# Precise Higgs-mass prediction in the Next-to-Minimal Supersymmetric Standard Model

Peter Drechsel[†] and Sebastian Paßehr[‡]

in collaboration with

Sven Heinemeyer[§] and Georg Weiglein[‡]

[†]Universität Hamburg, [‡]DESY, Hamburg, [§]CSIC, Santander

SUSY 2016,

Melbourne, Australia,
5th of July 2016

# Motivation

see my previous talk on Higgs mass in the MSSM

# $\mu$ problem

dimensionful parameter in superpotential:

$$\mathcal{W}_{\text{MSSM}} \supset \mu\, H_1 \cdot H_2$$

- necessary for reasonable Higgsino masses
- naturalness: should be close to electroweak scale,
  natural cut-off scale: Planck scale

possible solution:
dynamical evolution of $\mu$ term from spontaneous symmetry breaking,

NMSSM: add scalar singlet field $S$ with non-zero vev $v_S$ to MSSM,

$$\begin{aligned}\mathcal{W}_{\text{NMSSM}} &\supset \lambda\, S\, H_1 \cdot H_2 \\ &\to \lambda\, v_S\, H_1 \cdot H_2 = \mu_{\text{eff}}\, H_1 \cdot H_2\end{aligned}$$

two complex $SU(2)$-Higgs doublets, one Higgs singlet (ten degrees of freedom):

$$\mathcal{H}_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}\left(\phi_1^0 + i\,\chi_1^0\right) \\ \phi_1^- \end{pmatrix}, \qquad \mathcal{H}_2 = e^{i\,\zeta} \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}\left(\phi_2^0 + i\,\chi_2^0\right) \end{pmatrix},$$

$$\mathcal{S} = e^{i\,\zeta_S}\left(v_S + \frac{1}{\sqrt{2}}\left(\phi_S^0 + i\,\chi_S^0\right)\right)$$

positive real vacuum expectation values $v_1,\ v_2,\ v_S$,

relative phases $\zeta,\ \zeta_S$ ,

with superpotential

$$\mathcal{W}_{\text{NMSSM}} = \left(\mathcal{W}_{\text{MSSM}} - \mu\, H_1 \cdot H_2\right) + \lambda\, S\, H_1 \cdot H_2 + \frac{1}{3}\kappa\, S^3 \,.$$

tree-level mass eigenstates:

$CP$ mixed $h_1$, $h_2$, $h_3$, $h_4$, $h_5$; charged $H^\pm$

NMSSM **NOT** $CP$ conserving at tree level (unless only real parameters)

# Mass determination at higher orders

Higgs masses at $k$ loop order given by poles of propagator matrix

$$0 \stackrel{!}{=} \left[\mathbf{\Delta}^{(k)}\left(p^2\right)\right]^{-1} = -i\left[p^2\mathbf{1} - \mathbf{M}^{(k)}\left(p^2\right)\right]$$

in the following $k = 2$ and approximations:

$$\mathbf{M}^{(2)}\left(p^2\right) = \mathbf{M}^{(0)} - \left[\widehat{\mathbf{\Sigma}}^{(1)}\left(p^2\right)\right]_{\text{NMSSM}} - \left[\widehat{\mathbf{\Sigma}}^{(2)}(0)\right]_{\text{MSSM}}$$

in this talk:

- all parameters real, i. e. Higgs sector $CP$ conserving
- only investigate neutral $CP$ even sector
- $\left[\widehat{\mathbf{\Sigma}}^{(2)}(0)\right]_{\text{MSSM}}$ contains all relevant two-loop parts from `FeynHiggs` for the real MSSM, i. e. $\mathcal{O}(\alpha_t\alpha_s + \alpha_b\alpha_s + \alpha_t^2 + \alpha_t\alpha_b)$ at $p^2 = 0$

# Justification of approximation

missing two-loop parts:

- transition from Higgs doublet to Higgs singlet
- self-energy of singlet
- genuine NMSSM contributions

at one loop: $\mathcal{O}(\lambda Y_t + \lambda^2 + \lambda^4 + \kappa^4 + \lambda^2\kappa^2)$
leading contributions: $\mathcal{O}(\alpha_t = Y_t^2/(4\pi))$, do not appear in singlet couplings

top Yukawa coupling $Y_t \approx 1$
avoid Landau poles: $|\lambda|^2 + |\kappa|^2 \lesssim 0.5$

$\rightarrow$ at two-loop order leading contributions by Higgs-doublet self-energies, $\mathcal{O}(\alpha_t\alpha_s)$,

$\rightarrow$ singlet contributions suppressed, e. g. $\mathcal{O}(\lambda Y_t \alpha_s)$

# Scaling behaviour

check couplings $\mathcal{O}(\lambda)$ over $\mathcal{O}(Y_t)$

triple couplings:

$$\frac{\Gamma_{\phi_s \tilde{t}_a \tilde{t}_b}}{\Gamma_{\phi_1 \tilde{t}_a \tilde{t}_b}} = \lambda \frac{v}{\mu_{\text{eff}}} \cos\beta$$

$$\frac{\Gamma_{\phi_s \tilde{t}_a \tilde{t}_b}}{\Gamma_{\phi_2 \tilde{t}_a \tilde{t}_b}} = \begin{cases} \lambda \frac{v}{A_t} \cos\beta & \text{if } a \neq b \\ \lambda \frac{v \sin 2\theta_{\tilde{t}}}{2m_t \pm A_t \sin 2\theta_{\tilde{t}}} \cos\beta & \text{if } a = b \end{cases}$$

quartic couplings:

$$\frac{\Gamma_{\phi_s \phi_1 \tilde{t}_a \tilde{t}_b}}{\Gamma_{\phi_2 \phi_2 \tilde{t}_a \tilde{t}_b}} = \frac{\lambda}{Y_t} \left| \frac{1}{2} \sin 2\theta_{\tilde{t}} \right|$$

always suppressed by $\lambda$

# Sample scenario

- genuine NMSSM-scenario with
  - second lightest CP-even state at 125GeV
  - a lighter singlet-like state
- independent parameters

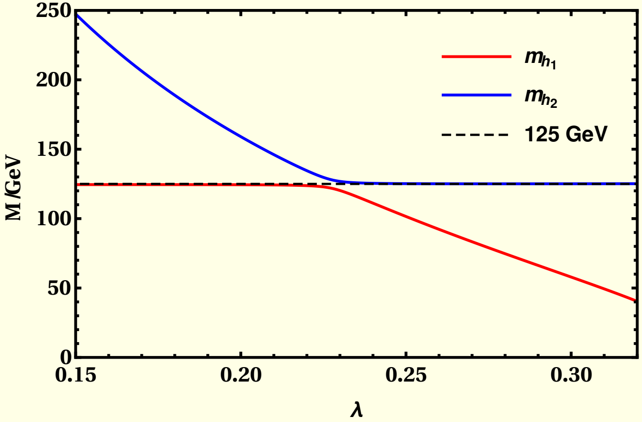
$$\underbrace{M_W, M_Z, M_{H^\pm}}_{\text{on-shell}},\ \underbrace{\lambda, \kappa, t_\beta, \mu_{\text{eff}}, A_\kappa}_{\overline{\text{DR}}\ @\ m_t},\ \underbrace{T_{h_1}, T_{h_2}, T_{h_s}}_{\text{classical minimum}}$$

$$M_{H^\pm} = 1000\text{GeV},\ \mu_{\text{eff}} = 125\text{GeV},\ A_\kappa = -300\text{GeV},$$
$$A_t = -2000\text{GeV},\ \tan\beta = 8,\ \kappa = 0.2$$

- stop- and gluino-masses

$$m_{\tilde{t}_1} \approx 1400\text{GeV},\ m_{\tilde{t}_2} \approx 1600\text{GeV}$$
$$m_{\tilde{b}_i} \approx 1500\text{GeV},\ m_{\tilde{g}} \approx 1500\text{GeV}$$

# Lighter masses at two-loop order




- singlet-like mass: decreasing with increasing $\lambda$
- doublet-like mass: constant
- deflection point: particles change admixture

# Suppression factors

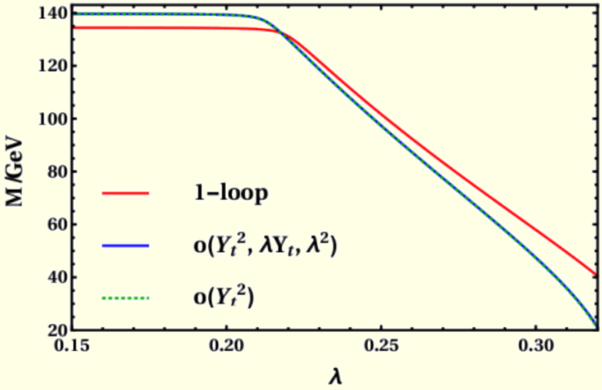
- diagrams with trilinear couplings can be compared by ratio of the couplings

$$\frac{\Gamma_{\phi_s \tilde{t}_a \tilde{t}_b}}{\Gamma_{\phi_1 \tilde{t}_a \tilde{t}_b}} \lesssim 5.5\%$$

$$\frac{\Gamma_{\phi_s \tilde{t}_a \tilde{t}_b}}{\Gamma_{\phi_2 \tilde{t}_a \tilde{t}_b}} \lesssim \begin{cases} 4‰ & \text{if } a \neq b \\ 3‰ & \text{if } a = b \end{cases}$$

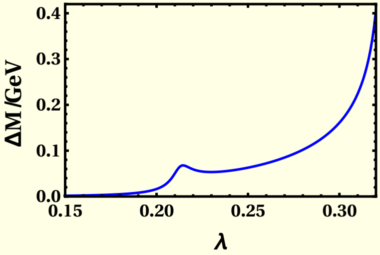
- diagrams with quartic couplings can be compared by ratio of the couplings

$$\frac{\Gamma_{\phi_s \phi_1 \tilde{t}_a \tilde{t}_b}}{\Gamma_{\phi_2 \phi_2 \tilde{t}_a \tilde{t}_b}} \lesssim 16.5\%$$

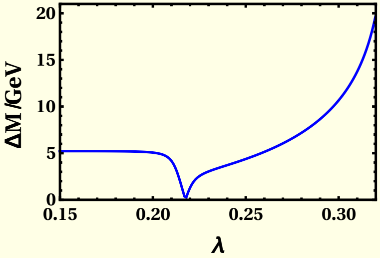



- prediction with or without corrections of order $\mathcal{O}(Y_t\lambda, \lambda^2)$ are not distinguishable in the plot
- influence of corrections $\propto Y_t\lambda,\ \lambda^2$ from stops is tiny

absolute difference between different mass predictions




$$\Delta M = \left| m_{h_1}^{(Y_t)} - m_{h_1}^{(Y_t,\lambda)} \right|$$



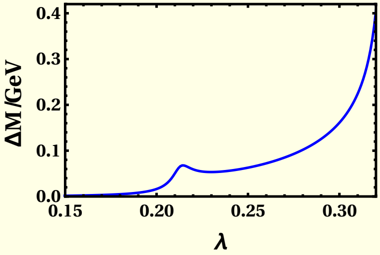

$$\Delta M = \left| m_{h_1}^{(Y_t,\lambda)} - m_{h_1}^{(1L)} \right|$$

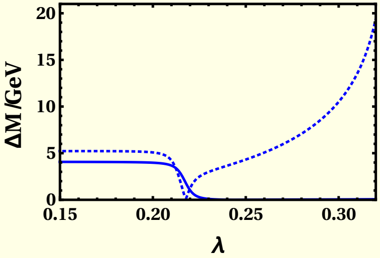
include Higgs- & gauge-sector

$\Longrightarrow$ influence of corrections beyond top/stop sector by far more important than those of the order $\mathcal{O}(Y_t\lambda, \lambda^2)$

# Lightest mass at one-loop order

absolute difference between different mass predictions




$$\Delta M = \left| m_{h_1}^{(Y_t)} - m_{h_1}^{(Y_t,\lambda)} \right|$$

$$\Delta M = \left| m_{h_1}^{(Y_t,\lambda+\mathrm{H}+\mathrm{G})} - m_{h_1}^{(1\mathrm{L})} \right|$$

include Higgs- & gauge-sector

$\Longrightarrow$ influence of corrections beyond top/stop sector by far more important than those of the order $\mathcal{O}(Y_t\lambda, \lambda^2)$

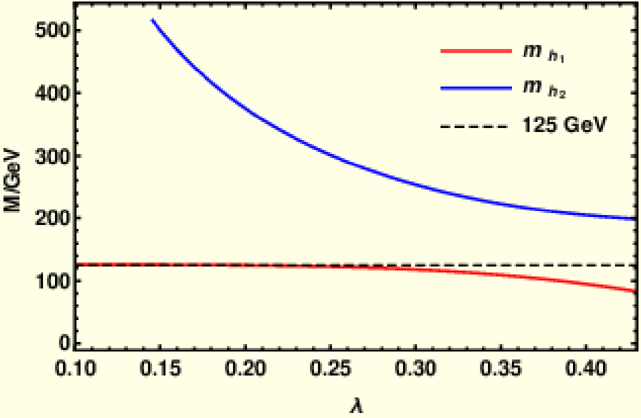
# Diphoton excess at 750GeV in the NMSSM

- benchmark point P1 from `hep-ph/1602.07691` can explain 750GeV diphoton excess for $\lambda = 0.1$,

$$M_A = 760\text{GeV},\ \mu_{\text{eff}} = 150\text{GeV},\ \tan\beta = 10,$$
$$A_\kappa \approx 3 \cdot 10^{-3}\text{GeV},\ \kappa = 0.25,$$
$$m_{\tilde{Q}} = 1750\text{GeV},\ A_t = -4000\text{GeV},\ m_{\tilde{g}} \approx 3000\text{GeV}$$

where $M_A = M_{H^\pm} - M_W^2 + \lambda^2 v^2$

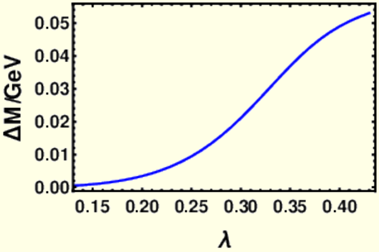
# Benchmark point P1, lighter *CP* even masses at two-loop order



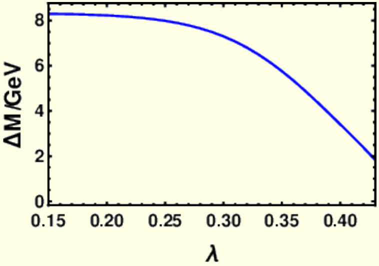

- singlet-like mass:
  decreasing with increasing $\lambda$
- doublet-like mass:
  constant
- deflection point:
  particles change admixture

# Benchmark point P1, lightest *CP* even mass at one-loop order

absolute difference between different mass predictions



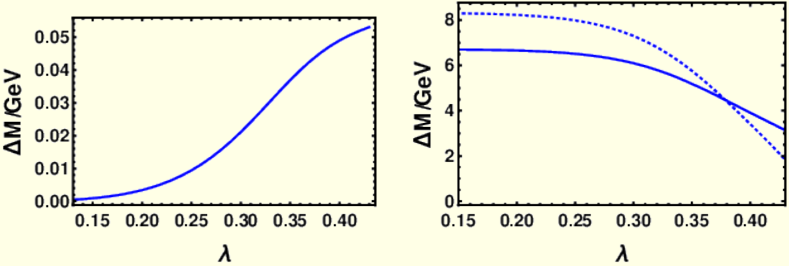

$$\Delta m = \left| m_{h_1}^{(Y_t)} - m_{h_1}^{(Y_t,\lambda)} \right|$$




$$\Delta m = \left| m_{h_1}^{(Y_t,\lambda)} - m_{h_1}^{(1L)} \right|$$

$\Longrightarrow$ results mirror sample scenario for small values of $\lambda$

absolute difference between different mass predictions




$$\Delta m = \left| m_{h_1}^{(Y_t)} - m_{h_1}^{(Y_t,\lambda)} \right|$$

$$\Delta m = \left| m_{h_1}^{(Y_t,\lambda+\mathrm{H}+\mathrm{G})} - m_{h_1}^{(1\mathrm{L})} \right|$$

include Higgs- & gauge-sector

$\Longrightarrow$ results mirror sample scenario for small values of $\lambda$

# Comparison with NMSSMCalc

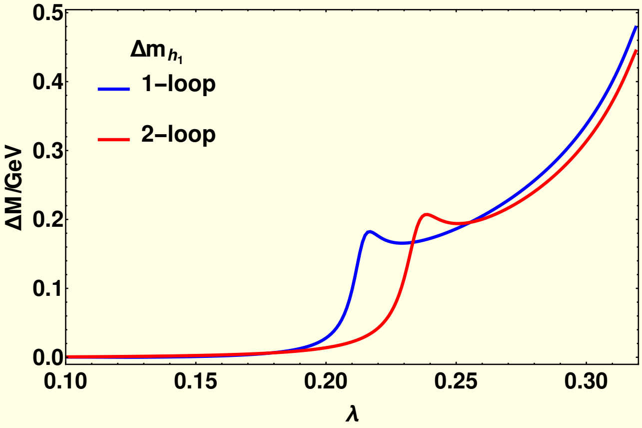
- differences between NMSSM-FeynHiggs and NMSSMCalc:

| | NMSSMCalc | | NMSSM-FeynHiggs |
|---|---|---|---|
| 1-loop | $\alpha(M_Z)$ **renormalised** | $\leftrightarrow$ | $\alpha(M_Z)$ **reparametrised** |
| 2-loop | NMSSM $\mathcal{O}(\alpha_t\alpha_s)$ $+\mathcal{O}(Y_t\lambda\alpha_s+\lambda^2\alpha_s)$ | $\leftrightarrow$ | MSSM $\mathcal{O}(\alpha_t\alpha_s)$ $+\ \mathcal{O}(\alpha_s\alpha_b, \alpha_t^2, \alpha_t\alpha_b)$ + LL- and NLL-resummation |

- results obtained with modified version of NMSSMCalc that takes on-shell stop-parameters as input

# Comparing codes: sample scenario

$$\Delta M = \left| m_{h_1}^{(\texttt{NMSSM-FH})} - m_{h_1}^{(\texttt{NMSSMCalc})} \right|$$




- Genuine NMSSM-Corrections at $\mathcal{O}(\alpha_t \alpha_s) \lesssim$ 100MeV
- two-loop MSSM approximation for top/stop contributions is well motivated
- full genuine NMSSM contributions at two-loop order could be sizeable

# Outlook

- shown results based on internal version of `FeynHiggs` for the NMSSM
- public version of `FeynHiggs` for the NMSSM, including
  - masses
  - $Z$ factors
  - decays
  - …, i. e. full functionality of `FeynHiggs` for the MSSM
- generalization to complex parameters
- far future:
  calculate genuine NMSSM contributions at two-loop order,
  especially Higgs and gauge parts