Higgs bosons beyond the Standard Model

Jack Gunion
U.C. Davis

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The present situation

- **We have now observed a very SM-like Higgs state near 125.5 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 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_γ (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:

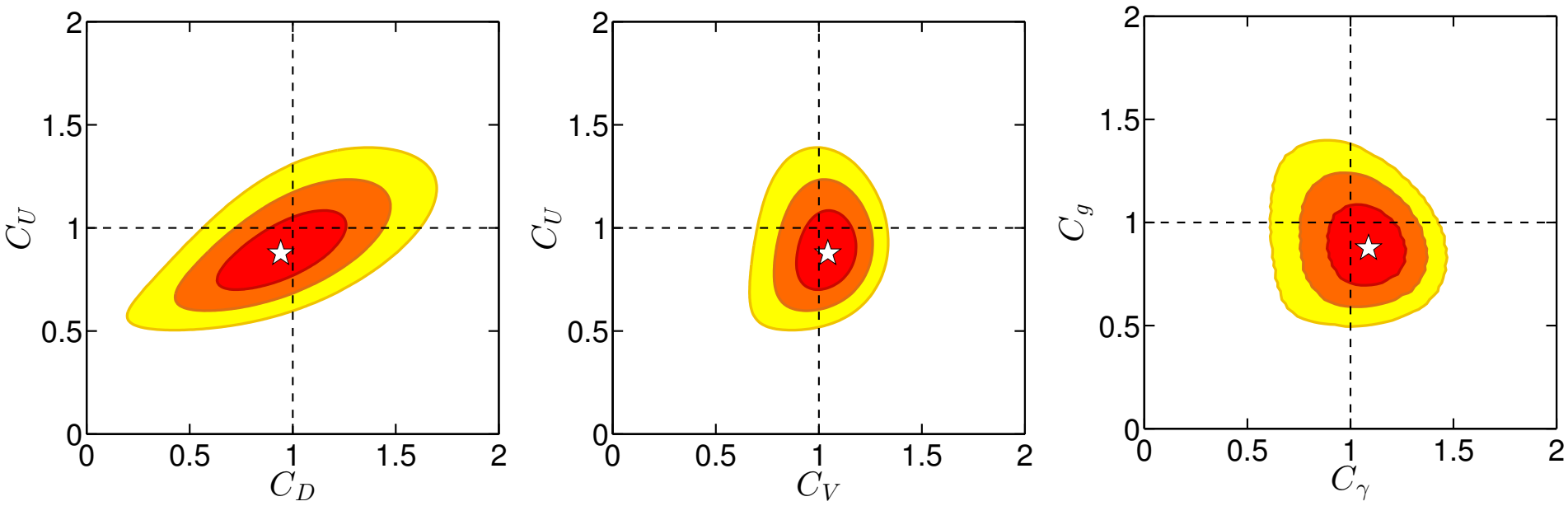


Figure 1: Coupling constant ellipses. The filled red, orange and yellow ellipses show the 68%, 95% and 99.7% CL regions, respectively,. The white stars mark the best-fit points.

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 ΔC_γ and ΔC_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 ${\rm inv} \to U$
  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 ${\rm inv} \to U$.
  (All $BR_{\rm inv}$ limits are given at 68% (95%) CL.)

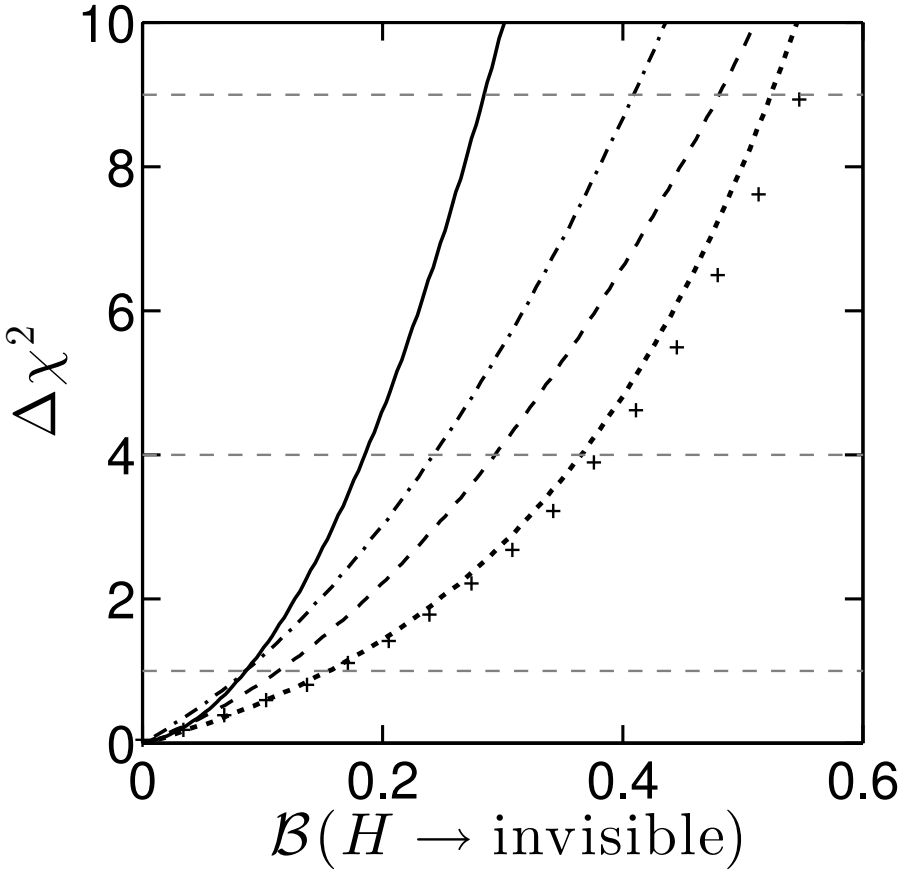


Figure 2: $\Delta\chi^2$ **distributions for the branching ratio of invisible Higgs decays for various cases. Solid: SM+invisible. Dashed: varying** ΔC_g **and** ΔC_γ **for** $C_U = C_D = C_V = 1$**. Dotted: varying** C_U**,** C_D **and** C_V **for** $\Delta C_g = \Delta C_\gamma = 0$**. Dot-dashed: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

Notes:

- **While $BR_{\rm inv}$ is certainly significantly limited by the current data set, there remains ample room for invisible decays.**
- **When $C_V \leq 1$, $H \to$ 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 $\rm inv \to U$**
- **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

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

The terms involving λ_6 and λ_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 λ_i. But, for our purposes, it is best to determine the λ_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 $m_h \sim 125$ 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?

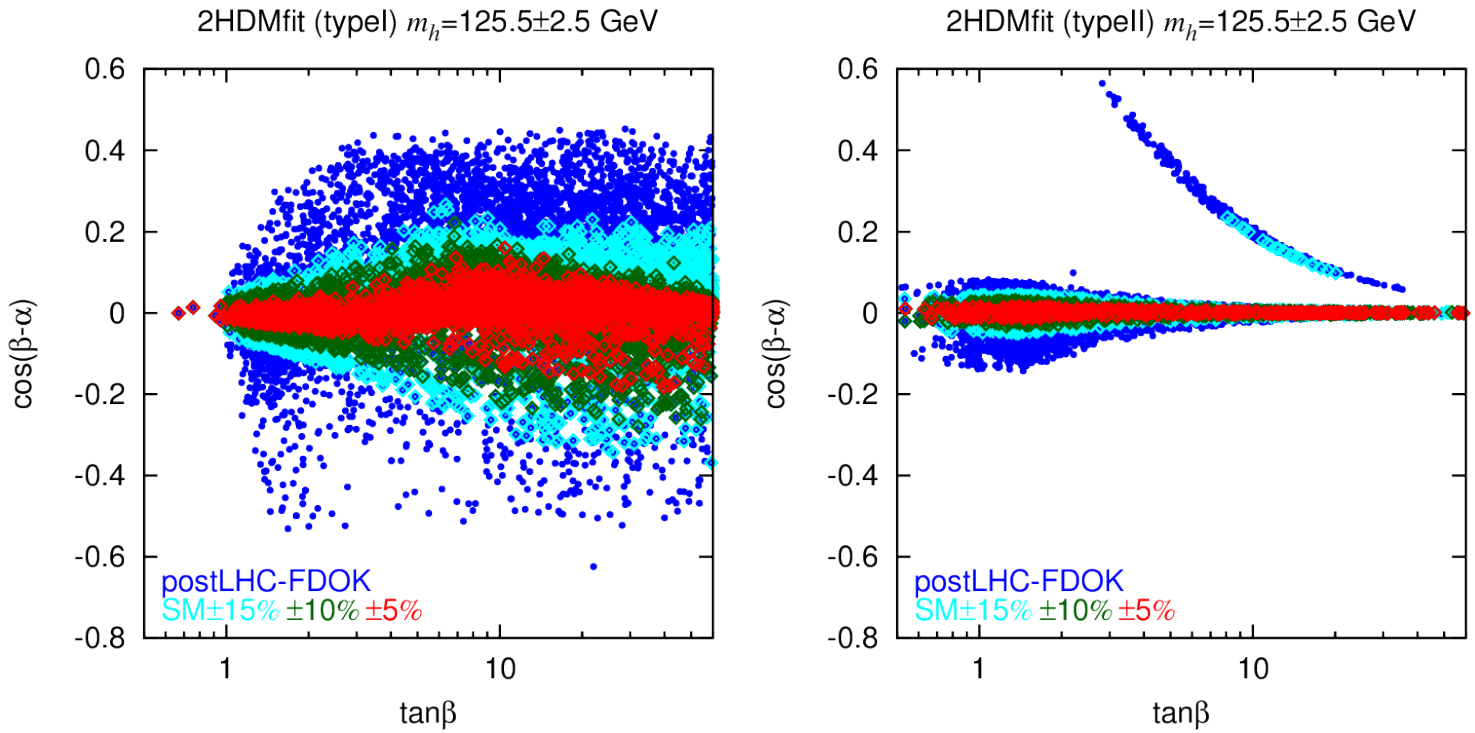


Figure 3: Constraints on the 2HDM models of Type I and II in the $\cos(\beta-\alpha)$ versus $\tan\beta$ plane for $m_h \sim 125.5$ GeV. All points obey preLHC constraints, existing LHC limits on H/A signals and all LHC Higgs measurements at 95% CL. Also shown are the changes associated with future higher precisions for $all\ X \to Y$ channels at the SM$\pm 15\%$, $\pm 10\%$, and $\pm 5\%$ 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.

$m_H = 125.5$ 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 λ_{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!

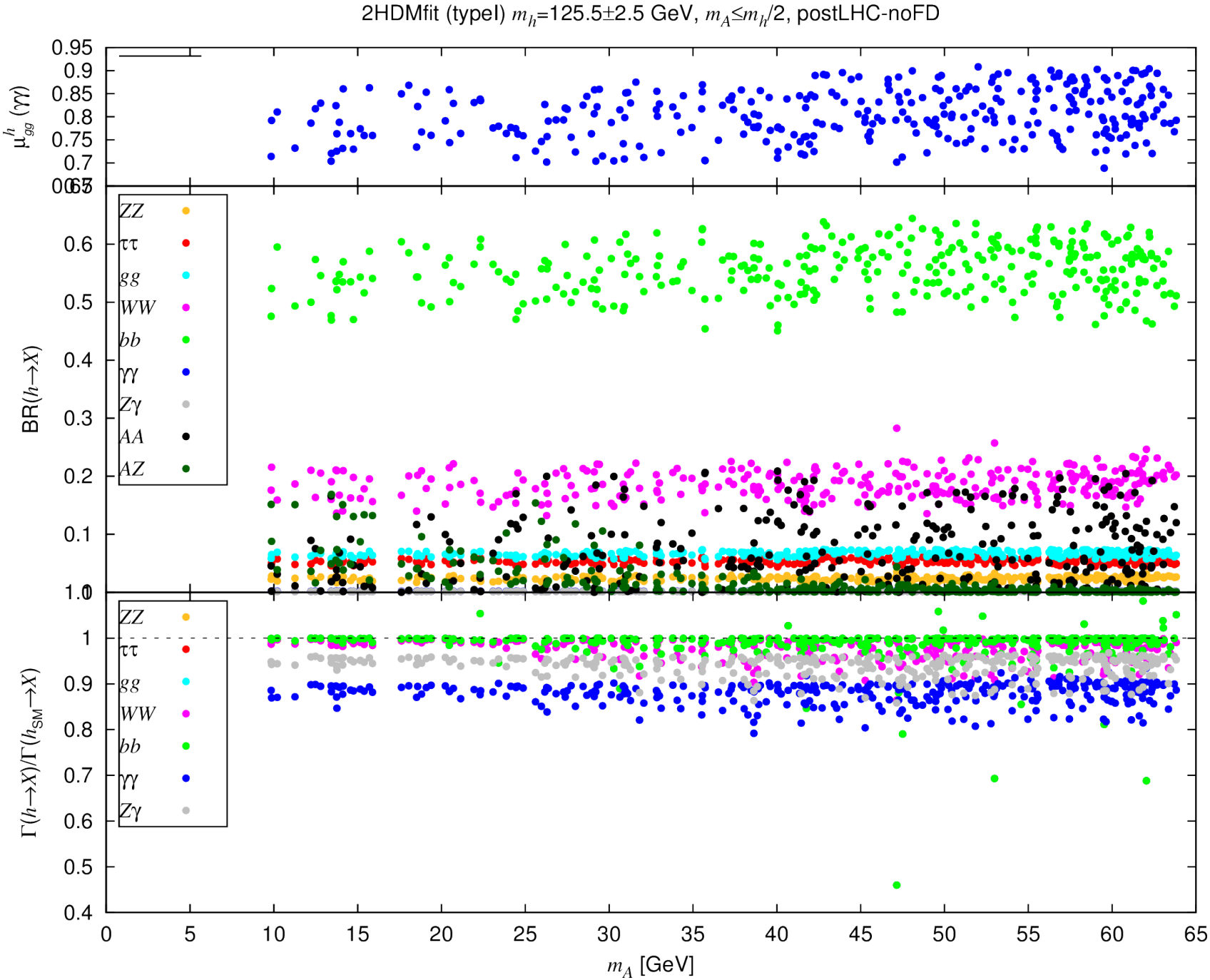


Figure 4: Features of Type-I postLHC points with $m_A < m_h/2$.

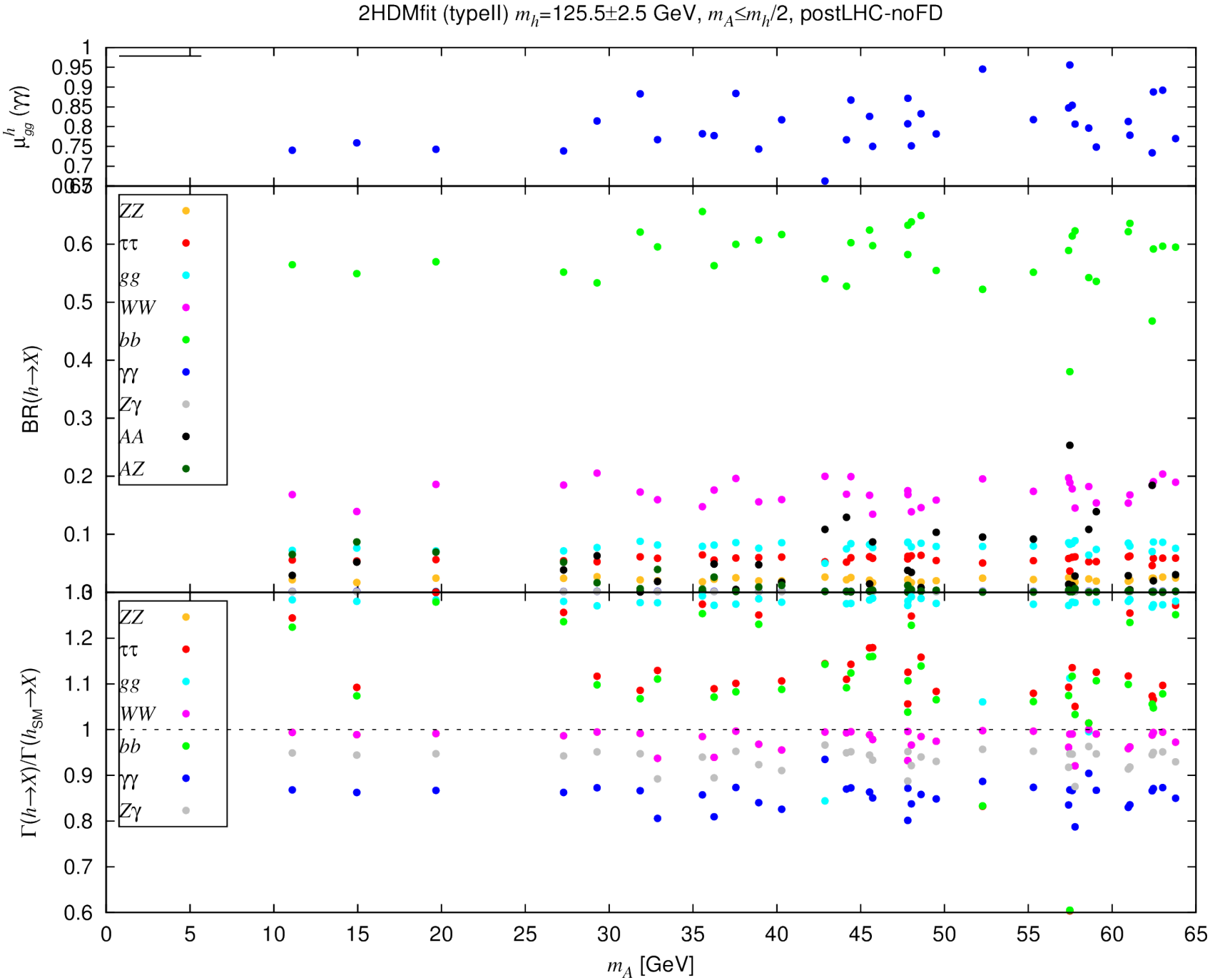


Figure 5: Features of Type-II postLHC points with $m_A < m_h/2$.

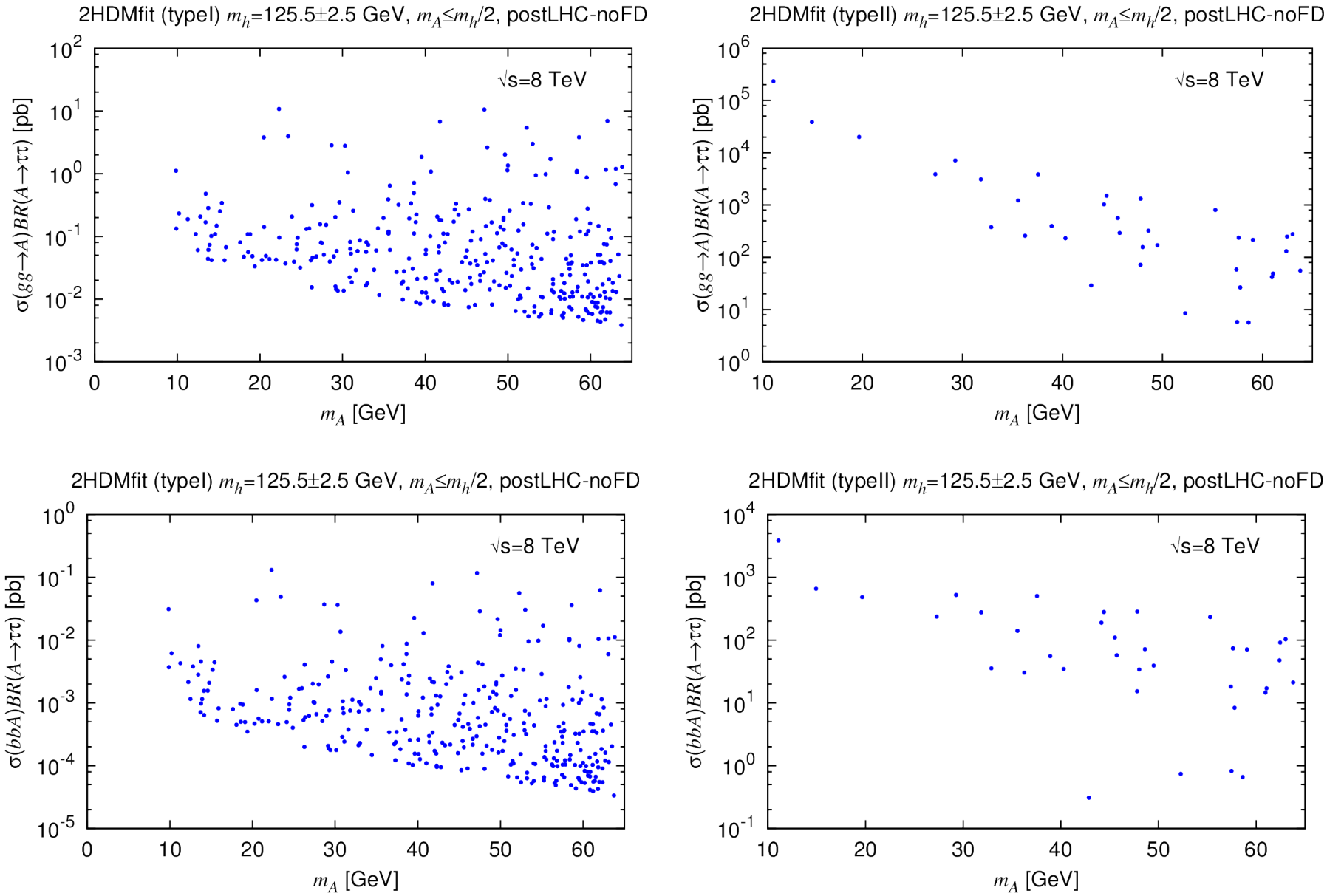


Figure 6: We plot the cross sections for $gg \to A$ and bbA with $A \to \tau\tau$ for $m_A < m_h/2$ in models of Type-I and Type-II at $\sqrt{s} = 8$ TeV. All points pass all constraints at the postLHC level, including $m_h = 125$ GeV higgs fitting. But, most (Type I), all (Type II) points are eliminated 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 $m_A \sim 11$ GeV, declining to 0.045 at high $m_A \gtrsim 15$ 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 σBR values to those shown.

Just to get a point of reference let us take $\sigma BR(A \to \tau\tau) \sim 10$ pb. With 20 fb^{-1} of data, there are 2×10^5 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 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
$gg \to A$	4×10^5	4×10^4	$2000 - 8000$	$200 - 2000$	$20 - 2000$	$10 - 1000$
bbA	10000	$1000 - 2000$	$80 - 1000$	$20 - 800$	$2 - 600$	$.2 - 200$

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 $\sigma(gg \to a)BR(A \to \mu\mu) \leq 2-3$ pb for $m_A \in [11-14]$ GeV using 1.3 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 $m_A < 14$ GeV, but not Type-I.

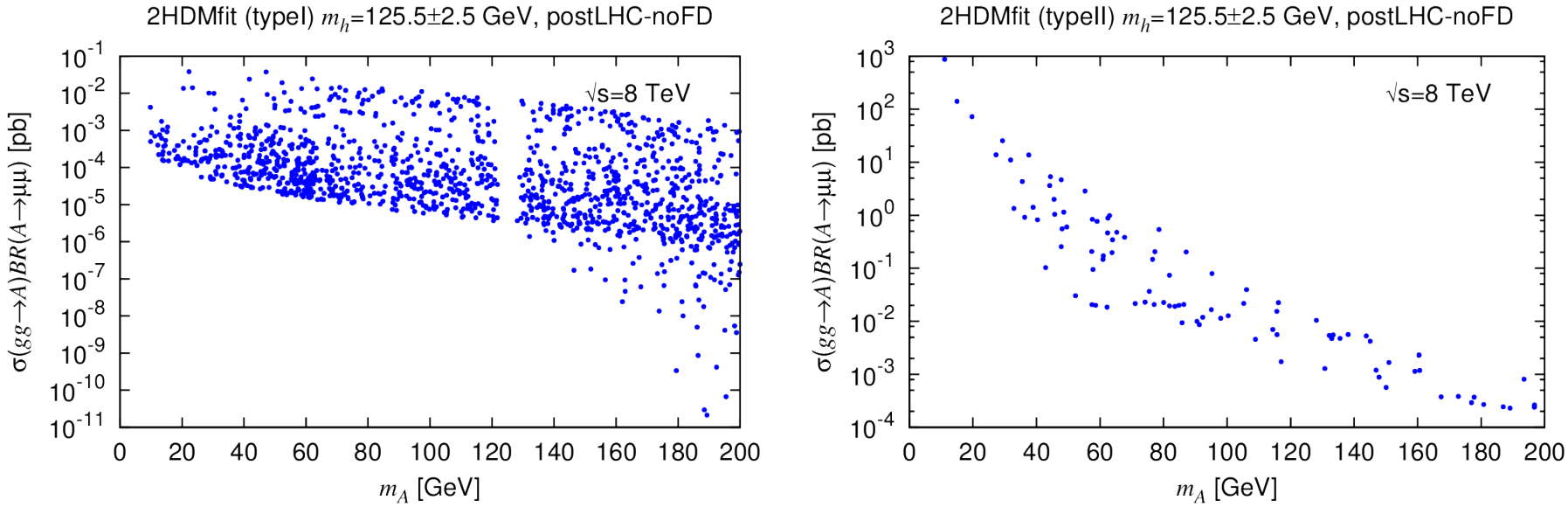


Figure 7: We plot $\sigma(gg \to A)BR(A \to \mu\mu)$ for $m_A < 200$ GeV in models of Type-I and Type-II. All points pass all constraints at the postLHC level, including $m_h = 125$ GeV higgs fitting.

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_γ 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 $v^2 g_{hH^+H^-}/m^2_{H^\pm} \sim -2$ 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_γ 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_γ.

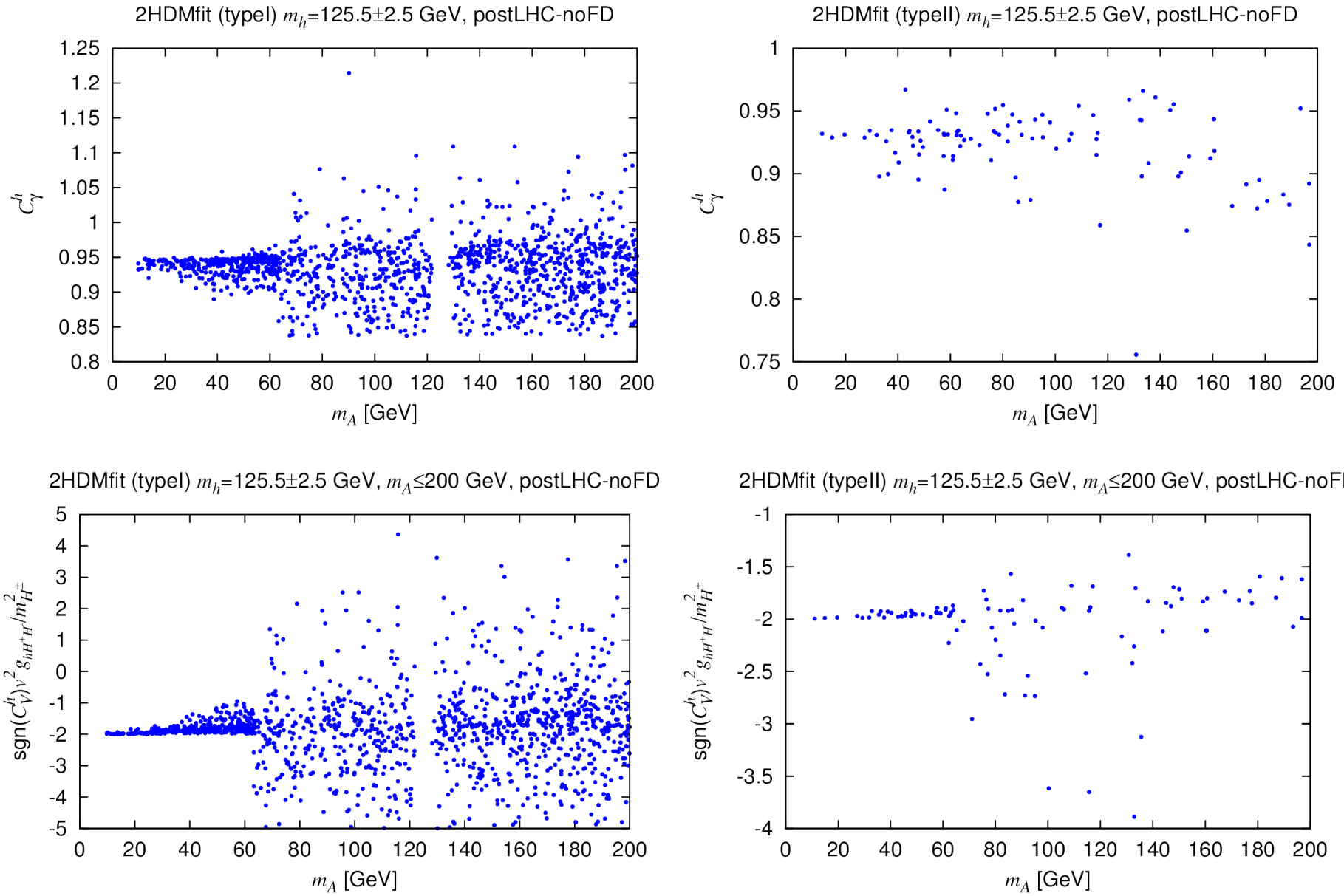


Figure 8: We plot C_γ vs. m_A (top) and $v^2 g_{hH^+H^-}/m_{H^\pm}^2$ (bottom) vs. m_A for $m_A < 200$ GeV in models of Type-I and Type-II. All points pass all constraints at the postLHC level, including $m_h = 125$ GeV higgs fitting.

- **Beyond the MSSM**

  Of course, you must recall that the MSSM with $m_h \sim 125$ 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 λ, κ, A_λ, A_κ, $\tan\beta = h_u/h_d$ and $\mu_{\rm eff} = \lambda s$, 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 μ problem via the development of $\mu_{\rm eff}$. In fact, it is useful to consider $\mu_{\rm eff} = \lambda s$ and $b_{\rm eff} = \kappa s$ as the relevant parameters rather than λ and κ.

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:

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

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 2×2 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 2×2 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

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

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_κ small we can get a very light a_1.

To compute the $h_1 a_1 a_1$ coupling, we must look as well at S_{13}, S_{23} and P_{12}, as is evident from

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

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

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

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

Now,

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

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

$$\lambda\kappa \sin(2\beta) < 0.01\,. \tag{23}$$

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**

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

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.

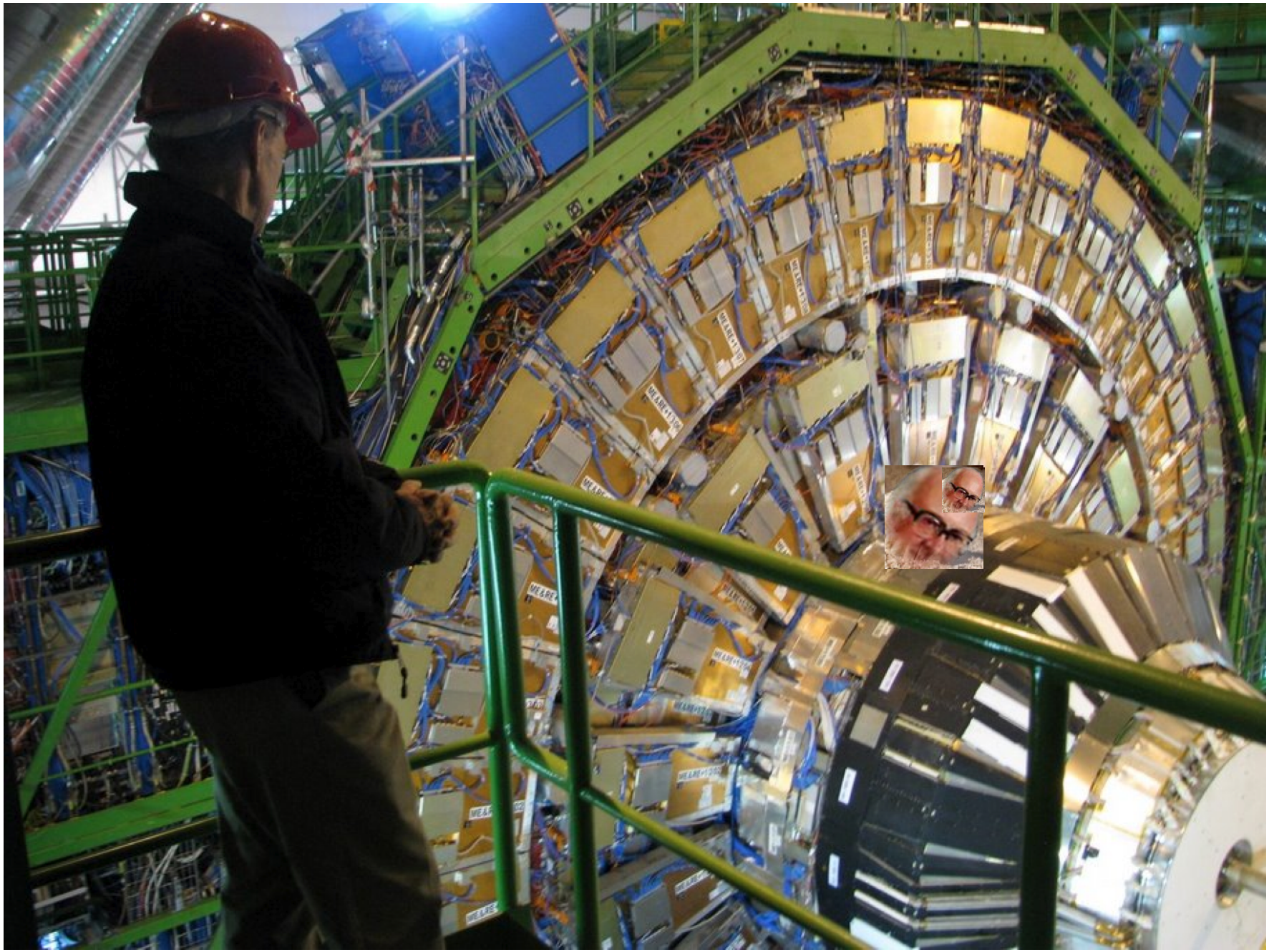
Conclusions

- **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 ~ 135 GeV and the old LEP excess at 98 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: