4TH International Workshop on "the Higgs as a Probe of New Physics" – HPNP 2019

Two-loop corrections to the Higgs trilinear coupling in a Two-Higgs-Doublet Model

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Structure of the scalar sector

SM established as (an EFT) at least until the electroweak scale, but...

- Shape of the Higgs potential is still **unknown!** → only v and m_h are known currently
- No particular reason for the Higgs sector to be minimal, and many BSM models **predict additional scalars**
- One observable that can help find evidence for BSM is λ_{hhh} → can deviate from SM because of **mixing effects** (tree-level) or of **radiative corrections**

Accessing the Higgs trilinear coupling λ_{hhh}

- Accuracy of measurement at colliders
  - HL-LHC 14 TeV (3 ab^{-1}) → $\mathcal{O}(100\%)$ or more
  - ILC 250+500 GeV (full data set) → 27%; 1 TeV (5000 fb^{-1}) → 10%
  - FCC-100 TeV (30ab^{-1}) → ∼ 7%

  (see *e.g.* [Di Vita et al. 1711.03978], [Fujii et al. '15,'17], [Chang et al. '18], etc.)
- Relation to cosmology
  - Shape of potential, and λ_{hhh}, determine whether electroweak phase transition (EWPT) can be strongly 1st order or not → possibility of EW baryogenesis!
  - Value of λ_{hhh} may be probed by spectrum of gravitational waves produced during EWBG

Two-Higgs-Doublet Model (2HDM)

- Scalar potential of the CP-conserving 2HDM, with softly broken $\mathbb{Z}_2$ symmetry

$$V^{(0)} = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_2^\dagger\Phi_1 + \Phi_1^\dagger\Phi_2) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \frac{\lambda_5}{2}\big((\Phi_2^\dagger\Phi_1)^2 + (\Phi_1^\dagger\Phi_2)^2\big) \qquad (m_i^2, \lambda_i \in \mathbb{R})$$

- Expand Higgs doublets as

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \phi_i^0/\sqrt{2}\end{pmatrix} \quad \text{where} \quad \begin{pmatrix}\phi_1^+\\ \phi_2^+\end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta\end{pmatrix}\begin{pmatrix} G^+ \\ H^+\end{pmatrix}, \quad \begin{pmatrix}\phi_1^0\\ \phi_2^0\end{pmatrix} = v\begin{pmatrix}c_\beta\\ s_\beta\end{pmatrix} + \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha\end{pmatrix}\begin{pmatrix} H \\ h\end{pmatrix} + i\begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta\end{pmatrix}\begin{pmatrix} G \\ A\end{pmatrix}, \quad \text{and} \quad \tan\beta \equiv \frac{\langle\phi_2^0\rangle}{\langle\phi_1^0\rangle}$$

- Lagrangian mass parameters m_1^2, m_2^2 eliminated via tadpole equations (at each order in perturbation theory), and m_3^2 replaced by $M^2 \equiv 2m_3^2/\sin 2\beta$ (*soft breaking scale*).
- Relate quartic couplings λ_i to mass parameters m_h, m_H, m_A, $m_{H^\pm}$ and CP-even mixing angle α at **tree-level** as

$$\lambda_1 = \frac{-s_\beta^2M^2 + s_\alpha^2m_h^2 + c_\alpha^2m_H^2}{v^2c_\beta^2}, \quad \lambda_2 = \frac{-c_\beta^2M^2 + c_\alpha^2m_h^2 + s_\alpha^2m_H^2}{v^2s_\beta^2}, \quad \lambda_3 = \frac{1}{v^2}\left[-M^2 + 2m_{H^\pm}^2 + \frac{s_{2\alpha}}{s_{2\beta}}(m_H^2 - m_h^2)\right], \quad \lambda_4 = \frac{M^2 + m_A^2 - 2m_{H^\pm}^2}{v^2}, \quad \lambda_5 = \frac{M^2 - m_A^2}{v^2}.$$

- Additional (heavy) scalar masses can be written as $m_\Phi^2 = M^2 + \tilde\lambda_\Phi v^2$, where $\tilde\lambda_\Phi$ is some combination of the quartic couplings λ_i.

Existing one-loop (and two-loop) works

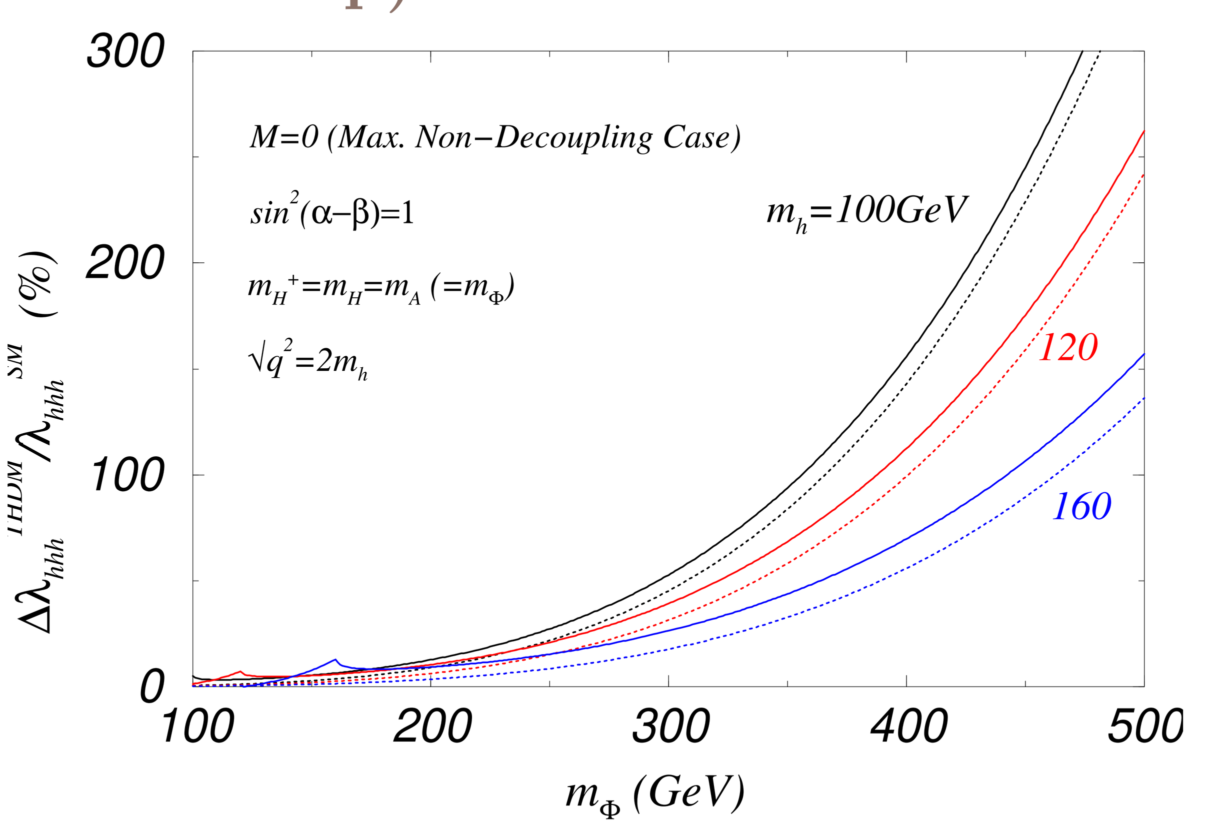
One loop

- radiative corrections to λ_{hhh} in 2HDM first studied in [Kanemura, Kiyoura, Okada, Senaha, Yuan '02] and [Kanemura, Okada, Senaha, Yuan '04]
- leading one-loop contributions (with $n_{H,A} = 1$, $n_{H^\pm} = 2$)

$$\delta^{(1)}\lambda_{hhh} = \underbrace{-\frac{48m_t^4}{v^3}}_{\text{SM-like}} + \underbrace{\sum_{\Phi=H,A,H^\pm}\frac{4n_\Phi m_\Phi^4}{v^3}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3}_{\text{BSM}}$$

→ for M small and m_Φ large, the BSM corrections can become very large – $\mathcal{O}(100\%)$ – without spoiling perturbativity
⇒ **non-decoupling effects**
⇒ can make EWPT become strongly 1st order

- complete one-loop calculation available for 2HDMs, HSM, IDM in `H-COUP` [Kanemura, Kikuchi, Sakurai, Yagyu '17]



(figure taken from [Kanemura, Okada, Senaha, Yuan '04])

What happens to the non-decoupling effects at two loops?

Two loops

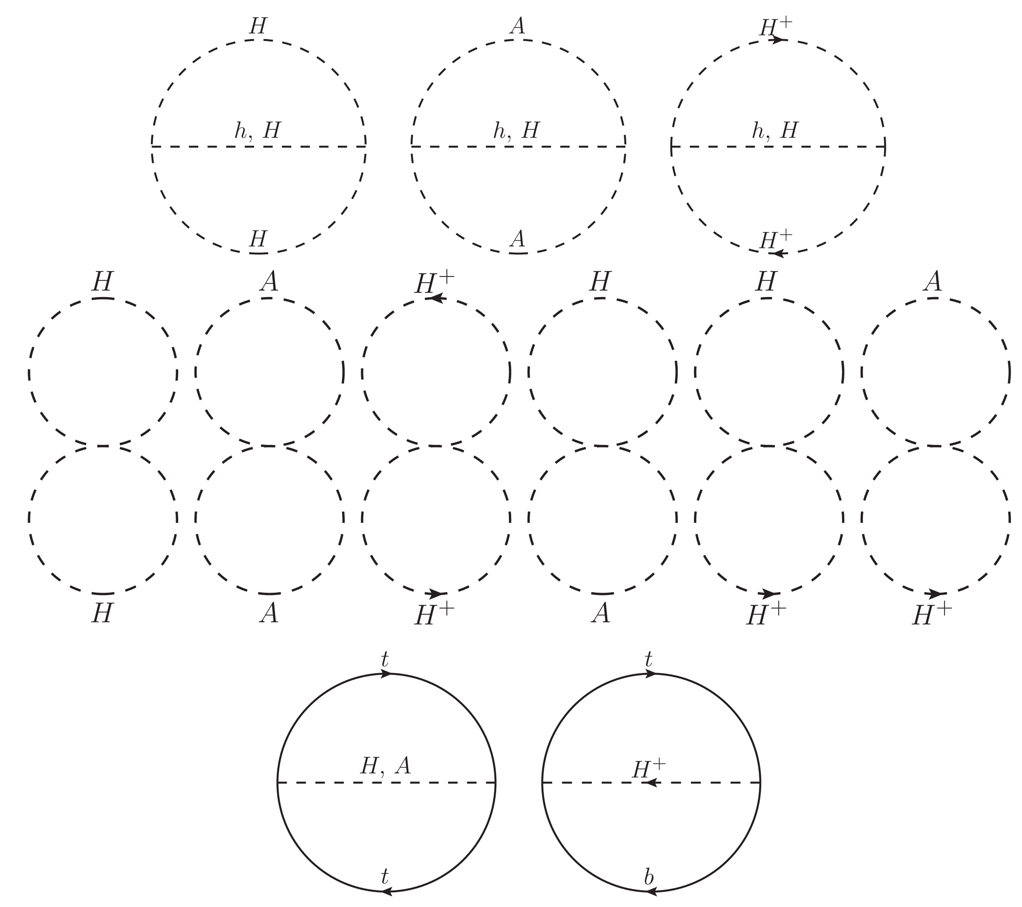
- leading scalar corrections calculated in the IDM [Senaha, 1811.00336]
  → two-loop effects found to be a few (∼ 2) %, and can weaken the strength of the first-order electroweak phase transition in the model
- leading $\mathcal{O}(\alpha_s\alpha_t)$ corrections in MSSM [Brucherseifer, Gavin, Spira '14] and NMSSM [Mühlleitner, Nhung, Ziesche '15]
  → two-loop effects can be up to $\mathcal{O}(10\%)$; significant reduction of scale dependence in $\overline{\text{DR}}'$ calculations

Our two-loop calculation: setup

- 2HDM with alignment, *i.e.* $\alpha = \beta - \pi/2$
  ⇒ no mixing between h, H
- Effective potential approximation

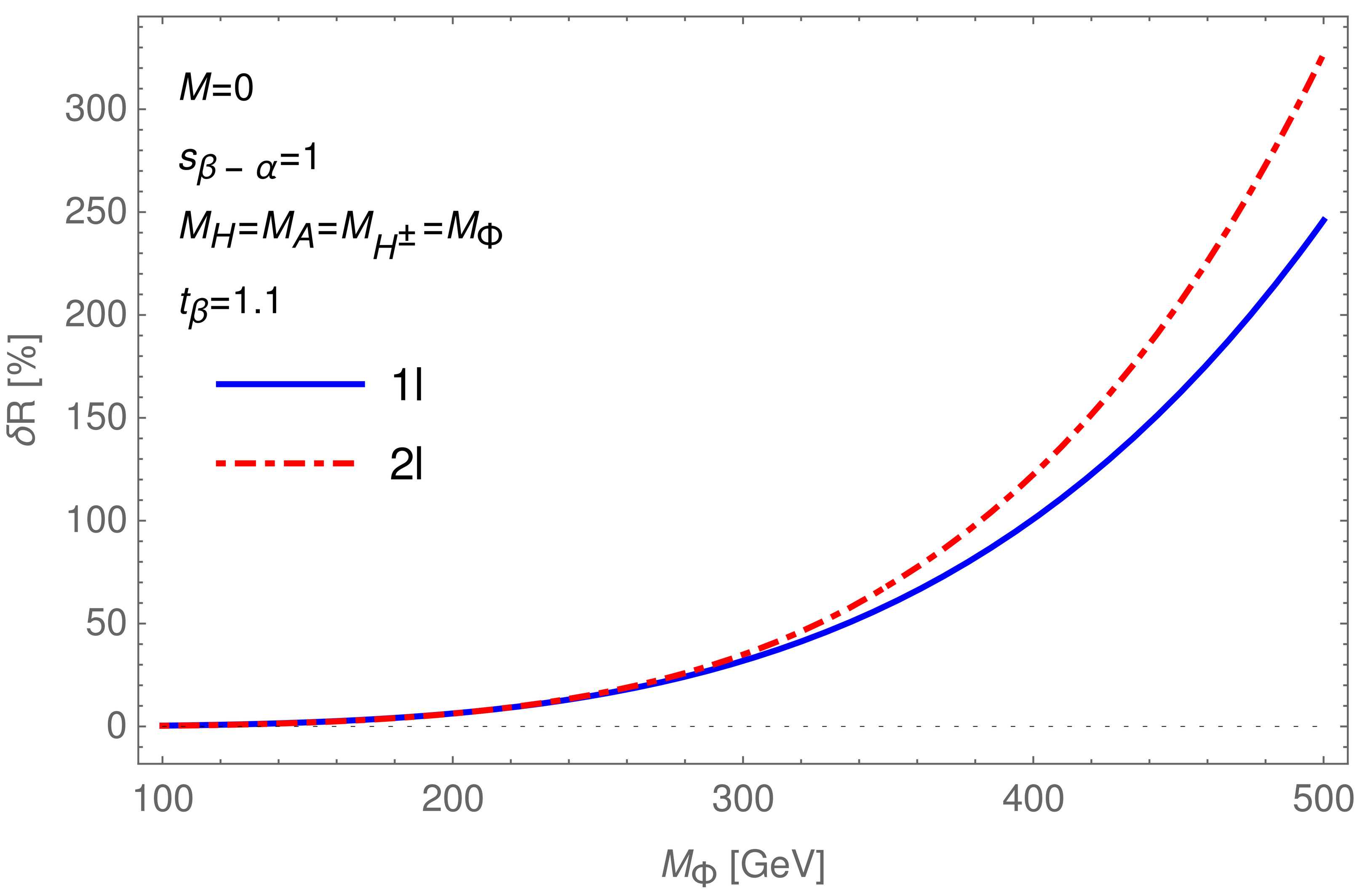
$$\delta^{(2)}\lambda_{hhh} = \left(\frac{\partial^3}{\partial h^3} - \frac{3}{v}\left[-\frac{1}{v}\frac{\partial}{\partial h} + \frac{\partial^2}{\partial h^2}\right]\right)V^{(2)}\Big|_{\text{min.}}$$

- Leading contributions from heavy scalars and top quark
- $\overline{\text{MS}}$ and on-shell scheme calculations

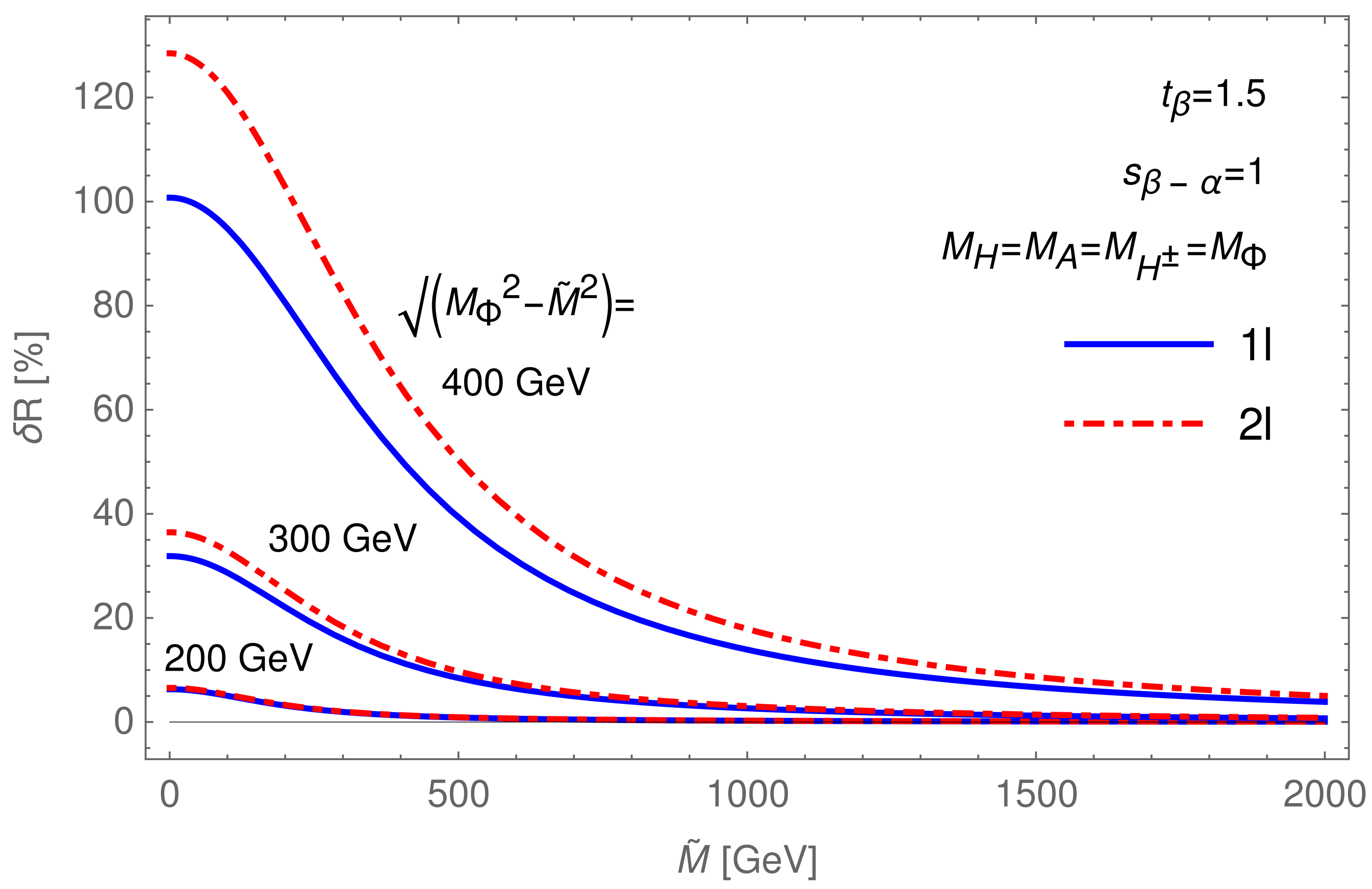


Our two-loop calculation: preliminary results

We show here some examples of results for $\delta R \equiv \Delta\lambda_{hhh}^{\text{2HDM}}/\lambda_{hhh}^{\text{SM}} = \lambda_{hhh}^{\text{2HDM}}/\lambda_{hhh}^{\text{SM}} - 1$ in the OS scheme:



Non-decoupling behaviour



Decoupling behaviour