SUSY Higgs sector

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BSM Higgs Workshop

Fermilab

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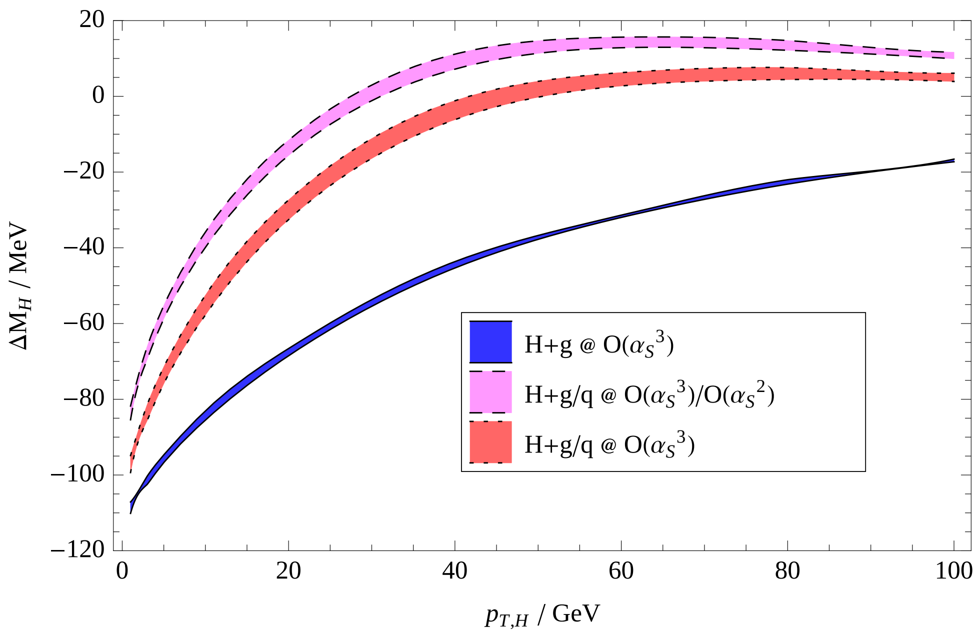
ATLAS: 125.36 ± 0.37(stat) $\pm\, 0.18$(sys) GeV

CMS: $125.03\,^{+0.26}_{-0.27}$(stat) $^{+0.13}_{-0.15}$(sys) GeV

As long as we're going to report M_h to the nearest 10 MeV...

Interference with background shifts the $\gamma\gamma$ peak lower

SPM 1208.1533, 1303.3342; deFlorian et al 1303.1397, Dixon and Li, 1305.3854.



Present state-of-the art is Dixon and Li 1305.3854, full NLO

Shift depends on $p_T(H)$.

Inclusive shift is 70 MeV.

Worthwhile taking into account in Run 2 just for M_h.

At tree-level, MSSM Higgs sector just a special case of a type-II Two Higgs Doublet Model.

$$\lambda_1 = \lambda_2 = (g^2 + g'^2)/4, \qquad \lambda_3 = (g^2 - g'^2)/4,$$
$$\lambda_4 = -g^2/2, \qquad \lambda_5 = \lambda_6 = \lambda_7 = 0.$$

Define mass-eigenstate Higgs bosons: h, H, A, G, H^+, G^+ by:

$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix} + \frac{i}{\sqrt{2}} \begin{pmatrix} \sin\beta & \cos\beta \\ -\cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

$$\begin{pmatrix} H_u^+ \\ H_d^{-*} \end{pmatrix} = \begin{pmatrix} \sin\beta & \cos\beta \\ -\cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$$

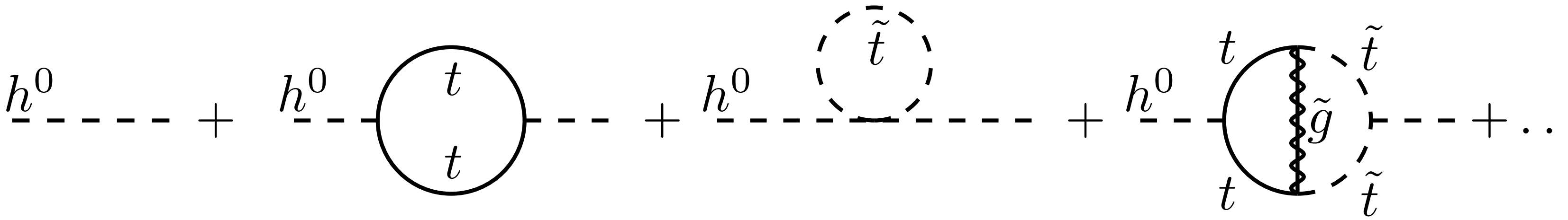
Now, expand the potential to second order in these fields to obtain the masses:

$$m_{H^\pm}^2 = m_A^2 + m_W^2$$
$$m_{h,H}^2 = \tfrac{1}{2}\left(m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 + m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta}\right),$$

Radiative corrections are large, necessarily, for m_h^2.

Loop corrections to the Higgs mass in SUSY:

$$m_{h^0}^2 = m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2} y_t^2 m_t^2 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \text{stop-mixing term} + \ldots$$



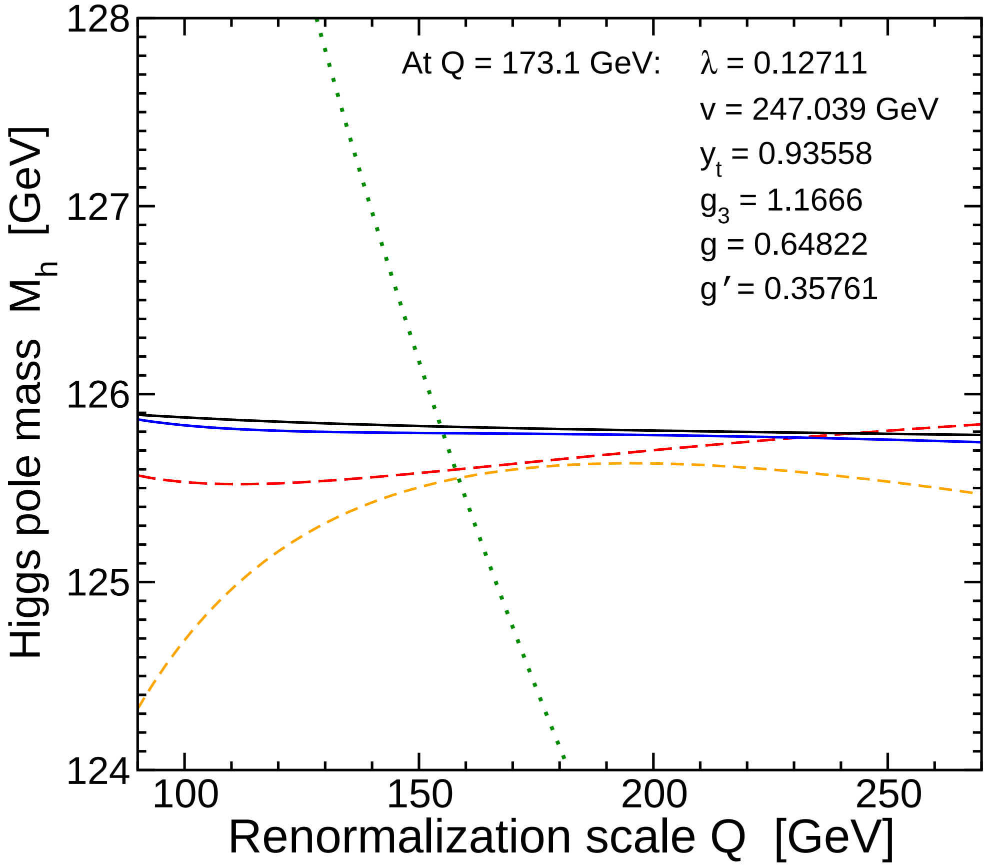
Either $m_{\tilde{t}_1} m_{\tilde{t}_2} \gg 1$ TeV^2, or large stop mixing, is necessary to give $M_h = 125$ GeV.

In principle, knowing $M_h = 125$ GeV reduces the dimension of the MSSM parameter space by 1. However, calculation of M_h is problematic:

0-loop:	m_Z^2	pure electroweak
1-loop:	$y_t^2 m_t^2$	top Yukawa comes in
2-loop:	$\alpha_S y_t^2 m_t^2$	SUSYQCD comes in
3-loop:	$\alpha_S^2 y_t^2 m_t^2, \alpha_S y_t^4 m_t^2$	Not at all negligible!

Many efforts in last 20+ years to increase precision of this calculation.

Full 2-loop + leading 3-loop **Standard Model** Higgs pole mass: 1407.4336, SPM and D. Robertson.



Green dotted: tree-level

Orange short dashed: 1-loop

Red long-dashed: 1-loop + 2-loop QCD

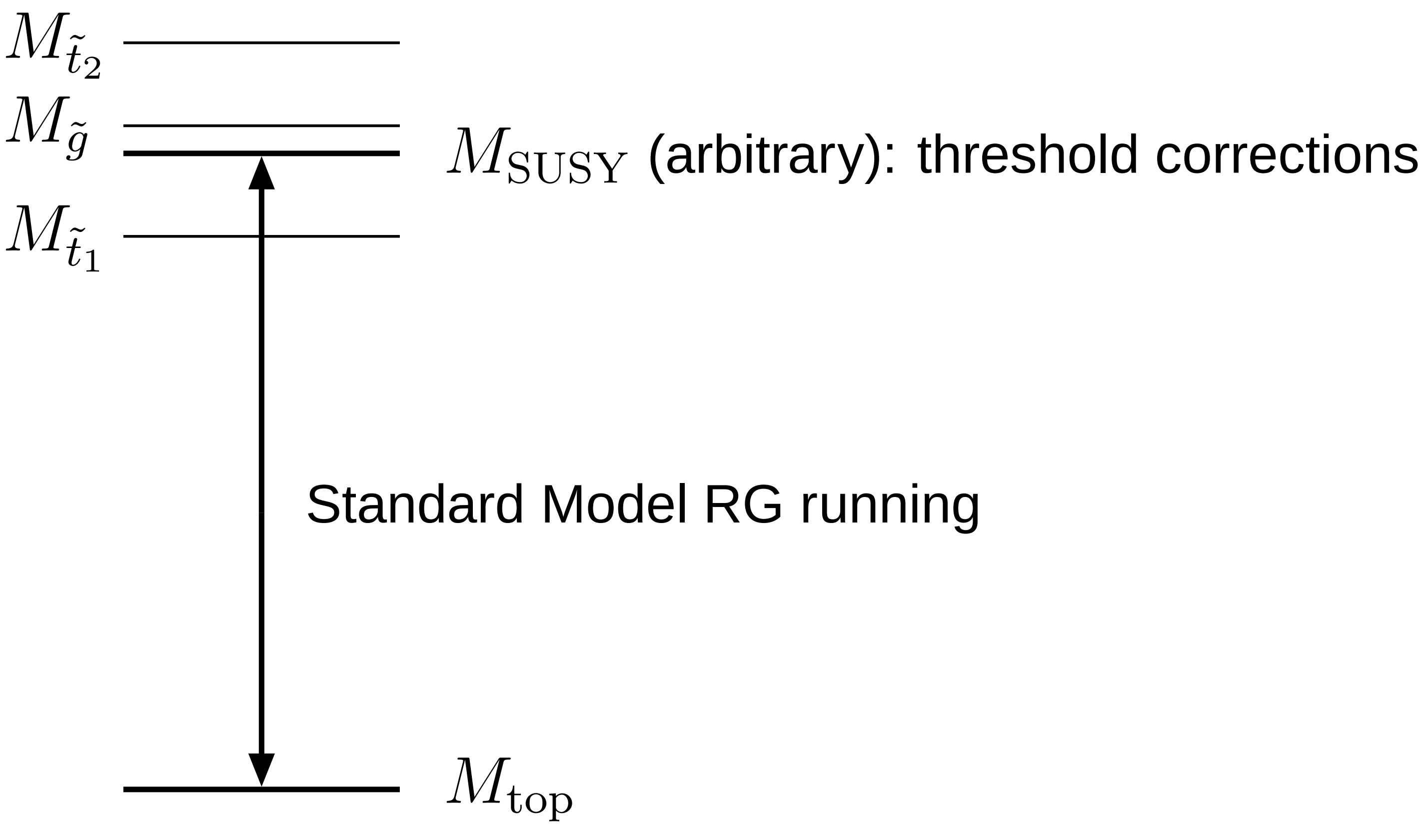
Blue solid: 2-loop

Black solid: 2-loop + leading 3-loop

2-loop EW part is new; not included yet in any MSSM calculations or codes.

Our public code is called `SMH`.

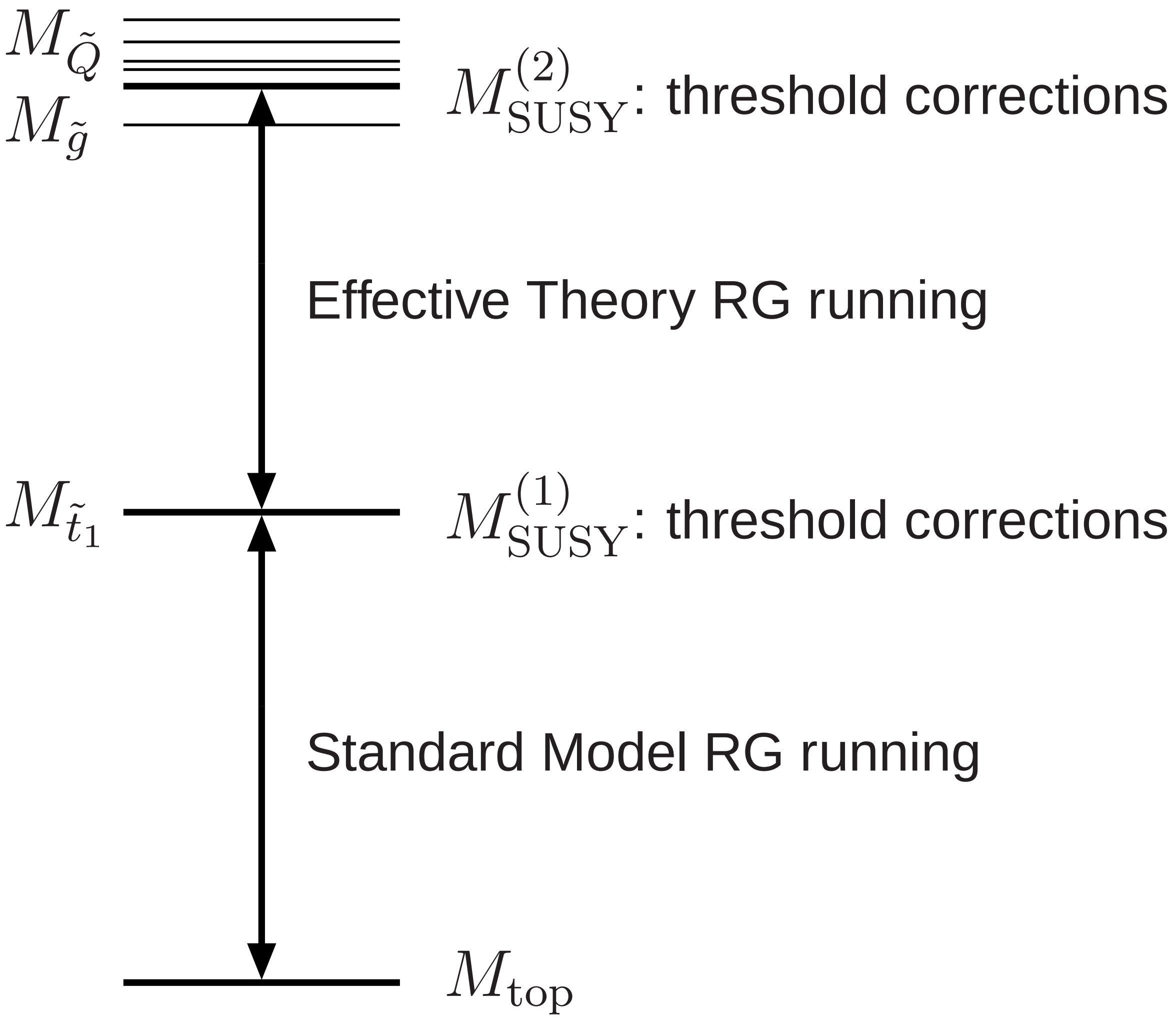
Motivation for SUSY people: the effective field theory approach to M_h



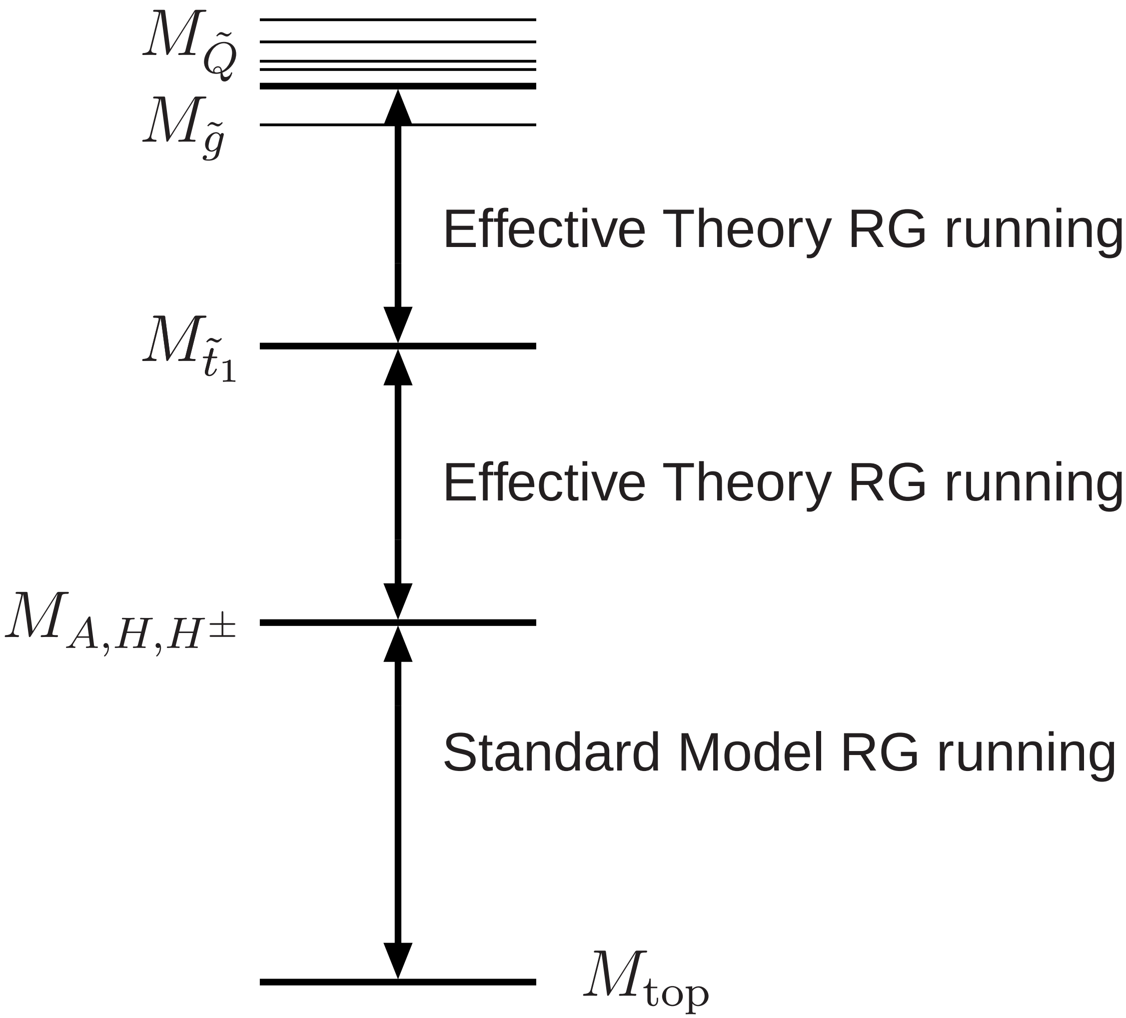
My opinion: this is the best way forward for M_h in SUSY.

Modular approach, needs M_h computation **in the Standard Model**.

Might need modification, perhaps:



Or perhaps, something more like this:

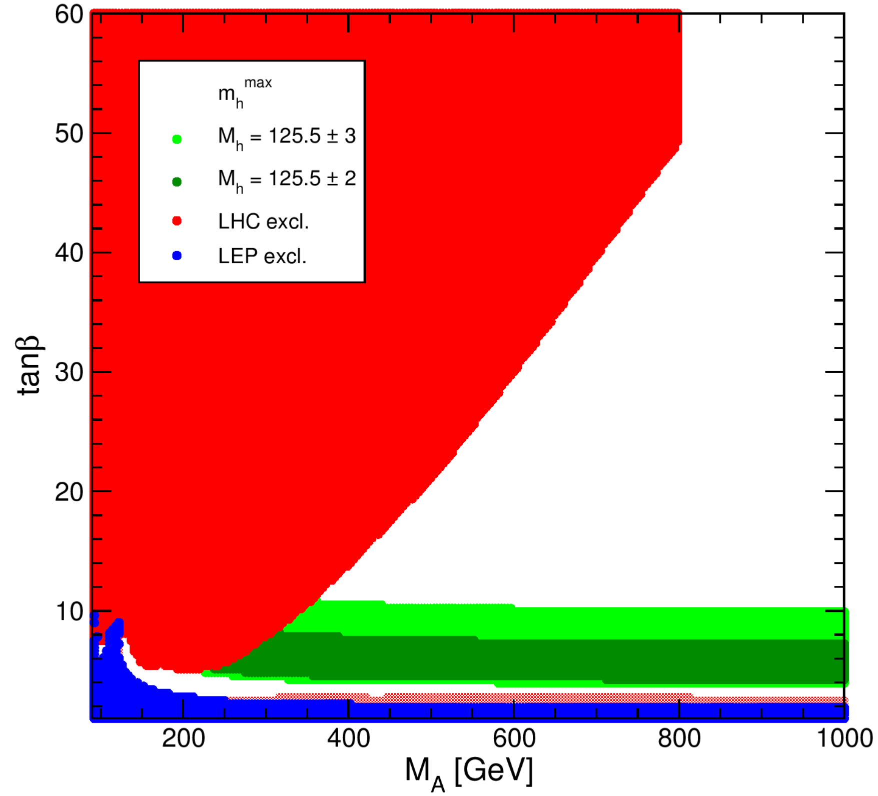


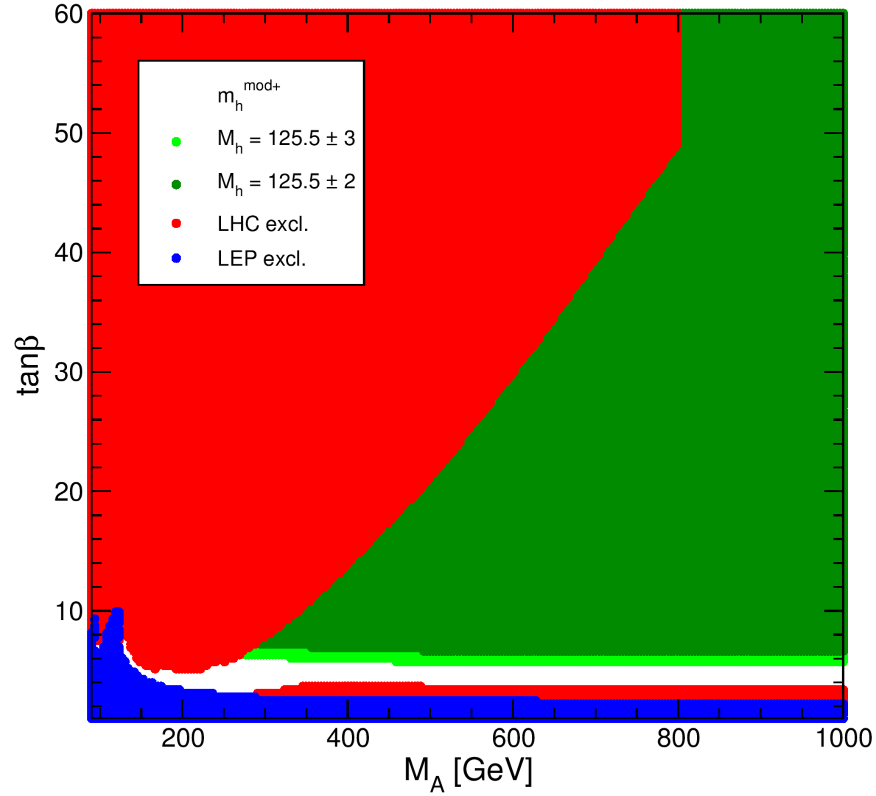
Make use of knowledge that $M_h = 125$ GeV, and $A, H, H^{\pm}$ haven't shown up

Benchmark models (1302.7033 Carena, Heinemeyer, Stal, Wagner, Weiglein):

m_h^{max}: maximize M_h by choosing A_t, with other parameters fixed.

$m_h^{\text{mod+}}$: make $M_h = 125$ GeV by choosing A_t, with other parameters fixed.



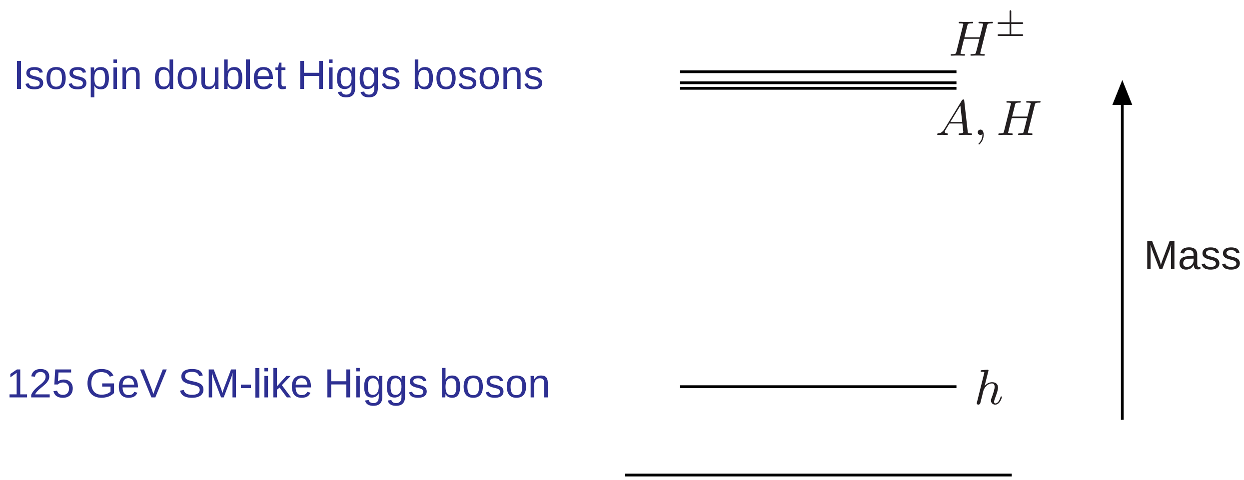


Bounds imposed using `HiggsBounds` linked to FeynHiggs. (1102.1898 and 1301.2345, Bechtle Brein, Heinemeyer, Stal, Stefaniak, Weiglein, Williams)

The decoupling limit for the Higgs bosons

If $m_A \gg m_Z$, then:

- h has the same couplings as would a SM Higgs boson of the same mass
- $\alpha \approx \beta - \pi/2$
- $A, H, H^\pm$ form an isospin doublet, and are much heavier than h



Tree-level:

$$m_H \approx m_A\left(1 + \sin^2(2\beta)\frac{m_Z^2}{2m_A^2}\right)$$

$$m_{H+} \approx m_A\left(1 + \frac{m_W^2}{2m_A^2}\right)$$

An argument in favor of the decoupling limit:

At tree-level,

$$m_A^2 \;\; = \;\; 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2$$

Each term on right side gets loop corrections from superpartner masses, so if M^2_{SUSY} is large, might expect large m_A^2.

Why above argument might be bogus:

We also have:

$$m_Z^2 \;\; = \;\; -2(|\mu|^2 + m_{H_u}^2) + \mathcal{O}(1/\tan^2\beta) + \text{loop corrections}$$

Again, each term on right side gets loop corrections from superpartner masses. This is the SUSY little hierarachy problem.

An important related question: do we need decoupling, if the $h(125)$ turns out to behave just like a Standard Model Higgs?

If decoupling were necessary, finding $H, A, H^{\pm}$ might be problematic at the LHC.

Alignment: h has the same coupling strengths as a Standard Model Higgs boson.

Decoupling is a special case of this; sufficient but not necessary. Gunion+Haber 0207010.

Couplings of Standard Model gauge bosons $V = W, Z$ to h, H, A

At **tree-level**:

$$\begin{aligned} g_{hVV} &= \sin(\beta - \alpha)\, g_{hVV}^{\text{SM}} \\ g_{HVV} &= \cos(\beta - \alpha)\, g_{hVV}^{\text{SM}} \\ g_{AVV} &\sim \cos(\beta - \alpha) \end{aligned}$$

For h to mimic a Standard Model Higgs, need $|\cos(\beta - \alpha)| \ll 1$, and HVV and AVV are suppressed.

In the decoupling limit, at tree-level:

$$\begin{aligned} \cos(\beta - \alpha) &= -\frac{m_Z^2 |\sin(4\beta)|}{2m_A^2} \\ \sin(\beta - \alpha) &= 1 - \frac{m_Z^4 \sin^2(4\beta)}{8m_A^4} \end{aligned}$$

Couplings of Standard Model fermions to h, H, A

At **tree-level**:

$$\begin{aligned} y_{hb\bar{b}} &= \frac{m_b}{247\text{ GeV}}[\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)] \\ y_{Hb\bar{b}} &= \frac{m_b}{247\text{ GeV}}[\cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha)] \\ y_{Ab\bar{b}} &= \frac{m_b}{247\text{ GeV}}\tan\beta \end{aligned}$$

and same for $b \to \tau$. Also:

$$y_{ht\bar{t}} = \frac{m_t}{247\text{ GeV}}[\sin(\beta-\alpha) + \cos(\beta-\alpha)/\tan\beta].$$

To ensure alignment, with $\tan\beta > 1$, can impose:

$$\tan\beta\,|\cos(\beta-\alpha)| \ll 1.$$

Alignment without decoupling: For the $h(125)$ to behave just like the Standard Model Higgs, the decoupling limit $m_A^2/m_Z^2 \gg 1$ is sufficient but **not necessary**. Gunion+Haber 0207010, Craig+Galloway+Thomas 1305.2424, Carena+Low+Shah+Wagner 1310.2248, Carena+Haber+Low+Shah+Wagner 1410.4969.

From the last reference, an approximate formula valid for large $\tan\beta$:

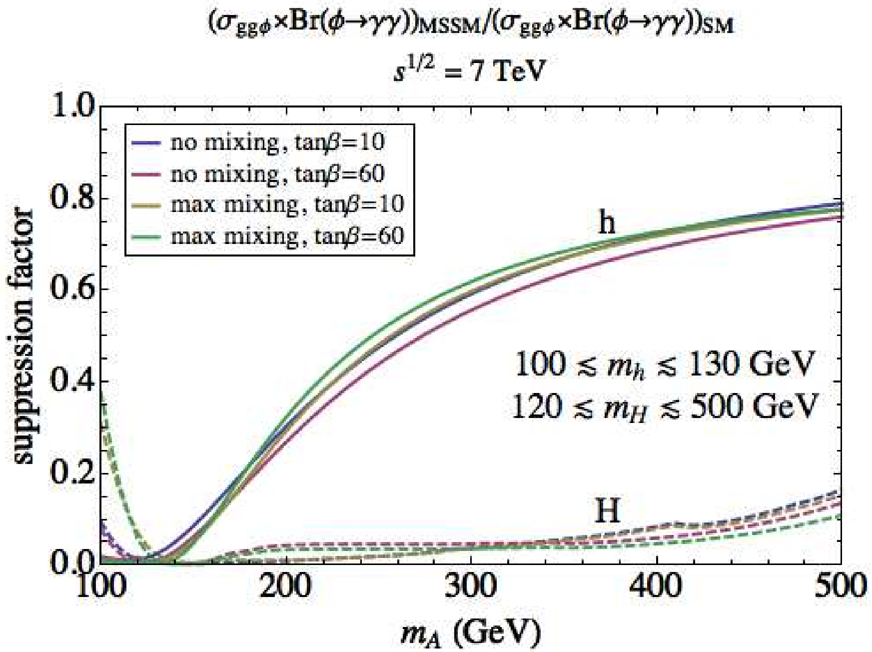
$$\begin{aligned}\tan\beta\cos(\beta-\alpha) \;=\; & \frac{1}{m_h^2 - m_H^2}\Big[m_h^2 + m_Z^2 \\ & +\frac{3m_t^4}{4\pi^2 v^2 M_S^2}\Big\{\mu A_t\big(1-\frac{A_t^2}{6M_S^2}\big)\tan\beta - \mu^2\big(1-\frac{A_t^2}{2M_S^2}\big)\Big\}\Big]\end{aligned}$$

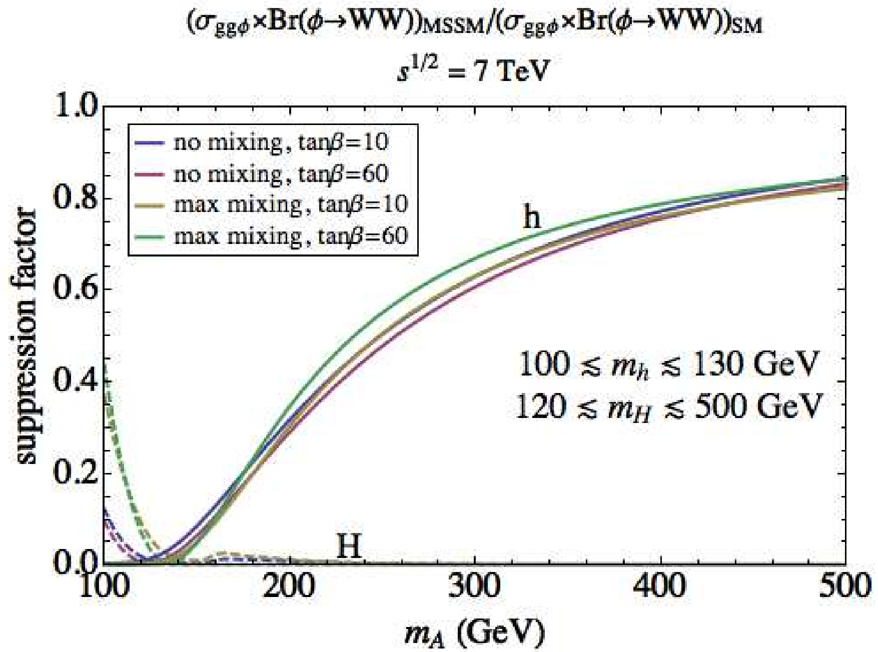
Can set to 0 and solve for $\tan\beta$, provided $|\mu|$ not too small.

Depends crucially on loop corrections; alignment without decoupling cannot occur in the MSSM at tree-level.

Examples of non-decoupling $A, H, H^{\pm}$ **without** alignment:

look at $pp \to h \to \gamma\gamma$ and $pp \to h \to W^+W^-$



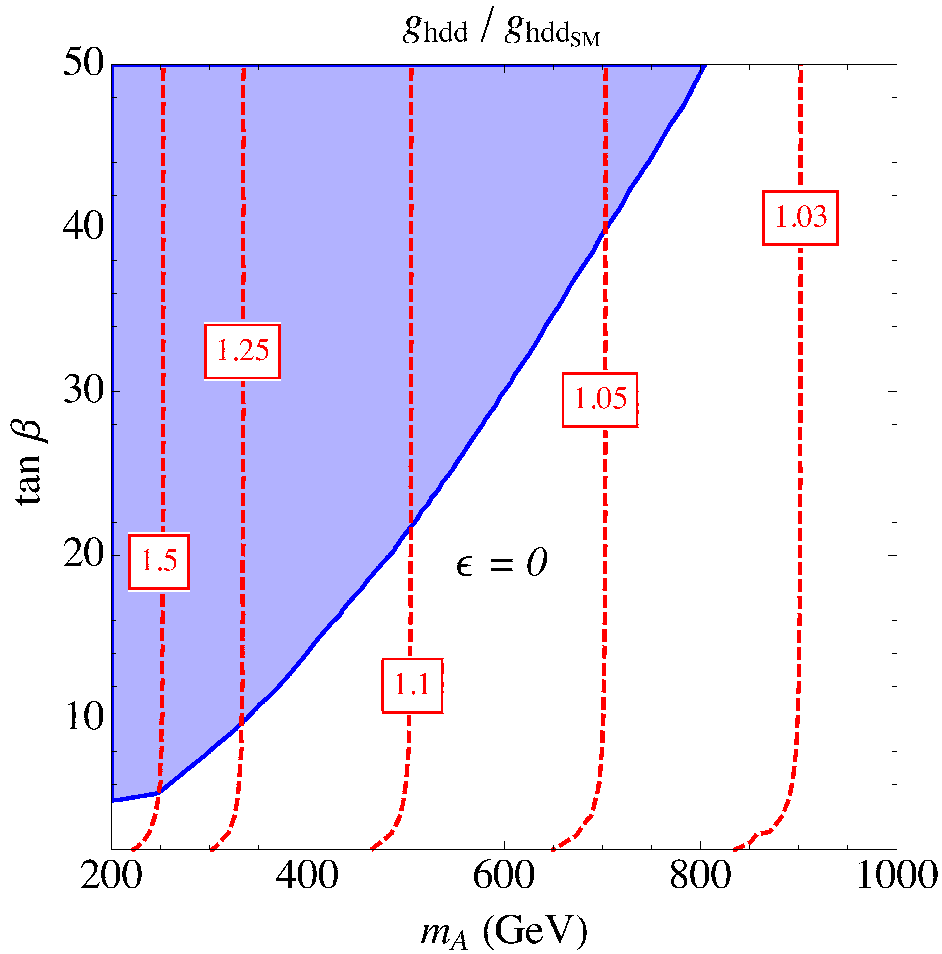


From 1107.4354 Carena, Draper, Liu, Wagner.

These models have small $\mu = 200$ GeV; in that case non-decoupling implies no alignment, independent of $\tan\beta$.

Reason for the suppression of $pp \to h \to \gamma\gamma$ is indirect.

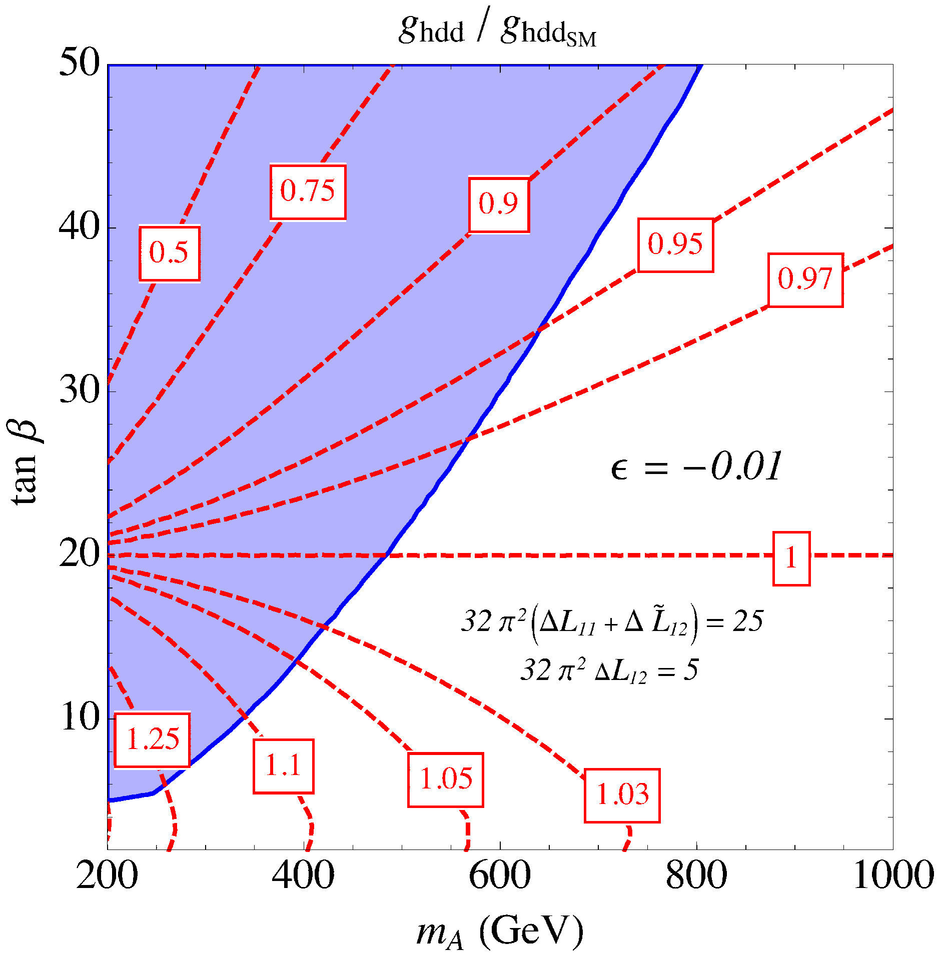
The $hb\bar{b}$ coupling is enhanced, leading to larger BR$(h \to b\bar{b})$ and thus smaller BR$(h \to \gamma\gamma)$.



From 1310.2248 Carena, Low, Shah, Wagner.

Enhancement of BR$(h \to b\bar{b})$ is nearly independent of $\tan\beta$.

For larger $|\mu|$, can have alignment, with $hb\bar{b}$ coupling equal to the Standard Model, for an appropriate $\tan\beta$.

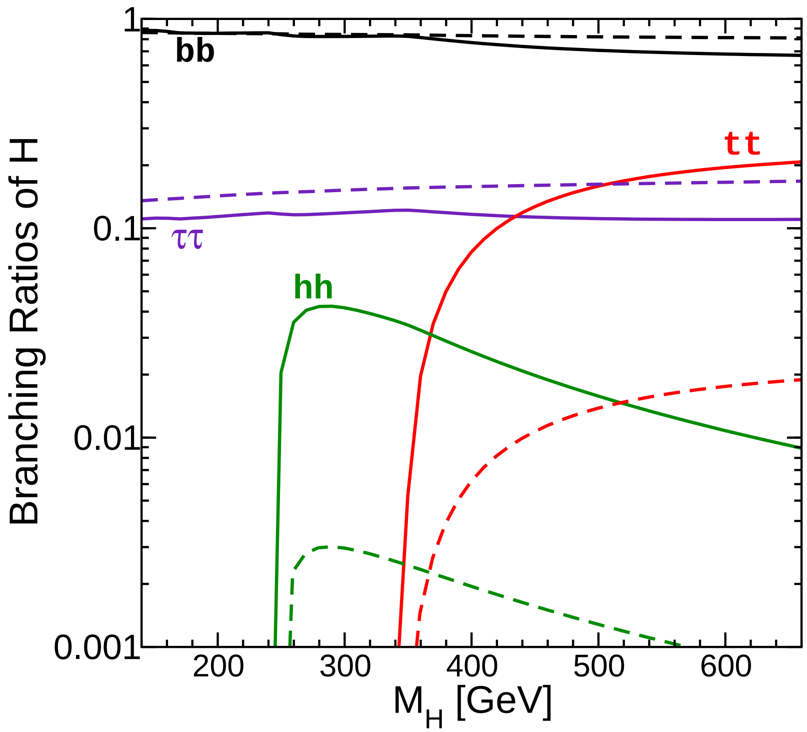


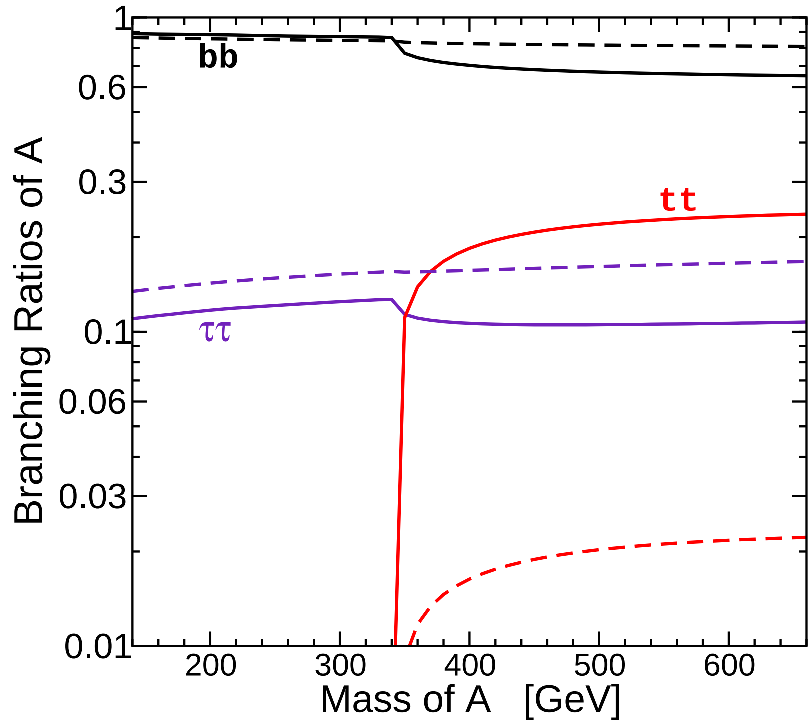
From 1310.2248 Carena, Low, Shah, Wagner.

Typical BRs for H, A, with large $M_{\rm SUSY}, \mu$ and $M_h = 125$ GeV.

(Computed with HDECAY by Djouadi, Kalinowski, Spira.)

Solid: $\tan\beta = 10$, dashed: $\tan\beta = 20$.

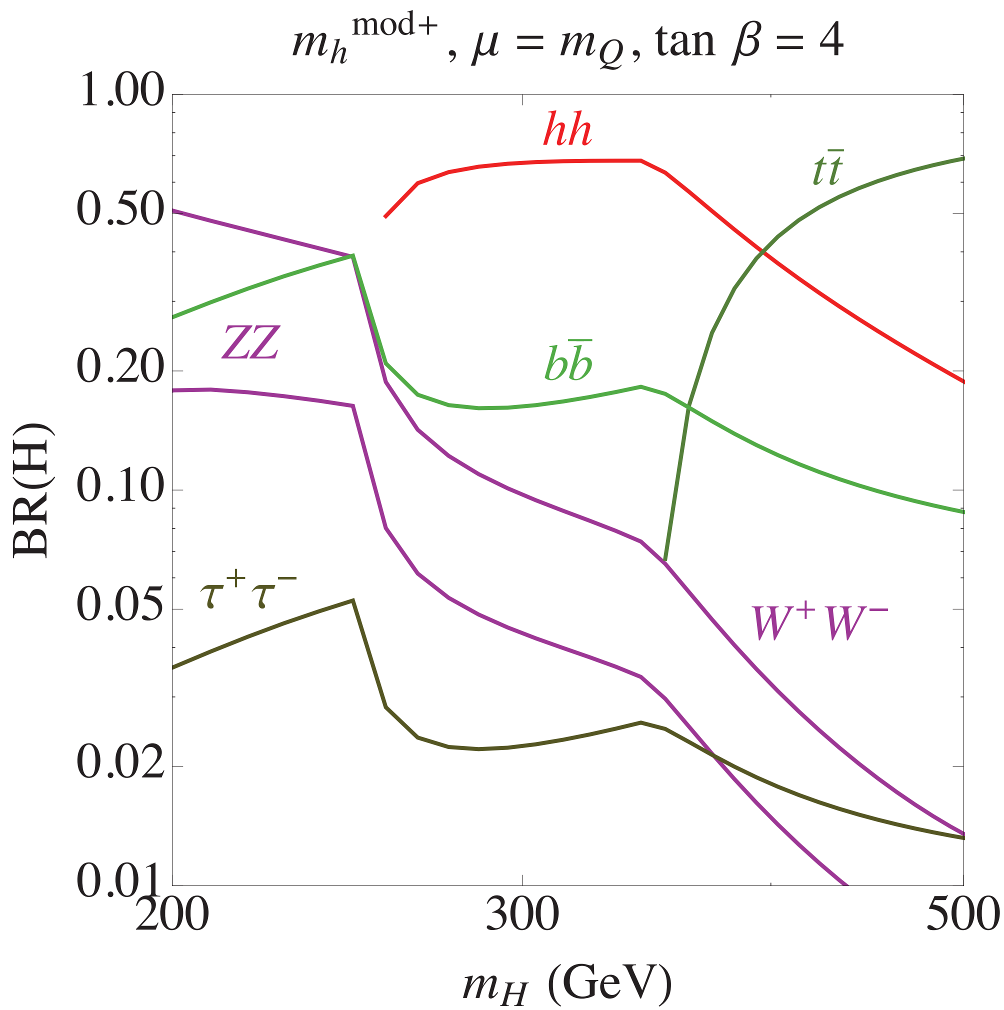




The Real World could be very different in important ways. . .

Enhanced $H \to hh$ and/or $t\bar{t}$ for lower $\tan\beta$:

From 1410.4969, Carena, Haber, Low, Shah, Wagner:

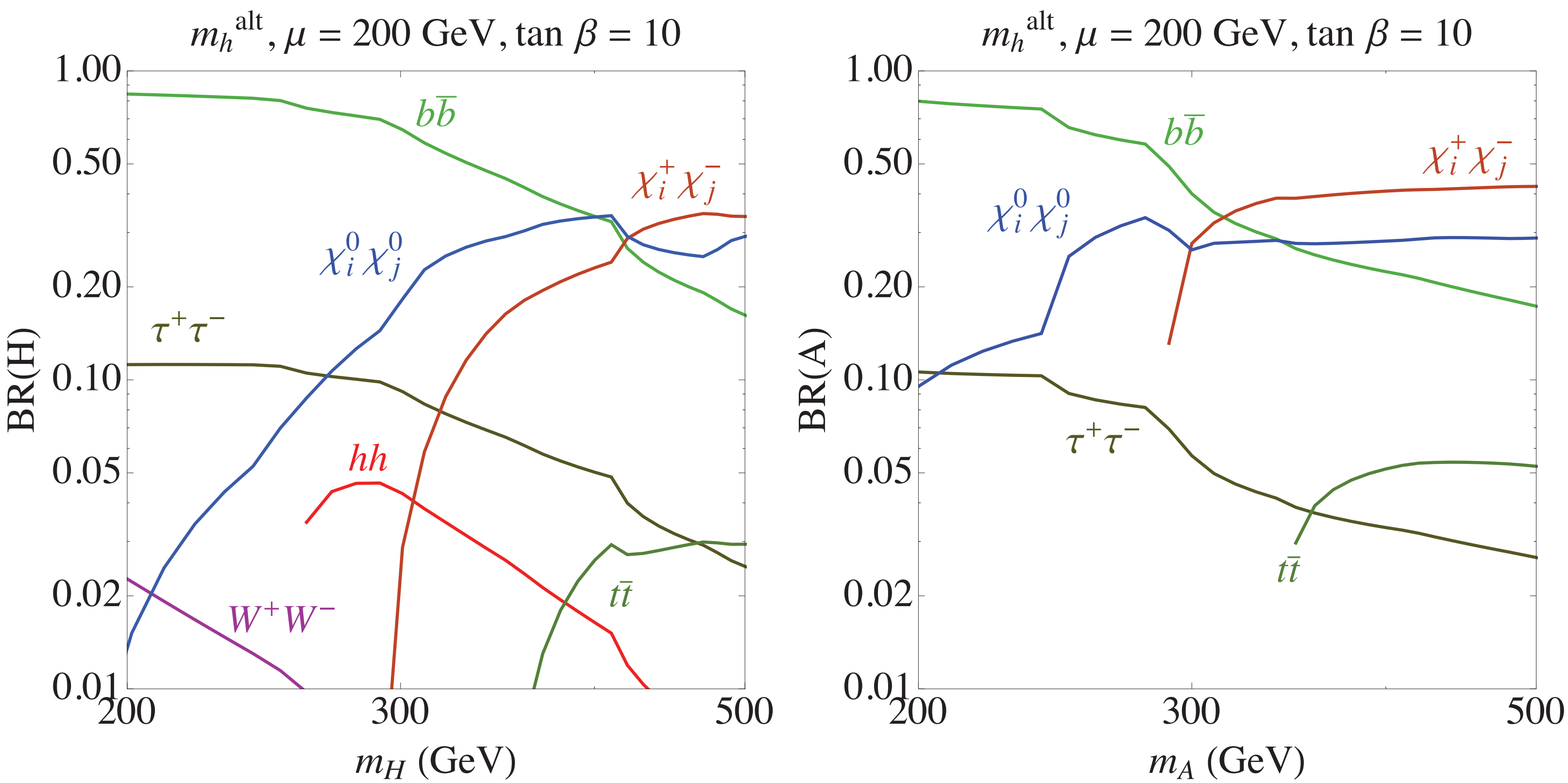


$m_h^{\rm mod+}$ benchmark models have parameters adjusted to make $M_h = 125$ GeV.

Computed with FeynHiggs, by Hahn, Heinemeyer, Hollik, Rzehak, Weiglein.

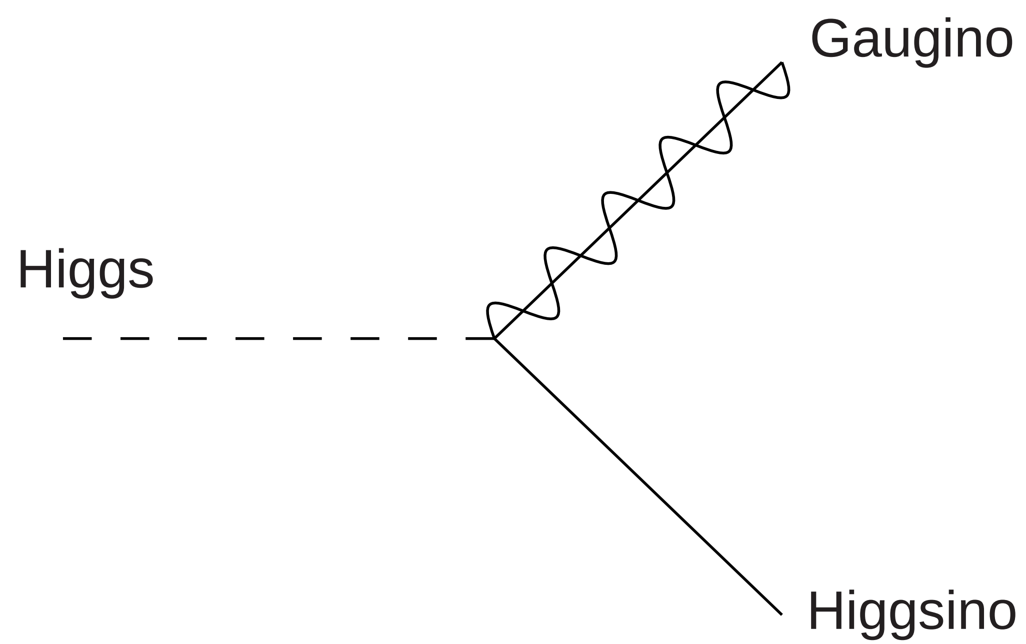
Enhanced $H, A \rightarrow$ Neutralinos and Charginos:

From 1410.4969, Carena, Haber, Low, Shah, Wagner:



However, note these branching ratios are **very** sensitive to both μ, M_2 = Higgsino, Wino masses. Here, $\mu = M_2 = 200$ GeV.

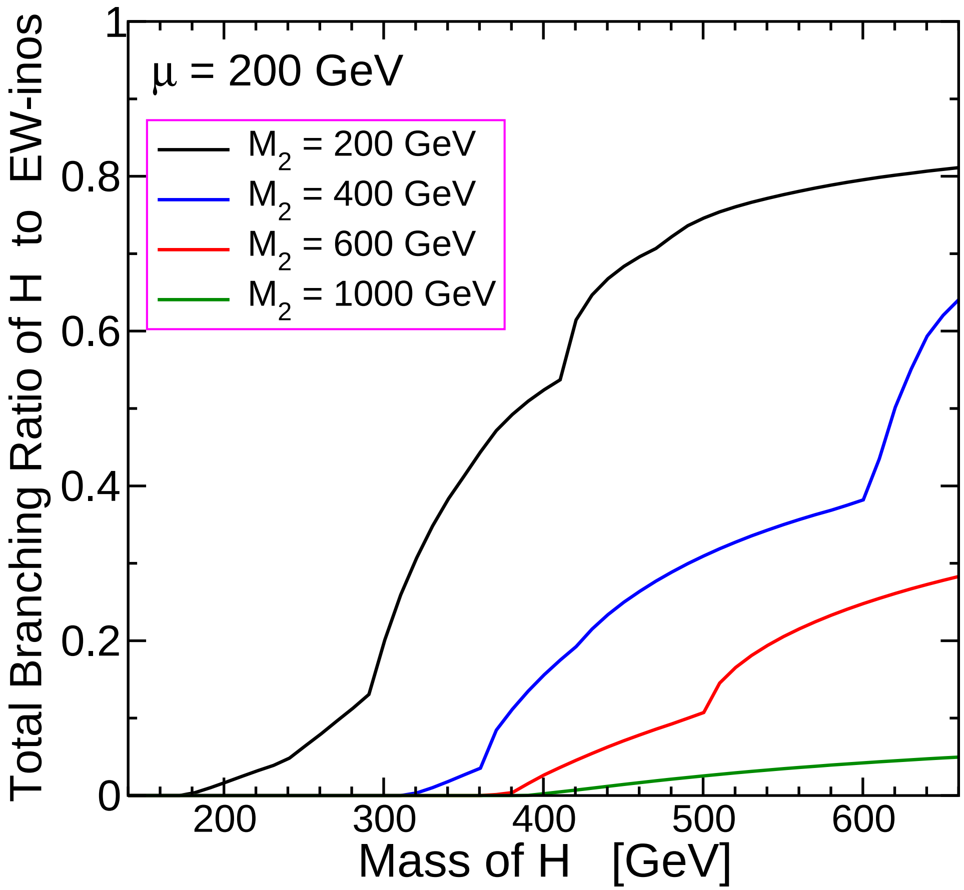
In SUSY, with no mixing, there are Higgs-higgsino-gaugino couplings:



But, Higgs-higgsino-higgsino and Higgs-gaugino-gaugino couplings do not exist.

Need both μ and M_2 or M_1 to be small to have significant decays $H, A, H^{\pm} \rightarrow$ EWinos.

Total Branching Ratios for H into Charginos and Neutralinos, for fixed $\tan\beta = 10$, $\mu = 200$ GeV, and various M_2:



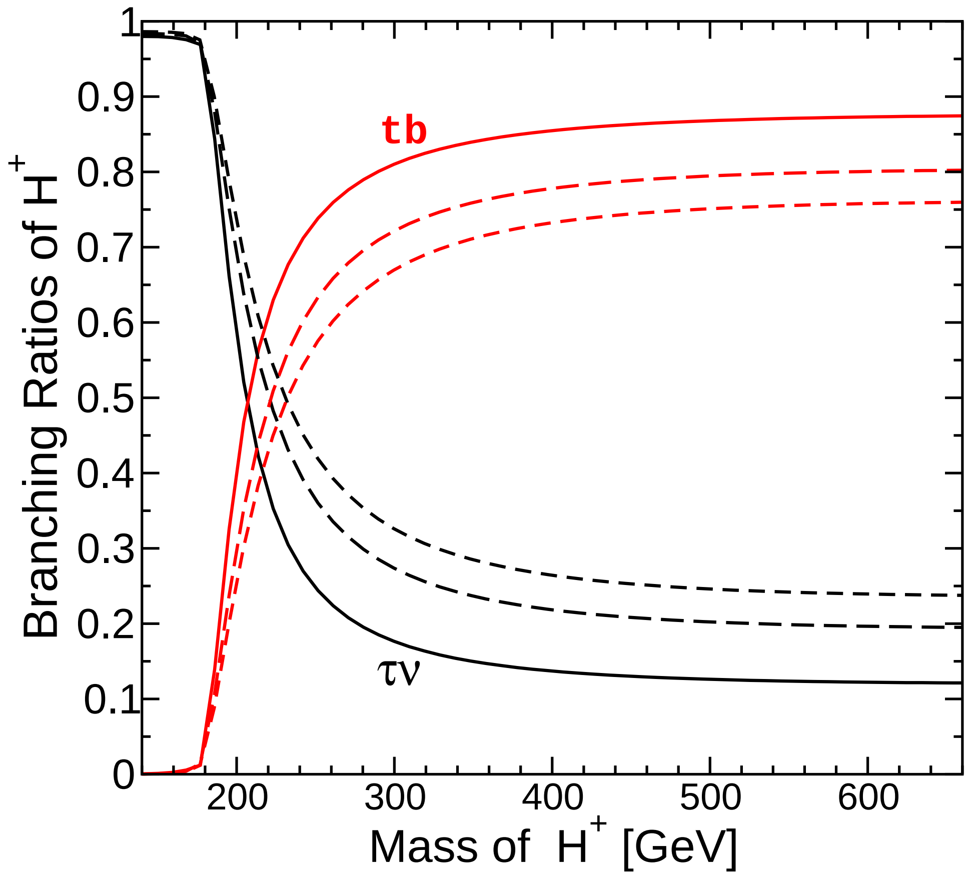
Decays to EWinos can be very important, or not important, for small μ.

Cases with $M_2 = \mu = 200$ GeV have been used for benchmark models in LHC searches. My opinion: do not do this!

If your $H, A, H^\pm$ search requires decays to Standard Model final states like $\tau\tau$ or bb or hh or $\tau\nu$ or tb, then **prioritize "generic" benchmark model scenarios with all charginos and neutralinos heavy (large μ, M_2, M_1) when reporting results.**

- Branching Ratios for $H, A \to$ SUSY are always very sensitive to input parameters. Not robust.
- Theoretical motivation for **both** $M_{1,2}$ and μ small is suspect.
- People who are interested in the special cases with small μ, M_2, M_1 can reinterpret the results accordingly.
- As always, most important and useful is model-independent limits on $\sigma\times$BR.

Branching ratios for $H^{\pm}$, in "generic" MSSM with heavy superpartners.



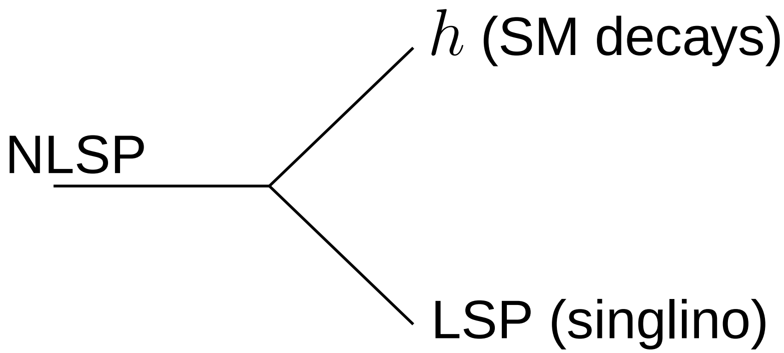
Solid: $\tan\beta = 10$,

long dashed: $\tan\beta = 20$,

short dashed: $\tan\beta = 30$.

Higher $\tan\beta$ gives more $\tau\nu$.

A NMSSM Higgs way of hiding SUSY (Ellwanger, Teixeira, 1406.7221)



NLSP could be Bino- or Higgsino-like.
If $M_{NLSP} - M_h - M_{LSP}$ and M_{LSP} are both small, then $E_T^{\rm miss}$ is small, SUSY signals much weaker.

Similar in spirit to Stealth SUSY (Fan Reece Ruderman).

SUSY signature is $hh + X$.

Non-resonant di-Higgs, X from cascade decays.

No $E_T^{\rm miss}$ except for neutrinos from decays through Ws.

Because $M_{\rm singlino}$ is controlled by a dimensionless coupling, it is "natural" for it to be as light as you want.

Done. No Conclusion. Thanks!

Public software code implementation: `SMH`

- Written in C, requires `TSIL`
- Link from C or C++. (Fortran interface is coming soon.)
- Library functions can be incorporated in your programs
- Sample user programs provided, reproduce all figures in our paper
- Stand-alone command line programs also provided
- tree-level, 1-loop, 2-loop, or 3-loop approximations, selected at run time

What `SMH` does:

- RG running of Standard Model parameters λ, y_t, g_3, g, g', v, m^2
- Minimization conditions for effective potential: find v given m^2, **or** find m^2 given v
- Compute M_h given λ, **or** compute λ given M_h

The main user library functions have obvious names:

- SMH_RGrun runs λ, y_t, g_3, g, g', v, m^2 from scale $Q_{\rm initial}$ to $Q_{\rm final}$.
- SMH_Find_vev minimizes $V_{\rm eff}$ to find v , given m^2, λ, y_t, g_3, g, g', Q.
- SMH_Find_m2 minimizes $V_{\rm eff}$ to find m^2 , given v, λ, y_t, g_3, g, g', Q.
- SMH_Find_Mh Computes M_h , given λ, v, y_t, g_3, g, g', Q.
- SMH_Find_lambda Computes λ , given M_h, v, y_t, g_3, g, g', Q.

For much more information, see the provided README.txt file.

Example command line usage:

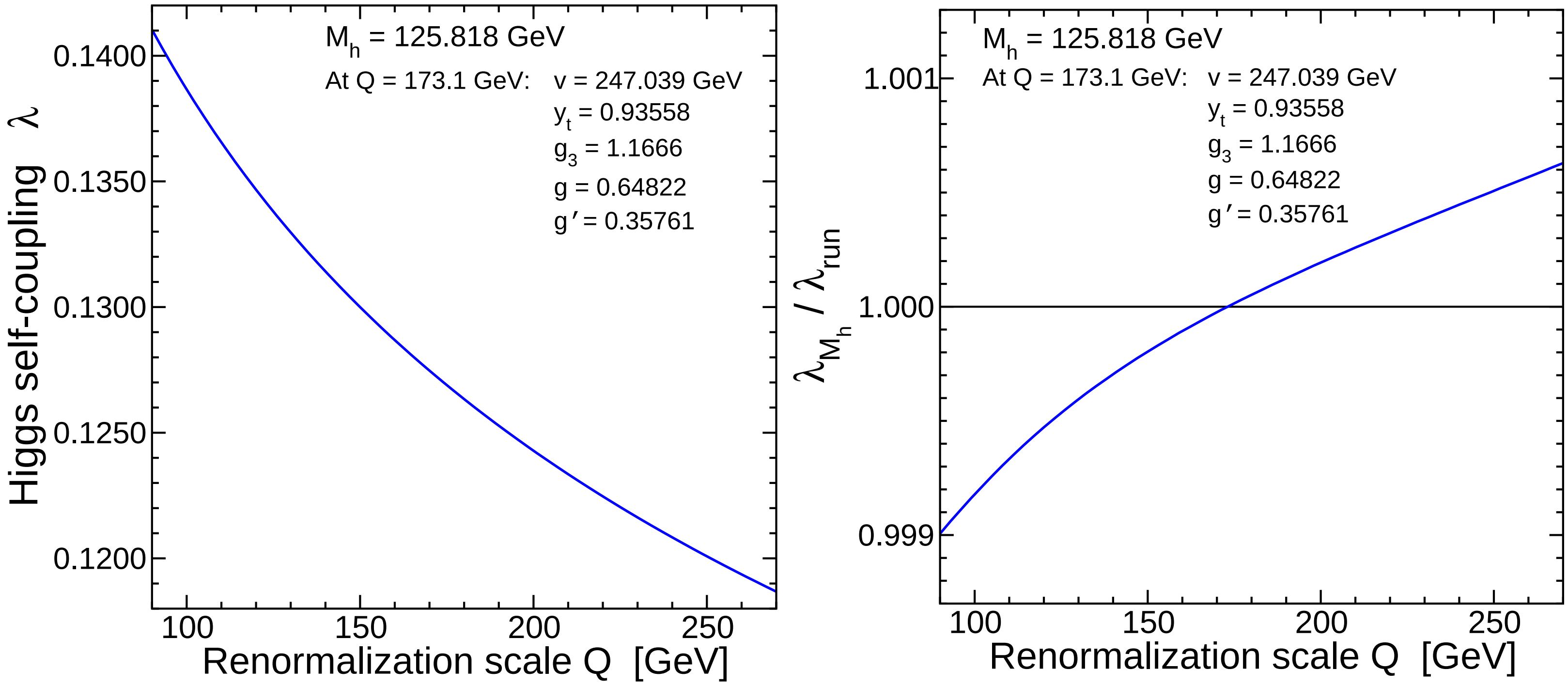
```
$ ./calc_Mh 0.127 247.0 0.936 1.167 0.648 0.358 173.1 3
(* SMH(iggs) Version 1.0 *)

Mh(loops = 3.0) = 125.742765

Total calculation time (s): 0.382756
```

Command-line arguments are in the order: λ, v, y_t, g_3, g, g', Q, loop-order.

The loop order can be chosen from:

```
0    tree level
1    1-loop
1.5  1-loop plus 2-loop QCD
2    2-loop
2.5  2-loop plus leading 3-loop QCD
3    2-loop plus leading 3-loop
```

The inverse question: given M_h, what is the self-coupling λ ?



Left panel: $\lambda_{M_h}(Q)$ as determined from the fixed pole mass M_h, calculated at Q.

Right panel: Compare $\lambda_{M_h}(Q)$ obtained at Q to $\lambda_{\rm run}(Q)$ obtained by running it from M_t to Q.

Scale dependence is well under 0.1%, for a reasonable range of Q.