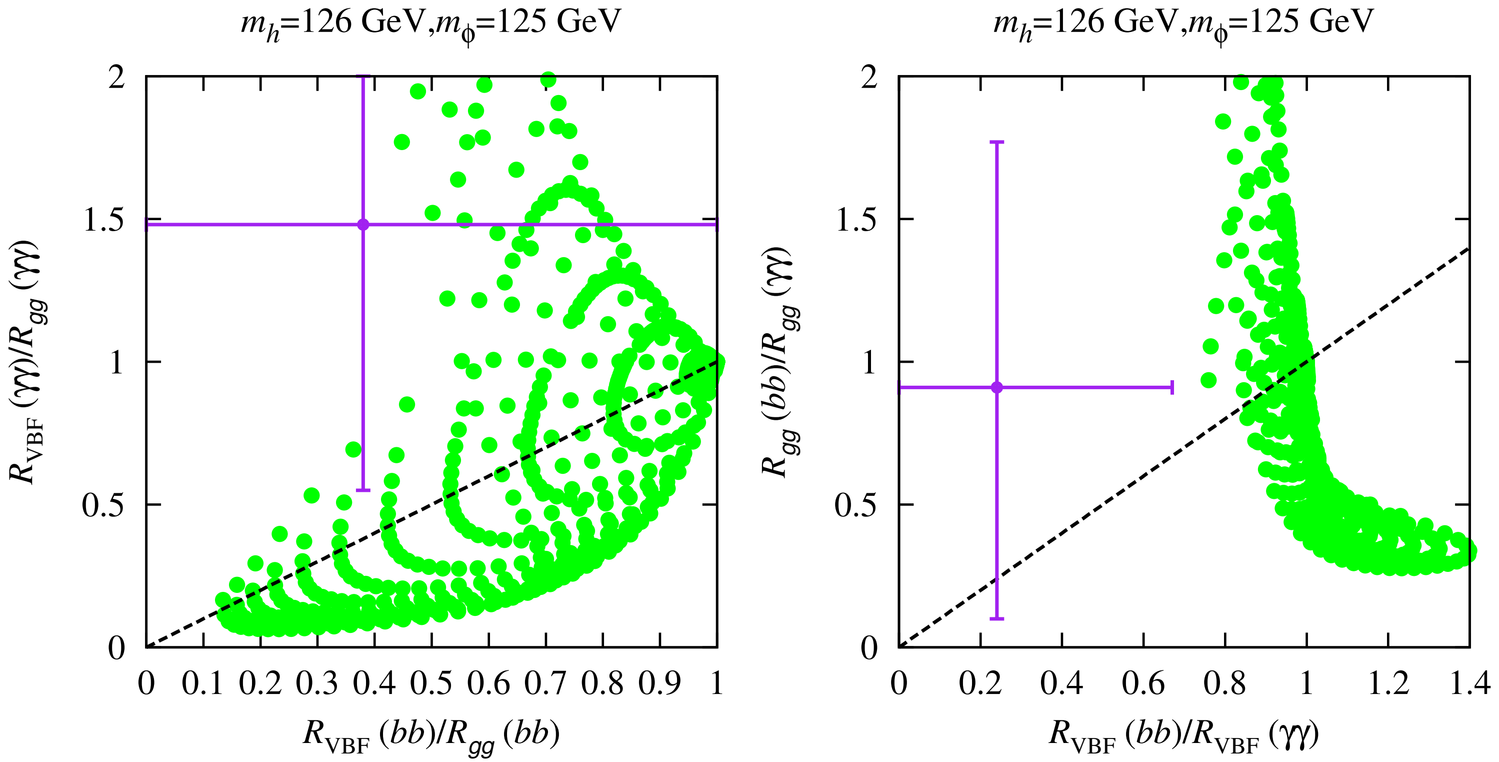

Figure 11: **A better scale to use when comparing to NMSSM case.**