High-Precision Higgs-mass prediction in the (N)MSSM

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in collaboration with

Georg Weiglein, arXiv:1705.07909

Florian Domingo and Peter Drechsel, arXiv:1706.00437

Sophia Borowka and Georg Weiglein, preprint

DESY Hamburg

LHC Physics Discussions: Higgs

DESY Hamburg, Germany
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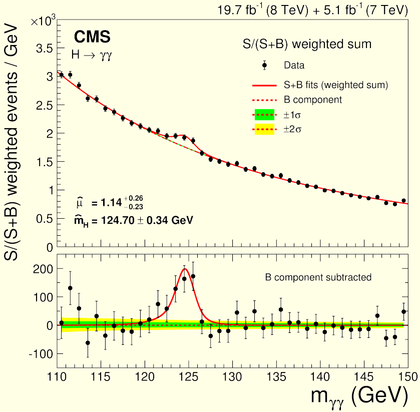
Contents

Experimental discovery and mass measurement

Higgs-like particle discovered: [ATLAS, arXiv:1207.7214 [hep-ex]], [CMS, arXiv:1207.7235 [hep-ex]],

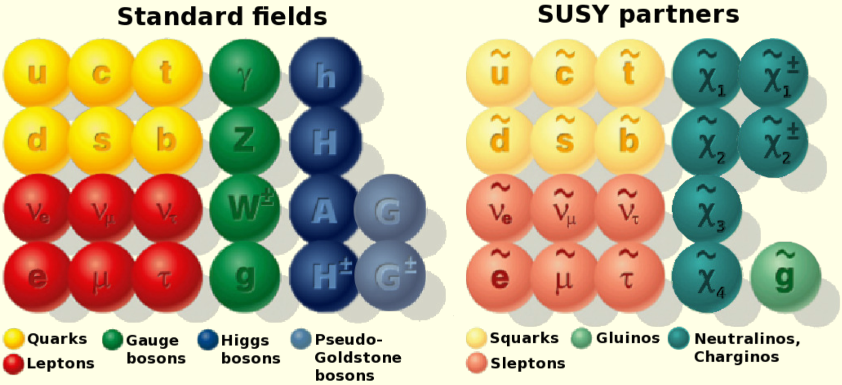
e. g. signal in $H \to \gamma\gamma$, [CMS, arXiv:1407.0558 [hep-ex]]



- very good agreement with SM Higgs boson
- but: SM has many deficiencies
- test models beyond the Standard Model, e. g. Supersymmetry, here: (N)MSSM
- experimental value: $125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$ GeV [ATLAS, CMS, arXiv:1503.07589]
- more measurements for couplings, *CP*, . . .

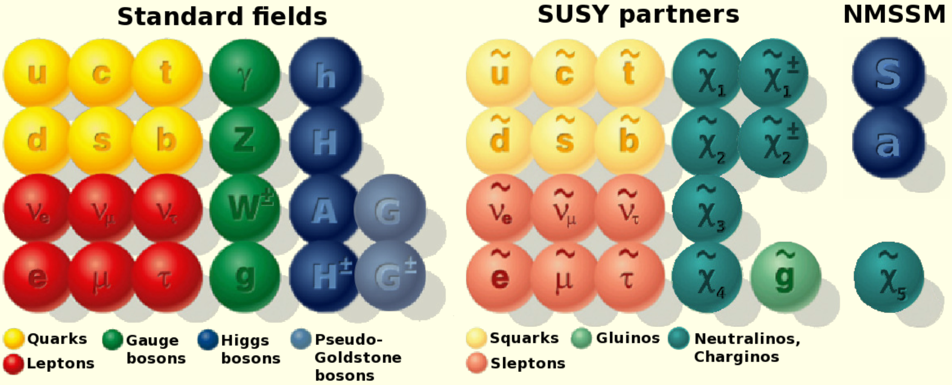
Particle content of the MSSM

- extension of the Standard Model by Supersymmetry
- two Higgs doublets



Particle content of the NMSSM

- extension of the Standard Model by Supersymmetry
- two Higgs doublets, one Higgs singlet



Higgs potential

non-kinetic part of the Lagrangian involving only Higgs fields:

$$V_H^{\text{MSSM}} = V_{\text{Higgs}}^{\text{MSSM}} + V_{\text{breaking}}^{\text{MSSM}} \,,$$

$$V_{\text{Higgs}}^{\text{MSSM}} = \tfrac{1}{8}\left(g_Y^2 + g_{\text{w}}^2\right)\left(|\mathcal{H}_2|^2 - |\mathcal{H}_1|^2\right)^2 + \tfrac{1}{2}\, g_{\text{w}}^2\, |\mathcal{H}_1^\dagger \mathcal{H}_2|^2 + |\mu|^2 \left(|\mathcal{H}_1|^2 + |\mathcal{H}_2|^2\right) \,,$$

$$V_{\text{breaking}}^{\text{MSSM}} = \tilde{m}_1^2\, |\mathcal{H}_1|^2 + \tilde{m}_2^2\, |\mathcal{H}_2|^2 + \left(\mu\, b_\mu\, \mathcal{H}_1 \cdot \mathcal{H}_2 + \text{h.c.}\right) \,,$$

minimization of potential relates bilinear and quartic terms $\Rightarrow$ mass prediction

Higgs potential

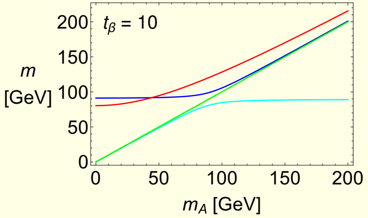
non-kinetic part of the Lagrangian involving only Higgs fields:

$$
\begin{aligned}
V_H^{\text{NMSSM}} &= V_{\text{Higgs}}^{\text{NMSSM}} + V_{\text{breaking}}^{\text{NMSSM}} \,, \\
V_{\text{Higgs}}^{\text{NMSSM}} &= \tfrac{1}{8}\left(g_Y^2 + g_{\text{w}}^2\right)\left(|\mathcal{H}_2|^2 - |\mathcal{H}_1|^2\right)^2 + \tfrac{1}{2}\, g_{\text{w}}^2\, |\mathcal{H}_1^\dagger \mathcal{H}_2|^2 + |\lambda\, \mathcal{S}|^2 \left(|\mathcal{H}_1|^2 + |\mathcal{H}_2|^2\right) \\
&\quad + \left|\lambda\, \mathcal{H}_1 \cdot \mathcal{H}_2 + \kappa\, \mathcal{S}^2\right|^2 \,, \\
V_{\text{breaking}}^{\text{NMSSM}} &= \tilde{m}_1^2\, |\mathcal{H}_1|^2 + \tilde{m}_2^2\, |\mathcal{H}_2|^2 + \left(\lambda\, A_\lambda\, \mathcal{S}\, \mathcal{H}_1 \cdot \mathcal{H}_2 + \text{h. c.}\right) \\
&\quad + \tilde{m}_S^2\, |\mathcal{S}|^2 + \left(\frac{1}{3}\, \kappa\, A_\kappa\, \mathcal{S}^3 + \text{h. c.}\right) \,,
\end{aligned}
$$

minimization of potential relates bilinear and quartic terms $\Rightarrow$ mass prediction

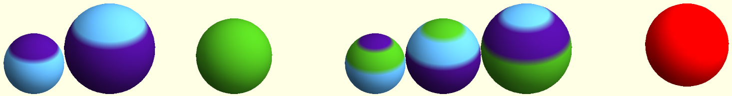
- lowest order mass eigenstates:

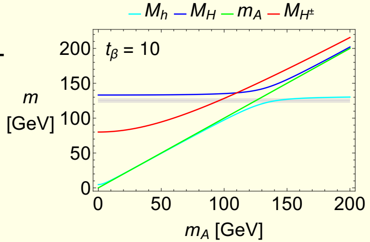
CP even	*CP* odd	charged



- higher orders: off-diagonal entries in $\hat{\mathbf{\Sigma}}_h^{(j)}(p^2)$ induce mixing,

real MSSM		complex MSSM	both
CP even	*CP* odd	*CP* mixed	charged





input parameter:	input parameter:
m_A or $m_{H^\pm}$	$m_{H^\pm}$

Mass determination at higher orders

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

$$\boldsymbol{\Delta}_h^{(k)}\left(p^2\right) = i\left[p^2\mathbf{1} - \mathbf{M}_h^{(k)}\left(p^2\right)\right]^{-1},$$

$$\mathbf{M}_h^{(k)}\left(p^2\right)\Big|_{k\,\geq\,1} = \mathbf{M}_h^{(0)} - \sum_{j\,=\,1}^{k}\hat{\boldsymbol{\Sigma}}_h^{(j)}\left(p^2\right),$$

$\mathbf{M}_h^{(0)}$: diagonal tree-level mass matrix

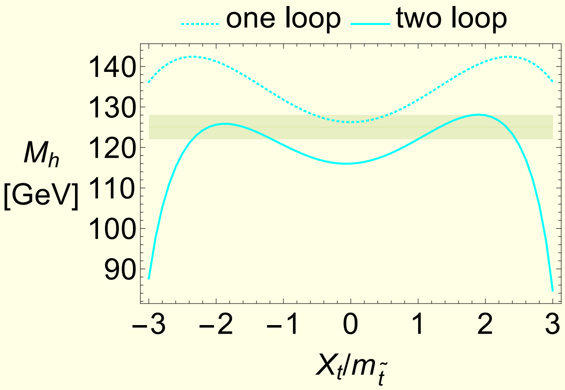
matrix of renormalized two-point vertex functions:

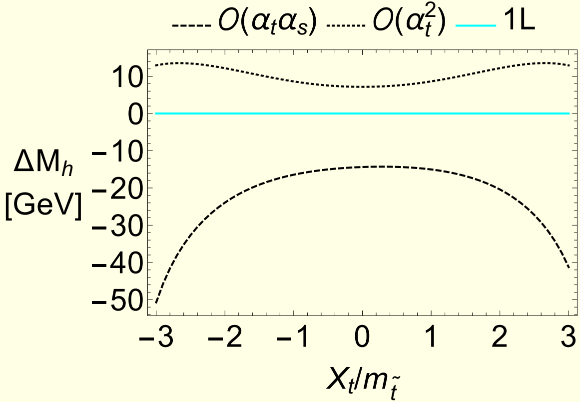
$$\hat{\boldsymbol{\Gamma}}_h^{(k)}\left(p^2\right) = -\left[\boldsymbol{\Delta}_h^{(k)}\left(p^2\right)\right]^{-1},$$

masses determined by

$$\det\left[\hat{\boldsymbol{\Gamma}}_h^{(k)}\left(p^2\right)\right]_{p^2\,=\,x_i^2} = 0\,,\quad M_{h_i}^2 = \Re\mathfrak{e}\left[x_i^2\right],\quad \begin{cases} i \in \{1,\,2,\,3\} & \text{for the MSSM,}\\ i \in \{1,\,2,\,3,\,4,\,5\} & \text{for the NMSSM.}\end{cases}$$

Known two-loop terms for the MSSM





- estimated uncertainty: $\approx$ 3GeV, but depends on scenario
- $X_t = A_t - \mu/t_\beta$

- huge effect by $\mathcal{O}(\alpha_t\alpha_s)$: ≈ -15GeV
- also big effect by $\mathcal{O}(\alpha_t^2)$: $\approx +7$GeV
- other corrections can be sizable, e. g. $\mathcal{O}(\alpha_b\alpha_s + \alpha_b\alpha_t)$ at large t_β

new two-loop contributions in the MSSM

1. Yukawa[4] terms, i. e. $\mathcal{O}(\alpha_t^2 + \alpha_t\alpha_b + \alpha_b^2)$: [SP, G. Weiglein, arXiv:1705.07909]
   extension for leading $\mathcal{O}(\alpha_t^2)$ [W. Hollik, SP, arXiv:1401.8275, 1409.1687]

   gauge-less approximation applied,
   subleading Yukawa terms included,
   no momentum dependence

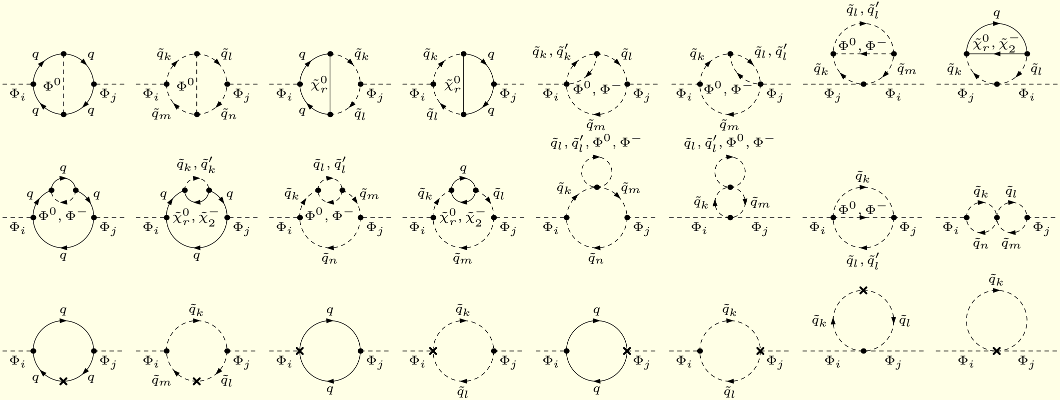
2. full lowest order QCD, $\mathcal{O}(\alpha_{\text{any}}\alpha_s)$, $\alpha_{\text{any}} = \alpha, \alpha_t, \alpha_b, \ldots$: [S. Borowka, SP, G. Weiglein, preprint]
   extension for leading $\mathcal{O}(\alpha_t\alpha_s)$ [S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein, arXiv:0705.0746]

   no approximations applied,
   all subleading terms included,
   momentum dependence taken into account

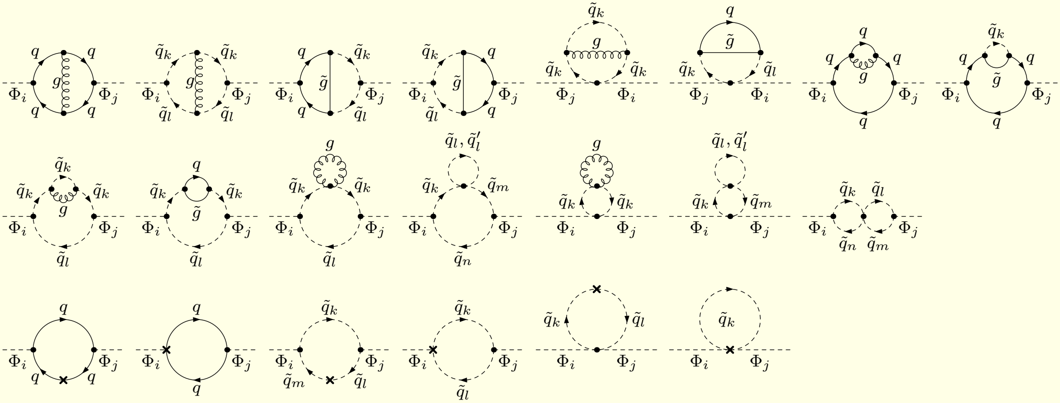
results generated with help of `FeynArts`, `FormCalc`, `TwoCalc`, `SecDec`
following previously developed scripts

[T. Hahn, SP, arXiv:1508.00562]
[S. Borowka, T. Hahn, S. Heinemeyer, G. Heinrich and W. Hollik, arXiv:1404.7074]

Yukawa terms, Feynman diagrams



two-loop two-point integrals with up to five different massive propagators,
momentum set to zero ⇒ known analytically



numerical evaluation of momentum dependent two-loop integrals

Renormalization of Yukawa terms

- $\mathcal{O}(\alpha_t^2 + \alpha_t\alpha_b + \alpha_b^2)$

  genuine two loop:
  $\delta m_{H^\pm}, \delta T_{h,H,A}$ on-shell

  subrenormalization, $\mathcal{O}(\alpha_t + \alpha_b)$:
  $\delta m_{\tilde{t}_{1,2}}, \delta m_{\tilde{t}_{12}}, \delta m_t, \delta m_{\tilde{b}_2}, \delta\mu$ on-shell

  $\delta m_b, \delta A_b$ $\overline{\text{DR}}$

  $\frac{\delta M_Z}{M_Z}, \frac{\delta M_W}{M_W}$ on-shell

  $\delta m_{H^\pm}, \delta T_{h,H,A}$ on-shell

  $\delta Z_{\mathcal{H}_1}, \delta Z_{\mathcal{H}_2}, \delta t_\beta$ $\overline{\text{DR}}$

- parametrization:

  G_F used in one-loop terms,
  corrections by Δr:

$$\left(\frac{2\, s_w\, M_W}{e}\right)^2 \sqrt{2}\, G_F = 1 + \Delta r$$

  in gauge-less limit $\Delta r = -\frac{\delta s_w^2}{s_w^2}$,

  $\Rightarrow$ no δs_w in Yukawa terms

Renormalization of QCD terms

- $\mathcal{O}(\alpha_{\text{any}}\alpha_s)$

  genuine two loop:
  $\delta m_{H^\pm}, \delta T_{h,H,A}, \delta m_W, \delta m_Z$ on-shell
  $\delta Z_{\mathcal{H}_1}, \delta Z_{\mathcal{H}_2}, \delta t_\beta$ $\overline{\text{DR}}$

  subrenormalization, only $\mathcal{O}(\alpha_s)$:
  $\delta m_{\tilde{t}_{1,2}}, \delta m_{\tilde{t}_{12}}, \delta m_t, \delta m_{\tilde{b}_2}$ on-shell
  $\delta m_b, \delta A_b$ $\overline{\text{DR}}$

Resummation of m_b

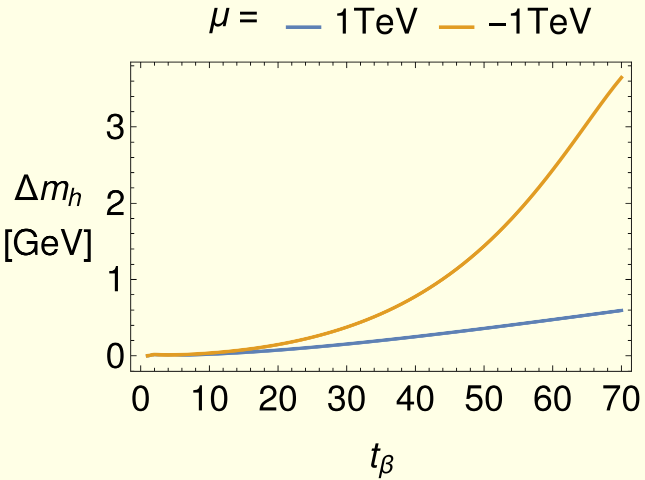
some corrections to h_b are $\propto t_\beta$,
at high t_β resummation necessary:

$$m_{b,\text{eff}} = \frac{m_b^{\overline{\text{DR}},\text{SM}}(m_t^{\text{os}})}{|1 + \Delta b|}$$

leading contributions:

$$\Delta b = \frac{2\alpha_s}{3\pi}\, \mu^*\, M_3^*\, t_\beta\, \mathcal{I}\Big(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, m_{\tilde{g}}^2\Big) + \left(\frac{h_t}{4\pi}\right)^2 \mu^*\, A_t^*\, t_\beta\, \mathcal{I}\Big(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, |\mu|^2\Big)$$

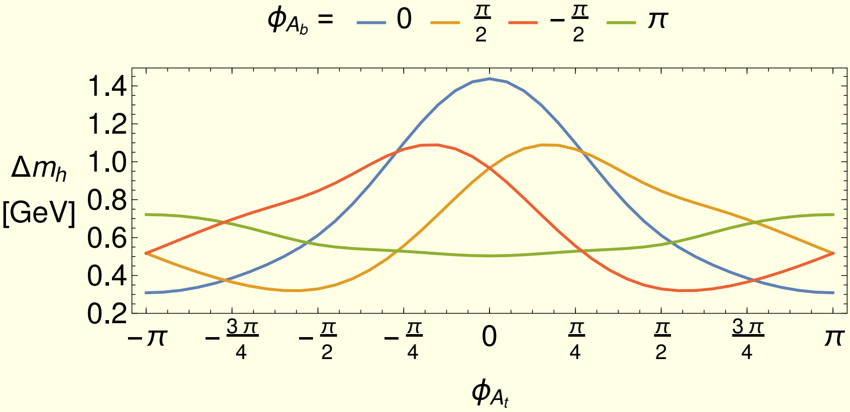
Numerical results: Yukawa terms t_β



- mass shift increasing with t_β, bottom coupling enhanced, too large t_β: not perturbative,
- negative μ looks more interesting, however, problem with $(g-2)_\mu$

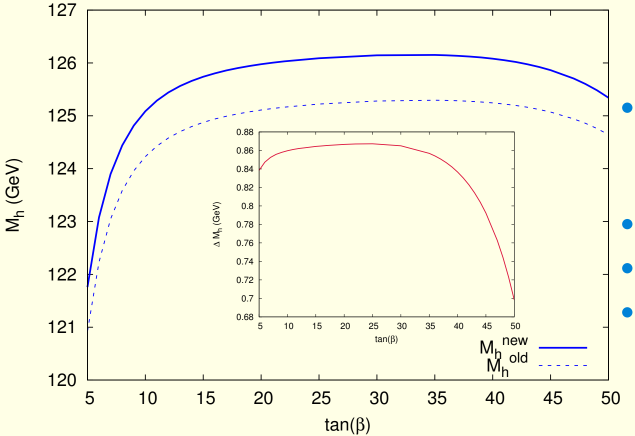
$M_{H^\pm} = 1.5\text{TeV}$, $\mu = -1\text{TeV}$, $m_{\text{SUSY}} = 2.0\text{TeV}$,
$M_{\tilde{g}} = 2.5\text{TeV}$, $X_t = 1.3 m_{\text{SUSY}}$, $A_b = 2.5 m_{\text{SUSY}}$

Numerical results: Yukawa terms ϕ_{A_t} and ϕ_{A_b}



- larger variations ($\approx$ 1GeV) of Δm_h if one phase equal to zero

Numerical results: QCD terms t_β

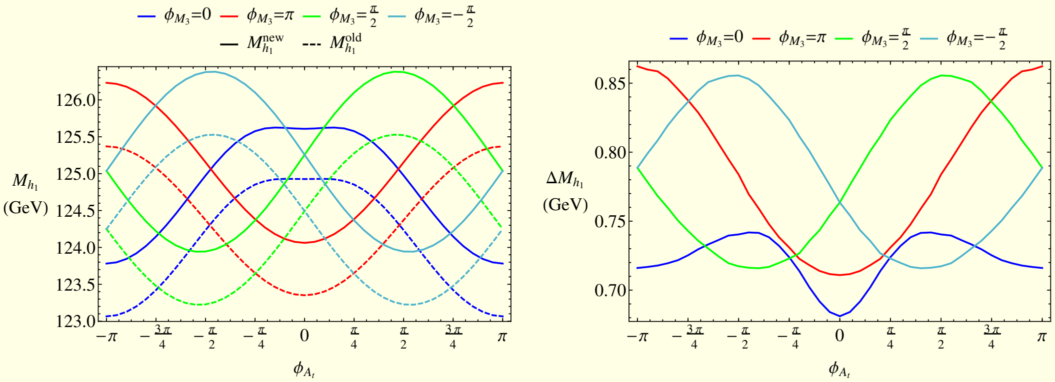


- rather large shift for all t_β originating from new $\tilde{t}$ and $\tilde{b}$ terms
- constant shift at low t_β
- large gradient at large t_β
- momentum-dependent integrals evaluated with help of SecDec

[S. Borowka, J. Carter, G. Heinrich, arXiv:1011.5493, 1204.4152, 1303.1157]

$M_{H^\pm} = 1.5\text{TeV}, \ \mu = -1.5\text{TeV}, \ M_{\tilde{g}} = 2.5\text{TeV},$
$m_{\text{SUSY}} = 2.0\text{TeV}, \ X_f = 1.3 m_{\text{SUSY}}$

Numerical results: QCD terms ϕ_{A_t} and ϕ_{M_3}



- $X_t/m_{\tilde{t}} \approx 1.3,\ M_3 = 2.5\text{TeV}$
- up to 2.5GeV shift via ϕ_{M_3}
- up to 2GeV shift via ϕ_{A_t}

- basically constant shift by new QCD contributions
- variations of up to $\approx 150\text{MeV}$ for different ϕ_{M_3}, ϕ_{A_t}

Strategy for Higgs masses in the NMSSM

for mass prediction here:

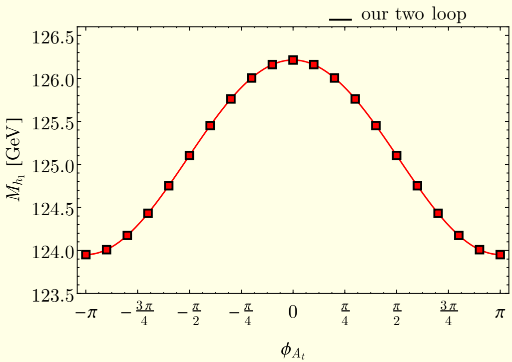
$$\widehat{\mathbf{\Gamma}}_h\left(p^2\right) = i\left[p^2\mathbf{1} - \mathbf{M}_h^{(0)} + \widehat{\mathbf{\Sigma}}_h^{(1)}\left(p^2\right) + \widehat{\mathbf{\Sigma}}_{hHA}^{\mathcal{O}(\alpha_t\alpha_s+\alpha_t^2),\ \text{MSSM}}(0)\right], \quad h = (h_1 h_2 h_3 h_4 h_5)$$

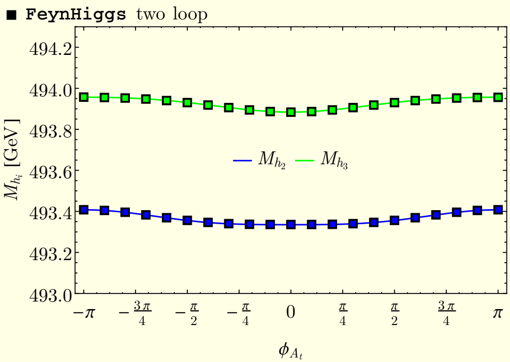
in general good agreement with `NMSSMCalc` [J. Baglio, R. Gröber, M. Mühlleitner, D. Nhung, H. Rzehak, M. Spira, J. Streicher, K. Walz, arXiv:1312.4788],
but discrepancies due to mass prediction by `NMSSMCalc` with

- all NMSSM terms in $\widehat{\mathbf{\Sigma}}_h^{\mathcal{O}(\alpha_t\alpha_s)}(0)$,
- no $\widehat{\mathbf{\Sigma}}_h^{\mathcal{O}(\alpha_t^2)}(0)$,
- no Δb

dependence on electric coupling already at tree level: inclusion of Δr^{NMSSM}

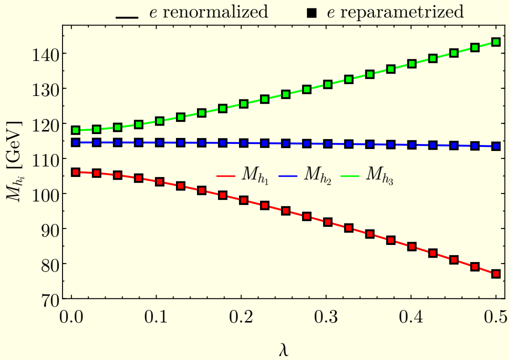
[O. Stal, G. Weiglein, L. Zeune, arXiv:1506.07465]

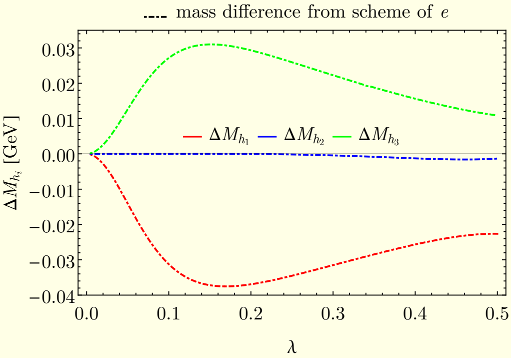




light SM-like state h_1 (left) and two heavy states h_2 and h_3 (right) over ϕ_{A_t},
solid lines: our calculation, squares: FeynHiggs,
scenario representative of MSSM-limit of the NMSSM:
$\lambda = \kappa = 10^{-5}$, $\tan\beta = 10$, $m_{H^\pm} = 500$ GeV, $\mu_{\text{eff}} = 250$ GeV, $A_\kappa = -100$ GeV,
$m_{\tilde{F}} = 1.5$ TeV, $|A_t| = A_b = 2.5$ TeV, $2\,M_1 = M_2 = M_3/5 = 0.5$ TeV.

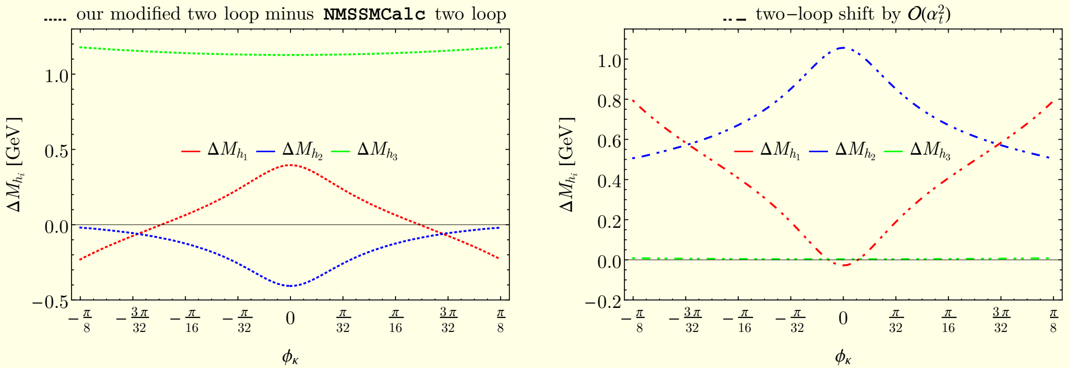
Comparison with NMSSM-FeynHiggs in the *CP*-conserving limit





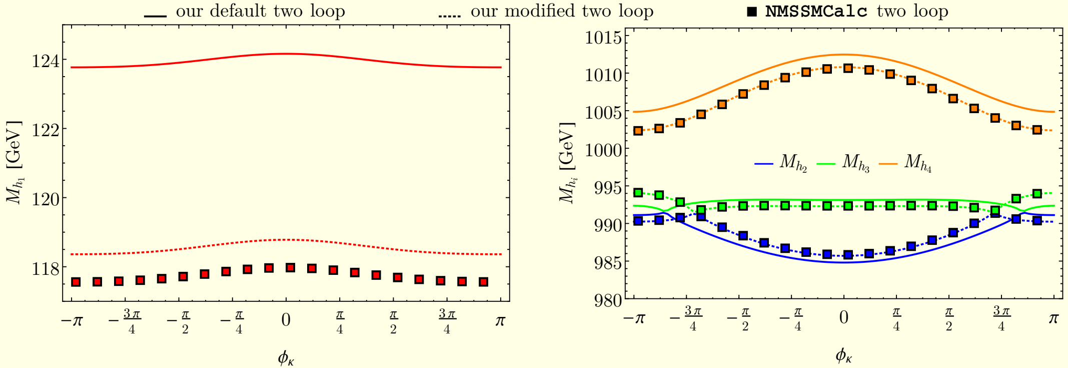
three lightest Higgs states h_1 (red), h_2 (blue), h_3 (green) over $\lambda = 2\,\kappa$,
solid: our result, squares: result of [P. Drechsel, L. Galeta, S. Heinemeyer, G. Weiglein, arXiv:1601.08100],
left: masses, right: mass differences,
input parameters in *CP*-conserving limit:
$\tan\beta = 10$, $M_{H^\pm} = 1\,\text{TeV}$, $\mu_{\text{eff}} = 125\,\text{GeV}$, $A_\kappa = -70\,\text{GeV}$, $m_{\tilde{F}} = 1.5\,\text{TeV}$, $A_t = 2\,\text{TeV}$, $A_{f\neq t} = 0.5\,\text{TeV}$, $2\,M_1 = M_2 = M_3/5 = 0.5\,\text{TeV}$.

Comparison with NMSSMCALC [J. Baglio, R. Gröber, M. Mühlleitner, D. Nhung, H. Rzehak, M. Spira, J. Streicher, K. Walz, arXiv:1312.4788]



left: corrections of $\mathcal{O}(\alpha_t^2)$ switched off, mass-differences due to NMSSM-like $\mathcal{O}(\alpha_t \alpha_s)$,
right: mass-shifts by $\mathcal{O}(\alpha_t^2)$,
input parameters:
$\lambda = 0.7$, $|\kappa| = 0.1$, $\tan\beta = 2$, $M_{H^\pm} = 1170$ GeV, $\mu_{\text{eff}} = 500$ GeV, $A_\kappa = -70$ GeV,
$m_{\tilde{Q}_3,\tilde{T},\tilde{B}} = 0.5$ TeV, $A_t = A_b = 0.1$ TeV, $2\,M_1 = M_2 = M_3/5 = 0.5$ TeV.

Comparison with NMSSMCALC [J. Baglio, R. Gröber, M. Mühlleitner, D. Nhung, H. Rzehak, M. Spira, J. Streicher, K. Walz, arXiv:1312.4788]



left: mass difference due to $\mathcal{O}(\alpha_t^2)$, right: mass differences due to Δb,

input parameters:

$\lambda = 0.2$, $|\kappa| = 0.6$, $\tan\beta = 25$, $M_{H^\pm} = 1000$ GeV, $\mu_{\text{eff}} = 200$ GeV, $A_\kappa = -750$ GeV,

$m_{\tilde{Q}_3,\tilde{T},\tilde{B}} = 1.1$ TeV, $A_t = A_b = -2$ TeV, $2\,M_1 = M_2 = M_3/5 = 0.5$ TeV.

Conclusions and outlook

- theoretical uncertainty far above experimental uncertainty
- new two-loop corrections improve general accuracy
- complex parameters can have significant impact on mass prediction
- all known corrections of the MSSM can be reused for the NMSSM, but new uncertainty due to missing genuine NMSSM contributions
- results will become publicly available via `FeynHiggs`