# Searches for low-mass (pseudo) scalars


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# The present situation

- We have now observed a very SM-like Higgs state near $125.5\ \mathrm{GeV}$.

  The observed mass is very exciting, both experimentally and theoretically, given the large number of production/decay modes in which a signal can be seen and given the fact that $125.5\ \mathrm{GeV}$ is close to being **too large** for SUSY to "naturally" predict and **too small** for the SM to be valid all the way to the Planck scale.

  The ongoing order of business is to quantify the observed signal. If we compute $C_g$ and $C_\gamma$ (relative to the SM values) using only SM loops and take $C_D = C_L$, and $C_W = C_Z \equiv C_V$ as is the case for many models, we obtain:

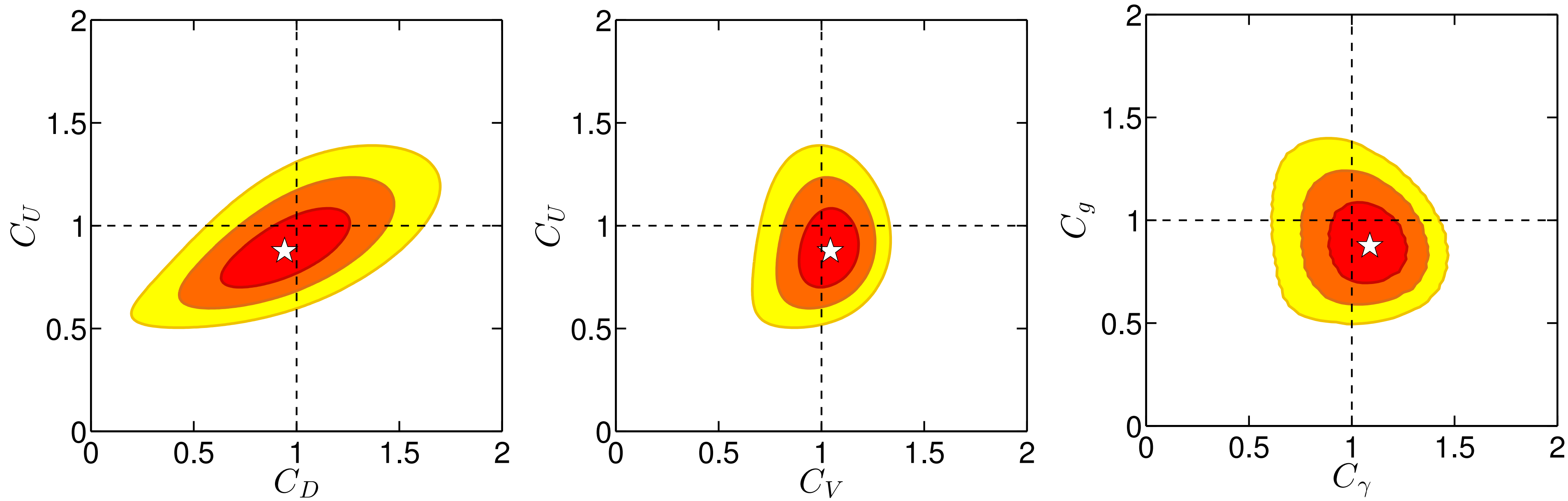


**Figure 1:** **Coupling constant ellipses. The filled red, orange and yellow ellipses show the 68%, 95% and 99.7% CL regions, respectively,. The white stars mark the best-fit points.**

**Certainly, the SM is doing quite well. Fitting to relative coupling constants for the SM-like Lagrangian, one finds that $C_U, C_D, C_V$ are fully consistent with SM-like values of unity, while extra contributions to the $\gamma\gamma$ and $gg$ loop diagrams are consistent with being absent.**

**However, this result could be misleading in a number of ways.**

- **In particular, there is the generic possibility of invisible (inv) and/or unseen ($U$), but not truly invisible, Higgs decays.**

  **Invisible decays are now somewhat constrained by searches for $ZH$ production with $Z$ detection in some channel or other and requiring that no tracks etc. are present that could come from the $H$.**

  **An overview of the current status of truly invisible decays, including the $ZH$ limits, is given in Fig. 2, which shows the behavior of $\Delta\chi^2$ as a function of $BR_{\rm inv}$ for various different cases of interest:**
  **a) SM, $C_U = C_D = C_V = 1$ and $\Delta C_\gamma, \Delta C_g = 0$, where $\Delta C_\gamma$ and $\Delta C_g$ are from BSM contributions to the $H\gamma\gamma$ and $Hgg$ couplings — one finds $BR_{\rm inv} < 0.09$ ($0.19$);**
  **b) $C_U = C_D = C_V = 1$ but $\Delta C_\gamma, \Delta C_g$ allowed for — $BR_{\rm inv} < 0.11$ ($0.29$);**
  **c) $C_U, C_D, C_V$ free, $\Delta C_\gamma = \Delta C_g = 0$, — $BR_{\rm inv} < 0.15$ ($0.36$); relaxed if $\text{inv} \to U$**
  **d) $C_U, C_D$ free, $C_V \leq 1$, $\Delta C_\gamma = \Delta C_g = 0$ — $BR_{\rm inv} < 0.09$ (0.24);**
  **e) $C_U, C_D, C_V, \Delta C_g, \Delta C_\gamma$ free — $BR_{\rm inv} < 0.16$ ($0.38$); relaxed if $\text{inv} \to U$.**
  **(All $BR_{\rm inv}$ limits are given at $68\%$ (95%) CL.)**

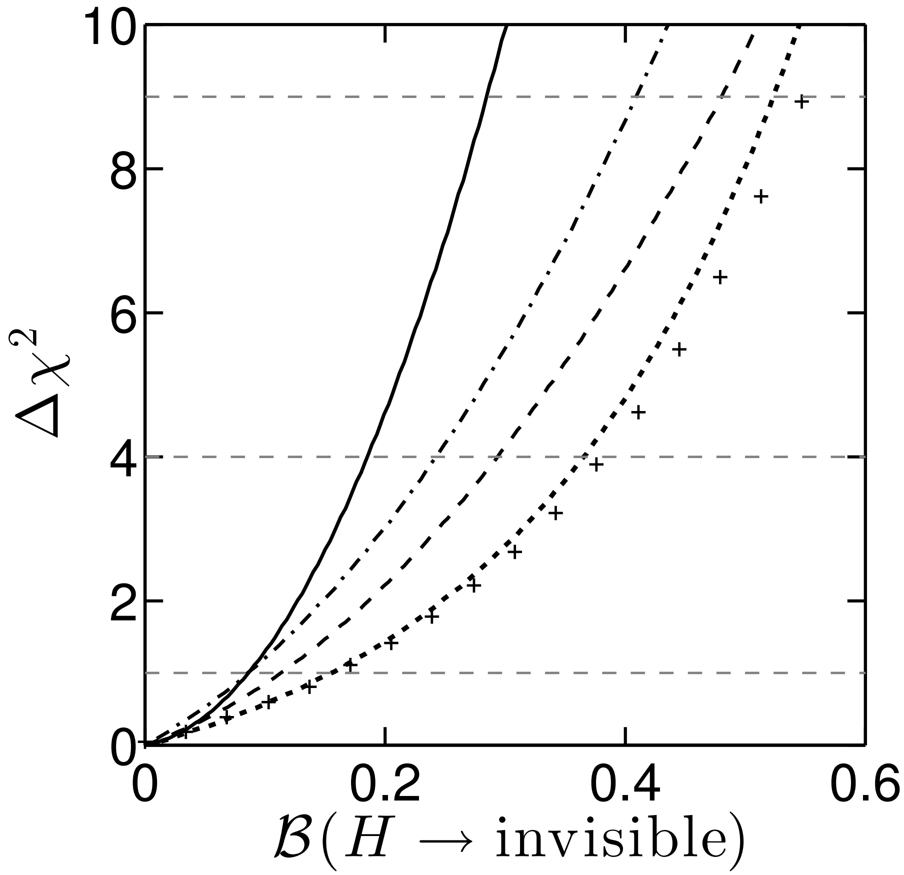


**Figure 2:** $\Delta\chi^2$ **distributions for the branching ratio of invisible Higgs decays for various cases. Solid: SM+invisible. Dashed: varying** $\Delta C_g$ **and** $\Delta C_\gamma$ **for** $C_U = C_D = C_V = 1$**. Dotted: varying** $C_U$**,** $C_D$ **and** $C_V$ **for** $\Delta C_g = \Delta C_\gamma = 0$**. Dot-dashed: varying** $C_U$**,** $C_D$ **and** $C_V \leq 1$ **for** $\Delta C_g = \Delta C_\gamma = 0$**. Crosses: varying** $C_U$**,** $C_D$**,** $C_V$**,** $\Delta C_g$ **and** $\Delta C_\gamma$**.**

## Notes:

– **While $BR_{\rm inv}$ is certainly significantly limited by the current data set, there remains ample room for invisible decays.**

– **When $C_V \leq 1$, $H \rightarrow$invisible is much more constrained by the global fits to the $H$ properties than by the direct searches for invisible decays, *cf.* the solid, dashed and dash-dotted lines in Fig. 2. $\Rightarrow$nothing changes if $\rm inv \rightarrow U$**

– **For unconstrained $C_U$, $C_D$ and $C_V$, on the other hand, *cf.* dotted line and crosses in Fig. 2, the limit comes from the direct search for invisible decays in the $ZH$ channel.**

**However, if the $H$ decays are simply unseen, but not truly invisible, the story can be very different.**

**There is a well-known flat direction in the Higgs fitting game. Let us postulate an unseen ($U$) mode (such as $aa$ or $6g$) with branching ratio $BR_U$. Then, if the LHC signal rates are well fit by certain choices of $C_U, C_D, C_V$ (say with $\Delta C_\gamma = \Delta C_g = 0$) for $BR_U = 0$ then an equally good**

**fit for any value of $BR_U$ is obtained by the rescaling**

$$C_i^2 \to \frac{C_i^2}{1 - BR_U} \tag{1}$$

**This can give a greatly increased rate for actually observing a difficult channel such as $H \to aa$; for example, if one takes $BR_U \sim \frac{1}{2}$ then *production* rates are increased by a factor of 2.**

**However, if $C_V \leq 1$ is imposed as a model constraint, then the Higgs fits alone imply (as stated above) $BR_U \leq 0.29$ at 95% CL if $\Delta C_\gamma = \Delta C_g = 0$.**

**Thus, at the moment, there is still significant room for the Higgs to deviate from SM expectations, in this and other ways to be discussed below.**

**It remains entirely possible that the $H$ could prove to be a portal to BSM physics.**

# Future possibilities

1. The Higgs measurements converge ever more closely towards the SM — how will this constrain various BSM models?

2. Deviations are detected such as an enhanced $\gamma\gamma$ rate in ggF or VBF.

In this talk, I will assume that the observed Higgs is highly SM-like and discuss the consequences for light pseudoscalars.

- The 2HDM — all constraints, including Higgs fits, imposed at 95% CL

(Dumont, Gunion, Jiang, Kraml, in preparation)

The most general 2HDM Higgs potential is given by

$$
\begin{aligned}
V &= m_1^2|H_1|^2 + m_2^2|H_2|^2 + \frac{\lambda_1}{2}|H_1|^2 + \frac{\lambda_2}{2}|H_2|^2 + \lambda_3|H_1|^2|H_2|^2 \\
&\quad + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left((H_1H_2)^2 + \mathrm{c.c.}\right) + m_{12}^2\left(H_1H_2 + \mathrm{c.c.}\right) \\
&\quad + \left(\lambda_6|H_1|^2(H_1H_2) + \mathrm{c.c.}\right) + \left(\lambda_7|H_2|^2(H_1H_2) + \mathrm{c.c.}\right) \ .
\end{aligned} \tag{2}
$$

**The terms involving $\lambda_6$ and $\lambda_7$ represent a hard breaking of the $Z_2$ symmetry that is used to avoid excessive FCNC, so set them to 0. We also assume no CP violation, $i.e.$ all parameters are taken to be real.**

**Various different ways of specifying the parameters are possible. The most direct way is to specify the $\lambda_i$. But, for our purposes, it is best to determine the $\lambda_i$ in terms of the parameter set**

$$m_h, \quad m_H, \quad m_{H^\pm}, \quad m_A, \quad \tan\beta, \quad m_{12}^2, \quad \alpha\,, \tag{3}$$

**with $\beta \in [0, \pi/2]$, $\alpha \in [-\pi/2, +\pi/2]$ and where $m_{12}^2$ (the parameter that softly breaks the $Z_2$ symmetry that prevents large FCNC) can have either sign.**

**The two simplest models are called Type-I and Type-II with fermion couplings as given in the table.**

| | Type I and II | Type I | | Type II | |
|---|---|---|---|---|---|
| **Higgs** | $C_V$ | $C_U$ | $C_D$ | $C_U$ | $C_D$ |
| $h$ | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ |
| $H$ | $\cos(\beta-\alpha)$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ |
| $A$ | **0** | $\cot\beta$ | $-\cot\beta$ | $\cot\beta$ | $\tan\beta$ |

**Table 1:** **Tree-level vector boson couplings $C_V$ ($V=W,Z$) and fermionic couplings $C_F$ ($F=U,D$) normalized to their SM values for the Type I and Type II Two-Higgs-Doublet models.**

**Here we will consider the case where $m_h \sim 125~\mathrm{GeV}$ and we will look at the possibilities for the $A$ of the model, which, since $m_A$ is just a parameter, can have small mass.**

**So, what are the current constraints, including precision Higgs fitting within 95% CL?**

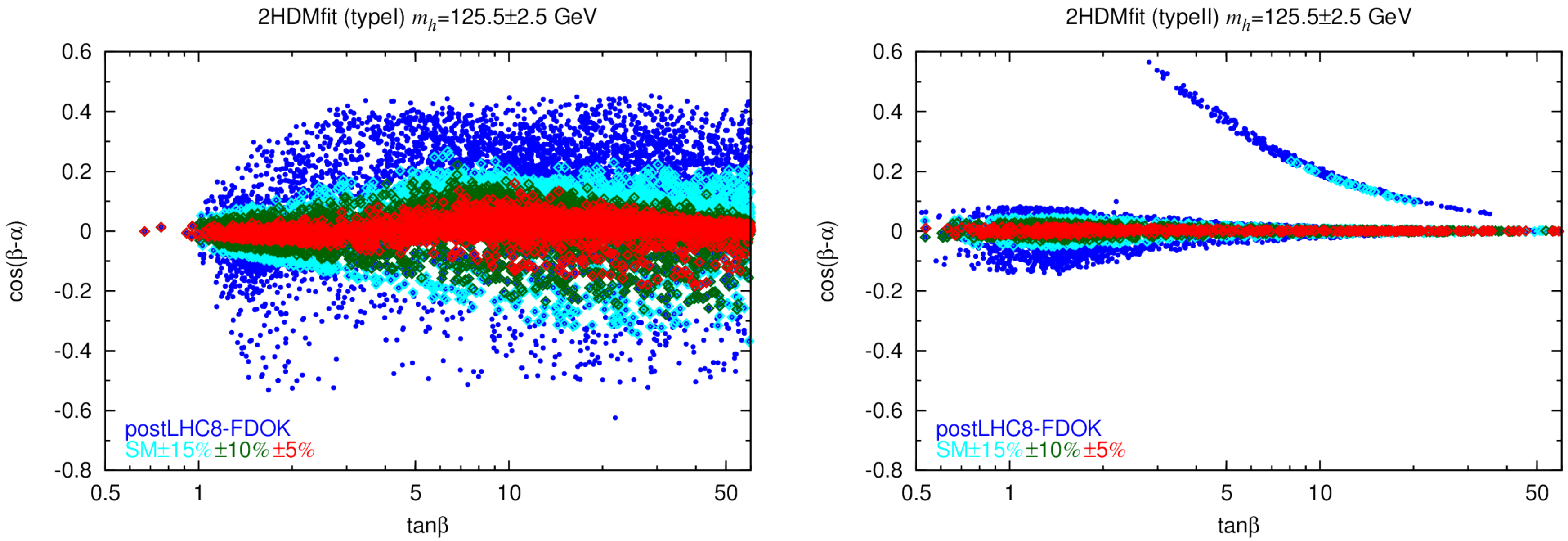


**Figure 3: Constraints on the 2HDM models of Type I and II in the $\cos(\beta-\alpha)$ versus $\tan\beta$ plane for $m_h \sim 125.5$ GeV. All points obey preLHC constraints, existing LHC limits on $H/A$ signals and all LHC Higgs measurements at 95% CL. Also shown are the changes associated with future higher precisions for *all* $X \to Y$ channels at the SM$\pm15\%$, $\pm10\%$, and $\pm5\%$ level.**

**The SM limit is $\cos(\beta-\alpha) \to 0$ for $m_h \sim 125$ GeV. For Type II there is a main branch that is very SM-like, but also an alternative branch that is quite different. The future LHC run can eliminate or confirm this branch.**

**$m_H = 125.5\ \mathrm{GeV}$ is also possible given current precisions, but this possibility will be eliminated if all signals are within $\pm 5\%$ of SM.**

**Let us now focus on low-$m_A < m_h/2$ points. Ones with sufficiently small $BR(h \to AA)$ and $BR(h \to ZA)$ exist, but it takes a highly tuned scan to find them since generically the coupling $\lambda_{hAA}$ is quite large. Since $g_{hZA} \propto \cos(\beta - \alpha)$, and $\cos(\beta - \alpha)$ is smallish, the $ZA$ channel is more easily suppressed given that the $h$ is fairly SM-like.**

**Features of the surviving points are shown in Figs. 4 and 5. Note the suppression of $\mu_{gg}(\gamma\gamma)$ and that $h \to ZA$ can still be an important channel. Obviously, both should be looked for!**

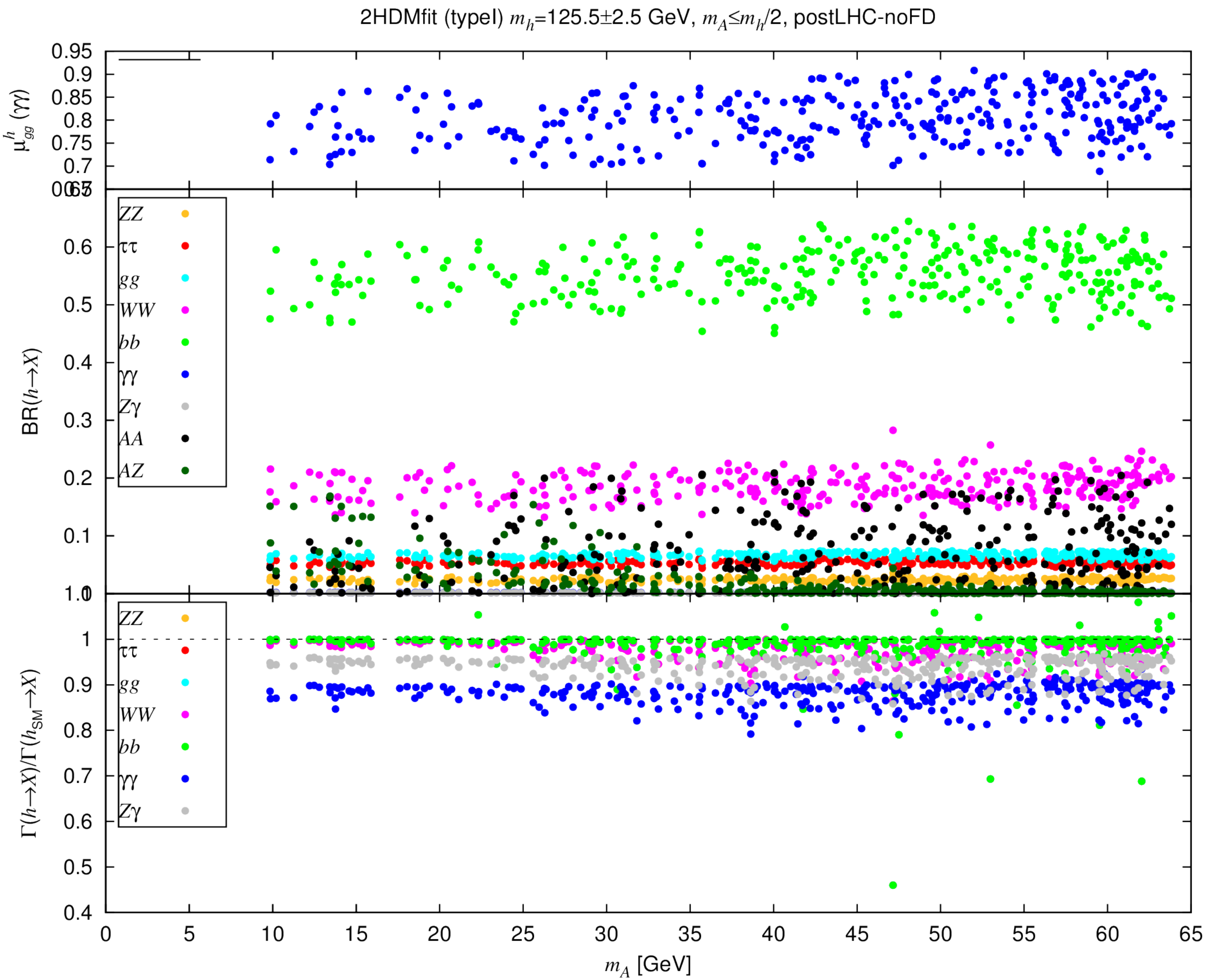


**Figure 4: Features of Type-I postLHC points with $m_A < m_h/2$.**

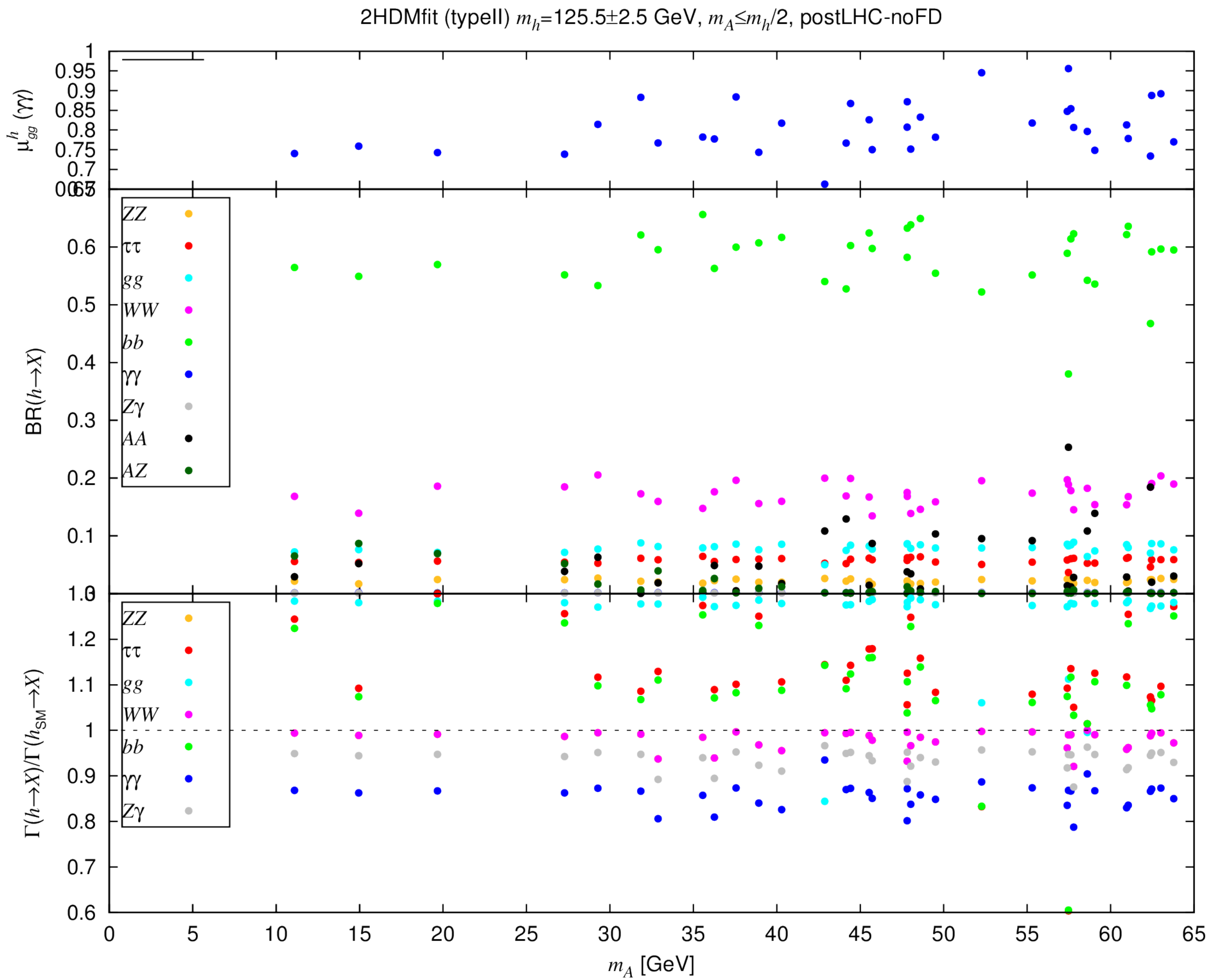


**Figure 5: Features of Type-II postLHC points with $m_A < m_h/2$.**

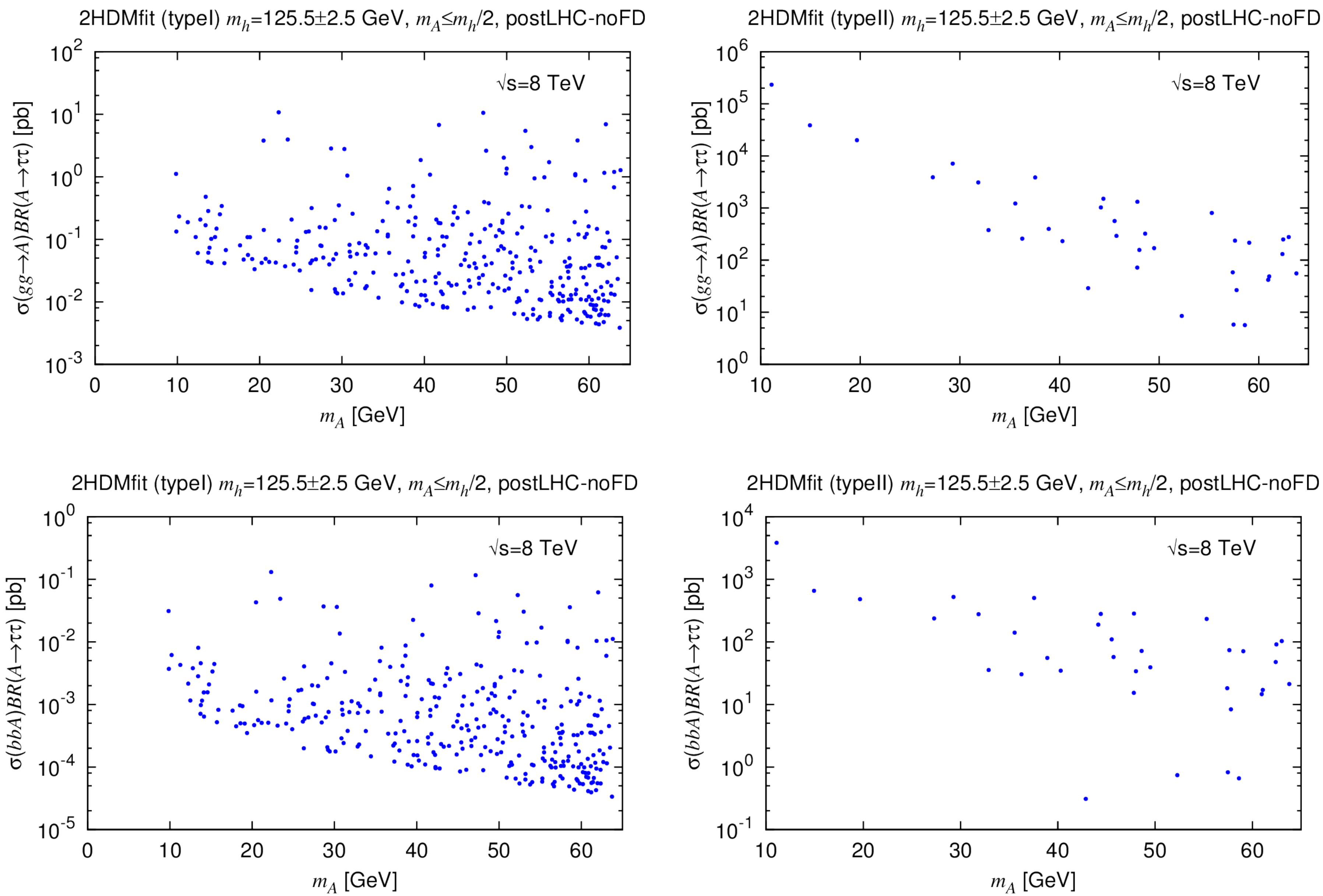


**Figure 6: We plot the cross sections for $gg \to A$ and $bbA$ with $A \to \tau\tau$ for $m_A < m_h/2$ in models of Type-I and Type-II at $\sqrt{s} = 8~\mathrm{TeV}$. All points pass all constraints at the postLHC level, including $m_h = 125~\mathrm{GeV}$ higgs fitting. But, most (Type I), all (Type II) points are eliminated by SM$\pm 15\%$**

**Fig. 6 shows that $gg \to A$ and $bbA$ with $A \to \tau\tau$ cross sections are very large! Spread in points comes from $\tan\beta$ variation.**

**Notes:**

**a) Even above the $b\bar{b}$ threshold $BR(A \to \tau\tau) \sim 0.07$ at $m_A \sim 11~\mathrm{GeV}$, declining to $0.045$ at high $m_A \gtrsim 15~\mathrm{GeV}$.**

**b) The constraints built into the Monte Carlo employed (2HDMC) are a bit naive for $m_A < 2m_b$ and so there are actually points with lower $m_A$ that have comparable $\sigma BR$ values to those shown.**

**Just to get a point of reference let us take $\sigma BR(A \to \tau\tau) \sim 10~\mathrm{pb}$. With $20~\mathrm{fb}^{-1}$ of data, there are $2 \times 10^5$ events before cuts and efficiencies. If the net efficiency is of order $10^{-4}$ (which is meant to include a final mode branching ratio such as $BR(\tau\tau \to \tau_\mu\tau_h) \sim 0.22$ as well as acceptance and other efficiencies, such as $b$-tagging), this still leaves about $20$ events.**

**In Type I, $\sigma(gg \to A)BR$ ($\sigma(bbA)BR$ is much smaller) can be as large as $10~\mathrm{pb}$, but mostly lower, so hard to see anything using current data.**

**In Type II, both $\sigma(gg \to A)BR$ and $\sigma(bbA)BR$ are potentially observable. One gets the following table.**

| $m_A$( GeV) | 10 | 20 | 30 | 40 | 50 | 60 |
|---|---|---|---|---|---|---|
| $gg \to A$<br>$bbA$ | $4 \times 10^5$<br>$10000$ | $4 \times 10^4$<br>$1000 - 2000$ | $2000 - 8000$<br>$80 - 1000$ | $200 - 2000$<br>$20 - 800$ | $20 - 2000$<br>$2 - 600$ | $10 - 1000$<br>$.2 - 200$ |

**Table 2:** Very crude event number table assuming $acceptance \times efficiency \times BR(\tau\tau \to mode)$ of order $10^{-4}$: more scanning needed to be sure of full ranges. Efficiency will depend on whether or not there is $b$-tagging and acceptance will probably increase at larger $m_A$.

$\Rightarrow$ much of the parameter space can probably be eliminated using current data and sophisticated analyses.

Of course, there is also the $\mu\mu$ final state. There are a number of relevant CMS analyses (probably also ATLAS). Recall the CMS analysis of arXiv:1206.6326, which obtained limits of $\sigma(gg \to a)BR(A \to \mu\mu) \leq 2 - 3~\mathrm{pb}$ for $m_A \in [11 - 14]~\mathrm{GeV}$ using $1.3~\mathrm{fb}^{-1}$ of data. This can be compared to the predictions shown in Fig. 7.

From this, it seems that Type-II is ruled out for $m_A < 14~\mathrm{GeV}$, but not Type-I.

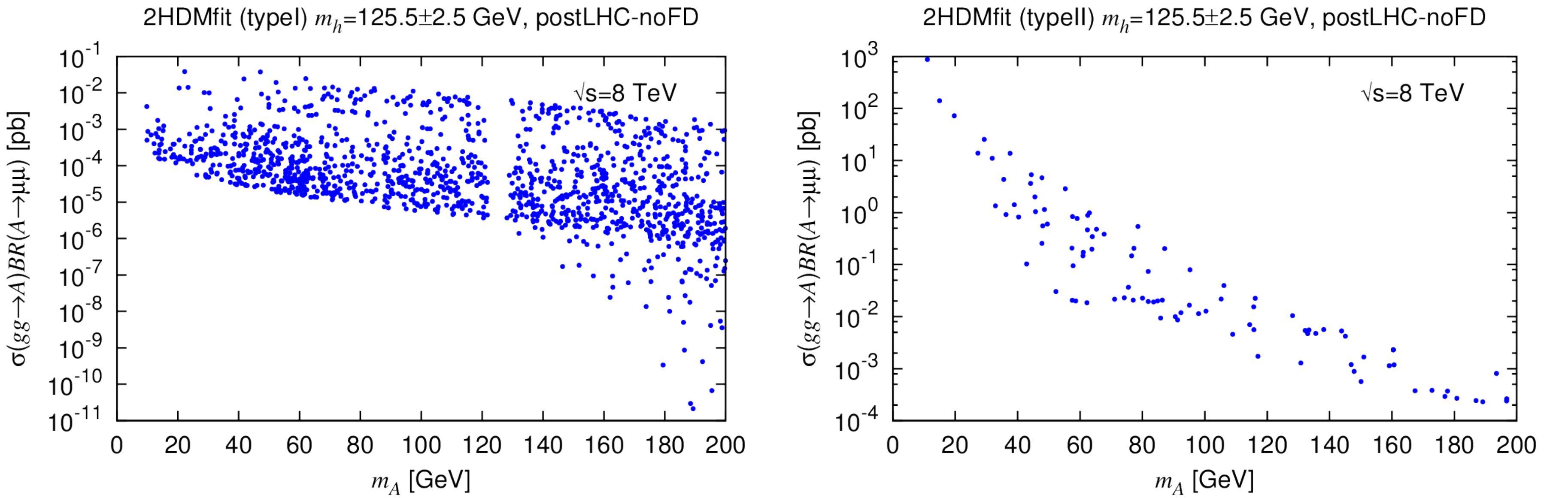


**Figure 7: We plot $\sigma(gg \to A)BR(A \to \mu\mu)$ for $m_A < 200$ GeV in models of Type-I and Type-II. All points pass all constraints at the postLHC level, including $m_h = 125$ GeV higgs fitting.**

**An aside: there are limits from CMS PAS HIG-13-007 of order $0.02 - 0.03$ pb for $m_A \in [100, 150]$ GeV assuming that the $A$ and $H$ behave similarly in the $\mu\mu$ channels as regards efficiencies and acceptance. These are not relevant for $m_A < m_h/2$, but, while the limits are not quite strong enough to impact either Type-I or Type-II, observation could be right around the corner if further analysis improvements are possible.**

**Above, I noted that most (Type I) or all (Type II) of the $m_A < m_h/2$ points do not fall within SM$\pm 15\%$. This arises because the $\gamma\gamma$ final state has a suppressed rate, as illustrated by plotting $C_\gamma$ vs. $m_A$, see Fig. 8. One finds $C_\gamma \sim 0.95$, implying a 10% decrease in $\Gamma(h \to \gamma\gamma)$.**

**As also illustrated in Fig. 8, this comes about because of non-decoupling of the charged Higgs loop contribution to the $h\gamma\gamma$ coupling. As a point of reference, if $v^2 g_{hH^+H^-}/m_{H^\pm}^2 \sim -2$ then the $H^\pm$ loop is in a maximally non-decoupling regime where it cancels against the sum of the $W$, $t$ and $b$ loops and reduces $C_\gamma$ by 5%. Also, most (Type I) or all (Type II) of the $m_A < m_h/2$ points have $\sin\alpha > 0$ which implies that $C_D < 0$ (wrong-sign Yukawa coupling) in the convention where $C_U > 0$.**

**There is an associated small increase in $C_g$ (top and bottom loops add together rather than the bottom partially canceling the top loop), implying that VBF is the best channel to see the decrease in $C_\gamma$.**

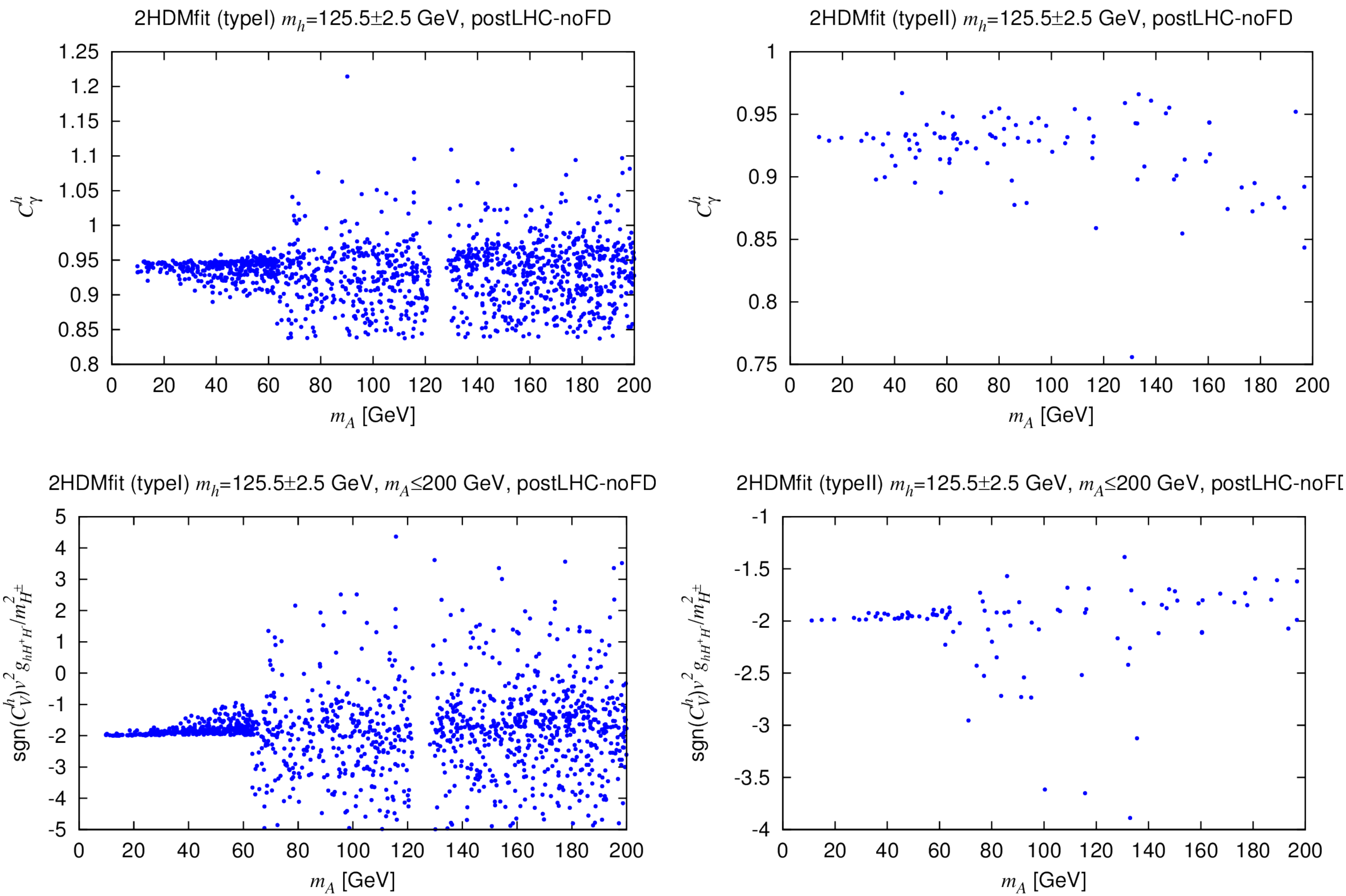


**Figure 8: We plot $C_\gamma$ vs. $m_A$ (top) and $v^2 g_{hH^+H^-}/m^2_{H^\pm}$ (bottom) vs. $m_A$ for $m_A < 200~\mathrm{GeV}$ in models of Type-I and Type-II. All points pass all constraints at the postLHC level, including $m_h = 125~\mathrm{GeV}$ higgs fitting.**

- **Beyond the MSSM**

  **Of course, you must recall that the MSSM with $m_h \sim 125~\mathrm{GeV}$ cannot have a light $A$. This means we should move to the NMSSM, as also motivated by a possible need to reduce the 2HDM signal rates to a not-yet-observable level.**

- **The NMSSM**

  **The most relevant model in the end may be the NMSSM, for which we take the simplest model with $Z_3$ symmetry implying that the superpotential and associated soft-SUSY-breaking trilnears take the forms:**

$$W \ni \lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3 \,, \qquad \lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 \,. \tag{4}$$

  **The parameter set is then $\lambda$, $\kappa$, $A_\lambda$, $A_\kappa$, $\tan\beta = h_u/h_d$ and $\mu_{\mathrm{eff}} = \lambda s$, where $h_{u,d} = \langle H_{u,d} \rangle$ and $s = \langle S \rangle$. The fact that $s \neq 0$ by virtue of EWSB yields the touted solution to the $\mu$ problem via the development of $\mu_{\mathrm{eff}}$. In fact, it is useful to consider $\mu_{\mathrm{eff}} = \lambda s$ and $b_{\mathrm{eff}} = \kappa s$ as the relevant parameters rather than $\lambda$ and $\kappa$.**

**We are concerned with the Higgs mass eigenstates and associated mass-square matrices.**

## CP-even neutral states

**In the basis $S^{bare} = (H_{uR}, H_{dR}, S_R)$ and using the minimization equations in order to eliminate the soft masses squared, one obtains, defining $g^2 = \frac{1}{2}(g_1^2 + g_2^2)$, the following mass-squared matrix entries:**

$$\begin{aligned}
\mathcal{M}^2_{S,11} &= g^2 h_u^2 + \lambda s \frac{h_d}{h_u}(A_\lambda + \kappa s), \\
\mathcal{M}^2_{S,22} &= g^2 h_d^2 + \lambda s \frac{h_u}{h_d}(A_\lambda + \kappa s), \\
\mathcal{M}^2_{S,33} &= \lambda A_\lambda \frac{h_u h_d}{s} + \kappa s(A_\kappa + 4\kappa s), \\
\mathcal{M}^2_{S,12} &= (2\lambda^2 - g^2) h_u h_d - \lambda s(A_\lambda + \kappa s), \\
\mathcal{M}^2_{S,13} &= 2\lambda^2 h_u s - \lambda h_d(A_\lambda + 2\kappa s), \\
\mathcal{M}^2_{S,23} &= 2\lambda^2 h_d s - \lambda h_u(A_\lambda + 2\kappa s).
\end{aligned} \tag{5}$$

**After diagonalization by an orthogonal matrix $S_{ij}$ one obtains 3 CP-even states (ordered in mass) $h_i = S_{ij} S_j^{bare}$, with masses denoted by $m_{h_i}$.**

## CP-odd neutral states

**In the basis $P^{bare} = (H_{uI}, H_{dI}, S_I)$ and using the minimization equations in order to eliminate the soft masses squared, one obtains the following mass-squared matrix entries:**

$$\begin{aligned}
\mathcal{M}^2_{P,11} &= \lambda s \frac{h_d}{h_u} (A_\lambda + \kappa s), \\
\mathcal{M}^2_{P,22} &= \lambda s \frac{h_u}{h_d} (A_\lambda + \kappa s), \\
\mathcal{M}^2_{P,33} &= 4\lambda\kappa h_u h_d + \lambda A_\lambda \frac{h_u h_d}{s} - 3\kappa A_\kappa s, \\
\mathcal{M}^2_{P,12} &= \lambda s (A_\lambda + \kappa s), \\
\mathcal{M}^2_{P,13} &= \lambda h_d (A_\lambda - 2\kappa s), \\
\mathcal{M}^2_{P,23} &= \lambda h_u (A_\lambda - 2\kappa s).
\end{aligned} \tag{6}$$

**The diagonalization of this mass matrix is performed in two steps. First, one rotates into a basis ($\tilde{A}, \tilde{G}, S_I$), where $\tilde{G}$ is a massless Goldstone mode:**

$$\begin{pmatrix} H_{uI} \\ H_{dI} \\ S_I \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \tilde{A} \\ \tilde{G} \\ S_I \end{pmatrix} \tag{7}$$

**where $\tan\beta = h_u/h_d$. Dropping the Goldstone mode, the remaining $2\times 2$ mass matrix in the basis ($\tilde{A}, S_I$) has the matrix elements**

$$\begin{aligned} \mathcal{M}^2_{P,11} &= \lambda s \frac{h_u^2 + h_d^2}{h_u h_d}(A_\lambda + \kappa s), \\ \mathcal{M}^2_{P,22} &= 4\lambda\kappa h_u h_d + \lambda A_\lambda \frac{h_u h_d}{s} - 3\kappa A_\kappa s, \\ \mathcal{M}^2_{P,12} &= \lambda\sqrt{h_u^2 + h_d^2}(A_\lambda - 2\kappa s). \end{aligned} \tag{8}$$

**It can be diagonalized by an orthogonal $2\times 2$ matrix $P'_{ij}$ such that the physical**

**CP-odd states $a_i$ (ordered in mass) are**

$$\begin{aligned} a_1 &= P'_{11}\tilde{A} + P'_{12}S_I \\ &= P'_{11}(\cos\beta H_{uI} + \sin\beta H_{dI}) + P'_{12}S_I, \\ a_2 &= P'_{21}\tilde{A} + P'_{22}S_I \\ &= P'_{21}(\cos\beta H_{uI} + \sin\beta H_{dI}) + P'_{22}S_I, \end{aligned} \tag{9}$$

**In now-conventional notation we write**

$$a_1 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S\,, \tag{10}$$

**implying that all the couplings of the $a_1$ to SM fermions are suppressed by $\cos\theta_A$ relative to a normal 2HDM $A$. This is, of course, what is needed if we are to evade the bounds on the latter.**

**The question: can we make the $h_1$ SM-like while avoiding large $h_1 \to a_1 a_1$ decays that would deplete signals in the SM channels.**

**Let us consider the following limit:**

$$A_\lambda, A_\kappa \to 0\,, \quad s \to \infty, \quad \mu_{\rm eff} = \lambda s \to fixed, \quad b_{\rm eff} = \kappa s \to fixed,$$
$$\mu_{\rm eff} b_{\rm eff} \gg v^2\,, \quad b_{\rm eff} \gg \mu_{\rm eff}\,. \quad \text{or} \quad \mu_{\rm eff} \gg b_{\rm eff}\,, \tag{11}$$

**the latter being perhaps the better choice if you have a $\kappa < \lambda$ preference. For $b_{\rm eff} \gg \mu_{\rm eff}$, we find**

$$m^2_{h_1} \sim g^2 v^2 \cos^2(2\beta), \quad m^2_{h_2} \sim \mu_{\rm eff} b_{\rm eff} \csc\beta \sec\beta + g^2 v^2 \sin^2(2\beta), \quad m^2_{h_3} \sim 4 b^2_{\rm eff} \tag{12}$$

**or if $\mu_{\rm eff} \gg b_{\rm eff}$**

$$m^2_{h_1} \sim g^2 v^2 \cos^2(2\beta), \quad m^2_{h_3} \sim \mu_{\rm eff} b_{\rm eff} \csc\beta \sec\beta + g^2 v^2 \sin^2(2\beta), \quad m^2_{h_2} \sim 4 b^2_{\rm eff} \tag{13}$$

**with**

$$S_{11} = \sin\beta, \quad S_{12} = \cos\beta, \quad S_{21} = -\cos\beta, \quad S_{22} = \sin\beta\,. \tag{14}$$

**Note that $m^2_{h_1}$ is the normal tree-level MSSM mass and that the $S_{11}$ and $S_{12}$ values imply that the $h_1$ is exactly SM-like.**

**In the $a_i$ sector, we find**

$$m_{a_1}^2 \sim -3b_{\rm eff}A_\kappa\,, \quad m_{a_2}^2 \sim \mu_{\rm eff}b_{\rm eff}\csc\beta\sec\beta\,, \tag{15}$$

**which shows that $m_{a_2}$ and $m_{h_2}$ ($\mu_{\rm eff} < b_{\rm eff}$) or $m_{h_3}$ ($b_{\rm eff} < \mu_{\rm eff}$) are in the usual decoupling limit with a common mass (also the $H^\pm$ has this mass). By taking $A_\kappa$ small we can get a very light $a_1$.**

**To compute the $h_1a_1a_1$ coupling, we must look as well at $S_{13}$, $S_{23}$ and $P_{12}$, as is evident from**

$$\begin{aligned} g_{h_a a_b a_c} \quad : \quad & \frac{\lambda^2}{\sqrt{2}}\left(h_u(\Pi_{abc}^{122}+\Pi_{abc}^{133}) + h_d(\Pi_{abc}^{211}+\Pi_{abc}^{233}) + s(\Pi_{abc}^{311}+\Pi_{abc}^{322})\right) \\ & +\frac{\lambda\kappa}{\sqrt{2}}\left(h_u(\Pi_{abc}^{233}-2\Pi_{abc}^{323}) + h_d(\Pi_{abc}^{133}-2\Pi_{abc}^{313})\right. \\ & \left.+2s(\Pi_{abc}^{312}-\Pi_{abc}^{123}-\Pi_{abc}^{213})\right) + \sqrt{2}\kappa^2 s\Pi_{abc}^{333} \\ & +\frac{\lambda A_\lambda}{\sqrt{2}}(\Pi_{abc}^{123}+\Pi_{abc}^{213}+\Pi_{abc}^{312}) - \frac{\kappa A_\kappa}{\sqrt{2}}\Pi_{abc}^{333} \\ & +\frac{g^2}{2\sqrt{2}}\left(h_u(\Pi_{abc}^{111}-\Pi_{abc}^{122}) - h_d(\Pi_{abc}^{211}-\Pi_{abc}^{222})\right) \end{aligned} \tag{16}$$

**where**

$$\Pi^{ijk}_{abc} = S_{ai}(P_{bj}P_{ck} + P_{cj}P_{bk}) \tag{17}$$

**and we are interested in** $a = b = c = 1$**.**

**An examination of the various terms in the limit being considered shows that it is the term, dominated by the 2nd and 3rd terms therein,**

$$\frac{\lambda\kappa}{\sqrt{2}} 2s(\Pi^{312}_{111} - \Pi^{123}_{111} - \Pi^{213}_{111}) \tag{18}$$

**that is dominant, yielding**

$$g_{h_1 a_1 a_1} \sim -\sqrt{2}\frac{\mu_{\rm eff} b_{\rm eff}}{s} \cos\theta_A \sin\theta_A \,, \tag{19}$$

**where**

$$\cos\theta_A \sim \frac{M^2_{P,12}}{M^2_{P,11}} = -\frac{v}{s}\sin 2\beta \,, \tag{20}$$

**yielding**

$$g_{h_1 a_1 a_1} \sim \sqrt{2}\frac{\mu_{\rm eff} b_{\rm eff}}{s^2} v \sin 2\beta = \sqrt{2}\lambda\kappa v \sin 2\beta \,. \quad (21)$$

**This coupling is thus naturally small as well as being adjustable.**

**Now,**

$$\Gamma(h_1 \to a_1 a_1) = \frac{1}{32\pi}\frac{g^2_{h_1 a_1 a_1}}{m_{h_1}}\sqrt{1 - 4m^2_{a_1}/m^2_{h_1}} \simeq \left(\frac{g_{h_1 a_1 a_1}/v}{0.03}\right)^2 \Gamma(h_1 \to SM) \,. \quad (22)$$

**Requiring** $\Gamma(h_1 \to a_1 a_1) \leq 0.2\Gamma(h_1 \to SM)$ **translates to**

$$\lambda\kappa \sin(2\beta) < 0.01 \,. \quad (23)$$

**If** $\tan\beta$ **is large, then this is fairly readily satisfied. If** $\tan\beta$ **is modest in size then small** $\lambda\kappa$ **is needed. If** $b_{\rm eff} < \mu_{\rm eff}$**, then this will most easily allow**

$$m^2_{a_1} \sim -3 b_{\rm eff} A_\kappa \quad (24)$$

**to be small in size since** $b_{\rm eff} = \kappa s$ **is then not sizeable.**

**Putting this together one finds that the 20% maximum $a_1 a_1$ width translates to**

$$A_\kappa > 50 \text{ GeV} \sin 2\beta \left(\frac{m_{a_1}}{60 \text{ GeV}}\right)^2 \left(\frac{1 \text{ TeV}}{s}\right) \left(\frac{\lambda}{0.4}\right) , \tag{25}$$

**an entirely reasonable range.**

**Of course, there have been detailed scans such as that of arXiv:1211.5074 (King, Muhlleitner, ....), arXiv:1303.2113 (Christensen, Han, ...), arXiv:1309.4939 (Cao et.al). My prejudice has been to adopt the simplest NMSSM scenario with a very SM-like $h_1$.**

**A general overview of $H \to AA$ scenarios is given in arXiv:1312.499 (Curtin, Essig, Gori, .....).**

**In any case, the important point about the NMSSM, or any model where the SM-like Higgs mixes with a singlet Higgs sector is that the light $A$ can be largely decoupled from SM particles and so it will be hard to make and see directly. Thus, we must keep a watch out for $H \to AA$, but this too could be arbitrarily small.**

# Conclusions

- It seems likely that the Higgs responsible for EWSB has emerged.
- At the moment, there is no sign of other Higgs-like signals except $\sim 1\sigma$ hints at $\sim 135~\mathrm{GeV}$ and the old LEP excess at $98~\mathrm{GeV}$.
- One may wish to focus on scenarios in which the observed Higgs is very SM-like.
- The possibility of a light $A$ in association with a SM-like scalar Higgs remains open and has very interesting implications.

  1. Strongly constrained for 2HDM models.
  2. A fully open possibility in the case of a model like the NMSSM where the light $A$ can be mainly singlet.

While the waiting for a 1st Higgs signal is over, watching for more Higgs or some sign of BSM is not: