Light Higgs Bosons
and the "cross roads"

Jack Gunion
U.C. Davis

MCTP, April 21, 2015

Even with the discovery of a SM-like Higgs boson of mass $126~\mathrm{GeV}$, there is still no guaranteed direction. But, at least the signs for the possible directions seem to be written in a language we can understand, as opposed to

In particular, we know it is fruitful to explore along the Higgs path.

125 GeV Higgs

- Just how SM-like is it?

  The most fundamental check — proportionality of fermionic couplings to mass and vector boson couplings to mass-squared.

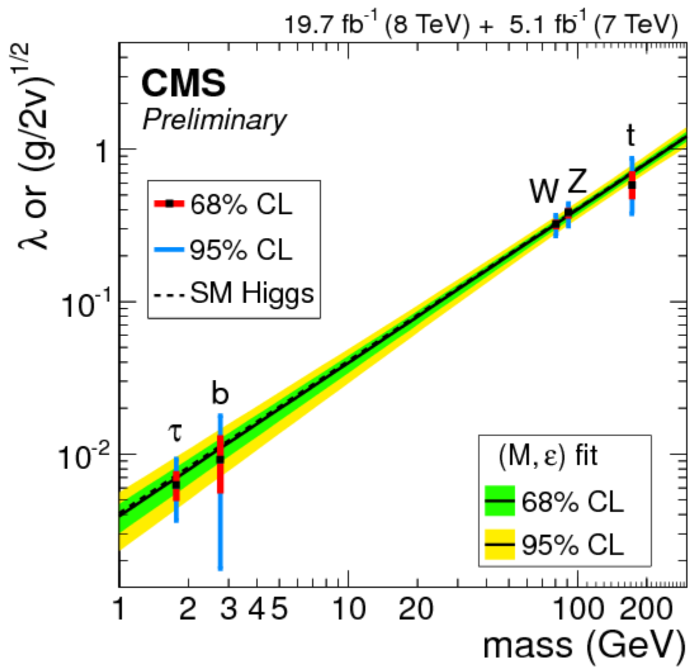


Figure 1: Plot of couplings vs. mass. (The t quark coupling is inferred from gluonic and photonic loops.)

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

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

In addition, define the loop-induced couplings C_g and C_γ of the H to gg and $\gamma\gamma$, respectively.

Figure 2 shows results for a 3-parameter fit of C_U, C_D, C_V, assuming custodial symmetry and taking $C_U, C_D > 0$. C_g and C_γ are computed using SM-loops.

We note that at 95.4% CL in 2D, C_U and C_V are constrained within roughly $\pm 20\%$; the uncertainty on C_D is about twice as large. Although not shown in Fig. 2, $C_U < 0$ is excluded at more than 2σ, while there is a sign ambiguity in C_D.

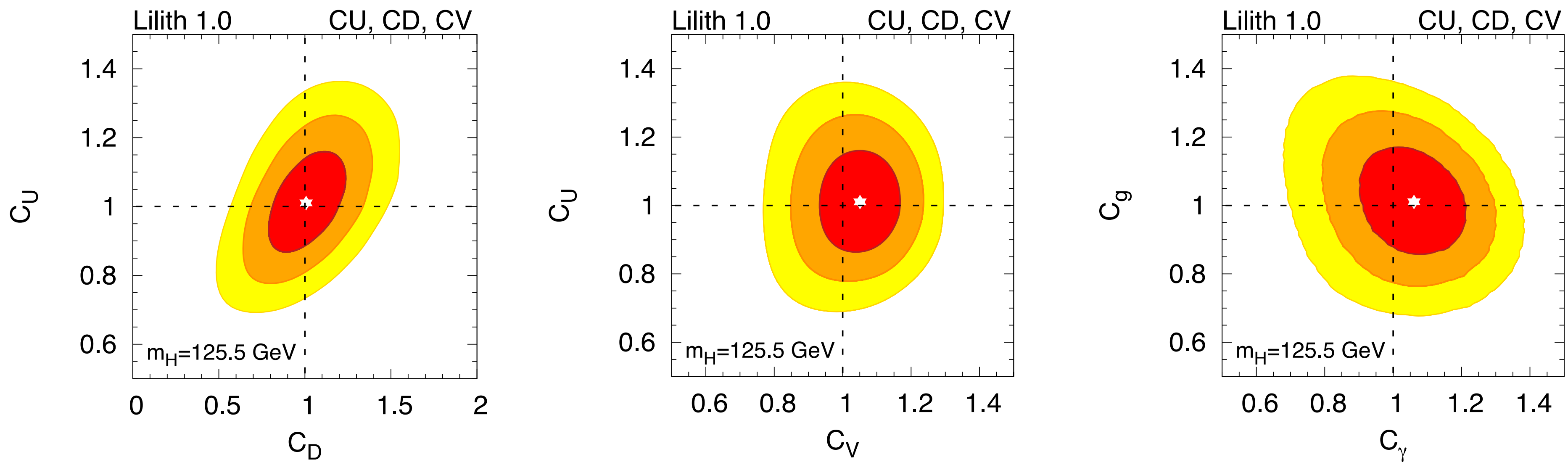


Figure 2: Fits of C_U, C_D and C_V (left and middle panels) and resulting C_g versus C_γ (right panel). The red, orange and yellow areas are the 68.3%, 95.4% and 99.7% CL regions, respectively. The best-fit points are marked as white stars. Invisible or undetected decays are assumed to be absent. (from arXiv:1409.1588, Bernon, Dumont, Kraml)

Obviously, a single simple SM Higgs boson is not excluded! But, within the errors there is still a lot of room for Higgs beyond the SM.

Other Higgs bosons can be present without disturbing significantly the quality of the fit to the $125.5\ \mathrm{GeV}$ 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 $125.5\ \mathrm{GeV}$ state.

- More generally, 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.

- Run 2 will bring larger production rates and increased precision and could either reveal deviations or strongly limit them.

	σ(pb) at 13 TeV	σ(pb) at 8 TeV
Gluon Fusion	43.9	19.27
Vector Boson Fusion	3.748	1.578
WH	1.38	.70
ZH	.87	.42
ttH	.51	.13
HH	.034	.008

Figure 3: Comparative cross sections for 13 TeV vs. 8 TeV, from Higgs xsec working group. **Cross sections ratios of at least 2, and as large as 4.**

- $m_{h_{SM}} \sim 125.5$ GeV is both maximally interesting (many competing final states) and maximally confusing [SM (Stable or Metastable Vacuum) or BSM (Multi-Higgs, MSSM Higgs, Composite Higgs, ...)].

- One problem for a strictly SM Higgs:

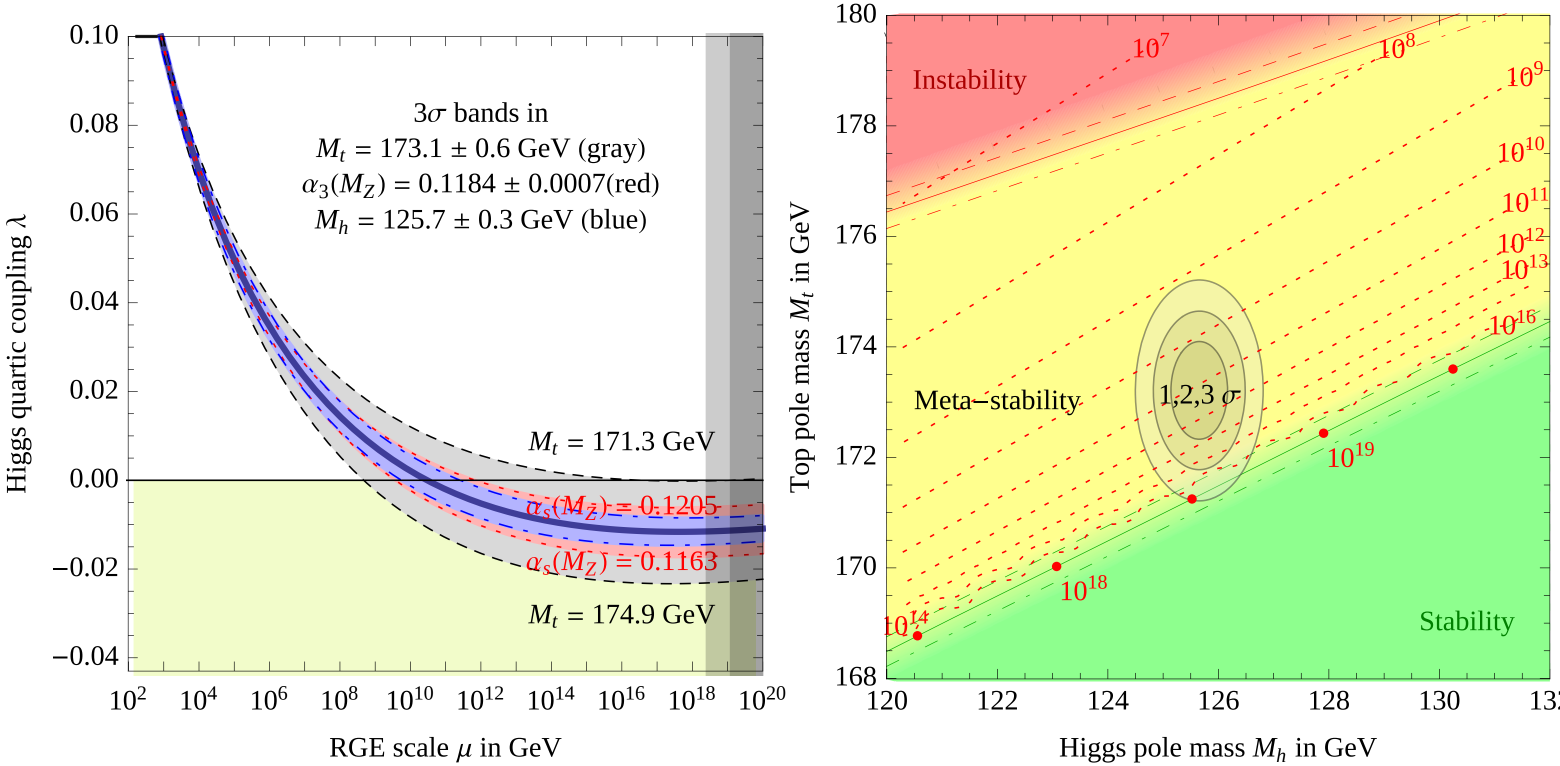


Figure 4: Pure SM implies $\lambda(m_{Pl}) < 0$ for $\mu > 10^{10} - 10^{12}$ GeV and metastable (but very long lifetime) early universe vacuum unless m_t is smaller than currently preferred. From arXiv:1307.3536, Buttazzo, *et al.*

- Meanwhile, the coefficient m^2 of the Higgs bilinear in the scalar potential is of order $m^2 \sim 0$, rather than being of order $\pm m_{Pl}^2$.

  Therefore, both the parameters of the Higgs potential are near critical lines that separate the EW phase ($\lambda > 0$, $m^2 < 0$) from a different (and inhospitable) phase of the SM.

  Is criticality just a capricious numerical coincidence or is it telling us something deep?

  The hope is that such criticality is the consequence of a symmetry, *e.g.* SUSY

- $125\ \mathrm{GeV}$ Higgs in SUSY?

  What does a Higgs mass of 125-126 GeV tell us about natural theories?

  – A Higgs mass smaller than 120 GeV would have been perfect for natural supersymmetry, while a mass larger than 130 GeV would have excluded all but very unnatural scenarios.
  – With a mass of 125 GeV, right in the middle, theorists are perplexed/unsure of what to think.
  – In particular, how consistent is a Higgs mass of 125 GeV with the MSSM?

It is often said that such a mass requires extreme values of the parameters, especially the masses and mixing of the stops.

However, this is not strictly true. In the phenomenological MSSM (pMSSM) with 19 independent low-scale parameters, the situation is more relaxed.

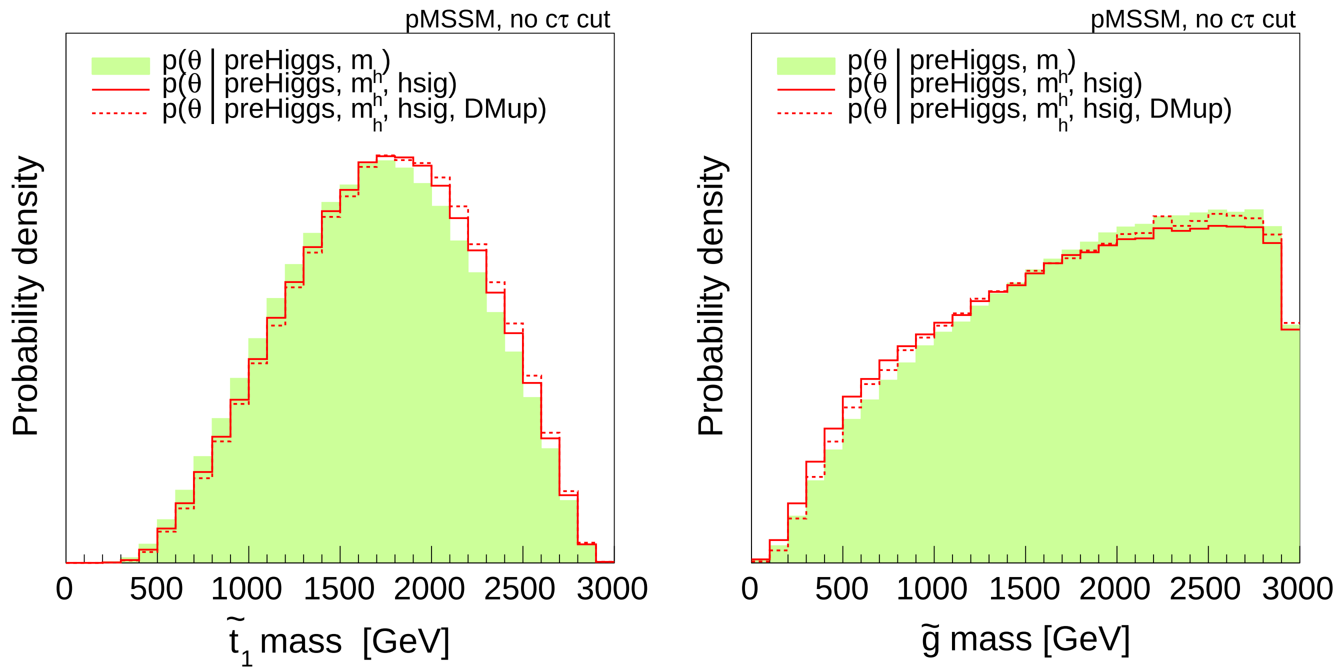


Figure 5: pMSSM bayesian probabillity distributions (arXiv:1312.7027, Dumont, Gunion, Kraml). Left: $m_{\widetilde{t}_1}$; Right: $m_{\widetilde{g}}$.

For example, after inputting Higgs LHC data and all preLHC constraints we obtain Fig. 5, which shows significant probability for $m_{\widetilde{t}_1}, m_{\widetilde{g}} < 1~\mathrm{TeV}$ even after precision Higgs data. Modest μ (also important for low fine-tuning) is also probable.

CMS and ATLAS are working to exclude the lower mass scenarios with small mass separations, ...

– What can be said is that certain GUT-scale setups, where parameters are correlated, are in bad shape (for instance gauge mediation, constrained MSSM), but the idea of low-energy supersymmetry of a pMSSM variety (which generically means no high-scale extrapolation, let alone unification) is not (yet) dead.

– Further, the more attractive NMSSM SUSY model still provides a good escape from being particularly unnatural even when GUT b.c. are employed. For example, in the NUH-NMSSM (NUH=non-universal Higgs soft masses squared), one has

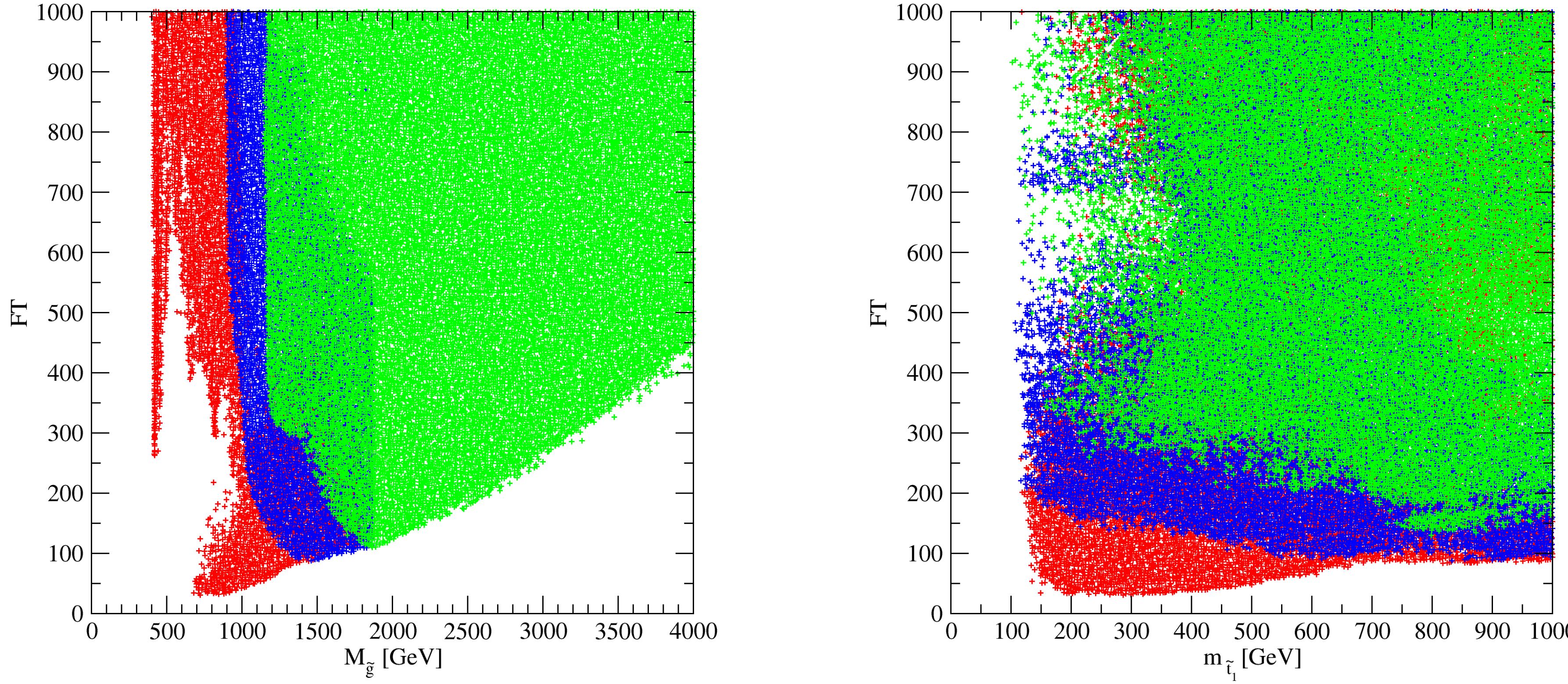


Figure 6: Fine Tuning in the NMSSM vs. $m_{\tilde{g}}$ and $m_{\tilde{t}_1}$. Red: absolutely excluded by LHC searches; Blue: still allowed if LSP=highly singlino; Green: still allowed even if LSP not singlino. (from arXiv:1405.6647, Ellwanger and Hugonie.)

We see:

* Although the LHC forbids the red region, increasing the lower bound on FT from ~ 20 to $FT \gtrsim 80$, this is far better than in the MSSM.
* In the MSSM – after imposing LHC constraints on squark and gluino masses, defining FT with respect to parameters at the GUT scale and allowing for non-universal Higgs mass terms at the GUT scale – one finds $FT \gtrsim 1000$.

– If the LHC eventually definitively forces all SUSY partners to be heavy and we simply give up on naturalness in a quantitative sense (but not in the sense that we give up on the symmetry), then $m_h \sim 126\ \mathrm{GeV}$ becomes quite accidental and forces another kind of fine tuning of the cutoff scale.

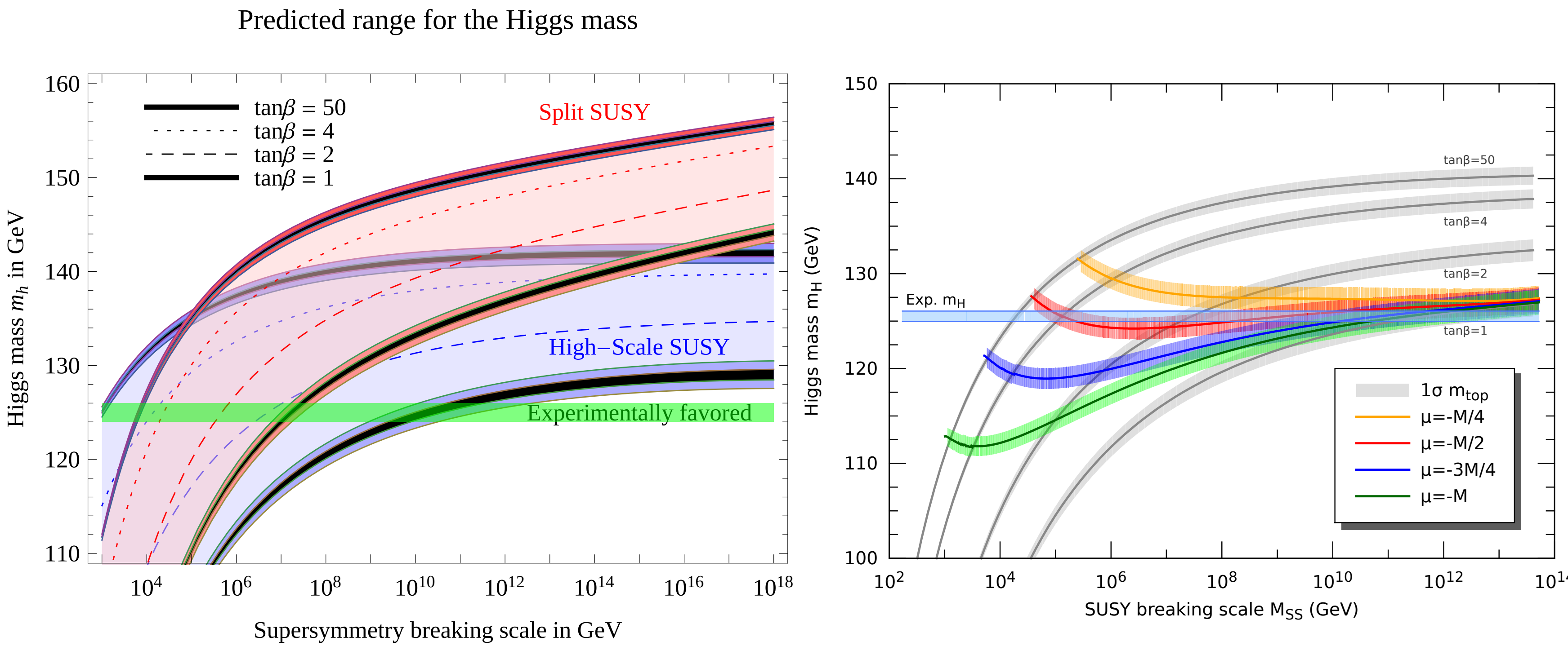


Figure 7: Left: NNLO prediction for the Higgs mass M_h in High-Scale Supersymmetry (blue, lower) and Split Supersymmetry (red, upper) for $\tan\beta = \{1, 2, 4, 50\}$ (from arXiv:1108.6077, Giudice *et al.*). Right: Higgs mass versus SUSY breaking scale M_{SS}. The grey bands correspond to the Higgs mass for different values of tanβ, for $X_t = 0$, without imposing unification of Higgs soft parameters. The other colored bands correspond to imposing tanβ values consistent with unification of soft terms, $m_{H_u} = m_{H_d}$. From arXiv:1301.5167, Ibanez, *et al.*

For example, Fig. 7 (l.h. plot) shows that a Higgs mass of 125 GeV rules out the idea of Split Supersymmetry with a high scale, say larger than 10^8 GeV. However, it fits very well with Split Supersymmetry with a low scale.
The r.h. plot shows that the correct m_h requires a conspiracy between the SUSY breaking scale, M_{SS}, and $\tan\beta$.

- 125 GeV Higgs in 2HDM (Dumont, Gunion, Jiang, Kraml, arXiv:1405.3584.)
  - The most general 2HDM Higgs potential is given by

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

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 we 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 $\beta \in [0, \pi/2]$, $\alpha \in [-\pi/2, +\pi/2]$; 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.

	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.

– Either the h or the H can be SM-like with mass $\sim 125.5~\mathrm{GeV}$, labelled $h125$ and $H125$, respectively.

– Proceed in steps:

1. Choose $h125$ or $H125$.
2. Scan:

$$\alpha \in [-\pi/2, +\pi/2]\,, \quad \tan\beta \in [0.5, 60]\,, \quad m_{12}^2 \in [-(2~\mathrm{TeV})^2, (2~\mathrm{TeV})^2]\,,$$
$$m_A \in [5~\mathrm{GeV}, 2~\mathrm{TeV}]\,, \quad m_{H^\pm} \in [m^*, 2~\mathrm{TeV}]\,, \tag{4}$$

   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 $125.5~\mathrm{GeV}$ (H and A in the $h125$ case, or just A in the $H125$ case).
5. Impose Higgs fitting for all channels as per arXiv:1306.2941 (Belanger, et.al.) at the 95% CL.
6. 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 $gg \to Z \to Zh$. (See also, arXiv:1311.1520, Arhrib, Ferreira and Santos.)
7. Look at consequences.

- **The $h125$ 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 $\sin\alpha > 0$.

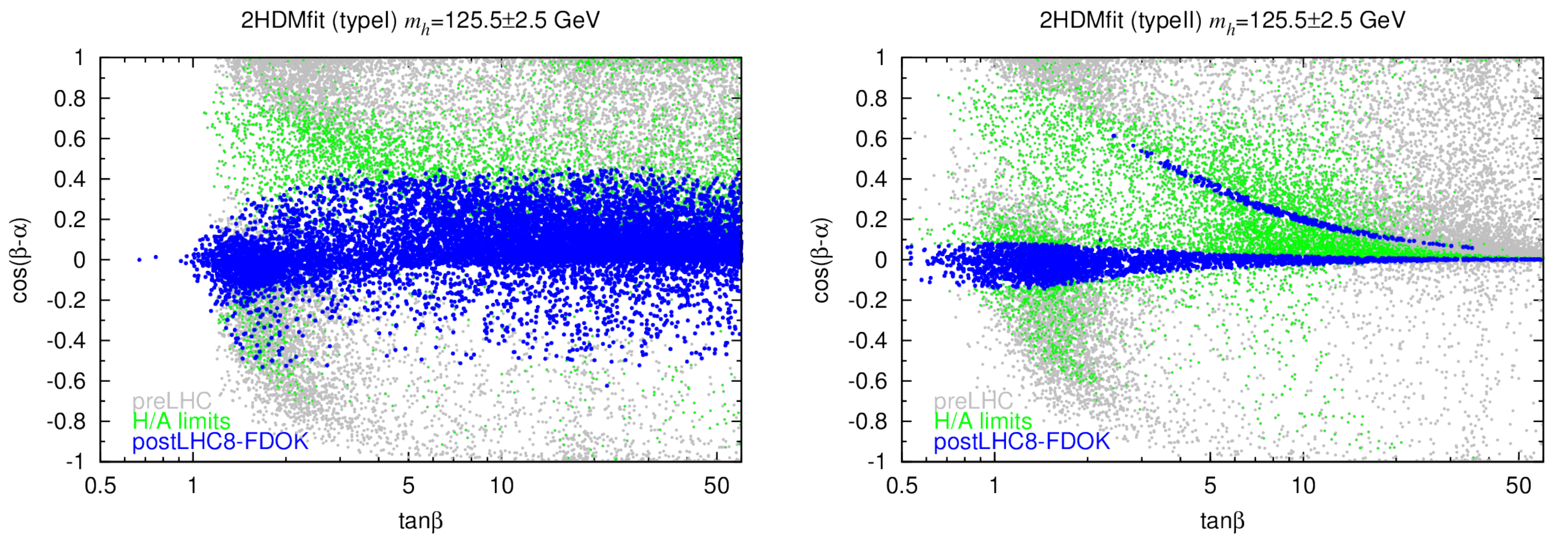


Figure 8: Constraints in the $\cos(\beta - \alpha)$ versus $\tan\beta$ plane for $m_h \sim 125.5$ GeV. Grey points satisfy preLHC constraints, while green points satisfy in addition the LHC limits on H and A production. Blue points fall in addition within the 7+8 TeV 95% CL ellipses in the $[\mu(\mathrm{ggF}+\mathrm{ttH}),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

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.)

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

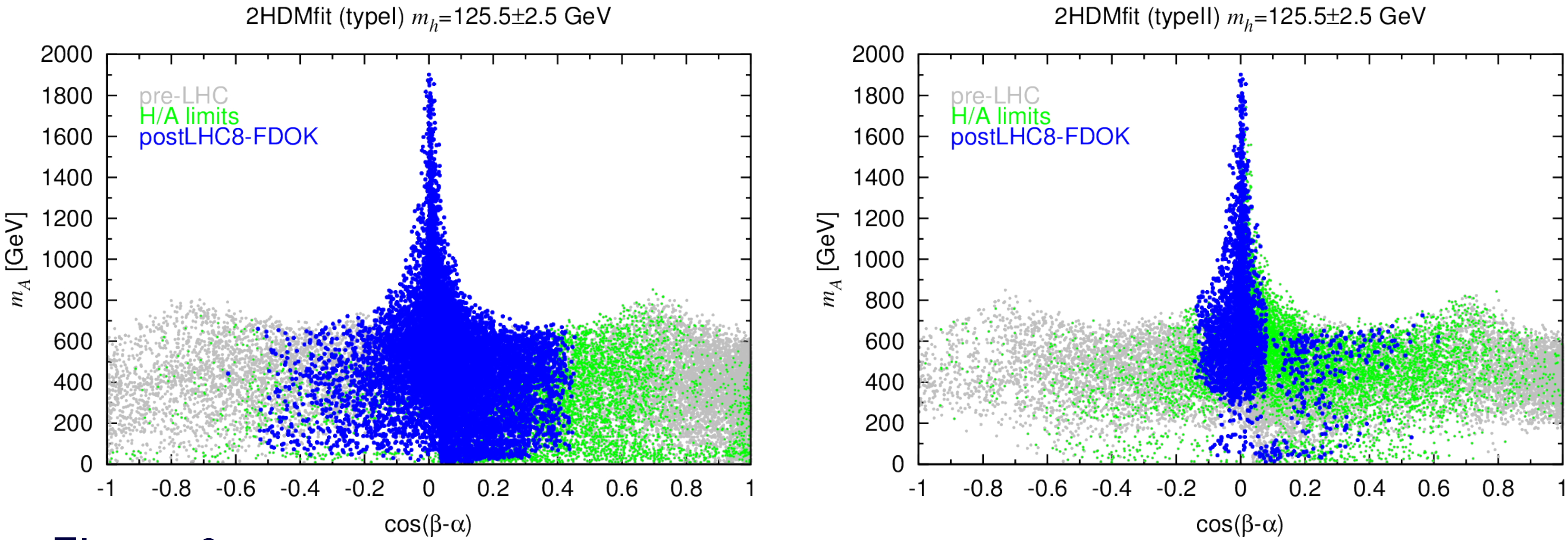


Figure 9: Constraints in the m_A versus $\cos(\beta-\alpha)$ plane for $m_h \sim 125.5~\mathrm{GeV}$.

The decoupling limit is clearly seen. The Type-II high $\cos(\beta-\alpha)>0$ points are those with $C^h_D \sim -1$. The latter arise because in Type II,

$$h\overline{D}D: \qquad -\frac{\sin\alpha}{\cos\beta} = -\sin(\beta+\alpha)+\cos(\beta+\alpha)\tan\beta\,, \tag{5}$$

$$h\overline{U}U: \qquad \frac{\cos\alpha}{\sin\beta} = \sin(\beta+\alpha)+\cos(\beta+\alpha)\cot\beta\,. \tag{6}$$

$\sin(\beta+\alpha)=1 \Rightarrow C^h_D=-1$ and $\sin(\beta-\alpha)=-\cos 2\beta \to 1$ if $\tan\beta$ is large.

– What are the implications of future higher-precision LHC measurements. Suppose we measure all the following channels with high precision ($\pm 15\%$, $\pm 10\%$, $\pm 5\%$)

$$(gg,\gamma\gamma),\ (gg,ZZ),\ (gg,\tau\tau),\ (\mathrm{VBF},\gamma\gamma),\ (\mathrm{VBF},ZZ),\ (\mathrm{VBF},\tau\tau)=(\mathrm{VH},bb),\ (\mathrm{ttH},bb)\,. \quad (7)$$

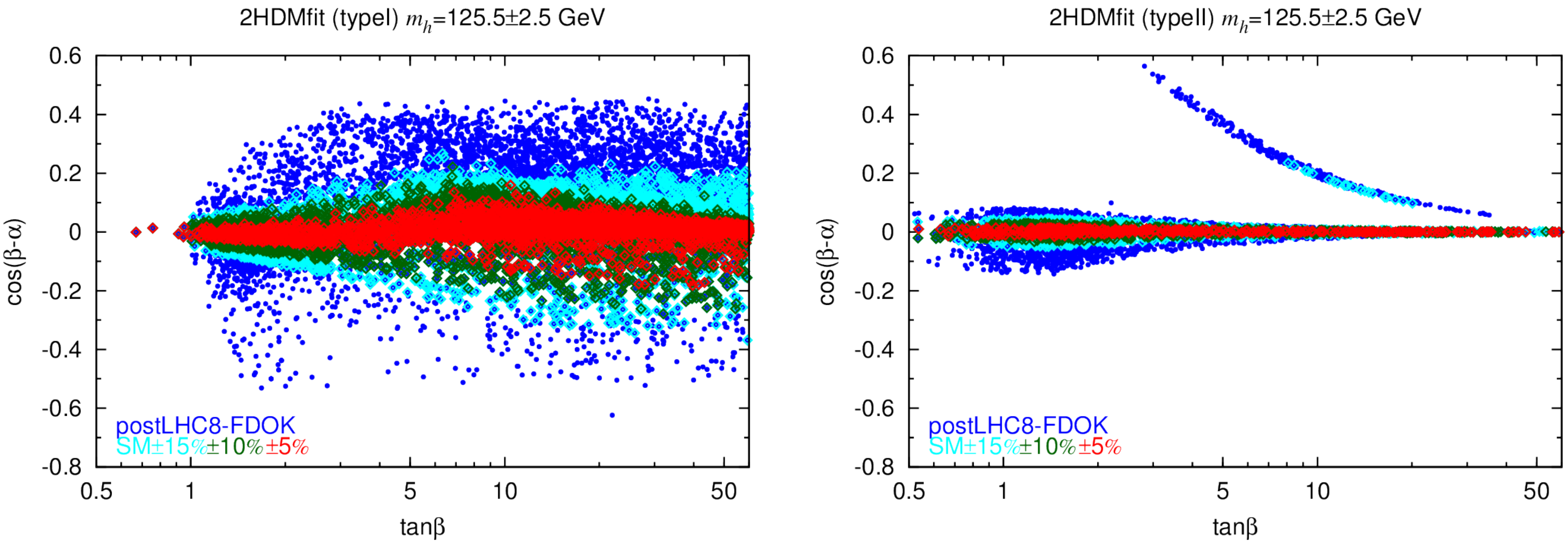


Figure 10: postLHC8-FDOK points in the $\cos(\beta-\alpha)$ vs. $\tan\beta$ plane for the $m_h \sim 125.5$ GeV scenario comparing current h fits (blue) to the case that all the channel rates are within $\pm 15\%$, $\pm 10\%$, $\pm 5\%$ of the SM Higgs prediction.

Observing a deviation from $C_{hhh} = 1$ becomes increasingly difficult, even at the ILC. For example, the predicted precision on λ_{hhh} for ILC1000 with $L = 500 - 1000\ \mathrm{fb}^{-1}$ is $\sim 21\%$ and for ILC1000 with $L = 1600 - 2500\ \mathrm{fb}^{-1}$ is $\sim 13\%$. At CLIC3000 with $L = 2000\ \mathrm{fb}^{-1}$ the accuracy would be $\sim 10\%$.

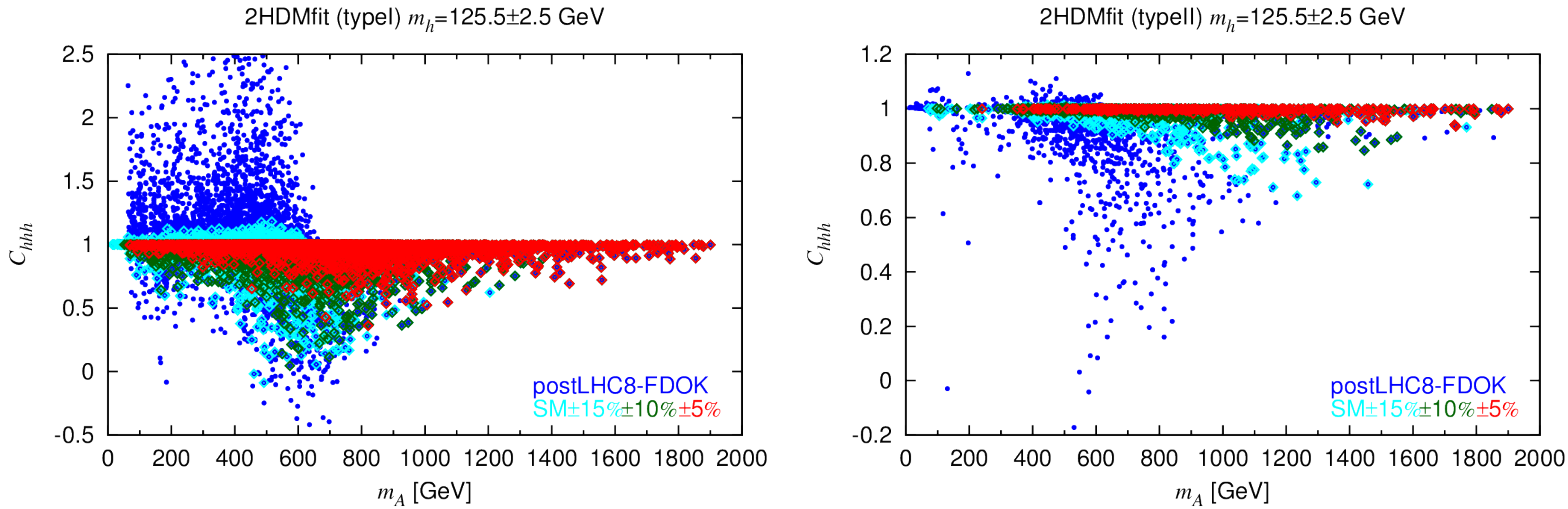


Figure 11: postLHC8-FDOK points in the C_{hhh} vs. m_A plane for the $m_h \sim 125.5$ GeV scenario comparing current h fits to the case where future measurements for all the channels are within $\pm 15\%$, $\pm 10\%$, $\pm 5\%$ of the SM Higgs prediction.

$\Rightarrow$ After $\pm 5\%$, there are some remaining prospects for seeing a λ_{hhh} deviation for the Type I model, but for Type II not much chance to see a deviation.

– Prospects for LHC observation of the H, A, $H^{\pm}$ are significant. *e.g.* $\tau\tau$ final state.

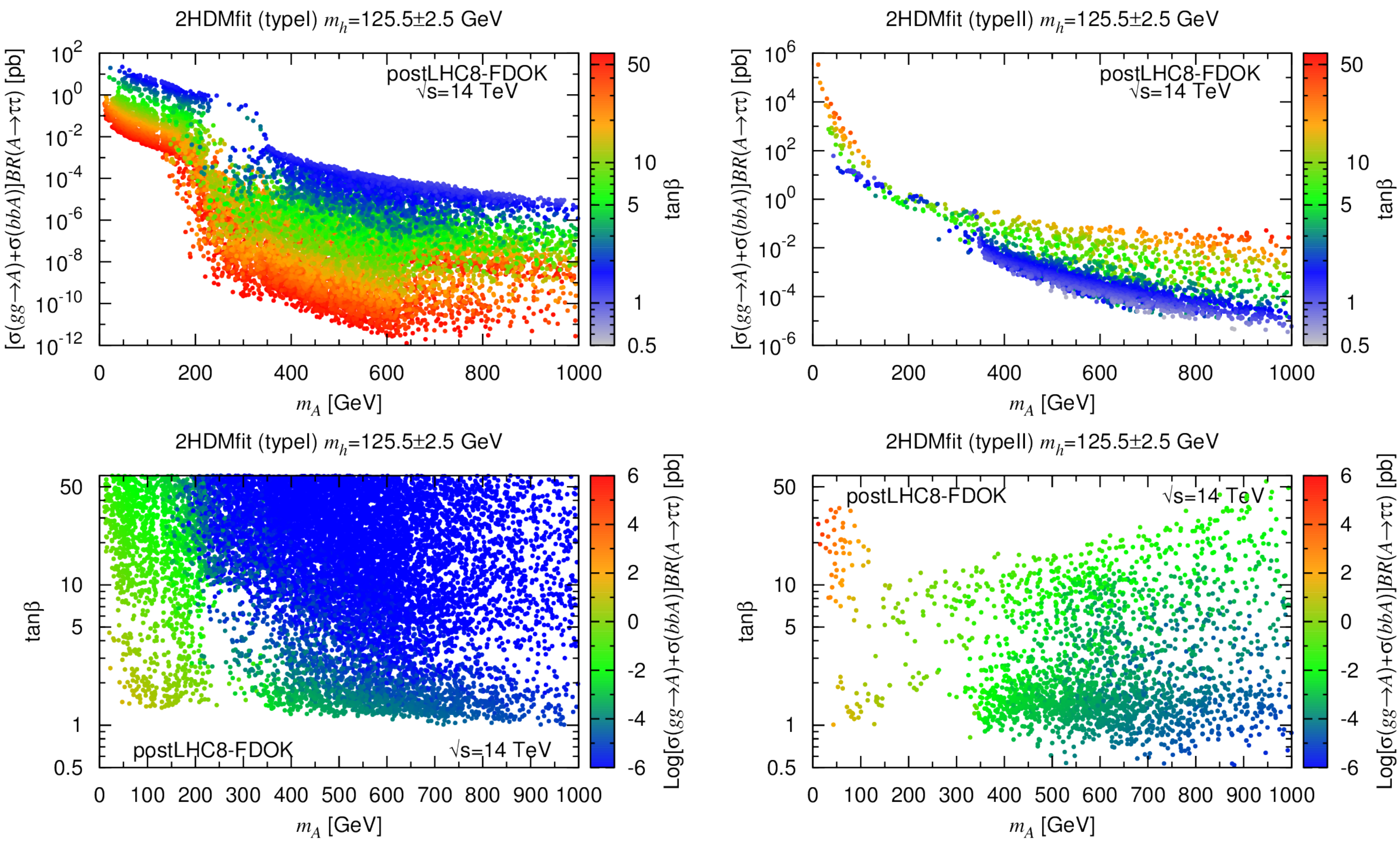
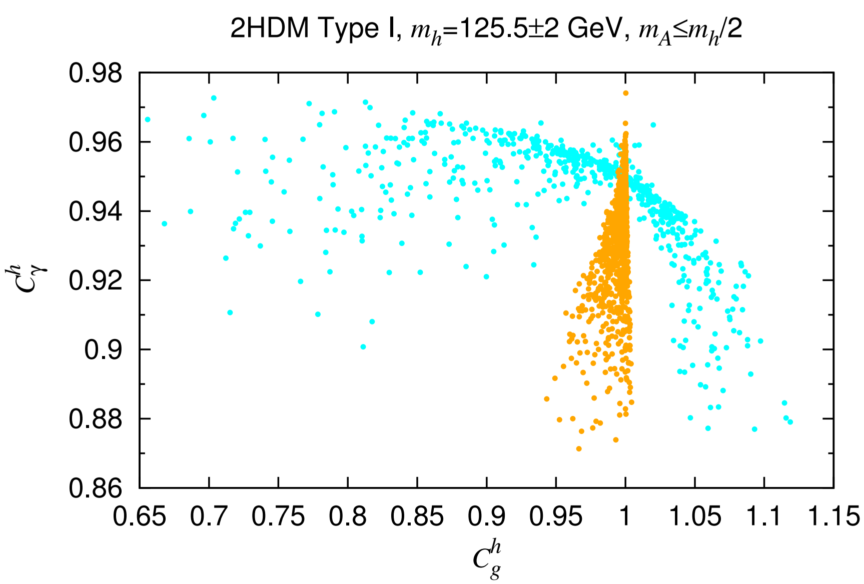
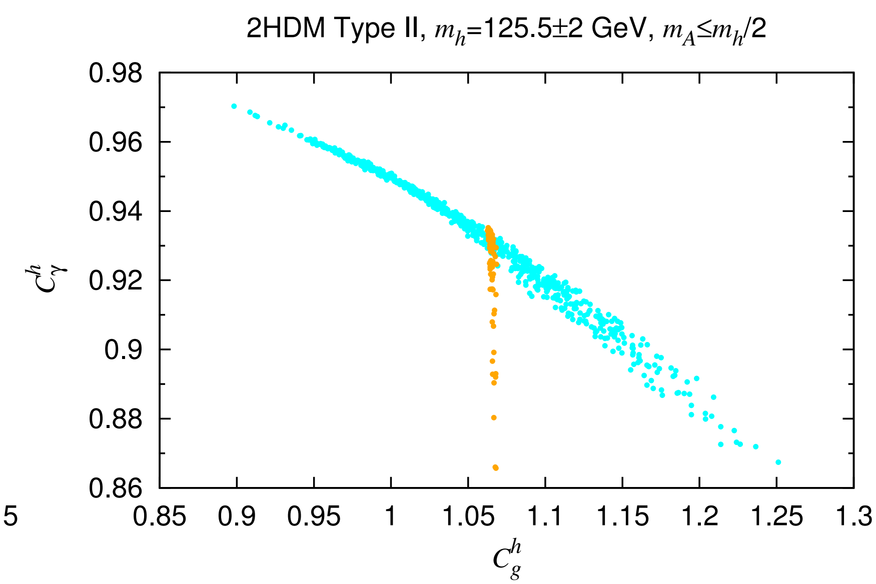


Figure 12: 2HDM points agreeing at 95% C.L. with precision Higgs data as well as B physics, ... From arXiv:1405.3584.

Note especially the very large possible cross sections (esp. Type II) of points at low m_A (with $\mathcal{B}(h \to AA) \lesssim 0.2$ to avoid messing with h fits). Remarkably, they are still allowed by LEP and by existing 7+8 TeV analyses, although I feel certain that the existing analyses can be extended to $M_{\tau\tau} < 90~\mathrm{GeV}$, in which case the bulk of these points would be eliminated (or observed).

These low-m_A points are also not exactly SM-like. Many of the Type II points (orange points) have $C_D^h < 0$ (opposite sign to normal but same magnitude) and are associated with a non-decoupling heavy charged Higgs loop contribution to the $h\gamma\gamma$ 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.)





Above, we plot C_g vs.C_γ, the hgg and $h\gamma\gamma$ couplings relative to the SM values. Expected accuracies at the LHC and ILC are:

* LHC:

  C_g to $6-8\%$ for $L=300~\mathrm{fb}^{-1}$ and $3-5\%$ for $L=3000~\mathrm{fb}^{-1}$ (based on fitting all the rates rather than directly observing the gg final state).

  C_γ to $5-7\%$ for $L=300~\mathrm{fb}^{-1}$ and $2-5\%$ for $L=3000~\mathrm{fb}^{-1}$.

* ILC:

  C_g to 2% for $L=250~\mathrm{fb}^{-1}$ at $\sqrt{s}=250~\mathrm{GeV}$ plus $L=500~\mathrm{fb}^{-1}$ at $\sqrt{s}=500~\mathrm{GeV}$.

  C_γ to 8.3% or $L=250~\mathrm{fb}^{-1}$ at $\sqrt{s}=250~\mathrm{GeV}$ plus $L=500~\mathrm{fb}^{-1}$ at $\sqrt{s}=500~\mathrm{GeV}$.

  The ILC estimates are based on determining the ZZh coupling using inclusive $e^+e^-\to Z^*\to Zh$ and, for C_g, the ability to isolate the gg final state at an e^+e^- collider.

  Bottom lines:

  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.

The deviations from SM will be detectable or excluded with increased luminosity at Run2 through the cross section ratios such as those shown in Fig. 13.

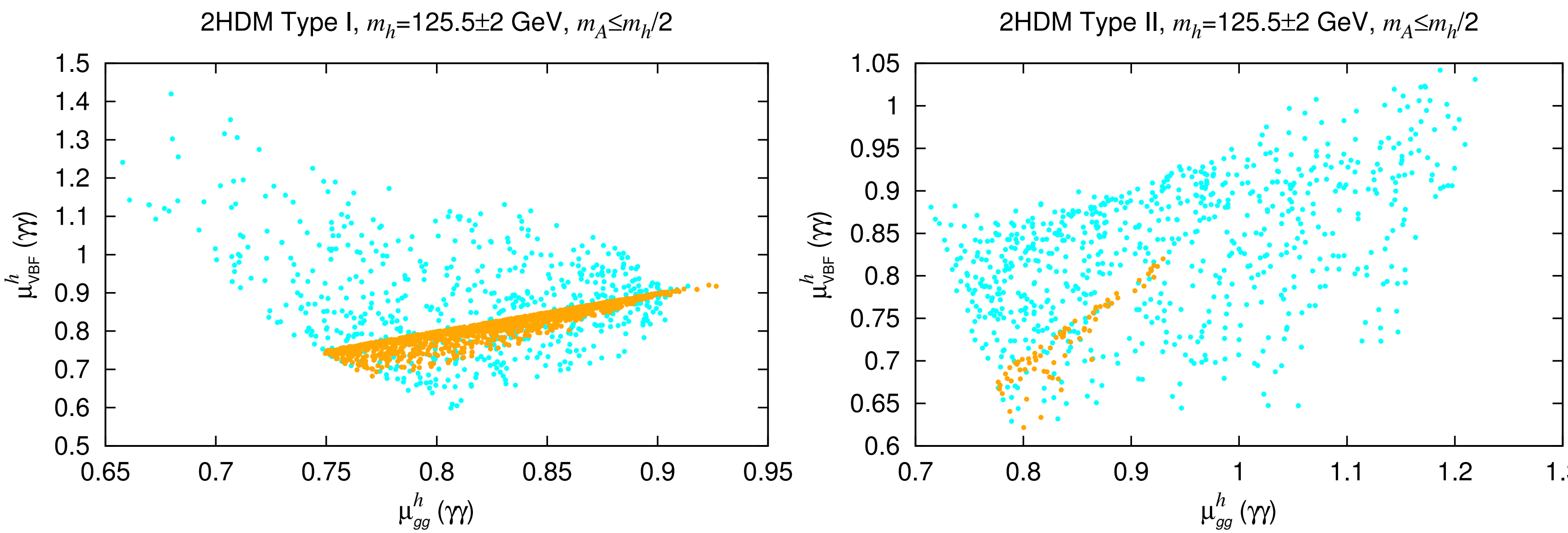


Figure 13: $\mu^h_{VBF}(\gamma\gamma)$ vs. $\mu^h_{gg}(\gamma\gamma)$ for the Type I and Type II models at the postLHC8(2014)-FDOK level.

More details of large cross sections are shown in Fig. 14.

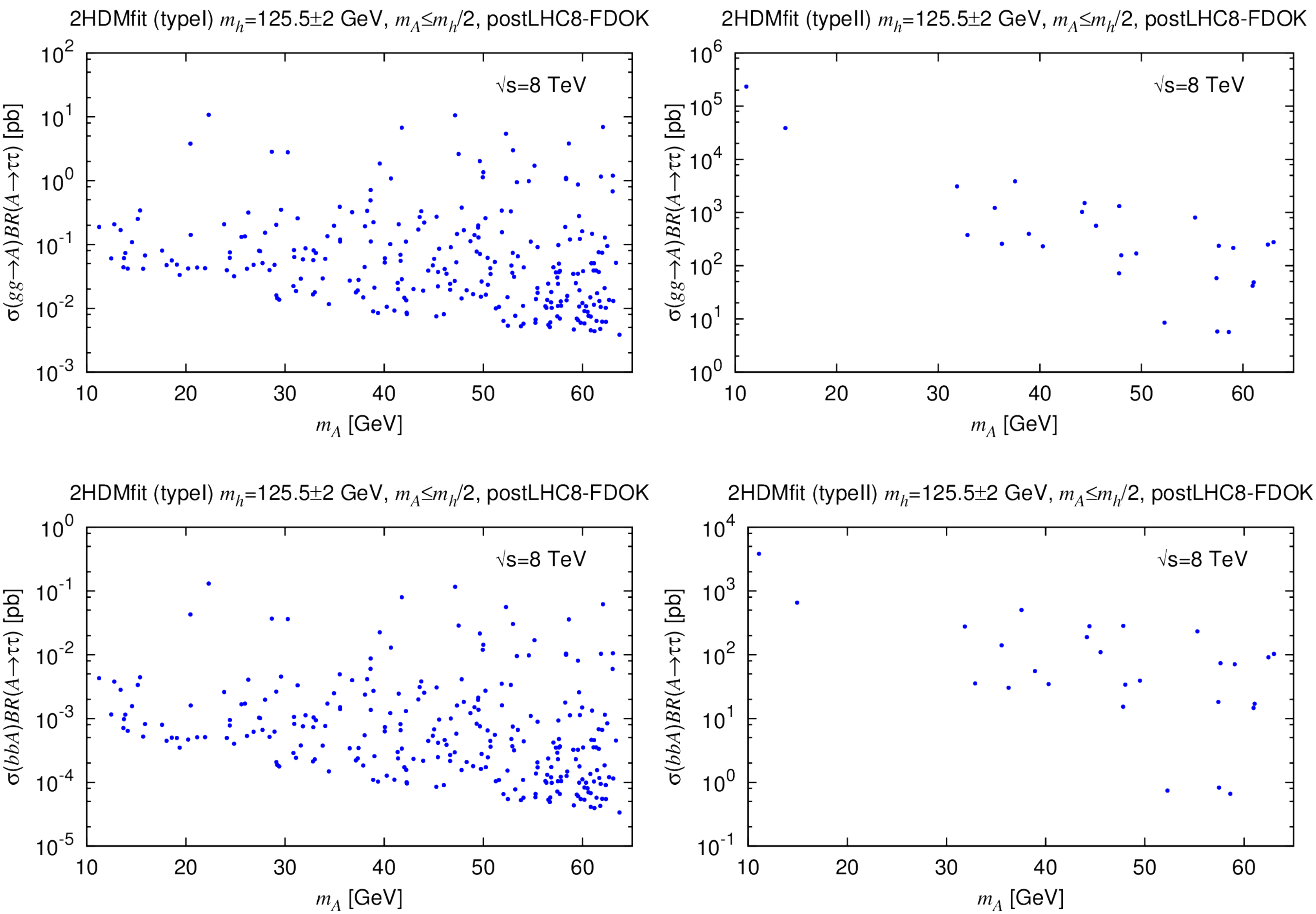


Figure 14: 8 TeV cross sections for light A production from gg fusion and $b\bar{b}$ associated production in the $\tau\tau$ final state. $\mu\mu$ final state cross sections are a factor of ~ 300 lower.

Naive estimates suggest that, before cuts and efficiencies, for the existing 8 TeV $L = 20 \text{ fb}^{-1}$ data set a cross section of order 10 pb ($200,000$ events) should be observable in the $\tau\tau$ final state while 0.1 pb (2000 events) should be observable in the $\mu\mu$ final state, especially in the case of $b\bar{b}$ associated production by using modest p_T b-tagging.

From the figure, we observe that these levels are reached in the case of Type II for essentially the entire $m_A \leq m_h/2$ region in the case of gg fusion and for the orange points in the case of $b\bar{b}$ associated production. Indeed, the orange point cross sections are really very large and should produce readily observable peaks.

Analyses by ATLAS and CMS for such signals at low m_A in the $\tau\tau$ channel have significant background from the Z peak. As a result, limits are currently only available for $m_A \gtrsim m_Z$.

– Other final states are also of great interest. In particular, A production with $A \to Zh$ can have large cross section. Current data are already relevant in limiting this scenario.

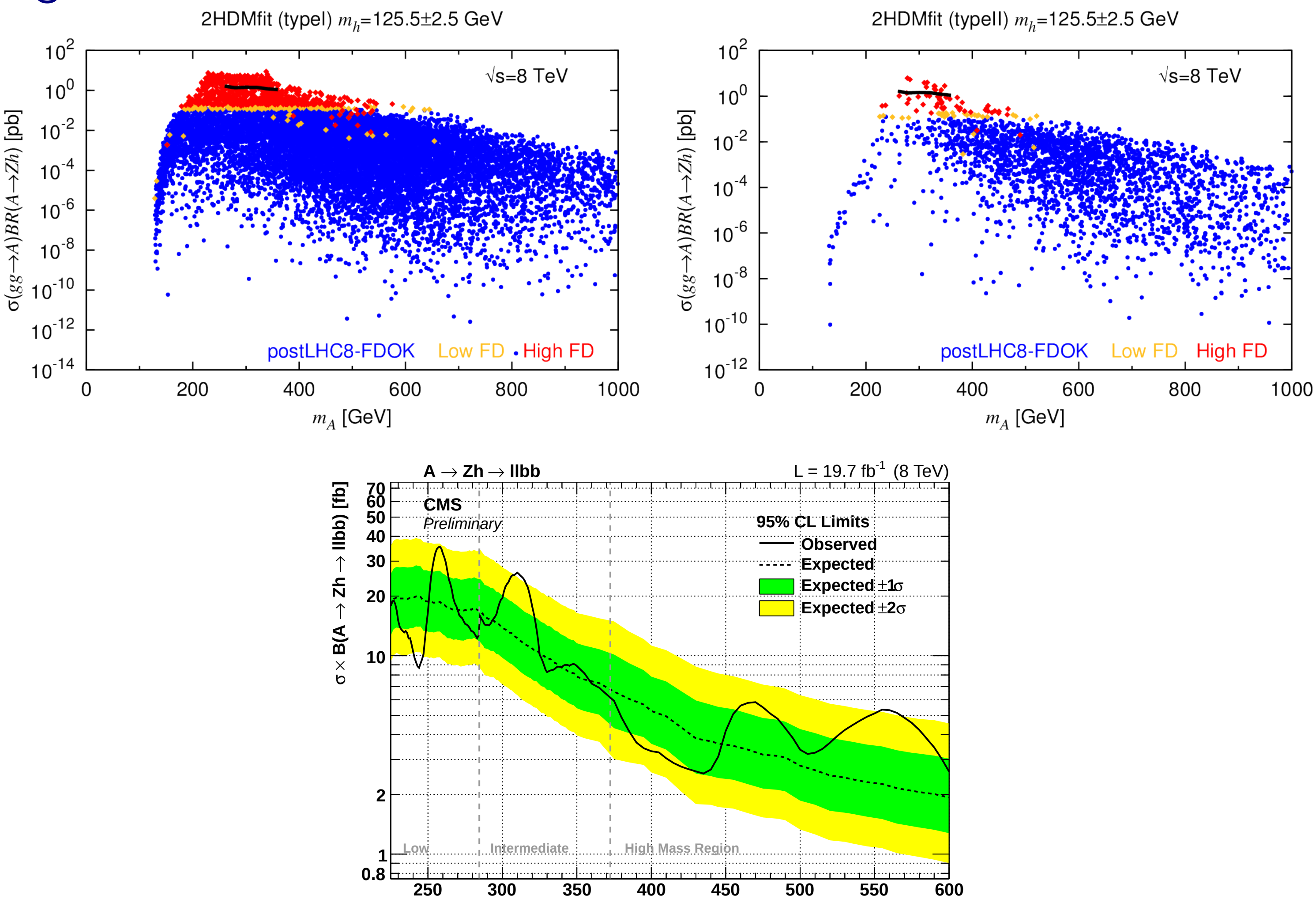


Figure 15: gg production of A with $A \to Zh$. Top: $\sqrt{s} = 8~\mathrm{TeV}$ predictions. Bottom: recent CMS limits — must multiply top figure results by $\sim 0.06 \times 0.75 = 0.045$ for the $\ell\ell b\bar{b}$ final state of CMS limits. Result: top of scatter plot matches largest excesses in bottom plot. ‘bumps’ FD to h.

- In the MSSM, m_A is tied to m_h and cannot be small. Expectations are generically that the A, H and $H^\pm$ will be heavy. In the pMSSM, we have the following.

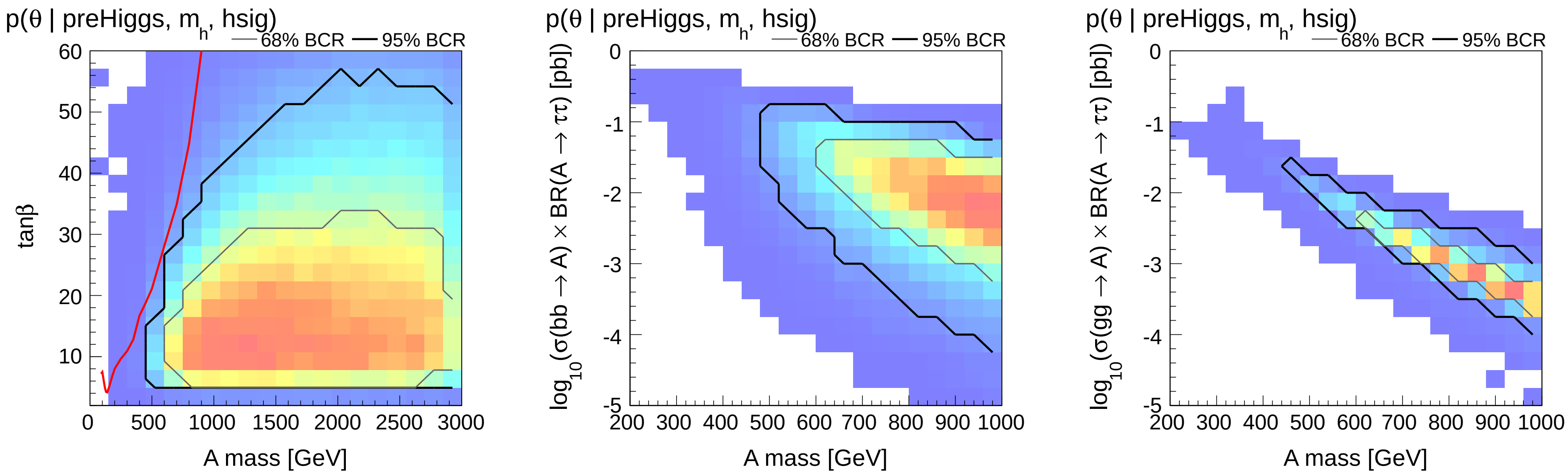


Figure 16: pMSSM results for the A after Higgs fitting. SUSY limits as per SUS-13-020 have no impact. Cross sections are for $\sqrt{s} = 14~\mathrm{TeV}$. Much of the predicted range can be probed at the next LHC run!. Plot taken from pMSSM Higgs paper, Dumont *et al.*, arXiv:1312.7027.

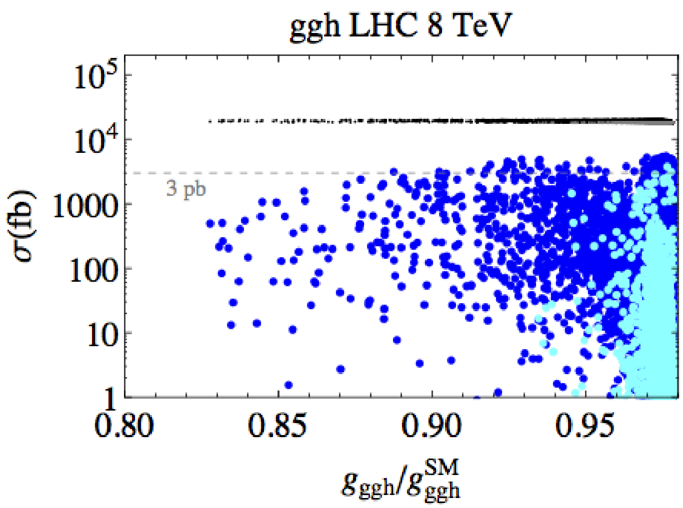
In arXiv:1302.7033, Carena *et al.* explore a specially constructed MSSM scenario with $m_H \sim 125~\mathrm{GeV}$. In this scenario, m_h can be as low as $\sim 77~\mathrm{GeV}$ for $m_A \sim 100~\mathrm{GeV}$. LEP plays an important role in not allowing $< 125.5/2$ masses for the h and A.

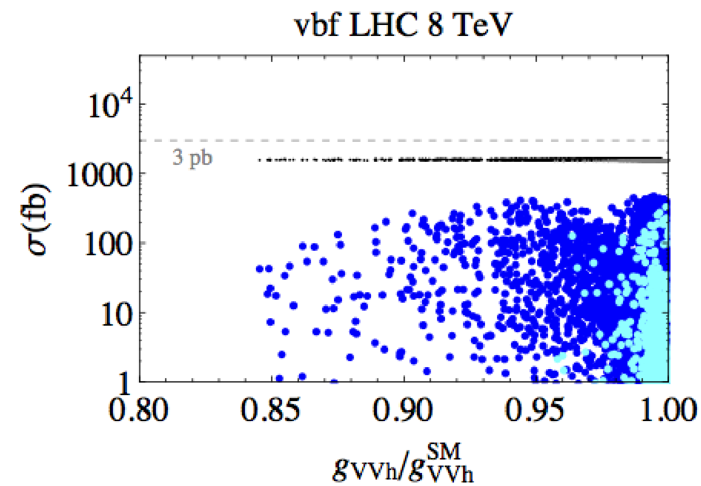
$\Rightarrow$ observation of a A (or h) with mass below one-half $125.5~\mathrm{GeV}$ rules out the MSSM.

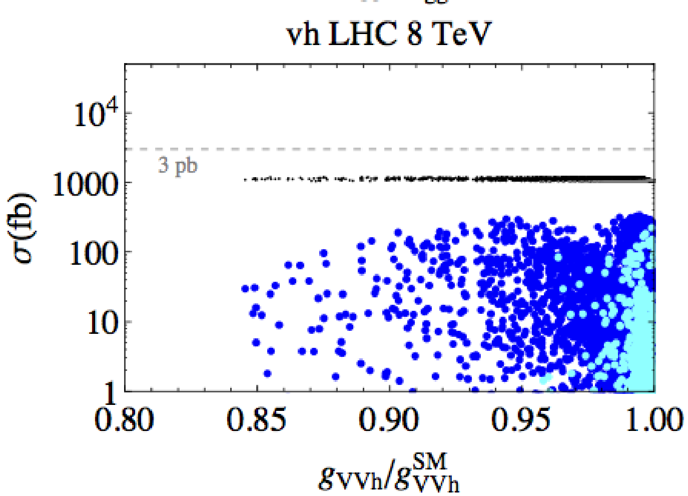
- In the NMSSM, we have h_1, h_2, h_3 and a_1, a_2 and $H^\pm$. Many possibilities!

  It is still very relevant to consider CP-even Higgs production with decay to $a_1 a_1$. Some recent scans from Barducci are of interest. He considers $A_\kappa \to 0$, $m_{a_1} < 10~\mathrm{GeV}$, and demands that h_1 or h_2 fit the Higgs data at 95% C.L. He also computes the contribution of the non-SM-like h_2 or h_1 to the 4τ final state. NB. 4τ mass resolution is poor.

$h_{1,2}^{SM} \to a_1 a_1 \to 4\tau$ topology ($m_{a_1} < 10$ GeV) LHC8

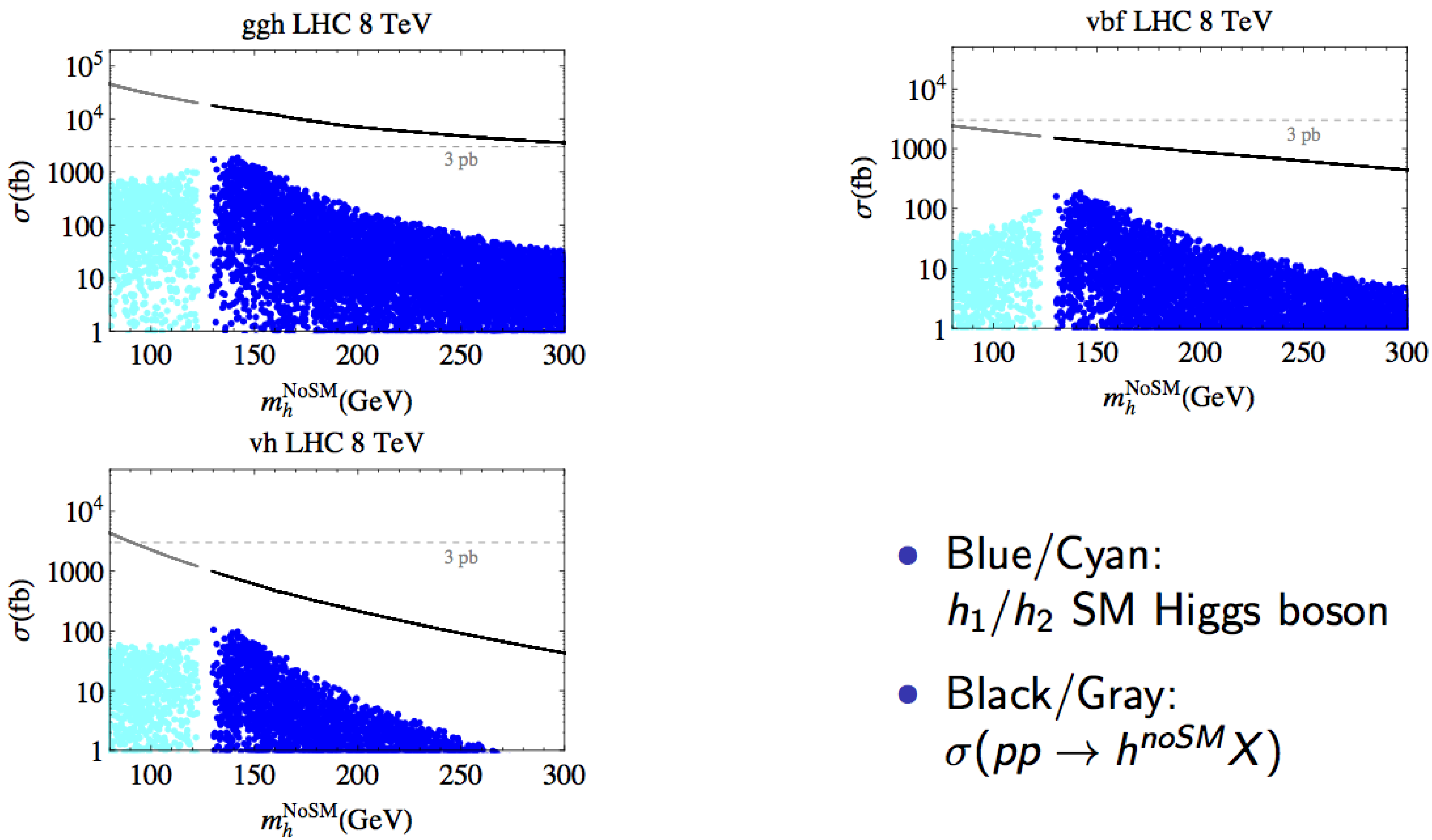






- Blue/Cyan:
  h_1/h_2 SM Higgs boson
- Black/Gray:
  $\sigma(pp \to h^{SM} X)$

$h_{1,2}^{SM} \to a_1 a_1 \to 4\tau$ topology ($m_{a_1} < 10$ GeV) LHC8



- Blue/Cyan:
  h_1/h_2 SM Higgs boson
- Black/Gray:
  $\sigma(pp \to h^{noSM} X)$

Contribution of both the lightest CP even Higgs to the signal

Higgs Dark Matter Models

- 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:

$$V(H_1, H_2, S) \quad = \quad V_{\rm 2HDM} + \frac{1}{2} m_0^2 S^2 + \frac{1}{4!} \lambda_S S^4 + \kappa_1 S^2 (H_1^\dagger H_1) + \kappa_2 S^2 (H_2^\dagger H_2) \tag{8}$$

  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 $\langle H_1 \rangle, \langle H_2 \rangle \neq 0$.

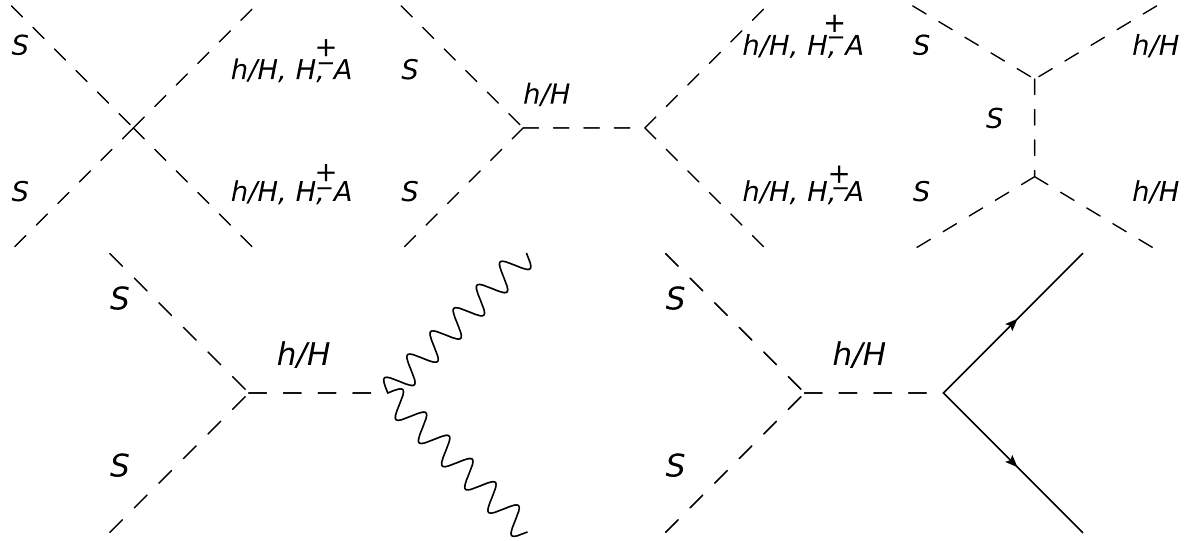


Figure 17: Singlet anihillation diagrams relevant for the relic density calculation.

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

Identifying h of 2HDM sector with the $126~\mathrm{GeV}$ state, one can retain good Higgs fits and get perfectly reasonable dark matter scenarios obeying all limits.

Possibilities in the $m_S < 125~\mathrm{GeV}/2$ region are limited by the need to have very small hSS coupling to keep $\mathcal{B}(h \to SS) < 0.1$ so as to preserve the Higgs fits.

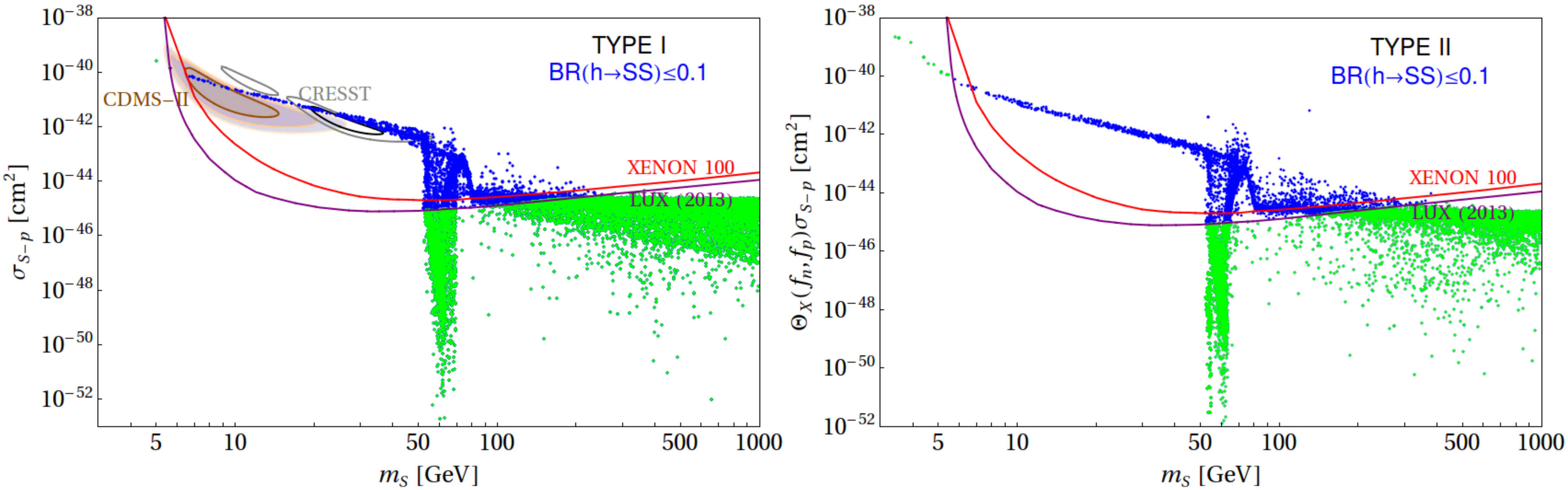


Figure 18: Cross section for DM - proton scattering for the Type I and Type II] models. All points shown satisfy the full set of preLUX constraints, including $\mathcal{B}(h \to SS) < 0.1$, while the green points satisfy in addition the LUX limits.

Conclusions

- It seems quite certain that the Higgs responsible for EWSB has emerged.

- At the moment, there is no sign of other Higgs-like signals except for the old LEP excess at $98~\mathrm{GeV}$.

- Survival of enhanced signals for the $125~\mathrm{GeV}$ state (as still seen by ATLAS) would be one of the most exciting outcomes of the next LHC run and would guarantee years of theoretical and experimental exploration of BSM models with elementary scalars.

- Close to SM signals at the LHC would imply that a linear collider or LEP3 or muon collider might be needed to look for BSM physics indirectly via deviations of Higgs properties from the SM.

- Although current data is converging to a SM-like Higgs, there is still room for additional Higgs bosons in important model classes.

  Thus, we must push hard to improve limits/sensitivity to additional Higgs bosons.

- SUSY remains the best-motivated technically natural model. But, it is being pushed.

  If there is some kind of high-scale unification, then low FT is best accommodated in the NMSSM.

  The pMSSM sets SUSY scales without regard to the ultimate high-scale theory — this may be quite appropriate in the context of the string landscape.

- The observed Higgs mass is, even on its own, highly constraining:
  - It is only the MSSM and NMSSM that both kind of predict a CP-even Higgs of mass near $125 \mathrm{~GeV}$.
  - The NMSSM does so without so much fine-tuning and, like the MSSM, preserves gauge coupling unification.
  - The Higgs mass in MSSM alternatives, like split-Supersymmetry, must be tuned.
  - Other models, $e.g.$ general 2HDM or Composite Higgs models do not really predict the observed Higgs mass, although it can be accommodated.

The two big questions/bottom lines are:

Whither Higgs? — Wither SUSY?.