Celebrating Georg Weiglein @ 60 at two loops (and beyond)

Howard E. Haber
DESY, Hamburg
13 November 2025

Challenge to Georg: identify the location and date of the picture shown here.

In the summer of 1997, I was visiting CERN for a few weeks. While hanging out with Marcela and Carlos, I was introduced to three junior German theorists: Georg, Gudi, and Sven.

For some reason, I cannot find any photographic evidence of this meeting, or any subsequent meetings in the three years that followed. Nevertheless, we surely met a number of times in the late 1990s at various conferences and elsewhere, which led to our first joint paper…

High Energy Physics – Phenomenology

[Submitted on 1 Jan 2000 (v1), last revised 13 Jul 2000 (this version, v3)]

Reconciling the Two-Loop Diagrammatic and Effective Field Theory Computations of the Mass of the Lightest CP-even Higgs Boson in the MSSM

M. Carena, H.E. Haber, S. Heinemeyer, W. Hollik, C.E.M. Wagner, G. Weiglein

The mass of the lightest CP-even Higgs boson of the minimal supersymmetric extension of the Standard Model (MSSM) has previously been computed including O(alpha alpha_s) two-loop contributions by an on-shell diagrammatic method, while approximate analytic results have also been obtained via renormalization-group-improved effective potential and effective field theory techniques. Initial comparisons of the corresponding two-loop results revealed an apparent discrepancy between terms that depend logarithmically on the supersymmetry-breaking scale, and different dependences of the non-logarithmic terms on the squark mixing parameter, X_t. In this paper, we determine the origin of these differences as a consequence of different renormalization schemes in which both calculations are performed. By re-expressing the on-shell result in terms of MS-bar parameters, the logarithmic two-loop contributions obtained by the different approaches are shown to coincide. The remaining difference, arising from genuine non-logarithmic two-loop contributions, is identified, and its effect on the maximal value of the lightest CP-even Higgs boson mass is discussed. Finally, we show that in a simple analytic approximation to the Higgs mass, the leading two-loop radiative corrections can be absorbed to a large extent into an effective one-loop expression by evaluating the running top quark mass at appropriately chosen energy scales.

Comments:	29 pages, 5 figures, LaTeX with axodraw and epsfig style files. Typographical errors have been fixed and references updated
Subjects:	**High Energy Physics – Phenomenology (hep-ph)**
Cite as:	arXiv:hep-ph/0001002
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Journal reference:	Nucl.Phys.B580:29-57,2000
Related DOI:	https://doi.org/10.1016/S0550-3213%2800%2900212-1

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[v2] Wed, 5 Jan 2000 01:18:43 UTC (44 KB)
[v3] Thu, 13 Jul 2000 19:21:15 UTC (52 KB)

I draw your attention to the submission time:

Submission history

From: Howard E. Haber [view email]

[v1] Sat, 1 Jan 2000 09:57:43 UTC (44 KB)

Apart from what this might imply about the activities of the authors on New Year's Eve, in fact we were trying to submit the paper in December 1999, as a paper by Espinosa and Zhang on a similar project appeared a few weeks earlier. At the time, we did not quite understand the arXiv rules for dating a submission.

arXiv > hep-ph > arXiv:hep-ph/0001001

Search...
Help |

High Energy Physics – Phenomenology

[Submitted on 1 Jan 2000 (v1), last revised 24 Jun 2011 (this version, v2)]

A Two-Loop Four-Gluon Helicity Amplitude in QCD

Z. Bern, L. Dixon, D.A. Kosower

We present the two-loop pure gauge contribution to the gluon-gluon scattering amplitude with maximal helicity violation. Our construction of the amplitude does not rely directly on Feynman diagrams, but instead uses its analytic properties in 4 – 2 epsilon dimensions. We evaluate the loop integrals appearing in the amplitude through O(epsilon^0) in terms of polylogarithms.

Comments: Latex, 27 pages, 12 figures; v2: normalizations corrected in (5.11), (A.6) and (A.7)
Subjects: **High Energy Physics – Phenomenology (hep-ph)**; High Energy Physics – Theory (hep-th)
Report number: SLAC-PUB-8324, UCLA/99/TEP/48, Saclay-SPhT-T99/147
Cite as: arXiv:hep-ph/0001001
(or arXiv:hep-ph/0001001v2 for this version)
https://doi.org/10.48550/arXiv.hep-ph/0001001
Journal reference: JHEP 0001:027,2000
Related DOI: https://doi.org/10.1088/1126-6708/2000/01/027

Submission history
From: Lance Dixon [view email]
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[v2] Fri, 24 Jun 2011 10:26:41 UTC (39 KB)

Submission history
From: Lance Dixon [view email]
[v1] Sat, 1 Jan 2000 00:00:58 UTC (30 KB)

Lance Dixon actually performed experimental tests on the arXiv before submitting his paper to ensure that it would be the first submitted paper of the year 2000.

The results of an MSSM two-loop diagrammatic computation of the Higgs mass (observed at the LHC) is well-approximated by a one-loop effective field theory formula in which m_t appearing in the X_t-independent leading double logarithmic term (the "no-mixing contribution'') is taken to be the running top quark mass evaluated at $(m_t\, M_S)^{1/2}$ and the leading single logarithmic term proportional to powers of X_t (the "mixing contribution") is taken to be the running top quark mass evaluated at the SUSY breaking scale M_S.

See H.E. Haber, R. Hempfling and A.H. Hoang, Z. Phys. C **75,** 539 (1997).

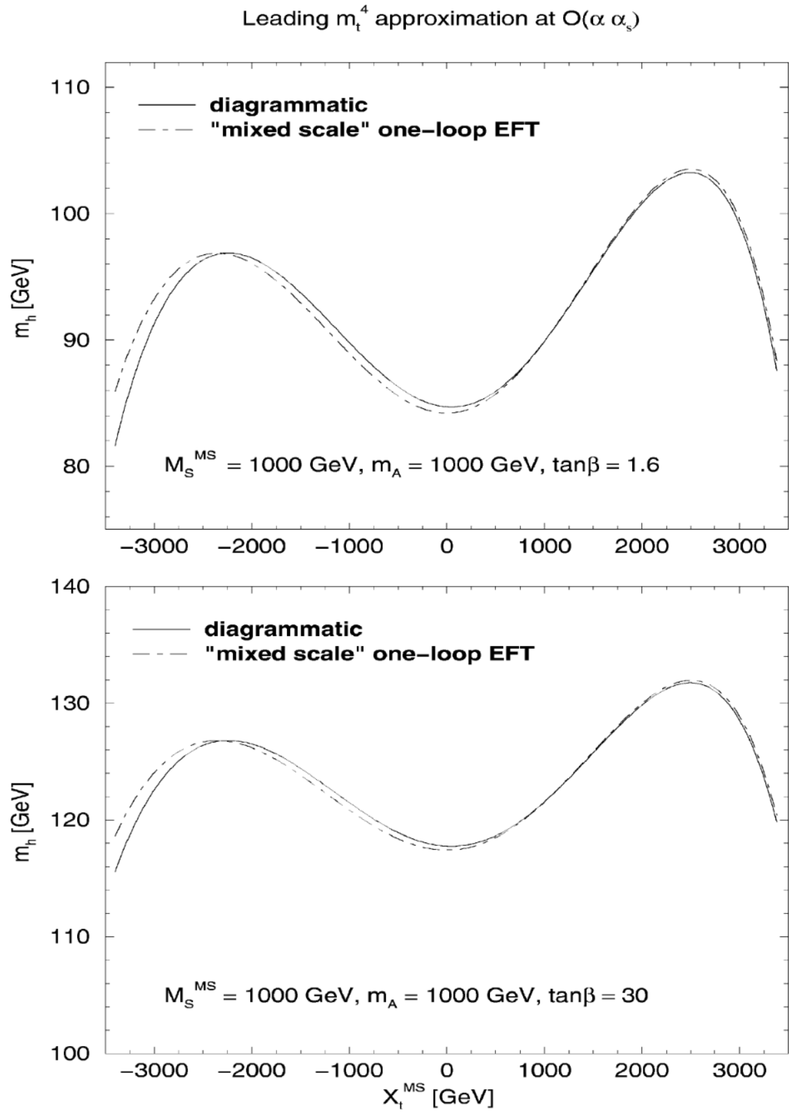

Fig. 2. Comparison of the diagrammatic two-loop $\mathcal{O}(m_t^2 h_t^2 \alpha_s)$ result for m_h, to leading order in $\overline{m}_t/\overline{M}_S$ (Eqs. (46) and (47)) with the "mixed-scale" one-loop EFT result (Eq. (49)). Note that the latter now includes the threshold corrections due to stop mixing in the evaluation of $\overline{m}_t(M_S)$ in contrast to the EFT results depicted in Fig. 1. "Mixed-scale" indicates that in the no-mixing and mixing contributions to the one-loop Higgs mass, the running top quark mass is evaluated at different scales according to Eq. (48). See text for further details. The two graphs above are plotted for $\overline{M}_S = m_A = (m_{\tilde{g}}^2 + \overline{m}_t^2)^{1/2} = 1$ TeV for the cases of $\tan\beta = 1.6$ and $\tan\beta = 30$, respectively.

First picture with Georg and Gudi---can you guess where and when?

The Snowmass 2001 meeting was the last of the Snowmass meetings to actually take place in Snowmass. The consensus of this meeting was that the number one priority of USA particle physics should be an e^+e^- linear collider at E_{CM}=500 GeV. Here is one of a number of contributions Georg made to this meeting.

arXiv > hep-ph > arXiv:hep-ph/0110219

Search

High Energy Physics – Phenomenology

[Submitted on 16 Oct 2001]

Soft SUSY-breaking scenarios in the light of Higgs searches at LEP2

A. Dedes, S. Heinemeyer, S. Su, G. Weiglein

The Higgs boson sector of the Minimal Supersymmetric Standard Model (MSSM) is investigated in a uniform way in the framework of the three most prominent soft SUSY-breaking scenarios, mSUGRA, mGMSB and mAMSB, especially concerning the Higgs searches at LEP2.

Comments: 4 pages, Contribution to the ``Workshop on the Future of Particle Physics'' (snowmass 2001), Snowmass, USA, July 2001
Subjects: **High Energy Physics – Phenomenology (hep-ph)**
Report number: BNL-HET-01/35, CALT-68-2353, DCPT/01/86, IPPP/01/43
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Journal reference: eConf C010630 (2001) P305

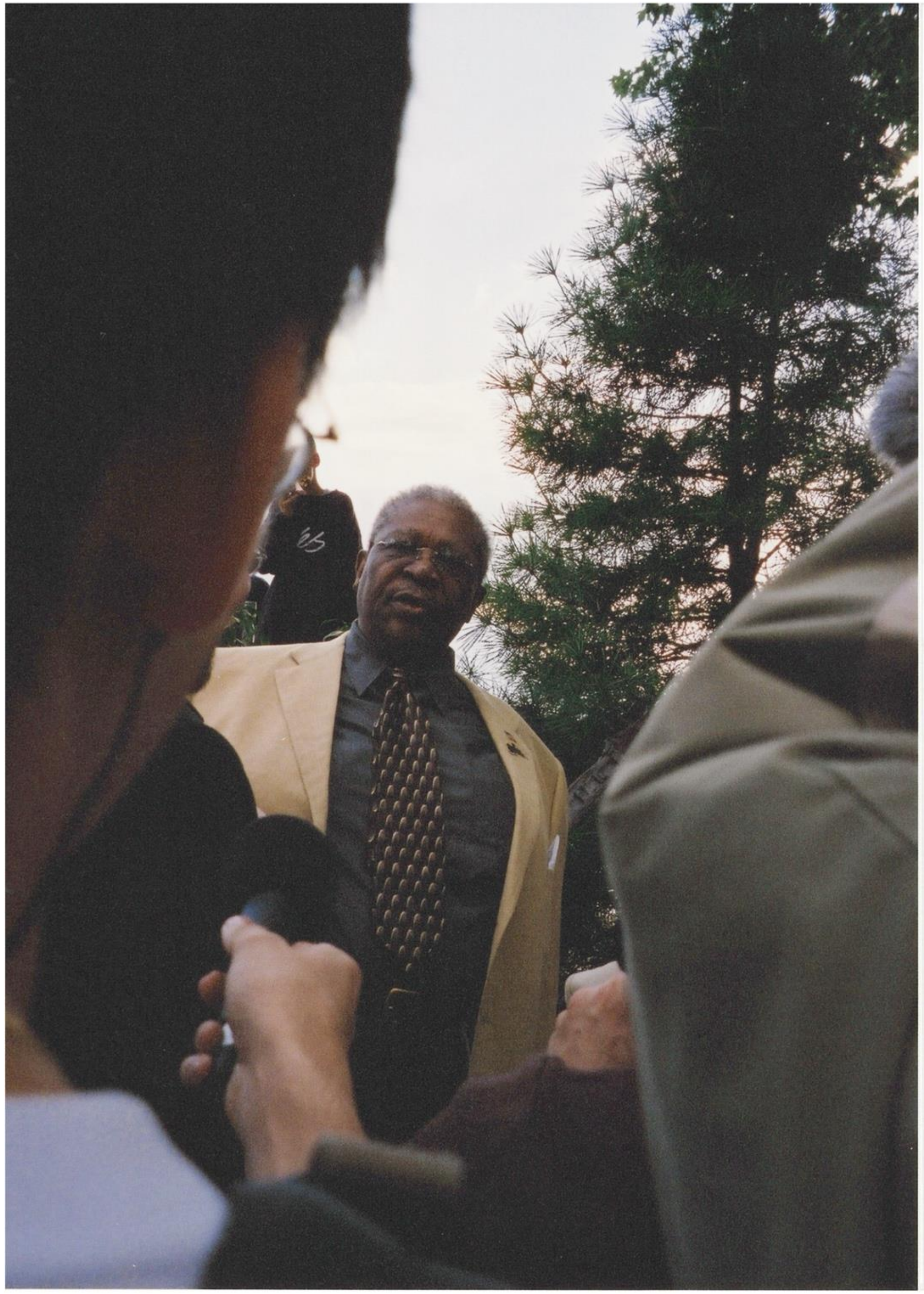
Submission history

From: Shufang Su [view email]
[v1] Tue, 16 Oct 2001 19:11:18 UTC (197 KB)

Back to the picture: On June 15, 2001, I joined Georg, Gudi, and Thorston Ohl on an attempt to reach Buckskin Pass. The hike was aborted due to a significant rainstorm, and we only made it as far as Crater Lake.

Back in Aspen, the weather improved significantly, so we decided to hike up the Ute trail. This provided a very nice view of Aspen.

I couldn't find any pictures of Georg from SUSY 2002 in Hamburg. But, we met up again at CERN in July 2002. That trip included opening night of the 2002 Montreux Jazz Festival, which took place on July 5, 2002, where we got to (sort of) meet B.B. King!




CHICAG
GIANTS

During the first three months of 2003, I spent a mini-sabbatical at the IPPP in Durham, UK. Georg, along with James Stirling, were instrumental in hosting me at the IPPP.   Georg and Gudi were extremely generous in providing me with accommodations in their home during the first week in January before I was able to move into a beautiful home at 20 The Peth (which belonged to Durham University professors who were taking sabbatical leave in East Asia).

At a dinner party hosted by Steve Abel in March, 2003.

My last night in Durham was on March 27, 2003.   Many of my IPPP friends joined me for a final dinner and party at 20 The Peth.

Musical instruments appeared and a lively music session followed.
It turned out to be the birth of the IPPP Ceilidh Band.

Georg was a strong supporter of the ILC. We both attended LCWS 04 in Paris, held at the old l'École Polytechnique. I found this picture of Georg and Sven with David Rainwater taken on April 23, 2004 in front of the conference center.

On September 18, 2004, we were hanging out in Naperville in the backyard of Carlos and Marcela. I can’t quite remember the event that led to this visit.

The LCWS 05 took place at SLAC in March 2005. That visit provided me with the opportunity to welcome Georg and Gudi to my home in Santa Cruz.

I returned to Durham in July 2005 to attend the SUSY 2005 conference. By then, the IPPP Ceilidh Band had been playing together for nearly two years. Georg had learned how to play the bodhran (Irish drum). I was most graciously welcomed back to join the Band for a performance on July 20, 2005 at the SUSY 2005 conference dinner.

The SUSY 2007 Conference took place in Karlsruhe, Germany. Although the conference picture shows a large number of participants, I am easy to spot due to the infamous MSSM T-Shirt, which was exhibited in public for the first time.


MSSM


SUSY
2007
Howard
Haber
UC Santa Cruz
UNITED STATES OF AMERICA

Three years later at SUSY 2010 in Bonn, Germany

At LCWS 11 in Granada, Spain

My 60^{th} birthday symposium (shared with Michael Dine) took place in January 2013.
I was happy to have Georg as one of the speakers. His talk is still available online.
https://scipp.ucsc.edu/fundamental_physics/weiglein-dinehaber_12.pdf
I suppose that my talk today is payback for that invitation.

In March, 2013, the Higgs boson discovery of the previous year was appropriately celebrated at the Aspen winter conference entitled
Higgs Quo Vadis.

Georg is a regular attendee of the Higgs Days conference that takes place in Santander, Spain each year in September. However, it took me three tries before finally getting Georg to appear in one of my photos in September 2013.

The discovery of the Higgs boson in 2012 was a triumph for low-energy supersymmetry. Is the discovery of supersymmetric particles imminent? Based on detailed two-loop computations, it seemed that there should be a good chance of discovering either sleptons or electroweakinos in the near future.

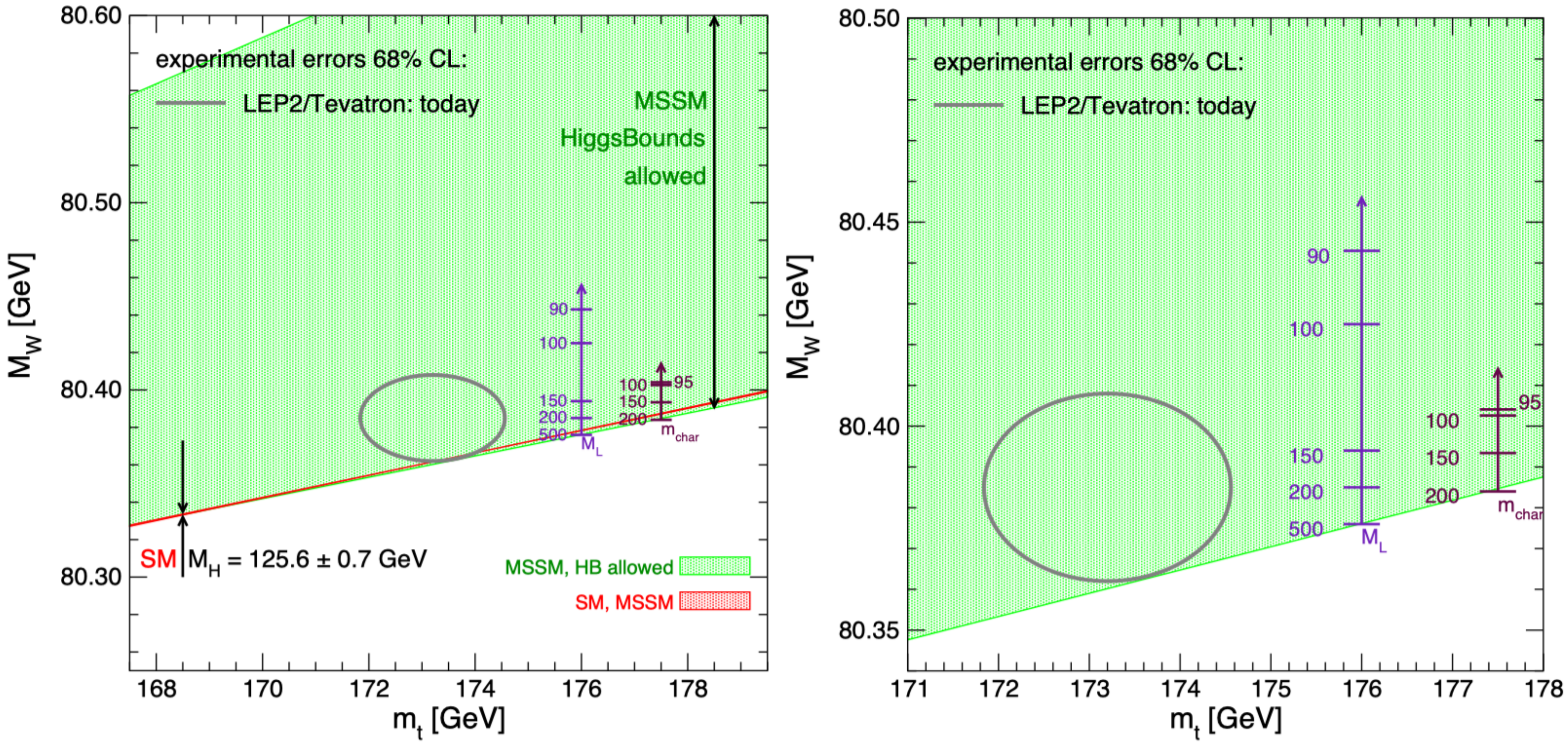


Figure 1: Prediction for M_W as a function of m_t. Left: The green region shows the HiggsBounds allowed region for the MSSM M_W prediction. It has been obtained by scanning over the MSSM parameters as described in the text. The cuts $m_{\tilde{t}_2}/m_{\tilde{t}_1} < 2.5$ and $m_{\tilde{b}_2}/m_{\tilde{b}_1} < 2.5$ are applied. The red strip indicates the overlap region of the SM and the MSSM, with $M_H^{\mathrm{SM}} = 125.6 \pm 0.7$ GeV. The two arrows indicate the possible size of the slepton and the chargino (and neutralino) contributions. Right: zoom into the most relevant region, with the SM area omitted.

Taken from S. Heinemeyer, W. Hollik, G. Weiglein, and L. Zeune, *JHEP* 12 (2013) 084 [arXiv:1311.1663 [hep-ph]].

Apparently, one Higgs meeting per year is not enough. Sometimes, Georg stops by the Paris Higgs Hunting meeting, as he did in July, 2015.

In July, 2016, Georg and I met up at the SUSY 2016 conference in Melbourne, Australia. But, we had some business to take care of—finalizing our paper on the Higgs alignment limit in the MSSM.

The Higgs alignment limit

In the Higgs alignment limit, the tree-level couplings of one neutral scalar field of an extended Higgs sector coincide with those of the Standard Model (SM) Higgs boson. In light of the LHC Higgs data, any extended Higgs sector must be close to the Higgs alignment limit.

Consider a two Higgs doublet model (2HDM) with two scalar doublet fields Φ_1 and Φ_2, and corresponding vacuum expectation values $\langle\Phi_i\rangle = v_i/\sqrt{2}$ (for $i = 1, 2$), where $\tan\beta \equiv v_2/v_1$ and $v \equiv (v_1^2 + v_2^2)^{1/2} \simeq 246$ GeV. One can rephase the Φ_i such that the v_i are real and nonnegative, in which case $0 \leq \beta \leq \pi/2$.

Define the following linear combinations of Higgs doublet fields,

$$\mathcal{H}_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \frac{v_1\Phi_1 + v_2\Phi_2}{v}, \qquad \mathcal{H}_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv \frac{-v_2\Phi_1 + v_1\Phi_2}{v}$$

such that $\langle H_1^0\rangle = v/\sqrt{2}$ and $\langle H_2^0\rangle = 0$, which defines the so-called *Higgs basis*.

The neutral scalar H_1^0 is *aligned* in field space with the vacuum expectation value v. If $\sqrt{2}\,\mathrm{Re}\,H_1^0 - v$ were a mass eigenstate, then its tree-level properties would coincide with those of the SM Higgs boson.

In the Higgs basis, the scalar potential is given by:

$$\begin{aligned}\mathcal{V} = {} & Y_1 \mathcal{H}_1^\dagger \mathcal{H}_1 + Y_2 \mathcal{H}_2^\dagger \mathcal{H}_2 + [Y_3 e^{-i\eta} \mathcal{H}_1^\dagger \mathcal{H}_2 + \text{h.c.}] + \tfrac{1}{2} Z_1 (\mathcal{H}_1^\dagger \mathcal{H}_1)^2 \\ & + \tfrac{1}{2} Z_2 (\mathcal{H}_2^\dagger \mathcal{H}_2)^2 + Z_3 (\mathcal{H}_1^\dagger \mathcal{H}_1)(\mathcal{H}_2^\dagger \mathcal{H}_2) + Z_4 (\mathcal{H}_1^\dagger \mathcal{H}_2)(\mathcal{H}_2^\dagger \mathcal{H}_1) \\ & + \left\{ \tfrac{1}{2} Z_5 e^{-2i\eta} (\mathcal{H}_1^\dagger \mathcal{H}_2)^2 + \left[Z_6 e^{-i\eta} (\mathcal{H}_1^\dagger \mathcal{H}_1) + Z_7 e^{-i\eta} (\mathcal{H}_2^\dagger \mathcal{H}_2) \right] \mathcal{H}_1^\dagger \mathcal{H}_2 + \text{h.c.} \right\}.\end{aligned}$$

Minimize the scalar potential: $Y_1 = -\frac{1}{2} Z_1 v^2$ and $Y_3 = -\frac{1}{2} Z_6 v^2$.

Remark:

Exact Higgs alignment $\Longleftrightarrow$ $Z_6 = 0$ (and $Y_3 = 0$ via the scalar potential minimum conditions), which implies no H_1^0–H_2^0 mixing.

Only the terms highlighted in red can yield an $\mathcal{H}_1^\dagger \mathcal{H}_2 + \text{h.c.}$ contribution to the quadratic terms of the scalar potential after imposing $\langle H_1^0 \rangle = v/\sqrt{2}$ and $\langle H_2^0 \rangle = 0$.

Approximate Higgs alignment in the CP-conserving 2HDM

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

$$\mathcal{M}_H^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}, \qquad \text{where } Z_5,\ Z_6 \in \mathbb{R}\,.$$

The CP-even Higgs boson fields are h and H with $m_h < m_H$.

Approximate Higgs alignment arises in 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 $m_A^2 \sim m_H^2 \sim m_{H^\pm}^2 \gg m_h^2 \simeq Z_1 v^2$.

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. $\Longrightarrow$ *Alignment without decoupling*.

In particular, the CP-even neutral scalar 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 $c_{\beta-\alpha} \equiv \cos(\beta-\alpha)$ and $s_{\beta-\alpha} \equiv \sin(\beta-\alpha)$ are defined in terms of the mixing angle α that diagonalizes the CP-even Higgs squared-mass matrix when expressed in the Φ_1–Φ_2 basis of scalar fields, $\{\sqrt{2}\,\mathrm{Re}\ \Phi_1^0 - v_1\,,\ \sqrt{2}\,\mathrm{Re}\ \Phi_2^0 - v_2\}$, and $\tan\beta \equiv v_2/v_1$.

Since $\sqrt{2}\,\mathrm{Re}\ H_1^0 - v$ possesses the tree-level couplings of the SM Higgs boson, it follows that

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

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

If h is SM-like

Then, $m_h^2 \simeq Z_1 v^2$ (i.e., $Z_1 \simeq 0.26$) and

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

That is, h is SM-like in either one of two cases:

- in the decoupling limit where $m_H \gg m_h$,

or

- in the Higgs alignment limit without decoupling where $|Z_6| \ll 1$ and $m_H^2 - m_h^2 \sim \mathcal{O}(v^2)$.

If H is SM-like

Then, $m_H^2 \simeq Z_1 v^2$ (i.e., $Z_1 \simeq 0.26$) and

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

That is, H is SM-like if $|Z_6| \ll 1$ corresponding to the Higgs alignment limit without decoupling.

No decoupling limit is possible in this case since $m_H \simeq 125$ GeV.

The MSSM Higgs sector is a special case of the 2HDM with

$$Z_1 = \tfrac{1}{4}(g^2 + g'^{\,2})c^2_{2\beta}\,, \qquad Z_5 = \tfrac{1}{4}(g^2 + g'^{\,2})s^2_{2\beta}\,, \qquad Z_6 = -\tfrac{1}{4}(g^2 + g'^{\,2})s_{2\beta}c_{2\beta}\,,$$

and the tree-level masses of the two neutral CP-even Higgs bosons h and H are

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

where g and g' are the SU(2)$_L$ and U(1)$_Y$ gauge couplings, respectively, $c_{2\beta} \equiv \cos 2\beta$ and $s_{2\beta} \equiv \sin 2\beta$.

Of course, including radiative corrections is essential for yielding a value of a SM-like neutral Higgs mass that is consistent with the observed value of 125 GeV.

The radiatively-corrected MSSM Higgs mass

Following a number of papers (including two by Ralf Hempfling and me) in the early 1990s, we realized that the tree-level MSSM Higgs mass bound of $m_h^2 \leq Z_1 v^2 = m_Z^2 c_{2\beta}^2$ can be significantly violated due to radiative corrections. For example, a one-loop computation yields[1]

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

$$Z_5 v^2 = s_{2\beta}^2\left\{m_Z^2 + \frac{3m_t^4}{8\pi^2 v^2 s_\beta^4}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t Y_t}{M_S^2}\left(1 - \frac{X_t Y_t}{12M_S^2}\right)\right]\right\},$$

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

where $M_S^2 \equiv m_{\tilde{t}_1} m_{\tilde{t}_2}$, $X_t \equiv A_t - \mu/\tan\beta$, and $Y_t \equiv A_t + \mu\tan\beta$.

[1] See M. Carena, H.E. Haber, I. Low, N.R. Shah, and C.E.M. Wagner, Phys. Rev. D **91**, 035003 (2015). In the formulae above, we assumed that all SUSY parameters are real (i.e., we are neglecting CP-violating effects that can enter the MSSM Higgs sector via radiative corrections).

Georg and collaborators initiated a research effort that obtained more precise results by providing a comprehensive treatment of the two-loop radiative corrections, along with powerful software tools such as `FeynHiggs`.

This research effort was expanded into the *Precision SUSY Higgs Mass Calculation Initiative* (also known as KUTS[2]), which was launched in 2014 to provide a forum for discussions among the different groups involved in Higgs-mass calculations in supersymmetric models. A review article that emerged from the KUTS effort appeared in 2021.[3]

Question: How is Higgs alignment realized in the MSSM?

One can achieve Higgs alignment easily in the decoupling limit. By assuming that $m_A \gg m_h$, it immediately follows that h is SM-like. But, is it possible to achieve Higgs alignment without decoupling in the MSSM? Is it still possible that H should be identified as the SM-like Higgs boson?

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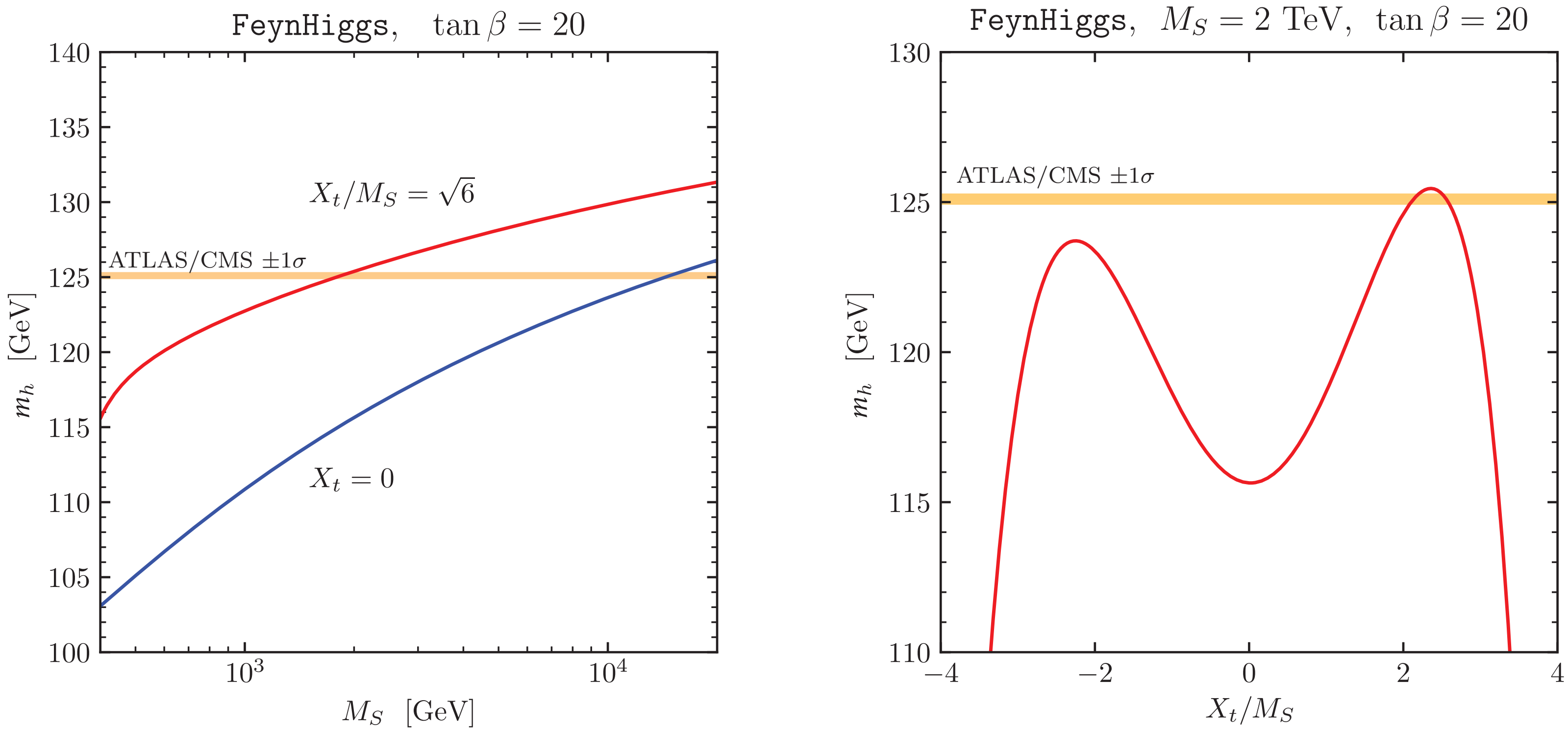
[2] Katharsis of Ultimate Theory Standards. See `https://sites.google.com/site/kutsmh/`.

[3] P. Slavich, S. Heinemeyer, et al., Eur. Phys. J. C **81**, 450 (2021).

The radiatively corrected MSSM Higgs sector results suggest that M_S must be larger (perhaps significantly larger) than 2 TeV, which provides some insight into why SUSY particles have yet to be discovered at the LHC.



The radiatively-corrected value of the MSSM Higgs mass, m_h, as a function of a common SUSY mass parameter M_S and the stop mixing parameter X_t (normalized to M_S), for $\tan\beta = 20$. The value of the observed Higgs mass currently measured by the ATLAS and CMS collaborations at the LHC is also shown. These figures have been adapted from P. Slavich, S. Heinemeyer, et al., Eur. Phys. J. C **81**, 450 (2021).

The hMSSM approximation

It is very challenging to employ the fully radiatively-corrected MSSM Higgs sector results in a comprehensive parameter scan. Djouadi and collaborators[4] proposed a simplified approach for analyzing the radiatively corrected Higgs sector, known as the hMSSM approximation.

The dominant one-loop radiative correction to m_h^2 that is proportional to $m_t^4 \ln(M_S^2/m_t^2)$ is entirely due to the radiatively-corrected value of $\mathcal{M}_{22}^2$, the 22 element of the CP-even neutral Higgs squared-mass matrix when expressed in the Φ_1–Φ_2 basis. In the hMSSM recipe, the tree-level expressions for $\mathcal{M}_{11}^2$ and $\mathcal{M}_{12}^2$ are used, whereas $\mathcal{M}_{22}^2$ is left unspecified. After diagonalizing the resulting squared-mass matrix, expressions of the form are obtained

$$m_{h,H}^2 = f_\pm(m_A^2, m_Z^2, \tan\beta, \mathcal{M}_{22}^2)\,,$$

$$\cos\alpha = g(m_A^2, m_Z^2, \tan\beta, \mathcal{M}_{22}^2)\,,$$

where the functions $f_\pm$ and g are the result of the diagonalization procedure.

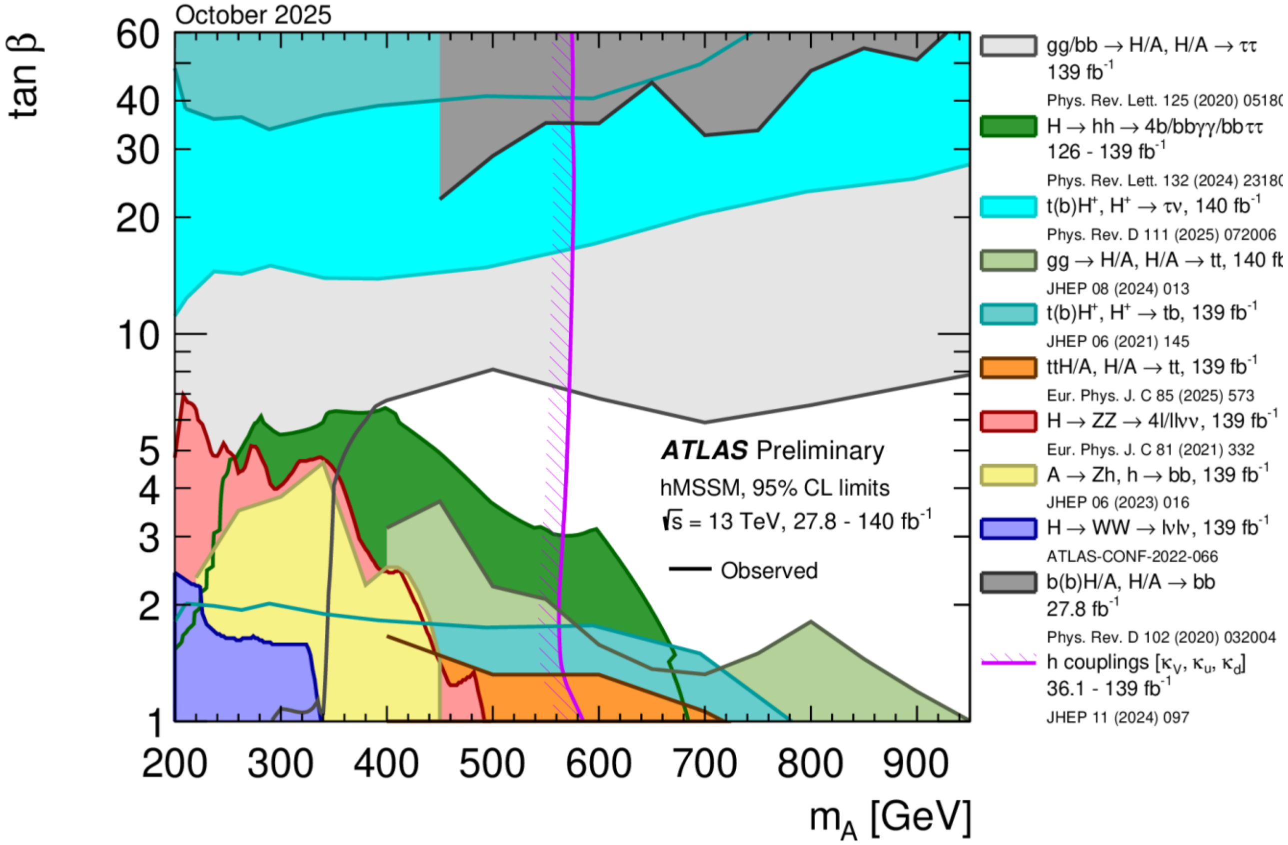
[4] A. Djouadi et al., Eur. Phys. J. C 73, 2650 (2013).

One then obtains expressions for m_H^2 and $\cos\alpha$ that are functions of the *measured* mass m_h, which replace the corresponding tree-level results. Having fixed $m_h \simeq 125$ GeV, the Higgs phenomenology of the hMSSM is entirely governed by two MSSM input parameters, m_A and $\tan\beta$. Note that the hMSSM framework is not relevant for describing the shift in the properties of the charged Higgs boson due to radiative corrections.

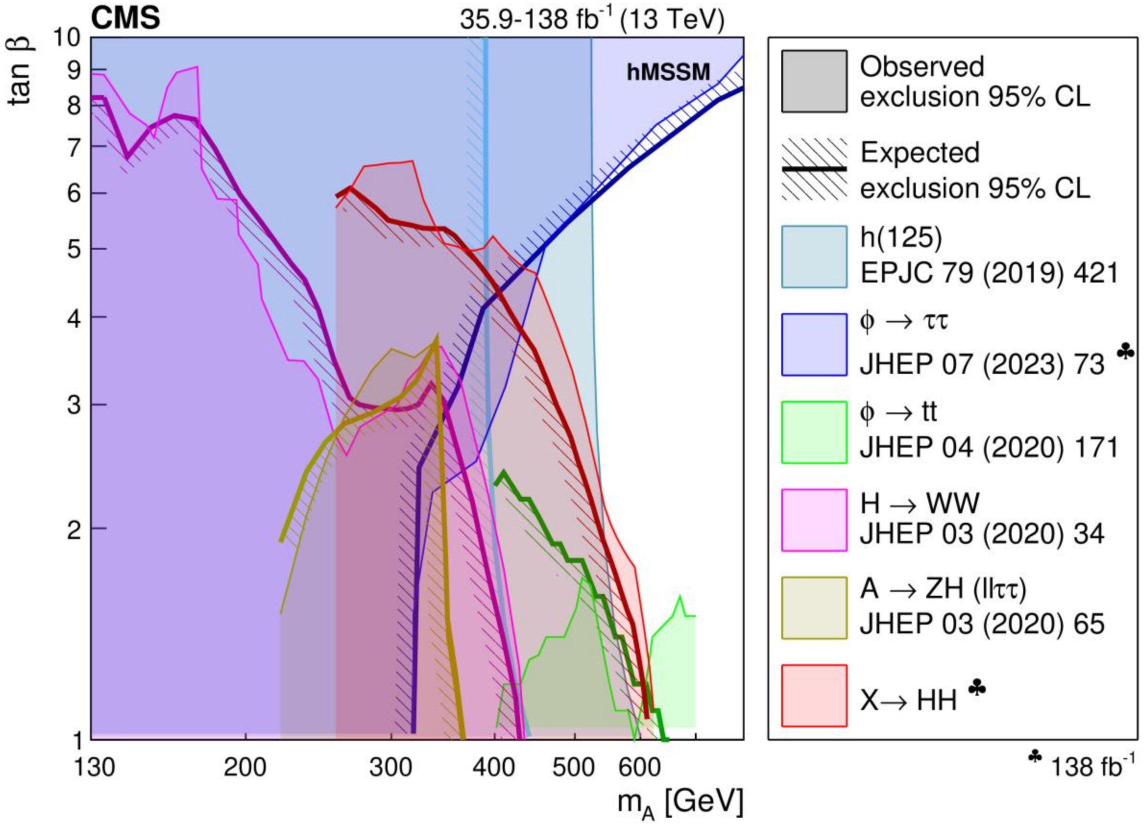
Although the hMSSM can be readily applied to LHC data to constrain the neutral CP-even Higgs sector of the MSSM, it can lead to results that are not robust in a more general MSSM parameter scan. For example, in the hMSSM approximation, Higgs alignment can only be achieved in the decoupling limit.

The hMSSM also does not account for the so-called "wrong-Higgs Yukawa couplings" generated by radiative corrections (which persist even when M_S is large). That is, the radiatively-corrected Higgs sector is not a type-II 2HDM.[5]

[5] For example, the constraints due to $b \to s\gamma$, which yield $m_{H^\pm} > 675$ GeV @ 95% CL (see M. Misiak, talk given at the Scalars 2025 Conference in September, 2025), is not necessarily applicable in the MSSM.



Taken from ATLAS Collaboration, ATL-PHYS-PUB-2025-042 (October 19, 2025).



Taken from CMS Collaboration, Physics Reports **1115** (2025) 368–447.

The analysis of the Higgs data in the framework of the hMSSM rules out values of $m_A < 570$ GeV. In particular, Higgs alignment without decoupling is not possible within the hMSSM approximation.

Accounting for the leading two-loop corrections of $\mathcal{O}(\alpha_s h_t^2)$

In my second paper with Georg and collaborators, we focused on the parameter regime of the MSSM that is consistent with the Higgs alignment limit.[6]

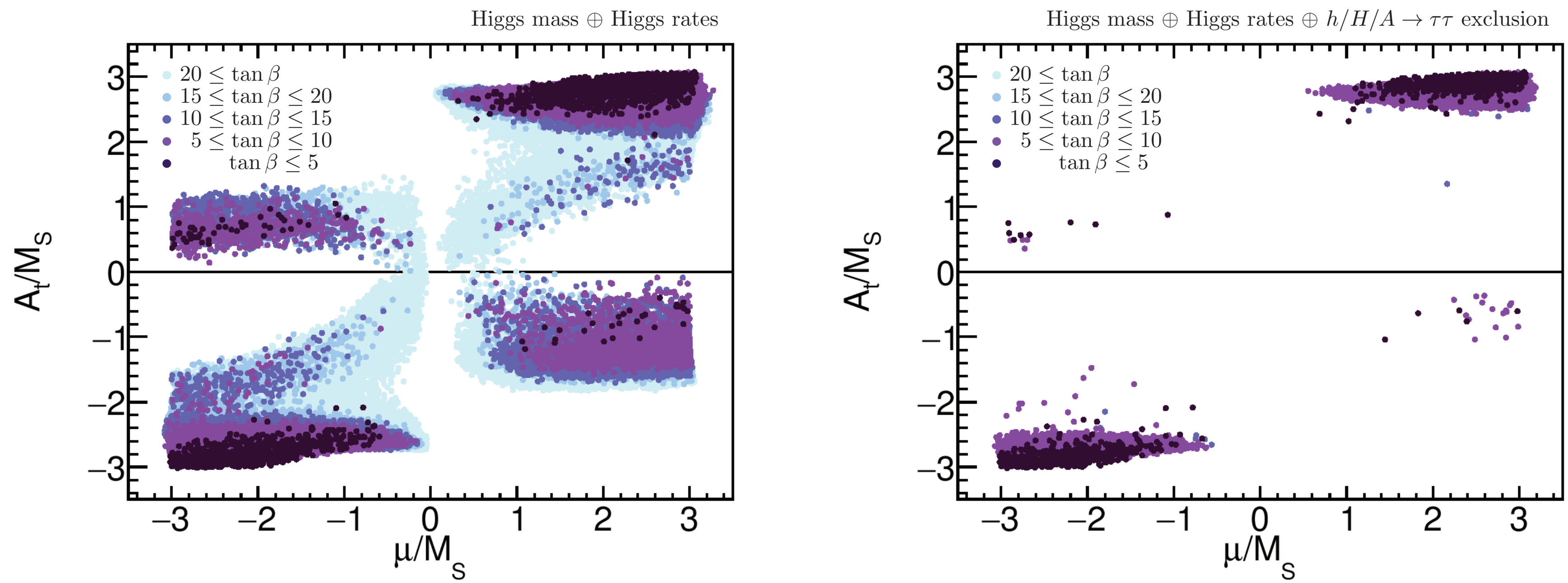
In addition to using the more complete two-loop formulae, we developed an analytic approximation based on the one-loop formula for Z_6 previously quoted. We followed the recipe used in a previous paper[7] by replacing the top quark Yukawa coupling h_t with $h_t(\lambda)$, where $\lambda \equiv \bigl[m_t(m_t)M_S\bigr]^{1/2}$ in the one-loop leading log pieces and $\lambda \equiv M_S$ in the leading threshold corrections.

Imposing the exact Higgs alignment limit by setting $Z_6 = 0$ leads to an 11th order polynomial equation in $\tan\beta$, which can be solved numerically. Note that $Z_6 = 0$ is achieved by an "accidental" cancellation of the tree-level and loop-level contributions, which is not possible in the hMSSM approximation.

[6] P. Bechtle, H.E. Haber, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein, and L. Zeune, Eur. Phys. J. C **77**, 67 (2017); H.E. Haber, S. Heinemeyer and T. Stefaniak, Eur. Phys. J. C **77**, 742 (2017).

[7] H.E. Haber, R. Hempfling and A.H. Hoang, Z. Phys. C **75**, 539 (1997); M. Carena, H.E. Haber, S. Heinemeyer, W. Hollik, C.E.M. Wagner, and G. Weiglein, Nucl. Phys. B **580**, 29 (2000).

The approximate two-loop results for the exact alignment limit[8] matched well with a comprehensive scan over the MSSM parameter space. An eight-parameter pMSSM scan was performed to determine allowed parameter regimes which contain a light CP-odd Higgs boson A. Typically, h is SM-like, although one cannot yet rule out the possibility of a SM-like H.



Preferred points of the pMSSM-8 scan with low $m_A \leq 350$ GeV for different selections of observables. The points are within the (approximate) 95% CL region, based on the following observables. Left panel: only Higgs mass and signal rates; Right panel: Higgs mass, signal rates and $h/H/A \to \tau^+\tau^-$ exclusion likelihood.

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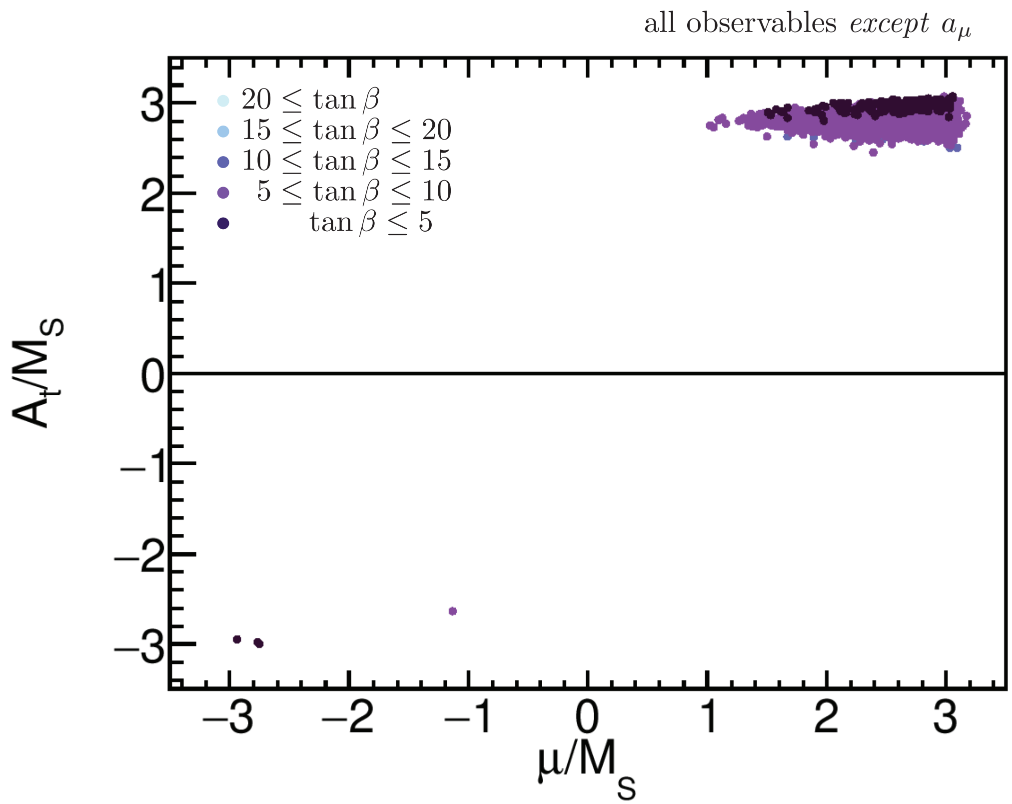
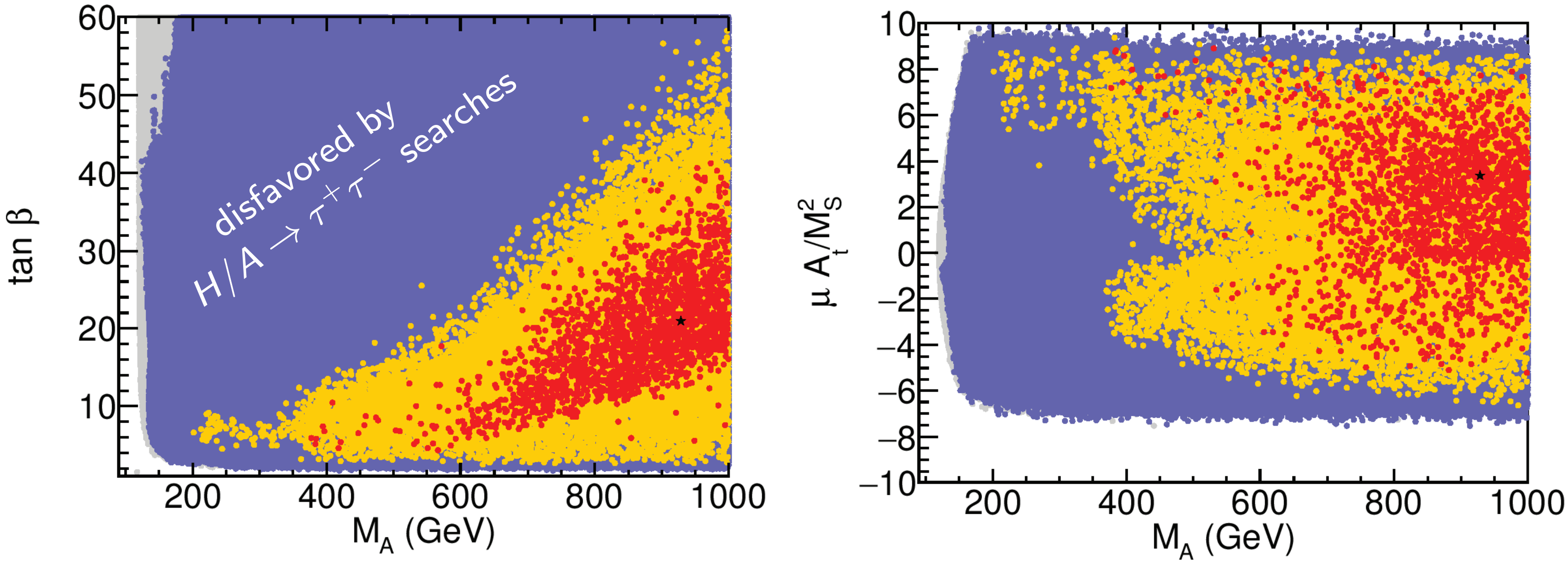
[8]Of course, the precision Higgs data only require that the condition of alignment is approximately satisfied.

Including additional constraints from SUSY particle searches and the impact of SUSY radiative corrections on SM observables, the allowed parameter regions of the pMSSM-8 scan shrinks further. For example, results from the SuperIso program show that the negative μ region is mostly disfavored by BR($B \to X_s\gamma$), whereas negative A_t is disfavored by BR($B_s \to \mu^+\mu^-$). Preferred points of the scan with values of $m_A \leq 350$ GeV are shown below.



Preferred parameter regions in a pMSSM-8 scan

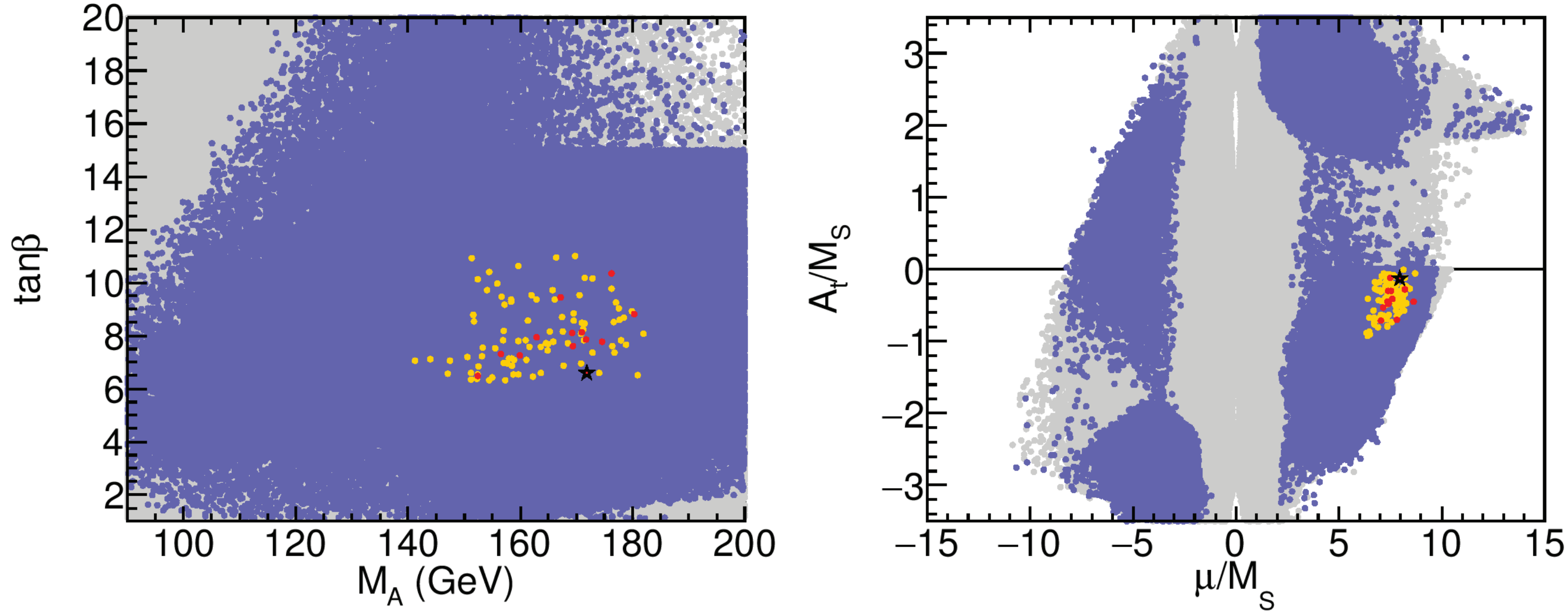
Case 1: h is SM-like



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 $\Delta\chi^2_h < 2.3$, yellow for $\Delta\chi^2_h < 5.99$ and blue otherwise. The best fit point is indicated by a black star.

Bottom line: m_A values as low as 200 GeV are still allowed in the MSSM.

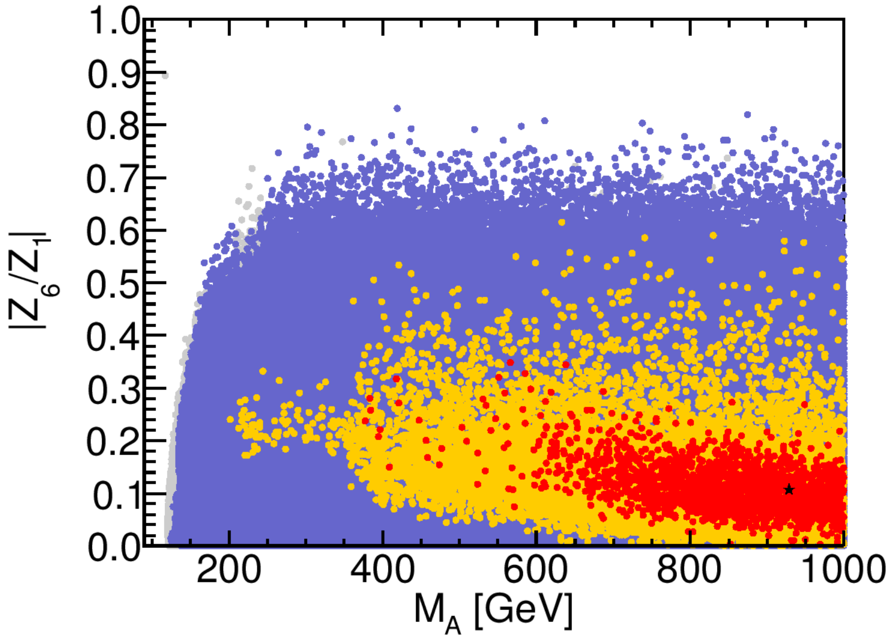
Case 2: H is SM-like



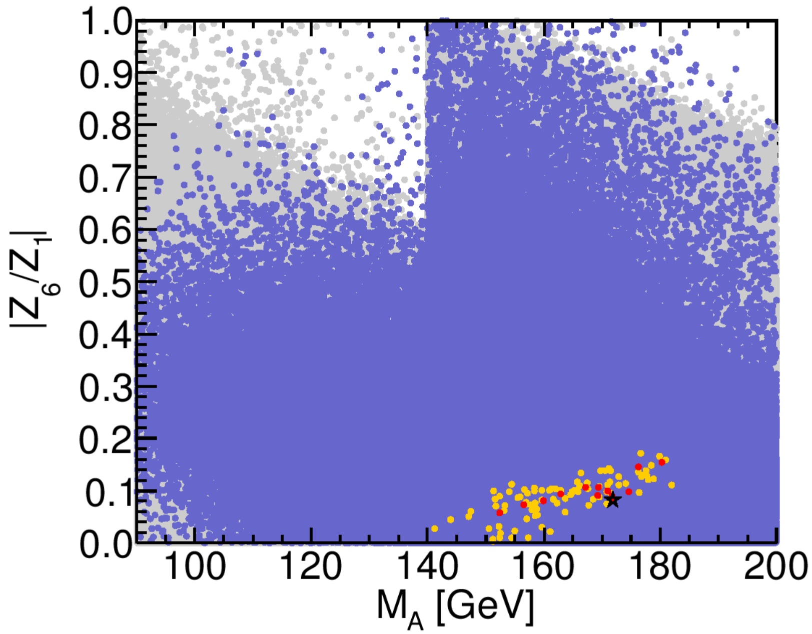
Note: In the preferred region of the pMSSM-8 parameter space with a SM-like H, $X_t \sim -1.5 M_S$ and $150~\text{GeV} \lesssim m_{H^\pm} \lesssim 200~\text{GeV}$ and $m_h \lesssim 100~\text{GeV}$.

Bottom line: The possibility that the heavier of two CP-even Higgs bosons of the MSSM is the observed 125 GeV Higgs boson is not yet excluded.

How fine-tuned is the alignment without decoupling region of the MSSM?



SM-like h



SM-like H

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 (to be compared with $Z_6 = 0$ at exact alignment).

Over the next eight years, I met up with Georg six times at Higgs Days in Santander. I have lots of pictures, which I admit become a little repetitive after a while. But, one picture stands out, taken on September 7, 2023 at Bodega Riojano, which I have titled “Typhoid Georg”.

At 3:03 pm Spanish time, the following email arrived in my mailbox.

not so great news Archives/friends × Archives/georg ×

Georg Weiglein Georg.Weiglein@desy.de via ucsc.edu Sep 8, 2023, 6:03 AM

to Sven, Howard, Carlos, Shinya, markus.schumacher, Karsten, Cheng-Wei, Johannes, mariaolalla, Kateryna, Thomas, Jose, Georg

Dear friends,

I am meanwhile back to Hamburg. When I arrived at home I took a Covid test, and this test turned out to be positive. I have no symptoms so far, but this of course does not rule out the possibility that I could have infected someone at Santander. I have been in quite close contact with all of you yesterday, and I very much hope that was not yet infectious yesterday.

I am very sorry for bothering you with this rather unpleasant message — I hope nobody of you will get infected!

Best wishes,

Georg

On Sept. 9, 2023, Sven, Maria, Pietro, and I were traveling to Paris (the Higgs Hunting 2023 meeting was starting on Sept. 11). We already had dinner reservations set for the evening of Sept. 9. Reacting to this email, Pietro self-quarantined, but Sven, Maria, and I had a lovely evening (and dinner) in Paris.

A false positive?

Georg Weiglein Georg.Weiglein@desy.de via ucsc.edu Sep 11, 2023, 1:19 AM

to Sven, Howard, Carlos, Shinya, markus.schumacher, Karsten, Cheng-Wei, Johannes, mariaolalla, Kateryna, Thomas, Jose, Georg

Dear friends,
just as a follow-up: I stayed symptom-free over the weekend, and my test this morning was negative.
Best wishes,
Georg

Although Sven and I never saw Pietro during the Higgs Hunting 2023 meeting in Paris, as far as we know, nobody who attended the Higgs Days conference dinner on Sept. 7 was infected. Typhoid Mary's friends should have been so lucky!

Georg and I attended SUSY 2024 in Madrid, Spain, hosted by Sven, which provided opportunities for many interesting physics discussions and dinners.

Sadly, Georg was not able to join us at SUSY 2025 in Santa Cruz.

I will share two more photos. This one was taken at Auberge des Chasseurs in Échenevex, France. I get hungry just looking at this. Our excuse for this trip was the Extended scalar sectors from all angles Workshop held at CERN in October, 2024.

The 7th International Workshop on "Higgs as a Probe of New Physics" (HPNP2025) in Osaka, Japan provided opportunities for interesting and exotic dinners. Photo taken on June 11, 2025.

Congratulations, Georg, for reaching this milestone—your 60th birthday. There is still a lot of mileage left in your tank. Enjoy the upcoming journey!

Looking forward to exciting new discoveries at a high luminosity LHC. Meanwhile, stay in good shape so that you are ready when FCC-ee (or equivalent) realizes our dream of a future Higgs factory.