Higgs Bosons: Present and Future

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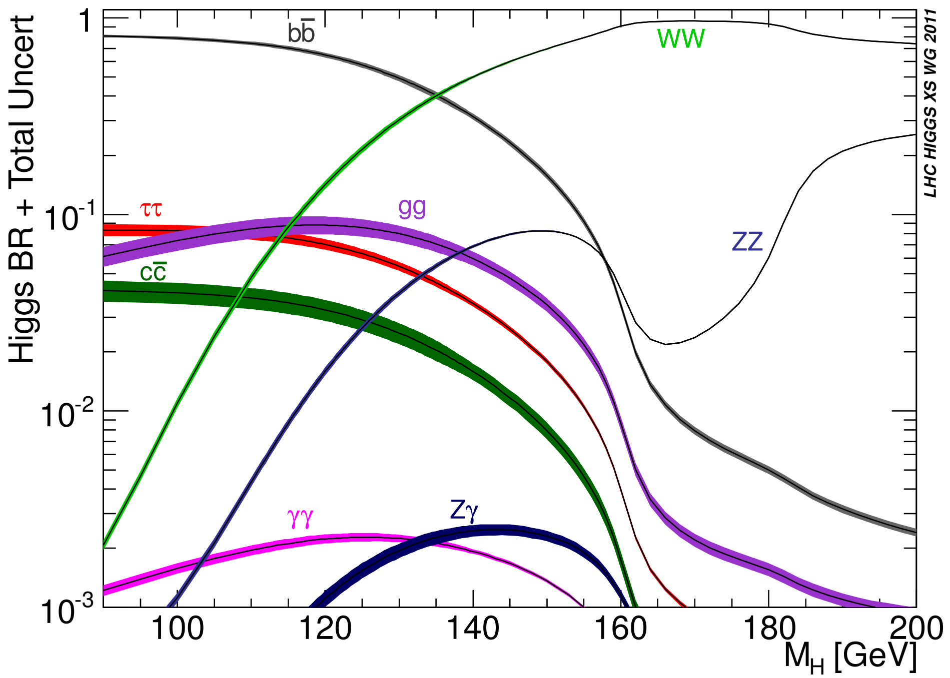
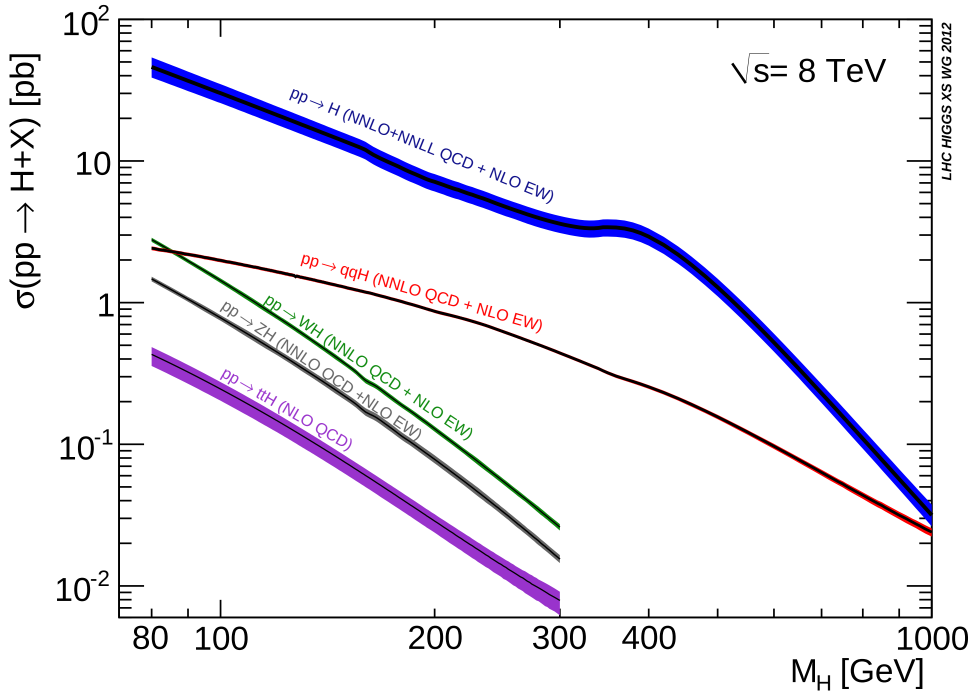
The present situation

The decay modes and production cross sections for a light SM Higgs are well-known and it is only a question of how well the data conform to the predictions.





The best discovery and highest precision modes for the now-observed mass of ~ 125.5 GeV have long been known to be $gg \to h_{SM} \to \gamma\gamma$ and $gg \to h_{SM} \to ZZ^* \to 4\ell$.

The current status of the signal is unassailable. And, it looks very SM-like!

The observed $\sim 125.5~\mathrm{GeV}$ 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 $125.5~\mathrm{GeV}$ 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. For this purpose, it is best to separate different production modes and different final decays:

- Production modes: ggF, ttH, VBF, VH
- Decay modes: $\gamma\gamma$, $ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau\tau$

Some simplifications are useful given current results.

1. Deviations from custodial symmetry are now strongly constrained and can for the moment be neglected.

   Hence, one can assume that the VBF and VH production modes both depend on a single generalized coupling of the Higgs boson to $V = W, Z$.

2. It is also convenient to combine ggF and ttH.

Of course, eventually, one will want to consider every $X \to H \to Y$ channel separately. For now, we have proceeded as follows.

- If we have custodial symmetry and if $b\bar{b}$ and $\tau\tau$ rescale by a common factor as in many models, then we are left with two independent production modes (VBF+VH) and (ggF+ttH), and three independent final states $\gamma\gamma$, $VV^{(*)}$ and $b\bar{b} = \tau\tau$.

- In recent publications by the ATLAS and CMS collaborations, likelihoods are given in the (VBF+VH) and (ggF+ttH) plane for relative signal strengths μ_i in the specific final states $\gamma\gamma$, $ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$, $\tau\tau$:

$$\mu_X^Y = \frac{\sigma(X \to H \to Y)}{\sigma(X \to h_{SM} \to Y)} \tag{1}$$

Using the the ellipses provided, we (Belanger, Dumont, Ellwanger, Gunion, Kraml) (many other similar works) are able to include the rather important correlations due to mutually common errors of the (VBF+VH) and (ggF+ttH) production processes.

- **We combine the information provided by ATLAS, CMS and the Tevatron on the likelihoods as function of the six independent signal strengths μ_i defined above. An illustration of the kind of plots we combine are those for ATLAS as given below —though not perfect ellipses, we fit them as ellipses and then combine with other experiments.**

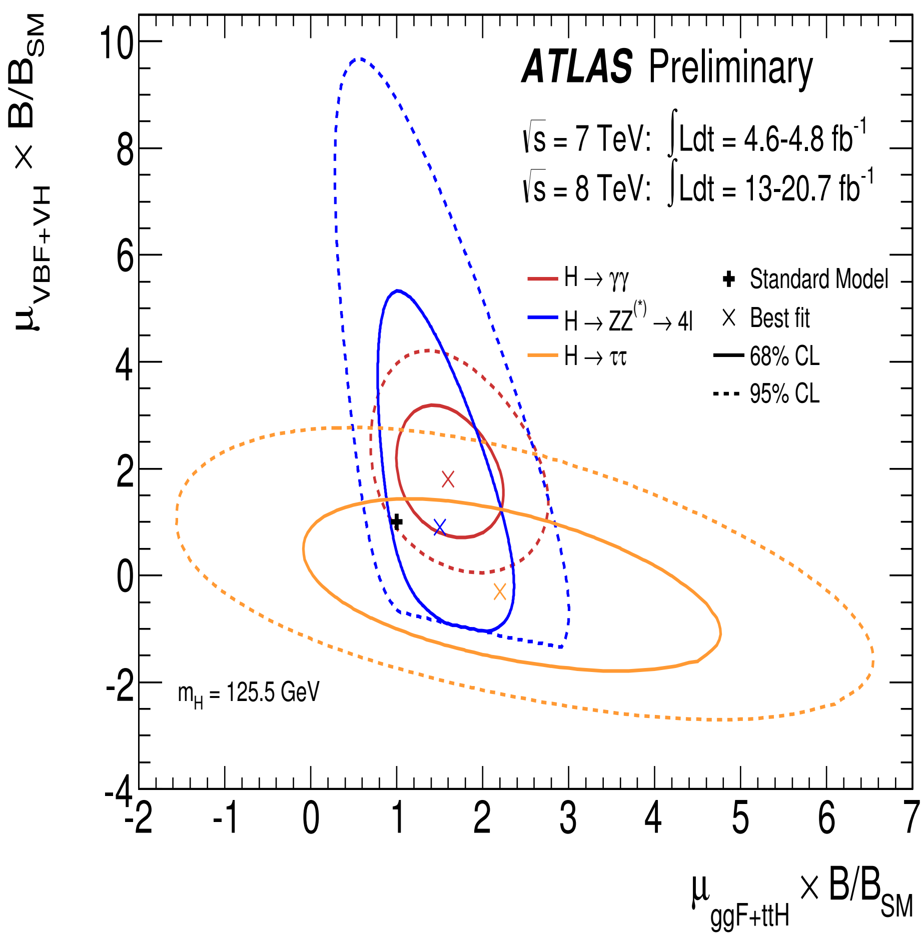


Figure 1: ATLAS results, including 4ℓ, $\gamma\gamma$ and $\tau\tau$.

- **The results appear in the following figure.**

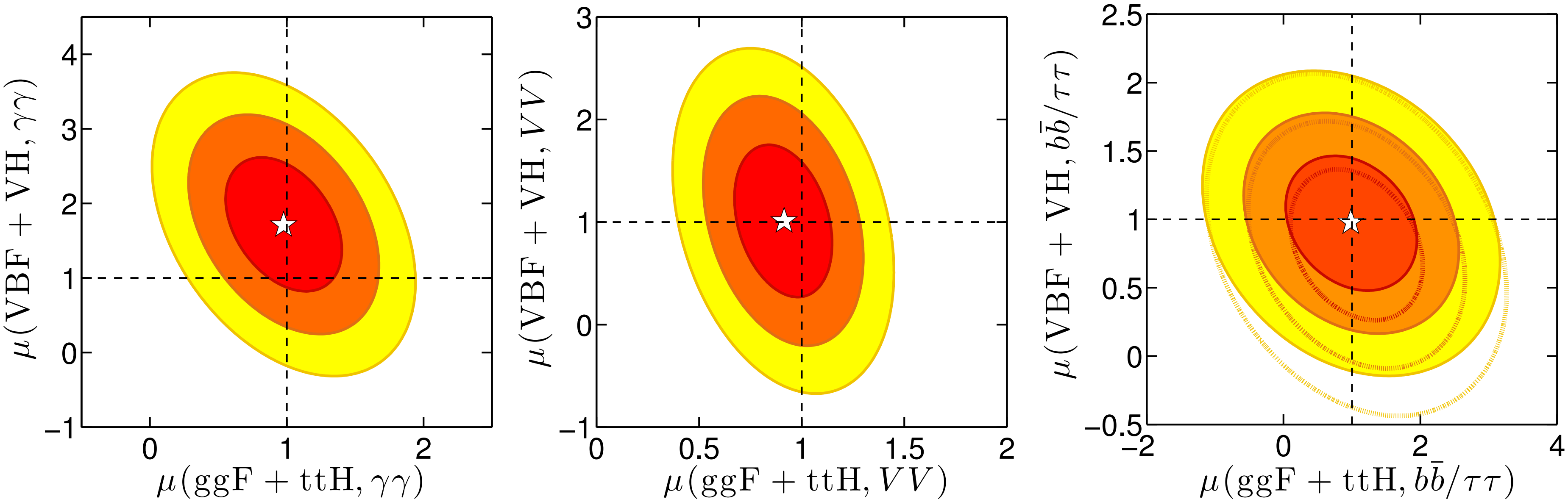


Figure 2: **Combined signal strength ellipses for the $\gamma\gamma$, $VV = ZZ, WW$ and $DD = b\bar{b}, \tau\tau$ channels. The filled red, orange and yellow ellipses show the 68%, 95% and 99.7% CL regions, respectively, derived by combining the ATLAS, CMS and Tevatron results. The line contours in the right-most plot show how these ellipses change when neglecting the Tevatron results. The white stars mark the best-fit points.**

Using these ellipses, it is possible to determine the underlying couplings associated with the Higgs Lagrangian for some particular model. For

example, take the tree-level Lagrangian

$$\mathcal{L} = g\left[C_W\, m_W W_\mu W^\mu + C_Z \frac{m_Z}{\cos\theta_W} Z_\mu Z^\mu - \sum_{F=U,D,L} C_F \frac{m_F}{2m_W}\bar{F}F\right] H\,, \qquad (2)$$

where the C_I are scaling factors for the couplings relative to their SM values. If we compute C_g and C_γ (relative to the SM values) using only SM loops and take $C_D = C_L$, and $C_W = C_Z \equiv C_V$ as is the case for many models, we obtain:

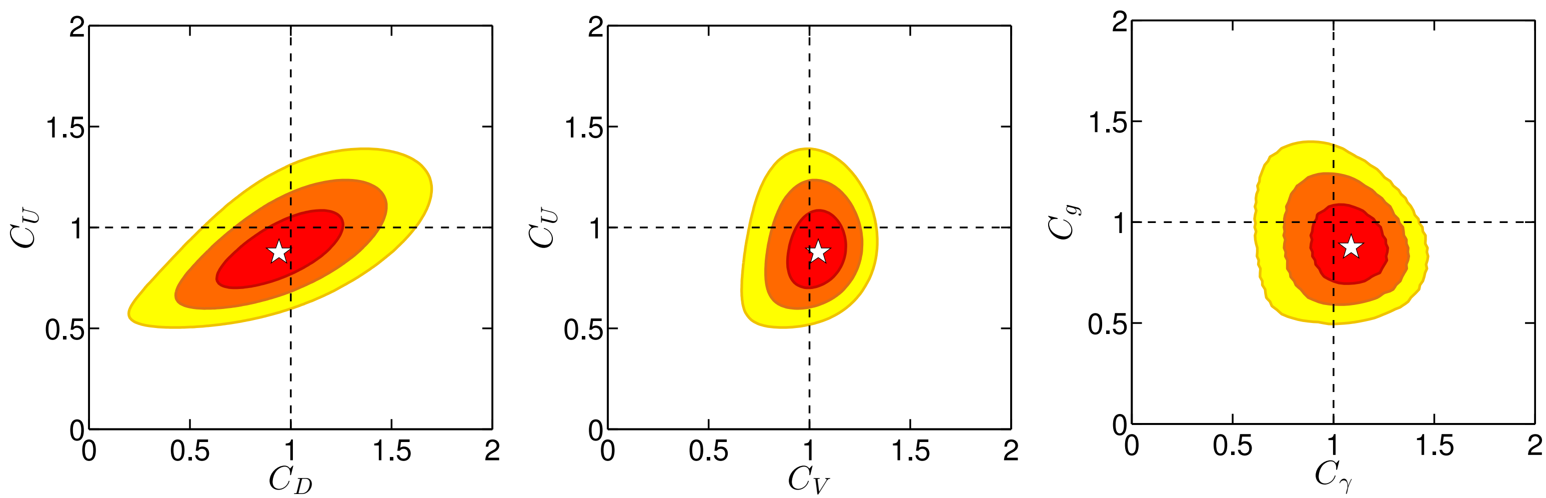


Figure 3: Coupling constant ellipses. The filled red, orange and yellow ellipses show the 68%, 95% and 99.7% CL regions, respectively,. The white stars mark the best-fit points.

Certainly, the SM is doing quite well. Fitting to relative couplings 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.

At the moment, however, there is still significant room for the Higgs to deviate from SM expectations.

But, *is it* the SM Higgs?

- For example, there are lots of NMSSM scenarios for which it need not be. Possibilities include:
  - A $98~\mathrm{GeV}$ Higgs, the h_1, consistent with the 20%$\times$SM LEP excess, plus a $125~\mathrm{GeV}$ h_2, consistent with LHC results. (Belanger, Ellwanger, Jiang, Gunion, Kraml, Schwarz, JHEP 1301 (2013) 069)
  - A $125~\mathrm{GeV}$ h_1 and a $\sim 135~\mathrm{GeV}$ h_2 that could describe excesses in the later region in the CMS $\gamma\gamma$ mode and the Tevatron WH with $H \to b\bar{b}$ excess. (Belanger, Ellwanger, Gunion, Jiang, Kraml, arXiv:1208.4952)
  - Degenerate Higgs bosons, $m_{h_1} \sim m_{h_2} \sim 125~\mathrm{GeV}$ with signals in the various final states being shared by the two Higgs bosons. (Gunion, Jiang, Kraml, Phys.Rev. D86 (2012) 071702)

    While this latter case was of particular interest when deviations from the SM results for $\gamma\gamma$ (especially) were present, it is also possible to have degenerate signals that combine to give a very SM-like result.

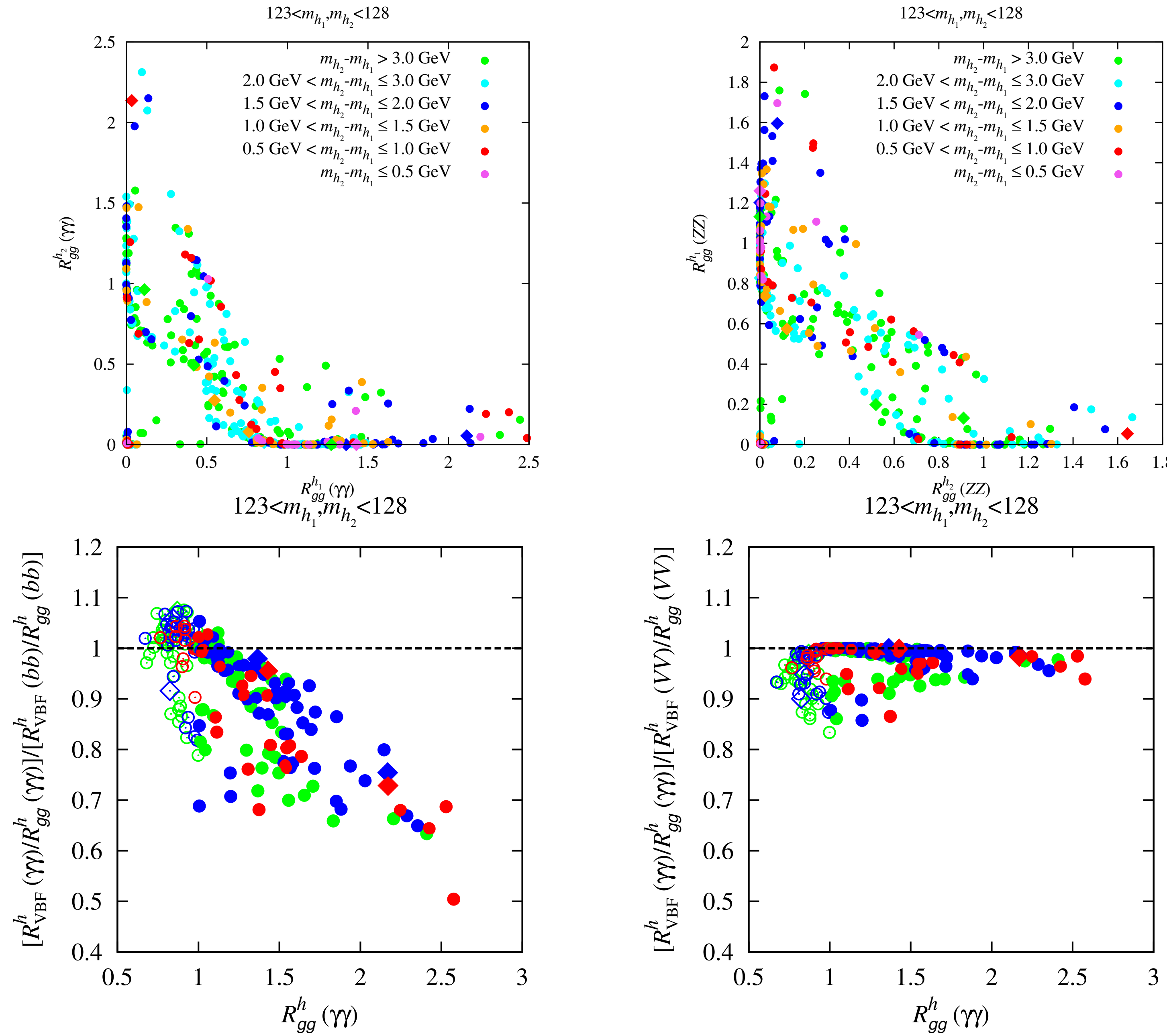


Figure 4: Top: Individual h_1 and h_2 contributions for $m_{h_1} \sim m_{h_2}$. Bottom: Ratios of double ratios, which must $= 1$ for a single Higgs, but generally $\neq 1$ for 2 or more degenerate Higgs, as functions of $R^h_{gg}(\gamma\gamma)$ (from Gunion, Jiang, Kraml, Phys.Rev.Lett. 110 (2013) 051801).

- **The 2HDM Again — all constraints, including Higgs fits, imposed at 95% CL (Dumont, Gunion, Jiang, Kraml, in preparation)**

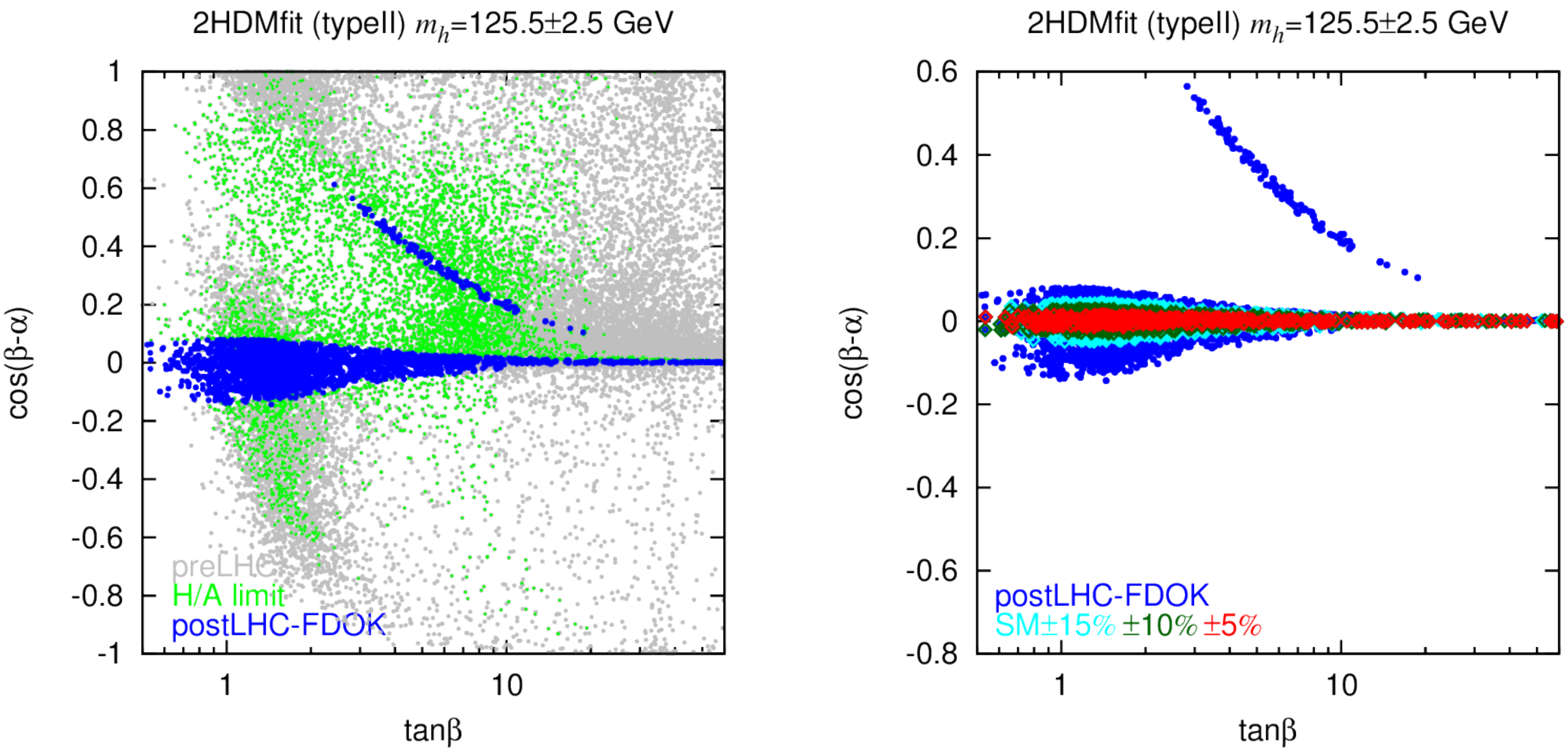


Figure 5: **Left: Constraints on the 2HDM models of Type II in the $\cos(\beta-\alpha)$ versus $\tan\beta$ plane for $m_h \sim 125.5$ GeV. Grey points obey preLHC constraints. Green points obey as well limits on H/A signals. Blue points obey, in addition, all LHC Higgs measurements at 95% CL. Right: Changes associated with future higher precisions for *all* $X \to Y$ channels are shown. Note: extra non-decoupling branch for current precisions is eliminated once all $X \to Y$ channels are within 15% of SM.**

The SM limit is $\cos(\beta - \alpha) \to 0$ for $m_h \sim 125$ GeV. For Type II there is a main branch that is very SM-like, but also an alternative branch that is quite different. The future LHC run can eliminate or confirm this branch.

As shown below, $m_H = 125.5$ GeV is also possible given current precisions, but will be eliminated if all signals are within $\pm 15\%$ of SM.

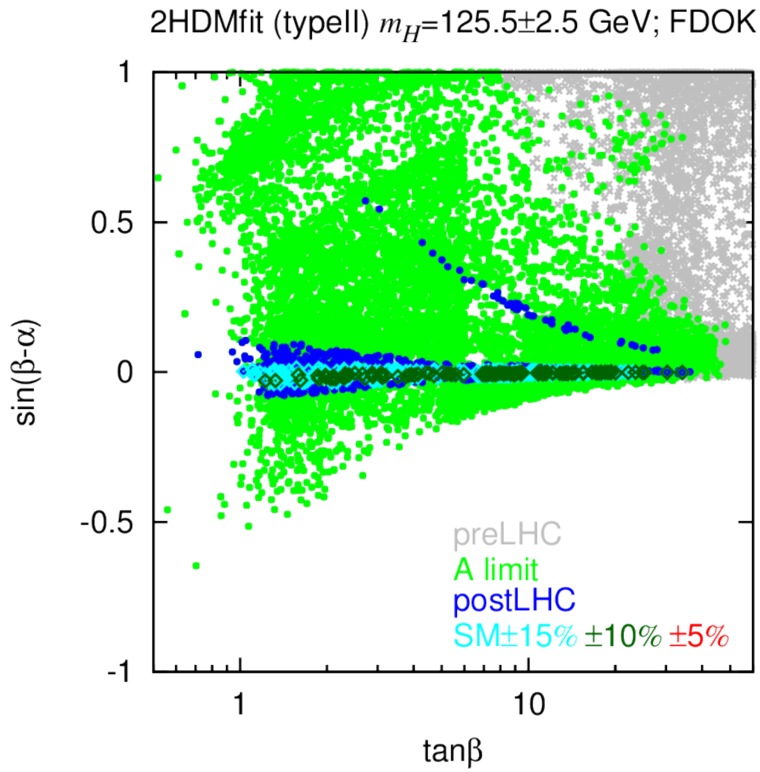


Figure 6: Constraints on the 2HDM models of Type II in the $\sin(\beta - \alpha)$ versus $\tan\beta$ plane for $m_H \sim 125.5$ GeV. Notation as in Fig. 5.

Assuming that it is a Type II h that is being observed, what will the future hold? The main questions are:

1. **Can we expect deviations of the triple Higgs coupling relative to the SM, C_{hhh}?**

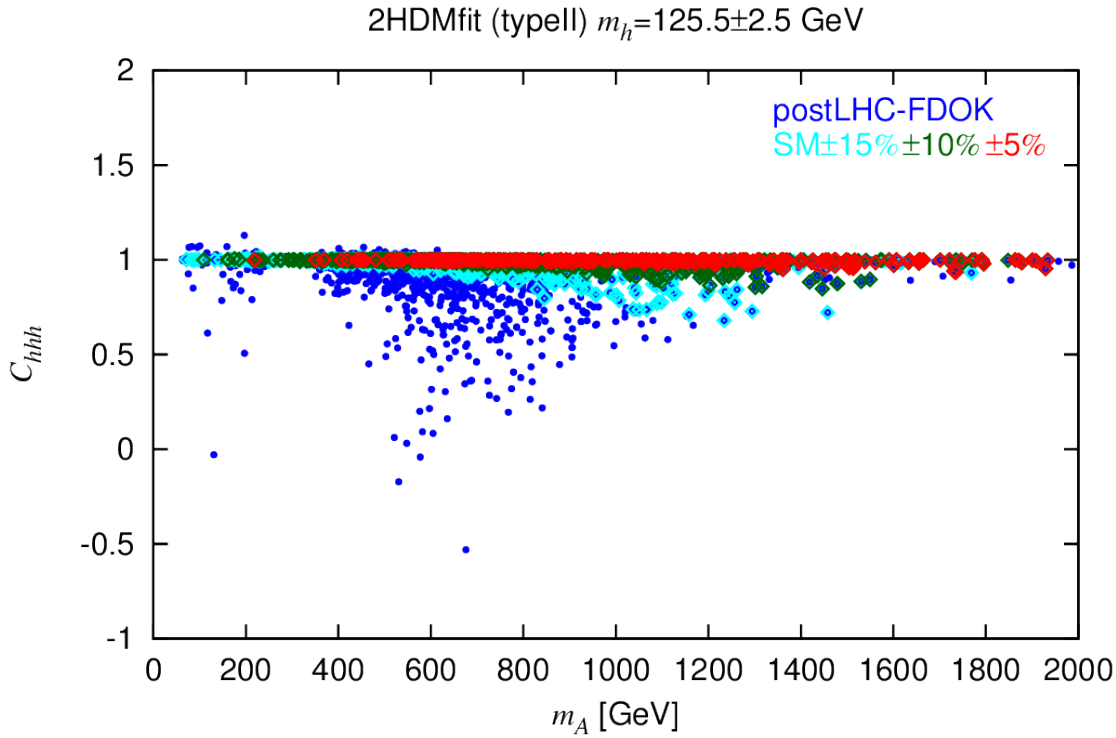


Figure 7: **We display points in the C_{hhh} vs. m_A plane for the $m_h \sim 125.5~\mathrm{GeV}$ scenario comparing current h fits to the case where future measurements show that all channel rates are within $\pm 15\%, \pm 10\%, \pm 5\%$ of the SM Higgs prediction; FDOK is required in all cases.**

2. **What are the prospects for seeing one or more of the heavier Higgs bosons?**

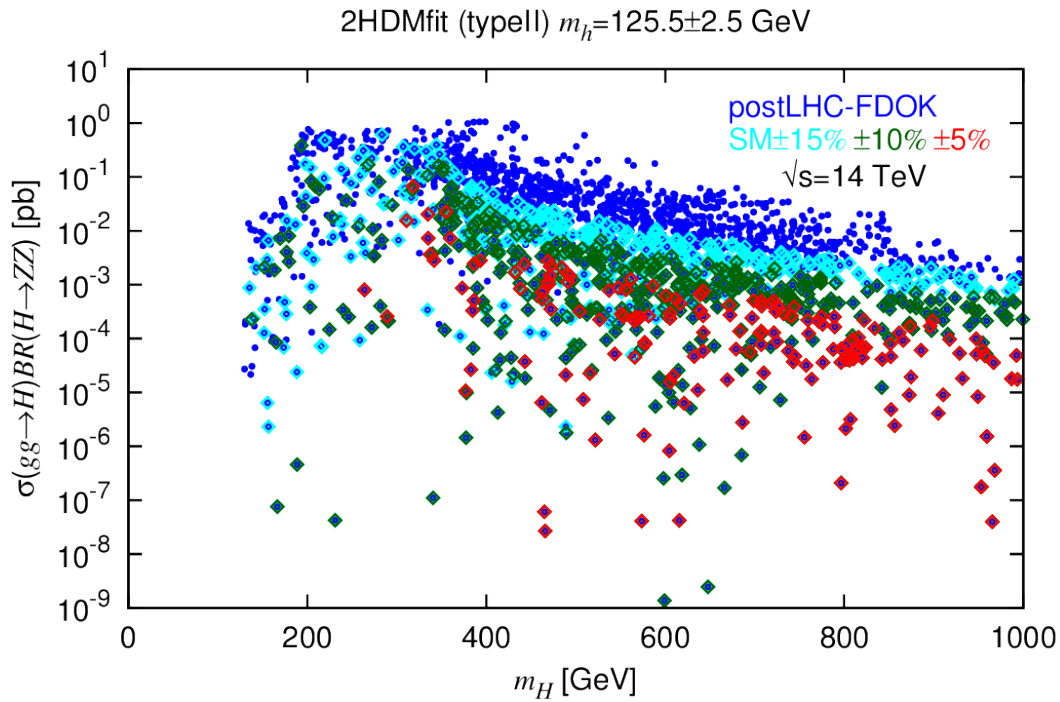


Figure 8: We plot $\sigma(gg \to H)\mathcal{B}(H \to ZZ)$ as a function of m_H, for Type II 2HDM models. As above, only FDOK points are shown. Implications of various levels of precision for future h measurements are displayed.

Since the h has 'eaten' up most of the ZZ coupling, the $H \to ZZ$ branching ratio is never large, but Γ_H does remain relatively small and so a distinct peak will be present. The narrow width of the H will be good for all final decays sof the H, most notably the $\gamma\gamma$ final state.

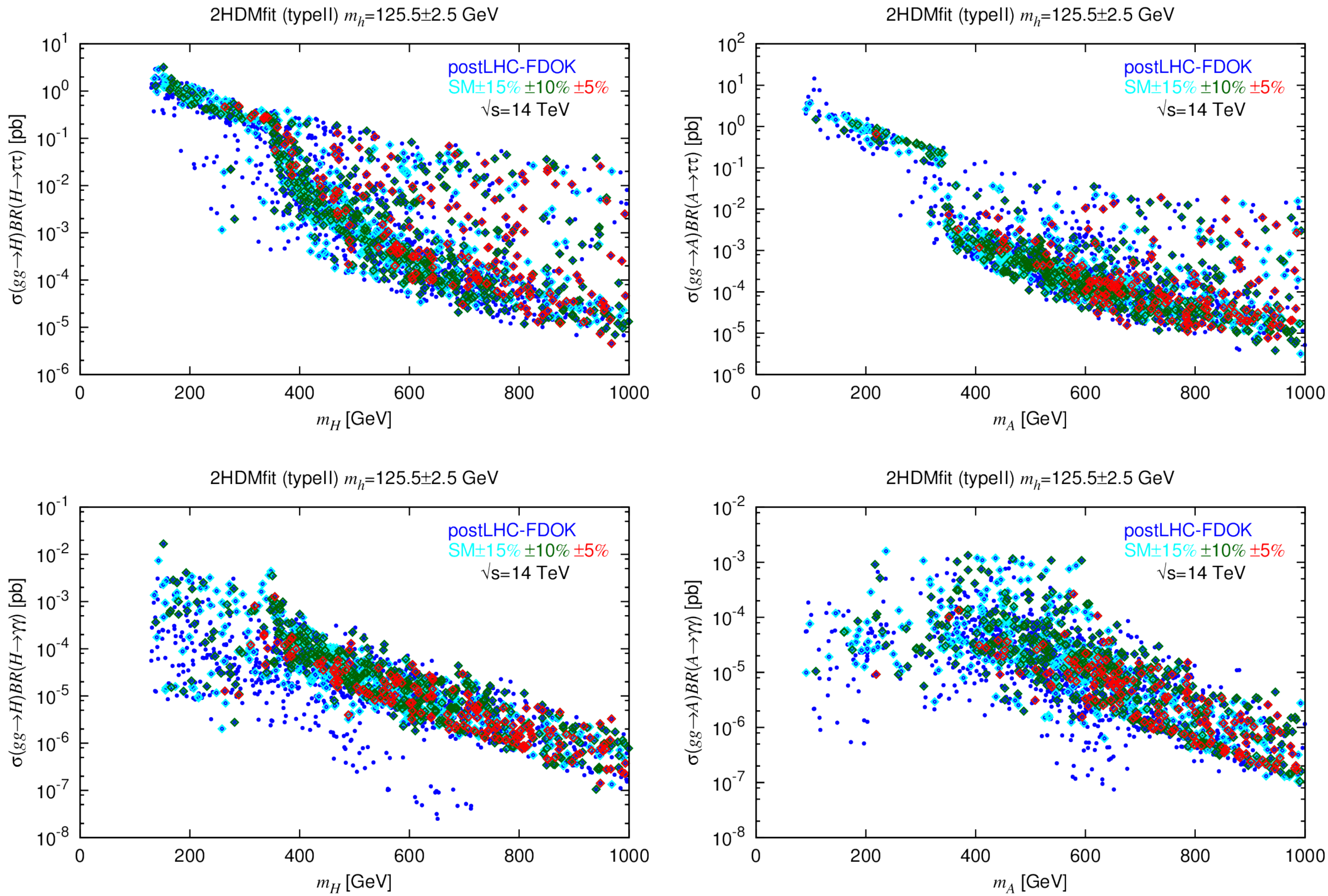


Figure 9: We plot $\sigma(gg \to H)\mathcal{B}(H \to \tau\tau)$ and $\sigma(gg \to A)\mathcal{B}(A \to \tau\tau)$ (upper) and $\gamma\gamma$ (lower) as functions of m_H and m_A, respectively, for Type II 2HDM models. Implications of various levels of precision for future h measurements are displayed.

- **The pMSSM (Dumont, Gunion, Kraml, Sekmen)**

The phenomenological MSSM (pMSSM) makes no assumptions about GUT scale unification — all parameters (16) are set at the electroweak scale. One can ask if the current precision of Higgs measurements has any impact on the SUSY particles (once all other constraints from B physics and so forth are applied). A sample result after a huge scan is shown below.

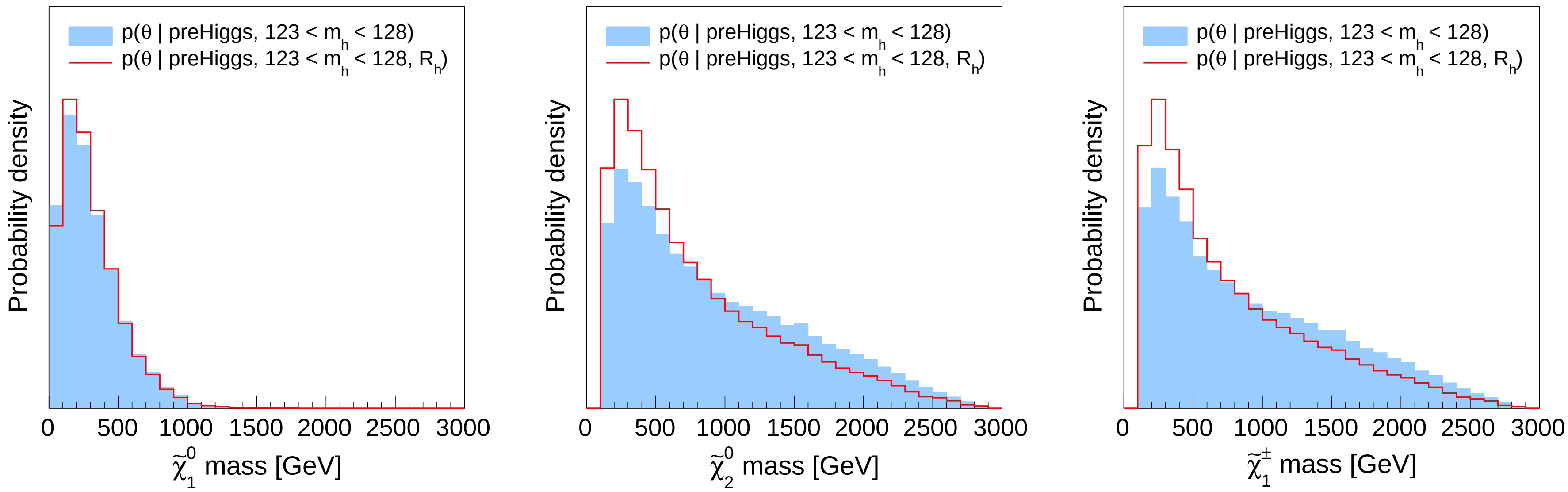


Figure 10: Marginalized 1D posterior densities for various pMSSM model parameters. The light blue histograms show the distributions based on the "preHiggs" measurements of Table ?? plus requiring in addition $m_h \in [123, 128]$ GeV. The red lines are the distributions when taking into account the measured Higgs signal strengths in the various channels.

Effects of the Higgs observations on the sparticle masses are shown in Fig. 10. A summary is the following:

– there is substantially increased probability for smaller $m_{\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^\pm}$;

– there is a small shift towards smaller $m_{\tilde{g}}$;

– $m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}$ are all shifted to higher values, as needed to get the predicted mass of the h into the $[123, 130]\ \mathrm{GeV}$ range.

- Finally, there is the very crucial issue of unseen (but not truly invisible) Higgs decays, a primary example being the NMSSM $h_1 \to a_1 a_1$ channel —- it is not dead! How can that be?

  There is a well-known flat direction in the Higgs fitting game. Let us postulate an unseen (U) mode (such as aa) with branching ratio $\mathcal{B}_U$. Then, if the LHC signal rates are well fit by certain choices of C_U, C_D, C_V (say with $\Delta C_\gamma = \Delta C_g = 0$) for $\mathcal{B}_U = 0$ then an equally good fit for any value of $\mathcal{B}_U$ is obtained by the rescaling

$$C_i^2 \to \frac{C_i^2}{1 - \mathcal{B}_U} \tag{3}$$

  Notes:

1. If U is an invisible final state, $\mathcal{B}_U$ is already significantly constrained by

ZH with $H \to$ invisible limits so that there are limits to this game in that case.

But, if $U = aa$ or $6g$ or .... then reliable constraints are not yet available.

2. Precision electroweak constraints depend on $C_V^2 \ln(m_H)$ and $C_U^2 m_t^2$ and so will limit this game as well.

Still, first estimates suggest that $\mathcal{B}_U$ as large as 50%, corresponding to a rescaling of C^2 upwards by as much as a factor of 2 will survive as a possibility.

This gives a greatly increased rate for actually observing a difficult channel such as $H \to aa$ given that $\mathcal{B}_U \sim \frac{1}{2}$ and production rates are increased by a factor of 2.

Conclusions

- **It seems likely that the Higgs responsible for EWSB has emerged.**
- **At the moment, there is no sign of other Higgs-like signals except $\sim 1\sigma$ hints at $\sim 135~\mathrm{GeV}$ and 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 current 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 is 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 errors on the nature of the $125\ \mathrm{GeV}$ state since even small deviations could be a first sign of such additional states.

Following G. Ross's question of Whither SUSY? (he insists we should not consider the Wither SUSY option) we can ask Whither Higgs? — fortunately, we need not worry about Wither Higgs.

While the waiting for a 1st Higgs signal is over, watching for more Higgs or some sign of BSM is not: