Constraints on the alignment limit of the MSSM Higgs sector

Howard E. Haber
LBL Theory Seminar
January 28, 2015

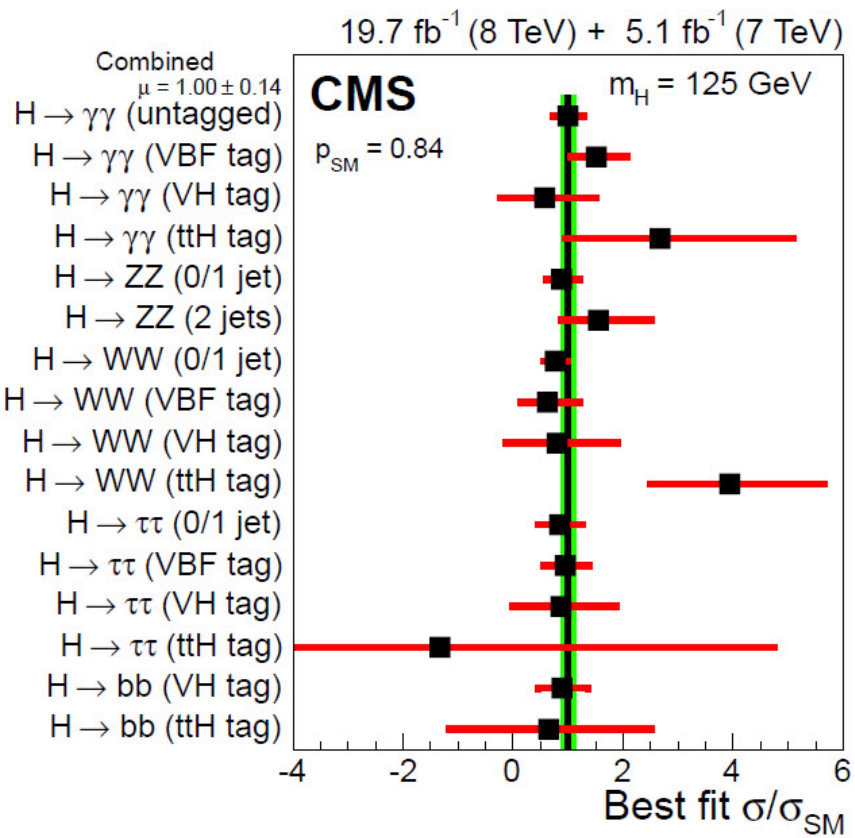
This talk is based on M. Carena, H.E. Haber, I. Low, N.R. Shah and C.E.M. Wagner, arXiv:1410.4969 [hep-ph], Phys. Rev. **D91** (2015), in press.

The Higgs boson discovered on the 4th of July 2012

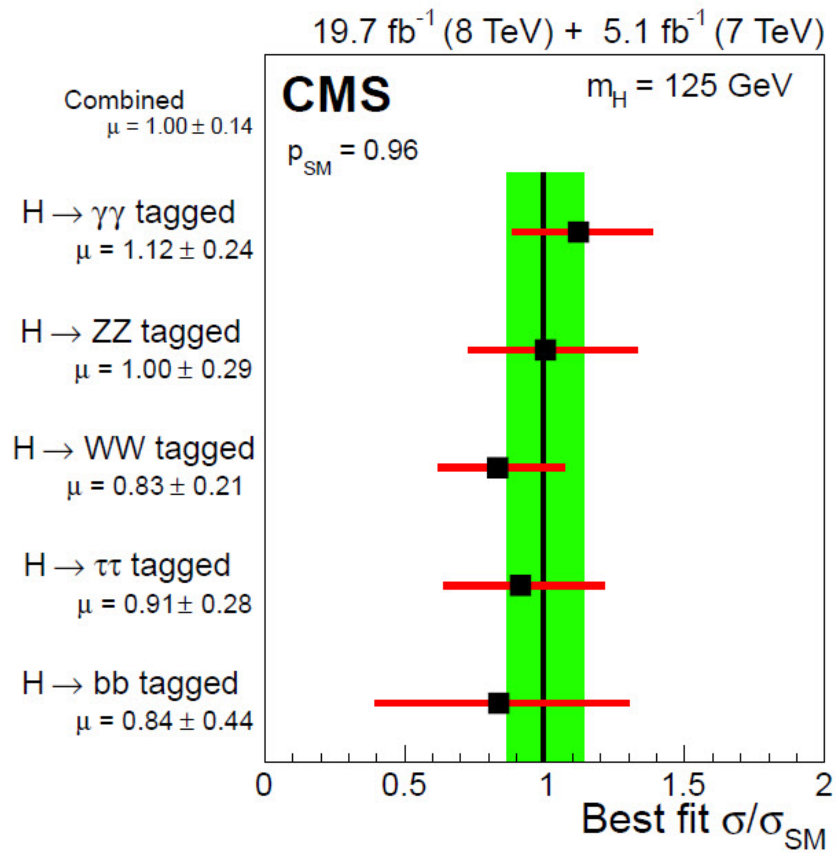
- Is it the Higgs boson of the Standard Model (SM)?
- Is it the first scalar state of an enlarged Higgs sector?
- Is it a scalar state of the minimal supersymmetric extension of the SM [MSSM]?

Let's look at a snapshop of the current LHC Higgs data.

Evidence for a Standard Model (SM)—like Higgs boson



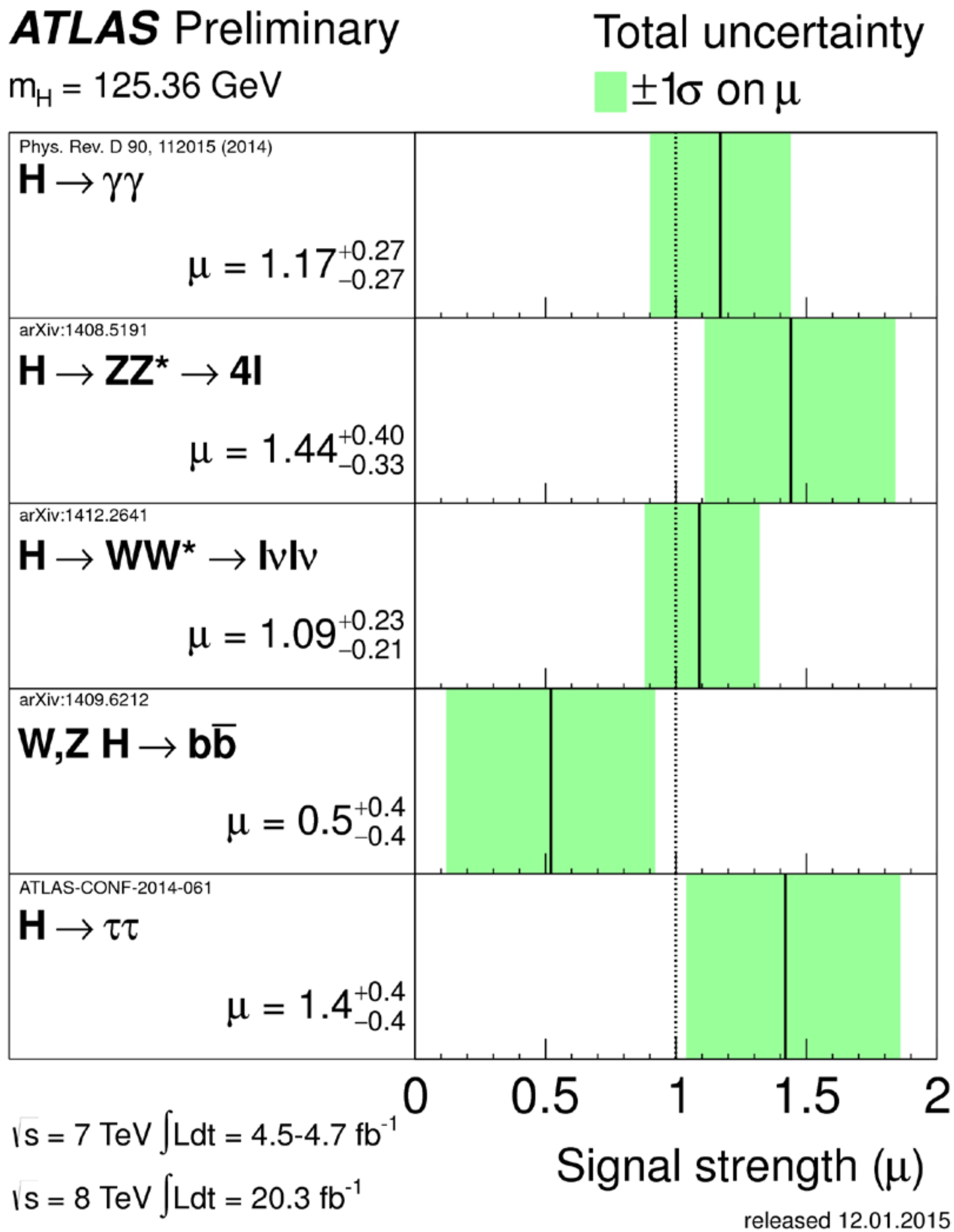
Values of the best-fit σ/σ_{SM} for the combination (solid vertical line) and for subcombinations by predominant decay mode and additional tags targeting a particular production mechanism. The vertical band shows the overall σ/σ_{SM} uncertainty. The σ/σ_{SM} ratio denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The horizontal bars indicate the ±1 standard deviation uncertainties in the best-fit σ/σ_{SM} values for the individual modes; they include both statistical and systematic uncertainties. Taken from arXiv:1412.8662 (December, 2014).



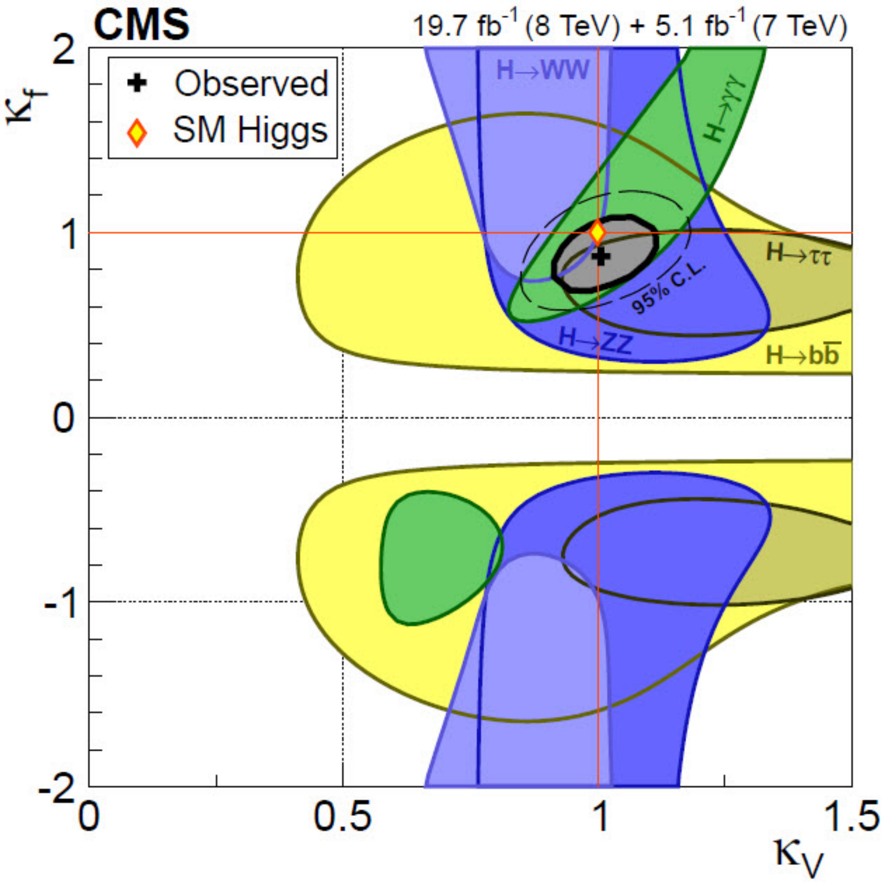
Values of the best-fit σ/σ_{SM} for the combination (solid vertical line) and for subcombinations by predominant decay mode. The vertical band shows the overall σ/σ_{SM} uncertainty. The σ/σ_{SM} ratio denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The horizontal bars indicate the ±1 standard deviation uncertainties in the best-fit σ/σ_{SM} values for the individual modes; they include both statistical and systematic uncertainties. Taken from arXiv:1412.8662 (December, 2014).

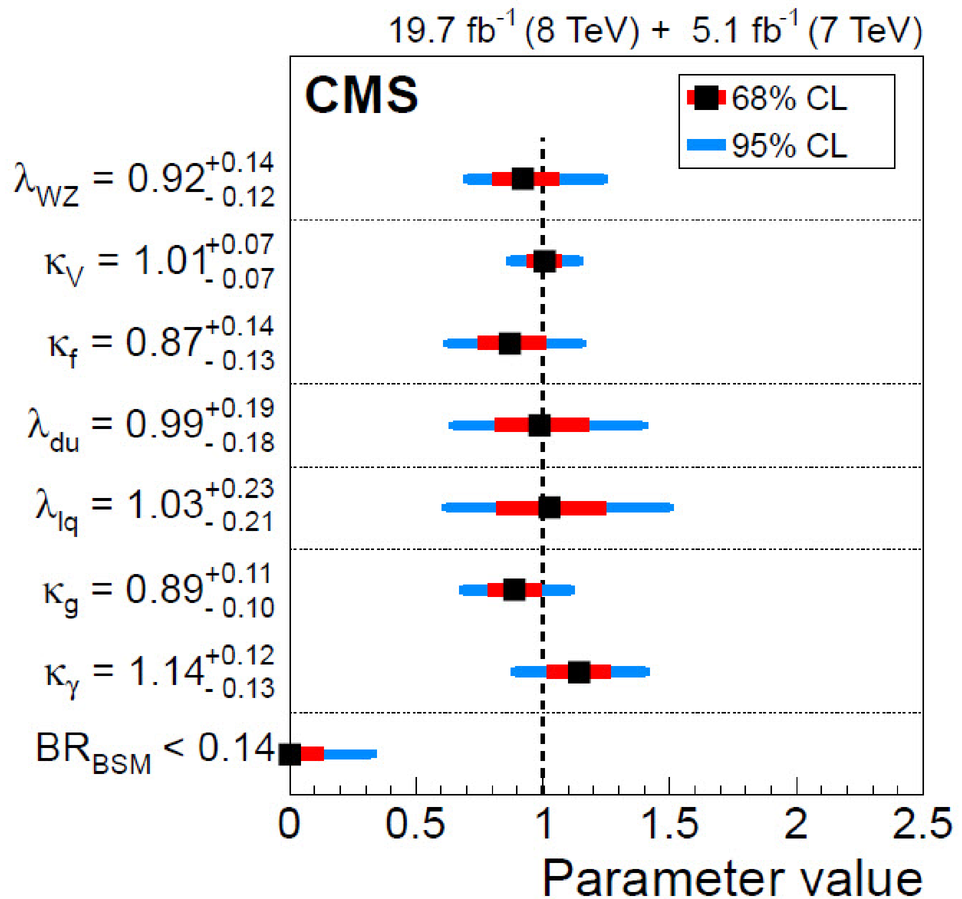
ATLAS evidence for a SM-like Higgs boson

The measured production strengths for a Higgs boson of mass m_H =125.36 GeV, normalized to the SM expectations, for the f=$H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$, $H \rightarrow WW^* \rightarrow l\nu l\nu$, $H \rightarrow \tau\tau$, and $H \rightarrow bb$ final states. The best-fit values are shown by the solid vertical lines. The total ±1σ uncertainty is indicated by the shaded band. Updated December 2014.



CMS search for deviations from SM-Higgs couplings





2D test statistics $q(\kappa_V, \kappa_F)$ scan for individual channels (colored swaths) and for the overall combination (thick curve). The cross indicates the global best-fit values. The dashed contour bounds the 95% CL region for the combination. The yellow diamond shows the SM point $(\kappa_V, \kappa_f) = (1, 1)$. Two quadrants corresponding to $(\kappa_V, \kappa_f) =$ (+,+) and (+,−) are physically distinct. Taken from arXiv:1412.8662 (December, 2014).

Summary plot of likelihood scan results for the different parameters of interest in benchmark models separated by dotted lines. The BR_{BSM} value at the bottom is obtained for the model with three parameters (κ_g, κ_γ, BR_{BSM}). The inner bars represent the 68% CL confidence intervals while the outer bars represent the 95% CL confidence intervals. Taken from arXiv:1412.8662 (December, 2014).

Any theory that introduces new physics beyond the Standard Model (BSM) must contain a SM-like Higgs boson. This constrains all future model building.

- If new BSM physics is present at the TeV scale, what is the nature of the dynamics that generates a SM-like Higgs boson?

- In this talk, I shall focus on the Higgs sector of the MSSM.

Outline

- The CP-conserving 2HDM—a brief review
  - The alignment limit with and without decoupling
- The MSSM Higgs Sector at tree-level
- The radiatively-corrected Higgs sector
  - The exact alignment limit via an accidental cancellation
- MSSM Higgs sector benchmark scenarios
- Is alignment without decoupling in the MSSM viable?
  - Recent results from the CMS search for $H\,,\,A \to \tau^+\tau^-$
  - Implications of the CMS limits for various MSSM Higgs scenarios
  - Constraining the m_A—$\tan\beta$ plane from the observed Higgs data
  - Complementarity of the H and A searches and the precision $h(125)$ data
- Conclusions

The CP-conserving 2HDM—a brief review

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) + \tfrac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \tfrac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2$$
$$+\lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \left[\tfrac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2 \right)^2 + \left[\lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2 \right] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right],$$

such that $\langle \Phi_i^0 \rangle = v_i/\sqrt{2}$ (for $i = 1, 2$), and $v^2 \equiv v_1^2 + v_2^2 = (246\ \text{GeV})^2$. For simplicity, we have assumed a CP-conserving Higgs potential where v_1, v_2, m_{12}^2, λ_5, λ_6 and λ_7 are real. We parameterize the scalar fields as

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \phi_i^0 + i a_i^0) \end{pmatrix}, \qquad \tan\beta \equiv \frac{v_2}{v_1}.$$

The two neutral CP-even Higgs mass eigenstates are then defined via

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \qquad (m_h < m_H),$$

where $c_\alpha \equiv \cos\alpha$ and $s_\alpha \equiv \sin\alpha$, and the mixing angle α is defined mod π.

The 2HDM with no tree-level Higgs-mediated FCNCs

By imposing a suitably chosen $\mathbb{Z}_2$ symmetry (which may be softly-broken) on the Higgs Lagrangian, one finds that the resulting 2HDM naturally has no tree-level Higgs-mediated flavor-changing neutral currents (FCNCs). If we set $\lambda_6 = \lambda_7 = 0$, then all dimension-four terms of the scalar potential are invariant under the discrete $\mathbb{Z}_2$ symmetry $\Phi_1 \to \Phi_1\,,\, \Phi_2 \to -\Phi_2$ (this symmetry is softly-broken by the term in the scalar potential proportional to m_{12}^2).

This discrete symmetry can be extended to the Higgs-fermion Yukawa interactions in a number of different ways.

	Φ_1	Φ_2	U_R	D_R	E_R	U_L, D_L, N_L, E_L
Type I	$+$	$-$	$-$	$-$	$-$	$+$
Type II (MSSM like)	$+$	$-$	$-$	$+$	$+$	$+$
Type X (lepton specific)	$+$	$-$	$-$	$-$	$+$	$+$
Type Y (flipped)	$+$	$-$	$-$	$+$	$-$	$+$

Four possible $\mathbb{Z}_2$ charge assignments that forbid tree-level Higgs-mediated FCNC effects.

The Higgs–fermion interactions

When re-expressed in terms of the quark and lepton mass-eigenstate fields, $U=(u,c,t)$, $D=(d,s,b)$, $N=(\nu_e,\nu_\mu,\nu_\tau)$, and $E=(e,\mu,\tau)$,

$$-\mathcal{L}_{\rm Y}=\overline{U}_L\Phi_i^{0\,*}h_i^U U_R-\overline{D}_L K^\dagger\Phi_i^- h_i^U U_R+\overline{U}_L K\Phi_i^+ h_i^{D\,\dagger}D_R+\overline{D}_L\Phi_i^0 h_i^{D\,\dagger}D_R$$
$$+\overline{N}_L\Phi_i^+ h_i^{E\,\dagger}E_R+\overline{E}_L\Phi_i^0 h_i^{E\,\dagger}E_R+{\rm h.c.}\,,\qquad \text{(summed over } i=1,2\text{)}$$

where K is the CKM quark mixing matrix, $h^{U,D,L}$ are 3×3 Yukawa coupling matrices. Applying the $\mathbb{Z}_2$ symmetry leads to four distinct model types:

1. Type-I Yukawa couplings: $h_1^U=h_1^D=h_1^L=0$,

2. Type-II Yukawa couplings: $h_1^U=h_2^D=h_2^L=0$,

3. Type-X Yukawa couplings: $h_1^U=h_1^D=h_2^L=0$,

4. Type-Y Yukawa couplings: $h_1^U=h_2^D=h_1^L=0$.

Implications of SM-like Higgs couplings to VV

Since the Higgs couplings to gauge bosons are more accurately measured, we first focus on these. The tree-level coupling of h to VV (where $VV = W^+W^-$ or ZZ), normalized to the corresponding SM coupling, is given by

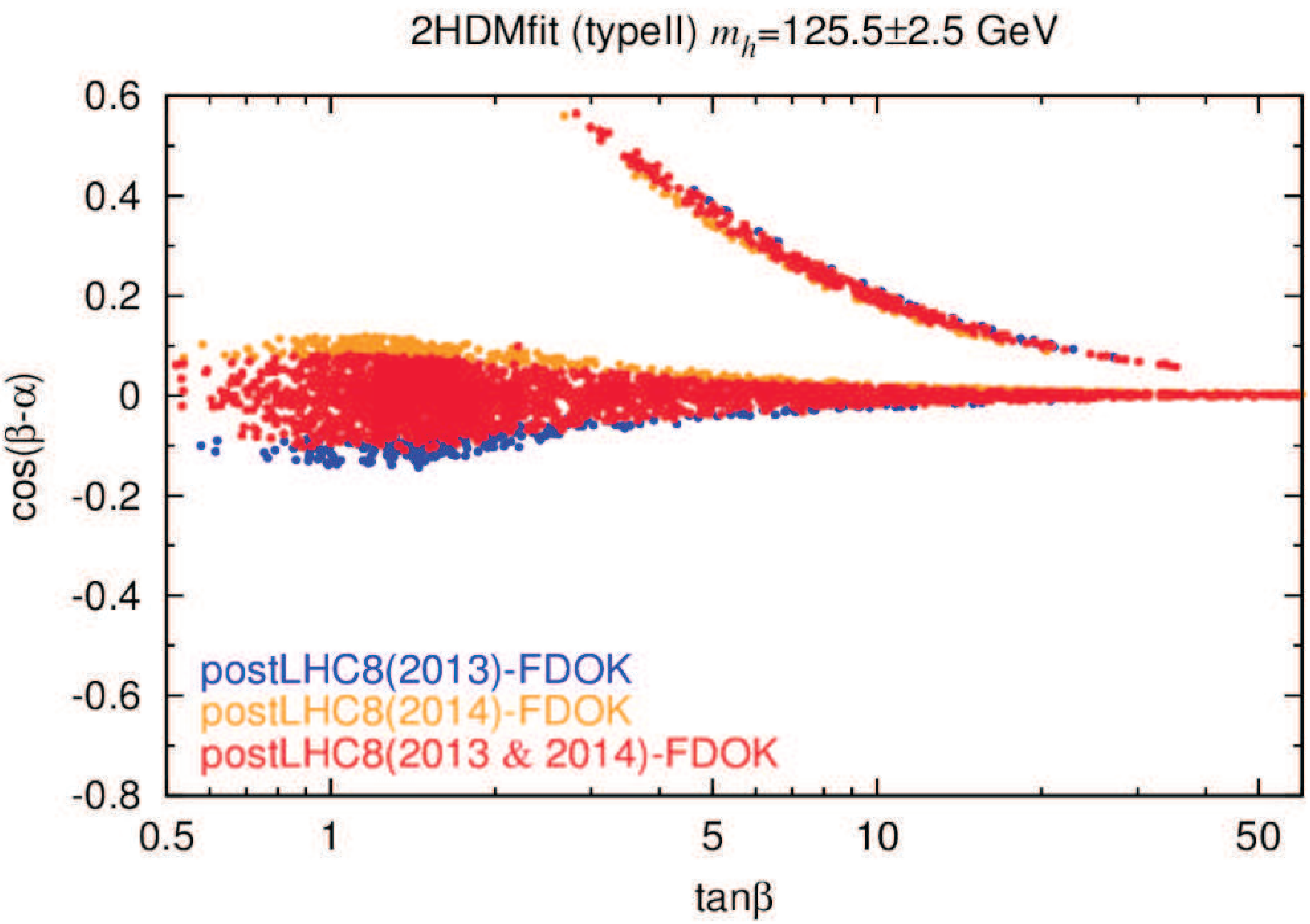
$$g_{hVV} = g_{hVV}^{\rm SM}\, s_{\beta-\alpha}\,.$$

Thus, if the hVV coupling is SM-like, it follows that

$$|c_{\beta-\alpha}| \ll 1\,,$$

where $c_{\beta-\alpha} \equiv \cos(\beta-\alpha)$ and $s_{\beta-\alpha} \equiv \sin(\beta-\alpha)$.

REMARK: If H is the SM-like Higgs, then we use $g_{HVV} = g_{hVV}^{\rm SM}\, c_{\beta-\alpha}$ to conclude that $|s_{\beta-\alpha}| \ll 1$. However, this region of parameter space is highly constrained, and is probably not viable within the MSSM.



Constraints in the $c_{\beta-\alpha}$ vs. $\tan\beta$ plane for $m_h \sim 125.5$ GeV. Blue points are those that passed all constraints given the Higgs signal strengths as of Spring 2013, red points are those that remain valid when employing the Summer 2014 updates, and orange points are those newly allowed after Summer 2014 updates. It is assumed that h produced through the decay of heavier Higgs states via "feed down" (FD) does not distort the observed Higgs data. Taken from B. Dumont, J.F. Gunion, Y. Jiang and S. Kraml, arXiv:1409.4088.

Under what conditions is $|c_{\beta-\alpha}| \ll 1$?

It is convenient to define the so-called *Higgs basis* of scalar doublet fields,

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \frac{v_1\Phi_1 + v_2\Phi_2}{v}\,, \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv \frac{-v_2\Phi_1 + v_1\Phi_2}{v}\,,$$

so that $\langle H_1^0\rangle = v/\sqrt{2}$ and $\langle H_2^0\rangle = 0$. The scalar doublet H_1 has SM tree-level couplings to all the SM particles. If one of the CP-even neutral Higgs mass eigenstates is SM-like, then it must be approximately aligned with the real part of the neutral field H_1^0. This is the *alignment limit*. In terms of the Higgs basis fields, the scalar potential contains:

$$\mathcal{V} \ni \ldots + \tfrac{1}{2}Z_1(H_1^\dagger H_1)^2 + \ldots + \left[\tfrac{1}{2}Z_5(H_1^\dagger H_2)^2 + Z_6(H_1^\dagger H_1)H_1^\dagger H_2 + \text{h.c.}\right] + \ldots\,,$$

$$Z_1 \equiv \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + \tfrac{1}{2}(\lambda_3+\lambda_4+\lambda_5)s_{2\beta}^2 + 2s_{2\beta}\left[c_\beta^2\lambda_6 + s_\beta^2\lambda_7\right]\,,$$

$$Z_5 \equiv \tfrac{1}{4}s_{2\beta}^2\left[\lambda_1+\lambda_2-2(\lambda_3+\lambda_4+\lambda_5)\right] + \lambda_5 - s_{2\beta}c_{2\beta}(\lambda_6-\lambda_7)\,,$$

$$Z_6 \equiv -\tfrac{1}{2}s_{2\beta}\left[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - (\lambda_3+\lambda_4+\lambda_5)c_{2\beta}\right] + c_\beta c_{3\beta}\lambda_6 + s_\beta s_{3\beta}\lambda_7\,.$$

In the Higgs basis, the CP-even neutral Higgs squared-mass matrix is

$$\mathcal{M}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix} ,$$

where m_A is the mass of the CP-odd neutral Higgs boson A, and $\alpha - \beta$ is the corresponding mixing angle.

It follows that $m_h^2 \leq Z_1 v^2$, whereas the off-diagonal element, $Z_6 v^2$, governs the H_1^0—H_2^0 mixing. If $Z_6 = 0$ and $Z_1 < Z_5 + m_A^2/v^2$, then $c_{\beta-\alpha} = 0$ and $m_h^2 = Z_1 v^2$. In this case $h = \sqrt{2} H_1^0 - v$ is identical to the SM Higgs boson. This is the exact alignment limit of the 2HDM.

Approximate alignment can occur if either $|Z_6| \ll 1$ and/or $m_A^2 \gg Z_i v^2$. In either case, $m_h^2 \simeq Z_1 v^2$ and $|c_{\beta-\alpha}| \ll 1$, i.e., h is SM-like. The case of $m_A^2 \gg Z_i v^2$ is the well-known decoupling limit of the 2HDM.

Thus, if h is SM-like then it follows that $|c_{\beta-\alpha}| \ll 1$, which implies that the 2HDM is close to the alignment limit.*

Explicit formulae:

$$\cos^2(\beta-\alpha) = \frac{Z_6^2 v^4}{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}\,,$$

$$Z_1 v^2 - m_h^2 = \frac{Z_6^2 v^4}{m_H^2 - Z_1 v^2}\,.$$

In both the decoupling limit ($m_H \gg m_h$) and the alignment limit without decoupling [$|Z_6| \ll 1$ and $m_H^2 - Z_1 v^2 \sim \mathcal{O}(v^2)$], we see that $c_{\beta-\alpha} \to 0$ and $m_h^2 \to Z_1 v^2$.

REMARK: Note the upper bound on the mass of h,

$$m_h^2 \leq Z_1 v^2\,.$$

---

*If $Z_1 > Z_5 + m_A^2/v^2$ then $Z_6 = 0$ implies that $s_{\beta-\alpha} = 0$ in which case $m_H^2 = Z_1 v^2$ and we identify $H = \sqrt{2}H_1^0 - v$ as the SM-like Higgs boson. This is the alignment limit without decoupling, but this case is much harder to achieve in light of the Higgs data.

The MSSM Higgs Sector at tree-level

The dimension-four terms of the MSSM Higgs Lagrangian are constrained by supersymmetry. At tree level,

$$\lambda_1 = \lambda_2 = -(\lambda_3 + \lambda_4) = \tfrac{1}{4}(g^2 + g'^{\,2}) = m_Z^2/v^2\,,$$
$$\lambda_4 = -\tfrac{1}{2}g^2 = -2m_W^2/v^2\,, \qquad \lambda_5 = \lambda_6 = \lambda_7 = 0\,.$$

This yields

$$Z_1 v^2 = m_Z^2 c_{2\beta}^2\,, \qquad Z_5 v^2 = m_Z^2 s_{2\beta}^2\,, \qquad Z_6 v^2 = -m_Z^2 s_{2\beta} c_{2\beta}\,.$$

It follows that,

$$\cos^2(\beta - \alpha) = \frac{m_Z^4\, s_{2\beta}^2 c_{2\beta}^2}{(m_H^2 - m_h^2)(m_H^2 - m_Z^2 c_{2\beta}^2)}\,.$$

The decoupling limit is achieved when $m_H \gg m_h$ as expected.

The exact alignment limit ($Z_6 = 0$) is achieved only when $\beta = 0$, $\frac{1}{4}\pi$ or $\frac{1}{2}\pi$. None of these choices are realistic. Of course, the tree-level MSSM Higgs sector also predicts $(m_h^2)_{\rm max} = Z_1 v^2 = m_Z^2 c_{2\beta}^2$ in conflict with the Higgs data. Radiative corrections can be sufficiently large to yield the observed Higgs mass, and can also modify the behavior of the alignment limit.

We complete our review of the tree-level MSSM Higgs sector by displaying the Higgs couplings to quarks and squarks. The MSSM employs the Type–II Higgs–fermion Yukawa couplings. Employing the more common MSSM notation,

$$H_D^i \equiv \epsilon_{ij} \Phi_1^{j\,*}\,, \qquad\qquad H_U^i = \Phi_2^i\,,$$

the tree-level Yukawa couplings are:

$$-\mathscr{L}_{\rm Yuk} = \epsilon_{ij} \big[h_b \bar{b}_R H_D^i Q_L^j + h_t \bar{t}_R Q_L^i H_U^j \big] + {\rm h.c.}\,,$$

which yields

$$m_b = h_b v c_\beta / \sqrt{2}\,, \qquad\qquad m_t = h_t v s_\beta / \sqrt{2}\,.$$

The leading terms in the coupling of the Higgs bosons to third generation squarks are proportional to the Higgs–top quark Yukawa coupling, h_t,

$$\mathscr{L}_{\rm int} \ni h_t\big[\mu^*(H_D^\dagger\widetilde Q)\widetilde U + A_t\epsilon_{ij}H_U^i\widetilde Q^j\widetilde U + {\rm h.c.}\big] - h_t^2\big[H_U^\dagger H_U(\widetilde Q^\dagger\widetilde Q + \widetilde U^*\widetilde U) - |\widetilde Q^\dagger H_U|^2\big]\,,$$

with an implicit sum over the weak SU(2) indices $i, j = 1, 2$, where $\widetilde Q = \begin{pmatrix}\widetilde t_L\\ \widetilde b_L\end{pmatrix}$ and $\widetilde U \equiv \widetilde t_R^*$. In terms of the Higgs basis fields H_1 and H_2,

$$\begin{aligned}\mathscr{L}_{\rm int} \ni h_t\epsilon_{ij}\big[&(s_\beta X_t H_1^i + c_\beta Y_t H_2^i)\widetilde Q^j\widetilde U + {\rm h.c.}\big]\\ &-h_t^2\Bigg\{\Big[s_\beta^2|H_1|^2 + c_\beta^2|H_2|^2 + s_\beta c_\beta(H_1^\dagger H_2 + {\rm h.c.})\Big](\widetilde Q^\dagger\widetilde Q + \widetilde U^*\widetilde U)\\ &\qquad -s_\beta^2|\widetilde Q^\dagger H_1|^2 - c_\beta^2|\widetilde Q^\dagger H_2|^2 - s_\beta c_\beta\big[(\widetilde Q^\dagger H_1)(H_2^\dagger\widetilde Q) + {\rm h.c.}\big]\Bigg\}\,,\end{aligned}$$

where

$$X_t \equiv A_t - \mu^*\cot\beta\,, \qquad\qquad Y_t \equiv A_t + \mu^*\tan\beta\,.$$

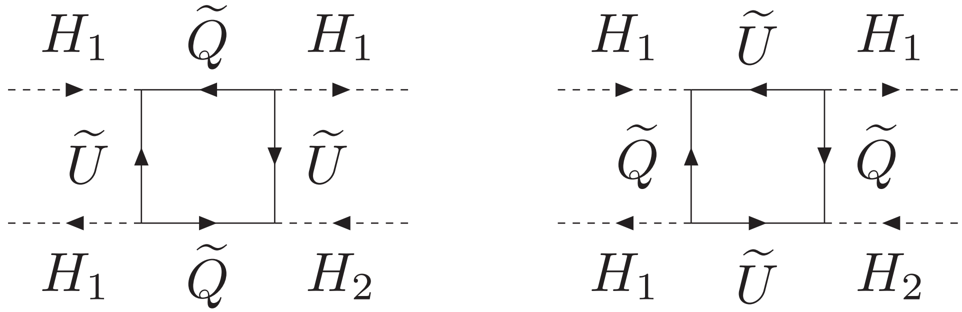
Assuming CP-conservation for simplicity, we shall henceforth take μ, A_t real.

The radiatively corrected MSSM Higgs Sector

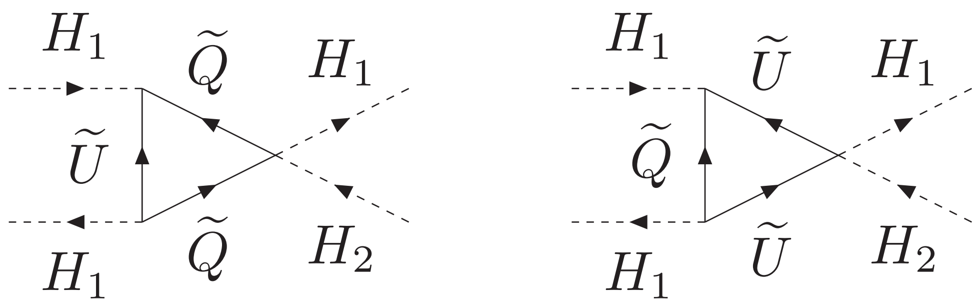
We are most interested in the limit where $m_h,\ m_A \ll m_Q$, where m_Q characterizes the scale of the squark masses. In this case, we can formally integrate out the squarks and generate a low-energy effective 2HDM Lagrangian. This Lagrangian will no longer be of the tree-level MSSM form but rather a completely general 2HDM Lagrangian. If we neglect CP-violating phases that could appear in the MSSM parameters such as μ and A_t, then the resulting 2HDM Lagrangian contains all possible CP-conserving terms of dimension-four or less.

At one-loop, leading log corrections are generated for $\lambda_1, \ldots \lambda_4$. In addition, threshold corrections proportional to A_t, A_b and μ can contribute significant corrections to all the scalar potential parameters $\lambda_1 \ldots, \lambda_7$.[†]

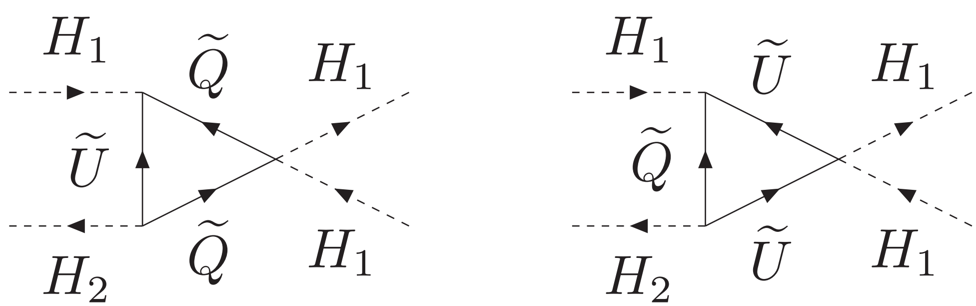
[†]Explicit formulae can be found in H.E. Haber and R. Hempfling, "The Renormalization group improved Higgs sector of the minimal supersymmetric model," Phys. Rev. **D48**, 4280 (1993).



$\propto s_\beta^3 c_\beta X_t^3 Y_t$



$\propto s_\beta^3 c_\beta X_t^2$



$\propto s_\beta^3 c_\beta X_t Y_t$

Threshold Corrections to Z_6

The leading corrections to Z_1, Z_5 and Z_6 are:

$$Z_1 v^2 = m_Z^2 c_{2\beta}^2 + \frac{3v^2 s_\beta^4 h_t^4}{8\pi^2}\left[\ln\left(\frac{m_Q^2}{m_t^2}\right) + \frac{X_t^2}{m_Q^2}\left(1 - \frac{X_t^2}{12 m_Q^2}\right)\right],$$

$$Z_5 v^2 = s_{2\beta}^2\left\{m_Z^2 + \frac{3v^2 h_t^4}{32\pi^2}\left[\ln\left(\frac{m_Q^2}{m_t^2}\right) + \frac{X_t Y_t}{m_Q^2}\left(1 - \frac{X_t Y_t}{12 m_Q^2}\right)\right]\right\},$$

$$Z_6 v^2 = -s_{2\beta}\left\{m_Z^2 c_{2\beta} - \frac{3v^2 s_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{m_Q^2}{m_t^2}\right) + \frac{X_t(X_t + Y_t)}{2m_Q^2} - \frac{X_t^3 Y_t}{12 m_Q^4}\right]\right\}.$$

The upper bound on the Higgs mass, $m_h^2 \leq Z_1 v^2$ can now be consistent with the observed $m_h \simeq 125$ GeV for suitable choices for m_Q and X_t. The exact alignment condition, $Z_6 = 0$, can now be achieved due to an accidental cancellation between tree-level and loop contributions,

$$m_Z^2 c_{2\beta} = \frac{3v^2 s_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{m_Q^2}{m_t^2}\right) + \frac{X_t(X_t + Y_t)}{2m_Q^2} - \frac{X_t^3 Y_t}{12 m_Q^4}\right].$$

A solution to this equation can be found at moderate to large values of $t_\beta \equiv \tan\beta = s_\beta/c_\beta$. By convention, we take $0 < \beta < \frac{1}{2}\pi$ so that $\tan\beta$ is always positive. Performing a Taylor expansion in t_β^{-1}, we find an (approximate) solution at

$$\tan\beta = \frac{m_Z^2 + \dfrac{3v^2h_t^4}{16\pi^2}\left[\ln\left(\dfrac{m_Q^2}{m_t^2}\right) + \dfrac{2A_t^2-\mu^2}{2m_Q^2} - \dfrac{A_t^2(A_t^2-3\mu^2)}{12m_Q^4}\right]}{\dfrac{3v^2h_t^4\mu A_t}{32\pi^2 m_Q^2}\left(\dfrac{A_t^2}{6m_Q^2}-1\right)}.$$

Since the above numerator is typically positive, it follows that a viable solution exists if $\mu A_t(A_t^2 - 6m_Q^2) > 0$. Note that in the approximations employed here, the so-called maximal mixing condition that saturates the upper bound for the radiatively-corrected m_h corresponds to $A_t = \sqrt{6}m_Q$. Thus, we expect to satisfy $t_\beta \gg 1$ for values of A_t slightly above [below] the maximal mixing condition if $\mu A_t > 0$ [$\mu A_t < 0$].

For completeness, we note that after integrating out the squarks, the resulting Yukawa couplings are no longer of Type-II,

$$-\mathscr{L}_{\rm Yuk} = \epsilon_{ij}\left[(h_b+\delta h_b)\overline{b}_R H_D^i Q_L^j+(h_t+\delta h_t)\overline{t}_R Q_L^i H_U^j\right]+\Delta h_b\overline{b}_R Q_L^i H_U^{i\,*}+\Delta h_t\overline{t}_R Q_L^i H_D^{i\,*}+{\rm h.c.}\,,$$

where $\delta h_{t,b}$ and $\Delta h_{t,b}$ are one-loop corrections from squark/gaugino loops. So,

$$m_b = \frac{h_b v}{\sqrt{2}}\cos\beta\left(1+\frac{\delta h_b}{h_b}+\frac{\Delta h_b \tan\beta}{h_b}\right) \equiv \frac{h_b v}{\sqrt{2}}\cos\beta(1+\Delta_b)\,,$$

$$m_t = \frac{h_t v}{\sqrt{2}}\sin\beta\left(1+\frac{\delta h_t}{h_t}+\frac{\Delta h_t \cot\beta}{h_t}\right) \equiv \frac{h_t v}{\sqrt{2}}\sin\beta(1+\Delta_t)\,,$$

which define the quantities Δ_b and Δ_t. E.g., the resulting $hb\bar{b}$ coupling is

$$g_{hb\bar{b}} = \frac{m_b}{v}\left(s_{\beta-\alpha}-c_{\beta-\alpha}t_\beta\right)\left[1+\frac{1}{1+\Delta_b}\left(\frac{\delta h_b}{h_b}-\Delta_b\right)\left(\frac{c_{\beta-\alpha}}{s_\beta s_\alpha}\right)\right]\,,$$

For $c_{\beta-\alpha}=0$, we recover the SM value, $g_{h\bar{b}b}=m_b/v$. However at large $\tan\beta$, Δ_b is $\tan\beta$-enhanced and the approach to the alignment limit is "delayed" since we approach the SM result only for $c_{\beta-\alpha}t_\beta \ll 1$.

Is alignment without decoupling in the MSSM viable?

Analysis strategy:

- Make use of model-independent CMS search for H, $A \to \tau^+\tau^-$ in the regime $m_A > 200$ GeV.[‡] Both gg fusion and $b\bar{b}$ fusion production mechanisms are considered. CMS also considers specific MSSM Higgs scenarios. Recent ATLAS results are similar to those of CMS (although CMS limits are presently the most constraining).

- Analyze various benchmark MSSM Higgs scenarios and deduce limits on $\tan\beta$ as a function of m_A.

- Compare resulting limits to the constraints imposed by the properties of the observed Higgs boson with $m_h \simeq 125$ GeV.

[‡]V. Khachatryan [CMS Collaboration], JHEP **10** (2014) 160 [arXiv:1408.3316].

All MSSM Higgs masses, production cross sections and branching ratios were obtained using the FeynHiggs 2.10.2 package, with the corresponding references for the cross sections given there. For further details, see `http://wwwth.mpp.mpg.de/members/heinemey/feynhiggs/cFeynHiggs.html`

FHHiggsProd contains code by:

- SM XS for VBF, WH, ZH, ttH taken from the LHC Higgs Cross Section WG, `https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections`
- SM bbH XS: Harlander et al. hep-ph/0304035
- SM ggH XS: `http://theory.fi.infn.it/grazzini/hcalculators.html` (Grazzini et al.)
- 2HDM charged Higgs XS: Plehn et al.
- heavy charged Higgs XS: Dittmaier et al., arXiv:0906.2648; Flechl et al., arXiv:1307.1347

All the parameters we quote are in the on-shell scheme and we use the two loop formulae improved by log resummation.

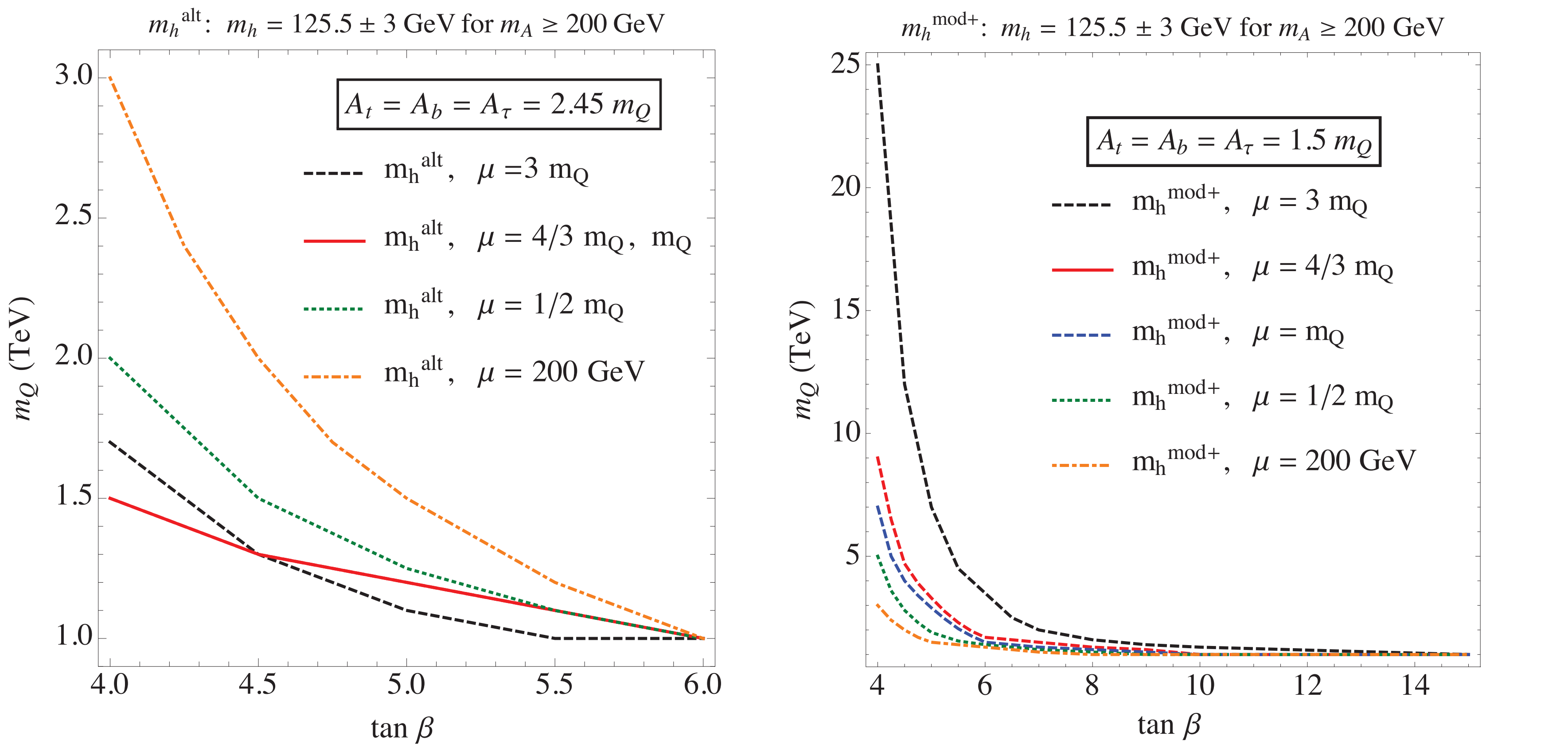
MSSM Higgs scenarios[‡]

	$m_h^{\mathrm{mod+}}$	m_h^{alt}
A_t/m_Q	1.5	2.45
$M_2 = 2\ M_1$	200 GeV	200 GeV
M_3	1.5 TeV	1.5 TeV
$m_{\tilde{\ell}} = m_{\tilde{q}}$	m_Q	m_Q
$A_\ell = A_q$	A_t	A_t
μ	free	free

The m_h^{alt} scenario (for large μ) has been chosen to exhibit a region of the MSSM parameter space where the exact alignment limit is approximately realized.

For $m_Q = 1$ TeV, $m_h = 125.5 \pm 3$ GeV for $\tan\beta > 6$ and $m_A > 200$ GeV. Here, we regard the ± 3 GeV as the theoretical error in the determination of m_h. Thus, for $\tan\beta < 6$, we increase m_Q such that m_h falls in the desired mass range for all $m_A > 200$ GeV.

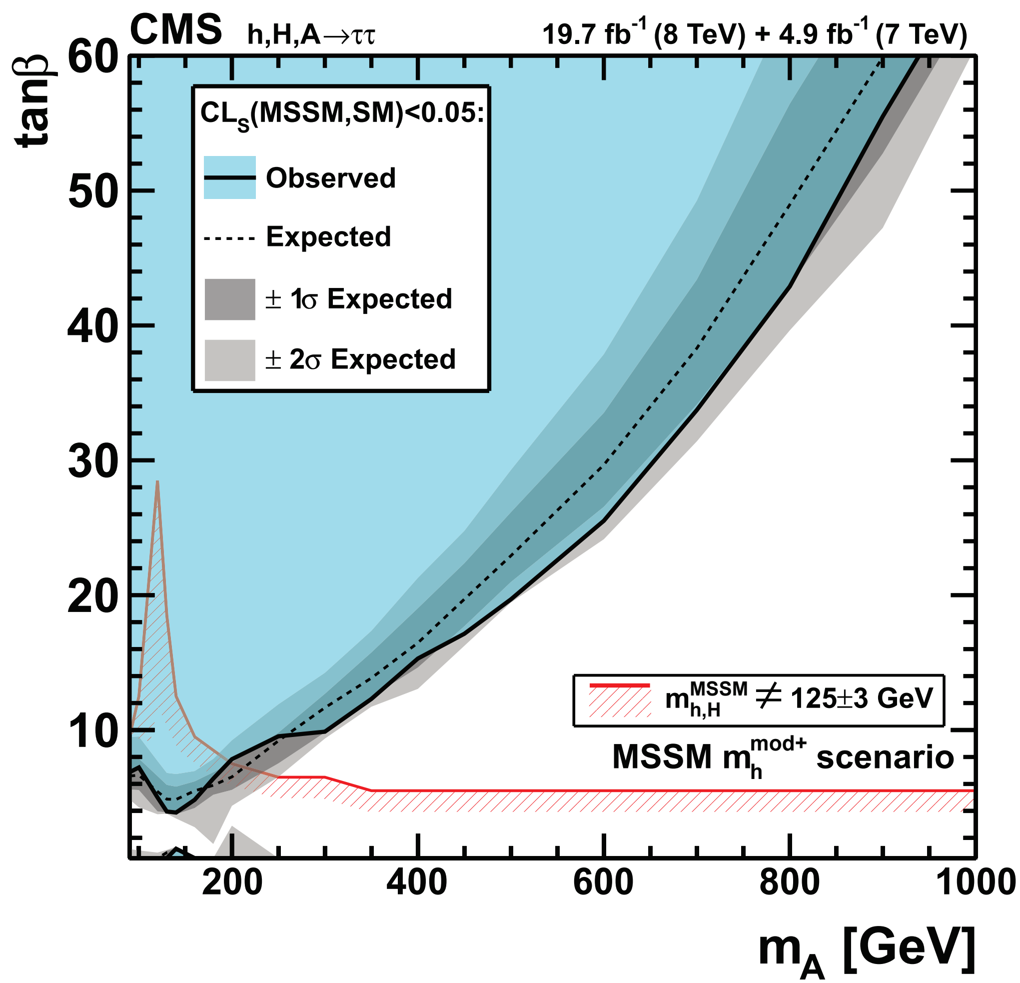
[‡]Additional benchmark scenarios can be found in M. Carena, S. Heinemeyer, O. Stål, C.E.M. Wagner and G. Weiglein, "MSSM Higgs Boson Searches at the LHC: Benchmark Scenarios after the Discovery of a Higgs-like Particle," Eur. Phys. J. **C73**, 2552 (2013).



Values of m_Q necessary to accommodate the proper value of the lightest CP-even Higgs mass, for different values of μ in the $m_h^{\rm alt}$ and $m_h^{\rm mod+}$ scenarios.

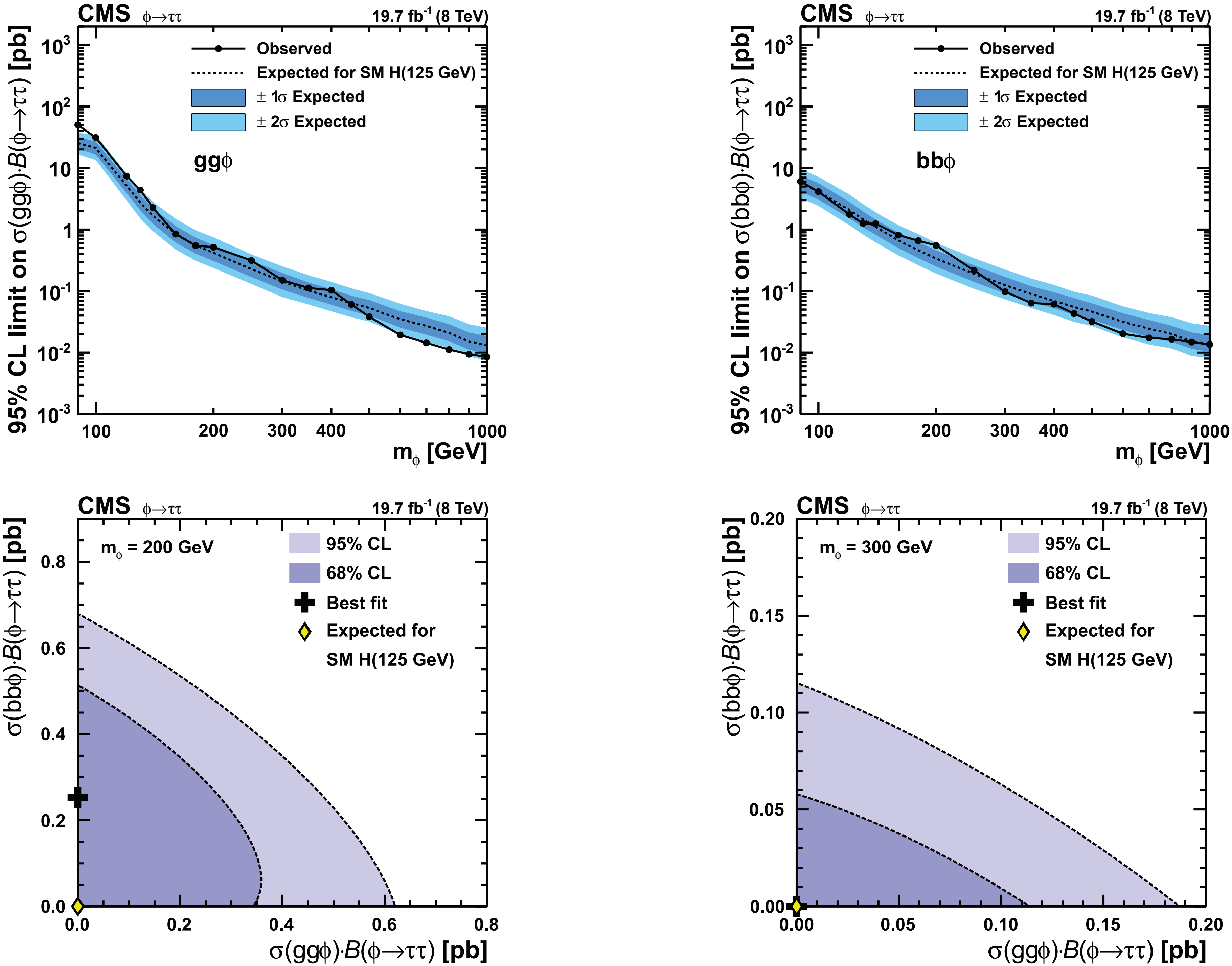
CMS search for $H,\ A \to \tau^+\tau^-$

1. Model-dependent analysis. Limits obtained in the MSSM $m_h^{\rm mod+}$ scenario.



2. Model-independent analysis

Search for a single scalar resonance produced in gg and $b\bar{b}$ fusion.



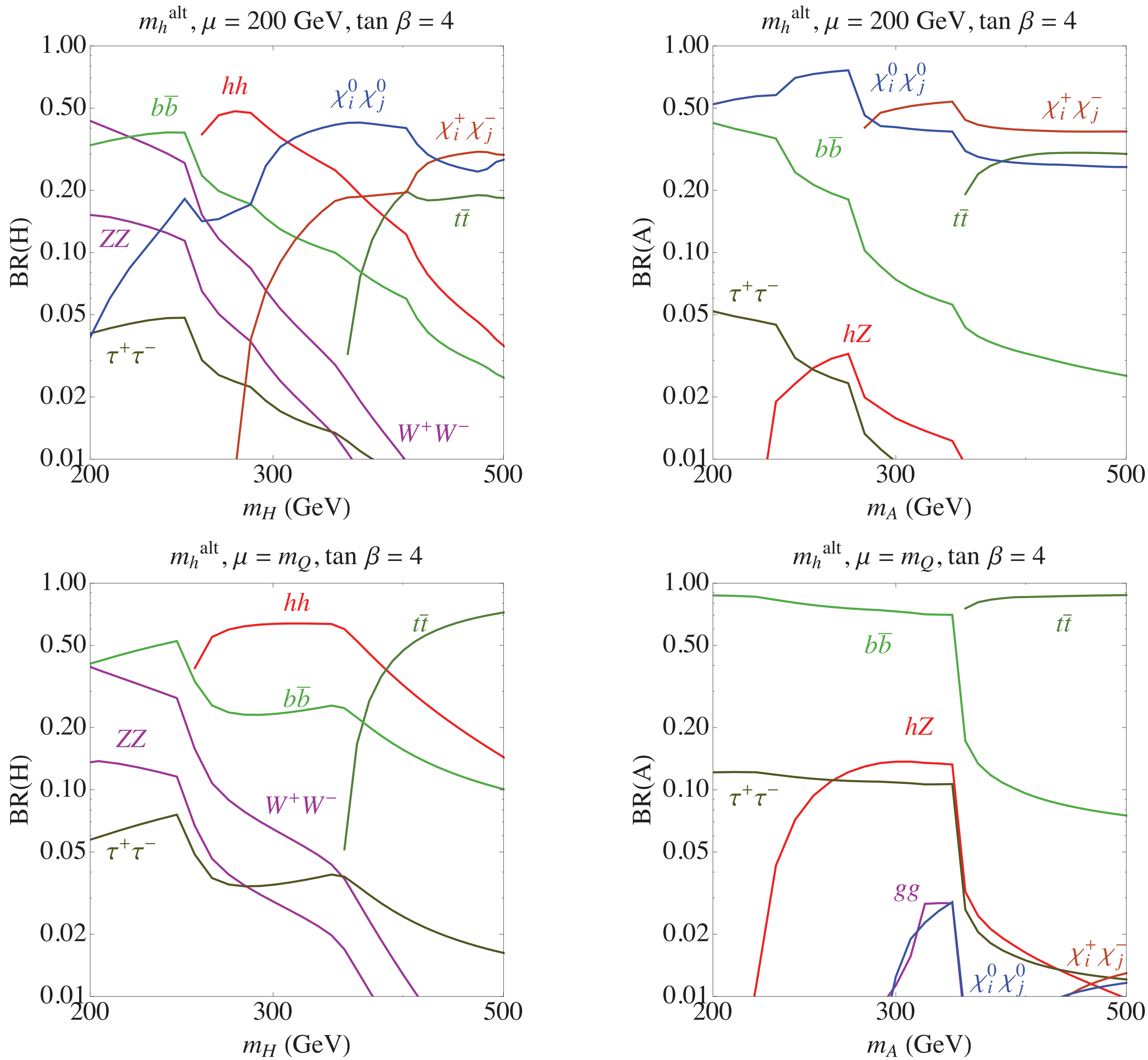
CMS φ→ττ
19.7 fb-1 (8 TeV)
Observed
Expected for SM H(125 GeV)
± 1σ Expected
± 2σ Expected
ggφ
bbφ
95% CL limit on σ(ggφ)·B(φ→ττ) [pb]
95% CL limit on σ(bbφ)·B(φ→ττ) [pb]
mφ [GeV]
mφ = 200 GeV
mφ = 300 GeV
95% CL
68% CL
Best fit
Expected for
SM H(125 GeV)
σ(bbφ)·B(φ→ττ) [pb]
σ(ggφ)·B(φ→ττ) [pb]

A note on the H and A branching ratios

CMS fixes $\mu = 200$ GeV in defining the $m_h^{\rm mod+}$ scenario. This is relevant for determining their limits, since there is a significant branching ratio of H and A into neutralino and chargino pairs, which therefore reduces the branching ratio of these scalars into $\tau^+\tau^-$.

In the mass region of $200\ \mathrm{GeV} \leq m_A\,, m_H \leq 2m_t$, the typical value of BR$(H\,, A \to \tau^+\tau^-) \sim \mathcal{O}(10\%)$ can be reduced by an order of magnitude if neutralino and/or chargino pair final states are kinematically allowed and $\tan\beta$ is moderate. For larger values of μ, the higgsino components of the lightest neutralino and chargino states become negligible and the corresponding branching ratios of H and A to the light electroweakinos become unimportant.

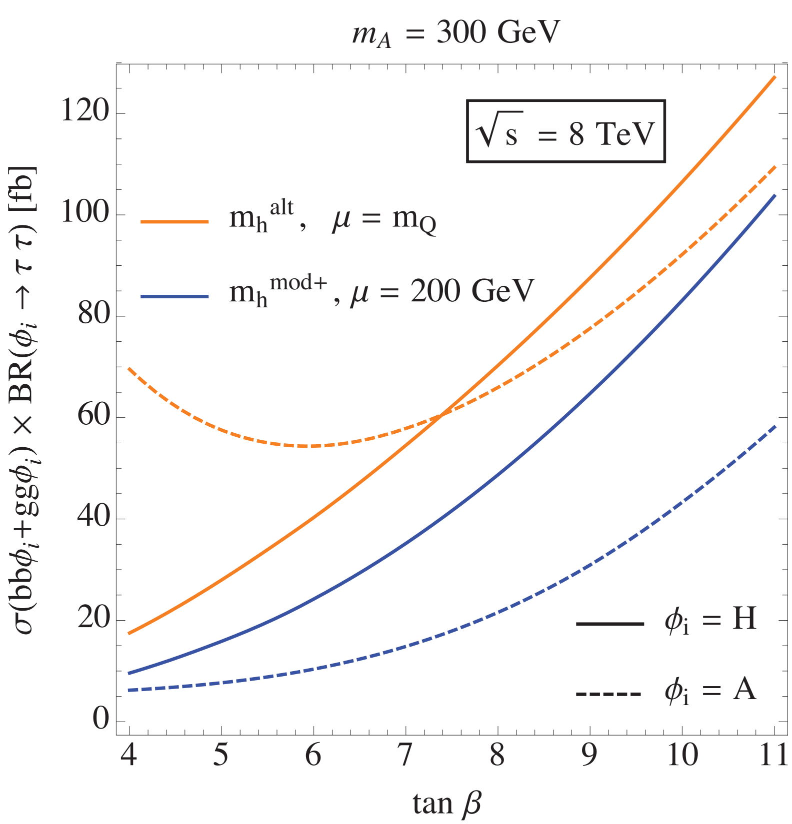
Note further that for low to moderate values of $\tan\beta$, $H \to hh$ can be a dominant decay mode in the mass range $2m_h < m_H < 2m_t$, thereby suppressing the branching ratio for $H \to \tau^+\tau^-$ in this mass range.

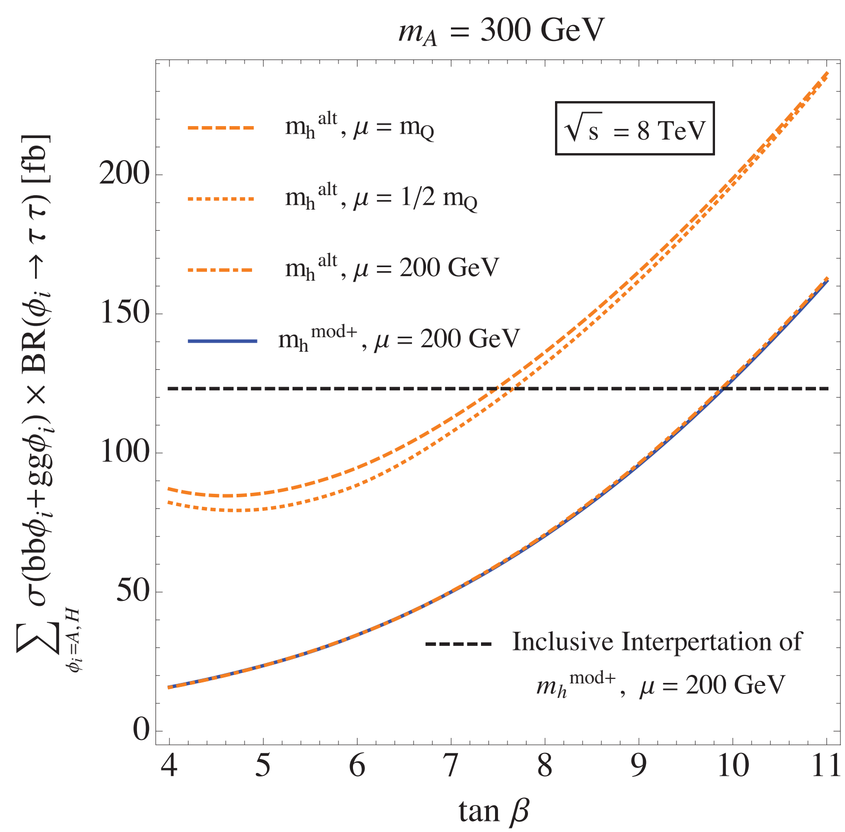


$m_h^{\rm alt}$, μ = 200 GeV, tan β = 4
BR(H)
m_H (GeV)
hh
$b\bar{b}$
$\chi_i^0\chi_j^0$
$\chi_i^+\chi_j^-$
$t\bar{t}$
ZZ
$\tau^+\tau^-$
W^+W^-
$m_h^{\rm alt}$, μ = 200 GeV, tan β = 4
BR(A)
m_A (GeV)
$\chi_i^0\chi_j^0$
$\chi_i^+\chi_j^-$
$b\bar{b}$
$t\bar{t}$
$\tau^+\tau^-$
hZ
$m_h^{\rm alt}$, $\mu = m_Q$, tan β = 4
BR(H)
m_H (GeV)
hh
$t\bar{t}$
$b\bar{b}$
ZZ
W^+W^-
$\tau^+\tau^-$
$m_h^{\rm alt}$, $\mu = m_Q$, tan β = 4
BR(A)
m_A (GeV)
$t\bar{t}$
$b\bar{b}$
hZ
$\tau^+\tau^-$
gg
$\chi_i^+\chi_j^-$
$\chi_i^0\chi_j^0$

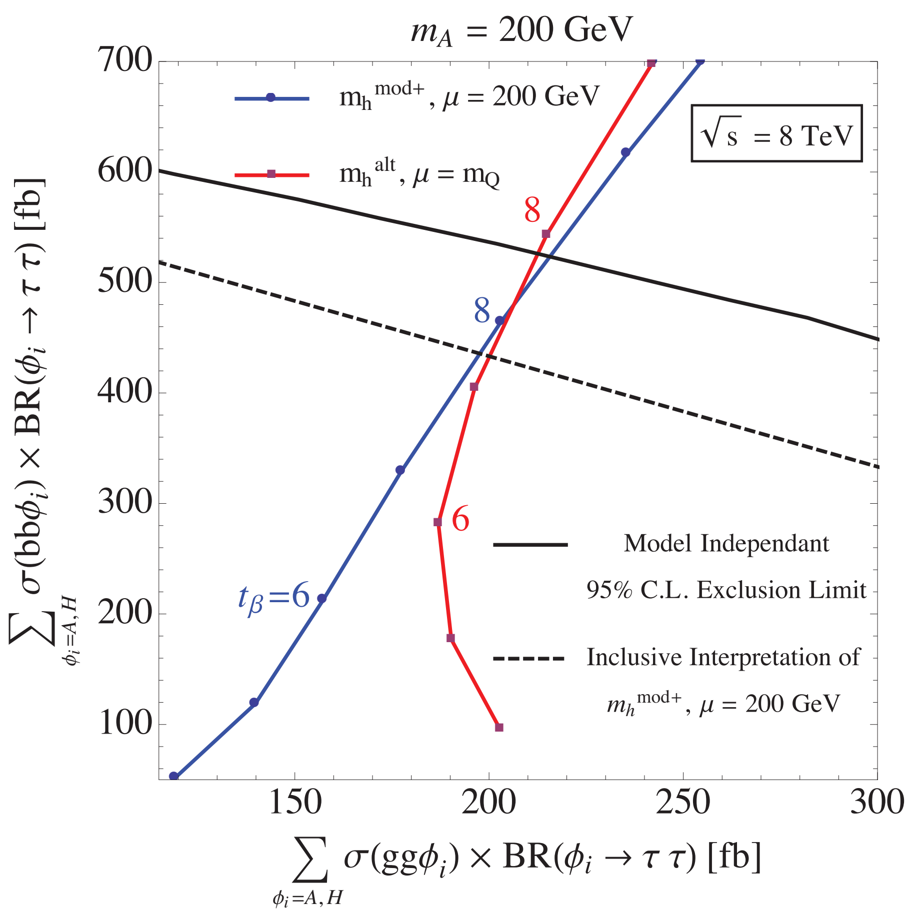
Implications of the CMS limits for various MSSM Higgs scenarios

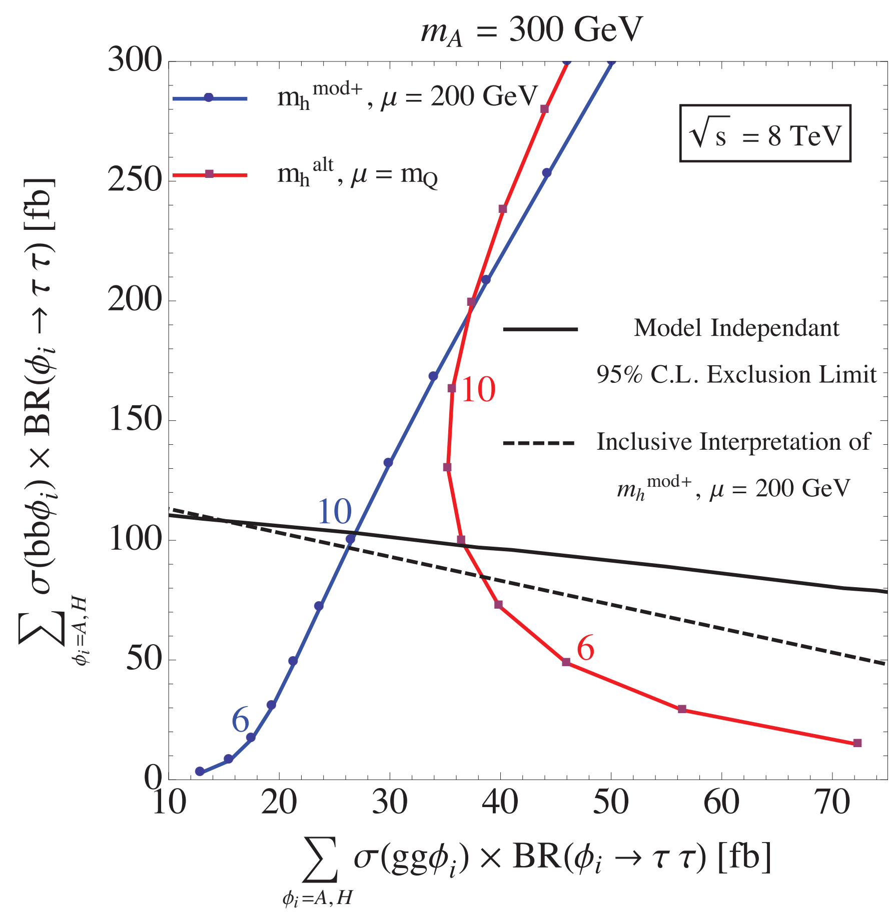
One strategy is to start with the CMS limits for H, $A \to \tau^+\tau^-$ in the $m_h^{\text{mod+}}$ scenario and extrapolate to other MSSM Higgs scenarios.





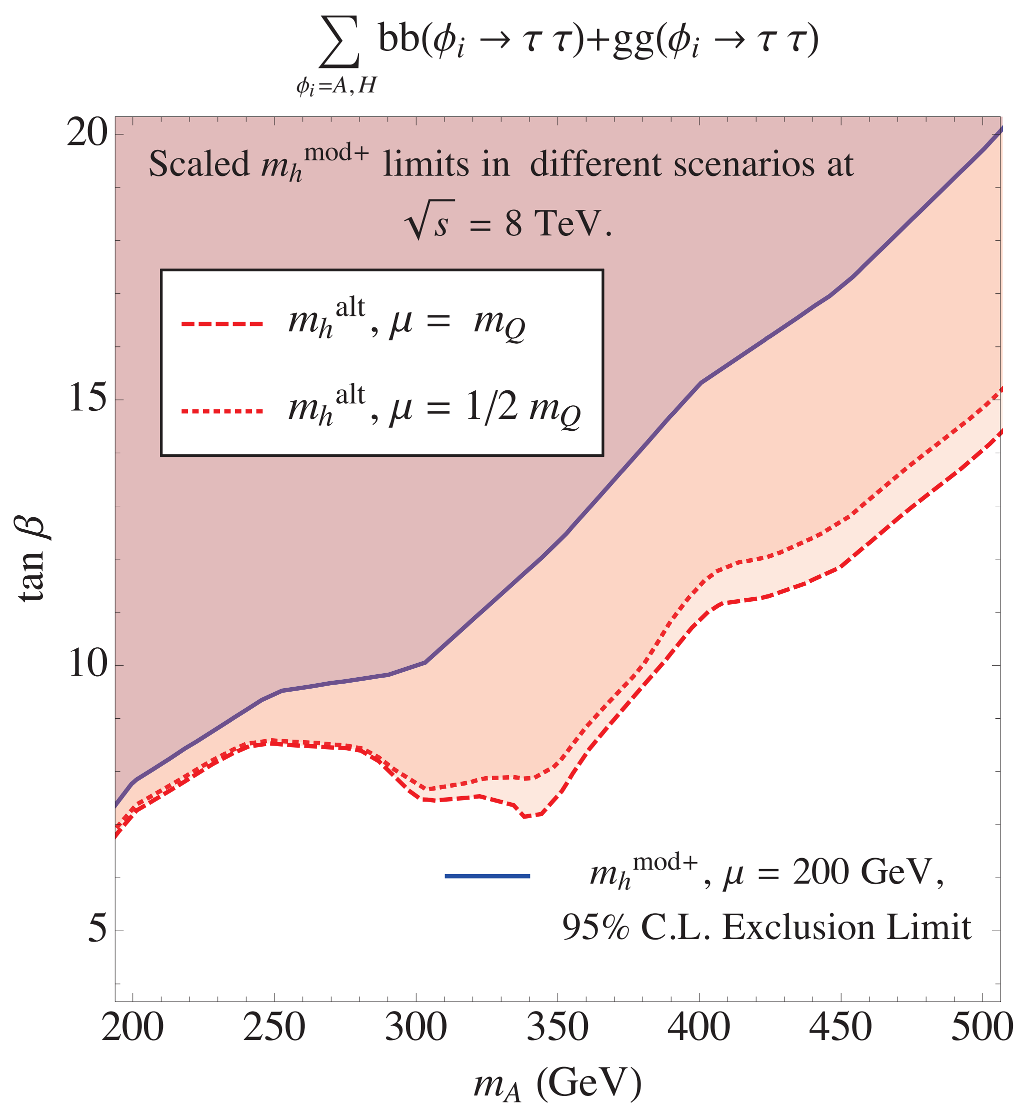
A more robust strategy would be to use the CMS two-dimensional likelihood contour plots based on the model-independent analysis.



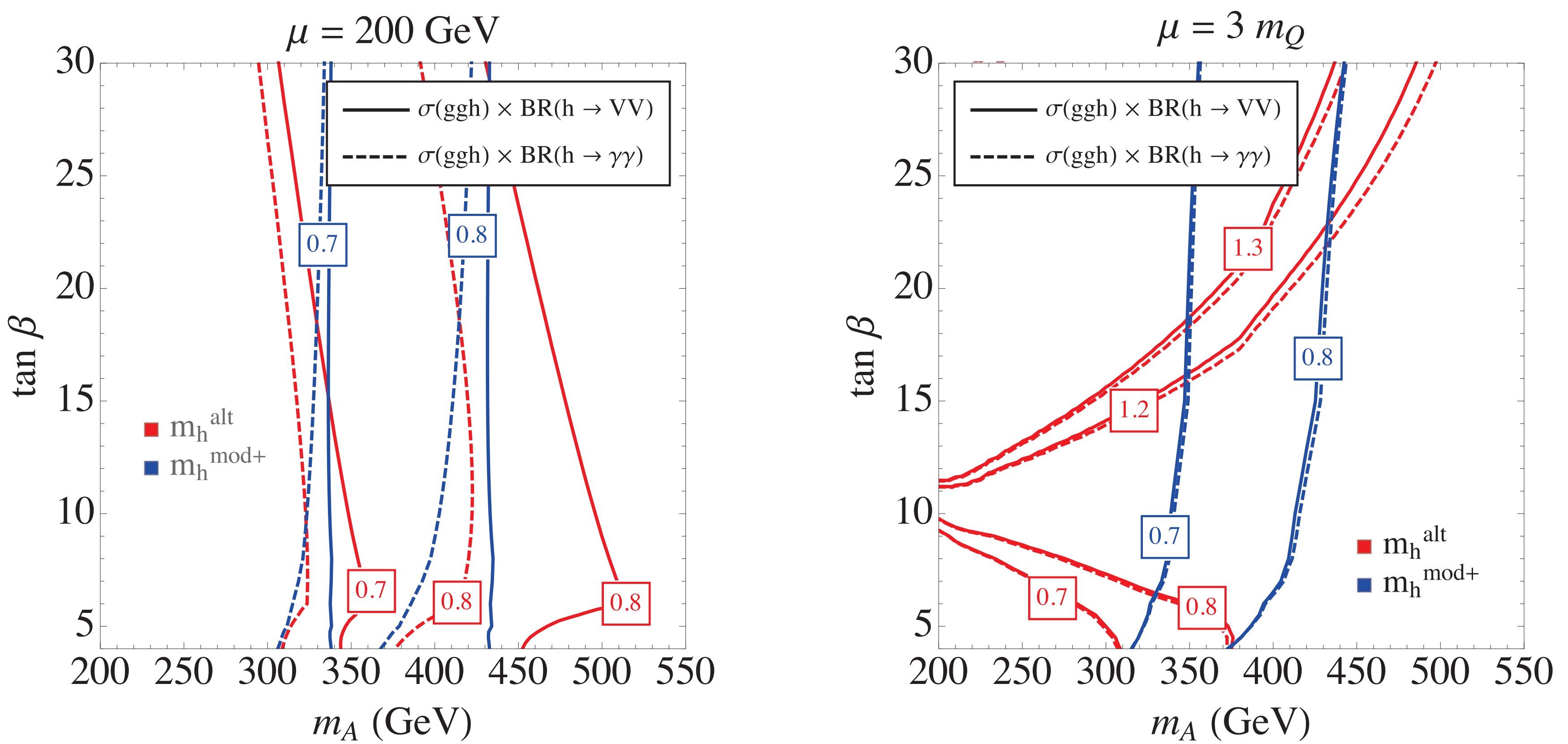


The $\tan\beta$ limits obtained by both methods are not the same, but they typically differ by no more than one unit.

Extrapolating the inclusive CMS $\tau^+\tau^-$ signal in the $m_h^{\text{mod+}}$ scenario, we can deduce the limits in the m_h^{alt} scenario for different choices of μ. A lower $\tan\beta$ value can be excluded at larger μ, in part due to the larger BR$(H\,,\,A \to \tau^+\tau^-)$.

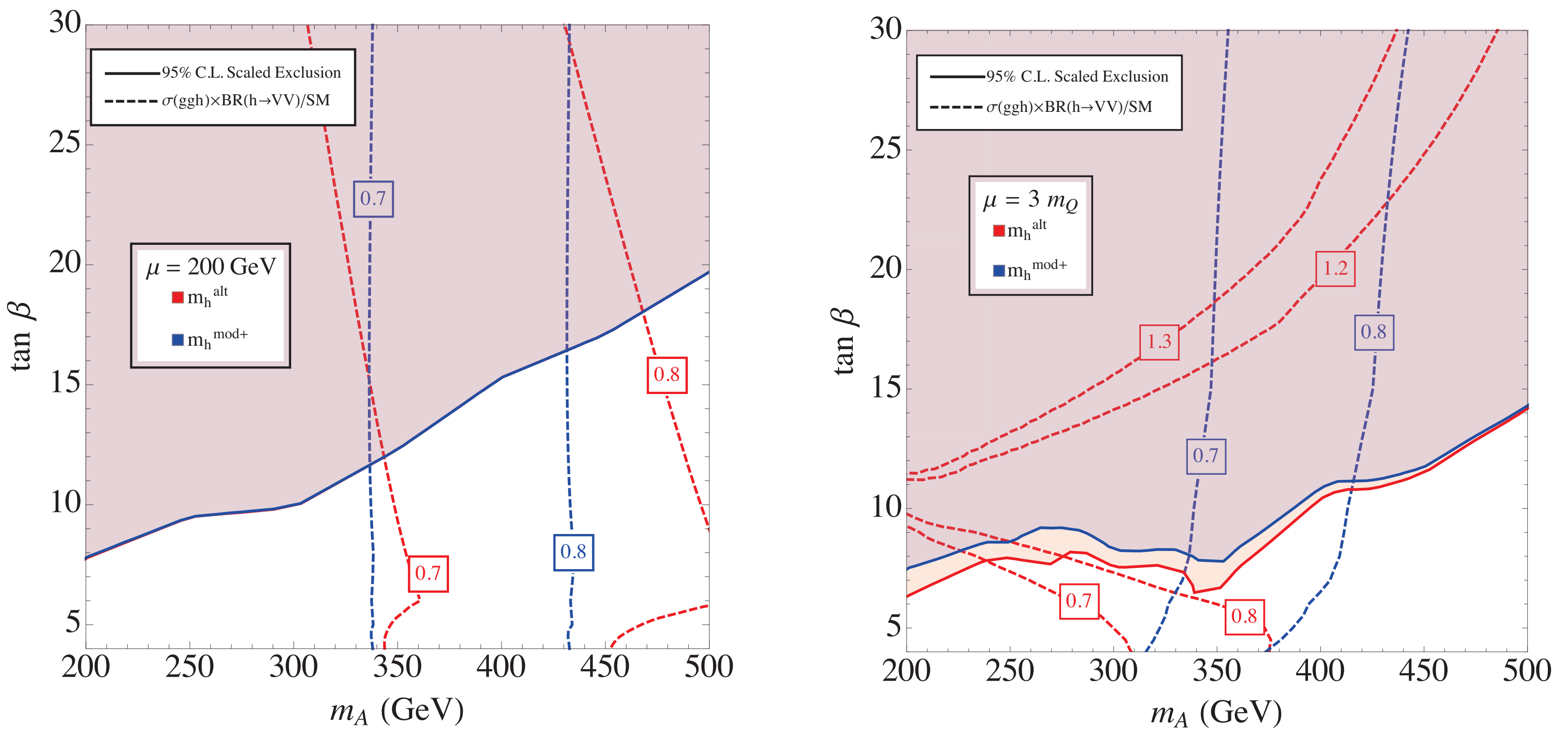


Constraining the m_A–$\tan\beta$ plane from the $h(125)$ data

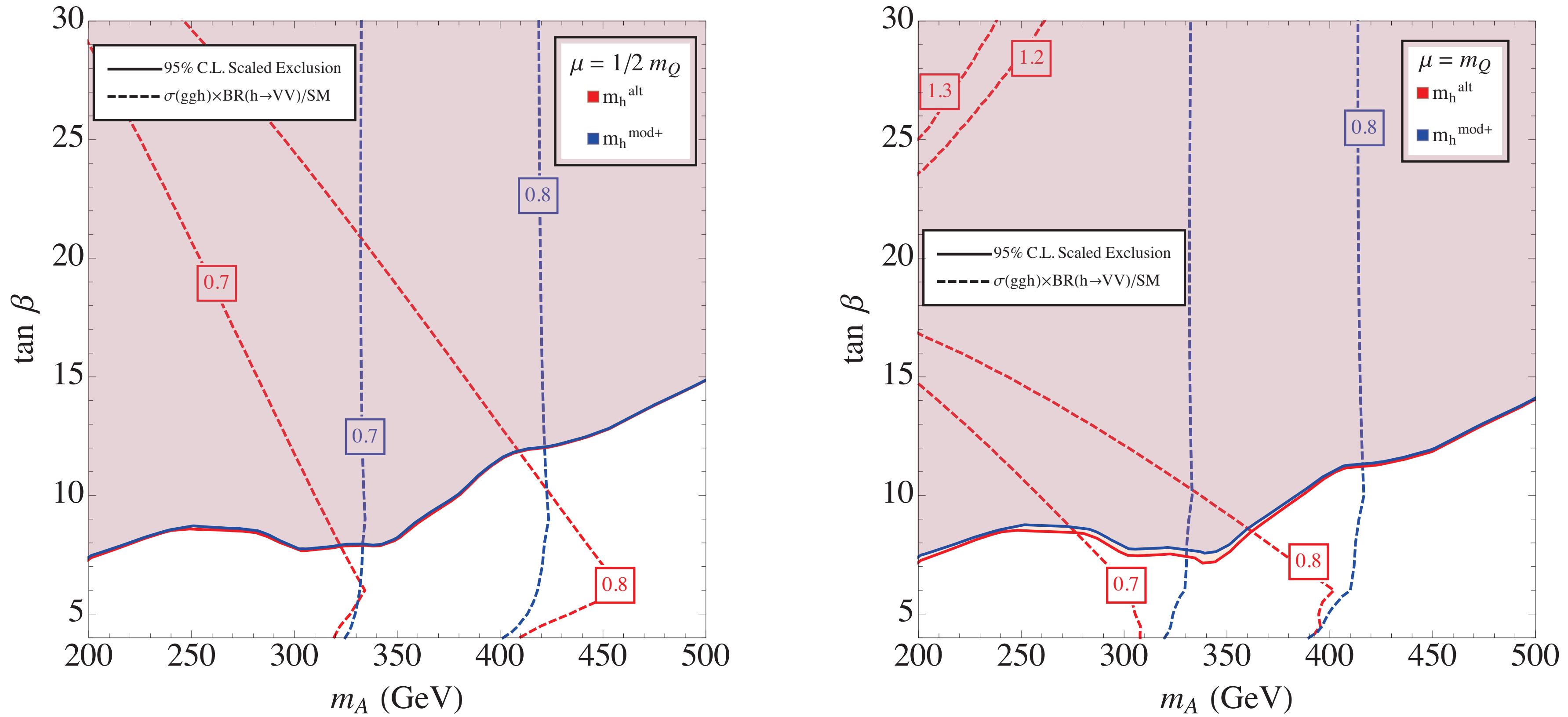


The observed h is SM-like, albeit with somewhat large errors. If the $\sigma \times \mathrm{BR}$ for $h \to VV$ and $h \to \gamma\gamma$ are within 20% or 30% of their SM values, then one can already rule out parts of the m_A–$\tan\beta$ plane.

Complementarity of the H , A search and the h data



The exact alignment limit is most pronounced at large μ in the $m_h^{\rm alt}$ scenario. Taking values of μ much larger than $3M_Q$ would result in color and charge violating vacua, which suggests that alignment for $\tan\beta$ values below 10 is not viable in the MSSM.

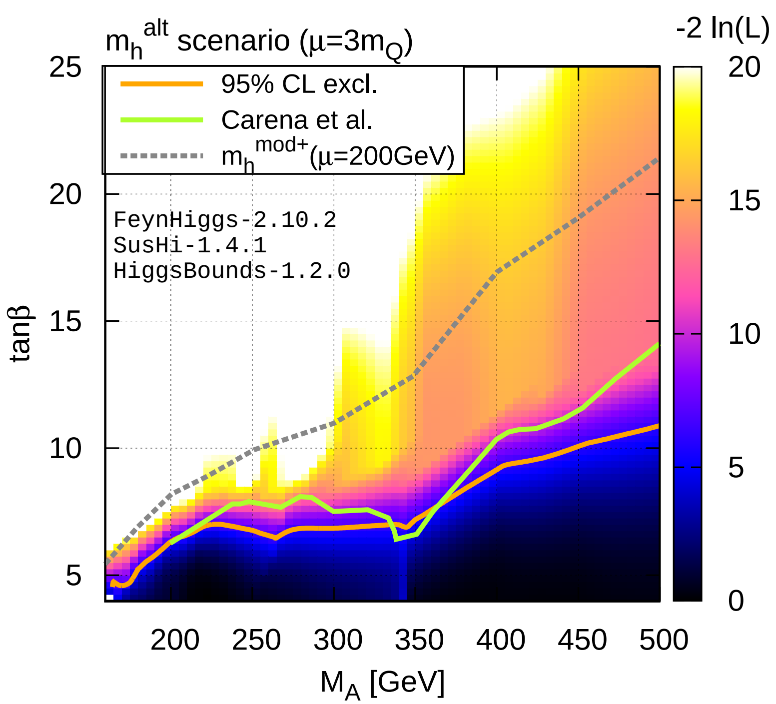


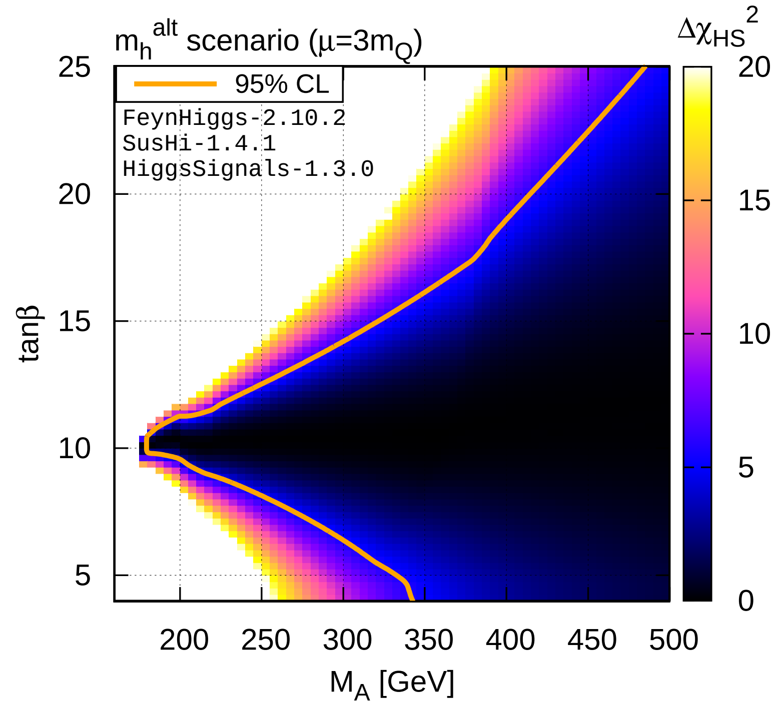
As μ is reduced, the $\tan\beta$ value at which exact alignment is realized in the $m_h^{\rm alt}$ scenario increases.

Note that the observation of $\sigma \times {\rm BR}(h \to VV)$ close to its SM value implies that ${\rm BR}(h \to b\bar{b})$ must also be close to its SM value since $h \to b\bar{b}$ is the dominant decay mode of h. The latter implies that $c_{\beta-\alpha}\tan\beta \ll 1$, which accounts for the nearly vertical blue dashed lines above.

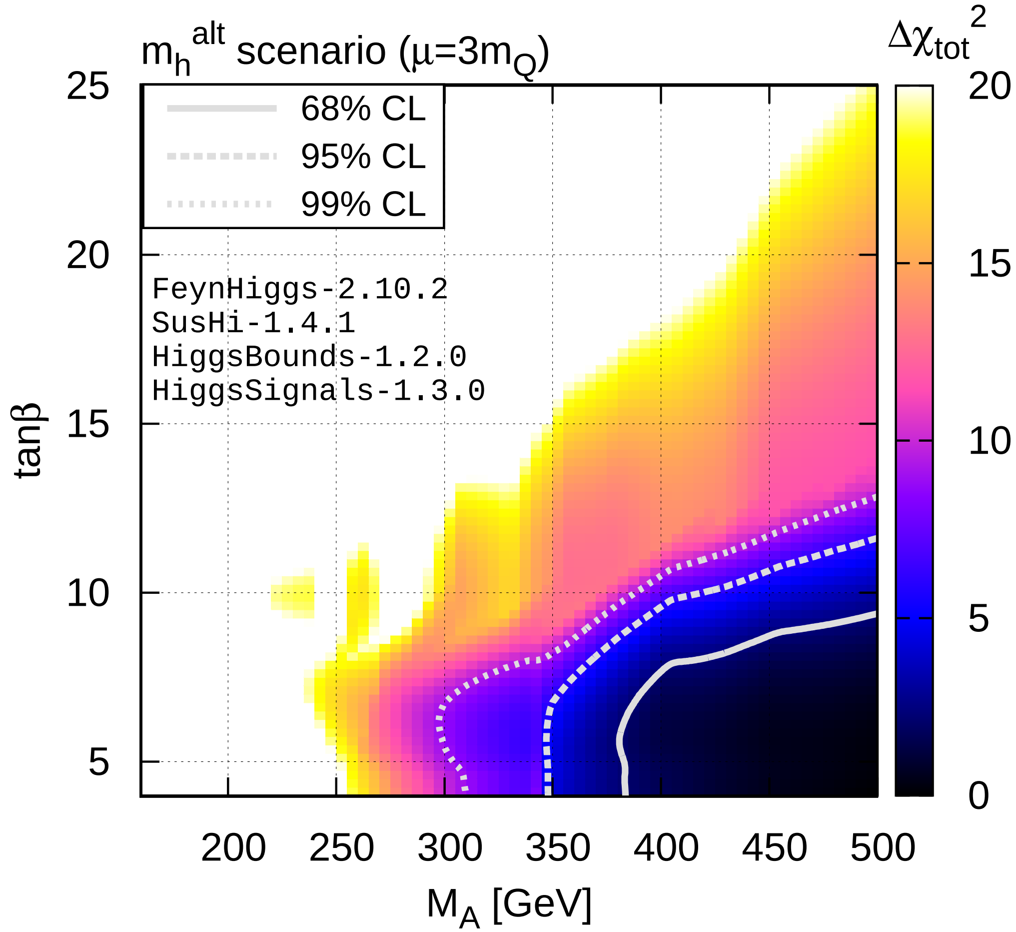
Likelihood analysis: Setting bounds in the $\tan\beta$–m_A plane

Tim Stefaniak has employed the programs HiggsBounds and HiggsSignals to derive bounds in the $\tan\beta$–m_A plane. Preliminary results are shown here for the $m_h^{\rm alt}$ scenario with $\mu = 3M_Q$.





Combining the CMS analysis of $H, A \to \tau^+\tau^-$ with the signal strength data for the observed Higgs boson yields the following exclusion region for the MSSM Higgs sector in the $m_h^{\rm alt}$ scenario with $\mu = 3M_Q$:



Global fit of the phenomenological MSSM

[P. Bechtle, S. Heinemeyer, O. Stål, TS, G. Weiglein, L. Zeune, 1211.1955]

here: updated preliminary results!

Perform a random scan over 7 MSSM parameters ($\sim$ 10 million points):

$$M_A, \quad \tan\beta, \quad \mu, \quad M_{\tilde{q}_3}, \quad M_{\tilde{\ell}}, \quad A_0, \quad M_2, \quad (+\, m_{top})$$

use FeynHiggs-2.10.2 and SuperIso-3.3 for MSSM predictions.

Construct global χ^2 from observables:

- Higgs mass and signal rates (HiggsSignals-1.3.0)
- Low energy observables: $b \to s\gamma,\ B_s \to \mu\mu,\ B_u \to \tau\nu,\ (g-2)_\mu,\ M_W$
- reconstructed $-2\ln\mathcal{L}$ from CMS $\phi \to \tau\tau$ search (HiggsBounds-4.2.0)

Further constraints:

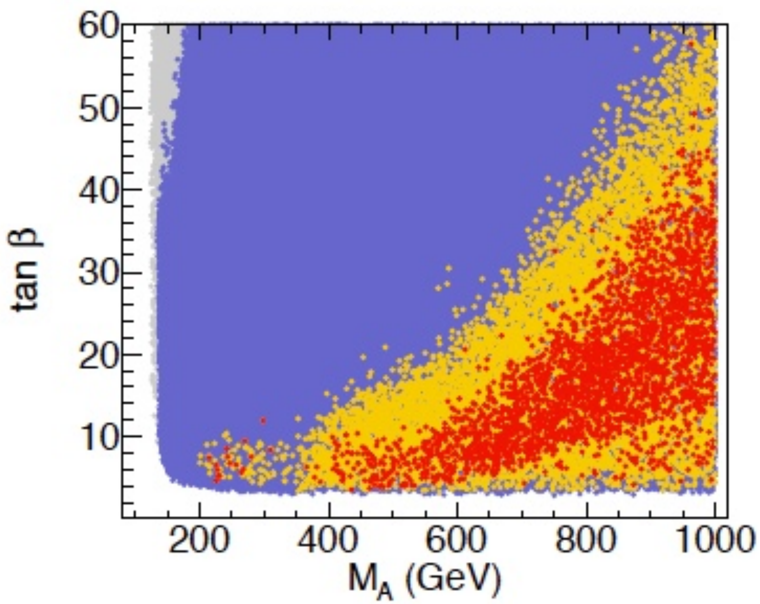
- 95% CL Higgs exclusion limits (*w/o MSSM $\phi \to \tau\tau$ limits*) (HiggsBounds-4.2.0)
- Sparticle mass limits from LEP, (fixed $m_{\tilde{q}_{1,2}} = m_{\tilde{g}} = 1.5\ \mathrm{TeV}$ to evade LHC limits)
- Require neutral lightest supersymmetric particle (LSP).

Scan ranges for the pMSSM-7 fit

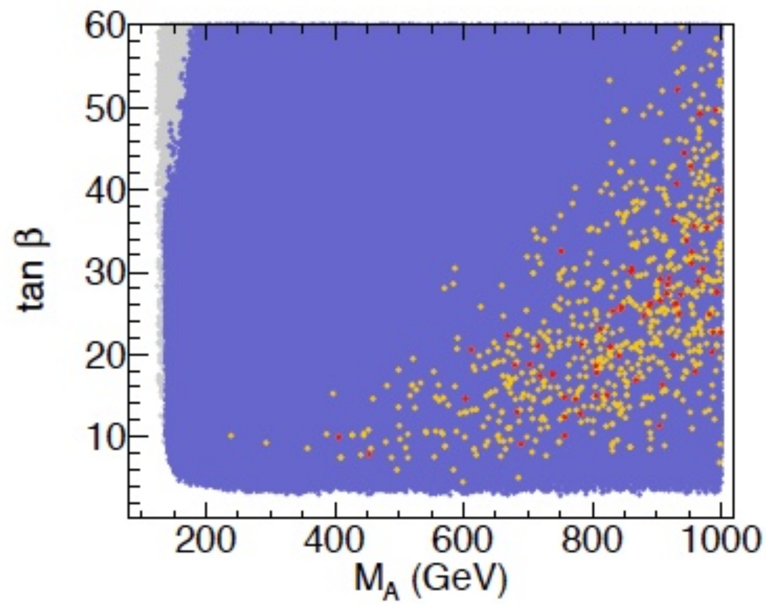
Parameter	Minimum	Maximum
M_A [GeV]	90	1000
$\tan\beta$	1	60
μ [GeV]	200	4000
$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3}$ [GeV]	200	1500
$M_{\tilde{L}_i} = M_{\tilde{E}_i}$ [GeV]	200	1500
A_f	$-3M_{\tilde{Q}_3}$	$3M_{\tilde{Q}_3}$
M_2 [GeV]	200	500

$$M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}} = M_3 = 1.5\ \mathrm{TeV}$$

Tim Stefaniak has also performed a more comprehensive 7 parameter PMSSM scan to see whether one could relax the bounds on m_A. The results depend on whether one imposes B physics constraints which tend to rule out lower values of $m_{H^\pm}$ (and hence lower values of m_A).

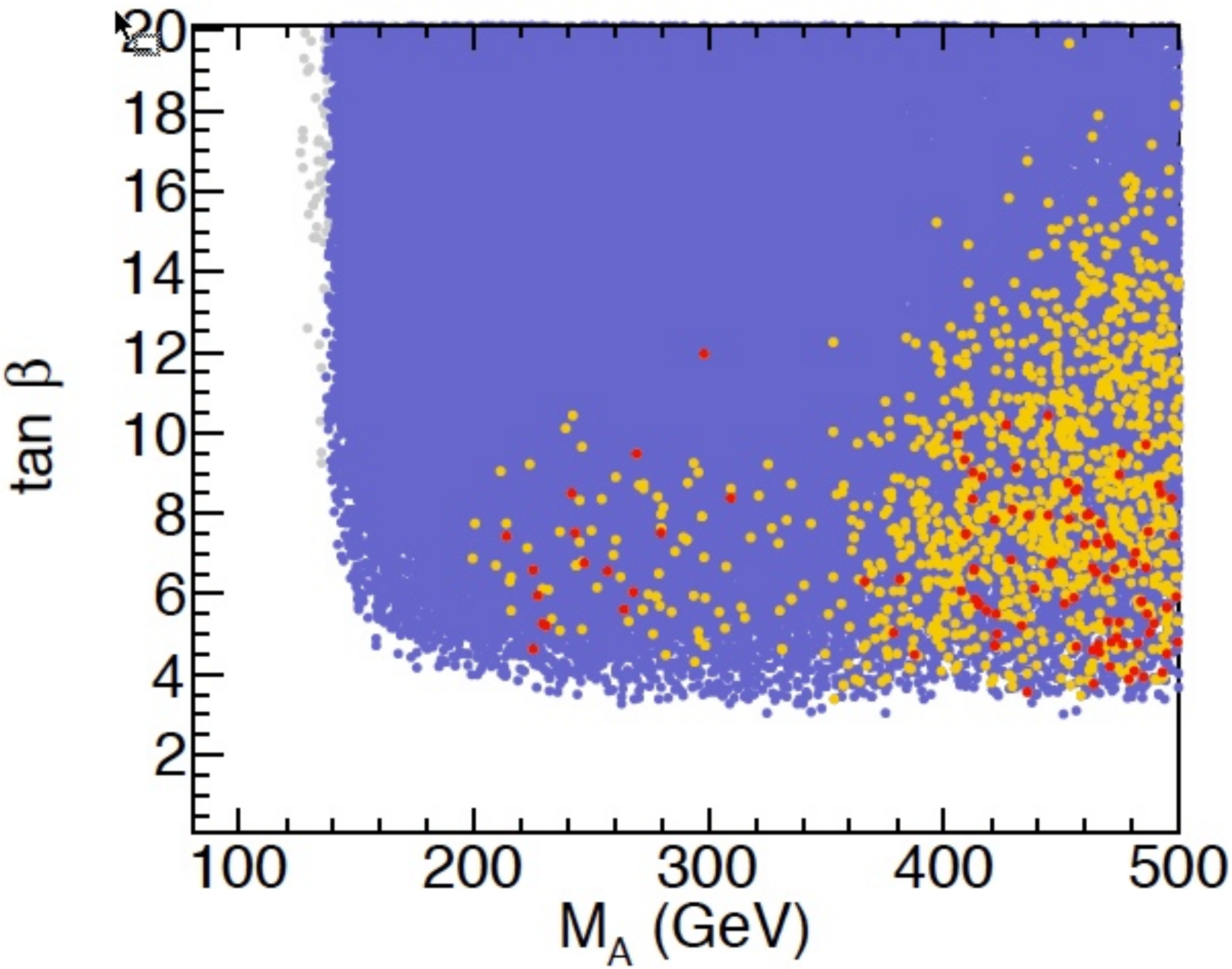


Low energy observables omitted



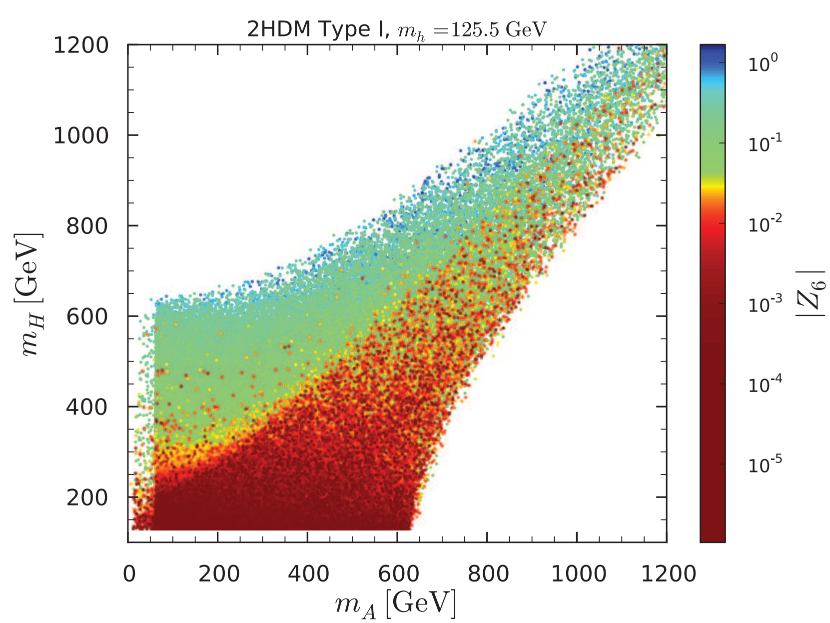
Low energy observables included

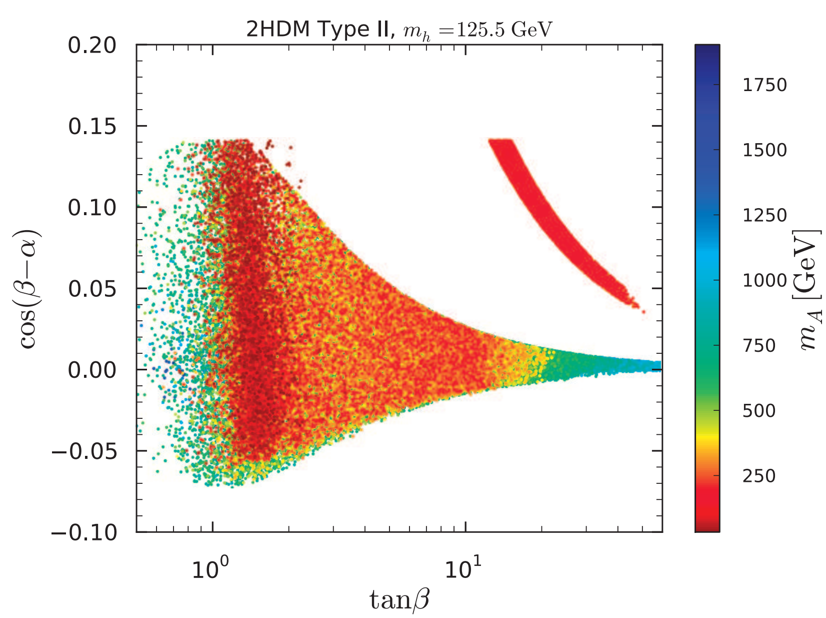
Before imposing constraints from low energy observables, it appears that some points with $m_A \sim 200$ GeV survive in the alignment without decoupling regime.



Alignment without decoupling in the 2HDM

In a generic Type-I or Type-II 2HDM (with no MSSM constraints applied), the parameter region corresponding to alignment without decoupling, consistent with present data, can be significant. In particular, in Type-I models, the constraints due to H, $A \to \tau^+\tau^-$ and B physics observables are rather weak. Here are two typical parameter scans (J. Bernon, J.F. Gunion, H.E. Haber, Y. Jiang and S. Kraml, in preparation):





Conclusions

- Current Higgs data suggest that h is SM-like, corresponding to the alignment limit. In the context of the 2HDM, this implies that $|c_{\beta-\alpha}| \ll 1$.

- Approximate alignment arises either in the decoupling limit (where $m_{H^\pm}, m_A, m_H \gg m_h$) and/or when the Higgs basis parameter $|Z_6| \ll 1$. Thus, alignment without decoupling is possible.

- In the MSSM Higgs sector, the exact alignment limit $Z_6 = 0$ cannot occur at tree-level (except at unrealistic values of $\tan\beta$). Including radiative corrections, an accidental (approximate) cancellation between tree-level and loop-level terms can yield $|Z_6| \ll 1$ at moderate to large values of $\tan\beta$.

- Combining LHC searches for H, $A \to \tau^+\tau^-$ with the constraints derived from a SM-like h yields excluded regions in the m_A–$\tan\beta$ plane. Present exclusion limits already exhibit significant tension with the scenario of alignment without decoupling in the MSSM Higgs sector.