Constraints on the alignment limit of the MSSM Higgs sector

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Physics Challenges in the face of LHC-14

25 September 2014

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The CP-conserving 2HDM—a brief review

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

such that $\langle\Phi_a^0\rangle = v_a/\sqrt{2}$ (for $a = 1, 2$), 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 define Higgs basis fields, $H_1 \equiv (v_1\Phi_1 + v_2\Phi_2)/v$ and $H_2 \equiv (v_1\Phi_2 - v_2\Phi_1)/v$, so that $\langle H_1^0\rangle = v/\sqrt{2}$ and $\langle H_2^0\rangle = 0$.

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

where $s_\beta \equiv v_2/v$ and $c_\beta \equiv v_1/v$ ($0 \leq \beta \leq \frac{1}{2}\pi$ without loss of generality) with

$$Z_1 \equiv \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + \tfrac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)s_{2\beta}^2 + 2s_{2\beta}\left[c_\beta^2\lambda_6 + s_\beta^2\lambda_7\right],$$
$$Z_5 \equiv \tfrac{1}{4}s_{2\beta}^2\left[\lambda_1 + \lambda_2 - 2(\lambda_3 + \lambda_4 + \lambda_5)\right] + \lambda_5 - s_{2\beta}c_{2\beta}(\lambda_6 - \lambda_7)\,,$$
$$Z_6 \equiv -\tfrac{1}{2}s_{2\beta}\left[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - (\lambda_3 + \lambda_4 + \lambda_5)c_{2\beta}\right] + c_\beta c_{3\beta}\lambda_6 + s_\beta s_{3\beta}\lambda_7\,.$$

In the $\{\Phi_1\,,\,\Phi_2\}$ basis, when the CP-even neutral Higgs squared-mass matrix is diagonalized, the resulting mixing angle is called α. 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. The CP-even neutral mass-eigenstates are h and H (with $m_h < m_H$).

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 alignment limit of the 2HDM.

Alternatively, we can take $m_A^2 \gg Z_i v^2$. In this case, standard perturbation theory shows that $m_h^2 \simeq Z_1 v^2$ and $|c_{\beta-\alpha}| \ll 1$. Again, h is SM-like. This is the well-known decoupling limit of the 2HDM.

Indeed, the normalized hVV coupling ($VV = W^+W^-$ or ZZ) is

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} = s_{\beta-\alpha}\,.$$

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

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 $m_h^2 \to Z_1 v^2$.

*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 also an alignment limit, 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 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 $(m_h^2)_{\rm max} = m_Z^2 c_{2\beta}^2$ 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 so-called 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,

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

where

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

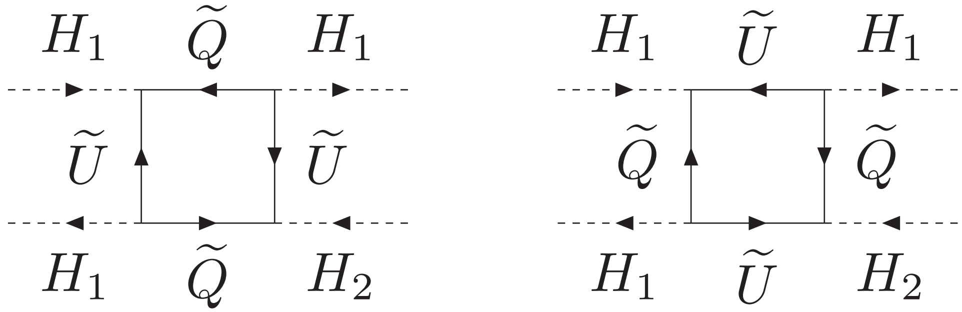
Assuming CP-conservation for simplicity, we shall henceforth take μ, A_t real.

The radiatively corrected MSSM Higgs Sector

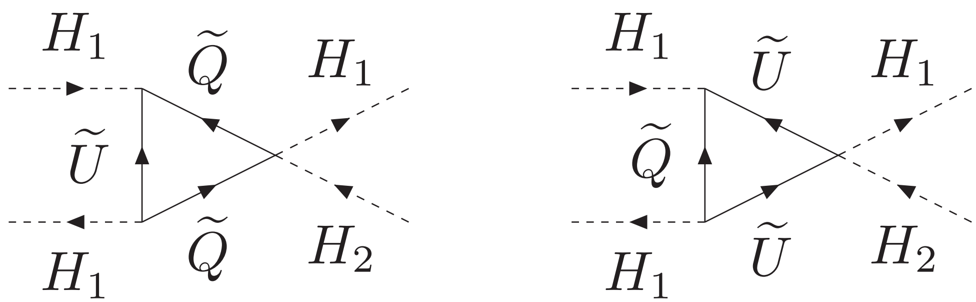
We are most interested in the limit where m_h, $m_A \ll m_Q$, where m_Q characterizes the scale of the squark masses. In this case, we can formally integrate out the squarks and generate a low-energy effective 2HDM Lagrangian. This Lagrangian will no longer be of the tree-level MSSM form but rather a compeltely 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 $\lambda_1 \ldots, \lambda_7$.[†]

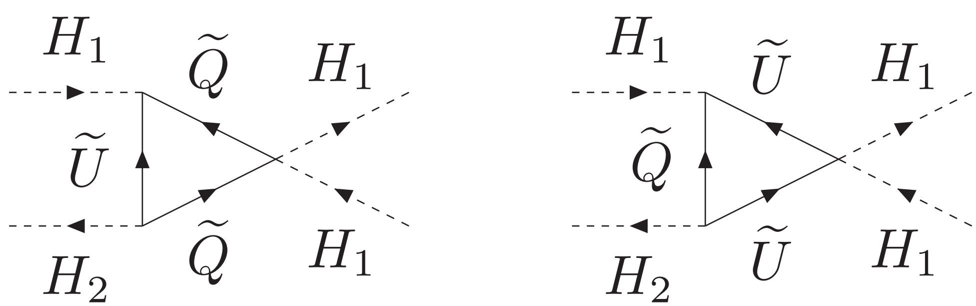
[†]Explicit formulae can be found in H.E. Haber and R. Hempfling, "The Renormalization group improved Higgs sector of the minimal supersymmetric model," Phys. Rev. **D48**, 4280 (1993).



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



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



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

Threshold Corrections to Z_6

The leading corrections to Z_1, Z_5 and Z_6 are:

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

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

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

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 alignment condition, $Z_6 = 0$, can now be achieved due to an accidental cancellation between tree-level and loop contributions,

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

A solution to this equation can be found at moderate to large values of $t_\beta \equiv \tan\beta = s_\beta/c_\beta$. Performing a Taylor expansion in t_β^{-1}, we find an (approximate) solution at

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

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 decoupling/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.

- Extrapolate to future LHC runs. Determine what is needed to rule out alignment without decoupling in the MSSM.

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.

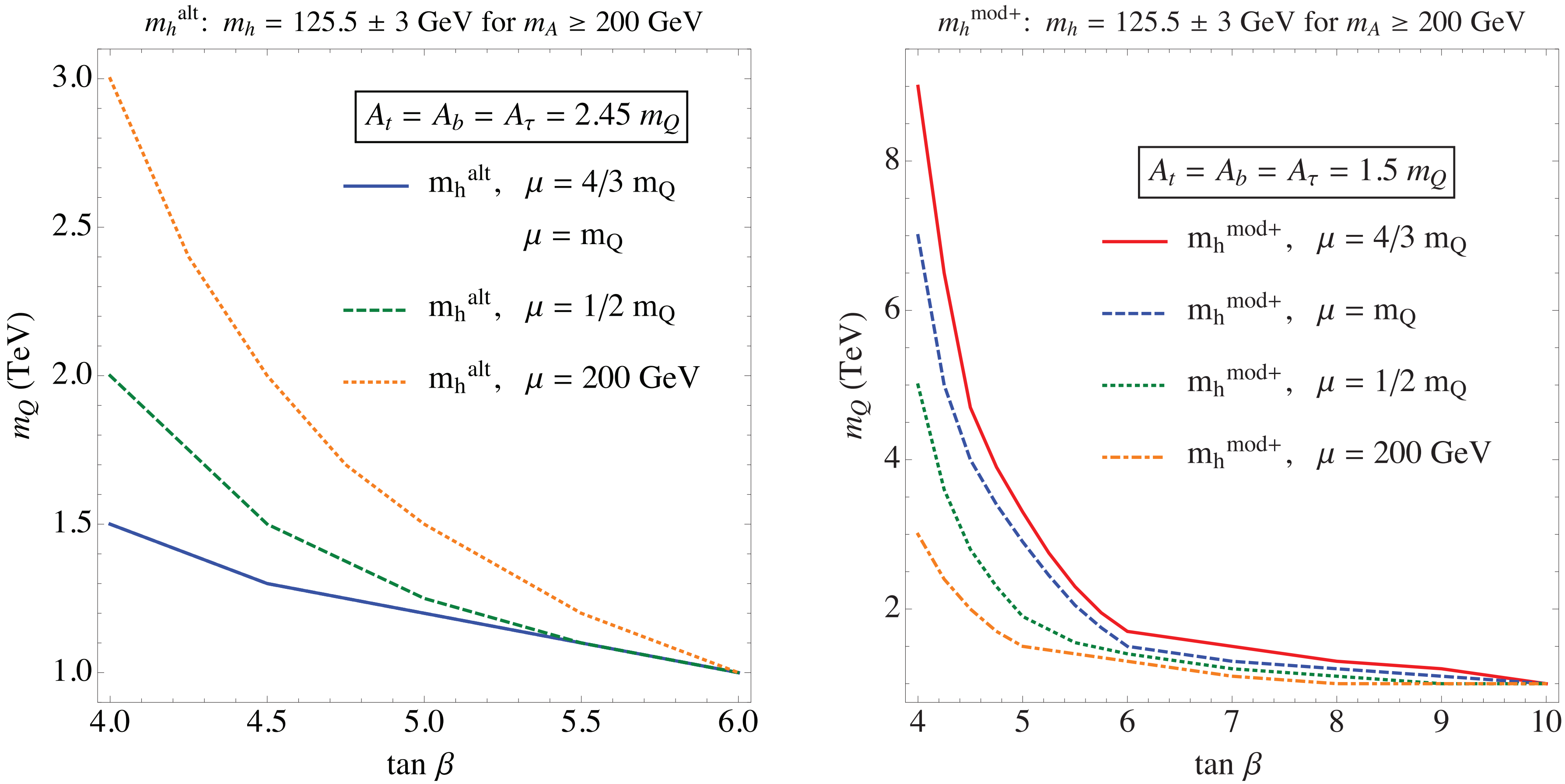
MSSM Higgs scenarios[‡]

	$\mathsf{m}_h^{\mathrm{mod}+}$	$\mathsf{m}_h^{\mathrm{alt}}$
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 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.

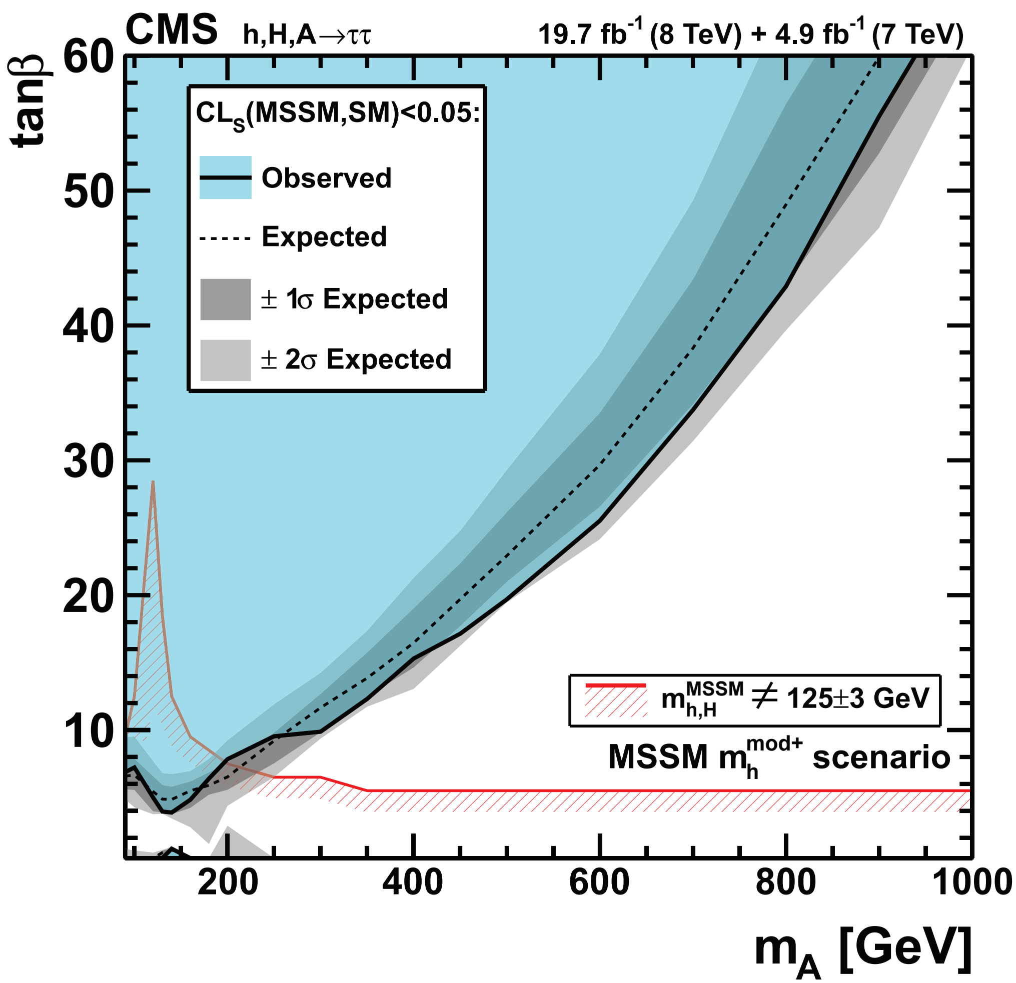
[‡]Additional benchmark scenarios can be found in M. Carena, S. Heinemeyer, O. Stål, C.E.M. Wagner and G. Weiglein, "MSSM Higgs Boson Searches at the LHC: Benchmark Scenarios after the Discovery of a Higgs-like Particle," Eur. Phys. J. **C73**, 2552 (2013).



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.

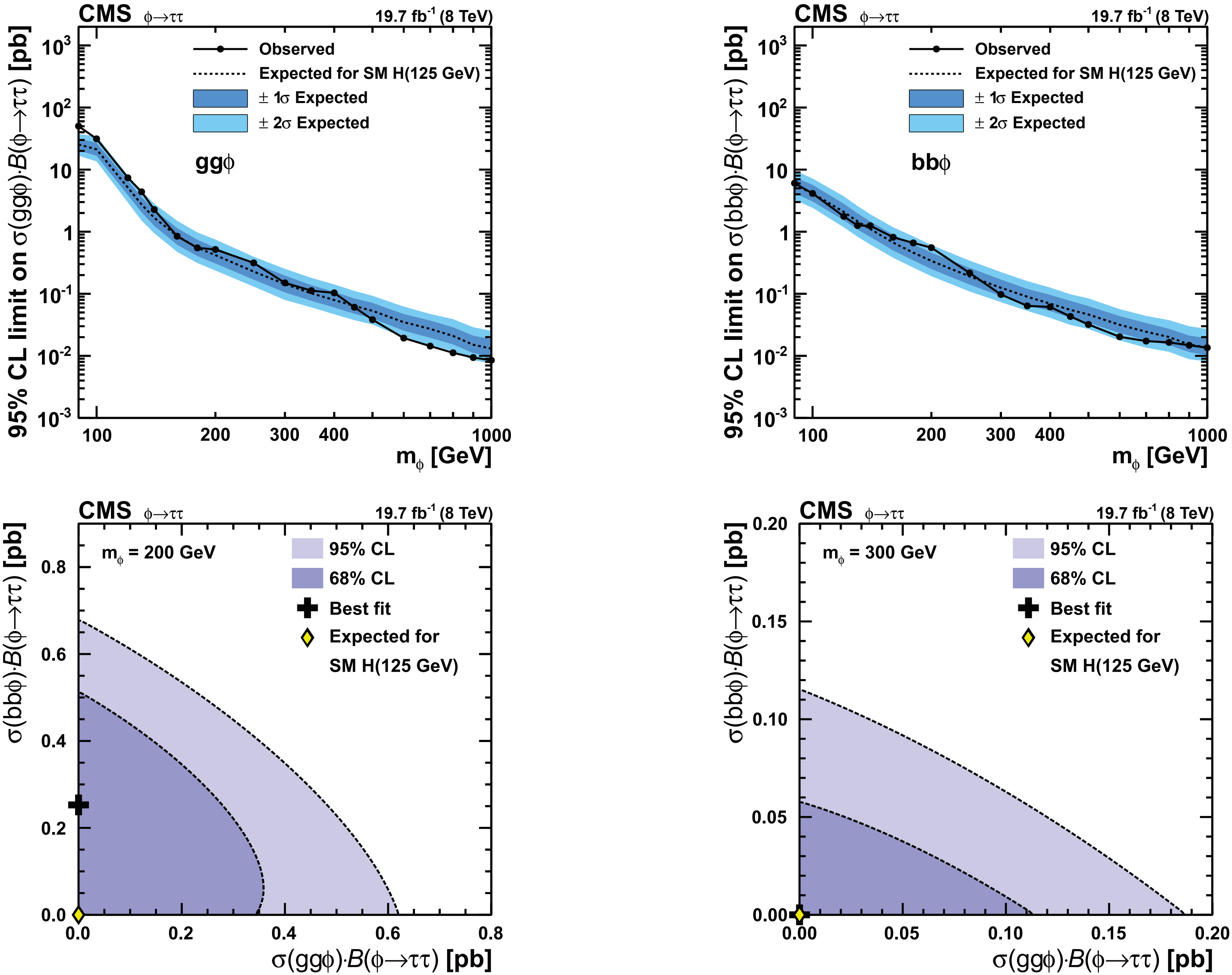
CMS search for H, $A \to \tau^+\tau^-$

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



2. Model-independent analysis

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



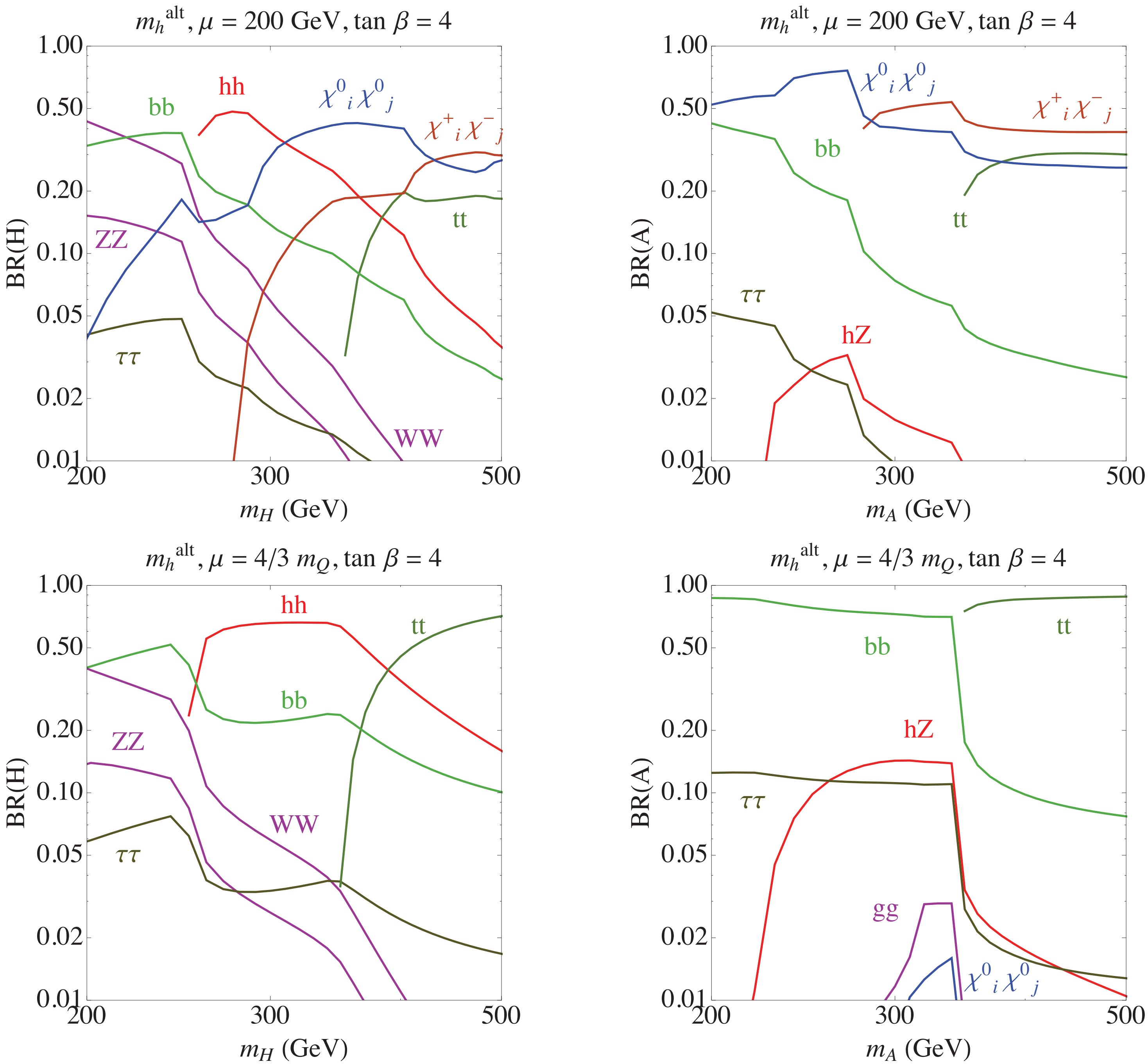
CMS $\phi\to\tau\tau$
19.7 fb^{-1} (8 TeV)
Observed
Expected for SM H(125 GeV)
± 1σ Expected
± 2σ Expected
ggϕ
bbϕ
95% CL limit on $\sigma(gg\phi)\cdot B(\phi\to\tau\tau)$ [pb]
95% CL limit on $\sigma(bb\phi)\cdot B(\phi\to\tau\tau)$ [pb]
m_ϕ [GeV]
m_ϕ = 200 GeV
m_ϕ = 300 GeV
95% CL
68% CL
Best fit
Expected for SM H(125 GeV)
$\sigma(bb\phi)\cdot B(\phi\to\tau\tau)$ [pb]
$\sigma(gg\phi)\cdot B(\phi\to\tau\tau)$ [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.

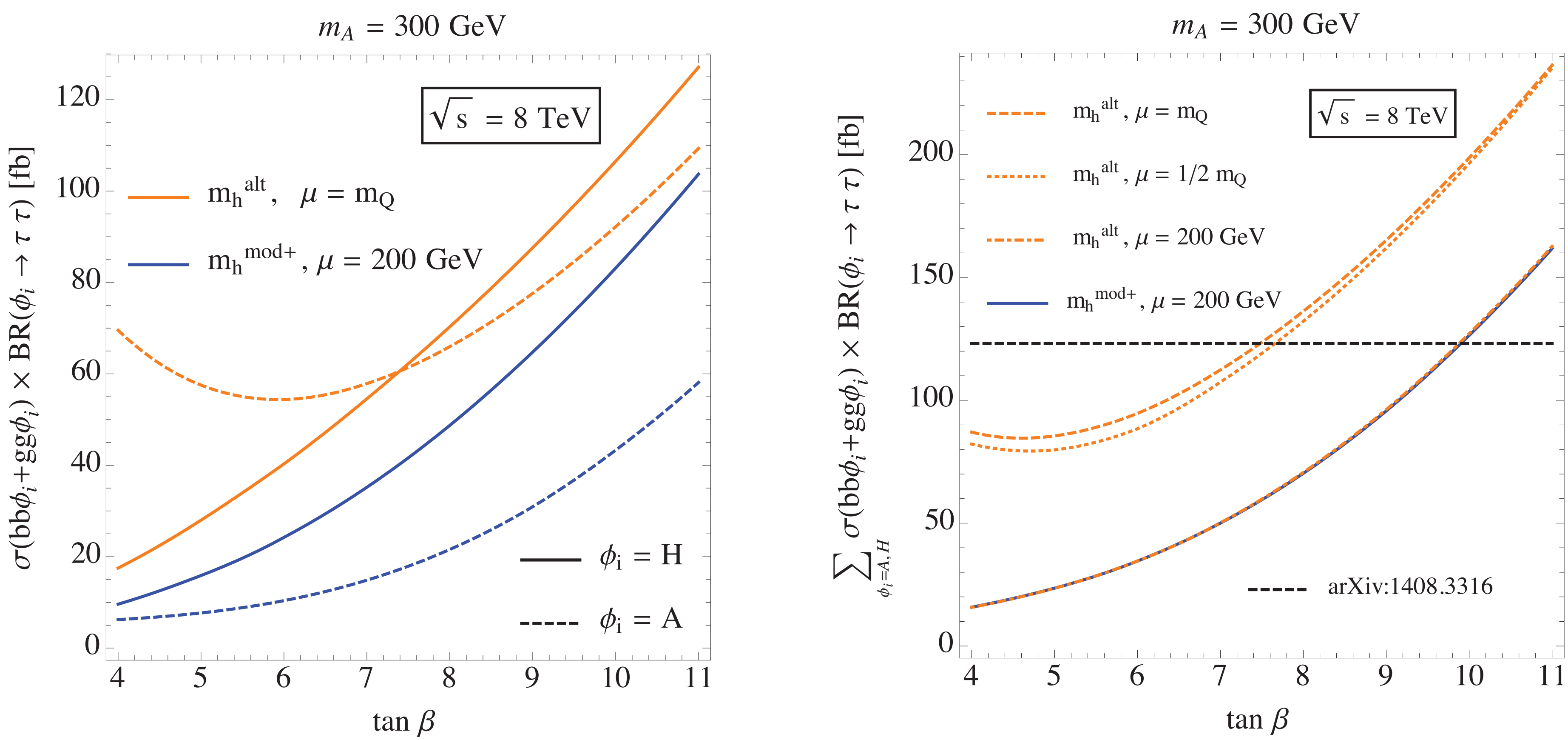
Note further that for low to moderate values of $\tan\beta$, $H\to hh$ can be a dominant decay mode in the mass range $2m_h < m_H < 2m_t$, thereby suppressing the branching ratio for $H\to\tau^+\tau^-$ in this mass range.



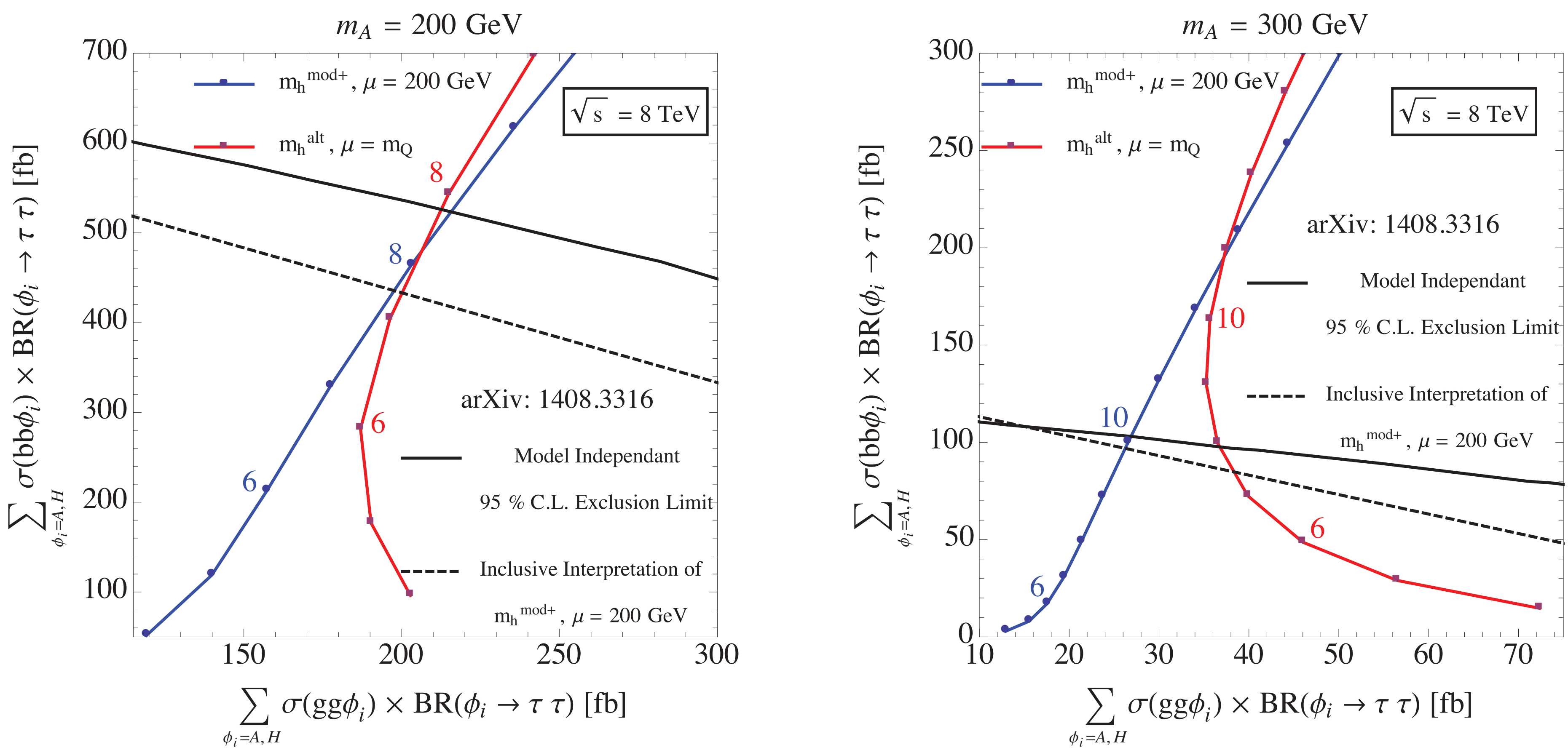
$m_h^{\rm alt}$, μ = 200 GeV, tan β = 4
BR(H)
m_H (GeV)
bb
hh
$\chi^0{}_i\chi^0{}_j$
$\chi^+{}_i\chi^-{}_j$
ZZ
tt
$\tau\tau$
WW
$m_h^{\rm alt}$, μ = 200 GeV, tan β = 4
BR(A)
m_A (GeV)
$\chi^0{}_i\chi^0{}_j$
$\chi^+{}_i\chi^-{}_j$
bb
tt
$\tau\tau$
hZ
$m_h^{\rm alt}$, μ = 4/3 m_Q, tan β = 4
BR(H)
m_H (GeV)
hh
tt
bb
ZZ
WW
$\tau\tau$
$m_h^{\rm alt}$, μ = 4/3 m_Q, tan β = 4
BR(A)
m_A (GeV)
tt
bb
hZ
$\tau\tau$
gg
$\chi^0{}_i\chi^0{}_j$
1.00
0.50
0.20
0.10
0.05
0.02
0.01
200
300
500

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 $m_h^{\mathrm{mod+}}$ scenario and extrapolate to other MSSM Higgs scenarios.

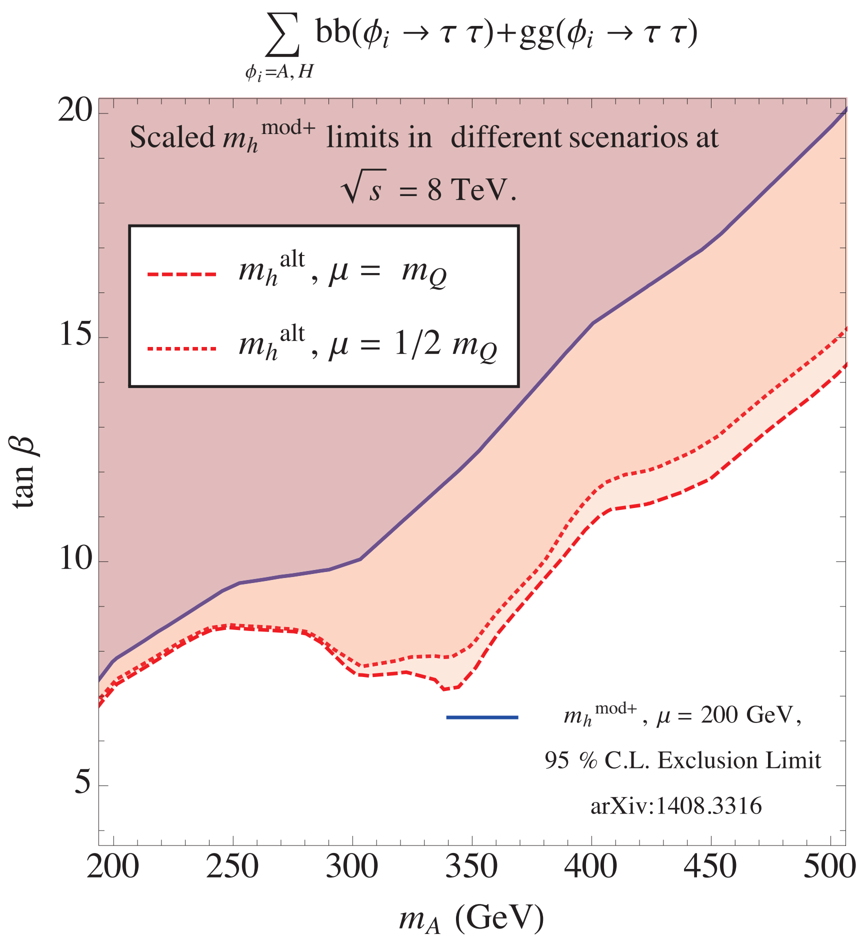


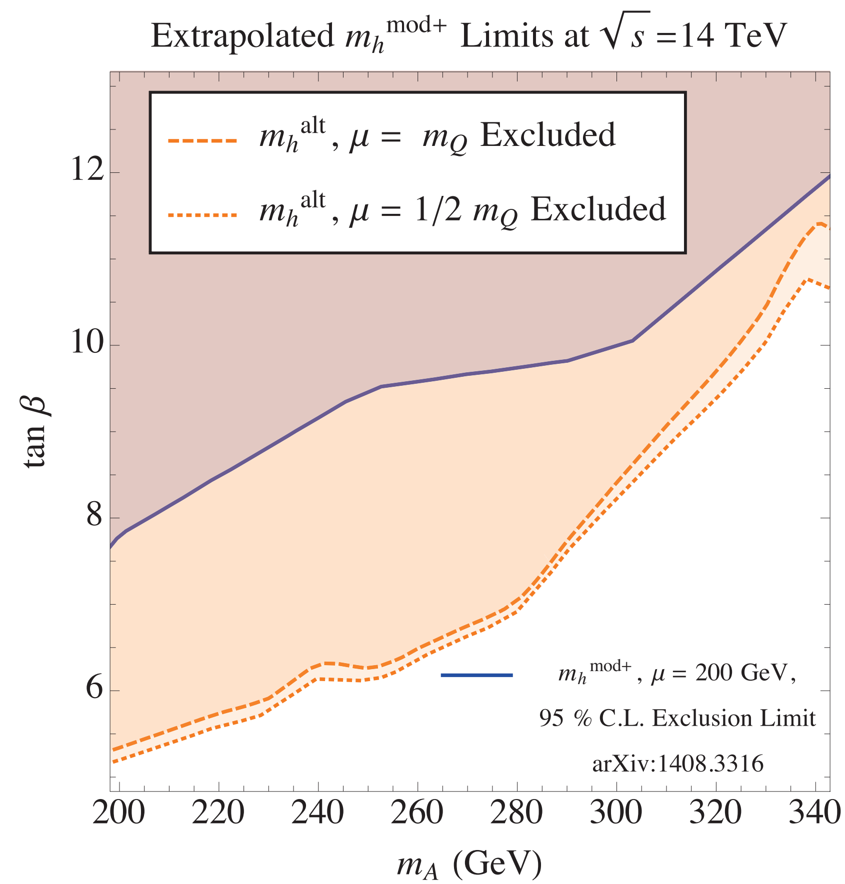
A more robust strategy would be to use the CMS two-dimensional likelihood contour plots based on the model-independent analysis.



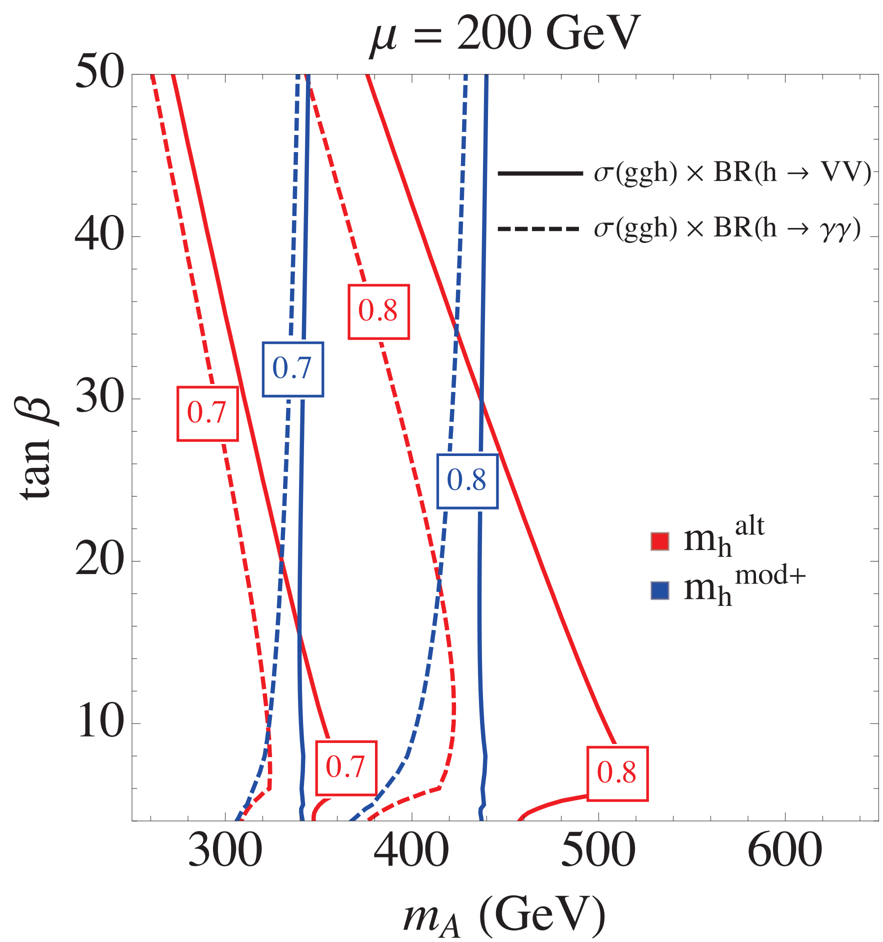
The $\tan\beta$ limits obtained by both methods are not the same, but they typically differ by no more than one unit.

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$(H\,,\ A \to \tau^+\tau^-)$. If the current CMS bound for the $m_h^{\text{mod}+}$ scenario is somewhat improved, then all values of $\tan\beta$ will be excluded in the m_h^{alt} scenario for large μ.



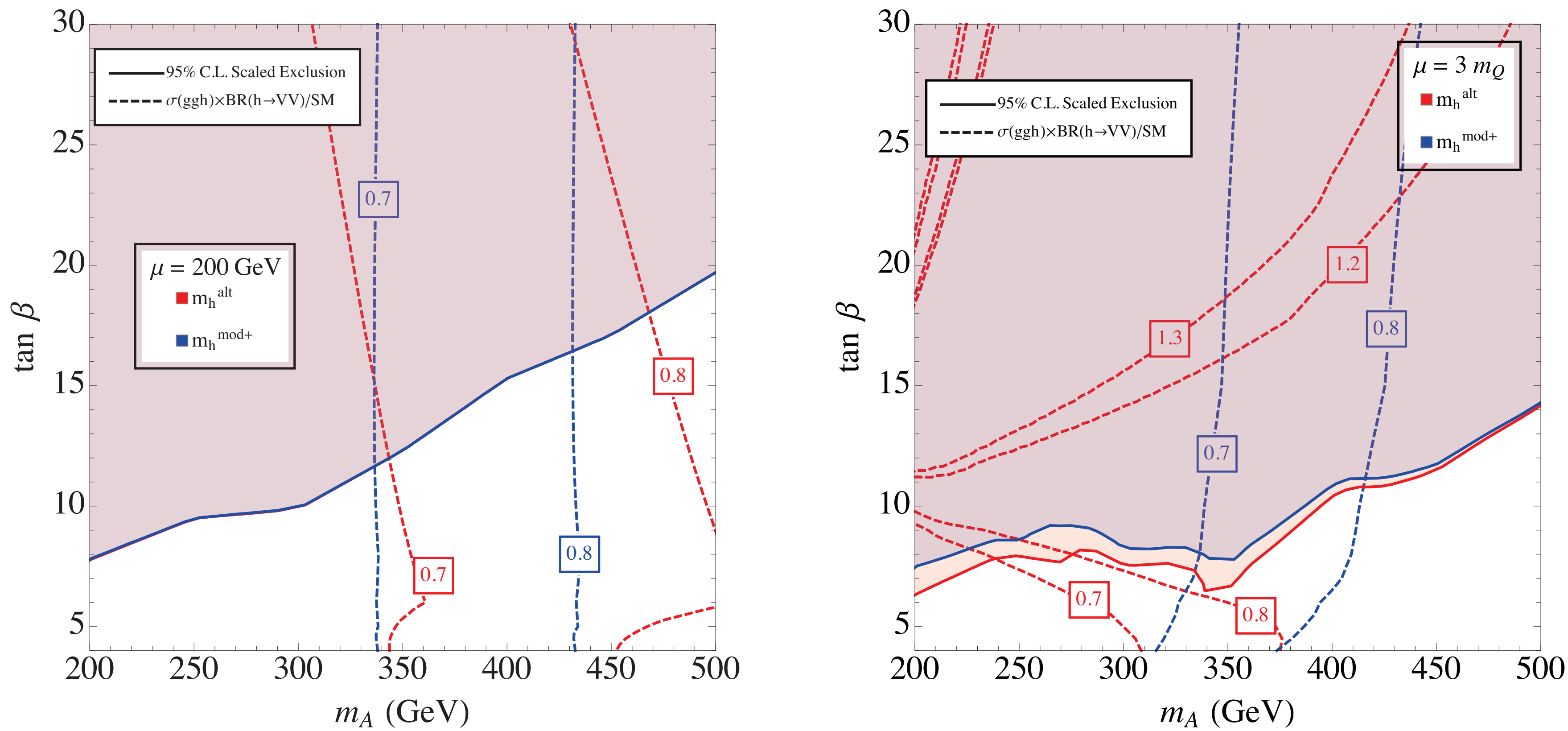


Constraining the m_A–$\tan\beta$ plane from the $h(125)$ data

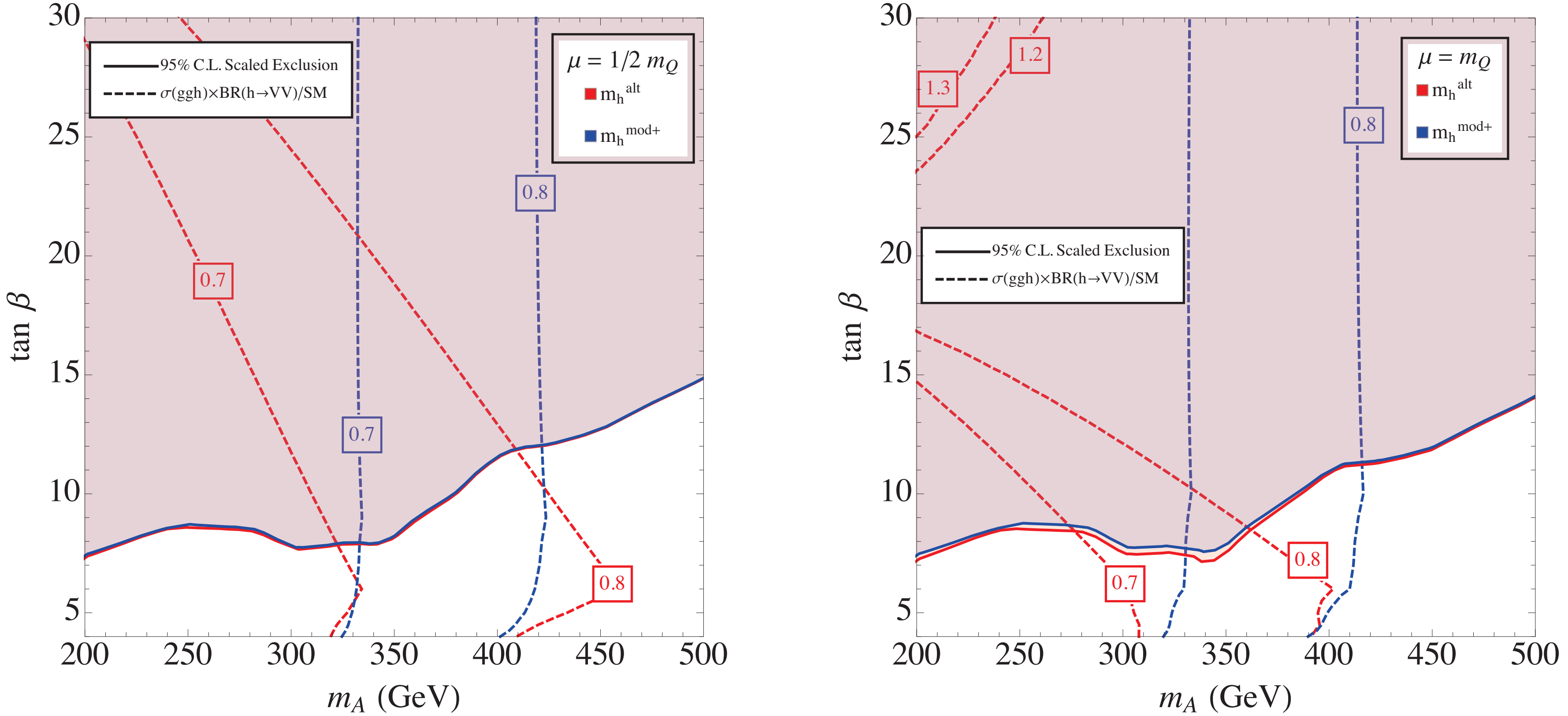


The observed h is SM-like, albeit with somewhat large errors. If the $\sigma \times \mathrm{BR}$ for $h \to VV$ and $h \to \gamma\gamma$ are within 20% or 30% of their SM values, then one can already rule out parts of the m_A–$\tan\beta$ plane.

Complementarity of the H , A search and the h data



The alignment limit is most pronounced at large μ in the m_h^{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 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.

Conclusions

- Current Higgs data suggests that h is SM-like. In the context of the 2HDM (assuming h is the lightest scalar state), this implies that $|c_{\beta-\alpha}| \ll 1$.

- A SM-like h can be achieved either in the decoupling limit (where $m_{H^\pm}, m_A, m_H \gg m_h$) or in the alignment limit where the Higgs basis parameter $|Z_6| \ll 1$. It is possible to have alignment without decoupling, in which case the masses of the heavier Higgs scalars may not be that much larger than m_h.

- In the MSSM Higgs sector, the alignment limit $|Z_6| \ll 1$ 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 tension with the possibility of the alignment limit without decoupling in the MSSM Higgs sector. Under the assumption that no deviation from SM behavior of h is observed, it may be possible to exclude alignment without decoupling in the MSSM at Run-2 of the LHC.