Electroweak precision calculations in Two Higgs doublet models at the two-loop order

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based on arXiv:1607.04610 (S.H., Wolfgang Hollik)

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Introduction

Electroweak precision observables:

Experiment		Theory
precise measurement of observables	Comparison restricts ⟷ model parameters	higher-order calculation of observables

- powerfull tool to constrain new physic
- examples: M_W, $\sin^2\theta_{\text{eff}} \Rightarrow$ complete two-loop calculation in the SM
- Universal corrections:

$\Sigma_{W,Z}$: self-energies

$$\Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2}$$

$$\Delta M_W \simeq \frac{M_W}{2}\frac{c_W^2}{c_W^2 - s_W^2}\Delta\rho, \quad \Delta\sin^2\theta_{\text{eff}} \simeq -\frac{c_W^2 s_W^2}{c_W^2 - s_W^2}\Delta\rho$$

SM: large corrections from the top quark

THDM: non-standard corrections also from extended Higgs sector

Precision Calculations in THDM:

- S. Bertolini; Nucl. Phys. **B272**, 77 (1986). ⇒ One-loop calculation
- W. Hollik; Z. Phys. **C32**, 291 (1986); Z. Phys. **C37**, 569 (1988)
  ⇒ One-loop calculation
- A. Denner, R. J. Guth, W. Hollik, J. H. Kühn; Z. Phys. **C51**, 695 (1991).
  ⇒ One-loop calculation
- C. D. Froggatt, R. G. Moorhouse, I. G. Knowles; Phys. Rev. **D45**, 2471 (1992).
  ⇒ One-loop calculation
- P. H. Chankowski, M. Krawczyk, J. Zochowski; Eur. Phys. J. **C11**, 661 (1999), arXiv:hep-ph/9905436. ⇒ One-loop calculation
- W. Grimus, L. Lavoura, O. M. Ogreid, P. Osland; J. Phys. **G35**, 075001 (2008), arXiv:0711.4022. ⇒ One-loop calculation
- D. Lopez-Val and J. Sola; Eur. Phys. J. **C73**, 2393 (2013), arXiv:1211.0311. ⇒ Approximation of higher order terms by effective couplings

⇒ no systematic two-loop calculation of non-standard corrections

⇒ **calculation of dominant two-loop corrections to $\Delta\rho$:**

- **top-Yukawa interaction**
- **Higgs-self-interaction**

Two Higgs doublet model

CP conserving potential ($\lambda_i \in \mathbb{R}$)

$$\begin{aligned}
V(\Phi_1, \Phi_2) =& \lambda_1 \left(\Phi_1^\dagger \Phi_1 - \frac{v_1^2}{2}\right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2 - \frac{v_2^2}{2}\right)^2 \\
&+ \lambda_3 \left[\left(\Phi_1^\dagger \Phi_1 - \frac{v_1^2}{2}\right) + \left(\Phi_2^\dagger \Phi_2 - \frac{v_2^2}{2}\right)\right]^2 \\
&+ \lambda_4 \left[\left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) - \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)\right] \\
&+ \lambda_5 \left[\mathrm{Re}\left(\Phi_1^\dagger \Phi_2\right) - \frac{v_1 v_2}{2}\right]^2 + \lambda_6 \left[\mathrm{Im}\left(\Phi_1^\dagger \Phi_2\right)\right]^2
\end{aligned}$$

- mass eigenstates:
  - h^0, H^0 (CP-even); A^0 (CP-odd); $H^\pm$
- 7 free parameters:
  - m_{h^0}, m_{H^0}, m_{A^0}, $m_{H^\pm}$, $t_\beta = \frac{v_2}{v_1}$, CP-even mixing angle α, λ_5
- Yukawa couplings restricted by abscence of FCNCs:
  - type I, type II, type X, type Y, ...

Non-standard two-loop corrections to $\Delta\rho$

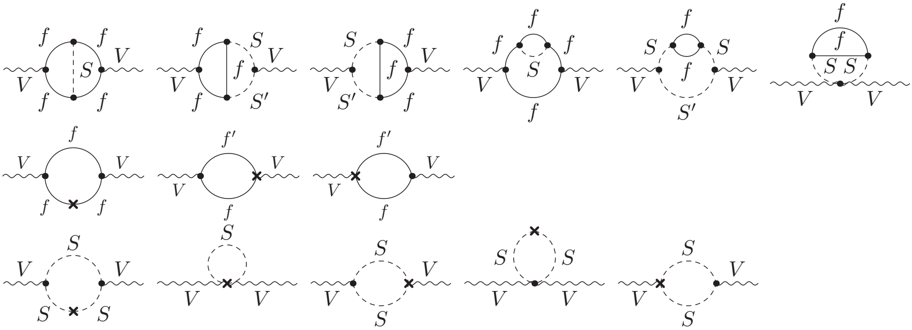
- corrections calculated with support of the Mathematica programs
  - `FeynArts` [T. Hahn; hep-ph/0012260]
  - `FormCalc` [T. Hahn et al.; hep-ph/9807565]
  - `TwoCalc` [G. Weiglein et al.; hep-ph/9310358]

Assumptions:

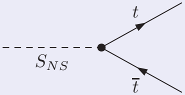
- one of the CP-even Higgs states can be identified with the resonance found at the LHC $\Rightarrow m_{h^0} = 125$ GeV
- couplings of h^0 should be SM-like $\Rightarrow \alpha = \beta - \frac{\pi}{2}$
- Gaugeless limit: neglect electroweak gauge couplings $g_{1,2}$
  $\Rightarrow\ M_W^2 \to 0, \quad M_Z^2 \to 0$, but $c_W = \frac{M_W}{M_Z} =$ const
- Top-Yukawa approximation $\Rightarrow m_f = 0, \quad f \neq t$

$\Rightarrow$**Two-loop corrections from**
- **scalar self interaction** $\Rightarrow \delta\rho_{\mathrm{H}}^{(2)}$
- **top-Yukawa interaction** $\Rightarrow \delta\rho_{\mathrm{t,NS}}^{(2)}$

Top-Yukawa contribution



Top Yukawa coupling



$\propto \dfrac{m_t}{v t_\beta}$

$(S_{NS} = H^0, A^0, H^\pm)$

Subloop renormalization:

- top mass counterterm δm_t
- scalar mass counterterms $\delta m_S^2, \quad (S = H^0, A^0, H^\pm)$

$\Rightarrow$ top-Yukawa corrections

$\Rightarrow$ calculated in the on-shell scheme

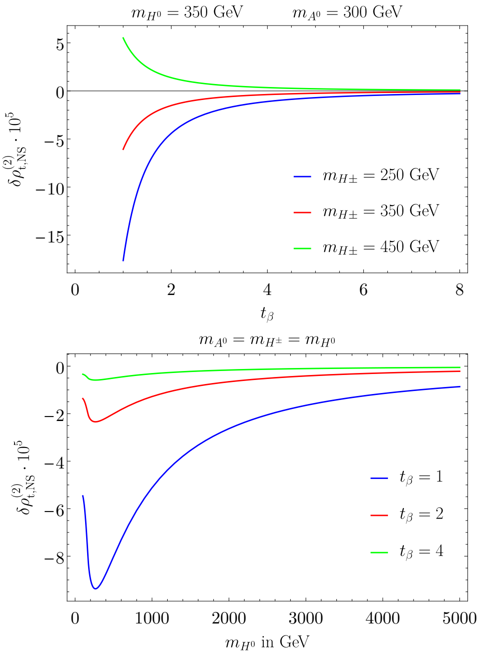
- $\delta\rho^{(2)}_{\mathrm{t,NS}}$: non-standard two-loop contribution involving the top-Yukawa coupling

$\Rightarrow$ proportional to t_β^{-2} and m_t^4

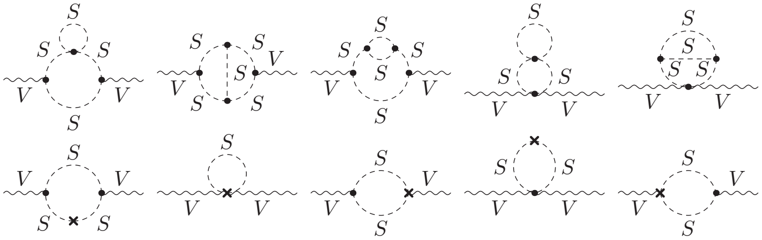
- degenerate Higgs states ($m_{H^0} = m_{A^0} = m_{H^+}$):

$$\delta\rho^{(2)}_{\mathrm{t,NS}} \to 0$$

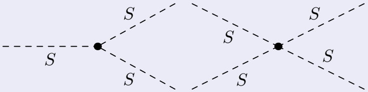
for large Higgs masses



Contribution from scalar self interaction



scalar self couplings



$\Rightarrow$ contain t_β and λ_5

$S = h^0, G^0, G^\pm, H^0, A^0, H^\pm$

Subloop renormalization:

- scalar mass counterterms
  $\delta m_S^2, \quad (S = H^0, A^0, H^\pm)$

$\Rightarrow$ corrections from scalar self interaction

$\Rightarrow$ calculated in the on-shell scheme

- $\Delta\rho_{\rm NS}^{(1)}$: non-standard one-loop correction

$\Rightarrow$ sensitive to mass differences

- $\delta\rho_{\rm H}^{(2)}$: two-loop corrections from scalar self interaction

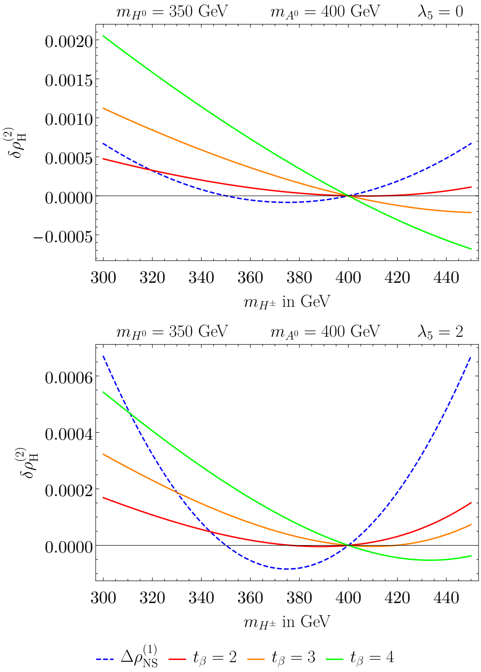
$\Rightarrow$ strong influence of t_β and λ_5 (new effects at two-loop level)

- effect of $\Delta\rho \simeq 10^{-4}$

$$\Rightarrow \Delta M_W \simeq 6 \text{ MeV}$$

exp. uncertainty:

$$\Delta M_W^{\rm exp} = 15 \text{ MeV}$$



Summary

- precision observables yield important constraints on BSM physic
- $\Delta\rho$: important ingredient for precision observables
- non-standard corrections in the THDM:
  - one-loop contribution: sensitive to large mass differences
  - two-loop effects from top-Yukawa and Higgs-self-interaction:
    - $\Rightarrow$ can be larger than the one-loop result
    - $\Rightarrow$ new sensitivity on additional parameters (t_β, λ_5)
- influence on electroweak precision observables

$$\Delta M_W \simeq \frac{M_W}{2} \frac{c_W^2}{c_W^2 - s_W^2} \Delta\rho, \quad \Delta \sin^2\theta_{\text{eff}} \simeq -\frac{c_W^2 s_W^2}{c_W^2 - s_W^2} \Delta\rho$$