News for Two-Higgs-Doublet Models

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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. The observables are various rates that are usually defined relative to the SM:

$$\mu^H_X(Y) = \frac{\sigma^H(X)BR(H \to Y)}{\sigma^{hSM}(X)BR(h_{SM} \to Y)}$$  \hspace{1cm} (1)

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, fitting the $[ggF + ttH, VBF + VH]$ ellipses in various final states $Y \Rightarrow$: 
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 does not imply that there are no other Higgs bosons.

Other Higgs bosons can be present without disturbing significantly the quality of the fit to the $125.5$ GeV data.
– Given the current data set, heavier or lighter Higgs bosons can have escaped detection due to inadequate cross section.
– Lighter Higgs bosons could even be present in the decays of the 125.5 GeV state.

• With regard to the latter, 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 is given in Fig. 2, which shows the behavior of $\Delta \chi^2$ as a function of $\text{BR}_{\text{inv}}$ for various different cases of interest; in particular note the result:

$$C_U, C_D \text{ free, } C_V \leq 1, \Delta C_\gamma = \Delta C_g = 0 \rightarrow \text{BR}_{\text{inv}} < 0.09 (0.24)$$

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 $\Delta C_\gamma$.

- 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. $\Rightarrow$ little change if $\text{inv} \rightarrow U$, e.g. $\text{BR}_U \leq 0.39$ at 95% CL.
The most general 2HDM Higgs potential is given by

\begin{equation}
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 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2} ((H_1 H_2)^2 + \text{c.c.}) + m_{12}^2 (H_1 H_2 + \text{c.c.}) + (\lambda_6 |H_1|^2 (H_1 H_2) + \text{c.c.}) + (\lambda_7 |H_2|^2 (H_1 H_2) + \text{c.c.}).
\end{equation}

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

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

(3)

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

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

<table>
<thead>
<tr>
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<th>Type I and II</th>
<th>Type I</th>
<th>Type II</th>
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<tbody>
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<td>Higgs</td>
<td>$C_V$</td>
<td>$C_U$</td>
<td>$C_D$</td>
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<tr>
<td>$h$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\cos \alpha/\sin \beta$</td>
<td>$\cos \alpha/\sin \beta$</td>
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<tr>
<td>$H$</td>
<td>$\cos(\beta - \alpha)$</td>
<td>$\sin \alpha/\sin \beta$</td>
<td>$\sin \alpha/\sin \beta$</td>
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<tr>
<td>$A$</td>
<td>0</td>
<td>$\cot \beta$</td>
<td>$-\cot \beta$</td>
</tr>
</tbody>
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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.

- Either the $h$ or the $H$ can be SM-like with mass $\sim 125.5$ GeV, labelled $h_{125}$ and $H_{125}$, respectively.
Proceed in steps:

1. Choose $h_{125}$ or $H_{125}$.
2. Scan:

\[ \alpha \in [-\pi/2, +\pi/2], \quad \tan \beta \in [0.5, 60], \quad m_{12}^2 \in [-(2 \text{ TeV})^2, (2 \text{ TeV})^2], \]
\[ m_A \in [5 \text{ GeV}, 2 \text{ TeV}], \quad m_{H\pm} \in [m^*, 2 \text{ TeV}], \]

where $m^*$ is the lowest value of $m_{H\pm}$ allowed by LEP direct production limits and $B$ physics constraints.

3. Apply all constraints from preLHC ($B$-physics, LEP limits, ....)
4. Impose LHC limits on Higgs bosons heavier than 125.5 GeV ($H$ and $A$ in the $h_{125}$ case, or just $A$ in the $H_{125}$ case).
5. Impose Higgs fitting for all channels as per arXiv:1306.2941 (Beranger, et.al.) at the 95% CL.
6. New: Require that feed down (FD) from heavier Higgs bosons not disturb the 125 GeV fits. e.g. for the $h_{125}$ case the most important channels are: $gg \rightarrow H \rightarrow hh$ and $gg \rightarrow Z \rightarrow Zh$.
7. Look at consequences.
The $h_{125}$ case

- **Note:** $|\alpha| \leq \pi/2$ implies that $C_U^h = C_D^h > 0$ for Type I, whereas for Type II $C_D^h < 0$ is possible when $\sin \alpha > 0$.

**Figure 3:** Constraints in the $\cos(\beta - \alpha)$ versus $\tan \beta$ for $m_h \sim 125.5$ GeV. Grey points satisfy preLHC constraints, while green points satisfy in addition the LHC limits on $H$ and $A$ production. Blue points fall in addition within the 7+8 TeV 95% CL ellipses in the $[\mu(ggF + ttH), \mu(VBF + VH)]$ plane for each of the final states considered, $Y = \gamma\gamma, ZZ, WW, b\bar{b}, \tau\tau$. 
The SM limit is \( \cos(\beta - \alpha) \rightarrow 0 \). For Type II there is a main branch that is very SM-like, but also an alternative branch that is quite different. This is a branch having \( C^h_D \sim -1 \). The future LHC run can eliminate or confirm this branch — more later. (arXiv:1403.4736, Ferreira, et. al.)

- What masses are possible for the heavy \( H \) and, possibly, \( A \)?

**Figure 4:** Constraints in the \( m_A \) versus \( \cos(\beta - \alpha) \) plane for \( m_h \sim 125.5 \) GeV.

The decoupling limit is clearly seen. The Type-II high \( \cos(\beta - \alpha) > 0 \) points are those with \( C^h_D \sim -1 \).
• Could the $A$ be hiding in current data? **YES!** At low $m_A$, very large $gg \rightarrow A$ and $bbA$, $A \rightarrow \tau\tau$ rates are possible in Type II.

![Cross sections in the $\tau\tau$ final state given current $h_{125}$ constraints.](image)

**Figure 5:** Cross sections in the $\tau\tau$ final state given current $h_{125}$ constraints.
Key point: CMS limits for \( m_A \lesssim 100 \text{ GeV} \) are a bit weak and only go down to 90 GeV, while LEP limits from \( Z^* \rightarrow hA \) are evaded because of small \( ZhA \) coupling (\( \propto \cos(\beta - \alpha) \)) when \( h \) is SM-like.

• Implications for the future

Figure 6: postLHC8-FDOK points in the \( \cos(\beta - \alpha) \) vs. \( \tan \beta \) plane for the \( h_{125} \) scenario comparing current \( h \) fits (blue) to the case that the rates for all the channels listed below are within \( \pm 15\% \) (cyan), \( \pm 10\% \) (green) or \( \pm 5\% \) (red) of the SM Higgs prediction.

\((X,Y) = (gg, \gamma \gamma), (gg, ZZ), (gg, \tau \tau), (VBF, \gamma \gamma), (VBF, ZZ), (VBF, \tau \tau) = (VH, bb), (ttH, bb)\).

Note that even SM\( \pm 10\% \) (\( \sim L = 300 \text{ fb}^{-1} \) at 14 TeV) on each of the individual \( \mu \)'s will have eliminated the “wrong-sign” down-quark Yukawa region (which corresponds to \( \sin \alpha > 0 \) or \( C^h_D > 0 \)) of the Type II model.
Looking forward, LHC and ILC will measure $C_{hhh} \equiv \lambda_{hhh}/\lambda_{hhh}^{SM}$. We find:

- Thus, $\mu_X(Y)$ excursions from unity at the currently allowed 95% level extreme, $\Rightarrow$ observation of a large deviation from $C_{hhh} = 1$ would be quite likely.

**Figure 7:** postLHC8-FDOK points in the $C_{hhh}$ vs. $m_A$ plane for the $h125$ scenario comparing current $h$ fits to the $\pm 15\%$, $\pm 10\%$, $\pm 5\%$ possibilities; FDOK is required in all cases. Color scheme is as for Fig. 6.
For example, at the high-luminosity LHC14, with $L = 3000 \text{ fb}^{-1}$ one can measure $C_{hhh}$ to the 50% level, and deviations of this order, indeed up to 100% or more, are possible.

- However, if future LHC measurements approach the SM then observing a deviation from $C_{hhh} = 1$ becomes increasingly difficult, even at the ILC.
- The predicted precision on $\lambda_{hhh}$ for ILC1000 with $L = 500 - 1000 \text{ fb}^{-1}$ is of order 21% and for ILC1000 with $L = 1600 - 2500 \text{ fb}^{-1}$ is of order 13%. At CLIC3000 with $L = 2000 \text{ fb}^{-1}$ the accuracy achievable would be about 10%.

- In Type I, SM±10% still allows $C_{hhh}$ as small as $\sim 0$, while SM±5% allows $C_{hhh}$ as small as 0.3, either of which will be observable for any of the listed machines and integrated $L$ values.

In contrast, for Type II, the smallest $C_{hhh}$ for SM±10% is $\sim 0.9$, while for SM±5% it is $\sim 0.95$.

The former would require CLIC3000 while the latter would be beyond the reach of any of the above $e^+e^-$ colliders.

$\sqrt{s} = 14 \text{ TeV}$ Results for $ggFH, A \rightarrow bbH, A$ production in the $\tau\tau$ final state are displayed in Fig. 8.
Figure 8: $[\sigma(gg \to H) + \sigma(bbH)]\text{BR}(H \to \tau\tau)$ and $[\sigma(gg \to A) + \sigma(bbA)]\text{BR}(A \to \tau\tau)$ in pb as functions of $m_H$ (top row) and $m_A$ (bottom row), for postLHC8-FDOK points with $m_h \sim 125.5$ GeV. The values of $\tan \beta$ are color-coded as indicated on the plots.
– Overall, the range of possible cross sections is quite large.
– For Type I, maximum values are of order $1 - 10 \text{ pb}$ and minimum values below $10^{-10} \text{ pb}$ (although this range is somewhat narrowed on average as the $h$ is required to be more and more SM-like).
– For Type II, minimum values are of order $10^{-4} - 10^{-5} \text{ pb}$ and maximum values at low mass, esp. low $m_A$ are very large. (Few points survive below $m_H \sim 300 \text{ GeV}$ if the 125.5 GeV state rates lie within 5% of the SM Higgs predictions.)
– An alternative view is in the $\tan \beta$ vs. $m_A$ plane, Fig. 9. Note the high $\sigma \text{BR}$ points at low $m_A$ that escape all limits and fall outside the usual “wedge”. Surely, LHC Run2 analyses can be designed that will eliminate this region despite the manifest experimental difficulties associated with $\tau \tau$ masses below and near 90 GeV.
We also see that if we can probe to $\sigma \text{BR} \gtrsim 10^{-2}$ (which we should be able to do at LHC Run2), then most of the normal wedge will be eliminated (or something seen) for $m_A \lesssim 500 \text{ GeV}$.
– Don’t forget the $\mu \mu$ final state with rates obtained by multiplying by $\text{BR}(\mu \mu)/\text{BR}(\tau \tau) \sim 3.5 \times 10^{-3}$. 
Figure 9: Same information as in Fig. 8 but in the $\tan \beta$ vs. $m_H$ (top row) and $\tan \beta$ vs. $m_A$ (bottom row) planes with the cross section color-coded as indicated by the scales on the right of the plots. Only FDOK points are shown.
Also, rates in the $\gamma\gamma$ final state can be at an interesting level.

**Figure 10:** $[\sigma(gg \rightarrow H) + \sigma(bbH)]\text{BR}(H \rightarrow \gamma\gamma)$ and $[\sigma(gg \rightarrow A) + \sigma(bbA)]\text{BR}(A \rightarrow \gamma\gamma)$ in pb as functions of $m_H$ (top row) and $m_A$ (bottom row), for postLHC8-FDOK points with $m_h \sim 125.5$ GeV. The values of $\tan \beta$ are color-coded as indicated on the plots.
Of course, once $m_A$ or $m_H$ is above the $ZZ$ and $t\bar{t}$ thresholds, the rates in the $ZZ$ and $t\bar{t}$ final states will be of great interest. The former (latter) are shown in Fig. 11(Fig 12).

**Figure 11:** We plot $[\sigma(gg \rightarrow H) + \sigma(bbH)]BR(H \rightarrow ZZ)$. Implications of various levels of precision for future $h$ measurements are displayed.

$ZZ$ rates are suppressed with increasingly SM-like $h_{125}$.

In $t\bar{t}$, large $\sigma \times BR$ values are certainly possible, but so also are very small values, although in the case of Type II the smallest values found at $m_H$ or $m_A$ of order 1 TeV is $\sim 10^{-4}$ pb.

This latter might be detectable for full Run2 luminosity of $L = 300$ fb$^{-1}$,
and is certainly of great interest for the high-luminosity run of the LHC which might accumulate $L = 3000 \, \text{fb}^{-1}$.

Figure 12: We plot $[\sigma(gg \to H) + \sigma(bbH)] \text{BR}(H \to t\bar{t})$ and $[\sigma(gg \to A) + \sigma(bbA)] \text{BR}(A \to t\bar{t})$. 
Wrong-sign $C_D^h$ and charged Higgs non-decoupling

The $C_D^h \sim -1$ Type II wing is eliminated if the $h$ is measured to be sufficiently SM-like.

It will also be eliminated or confirmed with sufficiently precise measurements at the ILC.

The crucial ingredients are deviations in $\kappa_g^2 \equiv \Gamma(h \to gg)/\Gamma_{\text{SM}}(h \to gg)$ and $\kappa_\gamma^2$. $\kappa_\gamma \sim 0.95$ as a result of a non-decoupling charged Higgs boson loop contribution to $h \to \gamma\gamma$. $\kappa_g \sim 1.13$ due to the change in the top-bottom loop interference. (I use Ferreira et. al notation. $C_g^h = \kappa_g$, $C_\gamma^h = \kappa_\gamma$)

- According to the recent Snowmass studies, the LHC can measure $\kappa_g$ to 6–8% for $L = 300$ fb$^{-1}$ and 3–5% for $L = 3000$ fb$^{-1}$, based on fitting all the rates rather than directly observing the $gg$ final state. At the ILC, $e^+e^- \to Z^* \to Zh$ determines the $ZZh$ coupling very accurately and isolation of the $gg$ final state is easier. The error on $\kappa_g$ estimated is 2% for a combination of $L = 250$ fb$^{-1}$ at $\sqrt{s} = 250$ GeV and $L = 500$ fb$^{-1}$ at $\sqrt{s} = 500$ GeV.
Thus, both the LHC and ILC will be able to determine whether or not $C^h_D$ is positive using the indirect fit and direct measurement of $\kappa_g$, respectively.

- The 5% suppression of $\kappa_\gamma$ for $C^h_D < 0$ should be measurable at the $\sqrt{s} = 14$ TeV LHC run for $L = 3000$ fb$^{-1}$.

At the ILC, for a combination of $L = 250$ fb$^{-1}$ at $\sqrt{s} = 250$ GeV and $L = 500$ fb$^{-1}$ at $\sqrt{s} = 500$ GeV the expected error on $\kappa_\gamma$ is $\sim 8.3\%$ (including a 0.5% theory uncertainty) based on measuring $e^+e^- \to Zh$ with $h \to \gamma\gamma$, implying that the sign of $C^h_D$ cannot be directly determined at the ILC using the $\gamma\gamma$ final state.

- Let’s explore further the charged-Higgs non-decoupling. (arXiv:1403.4736, Ferreira, et. al.)

In figures, the notations $\kappa_d = C^h_D$, etc. are employed.

First, it is easily seen that $C^h_D$ is negative when $\sin(\beta + \alpha) \sim 1$, i.e. not the usual $\sin(\beta - \alpha) \sim 1$ decoupling limit.
In this case, the relative $hVV$ and $hhh$ couplings satisfy

$$C^h_{VV}, C_{hhh} \to (\tan^2 \beta - 1)/(\tan^2 \beta + 1) \quad (\sin(\beta + \alpha) \to 1).$$

\[ (5) \]

⇒ at large $\tan \beta$ can’t use either $C^h_{VV}$ or $C_{hhh}$ to rule out wrong sign case.

We performed a scan very similar to that already discussed. After passing all preLHC constraints, the points were used to calculate the various $\mu^h_X(Y)$.

Figure 13: Ratio of the lightest Higgs couplings to down quarks in the 2HDM relative to the SM as a function of $\tan \beta$. Left - Type-I and right - Type-II. All $\mu$’s required to be within 20% of the SM value.
In Fig. 13 we show $\kappa_d \equiv C^h_D$ in Type-I and Type-II models as a function of $\tan \beta$ for those parameter space points that pass all theoretical and experimental constraints and have all $\mu^h_X(Y)$’s within 20% of the SM prediction of 1. The two regions with opposite sign for $\kappa_d$ are apparent.

If we increase the precision required for the $\mu^h_X(Y)$s, we find

![Diagram showing allowed regions for 2HDM Type-II with all $\mu^h_X(Y)$ within 20% (blue/black), 10% (green/light grey) and 5% (red/dark grey) of their SM values in: Left — $\kappa_\gamma$ vs. $\kappa_d$ space; Right — $\kappa_g$ vs. $\kappa_d$ space.]

Figure 14: Allowed regions for 2HDM Type-II with all $\mu^h_X(Y)$ within 20% (blue/black), 10% (green/light grey) and 5% (red/dark grey) of their SM values in: Left — $\kappa_\gamma$ vs. $\kappa_d$ space; Right — $\kappa_g$ vs. $\kappa_d$ space.
To understand the $\kappa_\gamma$ upper limit in the $\kappa_d < 0$ case, we note that the $hH^+H^-$ coupling has the form (JFG+Haber, decoupling) $g_{hH^+H^-} =$:

$$
(2m_A^2 - 2m_{H^\pm}^2 - m_h^2) \sin(\beta - \alpha) \sin \beta \cos \beta + (m_A^2 - m_h^2) \cos 2\beta \cos(\beta - \alpha) + \lambda_5 v^2 \cos(\beta + \alpha) \over v^2 \sin \beta \cos \beta .
$$

(6)

In the decoupling limit, we have $\sin(\beta - \alpha) \to 1$, $\cos(\beta - \alpha) \to 0$, and $m_A^2 \sim m_H^2 \sim m_{H^\pm}^2 \gg v^2$ and $g_{hH^+H^-} \propto v^2/m_{H^\pm}^2$ as follows:

- The first term inside the brackets of eq. (6) is of order $v^2$ because of the mass relations (keeping the $\lambda_i$ perturbative) and the second term is of order $v^2$ because $\cos(\beta - \alpha) \propto v^2/m_A^2$.
- To discuss the third term we need to note that for $\sin(\beta - \alpha) \to 1$ we have $\alpha \to \beta - \pi/2$.

Then, term 3 $\to 2v^2\lambda_5$ since $\cos(\beta + \alpha) \to \sin 2\beta = 2 \sin \beta \cos \beta$.

- The net result is that $g_{hH^+H^-}$ is not growing with the Higgs mass squared and so the charged Higgs loop contribution to the $h \to \gamma\gamma$ amplitude is suppressed by a factor of $m_W^2/m_{H^\pm}^2$ relative to the $W$ and $t$ and $b$ loops.

This agrees with the idea that a heavy particle that does not acquire mass from the Higgs vev should decouple.
Figure 15: We show points in the $v^2 g_{hH^+H^-}/m^2_{H^\pm}$ vs. $\kappa_d$ plane.

However, the situation is necessarily quite different in the case of $\kappa_d < 0$, where $\sin(\beta + \alpha) \to 1$, implying $\alpha \to \pi/2 - \beta$. In this limit, $\cos(\beta - \alpha) \to \sin 2\beta$ so that the second term in the numerator of eq. (6) is approximated by 

\[2(m_A^2 - m_h^2) \cos 2\beta\] which approaches $\sim 2m^2_{H^\pm} \cos 2\beta$ as $m_A^2 \sim m^2_H \sim m^2_{H^\pm} \to \infty$ (at fixed $m_h \sim 125$ GeV). Of course, if $\tan \beta$ is large then $\cos 2\beta \to -1$. Thus, we see from eq. (6) that for $\kappa_d < 0$ we have

\[\frac{v^2 g_{hH^+H^-}}{m^2_{H^\pm}} \sim -2,\]
i.e. the $H^\pm$ loop contribution to the $h \rightarrow \gamma\gamma$ amplitude will never decouple: $-2$ corresponds to $\kappa_\gamma \simeq 0.95$.

Of course, there are limits on the maximum $m_{H^\pm}$ deriving from unitarity of the partial wave scattering amplitudes. The strongest constraint comes from a certain eigenamplitude denoted $|a^+|$.

**Figure 16:** We plot: left panel: $|a^+|$ vs. $\kappa_d$; right panel: $|a^+|$ vs. $m_{H^\pm}$ for $\kappa_d < 0$ (blue) and $\kappa_d > 0$ (green) points with all $\mu^h_X(Y)$ within 20% of unity.

Should experiment eventually find that $\kappa_d < 0$ is preferred then we should also find $m_{H^\pm} < 650$ GeV.
Low-mass Higgs bosons in the 2HDM

Let us now focus on low-$m_A < m_h/2$ points.

They are present for both Type I and Type II and have similar features in the two cases in many respects, except $A$ production in Type I is much smaller than in Type II.

Points with acceptably small $\text{BR}(h \rightarrow AA)$ exist, but it takes a highly tuned scan to find them since generically the coupling $\lambda_{hAA}$ is quite large.

One must also have small $\text{BR}(h \rightarrow ZA)$. However, since $g_{hZA} \propto \cos(\beta - \alpha)$, and $\cos(\beta - \alpha)$ is smallish, $ZA$ is more easily suppressed given that the $h$ is fairly SM-like.

Features of the surviving points are shown in Figs. 17 and 18. Note the suppression of $\mu_{gg}(\gamma\gamma)$ and that $h \rightarrow ZA$ can still be an important channel. Obviously, both should be looked for!
Figure 17: Features of Type-I postLHC8 points with $m_A < m_h/2$.
Figure 18: Features of Type-II postLHC8 points with \( m_A < m_h/2 \).
We plot the cross sections for $gg \rightarrow A$ and $bbA$ with $A \rightarrow \tau\tau$ 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 postLHC8 level, including $m_h = 125$ GeV higgs fitting.

Figure 19:
Fig. 19 shows that $gg \rightarrow A$ and $bbA$ with $A \rightarrow \tau\tau$ cross sections are very large! Spread in points comes from $\tan \beta$ variation.

Notes:
a) Even above the $b\bar{b}$ threshold $\text{BR}(A \rightarrow \tau\tau) \sim 0.07$ 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 $\sigma\text{BR}$ values to those shown.

Just to get a point of reference let us take $\sigma\text{BR}(A \rightarrow \tau\tau) \sim 10$ pb. With 20 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 $\text{BR}(\tau\tau \rightarrow \tau\mu\tau\nu) \sim 0.22$ as well as acceptance and other efficiencies, such as $b$-tagging), this still leaves about 20 events.

In Type I, $\sigma(gg \rightarrow A)\text{BR}$ ($\sigma(bbA)\text{BR}$ 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 $\sigma(gg \rightarrow A)\text{BR}$ and $\sigma(bbA)\text{BR}$ are potentially observable. One gets the following table.
Table 2: A very crude event number table assuming acceptance $\times$ efficiency $\times$ BR($\tau \tau \rightarrow \text{mode}$) 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 $\sigma(gg \rightarrow A)BR(A \rightarrow \mu \mu) \leq 2 - 3 \text{ pb}$ for $m_A \in [11 - 14] \text{ GeV}$ using $1.3 \text{ fb}^{-1}$ of data. This can be compared to the predictions shown in Fig. 20.

From this, it seems that Type-II is ruled out for $m_A < 14 \text{ GeV}$, but not Type-I.
Figure 20: 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 postLHC8 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.
What happens as we move to SM\(\pm 15\%\), \(\pm 10\%\), \(\pm 5\%\) for the \(h125\)? In both Type I and Type II, the \(\gamma\gamma\) final state has a suppressed rate, as illustrated by plotting \(C^h_{\gamma}\) vs. \(m_A\), see Fig. 21. For \(m_A < 65\) GeV, \(\kappa_\gamma \equiv C^h_{\gamma} \sim 0.95\), implying a 10% decrease in \(\Gamma(h \to \gamma\gamma)\).

As also illustrated in Fig. 21, this comes about because of non-decoupling of the charged Higgs loop contribution to the \(h\gamma\gamma\) coupling.

Recall: 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 \(C^h_{\gamma}\) by 5%.

This is related to the fact that most (Type I) or all (Type II) of the \(m_A < m_h/2\) points have \(\sin\alpha > 0\). (For Type II, but not Type I, this also implies \(C^h_D < 0\).)

In the case of Type II, \(\kappa_g \equiv C^h_g\) gets enhanced by 1.13 because of the change in the sign of the top-bottom interference \(\Rightarrow\) easily eliminated if the Higgs rates are observed to be increasingly SM-like, as outlined earlier.
Figure 21: We plot $C_\gamma$ 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 postLHC8 level, including $m_h = 125$ GeV higgs fitting.
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 $\sim 135$ 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.

In models such as the 2HDM, heavier Higgs bosons may well be observable.

The possibility of a light $A$ in association with a nearly, but not quite ($\kappa_\gamma \equiv C^h_\gamma \sim 0.95$ and, for Type-II, $\kappa_g \equiv C^h_g \sim 1.13$) SM-like scalar Higgs remains open and has very interesting implications.

Strong signals could be present in the 8 TeV data in the case of Type-II 2HDM models.
While the waiting for a 1st Higgs signal is over, watching for more Higgs or some sign of BSM is not.