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SUSY Higgs-mass predictions: NMSSM vs. MSSM

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The NMSSM represents an elegant and well motivated description for the observed phenomenology in high energy physics. In this model a scalar singlet together with its superpartner is added to the Higgs sector of the Minimal Supersymmetric Standard Model (MSSM). In order to compare the NMSSM with experimental data at the same level of accuracy as the MSSM, precise predictions for Higgs-boson masses in the NMSSM are a necessity. This work will focus on the prediction for the Higgs masses in the NMSSM at one- and two-loop order obtained by Feynman diagrammatic method. While the one-loop calculation is performed in the full NMSSM, the two-loop contributions to the Higgs-boson self-energies are approximated by their MSSM counterparts. It is shown that in this way the two-loop contributions are well approximated for a wide range of parameters. The results are exemplified for a genuine NMSSM scenario and for a scenario with a candidate for the diphoton excess at 750 GeV.

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1. Introduction

The spectacular discovery of a boson with a mass around 125 GeV by the ATLAS and CMS experiments [1,2] at CERN constitutes a milestone in the quest for understanding the physics of electroweak symmetry breaking. Any model describing electroweak physics needs to provide a state that can be identified with the observed signal. The measured mass value of the observed signal has already reached the level of a precision observable, with an experimental accuracy of better than 300 MeV [3], and by itself provides an important test for the predictions of models of electroweak symmetry breaking. In order to fully exploit the precision of the experimental mass value for constraining the available parameter space of the considered models, the theoretical predictions should ultimately have an accuracy at the same level or better than the one of the experimental value.

In the case of the CP-conserving NMSSM (see e.g. [4] for reviews), which we assume throughout this work, the states in the NMSSM Higgs sector can be classified as three CP-even Higgs bosons, H_i ($i = 1,2,3$), two CP-odd Higgs bosons, A_j ($j = 1,2$), and the charged Higgs boson pair $H^\pm$. In addition, the SUSY partner of the singlet Higgs (called the singlino) extends the neutralino sector (to a total of five neutralinos). In the NMSSM the signal observed at ≈ 125 GeV can be interpreted as the lightest but also the second-lightest CP-even neutral Higgs boson. In order to improve the prediction for the Higgs masses in the NMSSM we present two-loop predictions [9] that include the one-loop contributions in the full NMSSM and two-loop NMSSM contribution approximated by the two-loop MSSM contributions within a mixed on-shell and $\overline{\text{DR}}$ renormalisation scheme, including the resummation of logarithms involving large SUSY masses [6]. We will show that this approximation is valid for a wide range of parameters. The approximation itself and its quality will be briefly discussed in this work. The presented results will be included in the NMSSM version of the public tool `FeynHiggs` [5–7]. For a comparison with the public code NMSSMCALC [8] see ref. [9].

2. The Next-to-Minimal Supersymmetric Standard Model (NMSSM)

The superpotential of the NMSSM for the third generation of fermions/sfermions reads

$$W = Y_t \left(\hat{H}_2 \cdot \hat{Q}_3\right) \hat{u}_3 - Y_d \left(\hat{H}_1 \cdot \hat{Q}_3\right) \hat{d}_3 - Y_\tau \left(\hat{H}_1 \cdot \hat{L}_3\right) \hat{e}_3 + \lambda \hat{S} \left(\hat{H}_2 \cdot \hat{H}_1\right) + \frac{1}{3} \kappa \hat{S}^3, \tag{2.1}$$

with the quark and lepton superfields $\hat{Q}_3$, $\hat{u}_3$, $\hat{d}_3$, $\hat{L}_3$, $\hat{e}_3$ and the Higgs superfields $\hat{H}_1$, $\hat{H}_s$, $\hat{S}$. The $SU(2)_\text{L}$-invariant product is denoted by a dot. The Higgs singlet and doublets are decomposed into CP-even and CP-odd neutral scalars ϕ_i and χ_i, and charged states $\phi_i^\pm$,

$$H_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}} (\phi_1 - i\chi_1) \\ -\phi_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}} (\phi_2 + i\chi_2) \end{pmatrix}, \quad S = v_s + \frac{1}{\sqrt{2}} (\phi_s + i\chi_s), \tag{2.2}$$

with the real vacuum expectation values for the doublet- and the singlet-fields, $v_{\{1,2\}}$ and v_s. Since $\hat{S}$ transforms as a singlet, the D-terms remain identical to the ones of the MSSM. The parameters Y_f denote the Yukawa couplings of the SM fermions. The parameters λ and κ are genuine to the

NMSSM and can be chosen freely. However, in order to keep the validity of perturbation theory up to the GUT scale [4], λ and κ are bound from above by

$$\lambda^2 + \kappa^2 \lesssim 0.5, \tag{2.3}$$

so that $\lambda \lesssim 0.7$, where the largest values are only allowed for vanishing κ. Thus, this constraint, which throughout this work will be assumed for the NMSSM, implies $Y_t \approx 1 > \lambda$.

The soft SUSY-breaking terms for the trilinear breaking parameters A read

$$\mathscr{L}_{\text{soft}} \supset Y_t A_t \tilde{t}_L H_2 \tilde{t}_R + Y_b A_b \tilde{b}_L H_1 \tilde{b}_R + Y_\tau A_\tau \tilde{\tau}_L H_1 \tilde{\tau}_R + + \lambda A_\lambda S H_2 H_1 + \frac{1}{3} \kappa A_\kappa S^3 + \text{h.c.}\ . \tag{2.4}$$

3. Incorporation of higher-order contributions

The masses of the CP-even Higgs bosons are obtained from the complex poles of the full propagator matrix. The inverse propagator matrix for the three CP-even Higgs bosons h_i is a 3×3 matrix that reads

$$\Delta^{-1}(k^2) = i \left[k^2 \mathbb{1} - \mathscr{M}_{hh} + \hat{\Sigma}_{hh}(k^2) \right]. \tag{3.1}$$

Here $\mathscr{M}_{hh}$ denotes the diagonalised mass matrix of the CP-even Higgs fields at tree level, and $\hat{\Sigma}_{hh}$ denotes the matrix of their renormalised self-energy corrections. The three complex poles of the propagator in the CP-even Higgs sector are given by the values of the external momentum k^2 for which the determinant of the inverse propagator-matrix vanishes,

$$\det \left[\Delta^{-1}(k^2) \right]_{k^2 = m_{h_i}^2 - i \Gamma_{h_i} m_{h_i}} \stackrel{!}{=} 0, \ i \in \{1,2,3\}. \tag{3.2}$$

The complex poles consist of the mass m_{h_i} and the total width Γ_{h_i}. The renormalised self-energy matrix $\hat{\Sigma}_{hh}$ is evaluated by taking into account the full contributions from the NMSSM at one-loop order and, as an approximation, the MSSM-like contributions at two-loop order of $\mathscr{O}(\alpha_t \alpha_s, \alpha_b \alpha_s, \alpha_t^2, \alpha_t \alpha_b)$ at vanishing external momentum taken over from `FeynHiggs`, including resummed leading and next-to-leading logarithms induced by heavy SUSY particles [6],

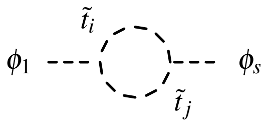
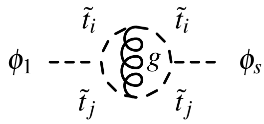
$$\hat{\Sigma}_{hh}(k^2) \approx \hat{\Sigma}_{hh}^{(1L)}(k^2) \Big|^{\text{NMSSM}} + \hat{\Sigma}_{hh}^{(2L+\text{beyond})}(k^2) \Big|^{\text{MSSM}}_{k^2=0}. \tag{3.3}$$

4. Employed Approximation

For the contributions from the top and stops the entries of the renormalised self-energy matrix can be classified by the dominant coupling constants. At one-loop order this classification separates the self energy into an MSSM-like 2×2 sub-matrix and corrections that are genuine to the NMSSM,

$$\Sigma_{hh}^{(1L)}(k^2) = \left(\begin{array}{cc|c} \multicolumn{2}{c|}{\mathscr{O}(Y_t^2)} & \mathscr{O}(\lambda Y_t) \\ & & \mathscr{O}(\lambda Y_t) \\ \hline \mathscr{O}(\lambda Y_t) & \mathscr{O}(\lambda Y_t) & \mathscr{O}(\lambda^2) \end{array} \right) \sim \left(\begin{array}{c|c} \text{MSSM-like} & \text{NMSSM} \\ \hline \text{NMSSM} & \end{array} \right). \tag{4.1}$$

In the regime where the NMSSM stays perturbative up to the GUT scale $\lambda < Y_t$ holds, so that the genuine NMSSM corrections are expected to be suppressed compared to the MSSM-like corrections. This suppression also applies to the contributions from top/stops and a gluon/gluino at two-loop order. Here the leading contributions consist of a one-loop topology with an inserted gluon or gluino propagator, like


$$= \mathcal{O}(\lambda Y_t),$$

$$= \mathcal{O}(\alpha_s \lambda Y_t). \tag{4.2}$$

The genuine two-loop NMSSM corrections are thus neglected for the presented results,

$$\Sigma_{hh}^{(2L)}\left(k^2=0\right) = \left(\begin{array}{cc|c} \multicolumn{2}{c|}{\mathcal{O}\left(Y_t^2 \alpha_s\right)} & \begin{array}{c}\mathcal{O}(\lambda Y_t \alpha_s)\\ \mathcal{O}(\lambda Y_t \alpha_s)\end{array} \\ \hline \mathcal{O}(\lambda Y_t \alpha_s) & \mathcal{O}(\lambda Y_t \alpha_s) & \mathcal{O}\left(\lambda^2 \alpha_s\right) \end{array}\right) \sim \left(\begin{array}{cc|c} \multicolumn{2}{c|}{\text{MSSM-like}} & \begin{array}{c}0\\0\end{array} \\ \hline 0 & 0 & 0 \end{array}\right). \tag{4.3}$$

Since the structure of the dominant contributions at the two-loop level of $\mathcal{O}(Y_t^2 \alpha_s)$ in comparison with the genuine NMSSM contributions of $\mathcal{O}(\lambda Y_t \alpha_s, \lambda^2 \alpha_s)$ is very similar to the corresponding contributions at one-loop order, the quality of the approximation performed at the two-loop level can be tested using the known one-loop result (for the two-loop corrections beyond $\mathcal{O}(Y_t^2 \alpha_s)$ the same kind of approximation by their MSSM counterparts as indicated above is employed).

5. Renormalisation Conditions

At one-loop order the parameters from the Higgs potential and the gauge sector have to be renormalised. We choose to renormalise the tadpoles to zero at all orders of perturbation theory. Rather than choosing the gauge couplings and the soft-breaking parameter A_λ as input parameters, the gauge-boson masses M_W, M_Z and charged Higgs mass $M_{H^\pm}$ were chosen as independent parameters. The following renormalisation schemes are chosen for the parameters entering at one-loop order

$$\text{on-shell: } M_W,\ M_Z,\ M_{H^\pm} \quad \overline{\text{DR}}\text{: } \lambda,\ \kappa,\ A_\kappa,\ \tan\beta,\ \mu_{\text{eff}} = \lambda v_s,\ v = \sqrt{v_1^2 + v_2^2}. \tag{5.1}$$

Since the vacuum expectation-value v is directly related to the electromagnetic coupling constant charge e, a reparametrisation for the electric charge e is necessary in order to use a given numerical value for the electromagnetic coupling constant. In the following the value for e derived from Fermi's constant is used, which is the parametrisation that was chosen for the results that are implemented in `FeynHiggs`.

6. Results I: A Sample NMSSM Scenario

The sample scenario investigated here is defined by the parameters in the Higgs sector given in eq. (6.1a), while λ is varied. For values $\lambda \gtrsim 0.32$ the mass of the lightest Higgs state becomes tachyonic at tree-level. The analyses will therefore be restricted to values of $\lambda \lesssim 0.32$. The parameters entering at higher order are chosen as given in eq. (6.1b).

$$M_{H^\pm} = 1000 \text{ GeV}, \; \mu_{\text{eff}} = 125 \text{ GeV}, \; A_\kappa = -300 \text{ GeV}, \; \kappa = 0.2, \; \tan\beta = 8, \tag{6.1a}$$

$$M_{\tilde{q}} = 1500 \text{ GeV}, M_{\tilde{l}} = 200 \text{ GeV}, \; M_1 = \frac{5}{3}\frac{s_\text{w}^2}{c_\text{w}^2} M_2 \approx 143 \text{ GeV}, \; M_2 = 300 \text{ GeV}, \; M_3 = 1500 \text{ GeV}.$$

$$A_t = -2000 \text{ GeV}, \; A_\tau = A_b = -1500 \text{ GeV}, \; A_q = -1500 \text{ GeV}, \; A_l = -100 \text{ GeV}. \tag{6.1b}$$

The parameters $M_{\tilde{f}}$ and A_f specify the universal sfermion-mass and trilinear breaking-parameters, while $M_{\{1,2,3\}}$ are the gaugino mass breaking parameters for $U(1)_\text{Y}$, $SU(2)_\text{L}$ and $SU(3)_\text{c}$. All stop-sector parameters are understood as on-shell parameters [7].

The masses of the two lightest CP-even Higgs fields in this genuine NMSSM scenario are given in fig. 1. At two-loop order the lightest state is singlet-like for values $\lambda \gtrsim 0.23$, while the second-lightest state in this parameter region is SM-like with a mass of ≈ 125 GeV. For values $\lambda \lesssim 0.23$ the lightest state is doublet-like with a mass of about 125 GeV, and the second-lightest state is singlet-like. The cross-over region between the doublet- and singlet-like state is seen to be confined to a small interval around $\lambda \approx 0.23$. The heaviest CP-even Higgs field (not shown in the figure) remains doublet-like with a mass of ≈ 1 TeV for the shown parameters. The scenario has been tested with `HiggsBounds 4.1.3` [10] to ensure its experimental viability.

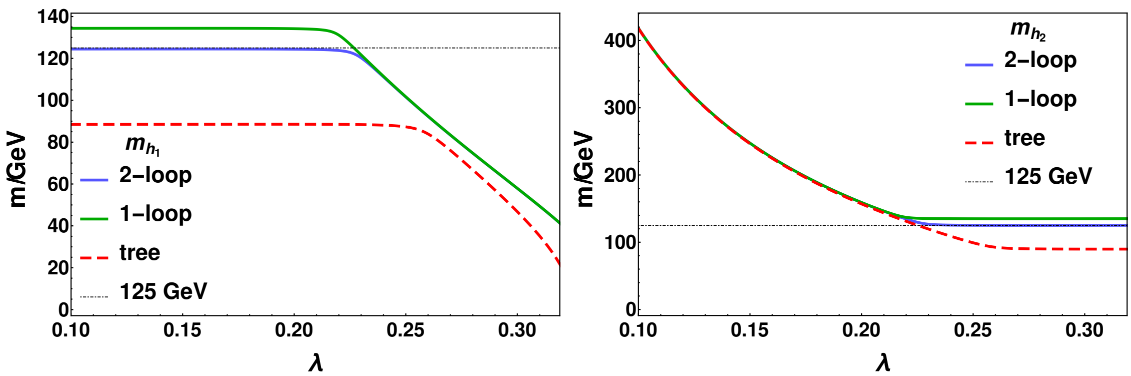


Figure 1: Masses of the two lightest CP-even Higgs fields as a function of λ at tree-, one-loop and two-loop level in the sample scenario.

7. Results II: Scenario with a candidate for the diphoton excess observed at 750 GeV

This scenario is inspired by the benchmark scenario P1 defined in [11]. It is motivated by the diphoton excess at an invariant mass of about 750 GeV that was observed by both ATLAS [12] and CMS [13]. In this scenario the CP-even Higgs boson at 750 GeV decays to two very light, highly boosted CP-odd Higgs bosons, which each decay to two photons, resembling each one photon in the detector and thus resulting in the "desired" signal. The Higgs sector parameters of this scenario are given in eq. (7.1a). The parameter λ will be varied, and $M_{H^\pm}^2 = M_A^2 + M_W^2 - \lambda^2 v^2$. For all values of $\lambda \gtrsim 0.43$ the lightest Higgs-state becomes tachyonic. The analyses will therefore be restricted to values of $\lambda \lesssim 0.43$. The parameters entering at higher order are chosen as given in eq. (7.1b) in the same fashion as above.

$$M_A = 760 \text{ GeV},\ \mu_{\text{eff}} = 150 \text{ GeV},\ A_\kappa = 3\cdot 10^{-3} \text{ GeV},\ \kappa = 0.25,\ \tan\beta = 10, \tag{7.1a}$$

$$M_{\tilde{q}} = 1750 \text{ GeV},\ M_{\tilde{l}} = 300 \text{ GeV},\ M_1 = 500 \text{ GeV},\ M_2 = 1000 \text{ GeV},\ M_3 = 3000 \text{ GeV}.$$
$$A_t = -4000 \text{ GeV},\ A_\tau = A_b = 1500 \text{ GeV},\ A_q = 1500 \text{ GeV},\ A_l = 1500 \text{ GeV}. \tag{7.1b}$$

The masses of the two lightest CP-even Higgs fields in this scenario are given in fig. 2. The lightest field is dominantly doublet-like, and the second-lightest state is singlet-like for the depicted values of λ. The cross-over region between the doublet- and singlet-like state is rather wide in this case and starts at $\lambda \approx 0.2$. Even for the largest value of $\lambda \approx 0.43$ in the plot the lightest field is still dominantly doublet-like. Thus, the qualitative behaviour in this scenario is very similar to the genuine NMSSM scenario discussed above, but the allowed range of λ is restricted to the region below the cross-over point in this case. The heaviest CP-even Higgs field (not shown in the figure) remains doublet-like with an near constant mass of ≈ 760 GeV.

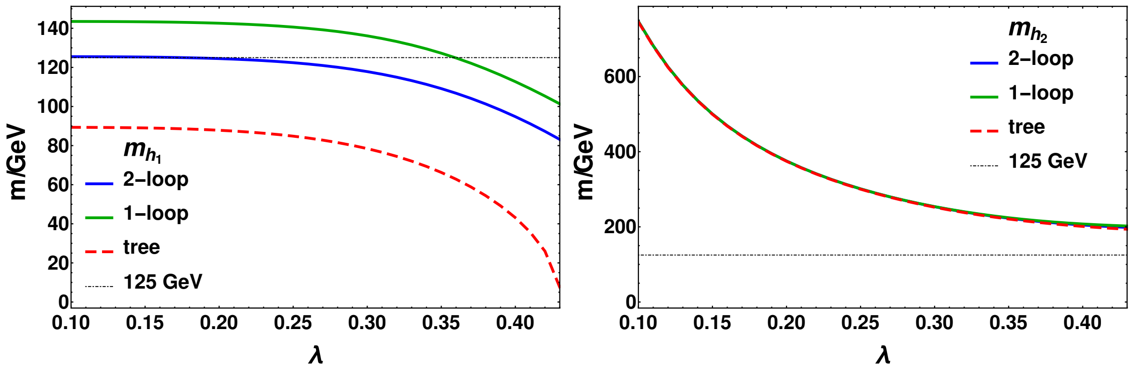


Figure 2: Masses of the two lightest CP-even Higgs fields as a function of λ at tree-, one-loop and two-loop level in the scenario inspired by the diphoton excess at 750 GeV.

8. Validity of Approximation

The masses of the two lightest CP-even Higgs fields are studied at one-loop order for the dominant contributions from top and stops in fig. 3 for the sample scenario given in eq. (6.1) and in fig. 4 for the scenario inspired by the diphoton excess given in eq. (7.1). In the left plot of fig. 3 the absolute difference between the results in- and excluding the genuine NMSSM corrections is shown. The impact of the genuine corrections is very small with less than 100 MeV for $\lambda \lesssim 0.25$, while the contribution to m_{h_1} sharply increases for larger values of λ in this case. In the right plot of fig. 3 the absolute difference between the result including only the top/stop contributions of $\mathcal{O}(Y_t^2, \lambda Y_t, \lambda^2)$, denoted by m_t^4, and the full one-loop mass prediction is shown by solid lines. The dashed lines show the same difference between the result including top/stop contributions plus contributions from the Higgs/higgsino/gauge-boson/gaugino sectors including their superpartners, denoted by $m_t^4 + \text{HG}$, and the full one-loop mass predictions.

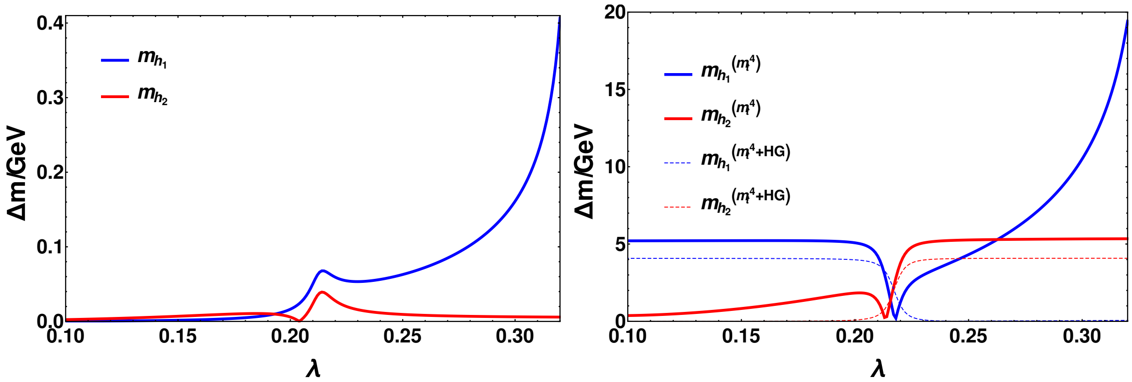


Figure 3: Difference between one-loop mass-predictions with different contributions for the two lightest CP-even Higgs fields. *Left:* Absolute difference between the results including leading top/stop corrections with and without the corrections of $\mathscr{O}(\lambda Y_t, \lambda^2)$. *Right:* Absolute difference between the result including the top/stop contributions of $\mathscr{O}(Y_t^2, \lambda Y_t, \lambda^2)$, denoted by m_t^4, and the full one-loop mass prediction (solid lines). Absolute difference between the result including top/stop contributions plus contributions from the Higgs/higgsino/gauge-boson/gaugino sectors including their superpartners, denoted by $m_t^4 + \text{HG}$, and the full one-loop mass predictions (dashed lines).

For the largest values of $\lambda \approx 0.32$ one-loop corrections from the Higgs/higgsino/gauge-boson/gaugino sectors amount to ≈ 20 GeV, roughly the same size as the leading top/stop contributions. Thus, in this region where genuine NMSSM corrections of $\mathscr{O}(\lambda Y_t, \lambda^2)$ in the stop sector gain numerical impact, the stop sector as a whole does not provide a suitable approximation of the full result. Improving on the approximation of MSSM-type contributions in the stop sector therefore requires the incorporation of the contributions from the Higgs and higgsino sector, while the genuine NMSSM contributions in the stop sector are of minor significance in this context.

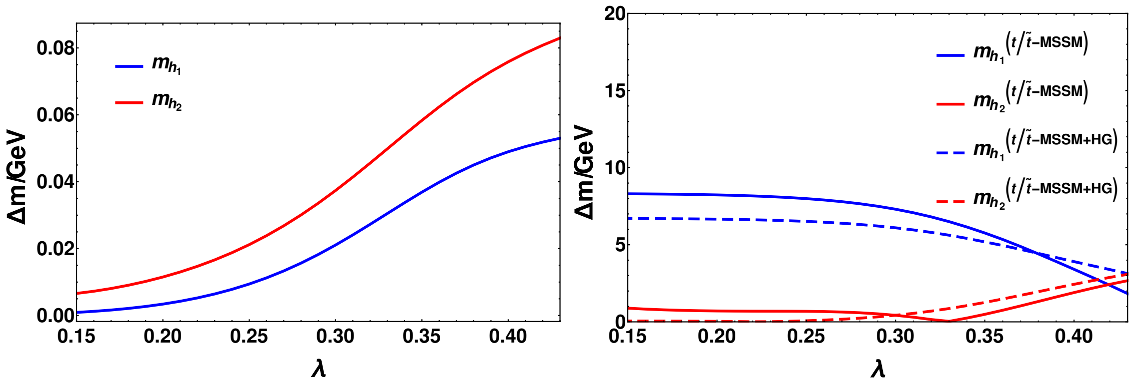


Figure 4: Difference between one-loop mass-predictions with different contributions for the two lightest Higgs fields in the scenario inspired by the diphoton excess at 750 GeV. The meaning of the curves is the same as in fig. 3.

In the second scenario, inspired by the observed diphoton excess at 750 GeV, the impact of the genuine NMSSM corrections is even smaller with less than 100 MeV for both the lightest CP-even Higgs fields, see fig. 4. By supplementing the partial one-loop results with the Higgs/higgsino/gauge-boson/gaugino contributions the mass prediction is improved by ≈ 1 GeV.

Both plots in fig. 4 show a λ dependence that is very similar to the sample scenario for $\lambda \lesssim 0.22$ depicted in fig. 3.

9. Conclusion

Higgs-mass predictions including the full one-loop result in the NMSSM and all available two-loop contributions from the MSSM have been presented for a genuine NMSSM-type scenario and for an NMSSM scenario with a candidate for the diphoton excess at about 750 GeV. The dependence on λ in the two scenarios has been shown to be very similar, where the allowed range of λ in the second scenario is restricted to the region below the cross-over point that is visible in the first scenario. The validity of the approximation to restrict to the MSSM-type contributions at the two-loop level has been confirmed in the perturbative regime for λ and κ.

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