Supersymmetry Confronts a SM-Like Higgs Boson

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Photo taken on July 1, 2023 at Maroon Lake [elevation: 2920 m], located 10 miles from the Aspen Center for Physics, in Colorado USA

Outline

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The LHC data favors a SM-like Higgs boson
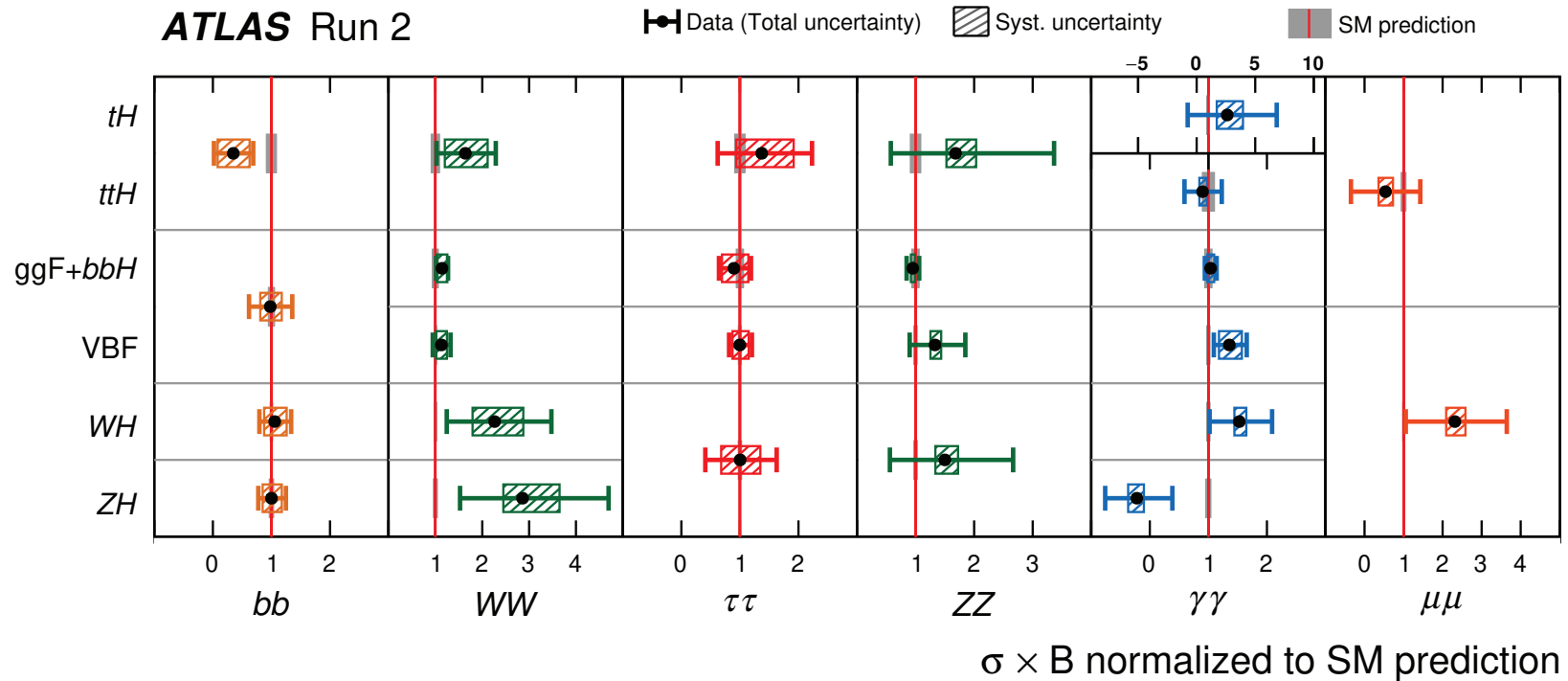
Ratio of observed rate to predicted SM event rate for different combinations of Higgs boson production and decay processes, as observed by the ATLAS Collaboration (based on 139 fb^{-1} of data). The horizontal bar on each point denotes the 68% confidence interval. The narrow grey bands indicate the theory uncertainties in the SM cross section times the branching fraction predictions. The p-value for compatibility of the measurement and the SM prediction is 72%. Taken from The ATLAS Collaboration, "A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery," Nature 607, no. 7917, 52-59 (2022) [arXiv:2207.00092 [hep-ex]].
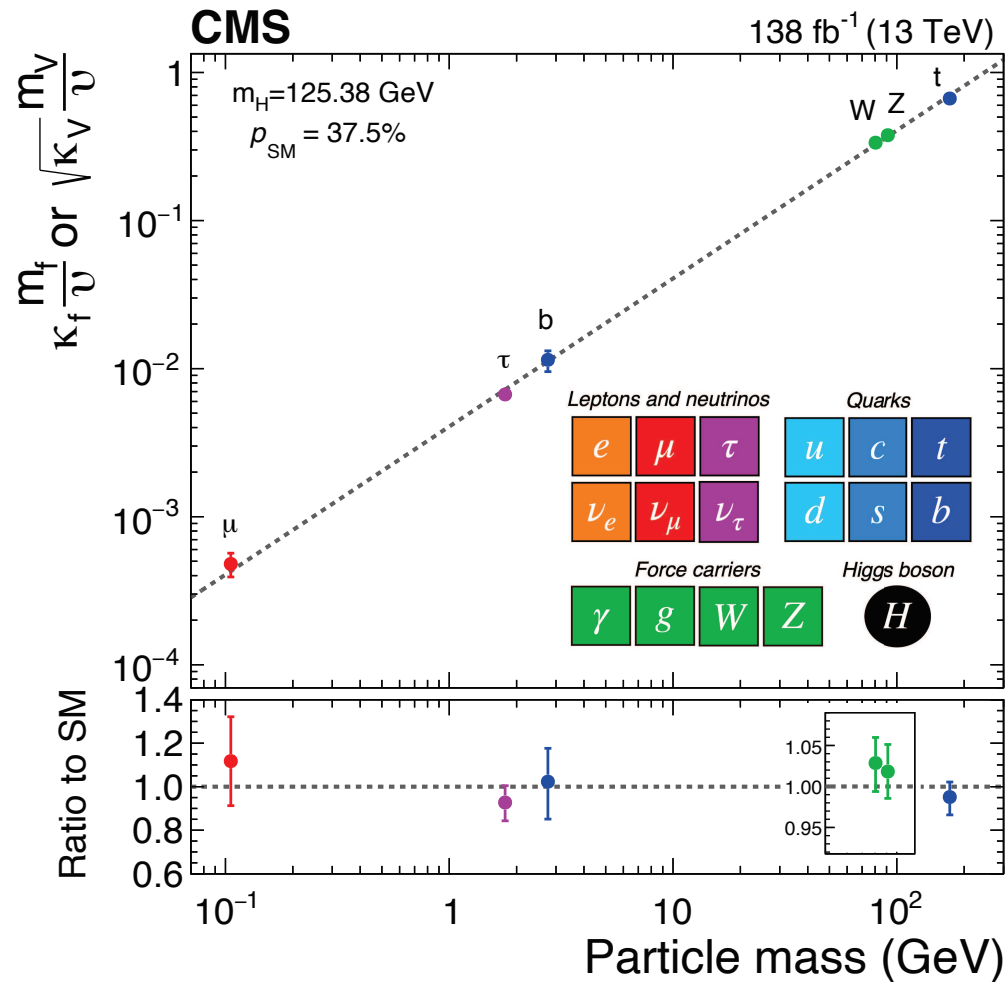
The measured coupling modifiers of the Higgs boson to fermions and heavy gauge bosons, observed by the CMS Collaboration, as functions of fermion or gauge boson mass, where v is the vacuum expectation value of the Higgs field. For gauge bosons, the square root of the coupling modifier is plotted, to keep a linear proportionality to the mass, as predicted in the SM. The p-value with respect to the SM prediction is 37.5%. Taken from The CMS Collaboration, "A portrait of the Higgs boson by the CMS experiment ten years after the discovery," Nature 607, no. 7917, 60-68 (2022) [arXiv:2207.00043 [hep-ex]].

The Higgs sector of the MSSM is a 2HDM with Type II Higgs-fermion Yukawa couplings and with a CP-conserving 2HDM scalar potential, whose dimension-four terms preserve supersymmetry.

Under what conditions does this model contain a SM-like Higgs boson of mass 125 GeV?

Recall that the tree-level bound $m_h \leq m_Z$ is significantly modified by radiative corrections. Including the leading one-loop corrections raises the upper bound,

$$m_h^2 \simeq m_Z^2 c_{2\beta}^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2} \left[\ln \left(\frac{M_S^2}{m_t^2} \right) + \frac{|X_t|^2}{M_S^2} \left(1 - \frac{|X_t|^2}{12 M_S^2} \right) \right],$$

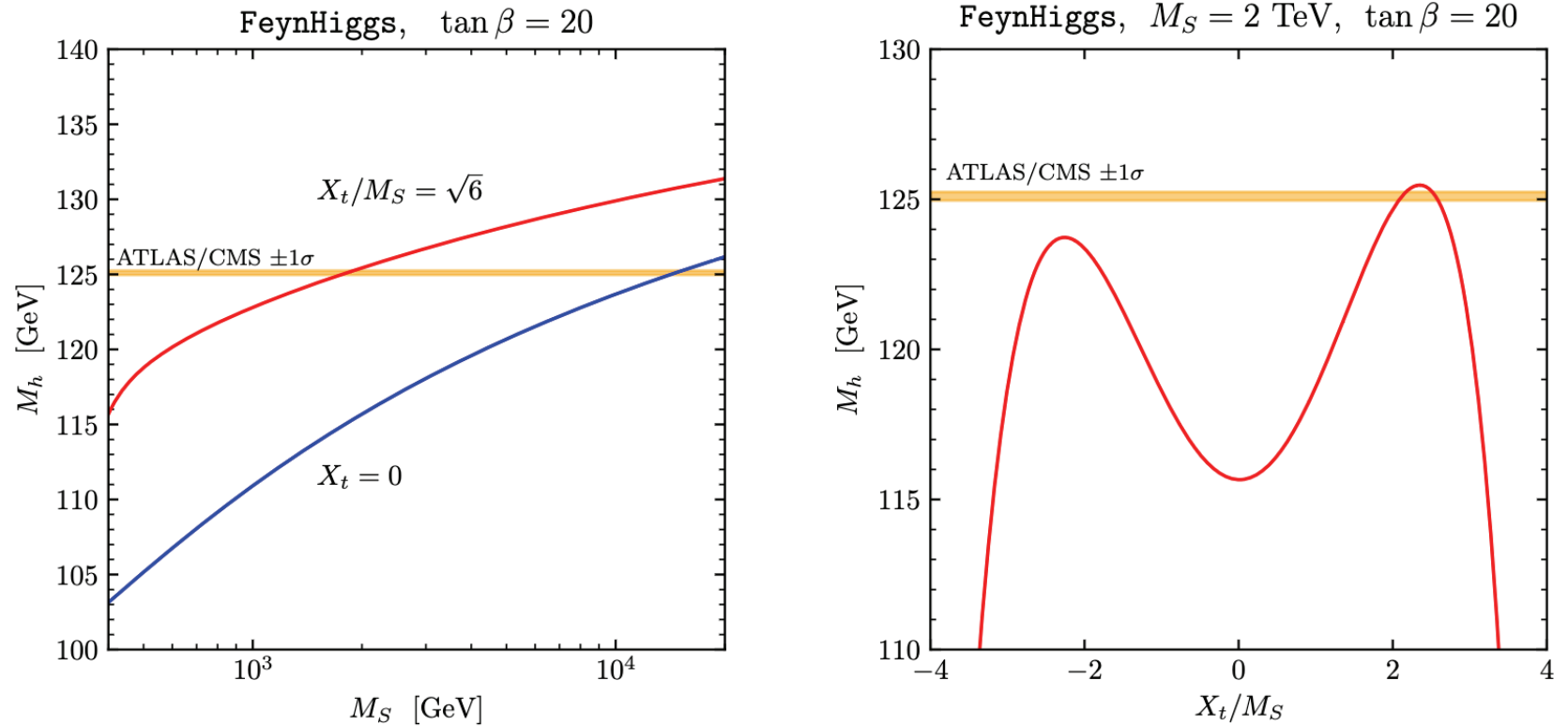where $c_{2\beta} \equiv \cos 2\beta$ and X_t governs top squark mixing.

Figure 1: *The lighter CP-even Higgs mass in the MSSM as a function of a common SUSY mass parameter M_S and of the stop mixing parameter X_t (normalized to M_S). Both parameters are defined in the $\overline{DR}$ scheme at the scale $Q = M_S$.*

Taken from: from P. Slavich, S. Heinemeyer, et al., "Higgs-mass predictions in the MSSM and beyond," Eur. Phys. J. C **81**, 450 (2021) [arXiv:2012.15629 [hep-ph]]. This review article summarizes the efforts of the "Precision SUSY Higgs Mass Calculation Initiative" and represents the state of the art of the radiatively corrected MSSM Higgs sector.

The observed Higgs mass of 125 GeV suggests that if the MSSM is realized in Nature, then the effective scale of SUSY breaking (M_S) is likely to be on the heavy side (i.e., closer to 10 TeV) rather than of $\mathcal{O}(1\ \mathrm{TeV})$ as initially assumed in light of the hierarchy problem.
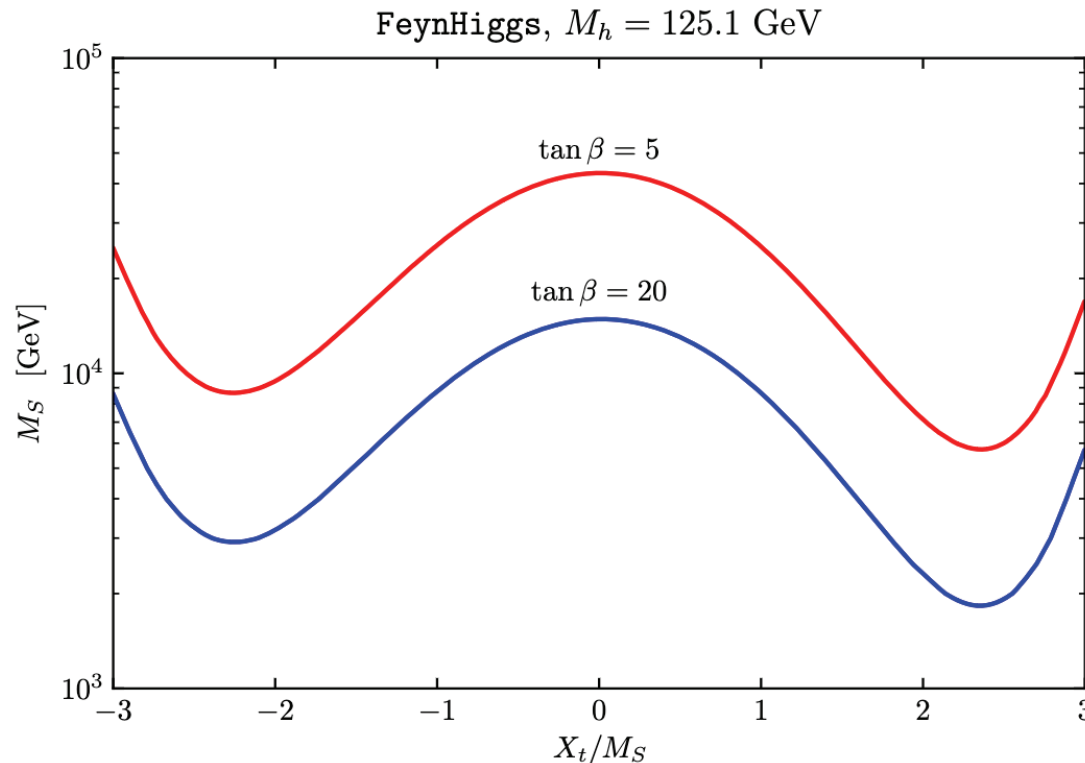

Figure 2: *Values of the SUSY mass parameter M_S and of the stop mixing parameter X_t (normalized to M_S) that lead to the prediction $M_h = 125.1$ GeV, in a simplified MSSM scenario with degenerate SUSY masses, for $\tan\beta = 20$ (blue) or $\tan\beta = 5$ (red).*

Brief Review of the 2HDM

The 2HDM consist of two identical complex hypercharge-one,[1] $SU(2)_L$ doublet scalar fields $\Phi_i(x) \equiv (\Phi_i^+(x), \Phi_i^0(x))$, where the index $i \in \{1,2\}$ labels the two Higgs doublet fields. The scalar is given by,

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}]$$

$$+ \tfrac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$

$$+ \left\{ \tfrac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2) \right] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\}.$$

After minimizing the scalar potential, $\langle \Phi_i \rangle = v_i/\sqrt{2}$, where $v_1 = |v_1|$ and $v_2 = |v_2| e^{i\xi}$ $(0 \leq \xi < 2\pi)$.[2] In particular, $v^2 \equiv |v_1|^2 + |v_2|^2 = (246 \text{ GeV})^2$ and $\tan\beta \equiv |v_2|/|v_1|$.

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[1] The $U(1)_Y$ hypercharge is normalized such that the electric charge is given by $Q = T_3 + Y/2$.

[2] Without loss of generality, we have performed a $U(1)_Y$ transformation to remove the phase of $v_1 = \langle \Phi_1^0 \rangle$.

The Higgs basis

It is convenient to introduce the Higgs basis fields:

$$H_1 = v_1^* \Phi_1 + v_2^* \Phi_2 \,, \qquad H_2 = -v_2 \Phi_1 + v_1 \Phi_2 \,,$$

which satisfy $\langle H_1^0 \rangle = v/\sqrt{2}$ and $\langle H_2^0 \rangle = 0$. The most general renormalizable gauge-invariant scalar potential, in terms of the Higgs basis fields, is given by

$$\mathcal{V} = Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + [Y_3 H_1^\dagger H_2 + \text{h.c.}]$$

$$+ \tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \tfrac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2)$$

$$+ Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \left\{ \tfrac{1}{2} Z_5 (H_1^\dagger H_2)^2 \right.$$

$$\left. + \left[Z_6 H_1^\dagger H_1 + Z_7 H_2^\dagger H_2 \right] H_1^\dagger H_2 + \text{h.c.} \right\} \,.$$

Minimization of the scalar potential fixes $Y_1 = -\frac{1}{2}Z_1 v^2$ and $Y_3 = -\frac{1}{2}Z_6 v^2$. The charged Higgs squared mass is given by

$$m_{H^\pm}^2 = Y_2 + \tfrac{1}{2}Z_3 v^2 \,.$$

For a CP-conserving scalar potential, one can rephase the Higgs basis field H_2 such that all scalar potential parameters (and the vevs v_1 and v_2) are real. In this case, the mass of the CP-odd scalar A is,

$$m_A^2 = m_{H^\pm}^2 + \tfrac{1}{2}(Z_4 - Z_5)v^2 \,.$$

The masses of the CP-even scalars h and H (where $m_h < m_H$) are obtained by diagonalizing a 2×2 squared mass matrix (denoted by $\mathcal{M}_H^2$).

With respect to Higgs basis states $\{\sqrt{2}\,\mathrm{Re}\,H_1^0 - v,\, \sqrt{2}\,\mathrm{Re}\,H_2^0\}$,

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

The CP-even Higgs bosons are h and H with $m_h \leq m_H$. The couplings of $\sqrt{2}\,\mathrm{Re}\,H_1^0 - v$ coincide with those of the SM Higgs boson. Approximate Higgs alignment[3] arises two limiting cases:

1. $m_A^2 \gg (Z_1 - Z_5)v^2$. This is the *decoupling limit*, where h is SM-like and $m_H^2 \sim m_A^2 \sim m_{H^\pm}^2 \gg m_h^2 \simeq Z_1 v^2$.

2. $|Z_6| \ll 1$. Then, h is SM-like if $m_A^2 + (Z_5 - Z_1)v^2 > 0$. Otherwise, H is SM-like.

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[3]Alignment refers to the scalar mass eigenstate aligning with the direction of the scalar vev in field space.

In particular, the CP-even mass eigenstates are:

$$
\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_{\beta-\alpha} & -s_{\beta-\alpha} \\ s_{\beta-\alpha} & c_{\beta-\alpha} \end{pmatrix} \begin{pmatrix} \sqrt{2}\,\mathrm{Re}\,H_1^0 - v \\ \sqrt{2}\,\mathrm{Re}\,H_2^0 \end{pmatrix},
$$

where α is the mixing angle obtained by diagonalizing the scalar squared-mass matrix when written with respect to the Φ-basis, and $\tan\beta \equiv v_2/v_1$. Since $h_{\mathrm{SM}} \equiv \sqrt{2}\,\mathrm{Re}\,H_1^0 - v$,

- h is SM-like if $|c_{\beta-\alpha}| \ll 1$ (alignment with or without decoupling, depending on the magnitude of m_A),

- H is SM-like if $|s_{\beta-\alpha}| \ll 1$ (alignment without decoupling).

The alignment limit in equations

The CP-even Higgs squared-mass matrix yields,

$$Z_1 v^2 = m_h^2 s_{\beta-\alpha}^2 + m_H^2 c_{\beta-\alpha}^2 \,,$$

$$Z_6 v^2 = (m_h^2 - m_H^2) s_{\beta-\alpha} c_{\beta-\alpha} \,,$$

$$Z_5 v^2 = m_H^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2 - m_A^2 \,.$$

If h is SM-like, then $m_h^2 \simeq Z_1 v^2$ (i.e., $Z_1 \simeq 0.26$) and

$$|c_{\beta-\alpha}| = \frac{|Z_6| v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}} \simeq \frac{|Z_6| v^2}{m_H^2 - m_h^2} \ll 1 \,,$$
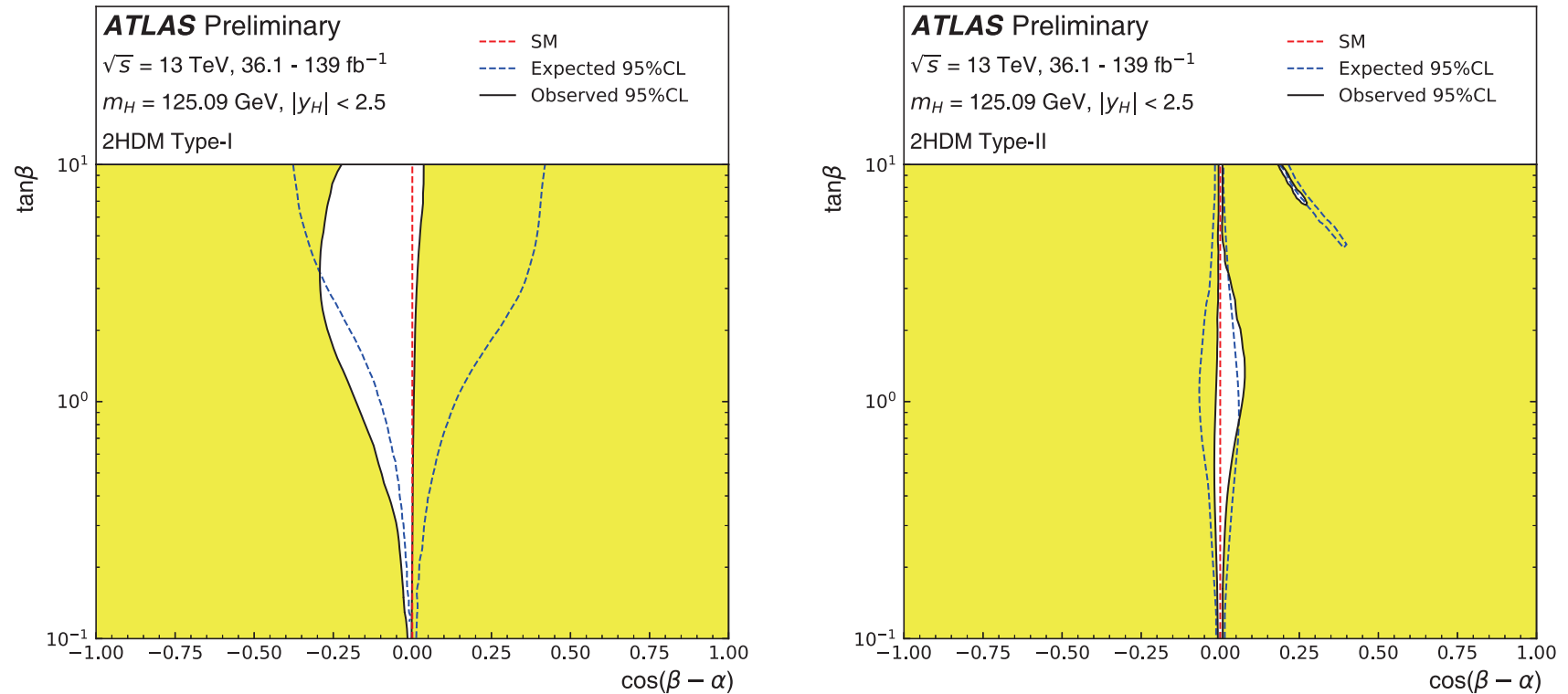
If H is SM-like, then $m_H^2 \simeq Z_1 v^2$ (i.e., $Z_1 \simeq 0.26$) and

$$|s_{\beta-\alpha}| = \frac{|Z_6| v^2}{\sqrt{(m_H^2 - m_h^2)(Z_1 v^2 - m_h^2)}} \simeq \frac{|Z_6| v^2}{m_H^2 - m_h^2} \ll 1 \,.$$

LHC constraints on Higgs alignment in the 2HDM

Regions excluded by fits to the measured rates of the productions and decay of the Higgs boson (assumed to be h of the 2HDM). Contours at 95% CL. The observed best-fit values for $\cos(\beta - \alpha)$ are -0.006 for the Type-I 2HDM and 0.002 for the Type-II 2HDM. Taken from ATLAS Collaboration, ATLAS-CONF-2021-053 (2 November 2021).

Achieving a SM-like Higgs boson in the MSSM

Consider a generic 2HDM. In the decoupling limit, $Y_2 \gg v$ which yields $m_h \ll m_H$ and $m_H \sim m_A \sim m_{H^\pm}$. The SM is the effective low energy theory below the mass scale of the Higgs basis field H_2, and $h \simeq h_{\mathrm{SM}}$.

The same result holds for the MSSM Higgs sector. In the decoupling limit, the discovery of H, A and $H^\pm$ at the LHC will be challenging (if not impossible) due to their large masses.

If the Higgs alignment without decoupling is realized, then $h \simeq h_{\mathrm{SM}}$ whereas H, A, and $H^\pm$ have masses of order the electroweak scale and are more readily produced and observed at the LHC.

Brief Review of the MSSM Higgs sector at tree-level

At tree level, the Higgs basis parameters of interest are fixed by SUSY:

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

It follows that,

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

The decoupling limit is achieved when $m_H \gg m_h$ as expected. Alignment without decoupling is (naively) possible at tree-level when $Z_6 = 0$, which yields $\sin 4\beta \simeq 0$. However, this limit is not phenomenologically viable. In any case, radiative corrections are required to obtain the observed Higgs mass of 125 GeV.

The MSSM employs the Type–II Higgs–fermion Yukawa couplings. In terms of $H_D^i \equiv \epsilon_{ij}\Phi_1^{j\,*}$ and $H_U^i = \Phi_2^i$,

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

which yields $m_b = h_b v c_\beta/\sqrt{2}$ and $m_t = h_t v s_\beta/\sqrt{2}$.

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, and depend on the SUSY parameters μ, A_t,

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

where $\widetilde{Q} = \begin{pmatrix}\widetilde{t}_L \\ \widetilde{b}_L\end{pmatrix}$ and $\widetilde{U} \equiv \widetilde{t}_R^*$.

Employing the Higgs basis fields H_1 and H_2,

$$\mathscr{L}_{\text{int}} \ni h_t \epsilon_{ij} \left[(\sin\beta X_t H_1^i + \cos\beta Y_t H_2^i) \widetilde{Q}^j \widetilde{U} + \text{h.c.} \right]$$

$$- h_t^2 \left\{ \left[s_\beta^2 |H_1|^2 + c_\beta^2 |H_2|^2 + \sin\beta\cos\beta (H_1^\dagger H_2 + \text{h.c.}) \right] (\widetilde{Q}^\dagger \widetilde{Q} + \widetilde{U}^* \widetilde{U}) \right.$$

$$\left. - s_\beta^2 |\widetilde{Q}^\dagger H_1|^2 - c_\beta^2 |\widetilde{Q}^\dagger H_2|^2 - \sin\beta\cos\beta \left[(\widetilde{Q}^\dagger H_1)(H_2^\dagger \widetilde{Q}) + \text{h.c.} \right] \right\},$$

where

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

Assuming CP-conservation for simplicity, we shall henceforth take μ, A_t real, and adopt a convention where $\tan\beta$ is (real and) positive.

One-loop corrections to the CP-even Higgs squared-mass matrix

The dominant one-loop corrected expressions for Z_1, Z_5, and Z_6, which appear in the squared-mass matrix of the CP-even scalars, are given by[4]

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

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

$$Z_6 v^2 = -s_{2\beta}\left\{ m_Z^2 c_{2\beta} - \frac{3 v^2 s_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t(X_t + Y_t)}{2 M_S^2} - \frac{X_t^3 Y_t}{12 M_S^4}\right]\right\},$$
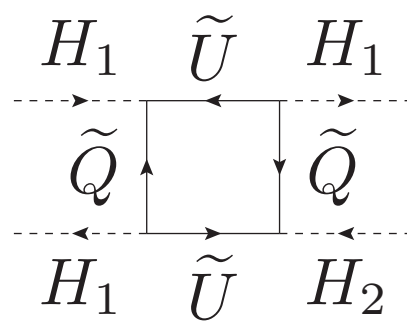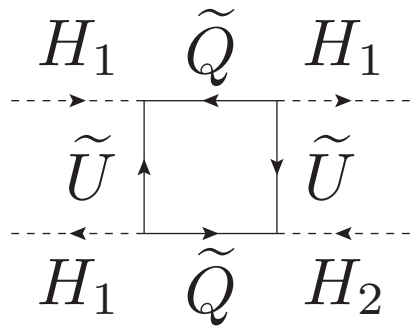
where $M_S^2 \equiv m_{\tilde{t}_1} m_{\tilde{t}_2}$, $X_t \equiv A_t - \mu \cot\beta$ and $Y_t = A_t + \mu \tan\beta$.
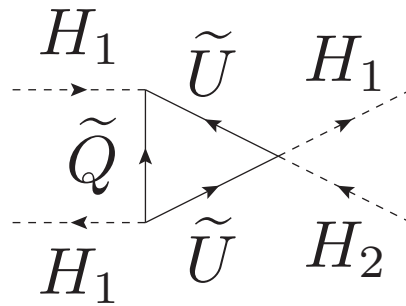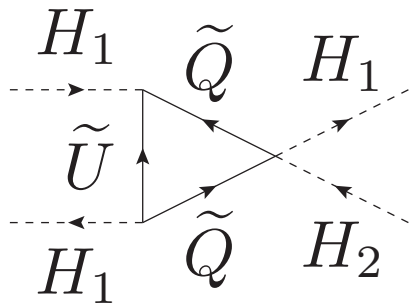
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[4] CP-violating phases that could appear in the MSSM parameters such as μ and A_t are neglected. For more details and an extension to the leading two-loop corrections, see H.E. Haber, S. Heinemeyer and T. Stefaniak, arXiv:1708.04416.
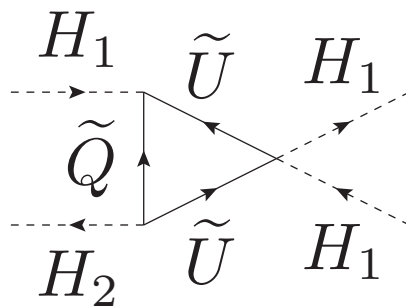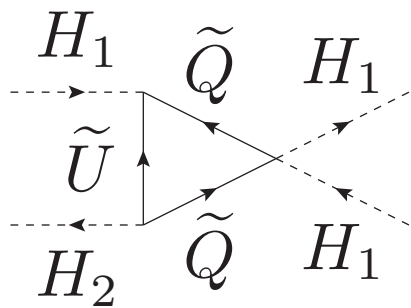
Example: One-loop threshold corrections to Z_6

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

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

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

Higgs alignment without decoupling (i.e., $Z_6 = 0$) can now be achieved due to an accidental cancellation between tree-level and loop contributions.

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

Solving for $\ln(M_S^2/m_t^2)$ in terms of Z_1,[5] we end up with a 7th order polynomial equation for $t_\beta \equiv \tan\beta$ as a function of $\widehat{A}_t \equiv A_t/M_S$ and $\widehat{\mu} \equiv \mu/M_S$,
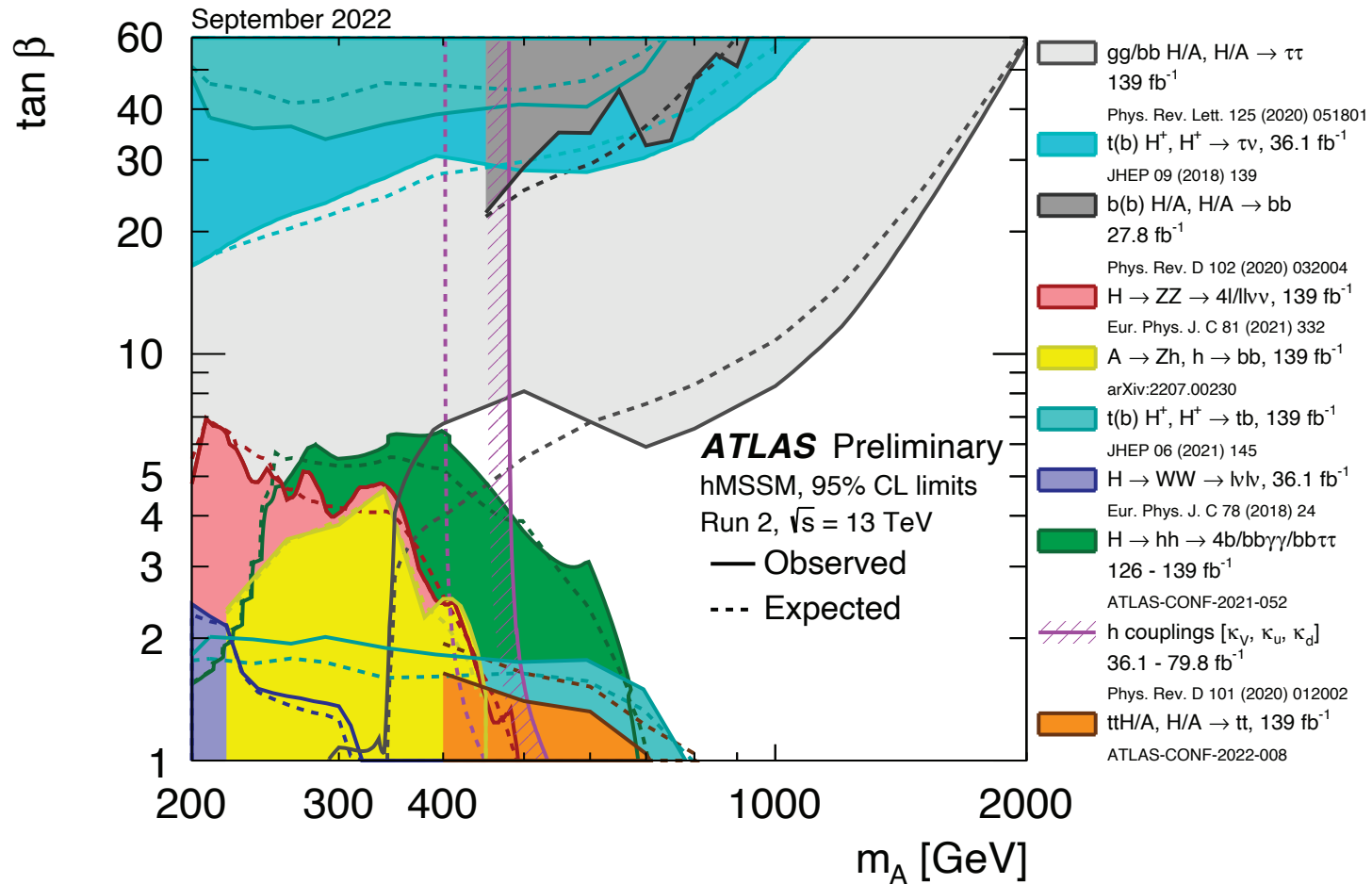
$$m_Z^2 t_\beta^4(1 - t_\beta^2) - Z_1 v^2 t_\beta^4(1 + t_\beta^2) + \frac{3m_t^4\widehat{\mu}(\widehat{A}_t t_\beta - \widehat{\mu})(1 + t_\beta^2)^2}{4\pi^2 v^2}\left[\tfrac{1}{6}(\widehat{A}_t t_\beta - \widehat{\mu})^2 - t_\beta^2\right] = 0\,,$$

which can be solved numerically for real positive solutions.

---

[5]Note that $m_h^2 \simeq Z_1 v^2$ yields the leading contribution to the one-loop radiatively corrected Higgs mass in the Higgs alignment limit.

Alignment without Decoupling in the MSSM Higgs sector?

Regions of the $(m_A, \tan\beta)$ plane in the hMSSM excluded via direct searches for heavy Higgs bosons and fits to the measured rates of observed Higgs boson production and decays. Limits are quoted at 95% CL and are indicated for the data (solid lines) and the expectation for the SM Higgs sector (dashed lines). Taken from ATL-PHYS-PUB-2022-043 (12 September 2022).

Comment on the hMSSM

Working in the Φ-basis (where the supersymmetry of the dimension-four terms of the scalar potential is manifest), the one-loop corrected CP-even Higgs squared mass matrix with respect to the basis $\{\sqrt{2}\,\mathrm{Re}\,H_d^0 - v_d\,,\ \sqrt{2}\,\mathrm{Re}\,H_u^0 - v_u\}$:

$$\mathcal{M}^2 = \begin{pmatrix} m_A^2 s_\beta^2 + m_Z^2 c_\beta^2 + \varepsilon_{11} & -(m_A^2 + m_Z^2)s_\beta c_\beta + \varepsilon_{12} \\ -(m_A^2 + m_Z^2)s_\beta c_\beta + \varepsilon_{12} & m_A^2 c_\beta^2 + m_Z^2 s_\beta^2 + \varepsilon_{22} \end{pmatrix}.$$

The leading one-loop radiative correction proportional to m_t^4 resides in ε_{22}. The hMSSM sets $\varepsilon_{11} = \varepsilon_{12} = 0$ and regards ε_{22} as a free parameter that is adjusted to obtain $m_h \simeq 125$ GeV.[6]

However, this is too crude an approximation, which can miss phenomena that arise in a more general pMSSM scan.

[6]A. Djouadi, L. Maiani, G. Moreau, A. Polosa, J. Quevillon and V. Riquer, arXiv:1307.5205.

For example, in the so-called MSSM m_h^{alt} benchmark scenario, the precision Higgs data places virtually no bound on m_A if $\tan\beta \sim 10$, due to Higgs alignment without decoupling.
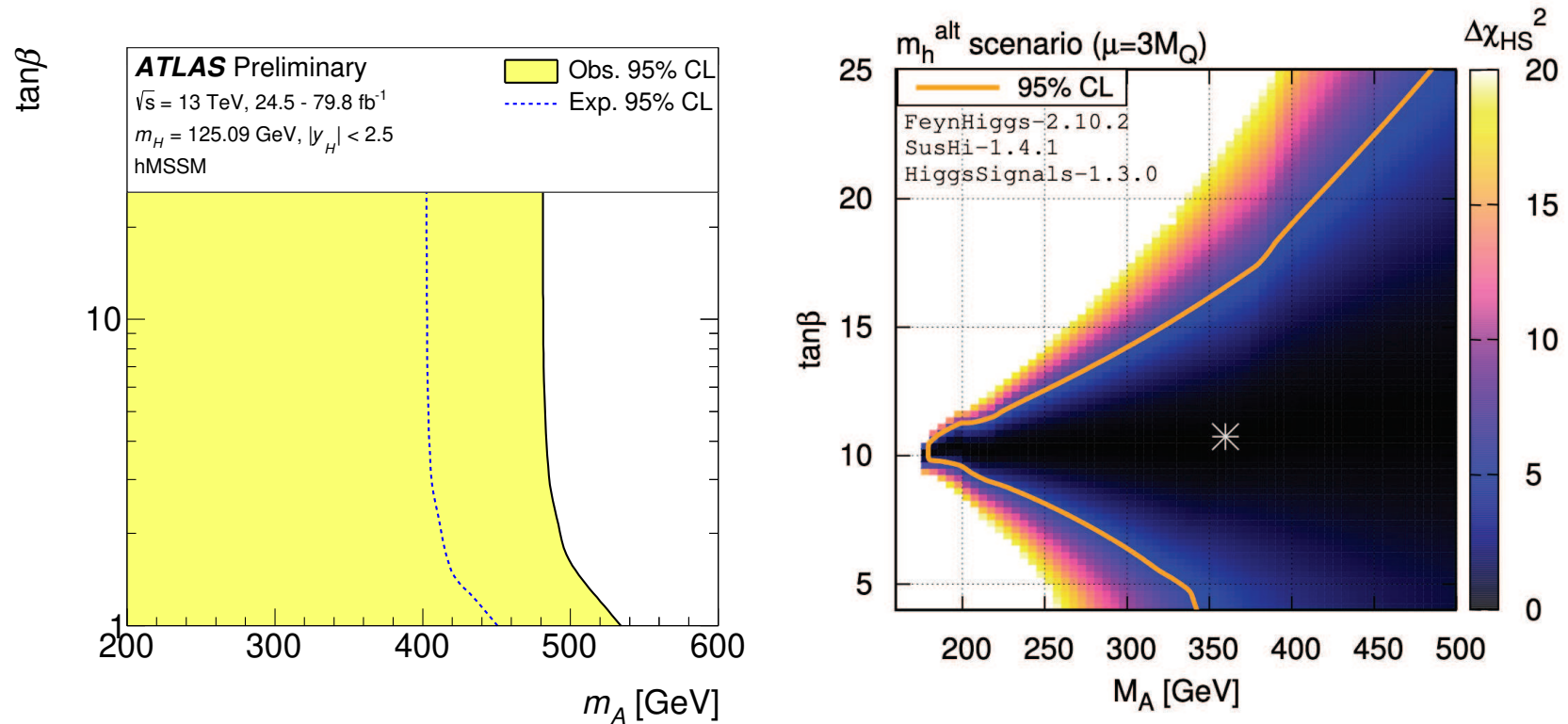
Right panel: Likelihood distribution, $\Delta\chi^2_{\mathrm{HS}}$ obtained from testing the signal rates of h against a combination of Higgs rate measurements from the Tevatron and LHC experiments, obtained with `HiggsSignals`, in the m_h^{alt} benchmark scenario proposed by M. Carena et al., arXiv:1410.4969. Taken from P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak and G. Weiglein, arXiv:1507.06706.

Benchmarks for MSSM Higgs alignment[7]

Case 1: h is SM-like

$$M_{Q_3} = M_{U_3} = M_{D_3} = 2.5 \text{ TeV}, \qquad M_{L_3} = M_{E_3} = 2 \text{ TeV},$$

$$\mu = 7.5 \text{ TeV}, \quad M_1 = 500 \text{ GeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV}$$

$$A_t = A_b = A_\tau = 6.25 \text{ TeV}.$$

Case 2: H is SM-like

$$M_{Q_3} = M_{U_3} = 750 \text{ GeV} - 2(m_{H^\pm} - 150 \text{ GeV}),$$

$$\mu = \left[5800 \text{ GeV} + 20(m_{h^\pm} - 150 \text{ GeV}) \right] M_{Q_3}/(750 \text{ GeV}),$$

$$A_t = A_b = A_\tau = 0.65 M_{Q_3}, \quad M_{D_3} = M_{L_3} = M_{E_3} = 2 \text{ TeV},$$

$$M_1 = M_{Q_3} - 75 \text{ GeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV}.$$

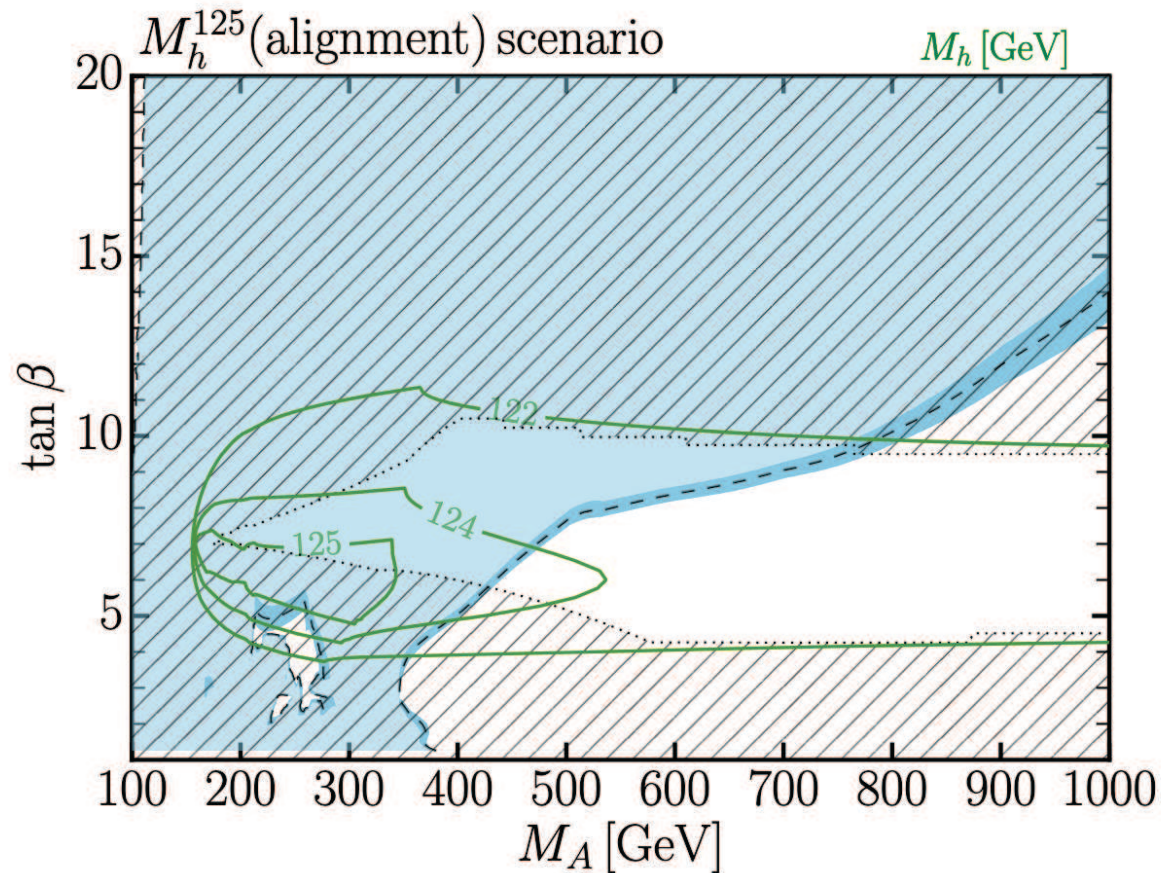[7]Taken from E. Bagnaschi et al., arXiv:1808.07542.

Case 1: h is SM-like

Figure 9: Constraints on the M_h^{125}(alignment) scenario from Higgs searches at the LHC, in the $(M_A, \tan\beta)$ plane. The green solid lines are predictions for the mass of the lighter $\mathcal{CP}$-even scalar h, the hatched area is excluded by a mismatch between the properties of h and those of the observed Higgs boson, and the blue area is excluded by the searches for additional Higgs bosons (the darker-blue band shows the theoretical uncertainty of the exclusion).

Taken from E. Bagnaschi et al., arXiv:1808.07542.

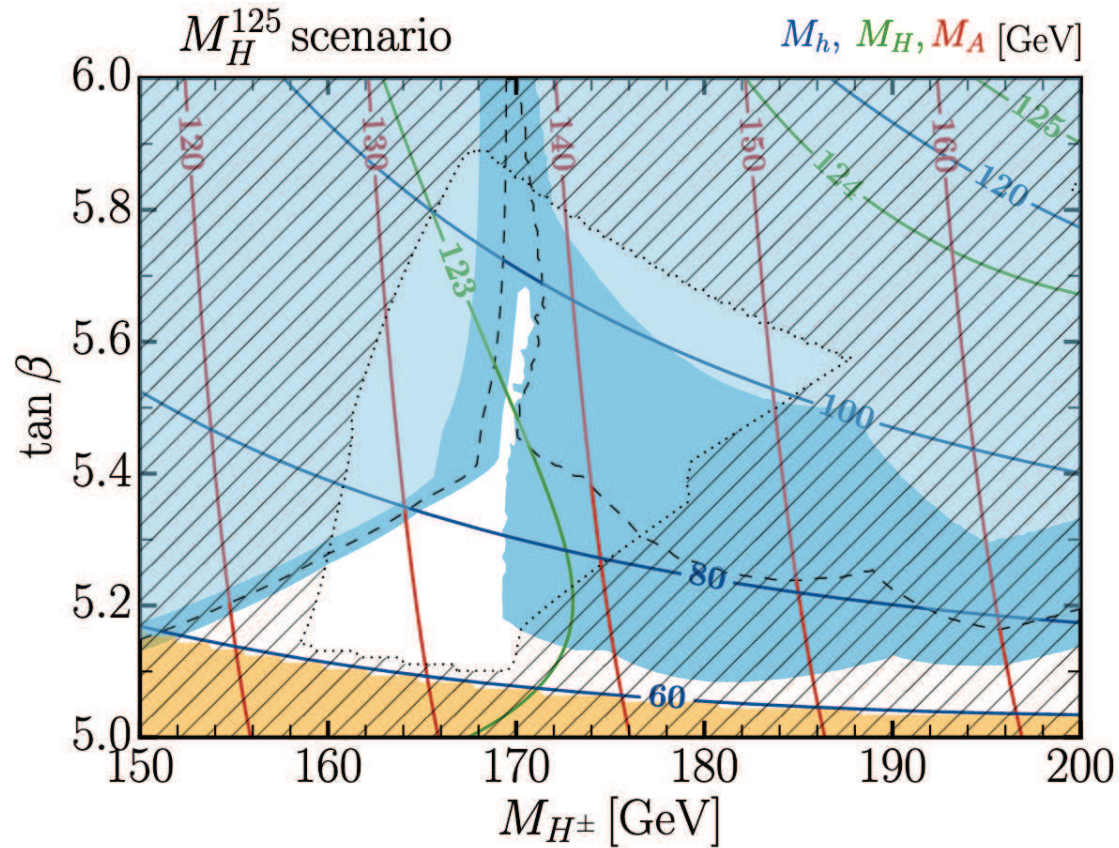## Case 2: H is SM-like (Higgs alignment without decoupling)

Figure 10: Constraints on the M_H^{125} scenario from Higgs searches at the LHC, in the $(M_{H^\pm}, \tan\beta)$ plane. The blue, green and red solid lines are predictions for the masses of h, H and A, respectively. The hatched area is excluded by a mismatch between the properties of H and those of the observed Higgs boson, and the areas bounded by dashed lines are excluded by the searches for additional Higgs bosons (the darker-blue band shows the theoretical uncertainty of the exclusion). At low $\tan\beta$, the orange area is excluded by searches for $H \to hh$.

Taken from E. Bagnaschi et al., arXiv:1808.07542.

How fine-tuned is the alignment without decoupling in the MSSM?
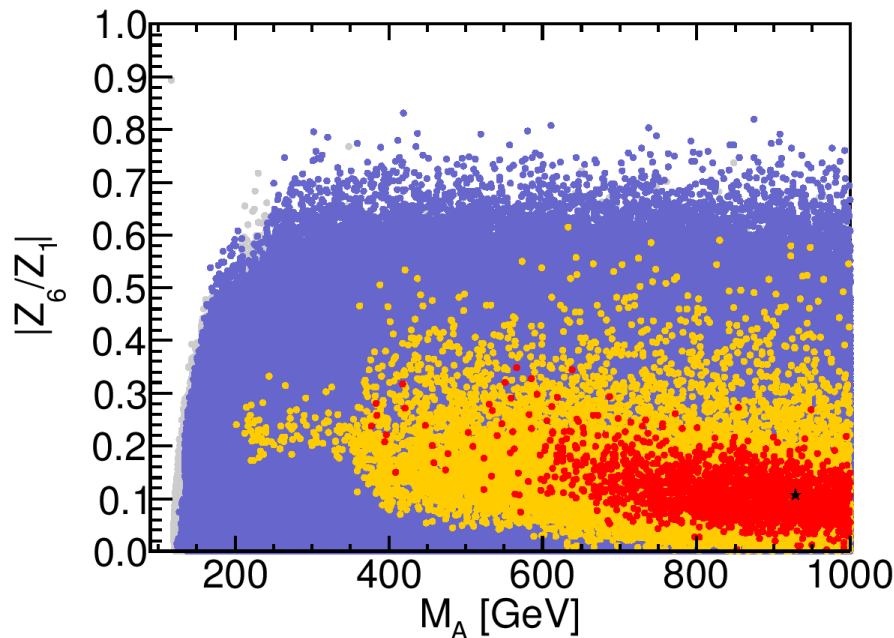
SM-like h
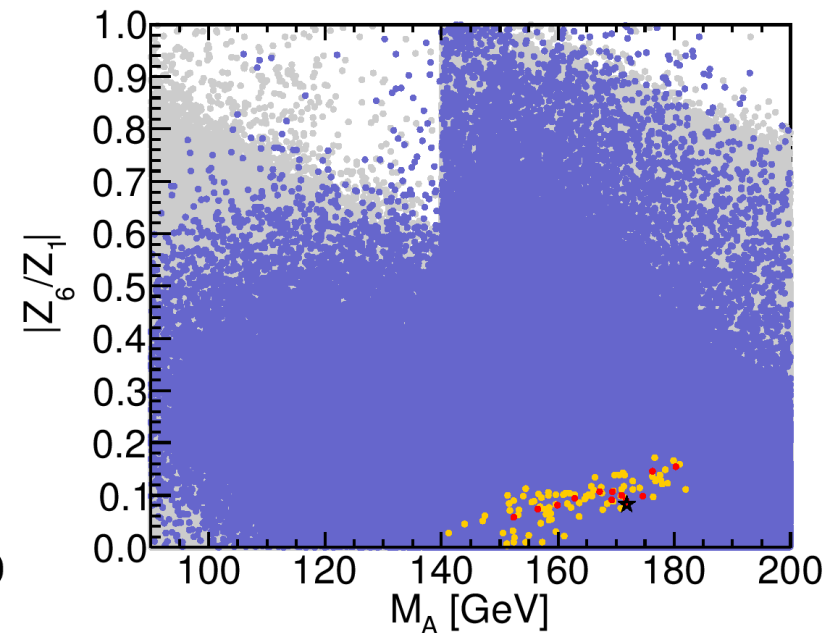
SM-like H

Points that do not pass the direct constraints from Higgs searches from `HiggsBounds` and from LHC SUSY particle searches from `CheckMATE` are shown in gray. Applying a global likelihood analysis to the points that pass the direct constraints, the color code employed is red for $\Delta\chi_h^2 < 2.3$, yellow for $\Delta\chi_h^2 < 5.99$ and blue otherwise. The best fit point is indicated by a black star. Near the alignment limit, $m_h = 125$ GeV corresponding to $Z_1 \simeq 0.26$. Parameter regions with $Z_6 \sim 0.05$ are compatible with approximate alignment without decoupling (cf. $Z_6 = 0$ at exact alignment). Taken from P. Bechtle, H.E. Haber, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein, and L. Zeune, arXiv:1608.00638.

Adding a Higgs singlet to the 2HDM

Consider a Higgs sector that consists of two hypercharge-one complex doublet and a complex neutral singlet S. We can define the doublet fields of the Higgs basis, H_1 and H_2 as before. The relevant scalar potential is more complicated than that of the 2HDM. Here we focus on the terms that are relevant for the scalar squared-mass matrices.

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

$$+ S^\dagger S\left[Z_{s1}H_1^\dagger H_1 + \ldots + (Z_{s3}H_1^\dagger H_2 + \text{h.c.}) + Z_{s4}S^\dagger S\right]$$

$$+ \left\{Z_{s5}H_1^\dagger H_1 S^2 + \ldots + Z_{s7}H_1^\dagger H_2 S^2 + Z_{s8}H_2^\dagger H_1 S^2 + Z_{s9}S^\dagger S\,S^2 + Z_{s10}S^4 + \text{h.c.}\right\}$$

$$+ \left[C_1 H_1^\dagger H_1 S + \ldots + C_3 H_1^\dagger H_2 S + C_4 H_2^\dagger H_1 S + C_5(S^\dagger S)S + C_6 S^3 + \text{h.c.}\right].$$

The squared-mass matrix of the CP-even Higgs bosons with respect to the basis $\{\sqrt{2}\,\mathrm{Re}\,H_1^0 - v\,,\ \sqrt{2}\,\mathrm{Re}\,H_2^0\,,\ \sqrt{2}\,(\mathrm{Re}\,S - v_s)\}$ is a real symmetric matrix,

$$
\mathcal{M}_S^2 =
\begin{pmatrix}
Z_1 v^2 & Z_6 v^2 & \sqrt{2}\,v\big[C_1 + (Z_{s1} + 2Z_{s5})v_s\big] \\[2mm]
 & \overline{M}_A^2 + Z_5 v^2 & \dfrac{v}{\sqrt{2}}\Big[C_3 + C_4 + 2(Z_{s3} + Z_{s7} + Z_{s8})v_s\Big] \\[2mm]
 & & -C_1\dfrac{v^2}{2v_s} + 3(C_5 + C_6)v_s + 4(Z_{s4} + 2Z_{s9} + 2Z_{s10})v_s^2
\end{pmatrix},
$$

where $\overline{M}_A^2$ is the 11 element of the CP-odd squared-mass matrix with respect to the basis $\{\sqrt{2}\,\mathrm{Im}\,H_2^0\,,\ \sqrt{2}\,\mathrm{Im}\,S\}$.

Exact alignment occurs when $(\mathcal{M}_S^2)_{12} = (\mathcal{M}_S^2)_{13} = 0$. That is,

$$
Z_6 = 0\,, \qquad\qquad C_1 + (Z_{s1} + 2Z_{s5})v_s = 0\,.
$$

The decoupling limit corresponds to $\overline{M}_A \gg v$ and $v_s \gg v$ and yields approximate alignment.

Approximate alignment can also be achieved with a combination of a subset of the above conditions. For example, $\overline{M}_A \gg v$ [with $Z_6 \sim \mathcal{O}(1)$] and $C_1 + (Z_{s1} + 2Z_{s5})v_s \simeq 0$ yields approximate alignment.

The alignment limit of the NMSSM Higgs sector

The NMSSM adds a singlet superfield $\hat{S}$, which couples to itself and to the Higgs superfields $\hat{H}_U$, $\hat{H}_D$ via the superpotential, $W = \lambda \hat{S} \hat{H}_U \hat{H}_D + \frac{1}{3}\kappa \hat{S}^3$.

Including the leading one-loop radiative corrections,

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

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

$$Z_6 v^2 = -s_{2\beta}\left\{(m_Z^2 - \tfrac{1}{2}\lambda^2 v^2)c_{2\beta} - \frac{3v^2 s_\beta^2 h_t^4}{16\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t(X_t + Y_t)}{2M_S^2} - \frac{X_t^3 Y_t}{12M_S^4}\right]\right\}.$$

The scalar singlet field S acquires a vev v_s. Consequently, an effective μ term and B term are generated:

$$\mu \equiv \lambda v_s \,, \qquad B \equiv A_\lambda + \kappa v_s \,,$$

where A_λ is a soft-SUSY-breaking trilinear scalar coupling parameter. We can identify

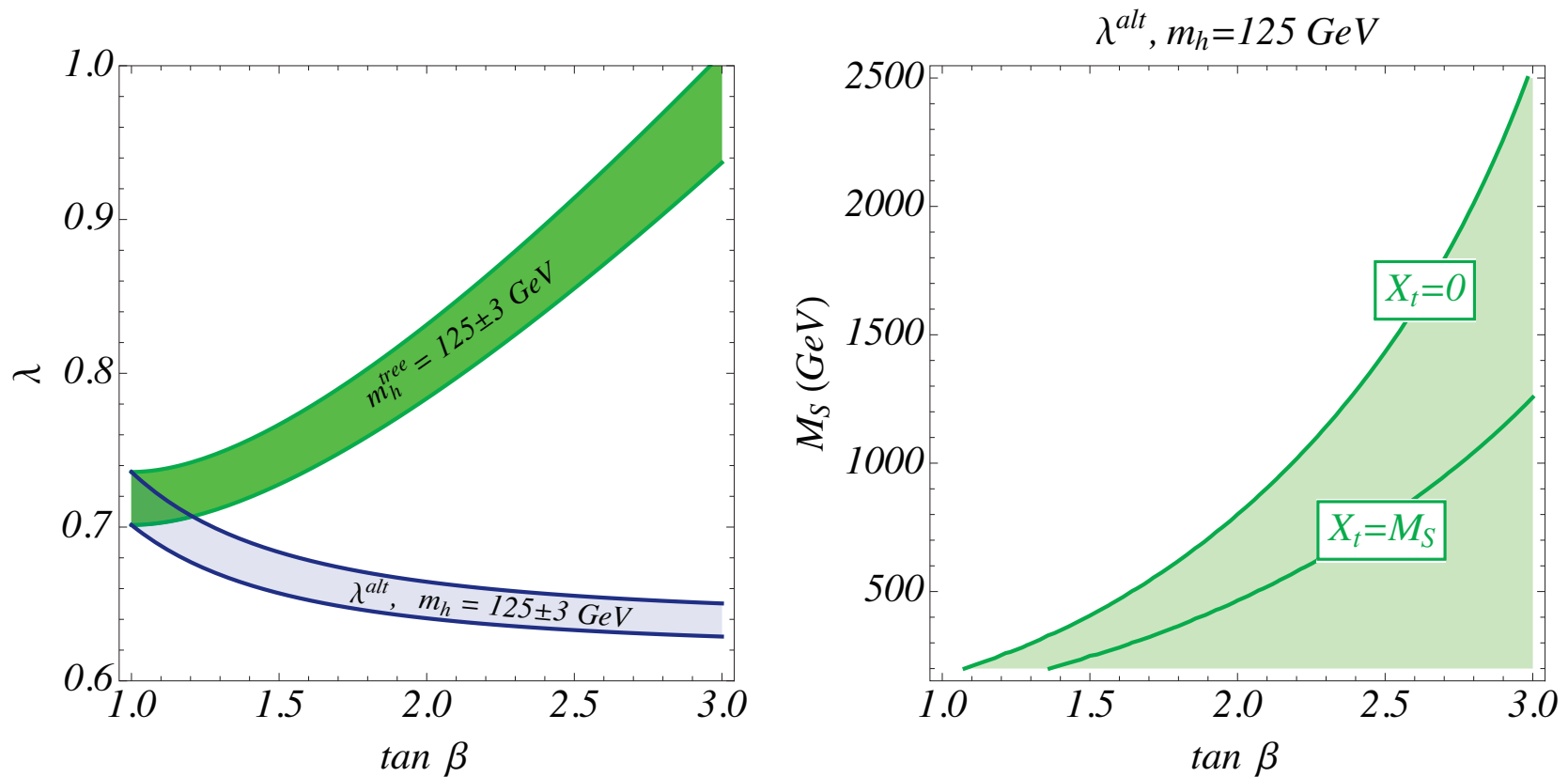$$\overline{M}_A^{\,2} \equiv \frac{\mu B}{s_\beta c_\beta} \,.$$

Imposing the Higgs alignment conditions for the NMSSM (namely, $Z_6 = 0$ and $C_1 + (Z_{s1} + 2Z_{s5})v_s = 0$) yields:

$$\lambda^2 \simeq (\lambda^{\rm alt})^2 \equiv \frac{m_h^2 - m_Z^2 c_{2\beta}}{v^2 s_\beta^2} \,, \qquad \frac{\overline{M}_A^{\,2} s_{2\beta}^2}{4\mu^2} + \frac{\kappa s_{2\beta}}{2\lambda} = 1 \,,$$

In the NMSSM with $Z_6 = 0$, one obtains $m_h = 125$ GeV, with only small contributions from the one-loop radiative corrections. This leads to a preferred choice of NMSSM parameters,[8]

$$\lambda \simeq \lambda^{alt} \sim 0.65 \,, \qquad \tan\beta \sim 2 \,.$$

[8]See M. Carena, H.E. Haber, I. Low, N.R. Shah and C.E.M. Wagner, arXiv:1510.09137.

The second Higgs alignment condition leads to further correlations among the parameters of the NMSSM Higgs sector.

$$\lambda^{alt}, \; \kappa = \lambda^{alt}/2,$$
$$m_{h_S}(GeV), \; t_\beta = 2, \; m_h = 125 \; GeV$$
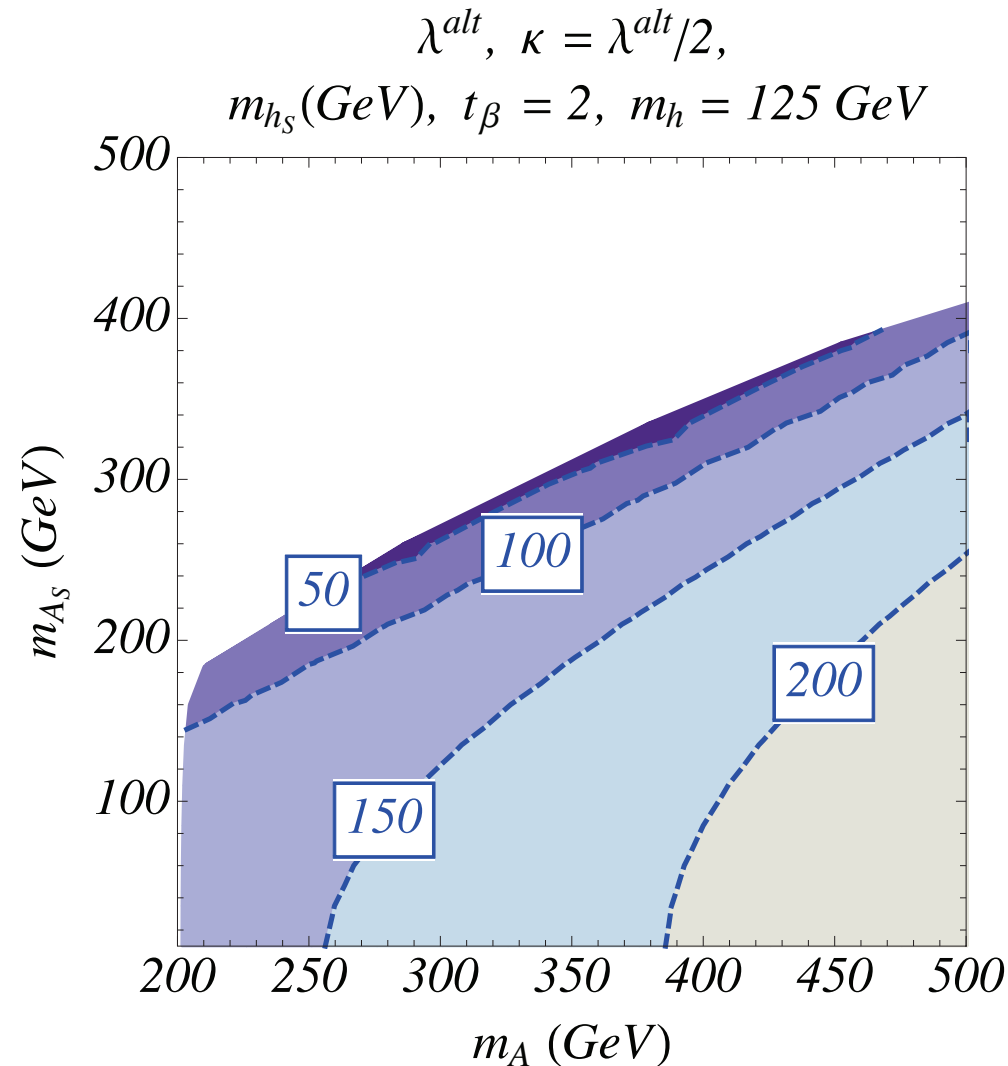
Near the Higgs alignment limit, we have $m_A \simeq m_H \simeq \overline{M}_A$.

Conclusions

- In light of the LHC Higgs data, one of the Higgs mass eigenstates is approximately aligned in field space with the direction of the Higgs vev.

- Higgs alignment is approximately satisfied in the decoupling regime where $m_A \gg m_h$. But, approximate Higgs alignment can also be achieved without decoupling if the Higgs basis parameter $|Z_6| \ll 1$.

- Higgs alignment without decoupling is possible in the MSSM, but it is achieved in a parameter regime in which there is an accidental approximate cancellation between tree-level and loop-level contributions to Z_6.

- Regions of approximate Higgs alignment without decoupling must necessarily appear in any comprehensive scan of the MSSM parameter space. This regime is still possible in light of current LHC data.

- Higgs alignment without decoupling in the NMSSM can arise in a compelling region of the parameter space, which leads to intriguing correlations among Higgs sector parameters.