The Alignment Limit and Light Higgs Bosons
constraints and prospects

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The existence of a SM-like Higgs constrains all directions of exploration.

125 GeV Higgs

- Just how SM-like is it?

One assessment is obtained by fits to a SM-like Lagrangian with rescaling factors:

$$\mathcal{L} = \left[C_W m_W W^\mu W_\mu + C_Z \frac{m_Z}{\cos\theta_W} Z^\mu Z_\mu - C_U \frac{m_t}{2m_W} \bar{t}t - C_D \frac{m_b}{2m_W} \bar{b}b - C_D \frac{m_\tau}{2m_W} \bar{\tau}\tau \right] H \quad (1)$$

In addition, define the loop-induced couplings C_g and C_γ of the H to gg and $\gamma\gamma$, respectively. ATLAS and CMS call these rescaling factors κ.

Figure 1 shows results for a fit to common rescaling factors C_F and C_V, with C_g and C_γ computed assuming only SM loops. One sees some discrepancy between CMS and ATLAS, but if we take the combination seriously, then at 68% CL we have $0.97 < C_V < 1.13$, $0.82 < C_F < 1.15$.

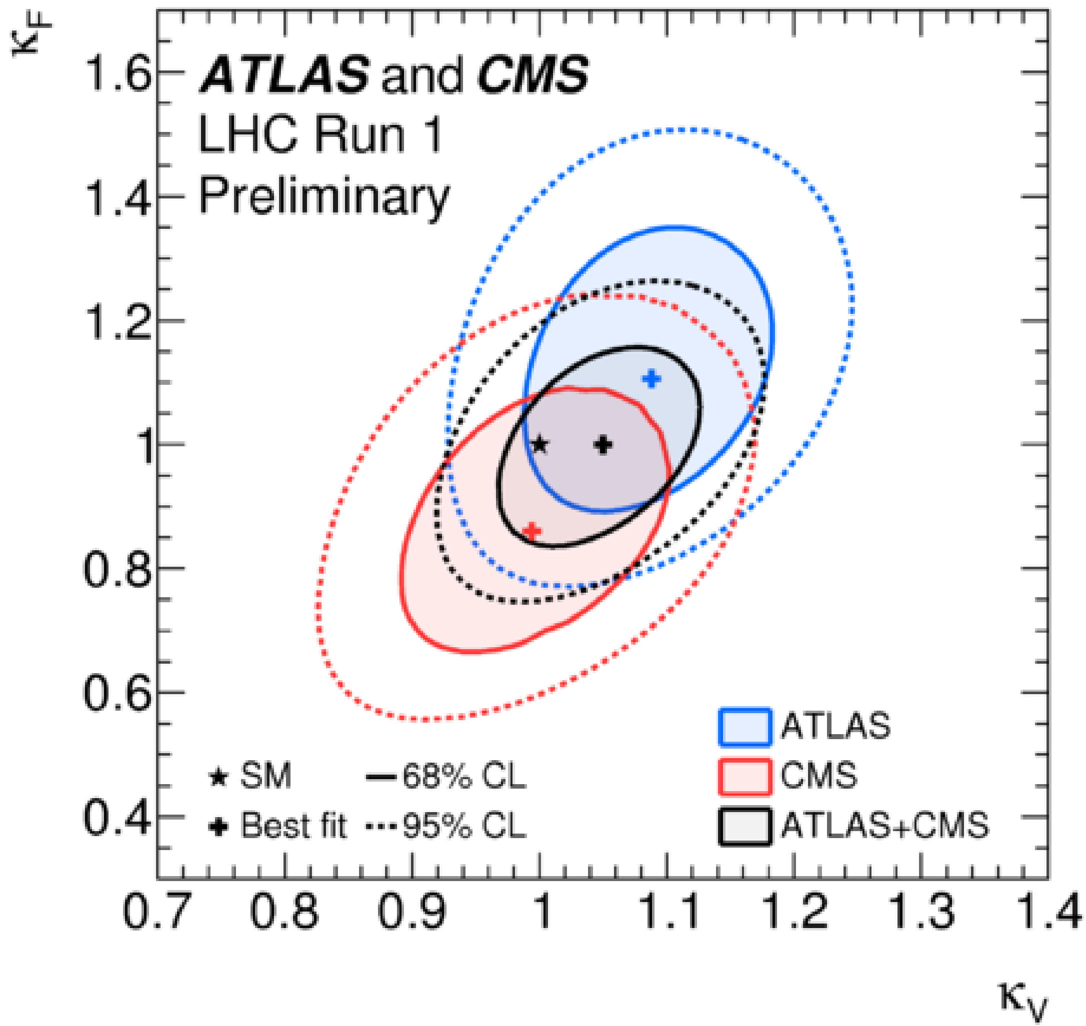


Figure 1: κ_F versus κ_V for the combination of ATLAS and CMS and for the global fit of all channels. Also shown are the contours obtained for each experiment. From ATLAS-CONF-2015-044.

- There can be unseen, U, but not truly invisible, Higgs decays.

  When C_U, C_D are free, $C_V \leq 1$ and $\Delta C_\gamma = \Delta C_g = 0$, $\mathcal{B}_U < 0.22$ at 95% CL.

- If the $125~\mathrm{GeV}$ Higgs is very SM-like, there are still many opportunities even if the only new particles are Higgs bosons. Increasing limits on new physics suggests that one should take seriously this possibility.

  In particular,

  - we should consider limits of multi-Higgs models in which one of the Higgs bosons is really very SM-like;
  - 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 $125~\mathrm{GeV}$ state so long as the corresponding branching ratio is not very large.

Theoretical Structure of Alignment

The most general 2HDM Higgs potential can be specified in many bases, but two are most useful.

Higgs basis

In the Higgs basis the vev, $v = 2m_W/g \simeq 246$ GeV resides entirely in one of the two Higgs doublet fields,

$$\langle H_1^0 \rangle = v/\sqrt{2} \quad \text{and} \quad \langle H_2^0 \rangle = 0\,. \tag{2}$$

The scalar potential in the Higgs basis is written

$$\begin{aligned} \mathcal{V} \;=\; & Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + Y_3[H_1^\dagger H_2 + \text{h.c.}] + \frac{1}{2}Z_1(H_1^\dagger H_1)^2 + \frac{1}{2}Z_2(H_2^\dagger H_2)^2 \\ & + Z_3(H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4(H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + \left\{\frac{1}{2}Z_5(H_1^\dagger H_2)^2 + \big[Z_6(H_1^\dagger H_1) + Z_7(H_2^\dagger H_2)\big] H_1^\dagger H_2 + \text{h.c.}\right\}, \end{aligned} \tag{3}$$

where $Y_1 = -\frac{1}{2}Z_1 v^2$ and $Y_3 = -\frac{1}{2}Z_6 v^2$ at the scalar potential minimum. For simplicity, we assume that the field H_2 can be rephased such that the potentially complex parameters Z_5, Z_6 and Z_7 are real, in which case the scalar potential and Higgs vacuum are CP-conserving.

Two relations among the Z_i result from requiring absence of hard FCNC violation:

$$Z_2 = Z_1 + 2(Z_6 + Z_7)\cot 2\beta\,, \quad Z_3 + Z_4 + Z_5 = Z_1 + 2Z_6 \cot 2\beta - (Z_6 - Z_7)\tan 2\beta\,. \tag{4}$$

Under the assumption of a CP-conserving Higgs sector, the Higgs mass spectrum is easily determined. The squared-masses of the charged Higgs and CP-odd Higgs bosons are given by

$$m^2_{H^\pm} = Y_2 + \frac{1}{2}Z_3 v^2\,, \quad m^2_A = m^2_{H^\pm} + \frac{1}{2}(Z_4 - Z_5)v^2\,, \tag{5}$$

and the two CP-even squared masses are obtained by diagonalizing the CP-even Higgs squared-mass matrix,

$$\mathcal{M}^2_H = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m^2_A + Z_5 v^2 \end{pmatrix}\,. \tag{6}$$

The physical mass eigenstates are

$$H = (\sqrt{2}\,\mathrm{Re}\,H_1^0 - v)\cos(\beta-\alpha) - \sqrt{2}\,\mathrm{Re}\,H_2^0\,\sin(\beta-\alpha)\,, \tag{7}$$

$$h = (\sqrt{2}\,\mathrm{Re}\,H_1^0 - v)\,\sin(\beta-\alpha) + \sqrt{2}\,\mathrm{Re}\,H_2^0\,\cos(\beta-\alpha)\,, \tag{8}$$

where $m_h \leq m_H$. The resulting CP-even Higgs squared-masses are given by

$$m_{H,h}^2 = \frac{1}{2}\left[m_A^2 + (Z_5 + Z_1)v^2 \pm \sqrt{[m_A^2 + (Z_5 - Z_1)v^2]^2 + 4Z_6^2 v^4}\right], \tag{9}$$

and the diagonalization process gives

$$Z_6 v^2 = (m_h^2 - m_H^2)\sin(\beta-\alpha)\cos(\beta-\alpha). \tag{10}$$

In light of eq. (2), if $\sqrt{2}\,\mathrm{Re}\,H_1^0 - v$ were a mass eigenstate, then its tree-level couplings to SM particles and its self-couplings would be precisely those of the SM Higgs boson. That is, if one of the neutral CP-even Higgs mass eigenstates is approximately aligned in field space with the direction of the vev (the so-called alignment limit), then the couplings of this Higgs boson are SM-like.

From Eqs. (6) and (10) it is obvious that the alignment limit corresponds to $Z_6 = 0$ and either $\cos(\beta-\alpha) = 0$ or $\sin(\beta-\alpha) = 0$ in which cases the h or H is SM-like (the $h125$ or $H125$ scenarios, respectively). In the $h125$ case,

- alignment necessarily occurs in the decoupling limit in which $m_H \sim m_A \gg v$ since the mixing of states in $\mathcal{M}_H^2$, eq. (6), is automatically negligible.

- or it can be negligible if $|Z_6|v^2 \ll Z_1 v^2 < m_A^2 + Z_5 v^2$, alignment without decoupling.

In both cases, $h \simeq \sqrt{2}\,\mathrm{Re}\, H_1^0 - v$, corresponding to $|\cos(\beta-\alpha)| \ll 1$.

The $\mathbb{Z}_2$ basis

The FCNC nature of the theory is more transparent in the alternative $\mathbb{Z}_2$ basis, defined by the rotation

$$H_1 = \Phi_1 c_\beta + \Phi_2 s_\beta\,, \quad H_2 = -\Phi_1 s_\beta + \Phi_2 c_\beta\,. \tag{11}$$

In the $\mathbb{Z}_2$ basis the potential is written as

$$\begin{aligned} \mathcal{V} \;=\;& m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 + \frac{\lambda_1}{2}|\Phi_1|^2 + \frac{\lambda_2}{2}|\Phi_2|^2 + \lambda_3|\Phi_1|^2|\Phi_2|^2 \\ & + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\left((\Phi_1\Phi_2)^2 + \mathrm{c.c.}\right) - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \mathrm{c.c.}\right) \\ & + \left(\lambda_6|\Phi_1|^2(\Phi_1\Phi_2) + \mathrm{c.c.}\right) + \left(\lambda_7|\Phi_2|^2(\Phi_1\Phi_2) + \mathrm{c.c.}\right)\;. \end{aligned} \tag{12}$$

To avoid CP violation, all parameters are taken to be real.

The terms involving λ_6 and λ_7 must be zero in order to avoid tree-level FCNC. This is achieved by imposing $\mathbb{Z}_2$ symmetry under $\Phi_1 \to +\Phi_1$, $\Phi_2 \to -\Phi_2$ on $\mathcal{V}$. ($\lambda_6 = \lambda_7 = 0$ implies two relations among the Z_i.) $m_{12}^2 \neq 0$ breaks $\mathbb{Z}_2$ only softly.

According to the Gunion+Haber decoupling analysis (hep-ph/0207010), the h or H will be exactly SM-like, $\cos(\beta-\alpha)=0$ or $\sin(\beta-\alpha)=0$, respectively, if

$$\hat{\lambda} \equiv \frac{1}{2} s_{2\beta} \left[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - \lambda_{345} c_{2\beta}\right] = -Z_6\,, \tag{13}$$

where $\lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5$ and we have set $\lambda_6 = \lambda_7 = 0$.

For $h125$ case, $\hat{\lambda} \sim 0$ is a possible choice even if one or more of the other Higgs masses are relatively small.

For $H125$ case, $\hat{\lambda} \sim 0$ is possible, $m_h \leq m_H$ by definition and m_A and $m_{H^\pm}$ are free and can in principle be small.

Side remark: If $\lambda_6 = \lambda_7 = 0$ by $\mathbb{Z}_2$, then $\hat{\lambda} = 0$ for any β if $\lambda_1 = \lambda_2 = \lambda_{345}$. An amusing special case is $\lambda_1 = \lambda_2 = \lambda_3 = -\lambda_4 = +\lambda_5 > 0$ for which $m_{H^\pm}^2 = m_H^2 = m_A^2 + m_h^2$, allowing the A to be light, $m_h = 125~\mathrm{GeV}$ and $m_{H^\pm} = m_H$ is significantly heavier (but not sufficiently heavier in Type II where $m_{H^\pm} > 480~\mathrm{GeV}$ is required). For this choice $\mathcal{V} = \frac{1}{2}\lambda_1 \left[(\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2)^2 + (\Phi_1^\dagger\Phi_1 - \Phi_2^\dagger\Phi_2)^2\right]$. Other highly symmetric forms for $\mathcal{V}$ are possible for other choices.

As regards models with good FCNC properties, 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.

Decays and light Higgs bosons

- Of particular interest is $h \to AA$ or $H \to AA, hh$. Must suppress the couplings if these are kinematically allowed for acceptable $h125$ or $H125$ fits, respectively.

$$\begin{aligned} g_{hAA} &= -v\left[(Z_3+Z_4-Z_5)s_{\beta-\alpha}+Z_7c_{\beta-\alpha}\right] \\ &= -1/v\left\{\left[m_h^2+2(m_A^2-\bar{m}^2)\right]s_{\beta-\alpha}+2\cot 2\beta(m_h^2-\bar{m}^2)c_{\beta-\alpha}\right\} \end{aligned} \quad (14)$$

$$\overset{\sin(\beta-\alpha)\to 1}{\to} -\frac{1}{v}[m_h^2+2(m_A^2-\bar{m}^2)] \quad (15)$$

where $\bar{m}^2 = m_{12}^2/(s_\beta c_\beta)$. Fine tuning of $\bar{m}^2$ is required to get small enough

$h \to AA$ in the $h125$ scenario. Similarly,

$$
\begin{aligned}
g_{HAA} &= -\frac{1}{v}\left\{\left[m_H^2 + 2(m_A - \overline{m}^2)\right] c_{\beta-\alpha} - 2\cot 2\beta (m_H^2 - \overline{m}^2) s_{\beta-\alpha}\right\} \\
&\stackrel{c_{\beta-\alpha}\to 1}{\to} -\frac{1}{v}\left[m_H^2 + 2(m_A^2 - \overline{m}^2)\right]
\end{aligned} \tag{16}
$$

$$
\begin{aligned}
g_{Hhh} &= -\frac{c_{\beta-\alpha}}{v}\Big\{4\overline{m}^2 - m_H^2 - 2m_h^2 \\
&+2(3\overline{m}^2 - m_H^2 - 2m_h^2)(s_{\beta-\alpha}\cot 2\beta - c_{\beta-\alpha})c_{\beta-\alpha}\Big\} \\
&\stackrel{c_{\beta-\alpha}\to 1}{\to} -\frac{1}{v}\left[m_H^2 + 2(m_A^2 - \overline{m}^2)\right]
\end{aligned} \tag{17}
$$

Note: both g_{HAA} and g_{Hhh} will be suppressed simultaneously in the alignment limit of the $H125$ scenario! But, in the case of both h and A being below $m_H/2 = 62.5~\mathrm{GeV}$, LEP limits on $Z \to hA$ are strong since $g_{ZhA} \propto c_{\beta-\alpha}$ is maximal. So, only one or the other can be light enough to be present in H decays.

Scanning procedures

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

$$m_h, \quad m_H, \quad m_{H^\pm}, \quad m_A, \quad \tan\beta, \quad m_{12}^2, \quad \alpha\,, \tag{18}$$

with $\beta \in [0, \pi/2]$, $\alpha \in [-\pi/2, +\pi/2]$; m_{12}^2 (the parameter that softly breaks the $\mathbb{Z}_2$ symmetry) can have either sign.

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 $\sin\alpha > 0$.

Proceed in steps:

1. Choose $h125$ or $H125$.

2. Scan:

$$\alpha \in [-\pi/2, +\pi/2]\,, \quad \tan\beta \in [0.5, 60]\,, \quad m_{12}^2 \in [-(2~\mathrm{TeV})^2, (2~\mathrm{TeV})^2]\,,$$
$$m_A \in [5~\mathrm{GeV}, 2~\mathrm{TeV}]\,, \quad m_{H^\pm} \in [m^*, 2~\mathrm{TeV}]\,, \tag{19}$$

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

3. Impose stability, unitarity and perturbativity (SUP).

4. Impose precision electroweak constraints (STU).

5. Apply all constraints from preLHC (B-physics, LEP limits, ...)

6. Impose Higgs fitting for all channels as per arXiv:1306.2941 (Belanger, et.al.) at the 95% CL.

7. Require that feed down (FD) from heavier Higgs bosons not disturb the $125~\mathrm{GeV}$ fits. e.g. for the $h125$ case the most important channels are: $gg \to H \to hh$ and $gg \to Z \to Zh$.

8. Impose LHC limits on Higgs bosons either heavier or lighter than $125.5~\mathrm{GeV}$.

9. Look at consequences.

Step #8, in particular, is becoming increasingly interesting as more analyses and data become available.

All the plots I will show come from one of the following papers:

1. Constraints on and future prospects for Two-Higgs-Doublet Models in light of the LHC Higgs signal: Dumont, Gunion, Jiang, Kraml, arXiv:1405.3584.

2. Light Higgs bosons in Two-Higgs-Doublet Models: Bernon, Gunion, Jiang, Kraml, arXiv:1412.3385.

3. Scrutinizing the alignment limit in two-Higgs-doublet models: Bernon, Gunion, Haber, Jiang, Kraml, arXiv:1507.00933 ($h125$), arXiv:1511.03682 ($H125$). Plots in these papers are for $C_V \geq 0.99$.

The $h125$ case

- Basic picture

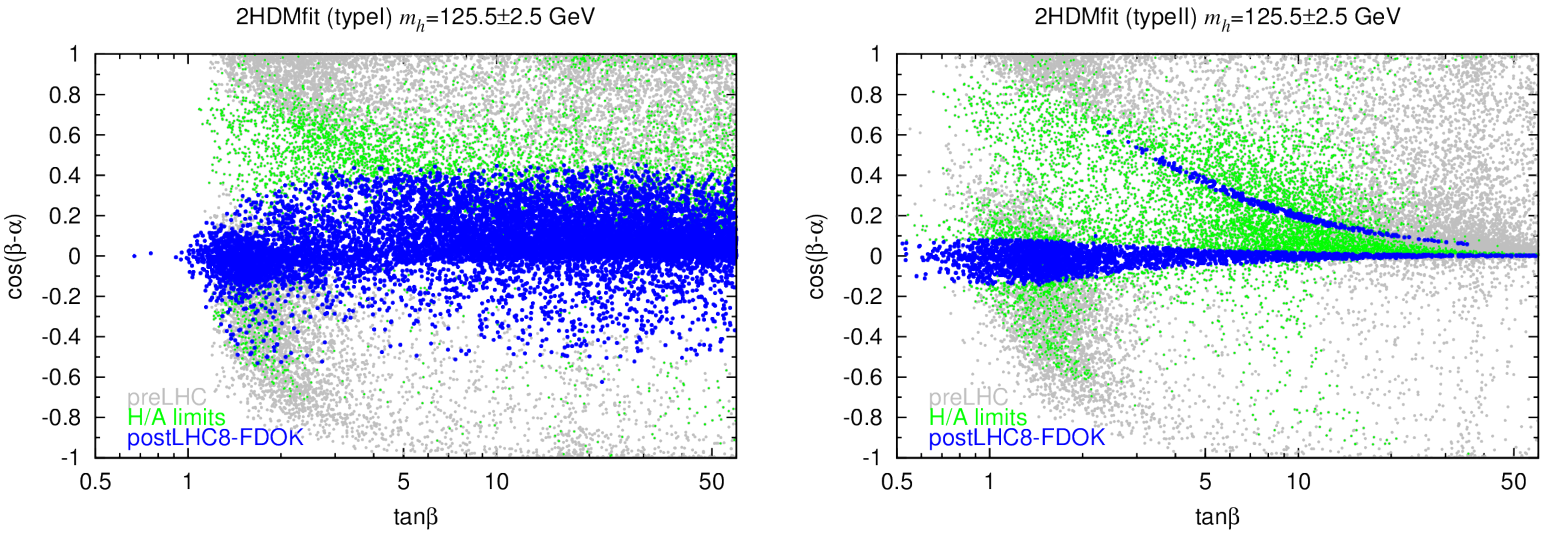


Figure 2: Constraints in the $\cos(\beta-\alpha)$ versus $\tan\beta$ plane for $m_h \sim 125.5$ GeV. Grey points satisfy preLHC constraints, while green points satisfy in addition the pre-May-2014 LHC limits on H and A production. Blue points fall in addition within the 7+8 TeV 95% CL ellipses in the $[\mu(\mathrm{ggF}+\mathrm{ttH}), \mu(\mathrm{VBF}+\mathrm{VH})]$ plane for each of the final states considered, $Y=\gamma\gamma, ZZ, WW, b\bar{b}, \tau\tau$. From paper #1.

The SM limit is $\cos(\beta-\alpha)\to 0$. 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 $C_D^h \sim -1$. The future LHC run can eliminate or confirm this branch. (see, in particular, arXiv:1403.4736, Ferreira, Gunion, Haber, Santos.) (NB: $C_U^h \sim -1$ is ruled out at $> 5\sigma$.)

- What masses are possible for the heavy H and the A?

  The situation is evolving rapidly as new constraints from Run1 are added and after latest $b \to s\gamma$ constraint of $m_{H^\pm} > 480$ GeV is included for Type II.

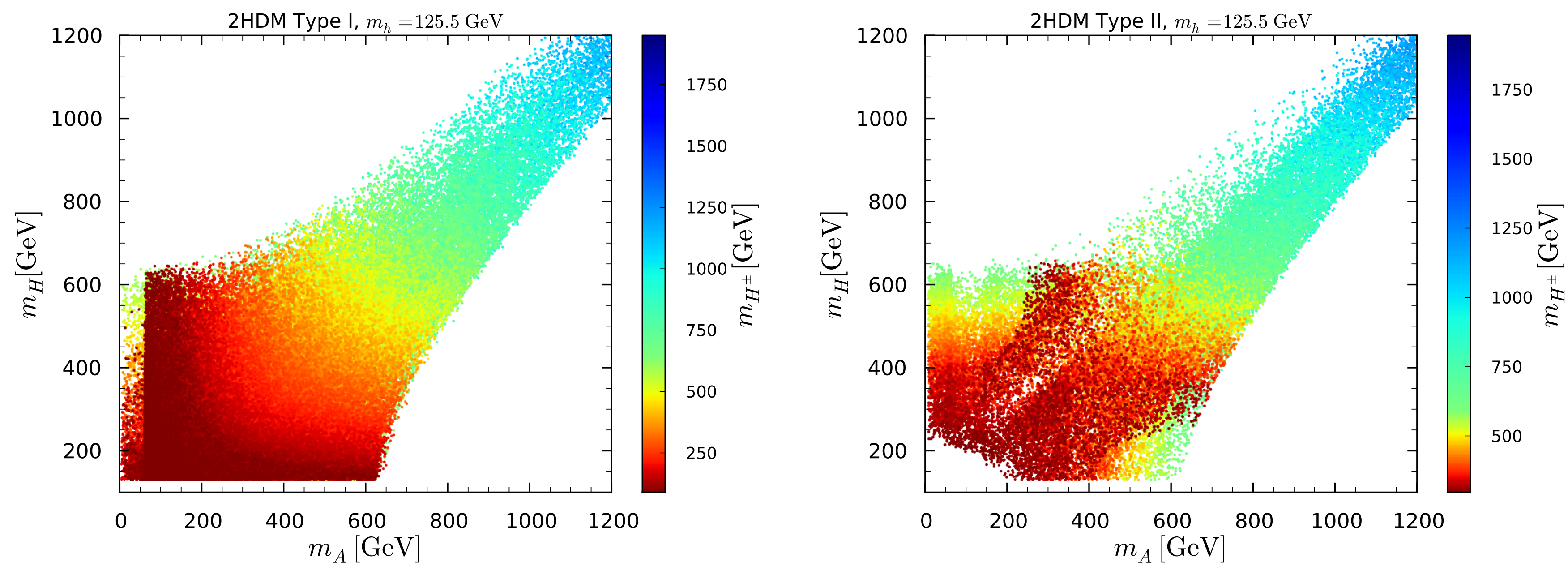


Figure 3: Constraints in the m_H vs m_A plane for $m_h \sim 125.5$ GeV, before recent constraints to be discussed. $m_{H\pm}$ coloring is done from high to low values.

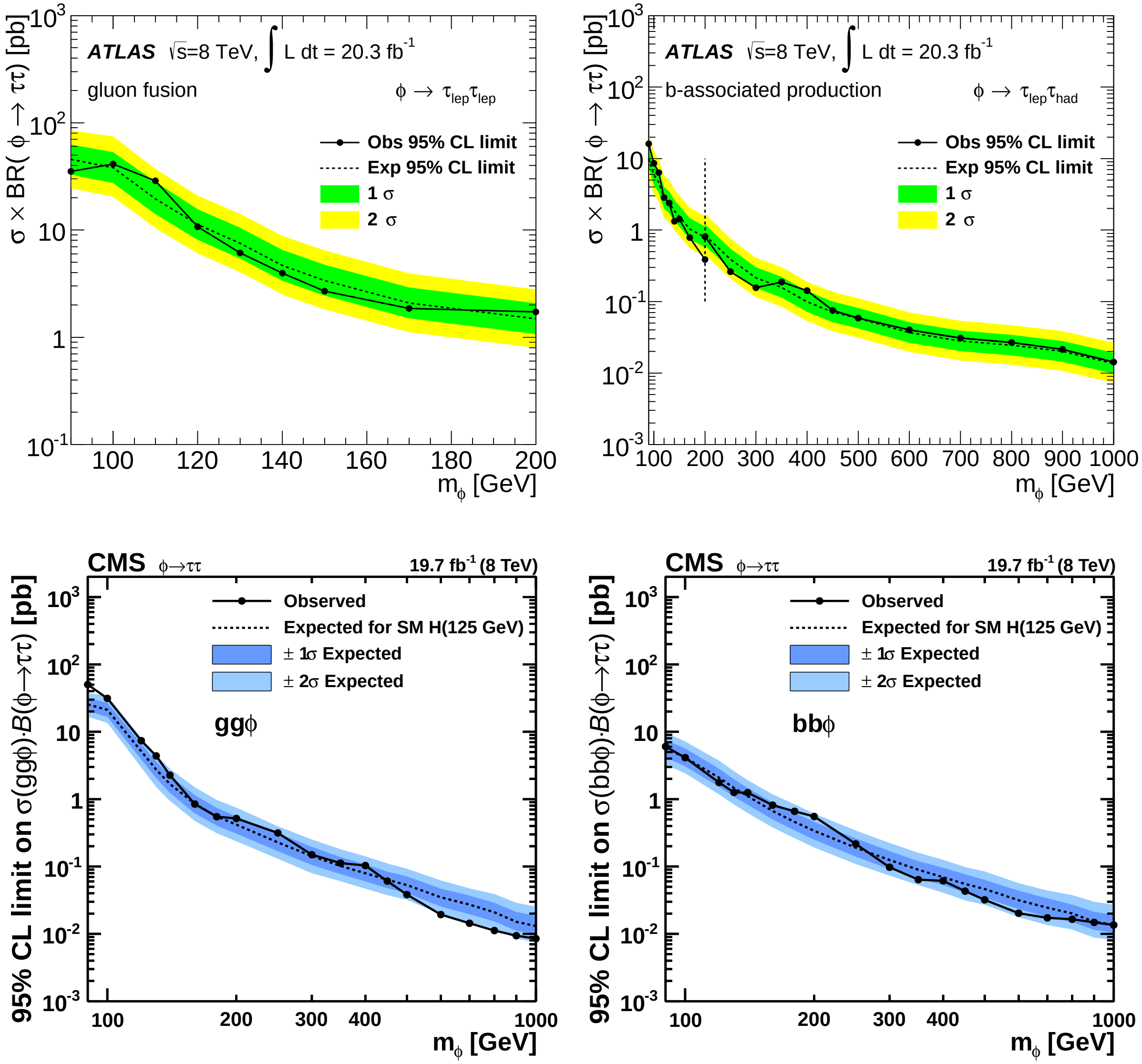
We see that very small values of m_A are possible even after:

– STU constraints,

– even after requiring $m_{H\pm} > 480$ GeV for Type II. (In Type I we have used the approximate lower bound of $m_{H\pm} > 90$ GeV from LEP.)

– even after requiring $h125$ precision, including $\mathcal{B}(h125 \to aa) < 0.22$.

Next, include limits on $bb\phi$ with $\phi \to \tau\tau$ from Run1 for $m_A > 100$ GeV: $\phi = A$. (In $H125$ case limits apply to both A and h.)



This creates a blank region at moderate m_A in the case of Type II.

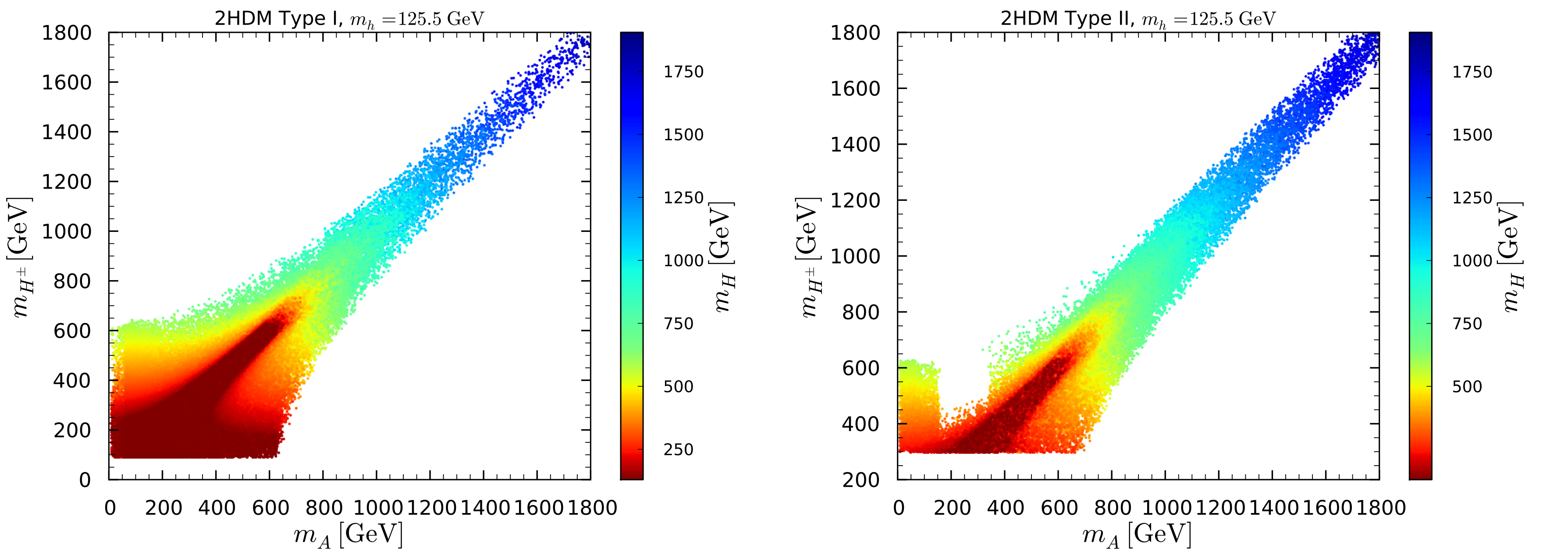


Figure 4: Constraints in the $m_{H^\pm}$ vs m_A plane for $m_h \sim 125.5\ \mathrm{GeV}$. Coloring in m_H from high to low. Plot done before recent $b \to s\gamma$ constraint of $m_{H^\pm} > 480\ \mathrm{GeV}$, but this does not affect the low m_A points significantly. From $h125$ paper of #3.

- Now put in $m_{H^\pm} > 480\ \mathrm{GeV}$ and limits on $b\bar{b}A$ with $A \to \tau\tau$ for $25\ \mathrm{GeV} < m_A < 80\ \mathrm{GeV}$ as well as LEP limits on $b\bar{b}\phi$ production.
  - wrong sign solution much more limited in $\tan\beta$ extent.

– gap in m_A appears since in above all the points in the gap have $m_{H^\pm} < 480$ GeV.

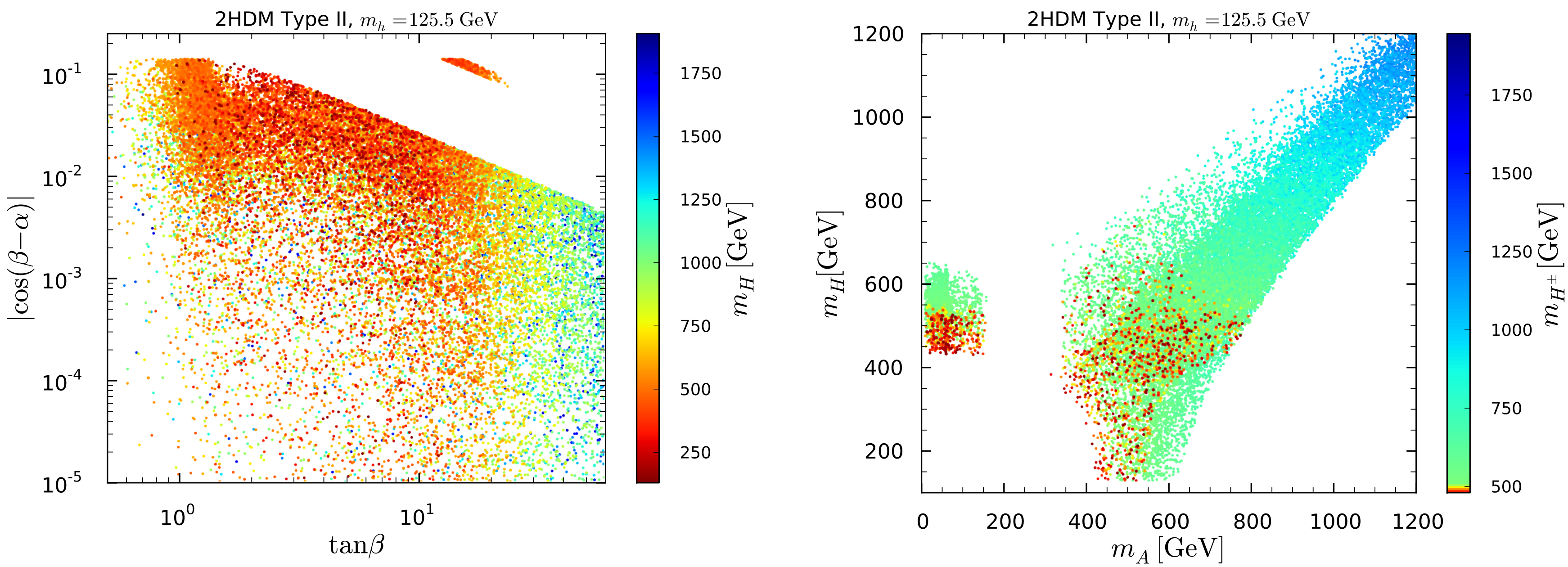


Figure 5: Constraints in the $\cos(\beta-\alpha)$ vs $\tan\beta$ and the m_H vs m_A plane for $m_h \sim 125.5$ GeV in Type II. Coloring in $m_{H^\pm}$ from high to low. Plot includes recent $b \to s\gamma$ constraint of $m_{H^\pm} > 480$ GeV and limits on bbA with $A \to \tau\tau$ for $25 \text{ GeV} < m_A < 80$ GeV, as well as constraints on $e^+e^- \to b\bar{b}A$.

To understand the impact of the $25 \text{ GeV} < m_A < 80$ GeV CMS limits from $b\bar{b}\phi$ with $\phi \to \tau\tau$ and the LEP limits on $b\bar{b}\phi$ with $\phi \to b\bar{b}$ let us step back away from imposing these and look at cross sections in particular in the $m_A < \frac{1}{2} \times 125$ GeV region. Very large Type II cross sections are possible at high $\tan\beta$.

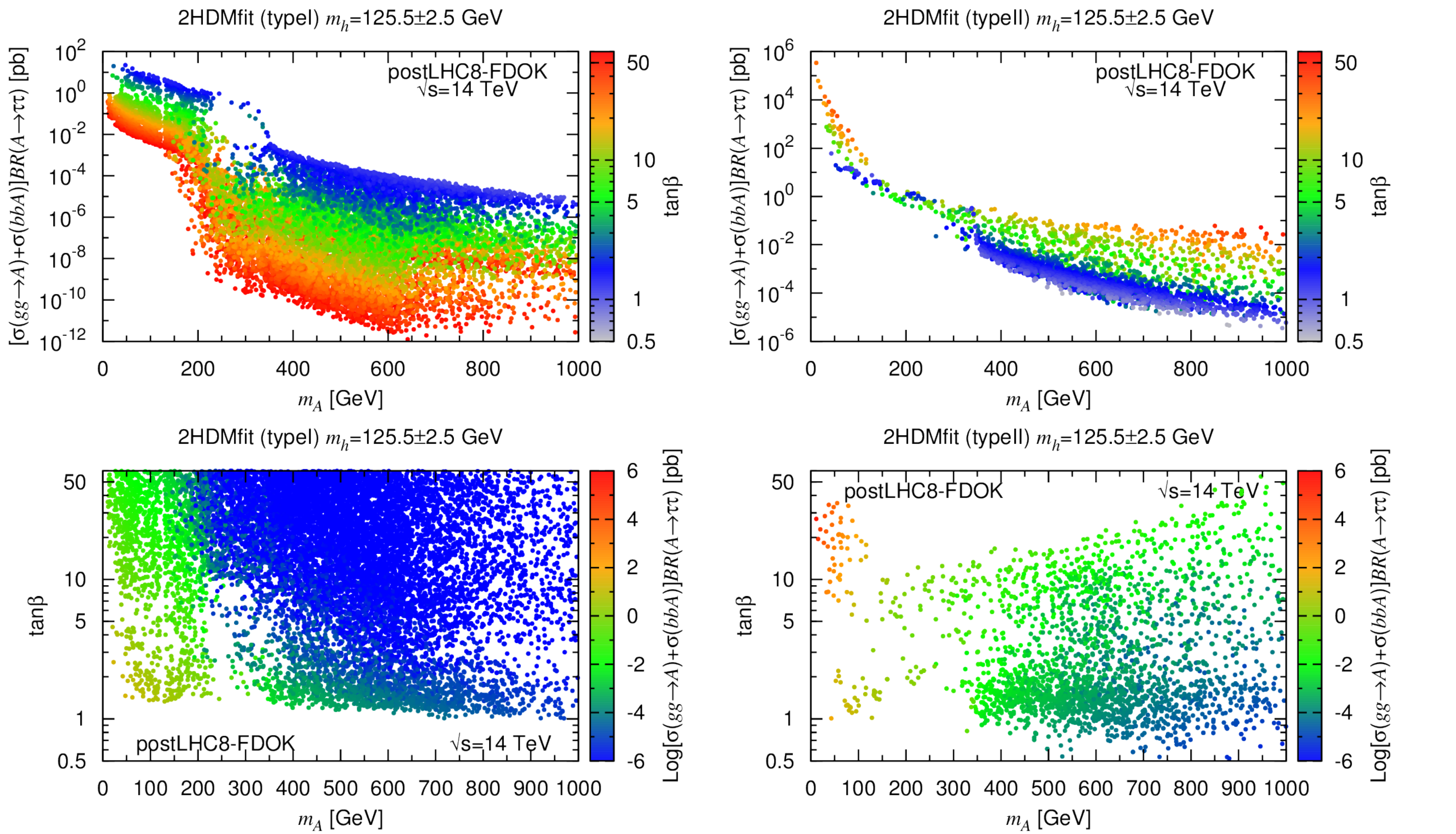
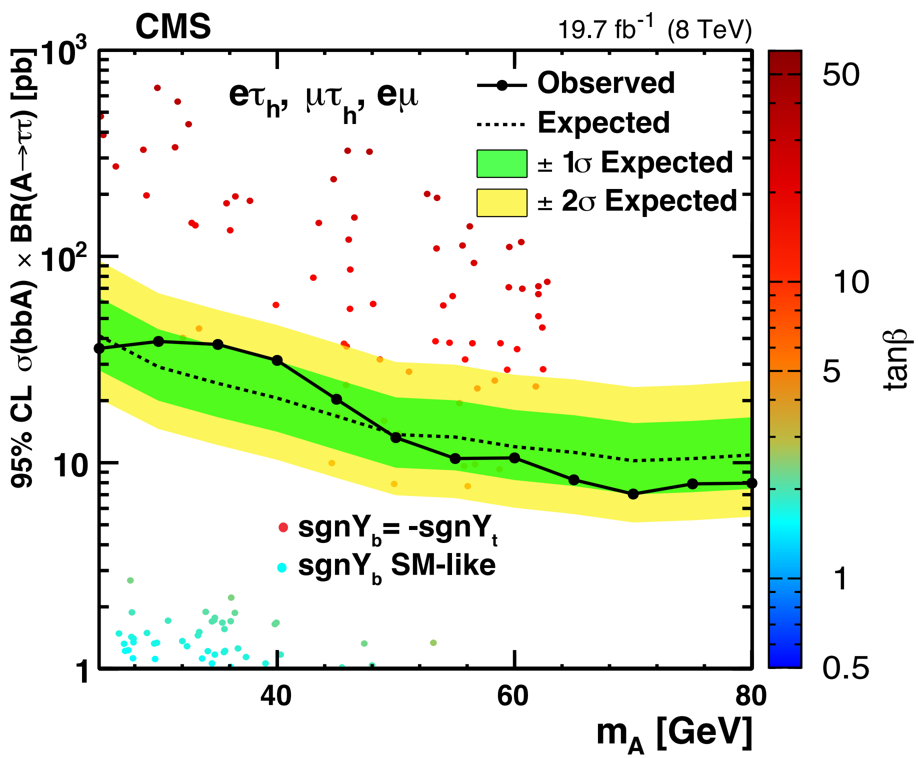
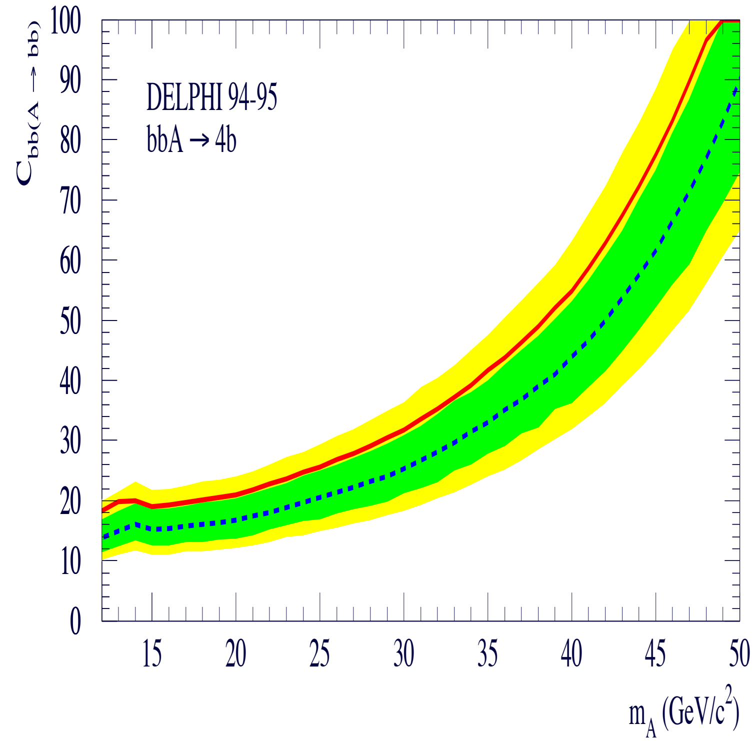


Figure 6: 2HDM points agreeing at 95% C.L. with precision Higgs data as well as B physics, ... From arXiv:1405.3584.

From CMS-HIG-14-033, arXiv:1511.03610 we eliminate nearly all the Type II orange points (with $m_A > 25$ GeV). In fact, these have $C_D^h < 0$ (opposite sign to normal but same magnitude). The $m_A < 25$ GeV wrong sign points are eliminated by the DELPHI LEP limit (both Z-pole data and continuum data).





All that is left of the wrong sign points are those with $m_A > 25$ GeV and $\tan\beta \leq 10$.

Note: These constraints apply equally to the (light) h of the Type II $H125$ scenario in the alignment limit where the $hb\bar{b}$ coupling is also $\simeq \tan\beta$.

- After all is said and done, we are left with the following $\tau\tau$ final state cross sections. A significant portion of the high σ cross sections should be probable during Run2.

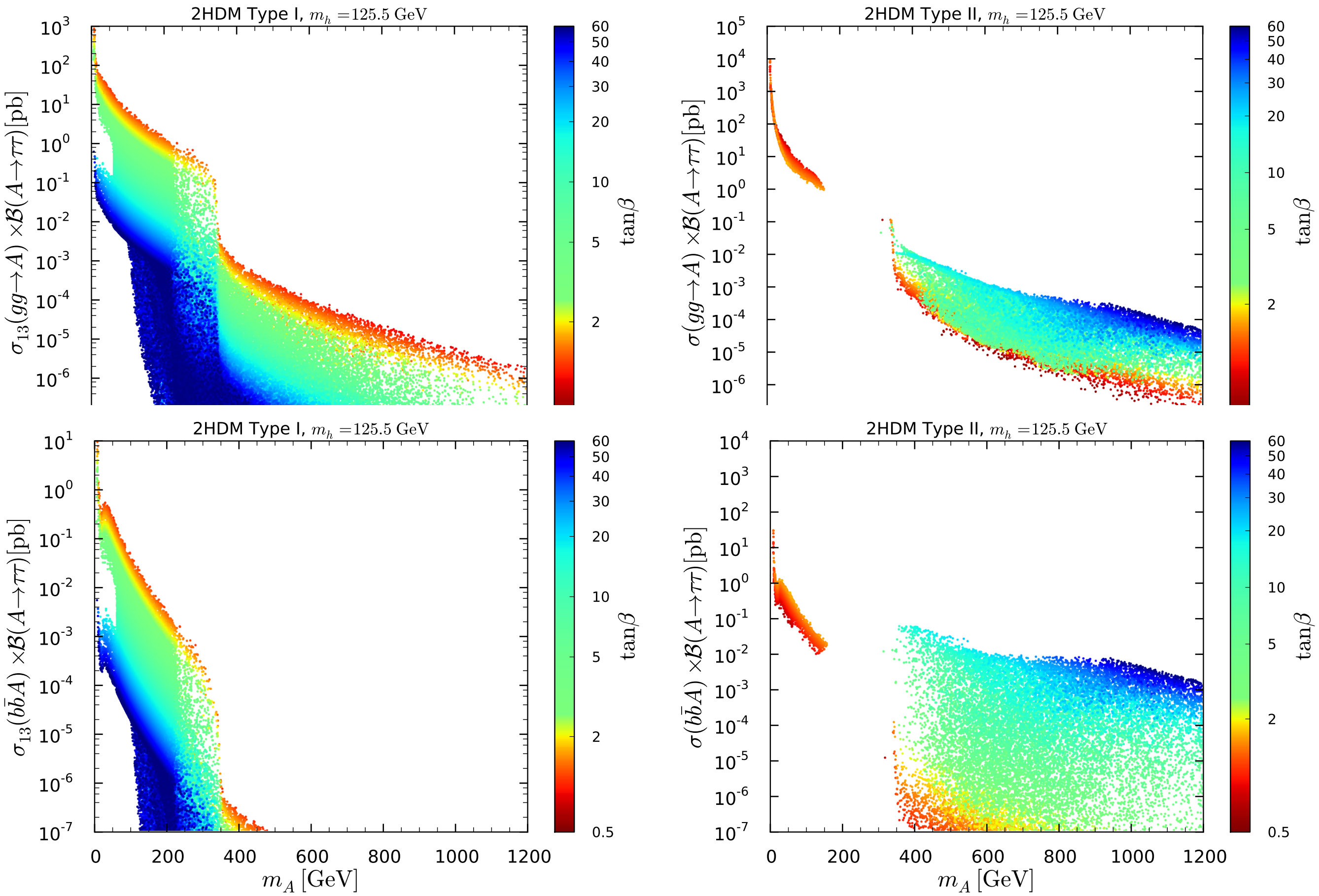
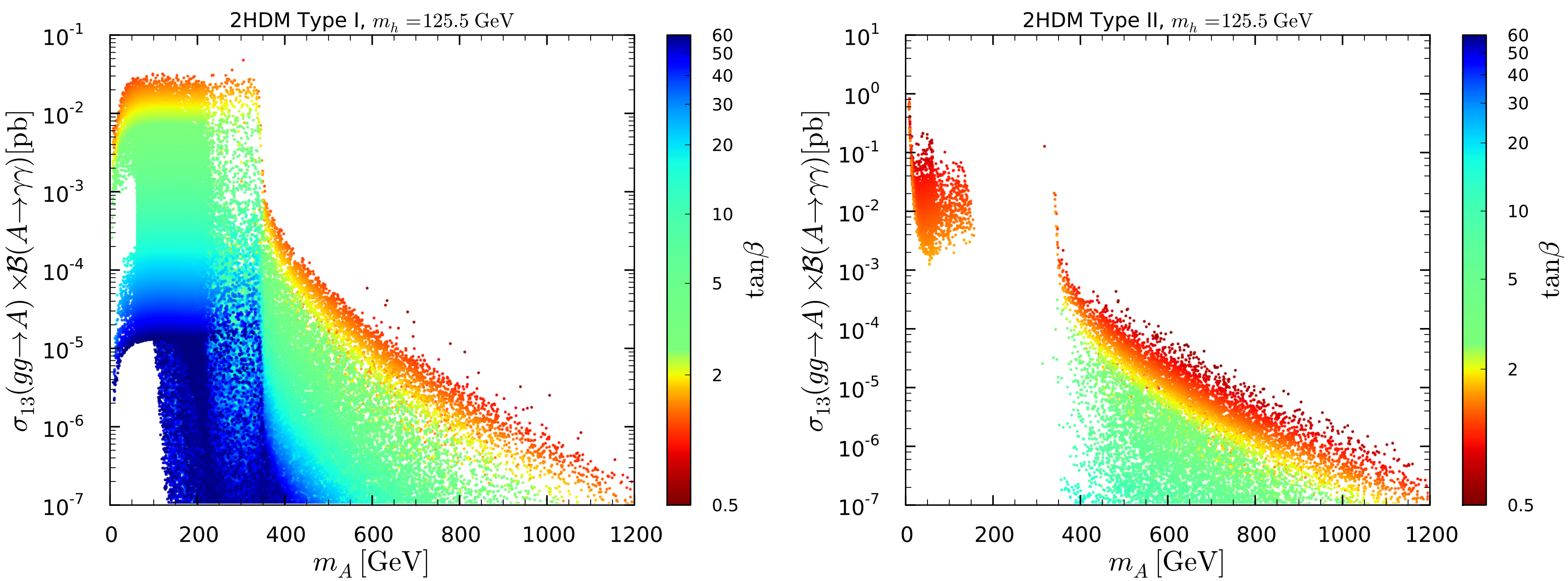


Figure 7: Coloring in $\tan\beta$ from low to high.

- The only other potentially interesting channel for a light A is the $\gamma\gamma$ final state.



Cross sections for Type II are really quite large at low m_A. (NB: the high $\tan\beta$ values in Type II were eliminated at low m_A by the bbA with $A\to\tau\tau$ CMS analysis and/or the LEP $b\bar{b}A$ limits so that we obtain a rather definitive cross section prediction.)

In Type I the cross section is also not so small if $\tan\beta$ is small, but is predicted to be very small at high $\tan\beta$.

- A note on the wrong sign points.

The wrong-sign points are associated with a non-decoupling heavy charged Higgs loop contribution to the $h\gamma\gamma$ coupling leading to $C_\gamma^h \lesssim 0.96$ while $C_g^h \sim 1.07$ because top and bottom loop contributions to the hgg coupling add. (See also Ferreira $et\ al.$, arXiv:1403.4736.)

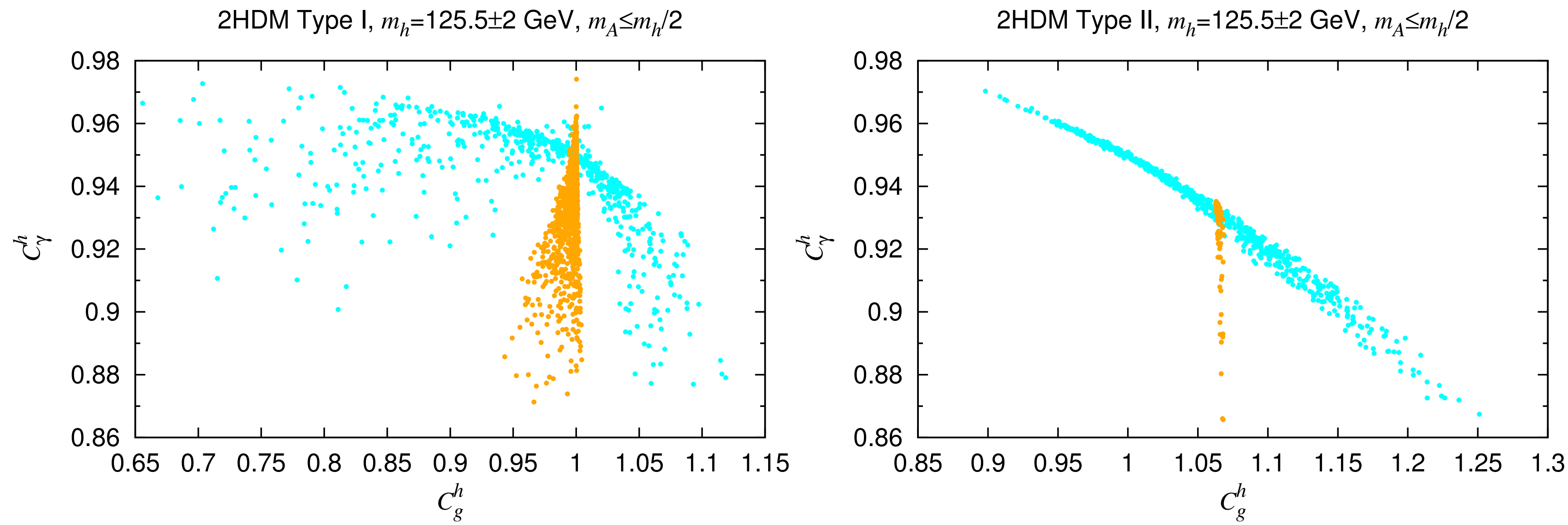


Figure 8: From paper #2. Orange points have $C_D \sim -1$.

Above, we plot C_g vs.C_γ, the hgg and $h\gamma\gamma$ couplings relative to the SM values. Can these deviations be measured? LHC, $but\ not\ ILC$ will measure C_γ sufficiently to discriminate from SM for Type II, and most Type I points. ILC and LHC reach similar C_g accuracies (2% vs. 3%) ultimately. But, C_g is useful only when correlated with C_γ.

$H125$ case

Some basics:

- Here, the h is guaranteed to be light, but the A need not be and, in fact, cannot be light in the case of Type II because of STU constraints given $m_{H^\pm} > 480~\mathrm{GeV}$.

- The LHC limits on $A \to Zh$ have significant impact since the AhZ coupling is maximal in the $H125$ scenario.

- Recent LHC ATLAS and CMS limits on the $\tau\tau$ final state cut away a bunch of points that would apriori be allowed before including such limits.

  In particular, you will see some cross section plots vs. m_h for Type II where constraints are strong for $m_h < 80~\mathrm{GeV}$ and for $m_h > 90~\mathrm{GeV}$ but much larger cross sections are possible for $m_h \in [80, 90]~\mathrm{GeV}$. This Z-peak region is one that ATLAS and CMS must work on even though it is clearly hard.

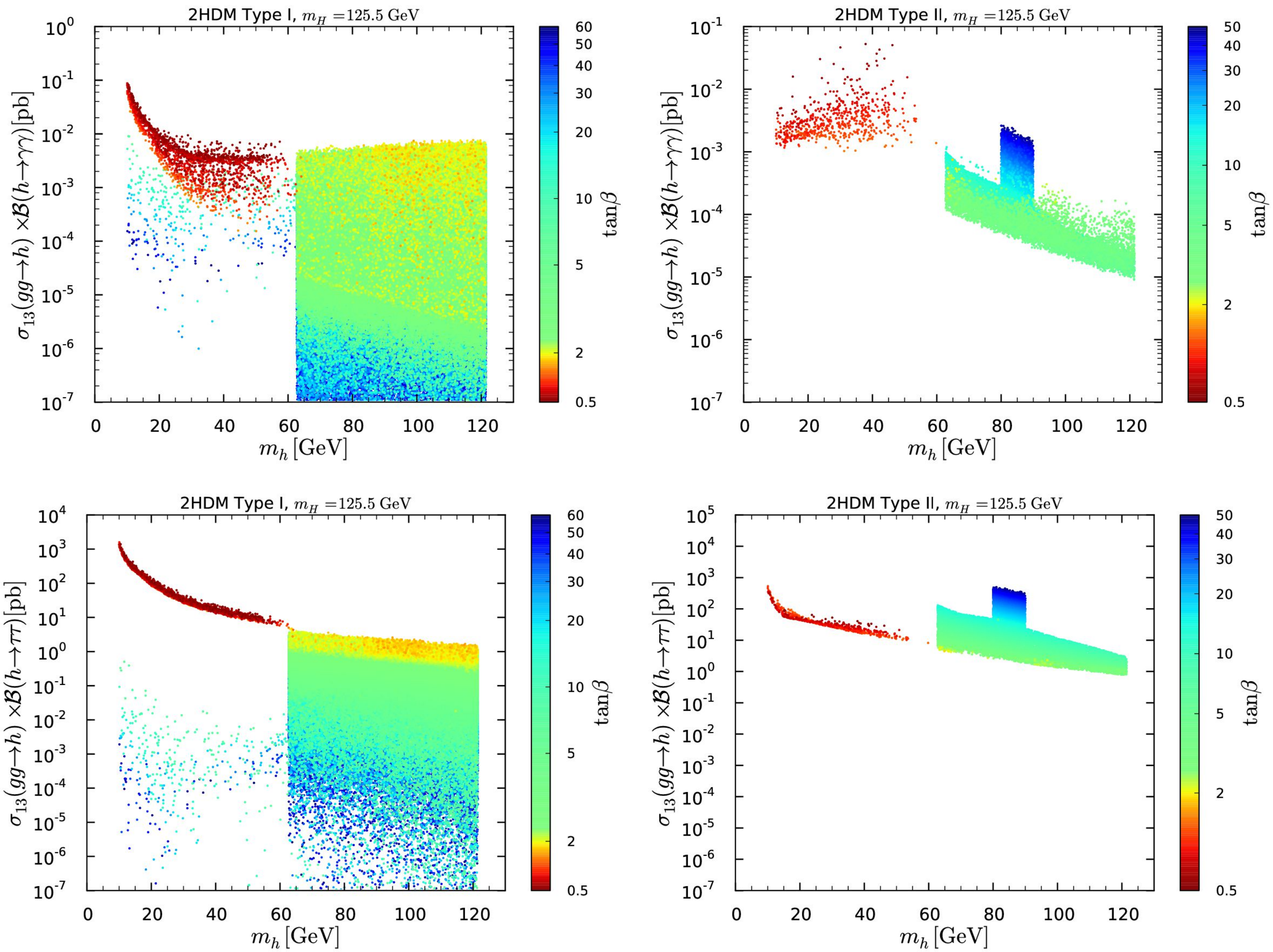


Figure 9: $\sigma(gg \to h \to Y)$ as functions of m_h for $Y = \gamma\gamma$ (upper panels) and $Y = \tau\tau$ (lower panels). Points are colored from high to low $\tan\beta$.

In the above plots, note the very well defined and large cross section for $gg \to h \to \tau\tau$ in the case of Type II. Type I $gg \to h$ cross sections get killed by large $\tan\beta$.

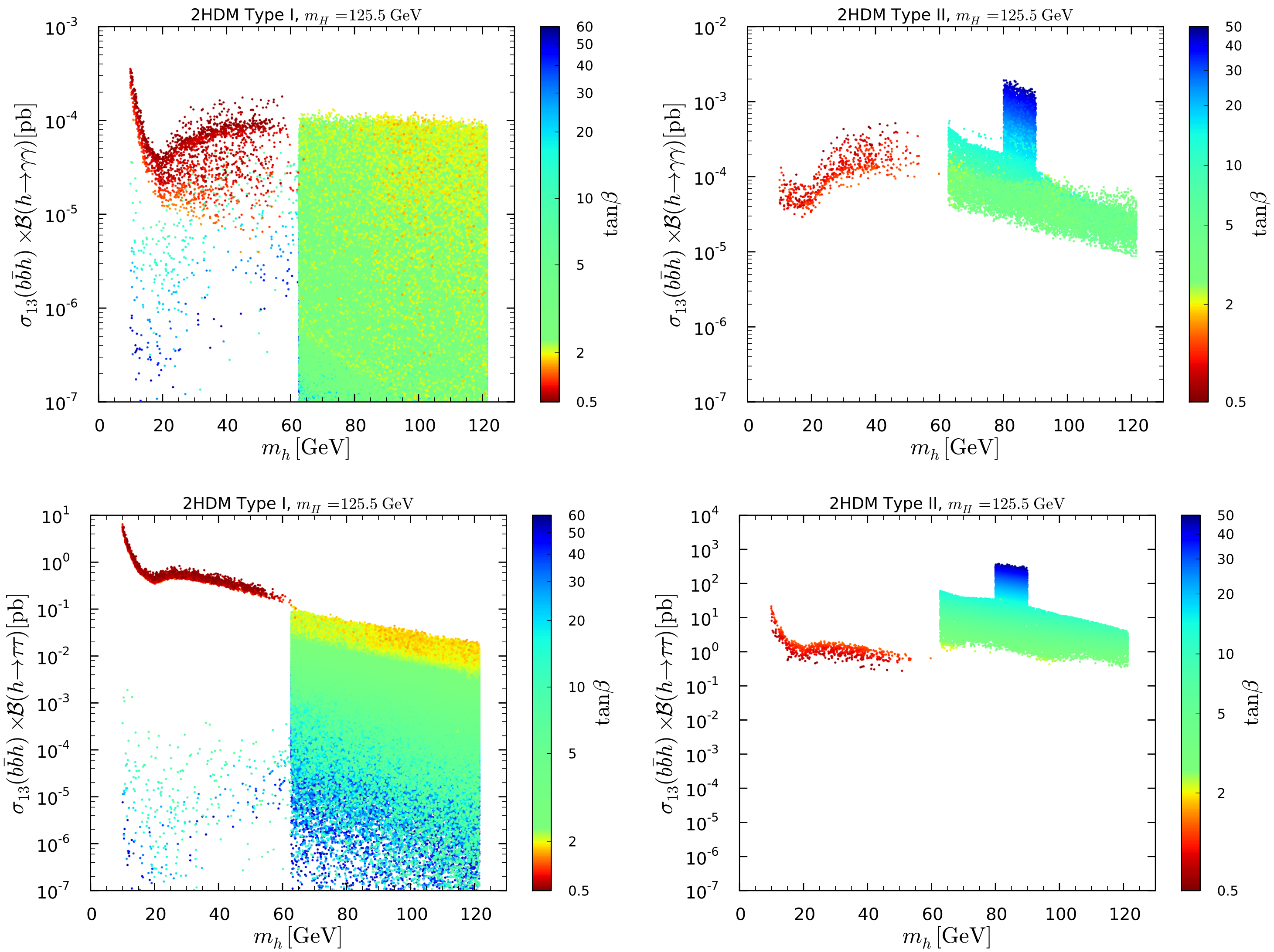


Figure 10: $\sigma(bbh) \times \mathcal{B}(h \to Y)$ as functions of m_h for $Y = \gamma\gamma$ (upper panels) and $Y = \tau\tau$ (lower panels). Points are colored from high to low $\tan\beta$.

The bbh cross sections are mostly somewhat lower than $gg \to h$.

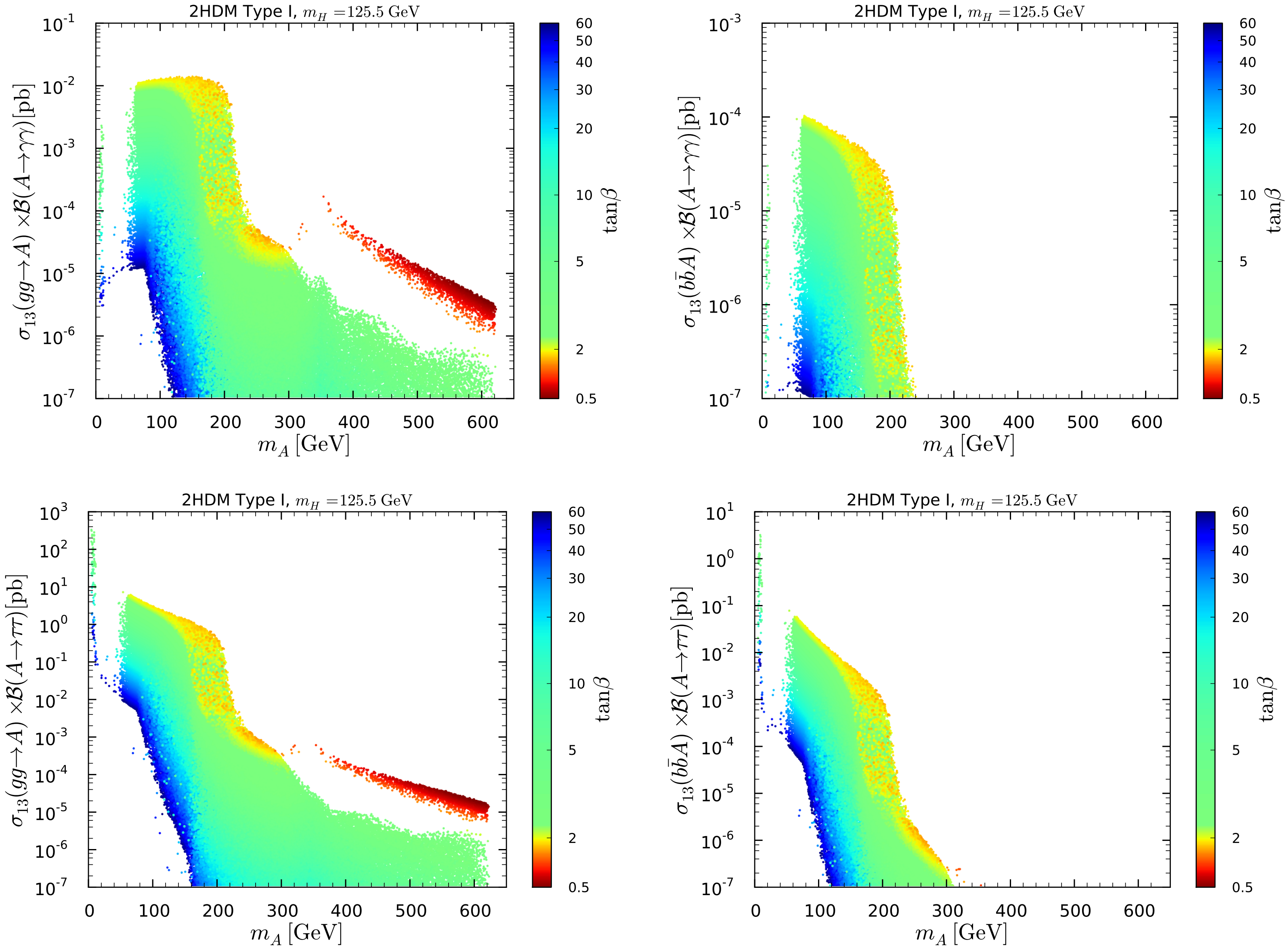


Figure 11: $\sigma \times \mathcal{B}(A \to Y)$ for $Y = \gamma\gamma$ and $\tau\tau$. Points are ordered from high to low $\tan\beta$.

Look closely for the low-m_A points that are possible in Type I (but not Type II).

Finally, there are the large cross sections for $gg \to A \to Zh$, where $Z \to \ell^+\ell^-$ and $h \to b\bar{b}, \tau\tau$, that are already constraining the $H125$ scenario.

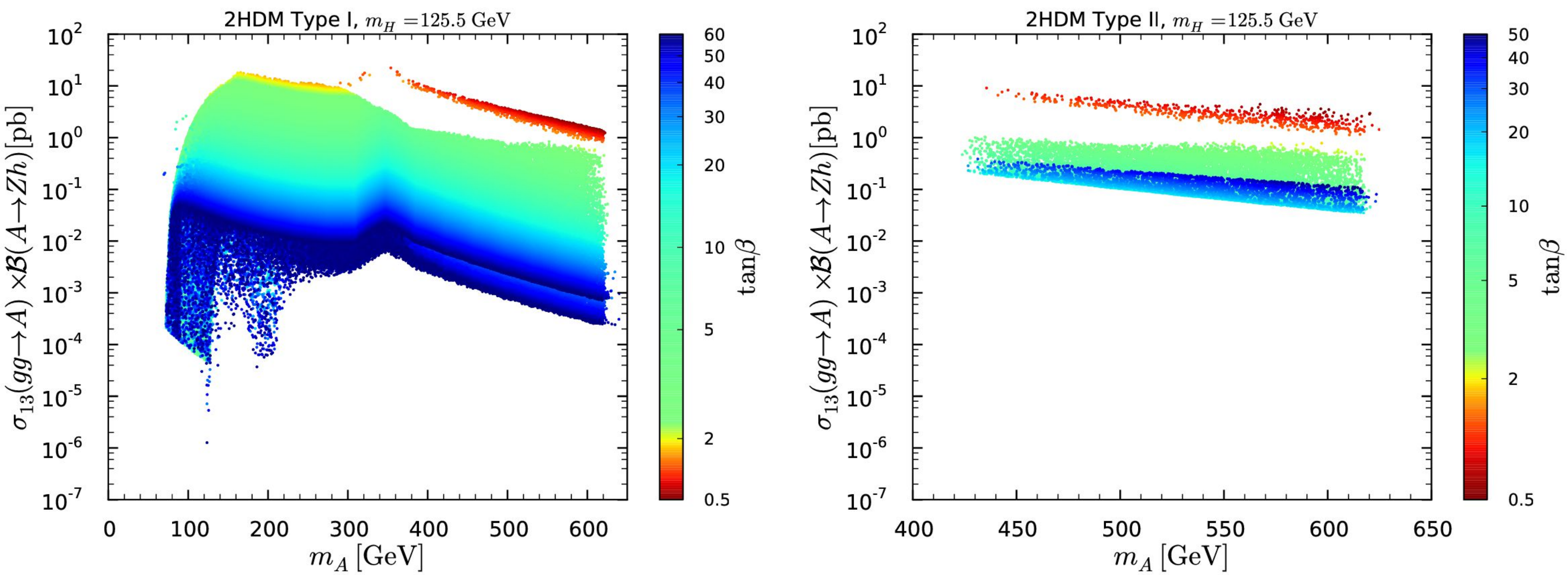


Figure 12: $\sigma(gg \to A) \times \mathcal{B}(A \to Zh)$ in Type I (left) and in Type II (right) at the 13 TeV LHC as functions of m_A with low-to-high $\tan\beta$ color code. Gaps show where current LHC limits have impacted.

Note the well-defined lower limits, which are particularly substantial in the case of Type II. With $\mathcal{B}(Z \to \ell^+\ell^-) \sim 0.06)$ per mode and assuming $\mathcal{B}(h \to \tau\tau) \sim 0.2$ or so for moderate m_h below 125 GeV, we get about 1 fb per mode in the worst Type II case!! This means we can eliminate the Type II $H125$ scenario fairly soon.

Higgs Dark Matter Models

1. "Extending two-Higgs-doublet models by a singlet scalar field - the Case for Dark Matter", Aleksandra Drozd, Bohdan Grzadkowski, John F. Gunion, Yun Jiang, arXiv:1408.2106.

2. "Isospin-violating dark-matter-nucleon scattering via 2-Higgs-doublet-model portals", Aleksandra Drozd, Bohdan Grzadkowski, John F. Gunion, Yun Jiang, arXiv:1510.07053

- Suppose there is no SUSY or similar.

  Where can dark matter come from?

- Expanded Higgs sector

  Add a singlet Higgs field that is stable because of an extra Z_2 symmetry that forbids it from having couplings to $f\overline{f}$ and from mixing with the Higgs-doublet field(s) required for standard EWSB.

  An example is starting from the 2HDM and adding a singlet S. After imposing symmetries one ends up with a Higgs potential of the form:

$$V(H_1, H_2, S) = V_{\rm 2HDM} + \frac{1}{2} m_0^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \kappa_1 S^2 (H_1^\dagger H_1) + \kappa_2 S^2 (H_2^\dagger H_2) \quad (20)$$

Symmetry forbids any linear terms in S. The Higgs portal couplings are the κ_1 and κ_2 terms that induce Higgs-SS couplings when $\langle H_1\rangle, \langle H_2\rangle \neq 0$.

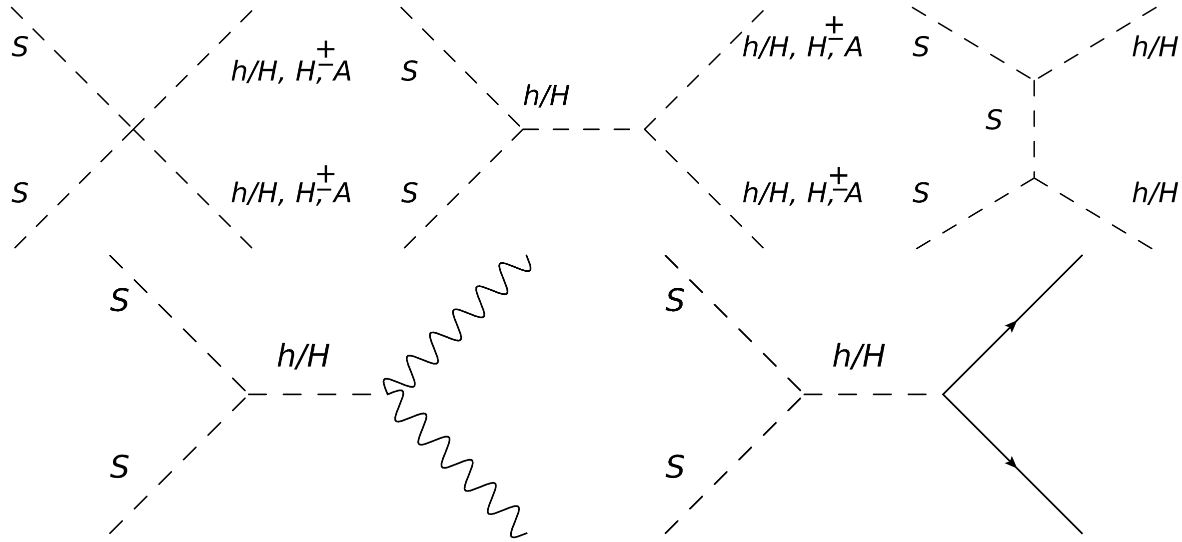


Figure 13: Singlet anihillation diagrams relevant for the relic density calculation.

Singlets are made and annihilate in the early universe by Higgs-related diagrams.

Identifying h of 2HDM sector with the $125~\mathrm{GeV}$ state, one can retain good Higgs fits and get perfectly reasonable dark matter scenarios with $\Omega h^2 \sim 0.11$ and obeying all limits.

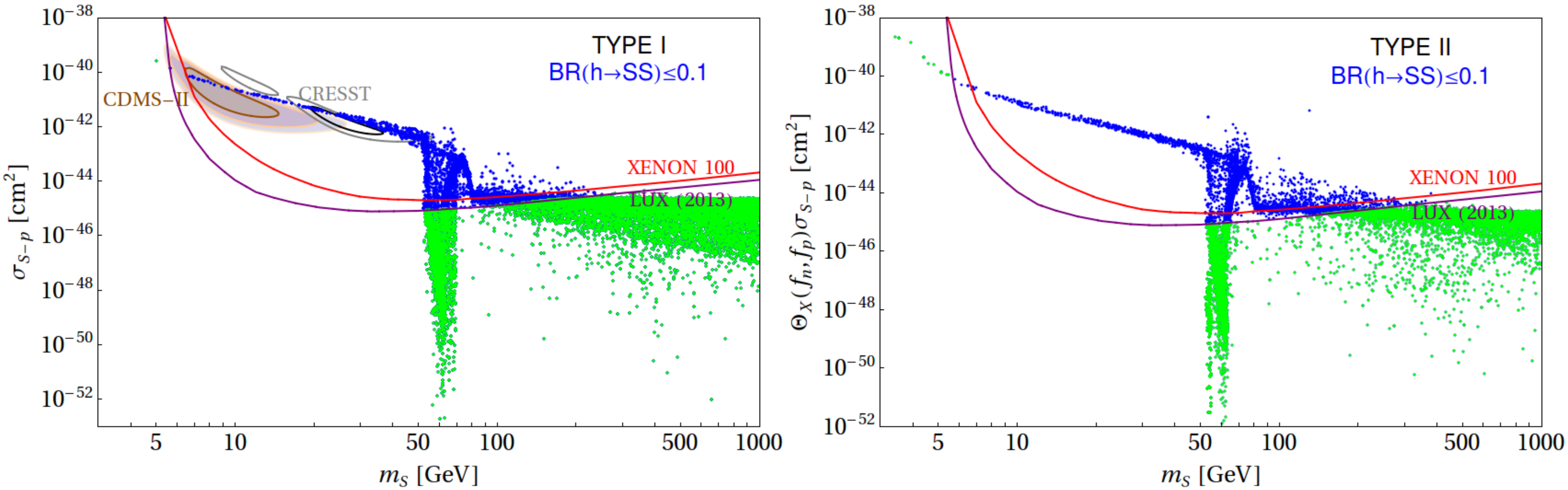


Figure 14: Cross section for DM - proton scattering for the Type I and Type II] models with $\Omega h^2 \sim 0.11$. All points shown satisfy the full set of preLUX constraints, including $\mathcal{B}(h \to SS) < 0.1$, while the green points satisfy in addition the LUX limits. Plots do not include the very fine-tuned 2HDM parameter points with $f_n/f_p \sim -0.7$.

We see that identifying the S with dark matter fails in the $m_S < 125 \text{ GeV}/2$ region because of the need to have very small hSS coupling to keep $\mathcal{B}(h \to SS) < 0.1$ so as to preserve the Higgs fits.

This can be fixed by going to a very special point in 2HDM parameter space: $\tan\beta \sim 1$ and $\alpha \sim -\pi/4$, for which $f_n/f_p \sim -0.7$ at which value the LUX constraints are greatly weakened.

It is also possible to have a similar story in the $H125$ 2HDM scenario.

Conclusions

- The Higgs responsible for EWSB has emerged and is really very SM-like.

  Is it SM-like because of decoupling or because of alignment? We hope for the latter!

- Really light Higgs bosons remain a possibility and in the alignment limit can have encouragingly large cross sections, at least in the 2HDM models.

- We are slowly chipping away at the possibilities for light Higgs bosons that could be present if the $125~\mathrm{GeV}$ state is SM-like because of alignment as opposed to decoupling.

  We must continue to push hard to improve limits/sensitivity to additional Higgs bosons.

- Higgs could be everything, even providing the dark matter.

  This is much easier/less-constrained in the 2HDM + Singlet context than in the SM + Singlet context because either h or H can be the SM-like Higgs at $125~\mathrm{GeV}$ while the other, H or h, respectively, can mediate dark matter annihilation.