Karlsruher Institut für Technologie

Higgs boson masses in the complex NMSSM at one-loop level

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R. Gröber, M. Mühlleitner, H. Rzehak and K. Walz

INSTITUTE FOR THEORETICAL PHYSICS

Outline

Motivation

Why Consider the Next-to-Minimal-Supersymmetric-SM?

- NMSSM solves the μ-problem of the MSSM
  $\rightarrow$ dynamical generation of the μ-term
- upper bound on lightest Higgs boson mass less strict ($\rightarrow$ less fine-tuned)
- Higgs sector slightly more complicated than MSSM:
  richer phenomenology (e.g. new Higgs-to-Higgs decays)
- new sources for CP-violation (already at tree-level)

Why One-Loop Masses?

- one-loop corrections essential to reach a mass of 125 GeV
- one-loop corrections are quite sizeable (can triple the mass) $\rightarrow$ huge phenomenological implications
- accurate predictions are important to distinguish the Higgs sectors of the different models

$\Longrightarrow$ Full one-loop calculation of Higgs boson masses in the complex NMSSM in the diagrammatic approach using a mixed renormalization scheme

What is the complex NMSSM?

- two complex Higgs doublets + one complex Higgs singlet

$$H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + h_d + ia_d) \\ H_d^- \end{pmatrix}$$

$$H_u = e^{i\phi_u} \begin{pmatrix} H_u^+ \\ \frac{1}{\sqrt{2}}(v_u + h_u + ia_u) \end{pmatrix}$$

$$S = \frac{1}{\sqrt{2}} e^{i\phi_s} (v_s + h_s + ia_s)$$

- Superpotential

$$W = \hat{u} Y_u \left(\hat{Q}^{\mathrm{T}} \epsilon \hat{H}_u\right) - \hat{d} Y_d \left(\hat{Q}^{\mathrm{T}} \epsilon \hat{H}_d\right) - \hat{e} Y_e \left(\hat{L}^{\mathrm{T}} \epsilon \hat{H}_d\right) + \lambda \hat{S} \left(\hat{H}_u^{\mathrm{T}} \epsilon \hat{H}_d\right) + \frac{1}{3} \kappa \hat{S}^3$$

- 5 neutral Higgs bosons: mix to mass eigenstates H_i with $i = 1..5$
- ordered by ascending mass $M_{H_1} < M_{H_2} < \ldots < M_{H_5}$
- SUSY has to be broken:

$$\underbrace{A_\lambda,\, A_\kappa,\, A_t,\, A_b,\, A_\tau,}_{\text{trilinear breaking parameters}} \; \underbrace{M_1,\, M_2,\, M_3,\, M_{\tilde{Q}},\, M_{\tilde{u}_R},\, \ldots}_{\text{soft susy breaking masses}}$$

Phases in the Higgs sector

- additional parameters compared to the real NMSSM:

$\phi_u, \phi_s, \phi_\lambda, \phi_\kappa, \phi_{A_\lambda}, \phi_{A_\kappa}$

- at first sight there are six independent phases

$\Longrightarrow$ reduce to one physical phase combination in the Higgs sector at tree-level:

$$\phi_I = \phi_u + \phi_\lambda - \phi_\kappa - 2\phi_s$$

- only three phase combinations in Higgs sector: ϕ_I, ϕ_{I_κ} and ϕ_{I_λ}
- tadpole conditions:

$$t_\Phi = \left\langle \frac{\partial V}{\partial \Phi} \right\rangle \stackrel{!}{=} 0 \qquad \text{for} \qquad \Phi = h_d, h_u, h_s, a_d, a_u, a_s$$

  no terms linear in the Higgs fields in the Lagrangian
- $t_{a_d} = 0$ and $t_{a_s} = 0$ can be used to eliminate ϕ_{I_κ} and ϕ_{I_λ}

Renormalization

- higher order corrections involve divergent contributions

  $\rightarrow$ renormalization of the Higgs sector

  $\rightarrow$ introduce counterterms for all parameters

  $\rightarrow$ fix counterterms via renormalization conditions

- we apply a mixed scheme:

  $\rightarrow$ OS parameters: M_W, M_Z, $M_{H^\pm}$, e, t_{h_d}, t_{h_u}, t_{h_s}, t_{a_d}, t_{a_s}

  $\rightarrow$ $\overline{\text{DR}}$ parameters: $\tan\beta$, $|\lambda|$, $|\kappa|$, $|A_\kappa|$, v_s, ϕ_u, ϕ_s, ϕ_λ, ϕ_κ

- non-trivial cross-check:
  take renormalization conditions from Higgs, Chargino and Neutralino sector (19 equations; only need a subset of 12)

- numerical calculation yields:

$$\delta\phi_\lambda = \delta\phi_\kappa = \delta\phi_u = \delta\phi_s = 0$$

$\Rightarrow$ complex NMSSM needs only two more counterterms than real NMSSM

One-Loop Masses

- two-point vertex function:

  $$\hat{\Gamma}(p^2) = i(\mathbb{1} \cdot p^2 - \mathcal{M}^{1l}(p^2)) \qquad \text{with} \quad \left(\mathcal{M}^{1l}\right)_{ij} = m^2_{h_i}\delta_{i,j} - \hat{\Sigma}_{h_i h_j}(p^2)$$

  renormalized self-energy:

  $$\hat{\Sigma}_{h_i h_j} = \Sigma_{h_i h_j} + \tfrac{1}{2}p^2\left(\delta\tilde{Z}^\dagger + \delta\tilde{Z}\right)\Big|_{ij} - \tfrac{1}{2}\left(\delta\tilde{Z}^\dagger\mathcal{M}^{\text{dia}}_{\text{H}} + \mathcal{M}^{\text{dia}}_{\text{H}}\delta\tilde{Z}\right)\Big|_{ij} - \left(\mathcal{R}\,\delta\mathcal{M}_{\text{H}}\,\mathcal{R}^{\text{T}}\right)\Big|_{ij}$$

  wavefunction renormalization constants:

  $$\delta\tilde{Z} = \mathcal{R}\ \text{diag}(c^2_\beta\,\delta Z_{H_u} + s^2_\beta\,\delta Z_{H_d}, \delta Z_S, \delta Z_{H_d}, \delta Z_{H_u}, \delta Z_S)\ \mathcal{R}^T$$

- one-loop masses squared are given by solution of

  $$\text{Det}(\hat{\Gamma}(p^2)) = 0 \qquad \leftrightarrow \qquad \text{eigenvalues of } \mathcal{M}^{1l}$$

- iterative procedure:

  a) $(\tilde{M}_{H_n,1})^2$=n-th eigenvalue of $\mathcal{M}^{1l}(m^2_{h_n})$
  b) $(\tilde{M}_{H_n,2})^2$=n-th eigenvalue of $\mathcal{M}^{1l}((\tilde{M}_{H_n,1})^2)$
  c) ...
  d) until $|(\tilde{M}_{H_n,k+1})^2 - (\tilde{M}_{H_n,k})^2| < 10^{-9}$

Numerical Analysis

Scenario Parameters

$\mu_{\text{ren}} = 500\text{GeV}, \quad |\lambda| = 0.72, \quad |\kappa| = 0.20, \quad \tan\beta = 3,$

$M_{H^\pm} = 629\text{GeV}, \quad A_\kappa = 27\text{GeV}, \quad |\mu| = 198\text{GeV},$

$|A_b| = 936\text{GeV}, \quad |A_t| = 876\text{GeV}, \quad |M_1| = 145\text{GeV}, \quad |M_2| = 200\text{GeV},$

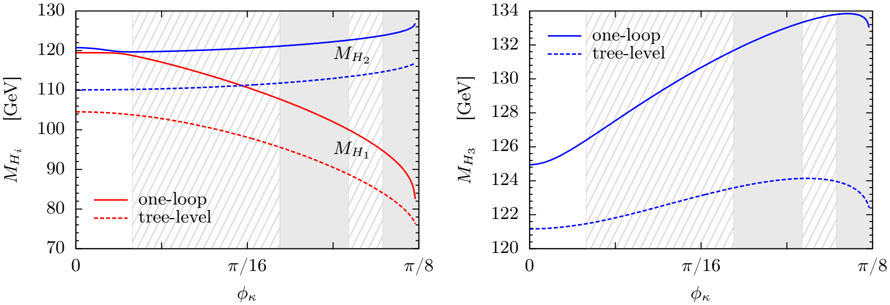
$M_{Q_3} = 490\text{GeV}, \quad M_{t_R} = 477\text{GeV}, \quad M_0 = 1000\text{GeV}, \quad A_0 = 1000\text{GeV},$

all phases not explicitly mentioned are zero

Phase variations

1. CP-violation at tree-level: $\phi_\kappa \neq 0$
2. radiatively induced CP-violation
   - 2.1 $\phi_{A_t} \neq 0$
   - 2.1 $\phi_I = 0$, but $\phi_\kappa = \phi_\lambda \neq 0$

CP-Violation at tree-level (1)

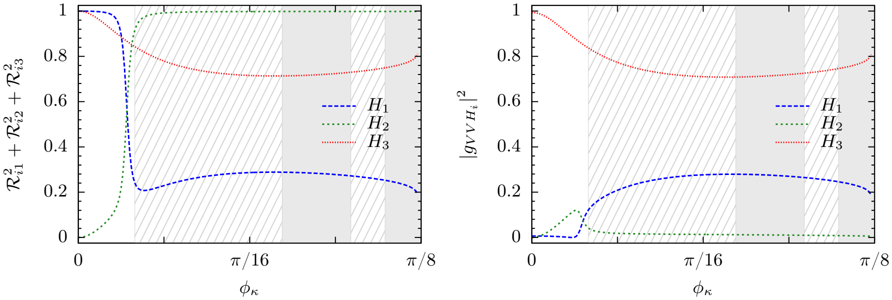


- **gray area:** excluded by experiment
  (LEP, Tevatron and LHC_{2011} checked with `HiggsBounds`)
- **dashed area:** not compatible with SM-like excess around 125GeV

Compatibility: $120\text{GeV} \leq M_{H_i^{\text{SM-like}}} \leq 130\text{GeV}$

$$S_{\text{tot}}^{\text{NMSSM}}(H_i^{\text{SM-like}}) = S_{\text{tot}}^{\text{SM}}(H^{\text{SM}}) \pm 20\% \quad \text{for} \quad M_{H^{\text{SM}}} = M_{H_i^{\text{SM-like}}}$$

CP-Violation at tree-level (2)



- CP-even component: $r_{\text{CP}}^i = \mathcal{R}_{ih_d}^2 + \mathcal{R}_{ih_u}^2 + \mathcal{R}_{ih_s}^2$

  $r_{\text{CP}}^i = 1 \rightarrow$ mass eigenstate H_i is completely CP-even

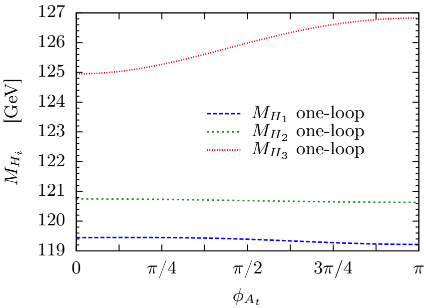
  $r_{\text{CP}}^i = 0 \rightarrow$ mass eigenstate H_i is completely CP-odd

- coupling to the vector bosons normalized to the SM:

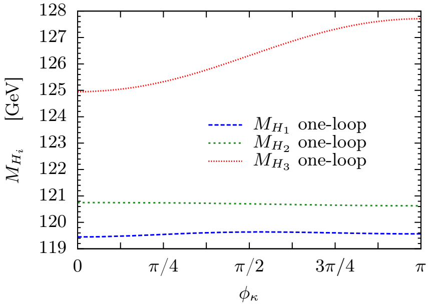
  $g_{VVH_i} = \cos\beta\, \mathcal{R}_{ih_d} + \sin\beta\, \mathcal{R}_{ih_u}$

Radiatively induced CP-violation

- Variation of ϕ_{A_t}



- Variation of $\phi_\kappa = \phi_\lambda \to \phi_I = 0$



- only M_{H_3} shows any notable dependence

  → variation of ϕ_{A_t} and ϕ_λ changes the stop masses

  → H_3 has the largest h_u component

  → H_3 is most sensitive to the corrections of the stop masses

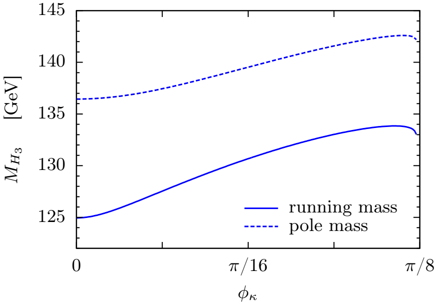
Summary & Outlook

- full one-loop result for the Higgs boson masses in the complex NMSSM
  $\rightarrow$ more details can be found in: [JHEP 1210 (2012) 122]
- mixed renormalization scheme: $\overline{\text{DR}}$ and OS conditions
  non-trivial cross-check: conditions from Higgs, neutralino and chargino sector
- one-loop corrections have a significant impact on Higgs spectrum (masses and coupling properties)
- even small phases can have significant effects
- availability of Higgs sector at higher orders is indispensable for a phenomenological discussion of the NMSSM
- theoretical uncertainty $\mathcal{O}(10\%)$
  $\rightarrow$ reduced by two-loop corrections
  $\rightarrow$ $\mathcal{O}(\alpha_t\alpha_s + \alpha_b\alpha_s)$ in the effective potential approach exist for the real NMSSM
  [Degrassi,Slavich]

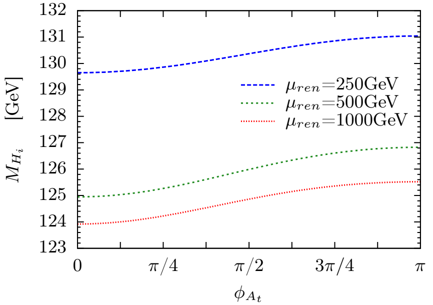
Thank You!

Theoretical Uncertainty

- Different renormalization schemes for m_t and m_b



- Variation of the renormalization scale μ_{ren}



$\Longrightarrow$ uncertainties can be conservatively estimated $\sim 5 - 10\%$

Renormalization Conditions

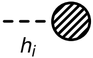
On-Shell Renormalization

- counterterms contain finite part and divergent part:

  $\delta p = \delta p|_{\text{fin}} + \delta p|_{\text{div}}$

- $\delta M_V^2 = \widetilde{\text{Re}}\Sigma^{\text{T}}_{VV}(M_V^2) \quad$ with $V = W^{\pm}, Z$

- $\delta M^2_{H^{\pm}} = \widetilde{\text{Re}}\Sigma_{H^+H^+}(M^2_{H^{\pm}})$

- $\delta t_\Phi = T_\Phi =$ 

  $\Phi = a_d, a_s, h_d, h_u, h_s$

- $\delta Z_e = \frac{1}{2} \frac{\partial \Sigma^{\text{T}}_{\gamma\gamma}(p^2)}{\partial p^2}\Big|_{p^2=0} + \frac{s_W}{c_W} \frac{\Sigma^{\text{T}}_{\gamma Z}(0)}{M_Z^2}$

$\overline{\text{DR}}$ Renormalization

- counterterms contain only divergent part

  $\delta p = \delta p|_{\text{div}}$

- δZ_{H_u}, δZ_{H_d} and δZ_S via residuum
- $\delta \tan\beta$ determined via δZ_{H_u} and δZ_{H_d}
- chargino sector: 4 conditions
- neutralino sector: 10 conditions
- Higgs sector: 5 conditions

$\Rightarrow$ 19 equations for 12 counterterms (take any subset)

$$\widetilde{\text{Re}}\left\{c \cdot B_0(p^2, m_1^2, m_2^2)\right\} = c \cdot \text{Re}\left\{B_0(p^2, m_1^2, m_2^2)\right\} \qquad c \in \mathbb{C}$$