

Improvements on the prediction of the light CP-even Higgs boson mass in the MSSM

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FeynHiggs collaboration

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The mass of the Higgs boson

In the Standard Model:

The Higgs boson mass is a free parameter.

In extensions of the Standard Model:

The Higgs boson mass can depend on other parameters of the theory,

e.g. in the Minimal Supersymmetric Standard Model.

The Higgs sector in the MSSM

Physical mass eigenstates (real parameters \Rightarrow no CP-violation):

- 5 Higgs bosons: 2 neutral, CP-even h, H ,
1 neutral, CP-odd A
2 charged H^\pm

Masses of the Higgs bosons:

- not all independent:
often: Mass M_A or M_{H^\pm} (and $\tan \beta$) as free parameters
 $\tan \beta = v_u/v_d$: ratio of the vacuum expectation values
- lightest Higgs boson: h
Upper theoretical Born mass bound: $M_h \leq M_Z = 91 \text{ GeV}$
with quantum corrections of higher orders: $M_h \lesssim 140 \text{ GeV}$



dependent on the MSSM parameters

Why a precise Higgs mass prediction?

- Needed as **consistent input** for the **calculation** of cross sections and decay widths in the MSSM
- The experimental measured value

CMS: $m_H = 125.7 \pm 0.3 \text{ (stat)} \pm 0.3 \text{ (syst)} \text{ GeV}$

ATLAS: $m_H = 125.5 \pm 0.2 \text{ (stat)} \quad {}^{+0.5}_{-0.6} \text{ (syst)} \text{ GeV}$

constrains the **viable parameter space** of the MSSM:

A **precise theoretical prediction** is needed to fully **exploit** this **constraint**.

- In the discussion of the **amount** of **fine-tuning** of the MSSM the precise theoretical prediction of the Higgs boson mass enters.

Calculation of Higgs masses in the MSSM

Two approaches:

- Feynman diagrammatic approach

(or effective potential approach for vanishing external momenta)

[Brignole, Chankowski, Choi, Dabelstein, Dedes, Degrassi, Demir, Drees, Ellis, Frank, Hahn, Harlander, Heinemeyer, Hollik, Kant, Lee, Martin, Mihaila, Pilaftsis, Pokarski, Ridolfi, Rosiek, H.R., Slavich, Steinhauser, Weiglein, Zwirner, ...]

- renormalization group equation approach

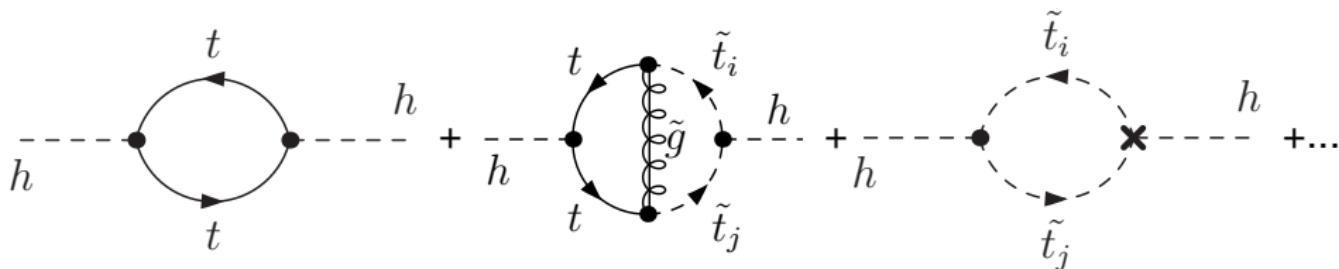
[Carena, Draper, Espinosa, Haber, Hempfling, Hoang, Lee, Quiros, Wagner, Zhang, ...]

very recent [Draper, Lee, Wagner, arXiv:1312.5743]

Feynman diagrammatic approach

Calculate Feynman diagrams

which contribute to the Higgs-boson self energies $\hat{\Sigma}$:



1-loop level $\mathcal{O}(\alpha_t)$

2-loop level $\mathcal{O}(\alpha_t \alpha_s)$

Counterterm contr.

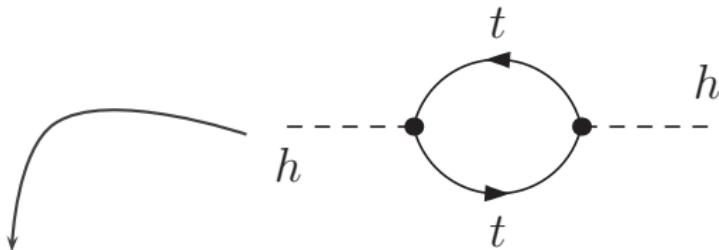
$$\alpha_t \sim (\text{top Yukawa coupl.})^2$$

Feynman diagrammatic approach

Two-point-function:

$$-i\hat{\Gamma}(p^2) = p^2 - \mathbf{M}(p^2)$$

with the matrix:



$$\mathbf{M}(p^2) = \begin{pmatrix} M_{h_{\text{Born}}}^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{Hh}(p^2) \\ -\hat{\Sigma}_{Hh}(p^2) & M_{H_{\text{Born}}}^2 - \hat{\Sigma}_{HH}(p^2) \end{pmatrix}$$

(CP-conserving case:
mixing only
betw. CP-even
Higgs bosons h, H)

Calculate the zeros of the determinant of $\hat{\Gamma}$

⇒ loop-corrected Higgs masses

Renormalization group equation approach

Assumption: all SUSY particles and the CP-odd Higgs boson mass M_A being heavy $\sim M_S$

- (i) Match quartic Higgs coupling λ at scale M_S
- (ii) Use SM-RGE running to obtain λ at scale m_t
- (iii) Higgs mass is given by $m_h^2(m_t) = 2\lambda(m_t)v^2$
with $v \approx 174 \text{ GeV}$ being the Higgs vacuum expectation value

Approach can be refined to allow for different scales

Advantages

- Feynman diagrammatic approach:

All **log-** and **non-log** terms are taken into account
at a **certain order** of perturbation theory:

Especially important for **lower mass scales**

- Renormalization group equation approach:

Resummation of potentially large **log-terms**:

Especially important for **larger mass scales**

⇒ **Combine** both approaches

Combination

- Feynman diagrammatic part: from FeynHiggs
- Renormalization group equation (RGE) part:
 - ★ 2-loop RGE for running for the **strong coupling** g_s with $\alpha_s = g_s^2/(4\pi)$
[Espinosa, Quiros '91]
 - ★ Matching at scale $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$: [Carena, Haber, Heinemeyer, Hollik, Wagner, Weiglein, hep-ph/0001002]

$$\lambda(M_S) = \frac{3y_t^4}{8\pi^2} \frac{X_t^2}{M_S^2} \left[1 - \frac{X_t^2}{M_S^2} \right]$$

$m_{\tilde{t}_i}$ = stop masses

$X_t = A_t - \mu \cot \beta$ = squark mixing parameter

⇒ leading + next-leading log $(\ln \frac{M_S}{m_t})$ resummation

Combination

- Combination of both approaches:

Avoid double counting of logs

⇒ Subtract logs from the Feynman diagrammatic (FD) result:

$$\Delta M_h^2 = (\Delta M_h^2)^{\text{FD}}(X_t^{\text{OS}}) - (\Delta M_h^2)^{\log}(X_t^{\text{OS}}) + (\Delta M_h^2)^{\text{RGE}}(X_t^{\overline{\text{MS}}})$$

★ Both approaches use a $\overline{\text{MS}}$ top quark mass

★ FD: X_t in **on-shell** scheme, RGE: X_t in $\overline{\text{MS}}$ scheme:

Conversion needed:

$$X_t^{\overline{\text{MS}}} = X_t^{\text{OS}} \left[1 + \ln \frac{M_S^2}{m_t^2} \left(\frac{\alpha_s}{\pi} - \frac{3\alpha_t}{16\pi} \right) \right]$$

Combination

For $M_A \gg M_Z$:

$$\hat{\Sigma}_{\phi_u \phi_u} \approx (\sin \beta)^{-2} \Delta M_h^2$$



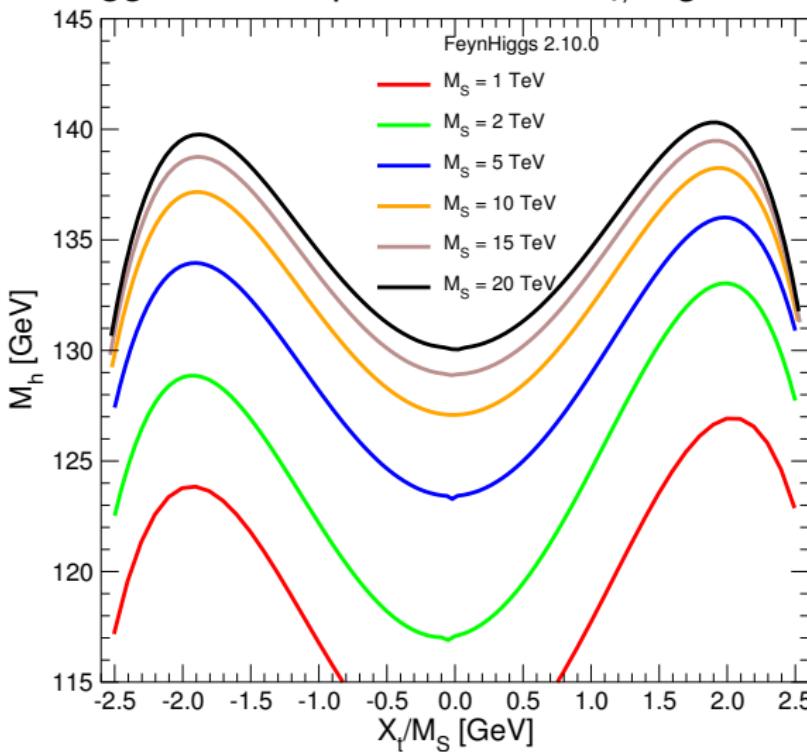
self energy of the
interaction eigenstates ϕ_u

ϕ_u couples to up-type quarks

Correction can be incorporated into the self energy matrix

Results

Higgs mass dependence on X_t/M_S and M_S :



lower scales:

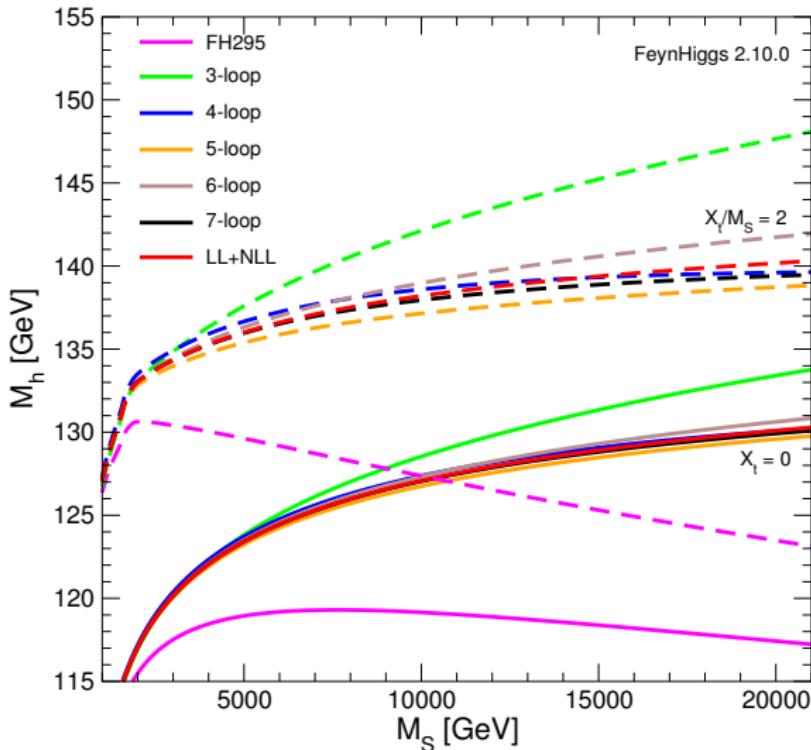
maxima: large difference
in size due to
non-log terms

larger scales:

differences between
maxima become smaller
(still sizeable in between)

$$M_A = M_2 = \mu = 1 \text{ TeV}, \\ m_{\tilde{g}} = 1.6 \text{ TeV}, \tan \beta = 10$$

Results

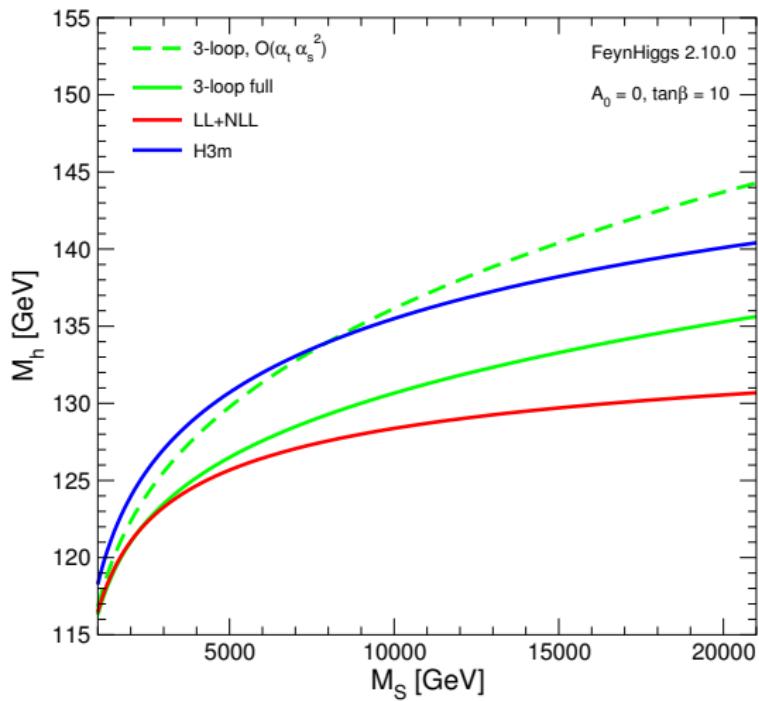


Comparison of:

- * old FeynHiggs reliable up to $M_s = \mathcal{O}(1\text{TeV})$
- * analyt. solution of RGE: 3-loop ... 7-loop level
- * numerical solution: logs resummed to all orders

$$M_A = M_2 = \mu = 1 \text{ TeV}, m_{\tilde{g}} = 1.6 \text{ TeV}, \tan \beta = 10$$

Results



Comparison with H3m:

[Kant, Harlander, Mihaila,
Steinhauser, arXiv:1005.5709]

3-loop: $\mathcal{O}(\alpha_t \alpha_s^2)$, $\mathcal{O}(\alpha_t^2 \alpha_s)$, $\mathcal{O}(\alpha_t^3)$

- * only leading and next-to leading logs
- * single scale M_S

H3m: * complete $\mathcal{O}(\alpha_t \alpha_s^2)$ result

- * different scales

At 2-loop: different ren. schemes

CMSSM: $m_0 = m_{1/2} = 200 \dots 15000$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$,
spectra generation with SoftSUSY [Allanach, hep-ph/0104145]

Conclusion

Lower SUSY scales: **Feynman diagrammatic approach**
(or effective potential approach)

Large SUSY scales: **Renormalization group equation approach**

⇒ Combination of both approaches:

Good prediction for **all scales**

Implemented to FeynHiggs: looplevel = 3

Further refinements:

- ★ Allow for different scales (smaller CP-odd Higgs boson mass,
large stop mass splitting)
- ★ Improve matching condition

How to calculate the zeros of the determinant of $\hat{\Gamma}$

Calculate the zeros of the determinant of $\hat{\Gamma}$:

$$\det[p^2 - \mathbf{M}(\mathbf{p}^2)] = 0$$

or calculate the eigenvalues $\lambda(p^2)$ of $\mathbf{M}(\mathbf{p}^2)$ (FeynHiggs approach):

$$\det[\lambda(p^2) - \mathbf{M}(\mathbf{p}^2)] = 0$$

and solve iteratively:

$$p^2 - \lambda(p^2) = 0$$

⇒ loop-corrected Higgs mass values

Renormalization Group Equations

- Renormalization group equation (RGE) part: 2-loop RGE for running

[Espinosa, Quiros '91]

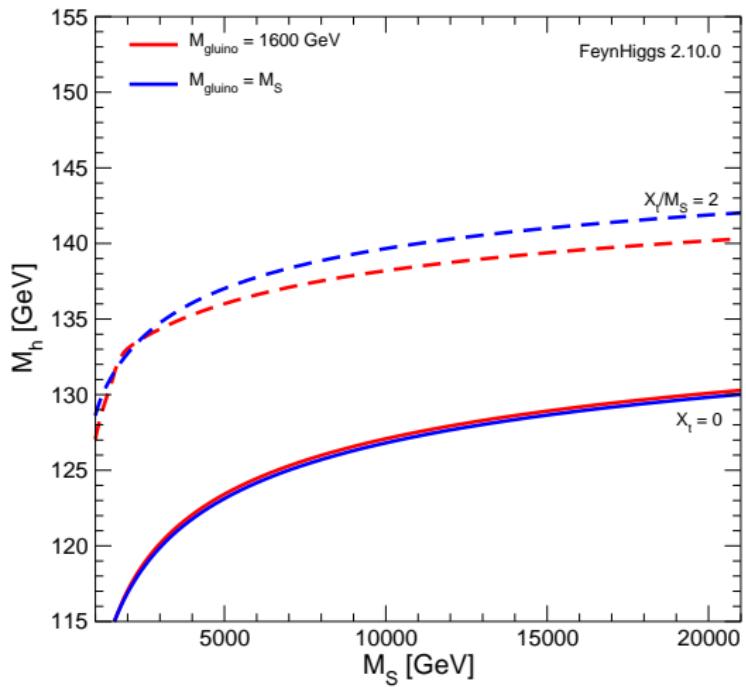
$$\mu \frac{d\lambda(\mu)}{d\mu} = \frac{1}{(16\pi^2)} \left[12\lambda^2 + 12y_t^2\lambda - 12y_t^4 \right]$$

$$+ \frac{1}{(16\pi^2)^2} \left[-78\lambda^3 + 60y_t^6 - 3\lambda y_t^4 - 64g_s^2 y_t^4 + 80\lambda g_s^2 y_t^2 - 72\lambda^2 y_t^2 \right]$$

$$\mu \frac{dg_s(\mu)}{d\mu} = \frac{g_s}{(16\pi^2)} \left[-7g_s^2 \right] + \frac{g_s}{(16\pi^2)^2} \left[-26g_s^4 - 2g_s^2 y_t^2 \right]$$

$$\begin{aligned} \mu \frac{dy_t(\mu)}{d\mu} &= \frac{y_t}{(16\pi^2)} \left[\frac{9}{2}y_t^2 - 8g_s^2 \right] && \text{quartic Higgs coupling} \\ &+ \frac{y_t}{(16\pi^2)^2} \left[-12y_t^4 + \frac{3}{2}\lambda^2 - 6\lambda y_t^2 + 36g_s^2 y_t^2 - 108g_s^4 \right] && \text{strong coupling} \\ &&& \text{top Yukawa coupling} \end{aligned}$$

Dependence on the gluino mass



$$M_A = M_2 = \mu = 1 \text{ TeV}, m_{\tilde{g}} = 1.6 \text{ TeV}, \tan \beta = 10$$