# Remarks on Two-Higgs-Doublet Models

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Papers/collaborators:

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 $C_V \geq 0.99$.

Experimental situation for heavy Higgs bosons decaying to lighter stuff was summarized in Klute's talk.

- The fairly SM-like nature of the 125 GeV state provides important constraints, but there is still a lot of freeedom.

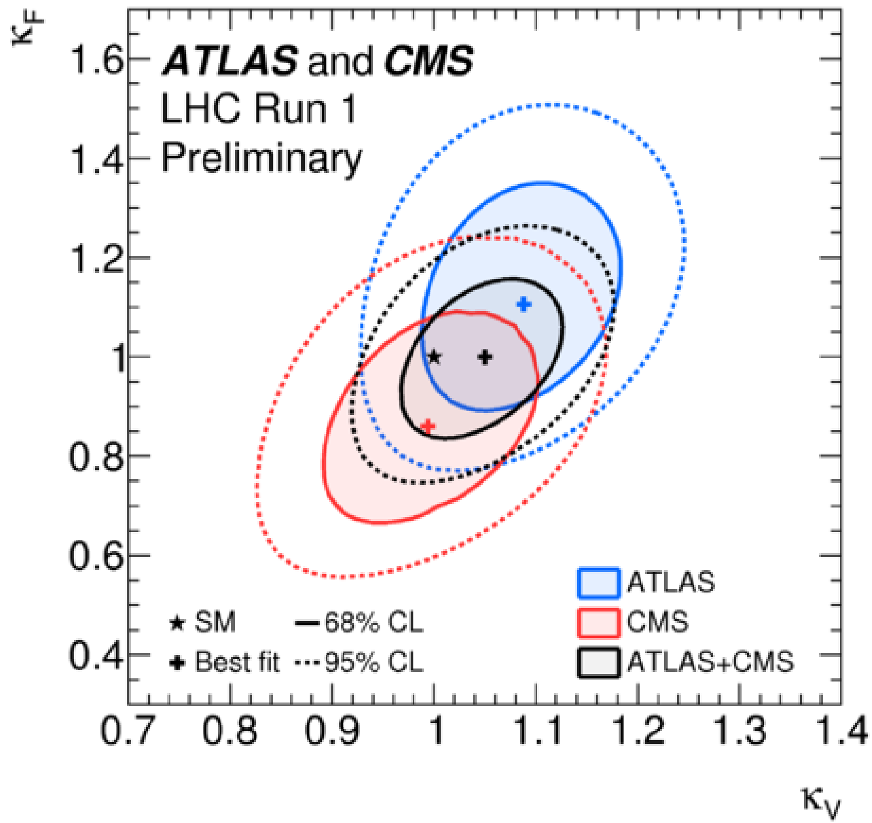



Figure 1: $\kappa_F$ versus $\kappa_V$ for the combination of ATLAS and CMS and for the global fit of all channels. Also shown are the contours obtained for each experiment. From ATLAS-CONF-2015-044.

- There can be unseen, $U$, but not truly invisible, decays of the SM-like Higgs.

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, i.e. the alignment limit, there are still many opportunities even if the only new particles are Higgs bosons. Ignoring the 750 GeV state, increasing limits on new physics suggests that one should take seriously this possibility.
  - 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 so large as to violate the $\mathcal{B}_U$ limits above.

  2HDM models are the simplest prototypes for these possibilities.

- Of course, purely Higgs sector new physics has severe hierarchy/naturalness problems unless placed in the context of warped extra dimensions (e.g. RS). In the RS context, you can have any Higgs structure you like — the warping takes care of hierarchy.

Returning to $h125$ decays to lighter Higgs, of particular interest in the 2HDM are $h \to AA$ or $H \to AA, hh$. For acceptable $h125$ or $H125$ fits, respectively, must suppress the couplings if these are kinematically allowed. This can be achieved with some level of parameter fine-tuning.

Meaningful limits are only currently available for $m_A \lesssim 20$ GeV. Of those shown by Klute, only HIG-14-022 and HIG-14-019 give a meaningful constraint when $m_A > 2m_\tau$.

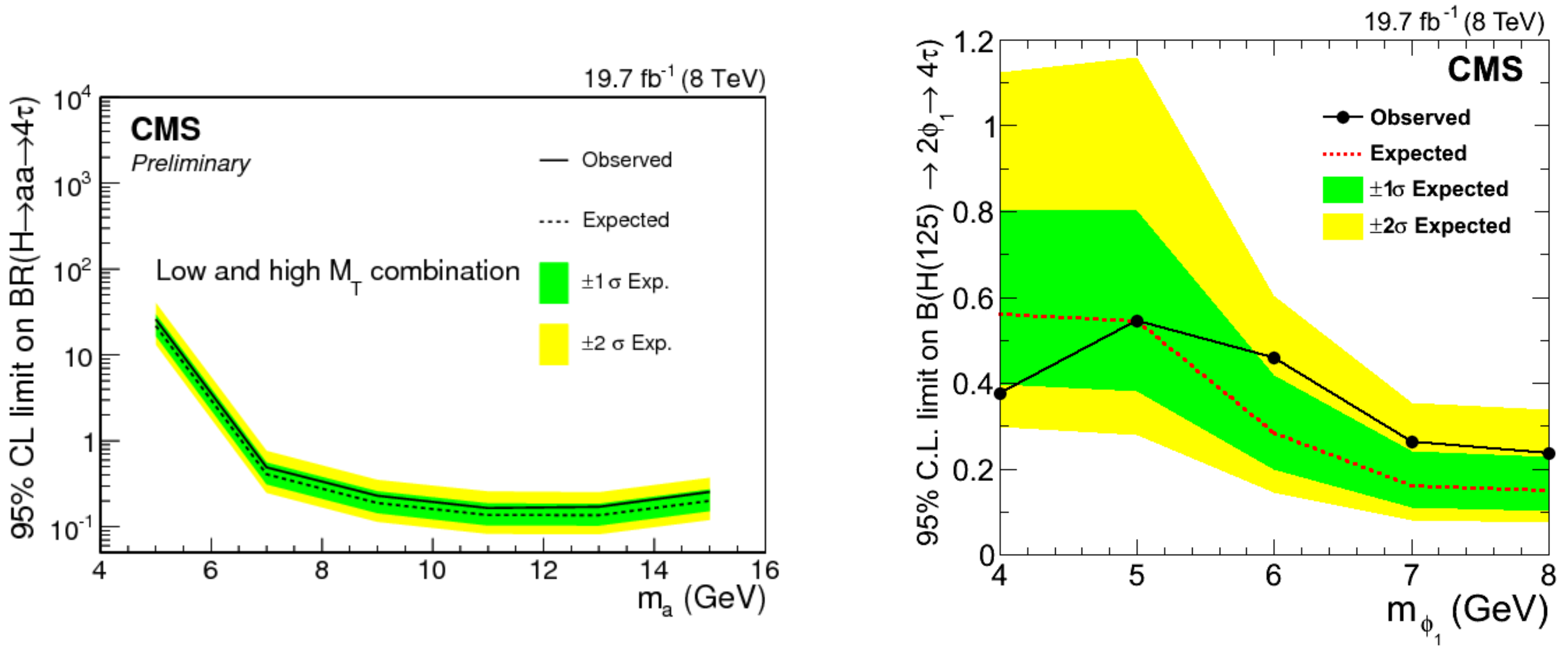



Figure 2: Limits on $\mathcal{B}(h125 \to aa \to 4\tau)$ from CMS analyses HIG-14-022 and HIG-14-019, respectively.

The $h125$ case

- Basic picture

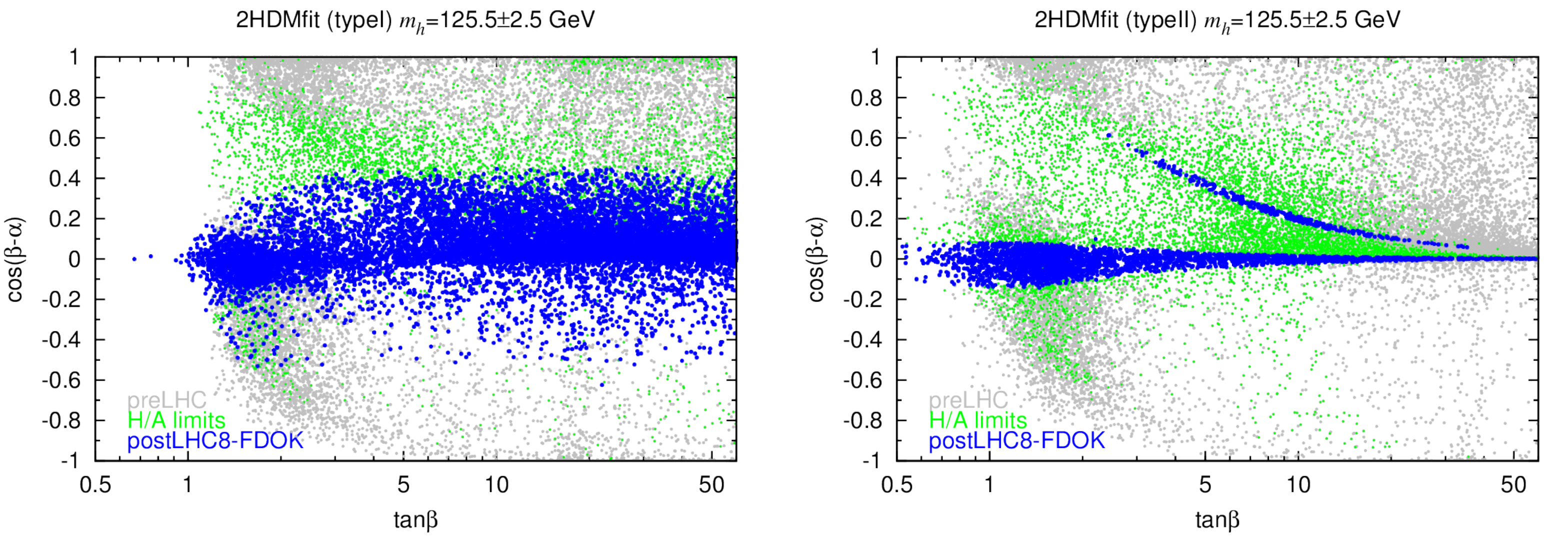



Figure 3: Constraints in the $\cos(\beta-\alpha)$ versus $\tan\beta$ plane for $m_h \sim 125.5$ GeV. Grey points satisfy preLHC constraints, while green points satisfy in addition the pre-May-2014 LHC limits on $H$ and $A$ production. Blue points fall in addition within the 7+8 TeV 95% CL ellipses in 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 $> 5\sigma$.)

In the alignment limit and after including data not included above (see below), the extent of this "wrong-sign" branch is considerably restricted.

- 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 $m_{H^\pm} > 480 \text{ GeV}$ is included for Type II. Of particular importance: the $25 \text{ GeV} < m_A < 80 \text{ GeV}$ CMS limits from $b\bar{b}\phi$ with $\phi \to \tau\tau$ and the LEP limits on $b\bar{b}\phi$.

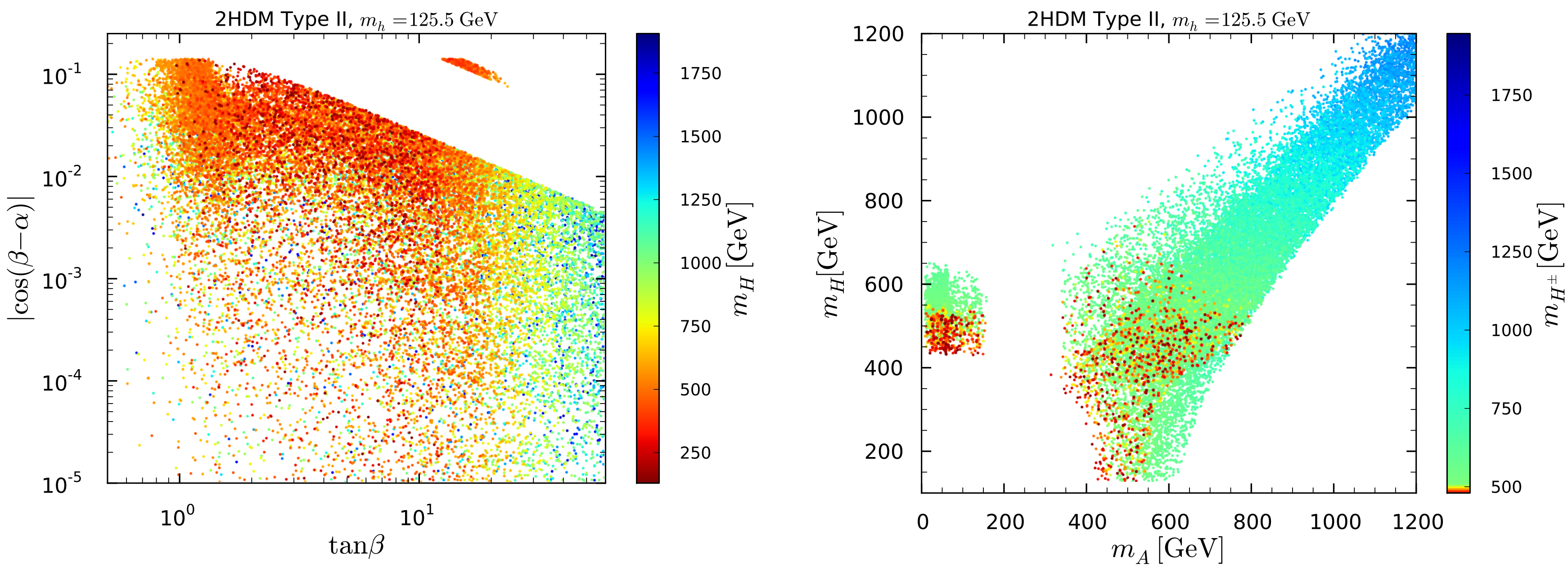



Figure 4: Constraints in the $\cos(\beta-\alpha)$ vs $\tan\beta$ and the $m_H$ vs $m_A$ plane for $m_h \sim 125.5$ GeV in Type II. Coloring in $m_{H\pm}$ from high to low. Plot includes recent $b \to s\gamma$ constraint of $m_{H\pm} > 480$ GeV and limits on $bbA$ with $A \to \tau\tau$ for $25\ \mathrm{GeV} < m_A < 80\ \mathrm{GeV}$, as well as constraints on $e^+e^- \to b\bar{b}A$.

From CMS-HIG-14-033, arXiv:1511.03610 we eliminate nearly all the Type II points with $m_A > 25$ GeV that 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 $\tan\beta \geq 10$.

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 $\simeq \tan\beta$.

- What channels could be of interest in the alignment limit.

1. should not see $ZZ$ and $WW$ decays of the $H$ since the $h$ saturates those couplings.
   Nor should you see $A \to Zh$. Excesses in these searches are thus particularly important.
   But, of course, the alignment limit may not be exact, or there may be higher Higgs representations present.
2. In $h125$ scenario should (eventually) see $H \to ZA$ if $m_A$ is small enough — nothing so far (Klute).
3. $H \to hh$ is certainly a possibility if $m_H > 250~\mathrm{GeV}$, but this channel is hard — nothing so far (Klute), and large cross section is not guaranteed.
4. In both Type I and Type II, $\sigma(gg \to A)$ have lower bounds. e.g. at $m_A = 1.2~\mathrm{TeV}$, $\sigma(gg \to A) > 10^{-6}~\mathrm{pb}$, $10^{-3}~\mathrm{pb}$ for Type I, Type II. — Obviously, Type II will be easier to eventually explore fully or eliminate.
5. In Type II, $gg \to A$ with $A \to \tau\tau$ cannot have arbitrarily small cross section — for $m_A \leq 1~\mathrm{TeV}$, $\sigma > 3 \times 10^{-3}~\mathrm{fb}$ (not wonderful, but something). Similar statement for $H$.

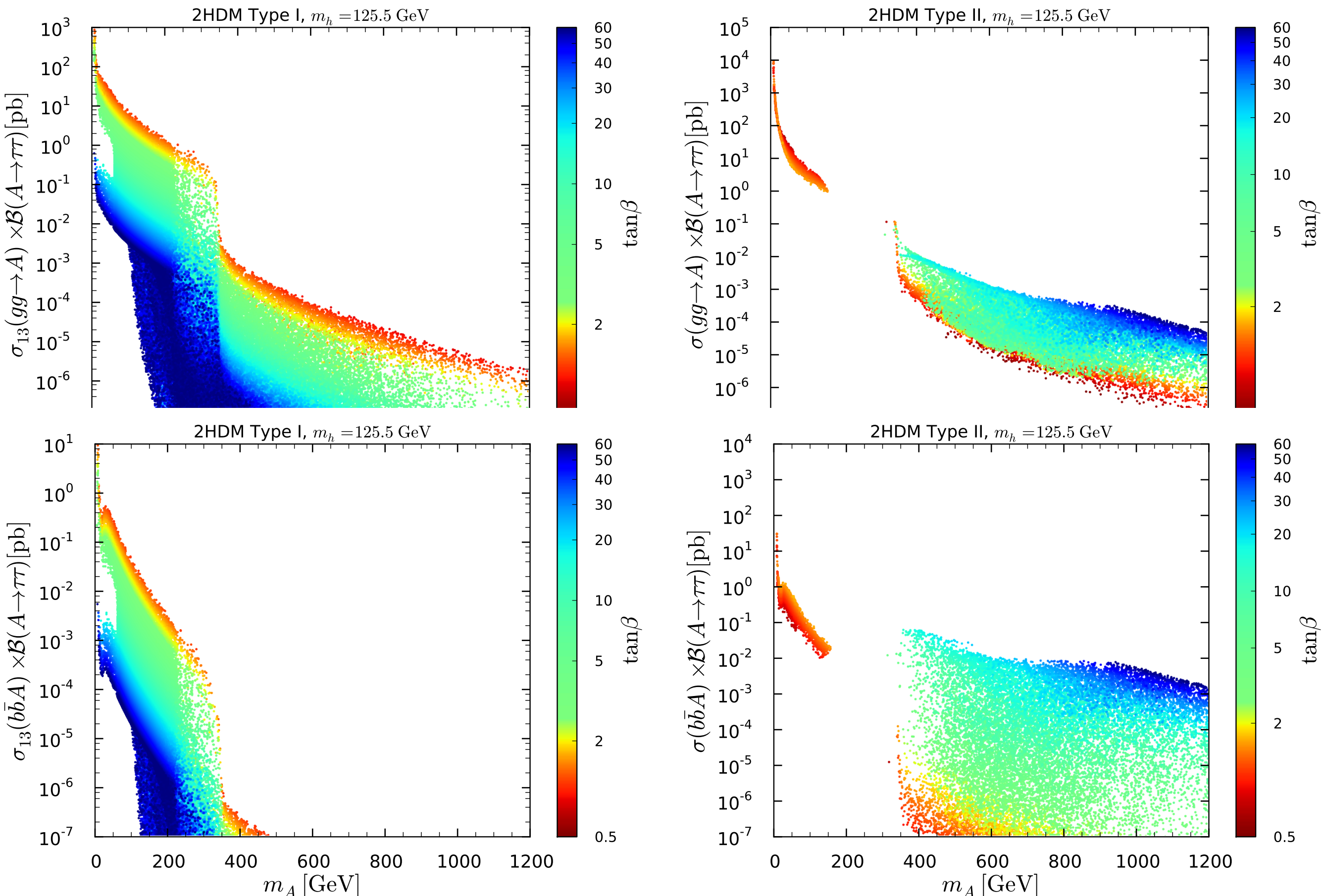
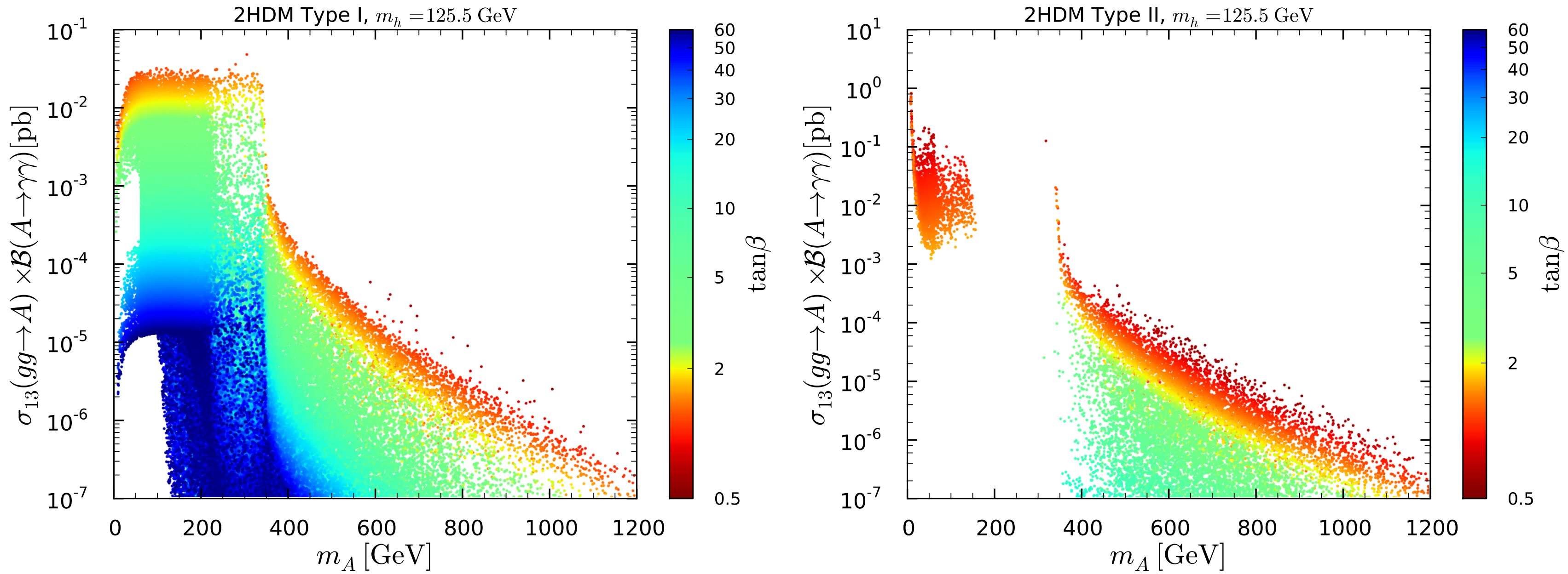



Figure 5: 2HDM points agreeing at 95% C.L. with precision Higgs data as well as $B$ physics, ..... Coloring in $\tan\beta$ from low to high.

- 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 $\tan\beta$.

At 750 GeV, $\gamma\gamma$ cross sections are of order a $few \times 10^{-2}$ fb, a factor 100 too small for claimed signal. Similar story for $H$. See also http://arxiv.org/abs/1512.07616

(Stefania and collaborators).

- 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.)

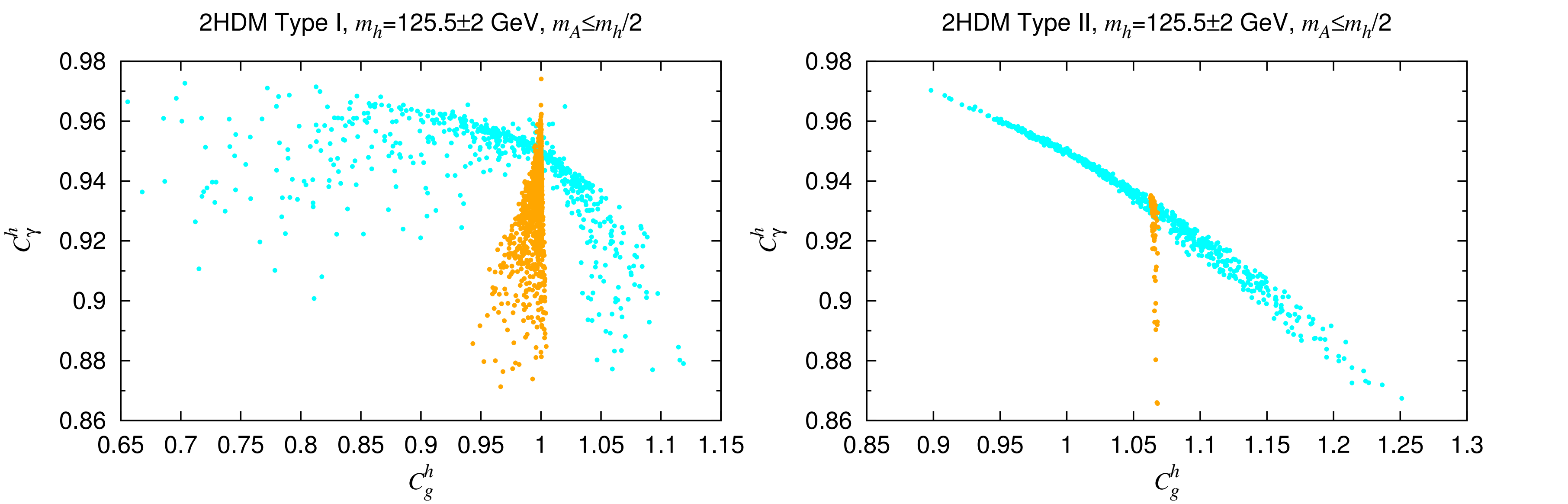



Figure 6: From paper #2. Orange points have $C_D \sim -1$.

Above, we plot $C_g$ vs.$C_\gamma$, the $hgg$ and $h\gamma\gamma$ couplings relative to the SM values. Can these deviations be measured? LHC, *but not ILC* will measure $C_\gamma$ 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 $C_\gamma$.

**$H125$ 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.

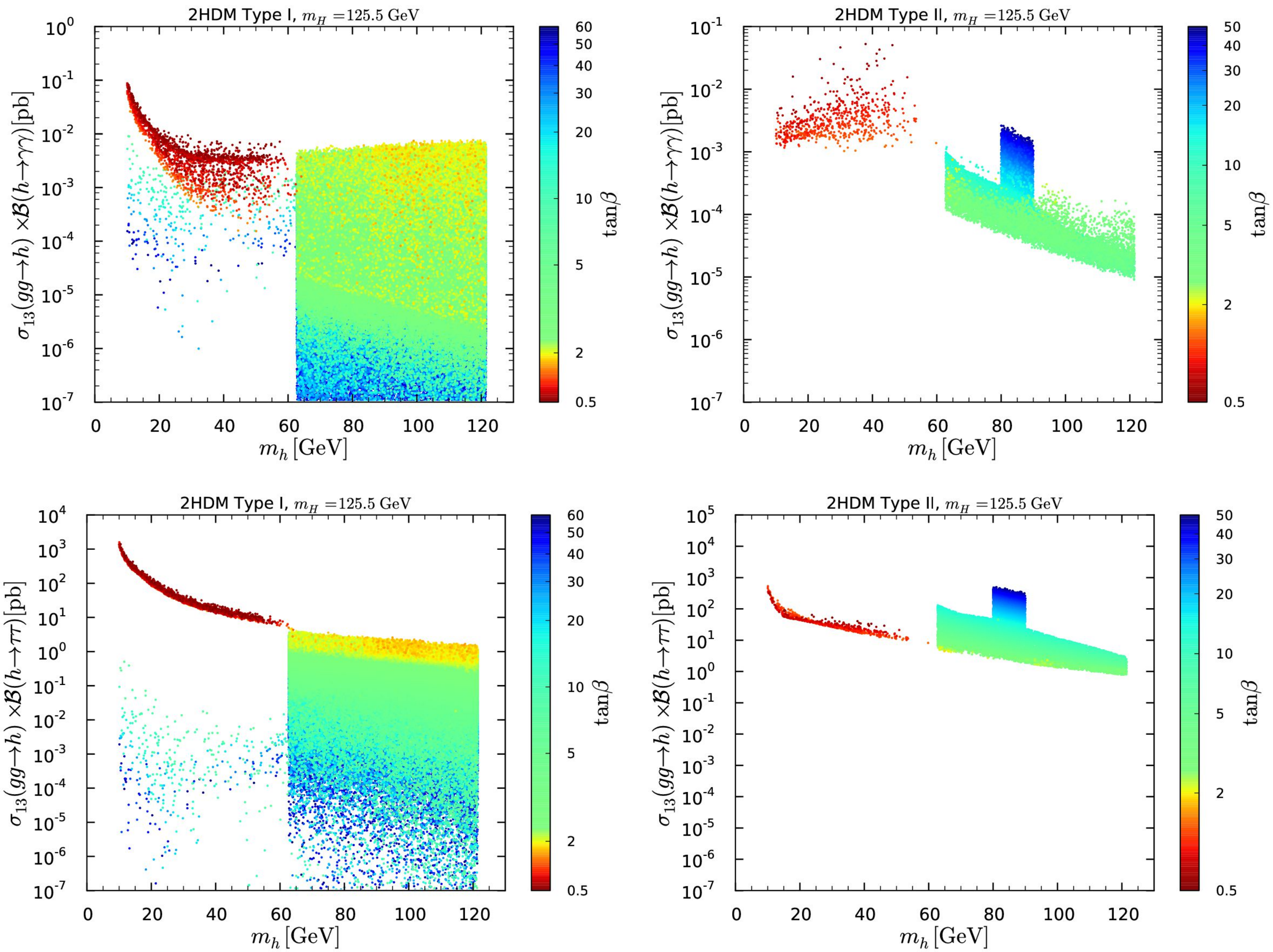



Figure 7: $\sigma(gg \to h \to Y)$ as functions of $m_h$ for $Y = \gamma\gamma$ (upper panels) and $Y = \tau\tau$ (lower panels). Points are colored from high to low $\tan\beta$.

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 $\tan\beta$.

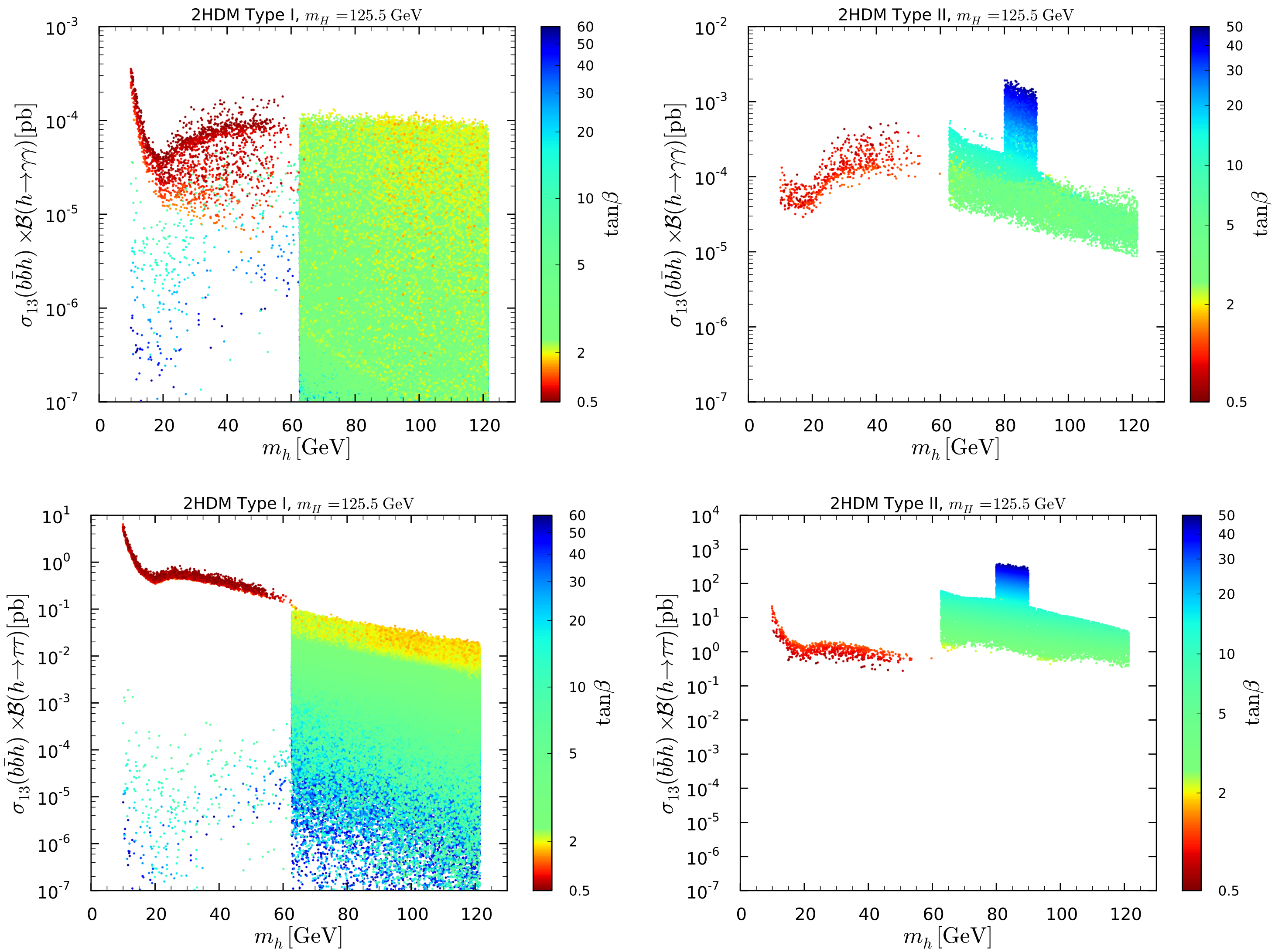



Figure 8: $\sigma(bbh) \times \mathcal{B}(h \to Y)$ as functions of $m_h$ for $Y = \gamma\gamma$ (upper panels) and $Y = \tau\tau$ (lower panels). Points are colored from high to low $\tan\beta$.

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

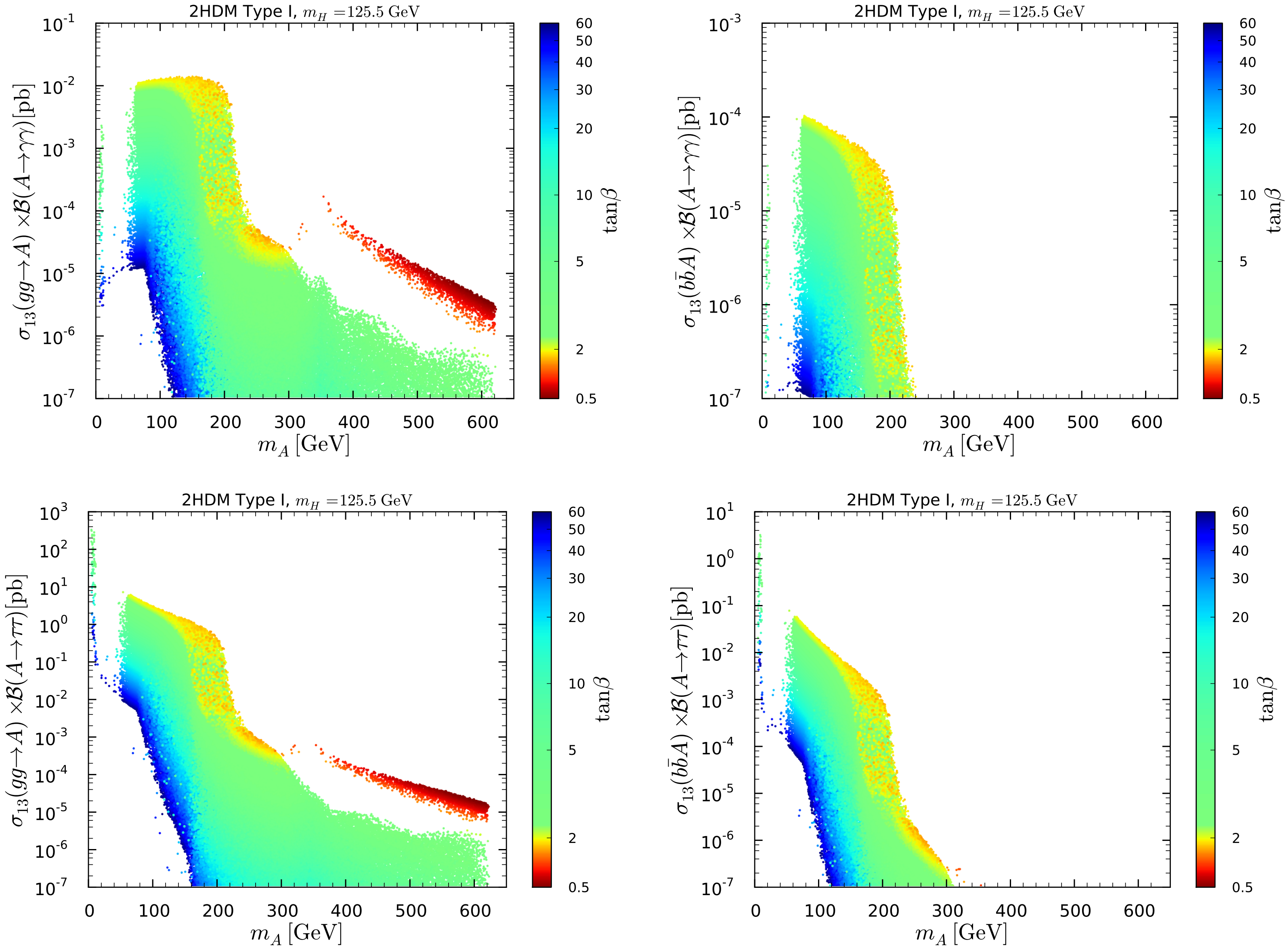



Figure 9: $\sigma \times \mathcal{B}(A \to Y)$ for $Y = \gamma\gamma$ and $\tau\tau$. Points are ordered from high to low $\tan\beta$.

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.

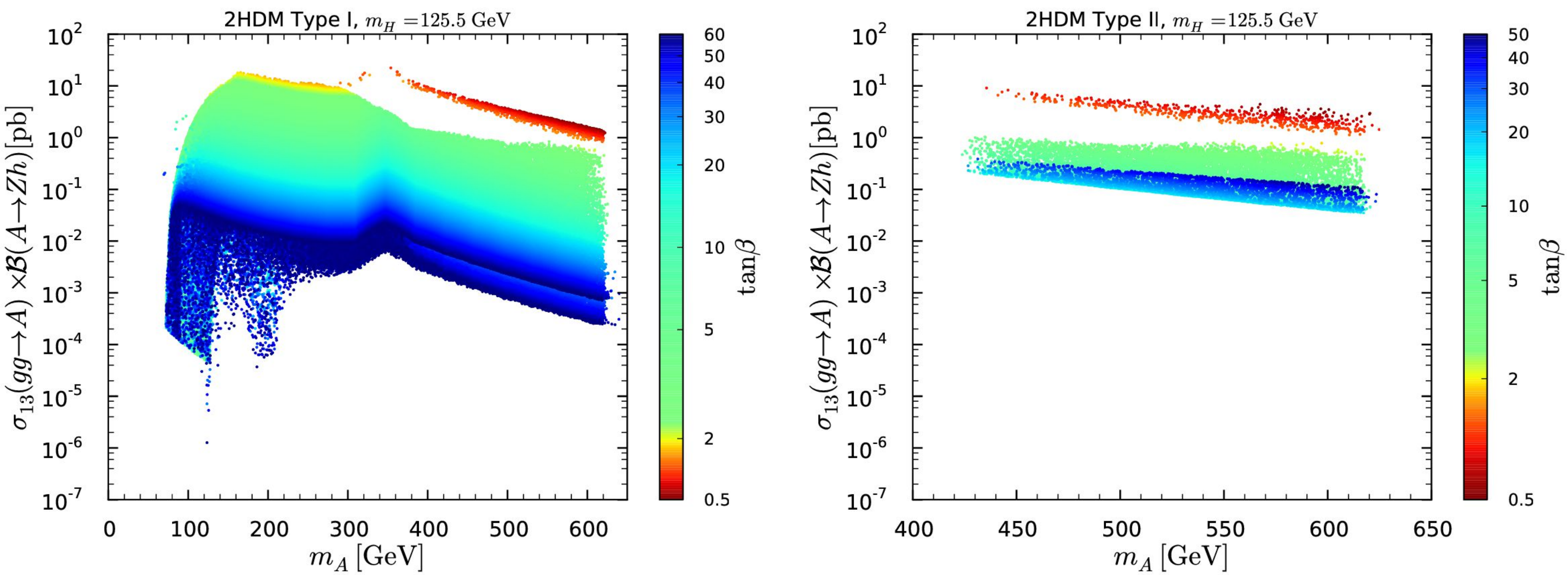
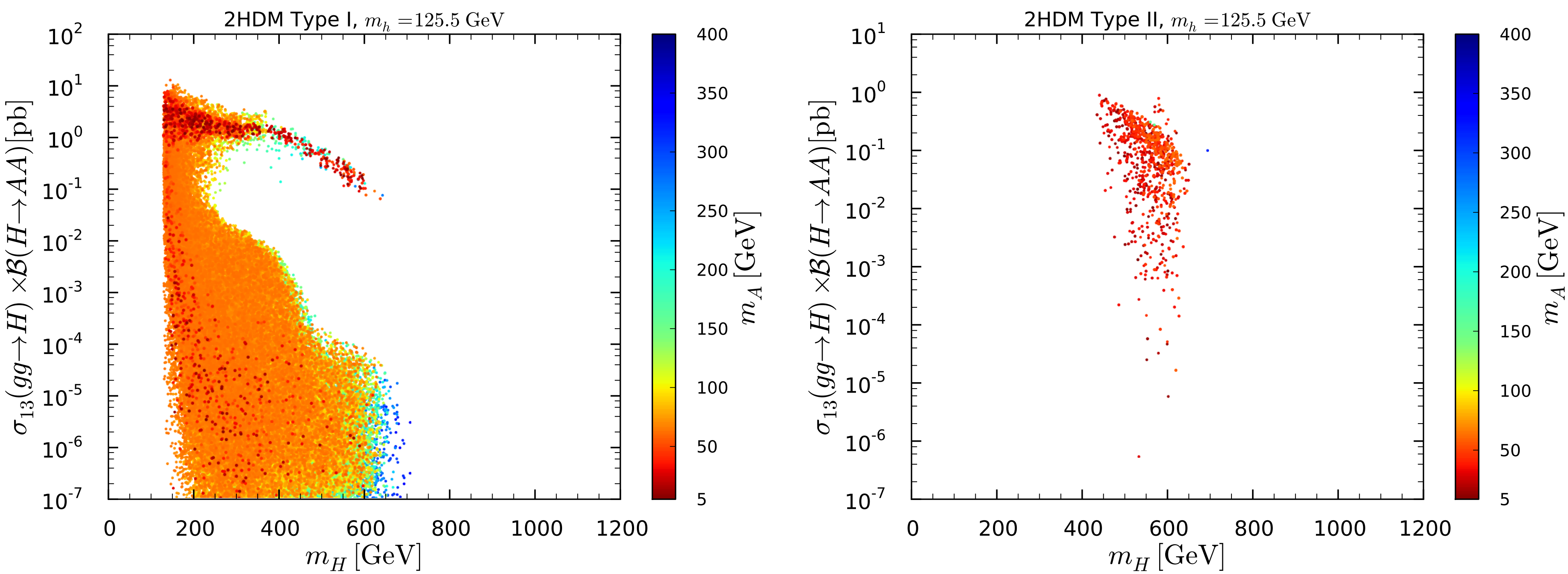



Figure 10: $\sigma(gg \to A) \times \mathcal{B}(A \to Zh)$ in Type I (left) and in Type II (right) at the 13 TeV LHC as functions of $m_A$ with low-to-high $\tan\beta$ color code. Gaps show where current LHC limits have impacted.

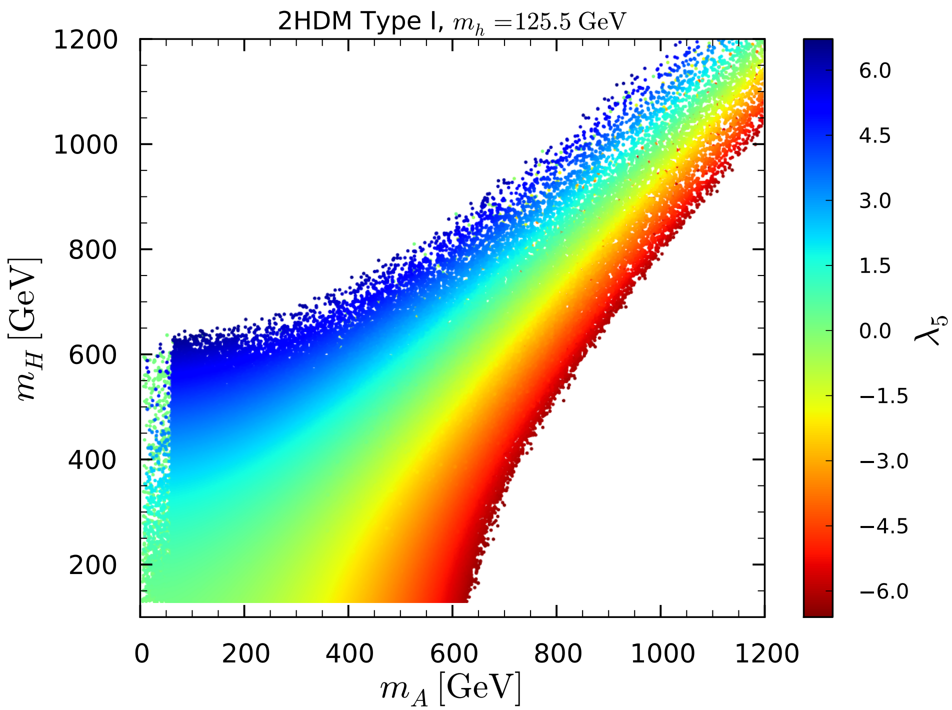
Note the well-defined lower limits, which are particularly substantial in the case of Type II. With $\mathcal{B}(Z \to \ell^+\ell^-) \sim 0.06)$ per mode and assuming $\mathcal{B}(h \to \tau\tau) \sim 0.2$ or so for moderate $m_h$ below $125$ GeV, we get about $1$ fb per mode in the worst Type II case!!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

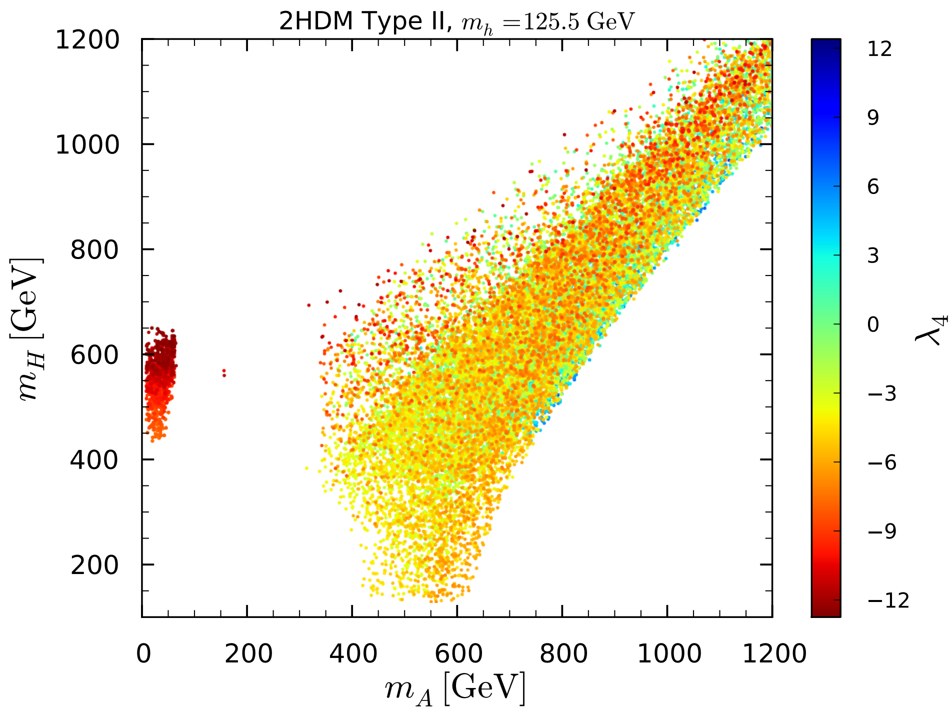
# 750 GeV diphoton signal

- There is a large cross section for $gg \to H \to AA$ over a wide range of $m_A$, including very low $m_A$.




But, the $m_H$ range ends at about $650$ GeV. This, upper bound can be expanded somewhat if you relax perturbativity limits on $\lambda_5$ 2HDM coupling. We restricted $|\lambda_5| < 2\pi$, but if you expand to $4\pi$ then no problem.




If so, then very easy to get $10\text{ fb} - 100\text{ fb}$ cross section for $gg \to H \to AA$ at very small $m_A$. Then if $A \to \gamma\gamma$ (e.g. it acts like a $\pi^0$ or $\eta$) then can explain the di-photon signal.

Must be careful about displaced "$A$" vertices, ...

# 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:

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

Symmetry forbids any linear terms in $S$. The Higgs portal couplings are the $\kappa_1$ and $\kappa_2$ terms that induce Higgs-$SS$ couplings when $\langle H_1 \rangle, \langle H_2 \rangle \neq 0$.

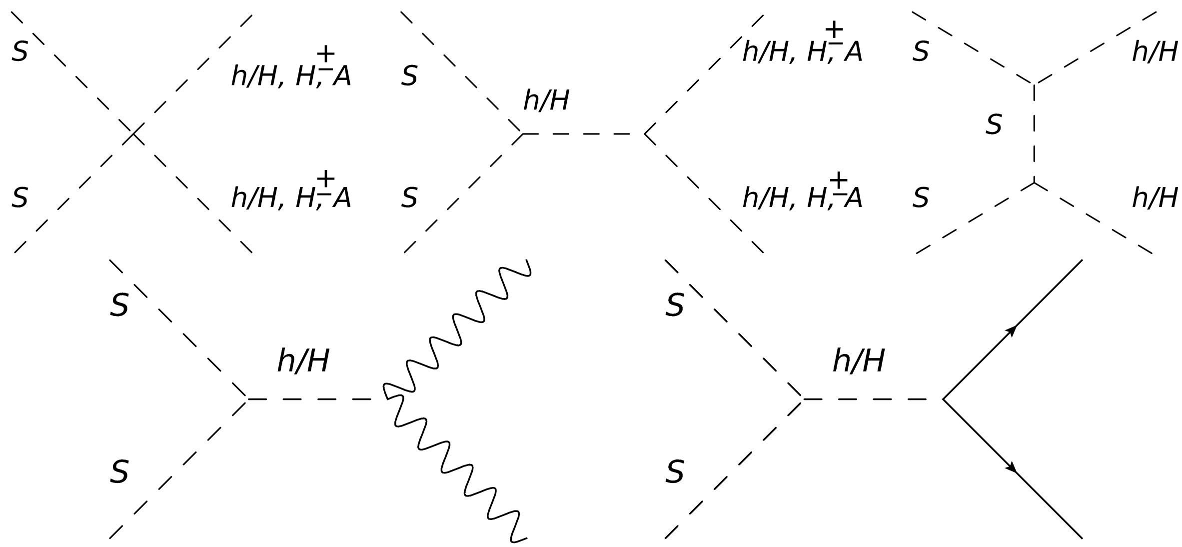



Figure 11: Singlet anihillation diagrams relevant for the relic density calculation.

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.

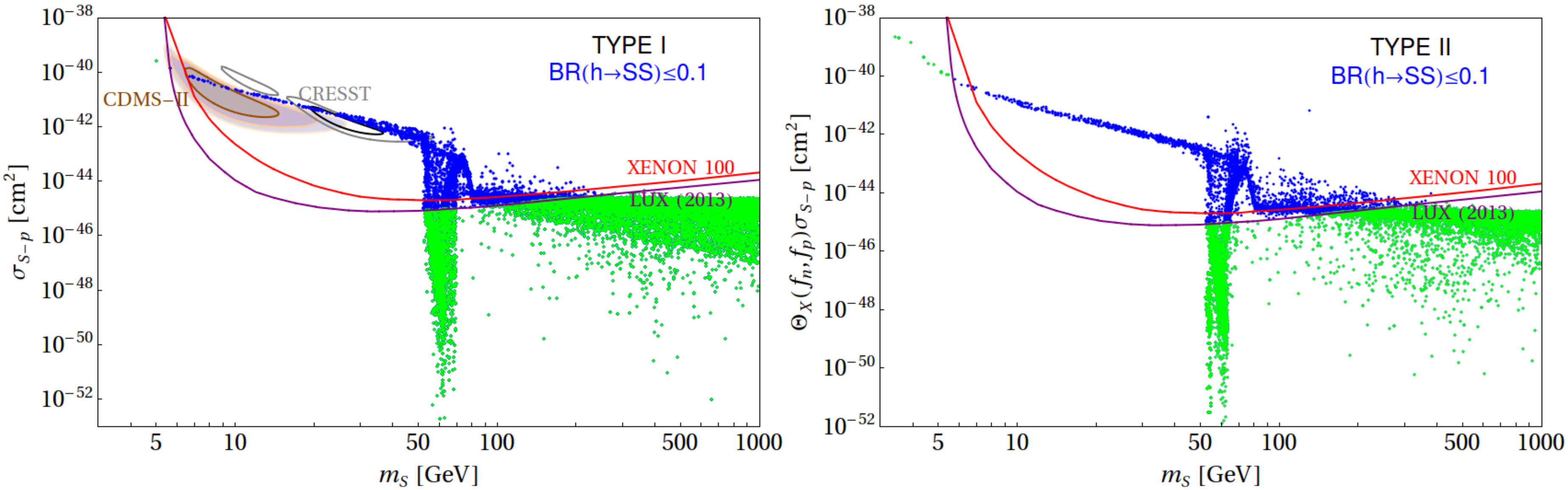



Figure 12: Cross section for DM - proton scattering for the Type I and Type II] models with $\Omega h^2 \sim 0.11$. All points shown satisfy the full set of preLUX constraints, including $\mathcal{B}(h \to SS) < 0.1$, while the green points satisfy in addition the LUX limits. Plots do not include the 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 $m_S < 125~\mathrm{GeV}/2$ 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.

- If the 2HDM explanations of the 750 GeV di-photon signal are correct, then we are in for some very exciting times, including heavy vector-like quarks and still more Higgs states.