

Improvements in Higgs-mass predictions with FeynHiggs

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Recent developments in the public code FeynHiggs for the prediction of the Standard Model-like Higgs mass in the Minimal Supersymmetric Standard Model are presented. Improvements in the prediction based on an effective-field theory concern the cases of multi-scale hierarchies where the gluino is much heavier than the sfermions or where the additional Higgs bosons have masses between the electroweak and supersymmetry scales. The fixed-order part is improved by a re-implementation and extension of the two-loop corrections, now containing the contributions of orders $(\alpha_t + \alpha_b) \cdot (\alpha_t + \alpha_b + \alpha_s)$ in the limit of vanishing electroweak gauge couplings for all implemented renormalization schemes. The updated version has a significantly improved numerical stability and thus an enhanced range of applicability for scenarios with heavy supersymmetric particles. All updates will be included in the upcoming version FeynHiggs-2.19.0.

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1. Introduction

The properties of the Standard Model (SM)-like Higgs boson discovered at the Large Hadron Collider (LHC) by the ATLAS and CMS experiments [1, 2] are measured with an accuracy that still leaves ample space for physics beyond the SM (BSM) [3, 4]. A theoretically well-motivated and extensively studied BSM theory is the Minimal Supersymmetric SM (MSSM). Due to the supersymmetry (SUSY) each degree of freedom of the SM gets a superpartner. Furthermore, a second Higgs doublet is required, yielding two CP -even Higgs bosons h, H , one CP -odd Higgs boson A as well as two charged Higgs bosons H^\pm after breaking of the electroweak symmetry. Both doublets have a non-zero vacuum expectation value (vev) whose quadratic mean is equal to the electroweak vev and whose ratio is a free input parameter called $\tan\beta$. The charged Higgs mass m_{H^\pm} or, in case of real parameters, the CP -odd Higgs mass m_A is another input parameter. Since the quartic Higgs self-couplings are related to the electroweak gauge couplings, the SM-like Higgs mass m_h is a predicted quantity that depends on the input parameters. In comparison with experimental measurements, it can be used to constrain the parameter space of the MSSM.

Two-point functions built from the Higgs fields shift the physical Higgs masses and induce a mixing of the tree-level mass eigenstates at higher order. The SM-like Higgs mass of the MSSM receives particularly large radiative corrections. The loop-corrected squared Higgs masses can be determined as the real parts of the poles in p^2 of the inverse matrix of two-point functions Γ^{-1} with

$$\Gamma(p^2) = i \left[p^2 \mathbb{1} - m_{\text{tree}}^2 + \hat{\Sigma}(p^2) \right], \quad (1)$$

where m_{tree} is the diagonal matrix of tree-level Higgs masses and $\hat{\Sigma}$ is the renormalized matrix of Higgs self-energies. The latter can be computed at a fixed order by evaluating renormalized Feynman diagrams. The radiative corrections contain logarithms of a SUSY mass M_S divided by a mass at the electroweak scale M_{EW} . Therefore, a pure fixed-order prediction becomes unreliable if one of the occurring SUSY masses is much larger than M_{EW} . In that case, methods of effective field theories (EFTs) can be employed in order to resum the large logarithms and to provide a reliable Higgs-mass prediction at the small scale M_{EW} . For the SM EFT, the effective quartic Higgs self-coupling $\lambda(Q)$ (Q denoting the energy scale) is matched to the corresponding object in the high-energy theory (e. g. the MSSM) at the high energy scale (e. g. $Q = M_S$) taking into account threshold corrections of a given order; this fixes a boundary condition. Afterwards, renormalization group equations (RGEs) of the SM are used to evaluate λ at the low scale $Q = M_{\text{EW}}$. The effective Higgs mass in the EFT is given by $m_{h,\text{eff}}^2(Q) = 2\lambda(Q)\bar{v}^2(Q)$ with the SM vev \bar{v} in the $\overline{\text{MS}}$ scheme. Finally, the physical Higgs mass at the low scale M_{EW} is obtained as the real part of the solution to

$$p^2 - m_{h,\text{eff}}^2(M_{\text{EW}}) + \hat{\Sigma}_{\text{SM}}(p^2) = 0, \quad (2)$$

where $\hat{\Sigma}_{\text{SM}}$ denotes the renormalized Higgs-boson self-energy in the SM. In the simplest versions of EFTs operators of dimension > 4 are neglected such that terms that are suppressed by powers of M_{EW}/M_S are discarded. Consequently, predictions based on the EFT approach are not reliable for small SUSY scales M_S . The public code FeynHiggs [5–12]¹ contains a consistent combination

¹The most recent release of FeynHiggs and links to its manual are available at <http://www.feynhiggs.de>.

of both approaches by adding the resummed logarithms of the EFT to the fixed-order corrections without double-counting; thus, reliable predictions are provided at low and high SUSY scales.

2. Improvements in the fixed-order part

The fixed-order corrections that are implemented in FeynHiggs-2.18.0 are the complete one-loop order and leading two-loop corrections of $\mathcal{O}(\alpha_t \alpha_s, \alpha_b \alpha_s, \alpha_t^2, \alpha_b^2, \alpha_t \alpha_b)$ in the limit of vanishing electroweak gauge couplings (gaugeless limit) [13–20]. The gaugeless limit implies that the squared momentum in the self-energies appearing in the corrections to the SM-like Higgs mass be set to $p^2 = m_h^2 \propto g_2^2 v^2 = 0$, thus significantly simplifying the evaluation of two-loop integrals.² It should be noted that only the corrections of $\mathcal{O}(\alpha_t \alpha_s, \alpha_t^2)$ are available in the case of complex input parameters or if the charged Higgs mass m_{H^\pm} is chosen as input parameter in replacement of the CP -odd Higgs mass m_A . In addition, the renormalization scheme of the sbottom sector varies by terms of higher order in the different corrections containing the bottom Yukawa coupling. For the case of real input parameters in the scheme of on-shell CP -odd Higgs also the momentum-dependent corrections of $\mathcal{O}(\alpha_t \alpha_s)$ are available [24].

2.1 Re-implementation of two-loop corrections

The upcoming version FeynHiggs-2.19.0 contains all above-mentioned two-loop corrections in the gaugeless limit, but allowing for real or complex input parameters with on-shell A or H^\pm and using the same renormalization scheme throughout the whole code; the latter point also facilitates the inclusion of new schemes, e. g. the MDR scheme that is described below. The re-implemented corrections are based on the former results of Refs. [25, 26]. Different from the previous formulas, the self-energies are now expressed in terms of generalized couplings and integrals, similar to Ref. [27], allowing for smaller expressions and better readability. In general, the occurring loop integrals need to be reduced to a basis of master integrals. Depending on the numerical equality of symbolically different masses, the reduction of certain integral topologies yields different results, see Fig. 1 for an illustration. In the old formulas, this reduction was already executed assuming non-degenerate spectra, thus generating mass differences in denominators due to the use of partial-fraction expansion; in the vicinity of scenarios with degenerate masses, e. g. the

²A deviation from the prescription of inserting tree-level masses (within the chosen approximation) into loop corrections breaks invariance under gauge-fixing and field-renormalization schemes and therefore introduces new sources of uncertainty [21–23].

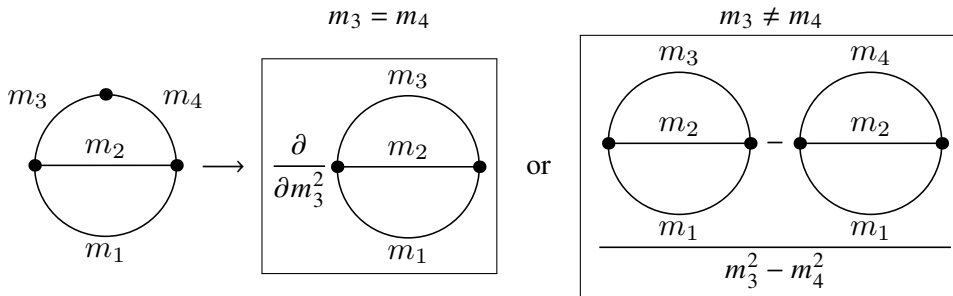


Figure 1: Example for an integral topology with different reduction rules depending on the equality of the masses m_3 and m_4 .

two stops, these expressions caused artificial divergences that were cured by an explicit small offset for one of the involved input parameters. Now, utilizing the results of Ref. [28], the generalized integrals are reduced to scalar integrals without introducing possibly divergent denominators. The final analytic reduction of the remaining scalar integrals to master integrals is implemented in FeynHiggs-2.19.0 and delayed until numerical evaluation. These manipulations allow for a significantly increased numerical stability.

2.2 Numerical examples

In the following, the predictions for the SM-like Higgs mass M_h by FeynHiggs-2.18.0 and FeynHiggs-2.19.0 are compared to each other. In addition to the results with default double precision (green and red curves), also results with quadruple precision (quad. prec.) are shown for the older version (blue curves). On the left-hand side of Fig. 2, the behavior for very heavy SUSY masses is shown: all bilinear soft SUSY-breaking parameters, the sfermion mixing parameters X_f , μ , and the charged Higgs mass are set equal to M_S ; $\tan\beta = 10$. To allow for a stable Higgs-mass prediction beyond $M_S \gtrsim 2$ TeV the large logarithms of M_S divided by masses at the electroweak scale M_{EW} that occur in the fixed-order expressions need to be resummed. For that purpose the resummation of next-to-next-to-leading logarithms (NNLL) of FeynHiggs is activated via the setup `FHSetFlags[4, 3, 0, 2, 3, 2, 0, 3]`. One can see that the green line becomes instable already below $M_S = 10$ TeV whereas the other curves remain smooth until $M_S \sim 50$ TeV. The reason for the instability in the green line is the increasingly suppressed mixing between the sfermion pairs of the same type as compared to the diagonal entries $m_{\tilde{f}}^2$ of their squared mass matrices, $m_f X_f = M_{EW} M_S \ll M_S^2 = m_{\tilde{f}}^2$, such that the masses become effectively degenerate above a certain value of M_S . A higher numerical precision can delay this instability at the expense of an increased run time (blue), while the adapted integral reduction (red) gets along without penalty. The instability of the blue and red curves can be addressed to a general breakdown of the numerical evaluation in FeynHiggs.

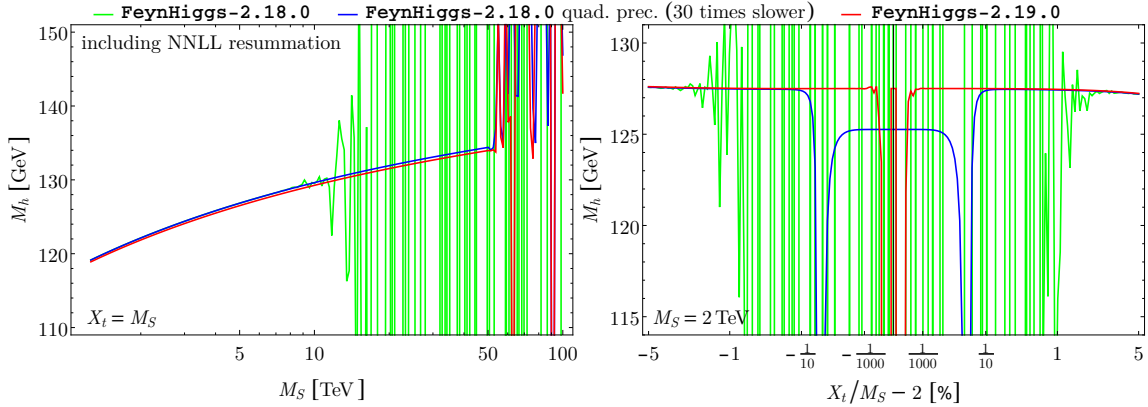


Figure 2: The numerical stability in the prediction of the SM-like Higgs mass M_h is compared for different versions of FeynHiggs: double precision with FeynHiggs-2.18.0 in green and with FeynHiggs-2.19.0 in red, quadruple precision with FeynHiggs-2.18.0 in blue. *Left:* the dependence of M_h on a common SUSY scale M_S is shown; the resummation of large logarithms is included. *Right:* the dependence of M_h on the ratio X_t/M_S with the common SUSY scale $M_S = 2$ TeV is scanned around the central value of 2.

Another situation with potential numerical instabilities is illustrated at the right-hand side of Fig. 2 with the setup `FHSetFlags [4, 3, 0, 2, 0, 0, 0, 3]`. There, the scale M_S is fixed to 2 TeV with the same relations to the input parameters as above except for the stop-mixing parameter X_t . The latter is scanned around the value of $X_t = 2 M_S$ which results in the two stop masses $m_{\tilde{t}_{1,2}} = M_S \pm m_t$. At this particular parameter point several loop integrals possess internal thresholds at which different reduction rules are to be deployed. The green line reveals numerical instabilities in FeynHiggs-2.18.0 already at about 5% away from the threshold. Again, a much better stability can be achieved at the cost of longer run time by switching to quad. prec. (blue), but an even better result is obtained with the improved integral reduction (red) without any detriment.

3. Improvements in the part based on effective-field theories

FeynHiggs supports several EFTs that can be stacked onto one another in different ways, see Fig. 3 for some examples. The low-energy EFT is always the SM and above the highest scale M_S the full MSSM is recovered. The following intermediary scales are allowed: the heavy Higgs-mass scale M_{THDM} for the additional Higgs bosons of the second doublet (see Refs. [29–31] for a description of the THDM EFT in FeynHiggs), the scale $M_{\tilde{\chi}}$ for the masses of the charginos and neutralinos (SUSY partners of electroweak gauge and Higgs bosons), the scale $M_{\tilde{f}}$ for the masses of the sfermions (SUSY partners of the fermions), and the scale $M_{\tilde{g}}$ for the gluinos (SUSY partners of the strong gauge bosons); for the latter, only EFTs with $M_{\tilde{g}} < M_{\tilde{f}}$ are implemented, but see below for the treatment of the converse case. Within the EFTs a resummation of the complete next-to-leading logarithms (NLL), the $\mathcal{O}(\alpha_t, \alpha_s)$ NNLL as well as partial $\mathcal{O}(\alpha_s^2)$ Next-to-NNLL is performed based on results of Refs. [32–39].

3.1 Intermediary heavy additional Higgs bosons

In scenarios with not-too-heavy CP -odd or charged Higgs input mass, $m_{A,H^\pm} \sim 250$ GeV, a noticeable mixing is present between the two CP -even Higgs bosons. As a consequence, the couplings of the two Higgs doublets can no longer be interpreted as separated. While the tree-level Higgs sector of the MSSM is a special version of a THDM of type-II, this is not the case at higher order: due to the loop-induced Higgs mixing the THDM of type-II is not a good EFT for the MSSM.

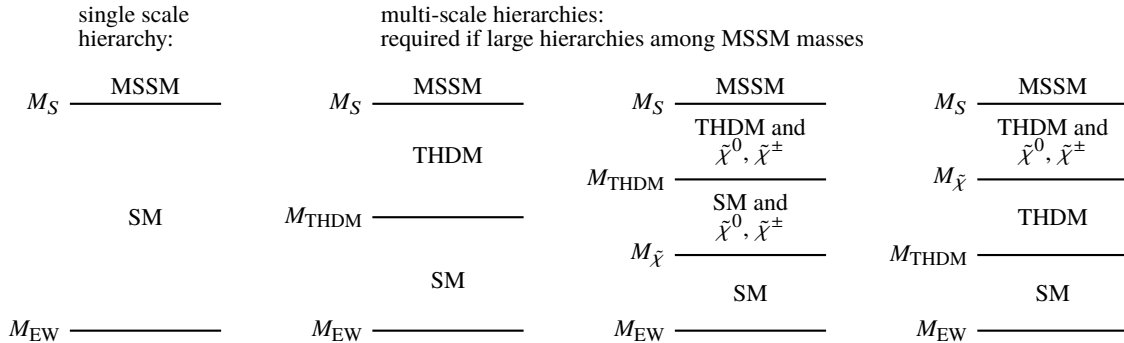


Figure 3: Some examples for possible towers of EFTs that are implemented in FeynHiggs are shown.

Also sizable loop corrections that map onto $\lambda_{5,6,7}$ are possible. Therefore, in general a large number of parameters needs to be considered in the THDM EFT. Since FeynHiggs-2.18.0 the implemented EFT for the THDM can manage complex parameters in the two-loop RGEs, in the complete one-loop threshold corrections, and in the two-loop threshold corrections of $\mathcal{O}(\alpha_t \alpha_s, \alpha_t^2)$ [30, 31]. E. g. in Fig. 3 of Ref. [31] a large difference in the Higgs-mass prediction is visible when employing the EFT for the SM or when using the intermediary EFT for the THDM. In the same figure, large differences are also observed between the new and old versions of the THDM EFTs when more than one phase is non-zero. The relevance of the new threshold corrections of $\mathcal{O}(\alpha_t^2)$ is shown e. g. in Fig. 4 of Ref. [30]: it can be seen that a large shift is induced for $\mu > M_{\tilde{f}}$ due to a polynomial dependence on the ratio of both scales.

3.2 Large gluino masses

The current exclusion limits by measurements at the LHC, see e. g. Ref. [40], allow for scenarios with much heavier gluinos \tilde{g} compared to the squarks \tilde{q} . However, the one-loop self-energies of the squarks contain polynomial contributions in the mass ratio $m_{\tilde{g}}^2/m_{\tilde{q}}^2$ leading to very large and unreliable shifts for ratios very different from 1. In the Higgs-mass calculation, these terms reappear at $\mathcal{O}(\alpha_t \alpha_s, \alpha_b \alpha_s)$ either in the fixed-order part if the squark masses are renormalized in the $\overline{\text{DR}}$ scheme or in the threshold corrections of the EFT. Since an EFT of the MSSM without gluino is currently not ready to be used for Higgs-mass calculations, the $\overline{\text{MDR}}$ renormalization scheme has been proposed in Ref. [33] and extended in Ref. [41].³ It relies on a reparametrization of the soft SUSY-breaking parameters of the squarks such that the terms with polynomial dependence on the gluino mass are removed from the self-energies. Originally only the bilinear terms have been reparametrized, while the extension also includes the trilinear breaking parameters:

$$m_{\tilde{t},\text{L,R}}^2|_{\overline{\text{MDR}}}(Q) = m_{\tilde{t},\text{L,R}}^2|_{\overline{\text{DR}}}(Q) \left[1 + \frac{\alpha_s}{\pi} C_F \frac{|M_3|^2}{m_{\tilde{t},\text{L,R}}^2} \left(1 + \ln \frac{Q^2}{|M_3|^2} \right) \right], \quad (3)$$

$$X_t|_{\overline{\text{MDR}}}(Q) = X_t|_{\overline{\text{DR}}}(Q) - \frac{\alpha_s}{\pi} C_F M_3 \left(1 + \ln \frac{Q^2}{|M_3|^2} \right). \quad (4)$$

One can see e. g. in Fig. 1 of Ref. [41] that all parameter shifts are required in order to obtain a stable Higgs-mass prediction. Analogous shifts are also implemented for the sbottom sector. When using the $\overline{\text{MDR}}$ scheme in combination with an EFT all terms of $\mathcal{O}(\alpha_s^n m_{\tilde{g}}^{2n}, \alpha_s^n m_{\tilde{g}}^n)$ are resummed, leading to a significantly reduced uncertainty in scenarios with heavy gluinos.⁴

4. Conclusions

Recent developments in the fixed-order and EFT parts of FeynHiggs have been discussed. A re-implementation of all two-loop corrections with dedicated integral reductions allows for consistent renormalization schemes throughout the code, simplifies the introduction of new schemes, improves

³The large gluino-mass limit is available for Higgs production in gluon fusion [42] and the stop sector [43]. For Higgs masses, the required matching conditions for the MSSM without gluino have been derived in Ref. [44], but the corresponding two-loop threshold corrections and RGEs are missing.

⁴A recent description of the uncertainty estimate for the SM-like Higgs mass in FeynHiggs is available in Ref. [45].

numerical stability, and facilitates readability. For the THDM EFT complex parameters are enabled and the threshold corrections of $\mathcal{O}(\alpha_t^2)$ have been added; both can have a significant impact on the mass prediction of the SM-like Higgs. The $\overline{\text{MDR}}$ scheme has been added to make a reliable prediction of the Higgs mass in scenarios where the gluinos are much heavier than the squarks. The new content will be released in the upcoming version FeynHiggs-2.19.0.

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