QCD corrections to the Higgs sector of the complex MSSM at the two-loop level

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Outline

- Higgs bosons in the MSSM
- Mass of the lightest Higgs boson
- Higher order contributions to this mass

Higgs bosons

At Born level: no CP-violation:

- one phase in the Higgs potential: $V_{\text{Higgs}} = \cdots + \epsilon_{ij} |m_3^2| e^{i\varphi_{m_3^2}} H_1^i H_2^j + \ldots$
  elimination via Peccei-Quinn transformation
- phase difference of Higgs doublets:
  vanishes because of minimum condition

Physical mass eigenstates (at Born level):

- 5 Higgs bosons: 3 neutral H^0, h^0, A^0; 2 charged $H^\pm$

Masses of the Higgs bosons:

- not all independent: here: $H^\pm$-mass $M_{H^\pm}$ (and $\tan\beta$) as free parameter
  $\tan\beta = \frac{v_2}{v_1}$: ratio of the Higgs vac. expect. values
- lightest Higgs boson: h^0

Mass of the lightest Higgs boson

Upper theoretical Born mass bound: $M_{h^0} \leq M_Z = 91$ GeV

with quantum corrections of higher orders: $M_h \lesssim 135$ GeV

dependent on the MSSM parameters:
particularly on parameter phases

- Discovery of the Higgs boson:

accurate measurement → mass of the Higgs boson ← precise prediction

⇒ strong bounds on the MSSM parameter, e.g. on $\tan\beta = \frac{v_2}{v_1}$

at the LHC: $\Delta M_{h^0}^{\text{exp}} = 0.2$ GeV (LC: $\Delta M_{h^0}^{\text{exp}} = 0.05$ GeV)

⇒ precision prediction needed,

i.e. inclusion of higher order corrections with full phase dependence

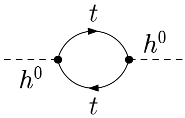
- Before the discovery: Exclusion of parts of the parameter space

Determination of the Higgs masses

Two-point-function:

$$\Gamma(k^2) = k^2 - \mathrm{M}^2_{\mathrm{Born}} + \begin{pmatrix} \hat{\Sigma}_{H^0 H^0}(k^2) & \hat{\Sigma}_{H^0 h^0}(k^2) & \hat{\Sigma}_{H^0 A^0}(k^2) \\ \hat{\Sigma}_{H^0 h^0}(k^2) & \hat{\Sigma}_{h^0 h^0}(k^2) & \hat{\Sigma}_{h^0 A^0}(k^2) \\ \hat{\Sigma}_{H^0 A^0}(k^2) & \hat{\Sigma}_{h^0 A^0}(k^2) & \hat{\Sigma}_{A^0 A^0}(k^2) \end{pmatrix}$$

diagonal matrix with squared Born masses $\mathrm{diag}(M^2_{H^0_{\mathrm{Born}}}, M^2_{h^0_{\mathrm{Born}}}, M^2_{A^0_{\mathrm{Born}}})$



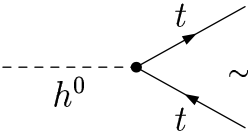
determining the zero of $\det\big(\Gamma(k^2)\big) \Rightarrow M_{h_1}, M_{h_2}, M_{h_3}$

Real parameters:

$$\hat{\Sigma}_{H^0 A^0}(k^2) = \hat{\Sigma}_{h^0 A^0}(k^2) = 0 \Rightarrow M_{h^0} = M_{h_1}$$

no mixing between CP-even and CP-odd states

Why large quantum corrections?

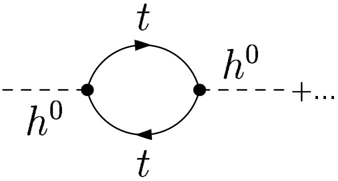


$\sim \quad \lambda_t \sim \frac{m_t}{M_W \sin\beta}$

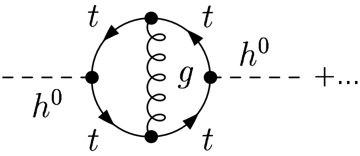
Yukawa coupling

Large contribution from the top sector

one-loop level:



two-loop level:



QCD corrections to the dominant one-loop contribution

Renormalized two-loop self energies

Calculation of the dominant two-loop contributions ($\alpha_t = \lambda_t^2/(4\pi)$):

- Terms of order $\mathcal{O}(\alpha_t \alpha_s)$ for complex parameters

  ← new

  known: two-loop leading-log contributions [Pilaftsis, Wagner]

  [Carena, Ellis, Pilaftsis, Wagner]

- Approximation of vanishing external momenta $\hat{\Sigma}^{(2)}(0)$

- Approximation of vanishing electroweak gauge couplings g, g'

Renormalized two-loop self energies

Calculation of the dominant two-loop contributions ($\alpha_t = \lambda_t^2/(4\pi)$):

- within an **on-shell** scheme in the Higgs sector:
  - no shift of the minimum of the Higgs potential
  - define the $H^\pm$-mass $M_{H^\pm}$ as the **pole mass**

    $\Rightarrow$ directly related to a **physical observable**
- with parameters of the top sector defined at one-loop:
  - quark mass and squark masses on-shell
  - generalization of the mixing angle condition:

$$\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{t}_{12}}(m_{\tilde{t}_1}^2) + \widetilde{\text{Re}}\hat{\Sigma}_{\tilde{t}_{12}}(m_{\tilde{t}_2}^2) = 0$$

Phases in couplings

Phases relevant at two-loop level:

- squark sector:
  - phase φ_{A_t} of the trilinear coupling A_t
  - phase of μ (small), μ: Higgsino mass parameter

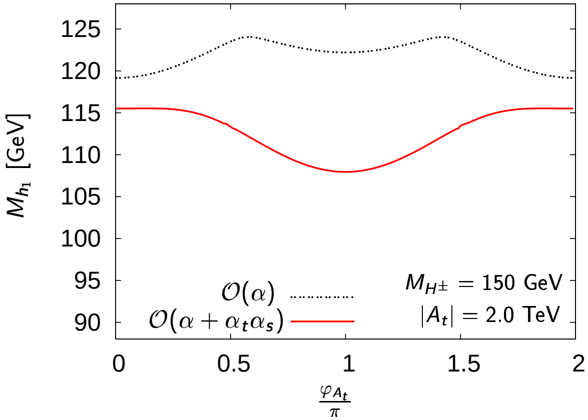
    constraints from measurements of electr. dipole moments

- gluino sector:
  - phase $\varphi_{\tilde{g}}$ of the gluino mass parameter

    in the gluino-squark-quark-vertex

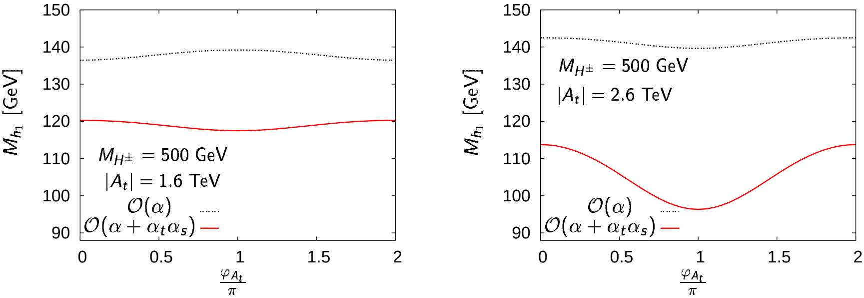
soft breaking parameter

Results: φ_{A_t}-dependence (small $M_{H^\pm}$)



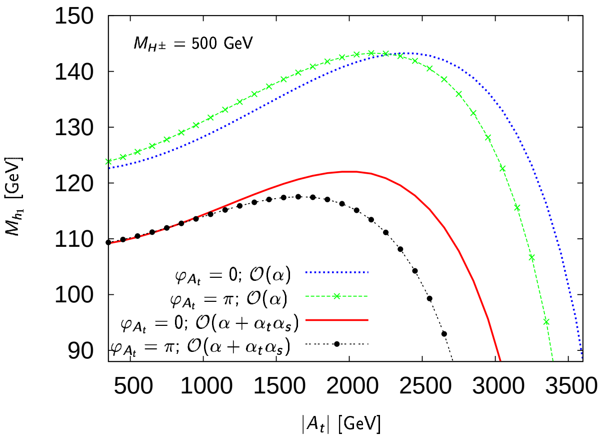
- Quantum corrections of $\mathcal{O}(\alpha_t\alpha_s)$ change the qualitative behaviour of M_{h_1}.

Results: φ_{A_t}-dependence (large $M_{H^\pm}$)



- Quantum corrections of $\mathcal{O}(\alpha_t\alpha_s)$ change the qualitative behaviour of M_{h_1}.
- Qualitative behaviour of M_{h_1} depends strongly on $|A_t|$.

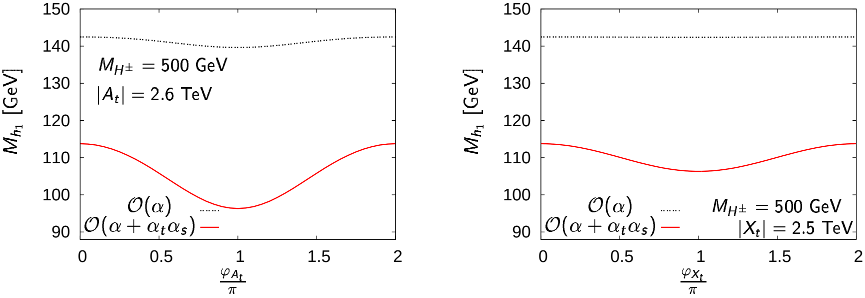
Results: $|A_t|$-dependence (large $M_{H^\pm}$)



- One-loop: $\varphi_{A_t} = \pi$ "shifts" towards lower values of $|A_t|$ with respect to $\varphi_{A_t} = 0$.
- Two-loop: also the value of the maximum of M_{h_1} depends on the phases.

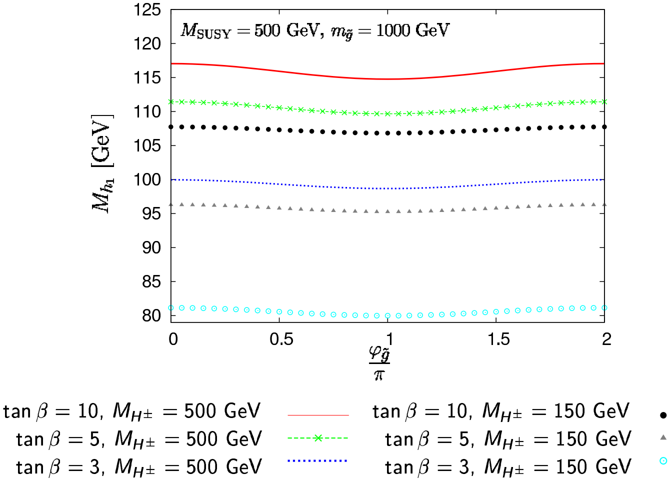
Results: φ_{A_t}- versus φ_{X_t}-dependence (large $M_{H^\pm}$)

size of the squark mixing: $X_t := A_t - \mu^* \cot\beta$



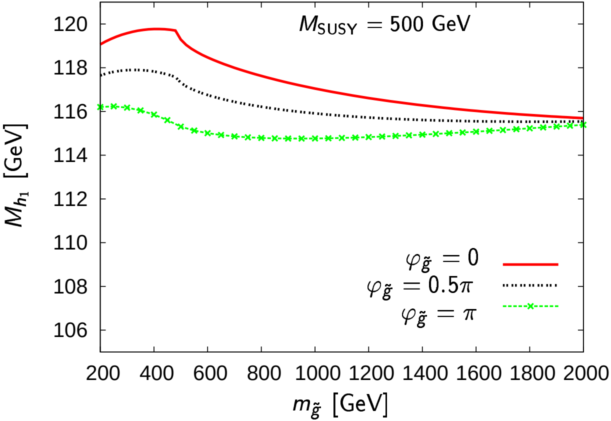
- Quantum corrections are smaller for constant absolute value of the squark mixing, $|X_t| = \text{const.}$

Results: $\varphi_{\tilde{g}}$-dependence



- M_{h_1} depends rather weakly on the phase $\varphi_{\tilde{g}}$.

Results: dependence on the gluino mass $m_{\tilde{g}}$



- Large effects in the threshold region: $m_{\tilde{t}_2} = m_{\tilde{g}} + m_t$

Conclusions

- Quantum corrections are important for a precise prediction of the mass of the lightest Higgs boson M_{h_1}:
  - They can induce CP-violation.
  - Dominant corrections: from the top sector
- Contributions of $\mathcal{O}(\alpha_t \alpha_s)$ for complex parameters:
  - Phases are relevant at the two-loop level.
  - Two-loop contributions can change qualitative behaviour of M_{h_1}.
  - will be included into FeynHiggs.