The $\mathcal{O}(\alpha_t\alpha_s)$-corrections to the trilinear Higgs-selfcouplings in the complex NMSSM

Hanna Ziesche in collaboration with Dao Thi Nhung and Margarete Mühlleitner

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- Introduction into the complex NMSSM
- Trilinear Higgs Self-Couplings
- The $\mathcal{O}(\alpha_t\alpha_s)$-corrections
- Results

Introduction into the complex NMSSM

Motivations for Supersymmetry:

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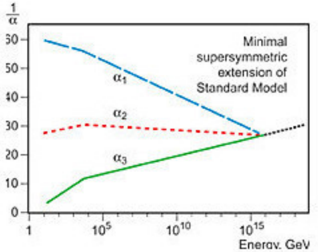

Introduction into the complex NMSSM

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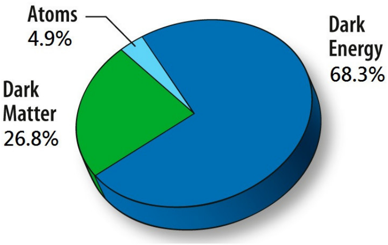
- Candidate for dark matter



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- The μ-problem: Finetuning of the μ-parameter of the Higgs potential necessary

$$V_H = \mu^2 (H_u^\dagger H_u + H_d^\dagger H_d) + \frac{1}{2} g_2^2 (H_u^\dagger H_d)^2 + \frac{1}{8}(g_1^2 + g_2^2)(H_u^\dagger H_u - H_d^\dagger H_d)^2 + V_{soft}$$

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$\Rightarrow$ Solution: NMSSM

Introduction into the complex NMSSM

NMSSM: Introduction of an additional scalar singlet and its superpartner

- Higgs sector of the NMSSM:

$$H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}\left(v_d + h_d + ia_d\right) \\ H_d^- \end{pmatrix} \qquad H_u = e^{i\varphi_u} \begin{pmatrix} H_u^+ \\ \frac{1}{\sqrt{2}}\left(v_u + h_u + ia_u\right) \end{pmatrix}$$

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

⇒ Higgs potential of the NMSSM:

$$\mathrm{V_H} = |\lambda|^2|S|^2\left(H_u^\dagger H_u + H_d^\dagger H_d\right) + \left|\lambda(H_u^T H_u - H_d^T H_d)^2 + \kappa S^2\right|^2 +$$

$$\mathrm{V_{D,MSSM}} + \mathrm{V_{soft,MSSM}} + m_s^2|S|^2 + \left(\lambda A_\lambda\left(H_u^T \epsilon H_d\right) S + \frac{1}{3}\kappa A_\kappa (S^3 + c.c.)\right)$$

Introduction into the complex NMSSM

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Introduction into the complex NMSSM

NMSSM

- μ problem:
- Upper limit on the tree-level Higgs mass:
- CP-violation in the Higgs sector:

Introduction into the complex NMSSM

NMSSM

- μ problem: μ parameter is generated dynamically

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- Upper limit on the tree-level Higgs mass: is relaxed

$$m_{h_1}^2 \leq M_Z^2 \cos(2\beta)^2 + \lambda^2 v^2 \sin(2\beta)$$

- CP-violation in the Higgs sector:

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- CP-violation in the Higgs sector:

  possible already at tree level

Trilinear Higgs Self-Couplings

Is it **the** Higgs boson of the **SM**? Or a **BSM** Higgs boson?

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For the NMSSM Higgs sector available:

- Corrections to the masses:
  - full 1-loop corrections in the real and complex NMSSM
    [Ellwanger et al., Degrassi et al., Graf et al., Cheung et al.]
  - Corrections up to $\mathcal{O}(\alpha_s(\alpha_t + \alpha_b))$ and beyond in the real NMSSM
    [Degrassi et al., Staub et al.] [Goodsell et al.]
  - $\mathcal{O}(\alpha_s\alpha_t)$ corrections in the complex NMSSM
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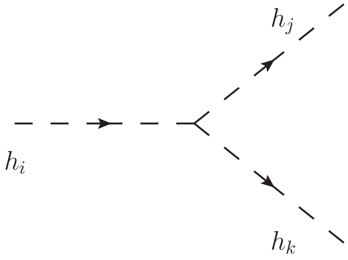
  - $\mathcal{O}(\alpha_s \alpha_t)$ corrections in the complex NMSSM
    [Mühlleitner, Dao, Rzehak, Walz]
- Corrections to the trilinear Higgs self-couplings
  - full 1-loop corrections to the trilinear Higgs self-couplings in the real NMSSM [Mühlleitner, Dao, Streicher, Walz]
  - $\mathcal{O}(\alpha_s \alpha_t)$ corrections in the complex NMSSM (this talk)
    [Mühlleitner,Dao,HZ arXiv:1506.0332]

The $\mathcal{O}(\alpha_t\alpha_s)$ Corrections

$\Rightarrow$ Consistent description of the NMSSM Higgs sector demands:

Calculation of $\mathcal{O}(\alpha_t\alpha_s)$ corrections to the trilinear Higgs self-couplings

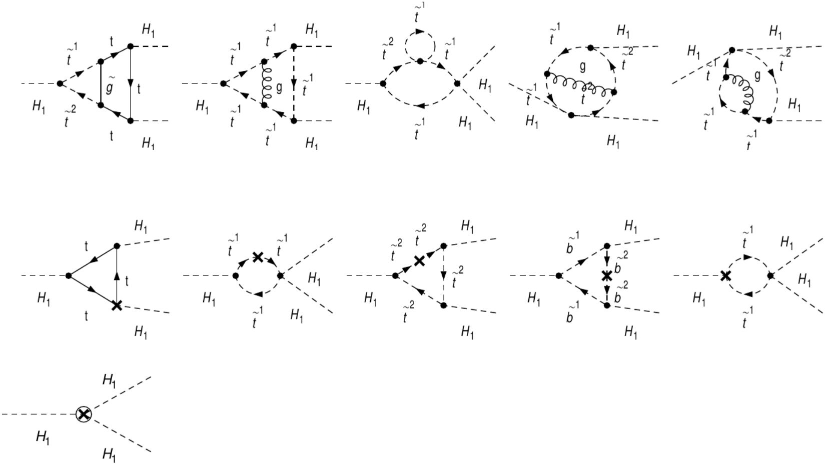


Approximations and Simplifications:

- "gaugeless limit": $e, g_1, g_2 = 0$
- vanishing external momenta $p_{\text{ext}} = 0$

The $\mathcal{O}(\alpha_t\alpha_s)$ Corrections

Typical diagrams:



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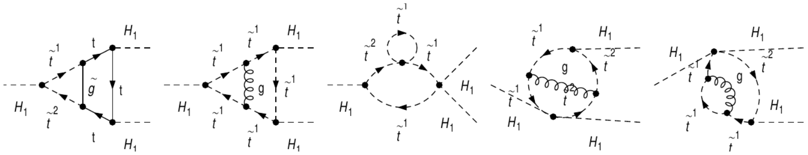

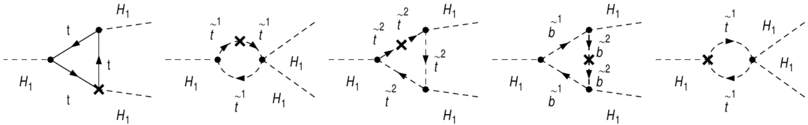

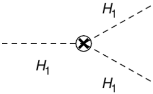

The $\mathcal{O}(\alpha_t \alpha_s)$ Corrections: genuine 2-loop diagrams

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After dimensional reduction, we encounter integrals like:

$$C^2 \int \mathrm{d}^d l_1 \, \mathrm{d}^d l_2 \, \frac{(l_1^2)^{\alpha_1} (l_2^2)^{\alpha_2} (l_1 \cdot l_2)^{\alpha_3}}{(l_1^2 - m_1^2)^{\nu_1} (l_2^2 - m_2^2)^{\nu_2} ((l_1 - l_2)^2 - m_3^2)^{\nu_3} (l_1^2 - m_4^2)^{\nu_4} (l_2^2 - m_5^2)^{\nu_5}}$$

$\alpha_i, \nu_i = 0, 1, 2 \qquad d = 4 - 2\epsilon \qquad C = \frac{\mu^{2\epsilon}}{(2\pi)^d}$

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Simplification with the Mathematica package TARCER [Mertig,Scharf arxiv:9801383] implemented in FeynCalc [Bohm,Denner,Mertig Comput.Phys.Commun **64**,345 (1991))]

- TARCER reduces integrals like

$$C^2 \int \mathrm{d}^d l_1 \, \mathrm{d}^d l_2 \, \frac{(l_1)^{\alpha_1} (l_2)^{\alpha_2} (l_1 \cdot l_2)^{\alpha_3} (l_1 \cdot p)^{\alpha_4} (l_2 \cdot p)^{\alpha_5}}{D_1^{\nu_1} D_2^{\nu_2} D_3^{\nu_3} D_4^{\nu_4} D_5^{\nu_5}}$$

$$D_j = ((l_i - p_j)^2 - m_j^2)$$

  to a set of “master integrals” (via Tarasov Algorithmus [Tarasov arxiv:9606018,arxiv:9703319])

The $\mathcal{O}(\alpha_t \alpha_s)$ Corrections: genuine 2-loop diagrams

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Here: all integrals reducable to **1-loop vacuum function**

$$A_0(m_1^2) = C \int \mathrm{d}^d l_1 \frac{1}{l_1^2 - m_1^2}$$

und **2-loop vacuum function** [Davydchev, Tausk (1993)]

$$K_0(m_1^2, m_2^2, m_3^2) = C^2 \int \mathrm{d}^d l_1 \mathrm{d}^d l_2 \frac{1}{(l_1^2 - m_1^2)(l_2^2 - m_2^2)((l_1 - l_2)^2 - m_3^2)}$$

A_0 and K_0 analytically known and expandable in a series in ϵ

$\Rightarrow$ UV divergencies of the 2-loop integrals appear as:

- simple poles $\propto \frac{1}{\epsilon}$
- double poles $\propto \frac{1}{\epsilon^2}$

Die $\mathcal{O}(\alpha_t\alpha_s)$-Korrekturen: Renormierung des Stop-Top-Sektors

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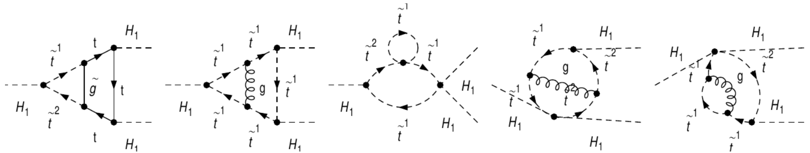

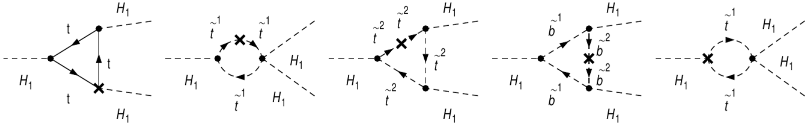

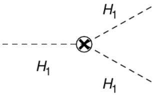

The $\mathcal{O}(\alpha_t\alpha_s)$ Corrections: Renormalization of the stop-top sector

- **Top sector:**
  1 parameter: $m_t \rightarrow m_t + \delta m_t$
- **Stop sector:**
  3 parameters: $m_{\tilde{t}_1} \rightarrow m_{\tilde{t}_1} + \delta m_{\tilde{t}_1}$, $m_{\tilde{t}_2} \rightarrow m_{\tilde{t}_2} + \delta m_{\tilde{t}_2}$, $A_t \rightarrow A_t + \delta A_t$

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Different renormalization schemes possible:

- On-Shell scheme (OS):
- $\overline{\text{DR}}$-Schema:

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Different renormalization schemes possible:

- On-Shell scheme (OS):
  δm_t, $\delta m_{\tilde{t}_1}$ $\delta m_{\tilde{t}_2}$: fixed via propagator pole condition
  δA_t: fixed via unmixing condition for on-shell stops
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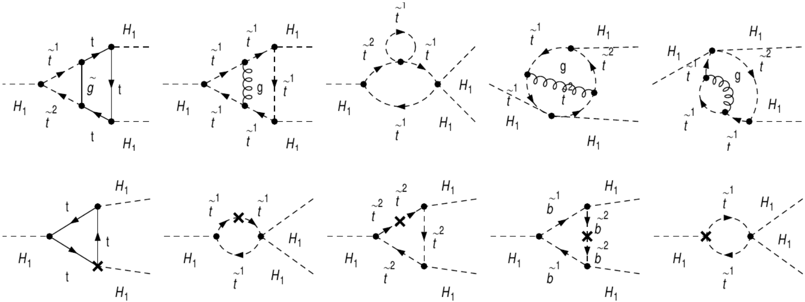
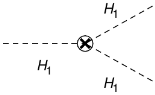
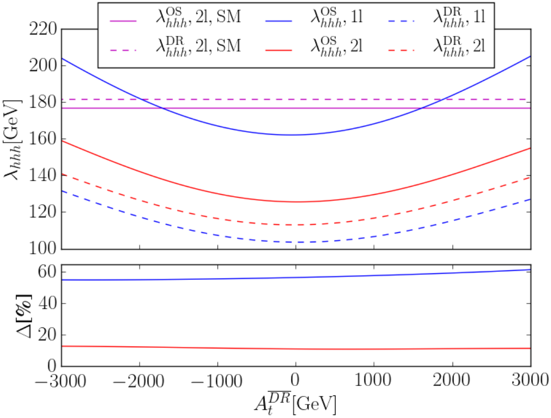
- $\overline{\text{DR}}$-Schema:
  δm_t, $\delta m_{\tilde{t}_1}$ $\delta m_{\tilde{t}_2}$, δA_t: contain only divergent terms

The $\mathcal{O}(\alpha_t \alpha_s)$ Corrections: Renormierung des Higgs sectors





Results



Mühlleitner, Dao, HZ arXiv:1506.0332

Size of corrections:

$$\frac{|\lambda^{(n)}_{hhh} - \lambda^{(n-1)}_{hhh}|}{\lambda^{(n-1)}_{hhh}}$$

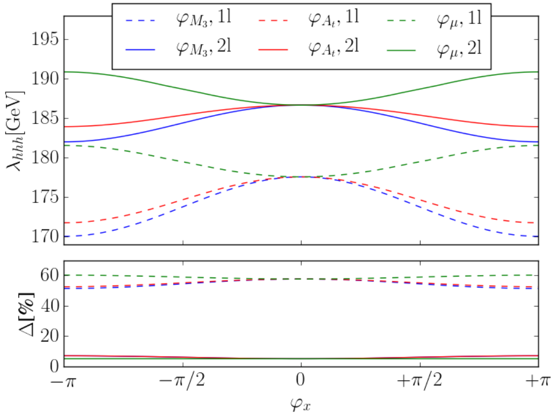
1-loop: 140% (OS), 24% ($\overline{DR}$)
2-loop: 74% (OS), 9% ($\overline{DR}$)

Estimation of theoretical uncertainty:

$$\Delta^{(n)} = \frac{|\lambda^{\overline{DR},(n)}_{hhh} - \lambda^{OS,(n)}_{hhh}|}{\lambda^{\overline{DR},(n)}_{hhh}}$$

1-loop: $\Delta^{(1)} \approx 60\%$
2-loop: $\Delta^{(2)} \approx 10\%$

Results



$\mu = \mu_{\text{eff}} = v_s\lambda$

Influence of the phases:

$$\delta^{\varphi} = \frac{|\lambda^{(2)}_{hhh}(\pi) - \lambda^{(2)}_{hhh}(0)|}{\lambda^{(2)}_{hhh}(0)}$$

$$\delta^{\varphi_{A_t}} = 1.6\%$$

$$\delta^{\varphi_{\mu}} = 2.2\%$$

$$\delta^{\varphi_{M_3}} = 2.7\%$$

Size of corrections:

$$\Delta^{(n)} = \frac{|\lambda^{(n)}_{hhh} - \lambda^{(n-1)}_{hhh}|}{\lambda^{(n-1)}_{hhh}}$$

1-loop: $\Delta^{(1)} \approx 50 - 60\%$
2-loop: $\Delta^{(2)} \approx 5 - 8\%$

Summary

- The $\mathcal{O}(\alpha_t, \alpha_s)$ corrections to the trilinear Higgs self-couplings in the complex NMSSM have been calculated.
- The renormalization of the stop-top sector in the OS- and the $\overline{DR}$ scheme allows an estimation of the theoretical uncertainty.
- The $\mathcal{O}(\alpha_t, \alpha_s)$ corrections reduce the theoretical uncertainty.

Summary

- The $\mathcal{O}(\alpha_t, \alpha_s)$ corrections to the trilinear Higgs self-couplings in the complex NMSSM have been calculated.
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Thank you for your interest!

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Scenario 1:

$$m_{\tilde{u}_R,\tilde{c}_R} = m_{\tilde{d}_R,\tilde{s}_R} = m_{\tilde{Q}_{1,2}} = m_{\tilde{L}_{1,2}} = m_{\tilde{e}_R,\tilde{\mu}_R} = 3\,\text{TeV}\,,\;\; m_{\tilde{t}_R} = 1909\,\text{GeV}\,,$$
$$m_{\tilde{Q}_3} = 2764\,\text{GeV}\,,\;\; m_{\tilde{b}_R} = 1108\,\text{GeV}\,,\;\; m_{\tilde{L}_3} = 472\,\text{GeV}\,,\;\; m_{\tilde{\tau}_R} = 1855\,\text{GeV}\,,$$
$$|A_{u,c,t}| = 1283\,\text{GeV}\,,\;\; |A_{d,s,b}| = 1020\,\text{GeV}\,,\;\; |A_{e,\mu,\tau}| = 751\,\text{GeV}\,,$$
$$|M_1| = 908\,\text{GeV},\;\; |M_2| = 237\,\text{GeV}\,,\;\; |M_3| = 1966\,\text{GeV}\,,$$
$$\varphi_{A_{d,s,b}} = \varphi_{A_{e,\mu,\tau}} = \varphi_{A_{u,c,t}} = \pi\,,\;\; \varphi_{M_1} = \varphi_{M_2} = \varphi_{M_3} = 0$$

$$|\lambda| = 0.374\,,\quad |\kappa| = 0.162\,,\quad |A_\kappa| = 178\,\text{GeV}\,,\quad |\mu_{\text{eff}}| = 184\,\text{GeV}\,,$$
$$\varphi_\lambda = \varphi_\kappa = \varphi_{\mu_{\text{eff}}} = \varphi_u = 0\,,\quad \varphi_{A_\kappa} = \pi\,,\quad \tan\beta = 7.52\,,\quad M_{H^\pm} = 1491\,\text{GeV}\,.$$

Scenario 2:

$$m_{\tilde{u}_R,\tilde{c}_R} = m_{\tilde{d}_R,\tilde{s}_R} = m_{\tilde{Q}_{1,2}} = m_{\tilde{L}_{1,2}} = m_{\tilde{e}_R,\tilde{\mu}_R} = 3\text{ TeV}\,,\;\; m_{\tilde{t}_R} = 1170\,\text{GeV}\,,$$
$$m_{\tilde{Q}_3} = 1336\,\text{GeV}\,,\;\; m_{\tilde{b}_R} = 1029\,\text{GeV}\,,\;\; m_{\tilde{L}_3} = 2465\,\text{GeV}\,,\;\; m_{\tilde{\tau}_R} = 301\,\text{GeV}$$
$$|A_{u,c,t}| = 1824\,\text{GeV}\,,\;\; |A_{d,s,b}| = 1539\,\text{GeV}\,,\;\; |A_{e,\mu,\tau}| = 1503\,\text{GeV}\,,$$
$$|M_1| = 862.4\,\text{GeV},\;\; |M_2| = 201.5\,\text{GeV}\,,\;\; |M_3| = 2285\,\text{GeV}$$
$$\varphi_{A_{d,s,b}} = \varphi_{A_{e,\mu,\tau}} = \pi\,,\;\; \varphi_{A_{u,c,t}} = \varphi_{M_1} = \varphi_{M_2} = \varphi_{M_3} = 0$$

$$|\lambda| = 0.629\,,\quad |\kappa| = 0.208\,,\quad |A_\kappa| = 179.7\,\text{GeV}\,,\quad |\mu_{\text{eff}}| = 173.7\,\text{GeV}\,,$$
$$\varphi_\lambda = \varphi_{\mu_{\text{eff}}} = \varphi_u = 0\,,\quad \varphi_\kappa = \pi\,,\quad \tan\beta = 4.02\,,\quad M_{H^\pm} = 788\,\text{GeV}\,.$$

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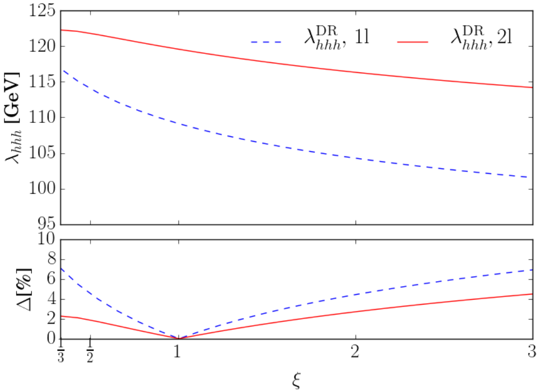
Scenario 3:

$$m_{\tilde{u}_R,\tilde{c}_R} = m_{\tilde{d}_R,\tilde{s}_R} = m_{\tilde{Q}_{1,2}} = m_{\tilde{L}_{1,2}} = m_{\tilde{e}_R,\tilde{\mu}_R} = 3\,\text{TeV}\,,\ m_{\tilde{t}_R} = 1940\,\text{GeV}\,,$$
$$m_{\tilde{Q}_3} = 2480\,\text{GeV}\,,\ m_{\tilde{b}_R} = 1979\,\text{GeV}\,,\ m_{\tilde{L}_3} = 2667\,\text{GeV}\,,\ m_{\tilde{\tau}_R} = 1689\,\text{GeV}\,,$$
$$|A_{u,c,t}| = 1192\,\text{GeV}\,,\ |A_{d,s,b}| = 685\,\text{GeV}\,,\ |A_{e,\mu,\tau}| = 778\,\text{GeV}\,,$$
$$|M_1| = 517\,\text{GeV},\ |M_2| = 239\,\text{GeV}\,,\ |M_3| = 1544\,\text{GeV}\,,$$
$$\varphi_{A_{d,s,b}} = \varphi_{A_{e,\mu,\tau}} = 0\,,\ \varphi_{A_{u,c,t}} = \pi\,,\ \varphi_{M_1} = \varphi_{M_2} = \varphi_{M_3} = 0$$

$$|\lambda| = 0.267\,, \quad |\kappa| = 0.539\,, \quad |A_\kappa| = 810\,\text{GeV}\,, \quad |\mu_{\text{eff}}| = 104\,\text{GeV}\,,$$
$$\varphi_\lambda = \varphi_\kappa = \varphi_{\mu_{\text{eff}}} = \varphi_u = 0\,, \quad \varphi_{A_\kappa} = \pi\,, \quad \tan\beta = 8.97\,, \quad M_{H^\pm} = 613\,\text{GeV}$$

Results



theoretische Unsicherheit:
Variation der Renormierungs -Skala μ_r um zentrale Skala $\mu_0 = M_{SUSY} = \sqrt{m_{\tilde{Q}_3} m_{\tilde{t}_R}}$

$$\xi = \frac{\mu_r}{\mu_0}$$

$$\Delta^{(n)} = \frac{\lambda_{hhh}^{(n)}(\mu_r) - \lambda_{hhh}^{(n)}(\mu_0)}{\lambda_{hhh}^{(n)}(\mu_0)}$$

1-loop: $\Delta^{(1)} = 7\%$

2-loop: $\Delta^{(2)} = 2 - 5\%$

Näherungsformel für Skalenvariation über Relation:

$$p^{\mathrm{OS}} = p^{\overline{\mathrm{DR}}}(\mu_1) - \delta p^{\mathrm{fin}}(\mu_1) = p^{\overline{\mathrm{DR}}}(\mu_2) - \delta p^{\mathrm{fin}}(\mu_2)$$

$$\Rightarrow p^{\overline{\mathrm{DR}}}(\mu_2) = p^{\overline{\mathrm{DR}}}(\mu_1) - \delta p^{\mathrm{fin}}(\mu_1) + \delta p^{\mathrm{fin}}(\mu_2)$$

Skalenvariation auf 1-Schleifen Niveau

Zusammenhang zwischen Parametern in unterschiedlichen Schemata:

$$p^0(Q_1) = p^{\text{OS}} + \delta p^{\text{OS}}(Q_1) = p^{\overline{\text{DR}}}(Q_1) + \delta p^{\overline{\text{DR}}}$$

$$p^{\text{OS}} = p^{\overline{\text{DR}}}(Q_1) + \underbrace{\delta p^{\overline{\text{DR}}} - \delta p^{\text{OS}}(Q_1)}_{-\delta p^{\text{fin}}(Q_1)} = p^{\overline{\text{DR}}}(Q_2) + \underbrace{\delta p^{\overline{\text{DR}}} - \delta p^{\text{OS}}(Q_2)}_{-\delta p^{\text{fin}}(Q_2)}$$

$$\Rightarrow p^{\overline{\text{DR}}}(Q_2) = p^{\overline{\text{DR}}}(Q_1) - \delta p^{\text{fin}}(Q_1) + \delta p^{\text{fin}}(Q_2)$$

Skalenvariation auf 1-Schleifen Niveau

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Auf 1-Schleifen-Niveau besteht $\delta p^{\text{fin}}(Q)$ aus A_0- und B_0-Funktionen:

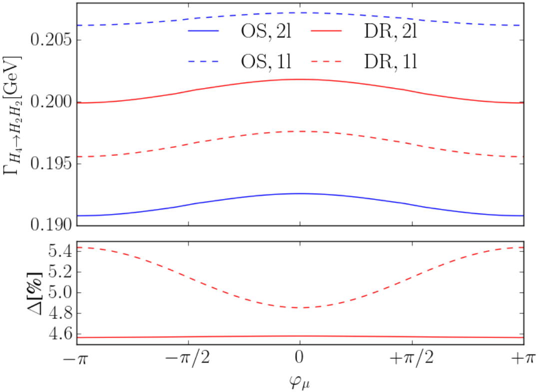
$$A_0(m_0^2) = m_0^2(\Delta - \ln\left(\frac{m_0^2}{Q^2}\right) + \underbrace{1}_{\text{konstanter Beitrag}}) + \mathcal{O}(\epsilon)$$

$$B_0(p_1^2, m_0^2, m_1^2) = \Delta + \ln\left(\frac{Q^2}{m_0^2}\right) + \underbrace{2 + f_B(x_+) + f_B(x_-)}_{\text{konstanter Beitrag}} + \mathcal{O}(\epsilon)$$

konstanter Term fällt bei Differenzbildung heraus
Koeffizient c vor Skalenabhängigem Anteil gleich dem Koeffizient vor der Divergenz Δ:

$$\Rightarrow p^{\overline{\text{DR}}}(Q_2) = p^{\overline{\text{DR}}}(Q_1) + c\ln\left(\frac{Q_2^2}{Q_1^2}\right)$$

Results



trilinear Higgs couplings relevant in Higgs-to-Higgs-decays

Size of corrections:

1-loop: 21% (OS), 6,5% ($\overline{DR}$)
2-loop: 7% (OS), 2% ($\overline{DR}$)

Estimation of theoretical uncertainty:

$$\Delta^{(n)} = \frac{|\lambda_{hhh}^{\overline{DR},(n)} - \lambda_{hhh}^{OS,(n)}|}{\lambda_{hhh}^{\overline{DR},(n)}}$$

Mühlleitner, Dao, HZ arXiv:1506.0332

$$\Gamma(H_i \to H_j H_k) = \frac{\lambda^{1/2}(M_{H_i}^2, M_{H_j}^2, M_{H_k}^2)}{16\pi f\, M_{H_i}^3} |\mathcal{M}_{H_i\to H_jH_k}|^2$$

$$\mathcal{M}_{H_i\to H_jH_k} = \sum_{i',j',k'=1}^{5} \mathbf{Z}_{ii'}\mathbf{Z}_{jj'}\mathbf{Z}_{kk'}\Gamma_{h_{i'}h_{j'}h_{k'}} + \delta M^{mix}_{H_i\to H_jH_k}$$