Di-Higgs production in the RxSM at the HL-LHC including one loop corrections to the trilinear Higgs couplings in a SFOEWPT scenario

Johannes Braathen, Sven Heinemeyer and **Alain Verduras Schaeidt**

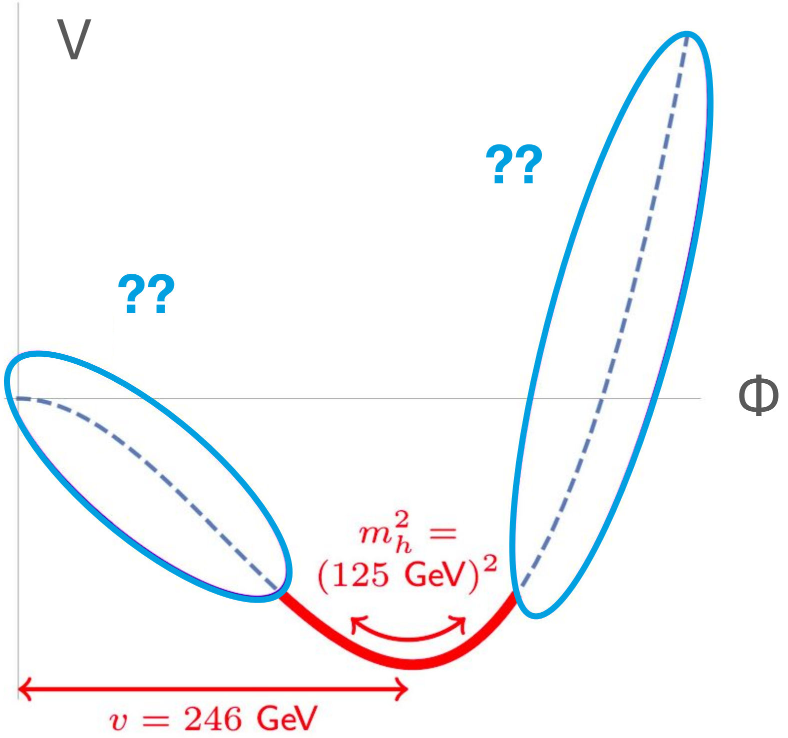
SUSY 2024 Conference

IFT, Madrid, 13-06-24

Motivation

- Why BSM models?
  - BAU, dark matter, neutrino masses…
- Why trilinear Higgs couplings?
  - Not measured: good portal for new physics
  - We don't know the shape of the Higgs potential
- Why SFOEWPT?
  - Explain BAU with EW baryogenesis

Di-Higgs production as a tool to probe trilinear Higgs couplings



Taken from J. Braathen

Real singlet extension of the SM (RxSM)

EW doublet: $\Phi = \begin{pmatrix} 0 \\ \frac{\phi+v}{\sqrt{2}} \end{pmatrix}$ Singlet: $S = s + v_S$

Potential:

$$V(\Phi,S) = \mu^2(\Phi^\dagger\Phi) + \frac{\lambda}{2}(\Phi^\dagger\Phi)^2 + \kappa_{SH}(\Phi^\dagger\Phi)S + \frac{\lambda_{SH}}{2}(\Phi^\dagger\Phi)S^2 + \frac{M_S}{2}S^2 + \frac{\kappa_S}{3}S^3 + \frac{\lambda_S}{2}S^4$$

Mass matrix:

$$\begin{pmatrix} \frac{d^2V}{d\phi^2} & \frac{d^2V}{d\phi ds} \\ \frac{d^2V}{d\phi ds} & \frac{d^2V}{ds^2} \end{pmatrix} = \begin{pmatrix} M_\phi^2 & M_{\phi s}^2 \\ M_{\phi s}^2 & M_s^2 \end{pmatrix}$$

Masses & mixing angle:

$$m_h^2 = M_\phi^2 \cos^2(\alpha) + M_s^2 \sin^2(\alpha) + M_{\phi s}^2 \sin(2\alpha)$$
$$m_H^2 = M_\phi^2 \sin^2(\alpha) + M_s^2 \cos^2(\alpha) - M_{\phi s}^2 \sin(2\alpha)$$
$$\tan(2\alpha) = \frac{2M_{\phi s}^2}{M_\phi^2 - M_s^2}.$$

RxSM: Tree level triple Higgs couplings

Parameters in scalar sector: $m_h^2, m_H^2, v, \alpha, v_S, \kappa_S, \kappa_{SH}, t_\phi, t_s$

$$\lambda_{hhh} = \frac{1}{8vv_S^2}(6v_S(-\kappa_{SH}v^2 + (2m_h^2 + m_H^2)v_S)c_\alpha + 3v_S(2\kappa_{SH}v^2 + 3m_h^2 v_S - m_H^2 v_S)c_{3\alpha} + 3(m_h^2 - m_H^2)v_S^2 c_{5\alpha} + 9\kappa_{SH}v^3 s_\alpha + 6vv_S(m_h^2 + 2m_H^2 - \kappa_S v_S)s_\alpha + v(-3\kappa_{SH}v^2 + v_S(3m_h^2 - 9m_H^2 + 2\kappa_S v_S))s_{3\alpha} + 3(m_H^2 - m_h^2)vv_S s_{5\alpha})$$

$$\lambda_{hhH} = \frac{s_\alpha}{8vv_S^2}(-v_S(2\kappa_{SH}v^2 + m_h^2 v_S + 5m_H^2 v_S) - 2v_S(3\kappa_{SH}v^2 + (m_h^2 + 2m_H^2)v_S)c_{2\alpha} + (m_H^2 - m_h^2)v_S^2 c_{4\alpha} + v(3\kappa_{SH}v^2 + 6m_h^2 - 2\kappa_S v_S^2)s_{2\alpha} + (m_h^2 - m_H^2)vv_S s_{4\alpha})$$

Renormalization scheme: “OS” scheme

- Masses: m_h^2, m_H^2 — Renormalization of two-point functions
- EW VEV: v — SM-like electroweak sector
- Singlet VEV: v_S — No divergences
- Mixing angle: α — Rotation matrix: [Kanemura, Kikuchi, Yagyu, ‘15]
- Tadpoles: $t_\phi,\, t_s$ — OS/Standard scheme
- Kappas: κ_S, κ_{SH} — ?

Renormalization scheme: κ_S, κ_{SH}

Renormalization conditions:

$$\hat{\lambda}^{(1)}_{hHH} \overset{!}{=} \lambda^{(0)}_{hHH} \qquad \hat{\lambda}^{(1)}_{HHH} \overset{!}{=} \lambda^{(0)}_{HHH}$$

$$\lambda^{(0)}_{hHH} + \delta\lambda^{(1)}_{hHH} + \delta\lambda^{m^2}_{hHH} + \delta\lambda^{v}_{hHH} + \delta\lambda^{tad}_{hHH} + \delta\lambda^{wfr}_{hHH} + \delta\kappa_S \frac{\partial\lambda^{(0)}_{hHH}}{\partial\kappa_S} + \delta\kappa_{SH} \frac{\partial\lambda^{(0)}_{hHH}}{\partial\kappa_S H} = \lambda^{(0)}_{hHH}$$

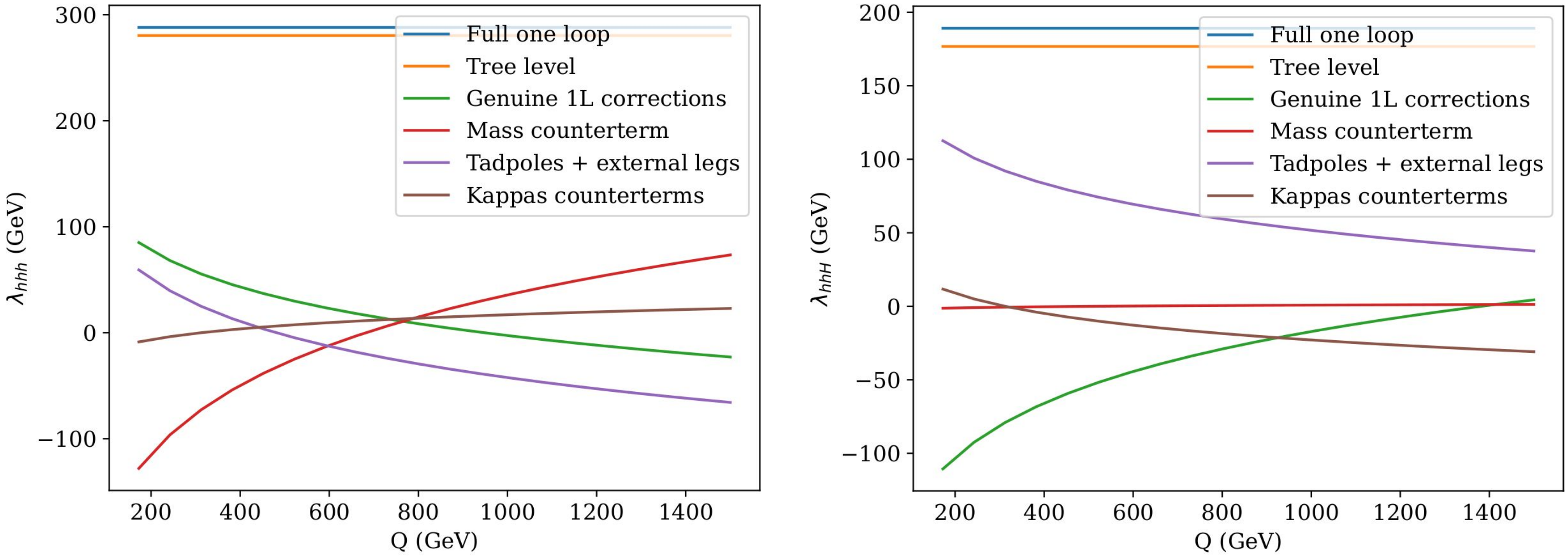
$$\lambda^{(0)}_{HHH} + \delta\lambda^{(1)}_{HHH} + \delta\lambda^{m^2}_{HHH} + \delta\lambda^{v}_{HHH} + \delta\lambda^{tad}_{HHH} + \delta\lambda^{wfr}_{HHH} + \delta\kappa_S \frac{\partial\lambda^{(0)}_{HHH}}{\partial\kappa_S} + \delta\kappa_{SH} \frac{\partial\lambda^{(0)}_{HHH}}{\partial\kappa_S H} = \lambda^{(0)}_{HHH}$$

Renormalization scheme: κ_S, κ_{SH}

$$\delta\kappa_S = \frac{\frac{\partial\lambda^{(0)}_{HHH}}{\partial\kappa_{SH}}\left(\lambda^{(1)}_{hHH} + \sum\delta\lambda^i_{hHH}\right) - \frac{\partial\lambda^{(0)}_{hHH}}{\partial\kappa_{SH}}\left(\lambda^{(1)}_{HHH} + \sum\delta\lambda^i_{HHH}\right)}{\frac{\partial\lambda^{(0)}_{hHH}}{\partial\kappa_{SH}}\frac{\partial\lambda^{(0)}_{HHH}}{\partial\kappa_S} - \frac{\partial\lambda^{(0)}_{hHH}}{\partial\kappa_S}\frac{\partial\lambda^{(0)}_{HHH}}{\partial\kappa_{SH}}}$$

$$\delta\kappa_{SH} = \frac{\frac{\partial\lambda^{(0)}_{hHH}}{\partial\kappa_S}\left(\lambda^{(1)}_{HHH} + \sum\delta\lambda^i_{HHH}\right) - \frac{\partial\lambda^{(0)}_{HHH}}{\partial\kappa_S}\left(\lambda^{(1)}_{hHH} + \sum\delta\lambda^i_{hHH}\right)}{\frac{\partial\lambda^{(0)}_{hHH}}{\partial\kappa_{SH}}\frac{\partial\lambda^{(0)}_{HHH}}{\partial\kappa_S} - \frac{\partial\lambda^{(0)}_{hHH}}{\partial\kappa_S}\frac{\partial\lambda^{(0)}_{HHH}}{\partial\kappa_{SH}}}$$

Renormalization scheme: Q dependence



Computed with anyH3 [Bahl, Braathen, Gabelmann, Weiglein, '23]

Loop correction set-up

Theoretical constraints → One-loop corrections → Experimental constraints → Cross section calculation

Potential stability

Coupling pertubativity
[Li, Ramsey-Musolf, Willocq, ‘19]

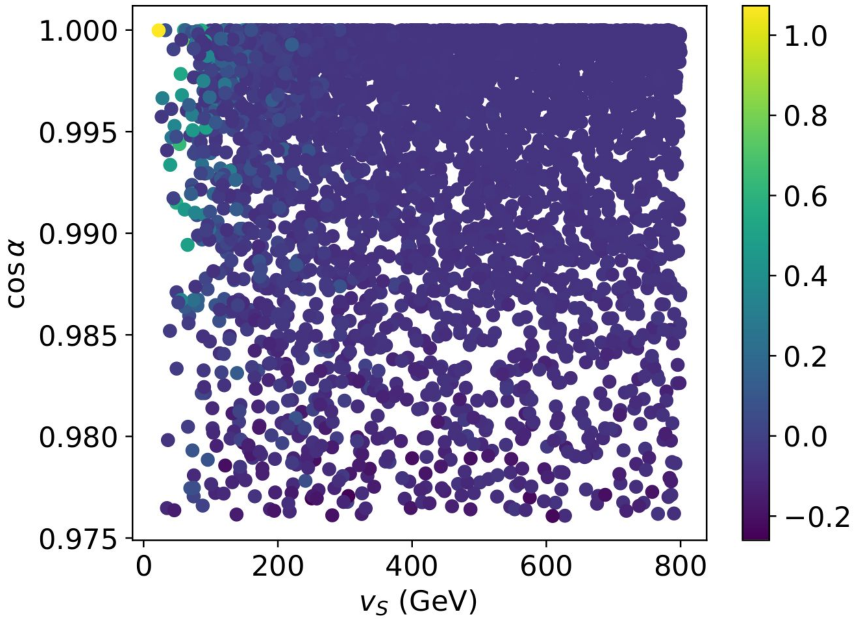
anyH3
[Bahl, Braathen, Gabelmann, Weiglein, ‘23]
anyBSM
[Bahl, Braathen, Gabelmann, Radchenko Weiglein, WIP]

HiggsTools
[Bahl et al., ‘22]
HiggsBounds
[Bechtle et al., ‘20]
HiggsSignals
[Bechtle et al., ‘21]

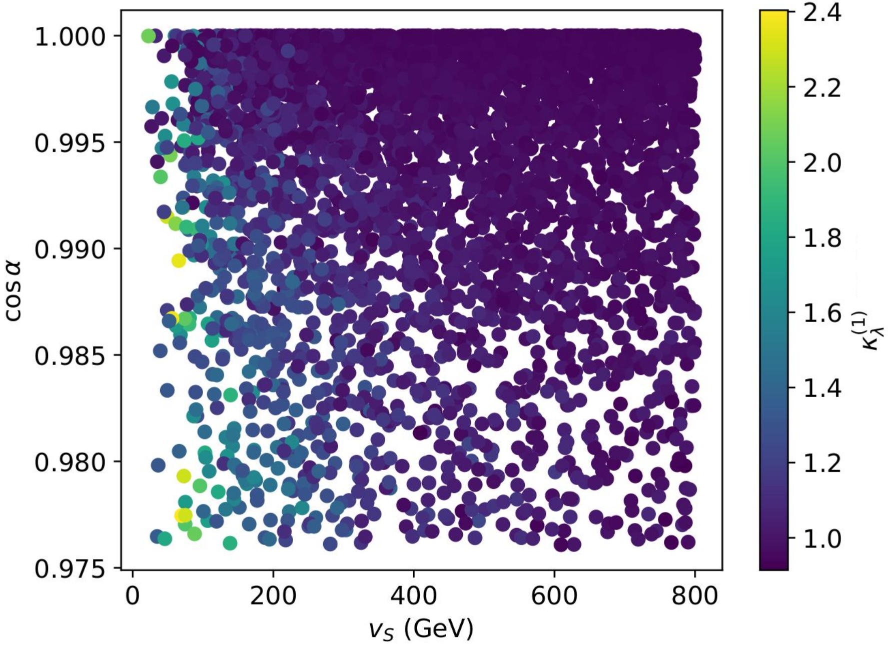
HPAIR
[T. Plehn, M. Spira, P.M. Zerwas, ‘96]
[S.Dawson, S.Dittmaier, M.Spira, ‘98]
[Abouabid et al., ‘22]

One loop corrections to κ_λ

Difference between one loop and tree level

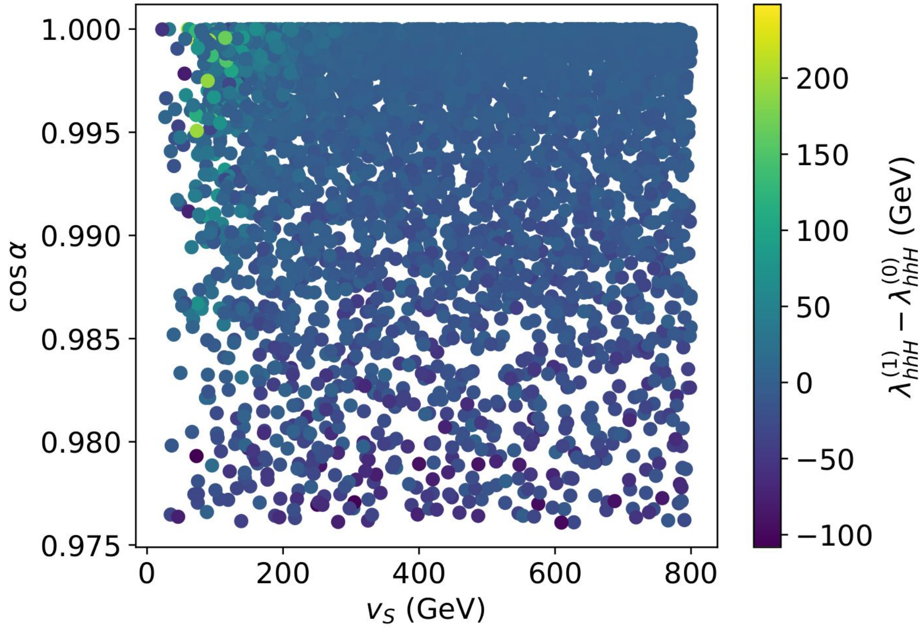


One loop value

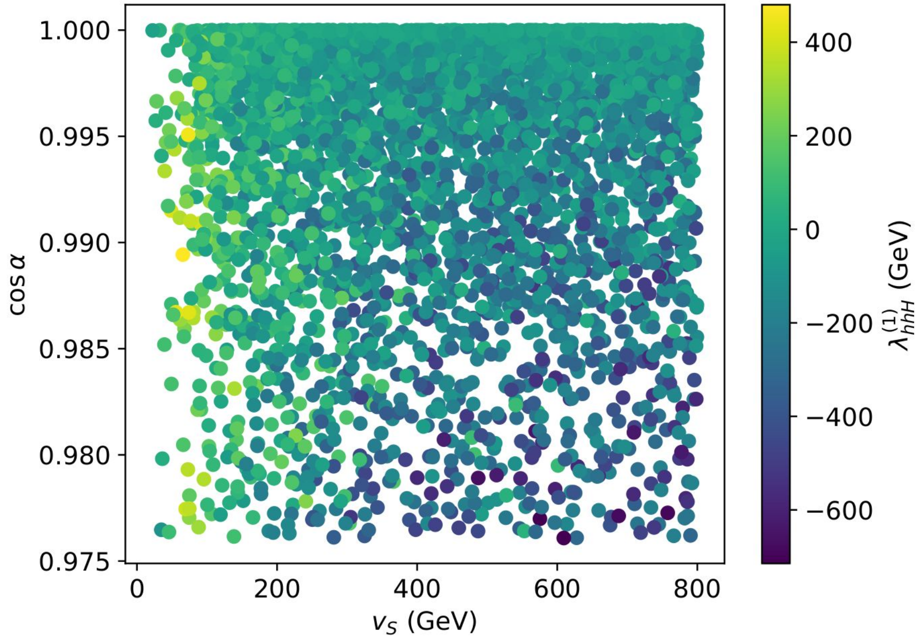


One loop corrections to λ_{hhH}

Difference between one loop and tree level



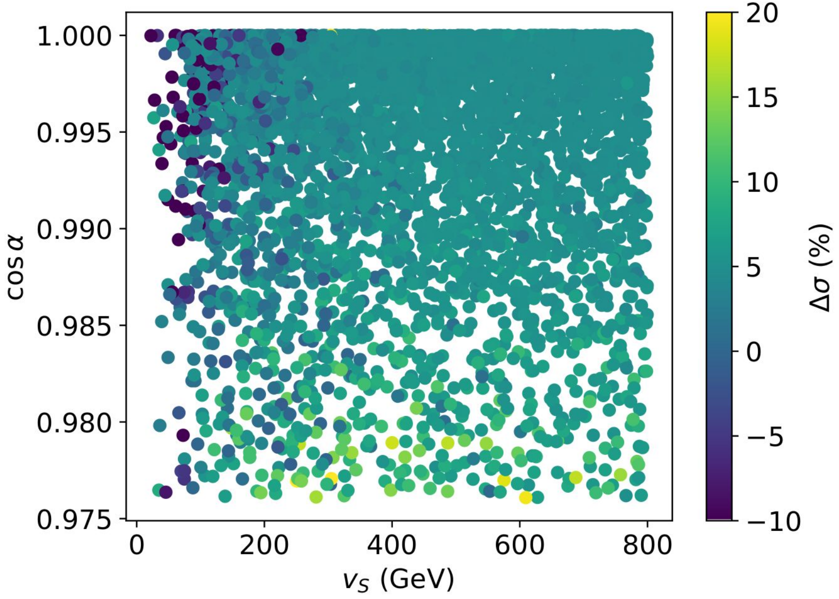
One loop value

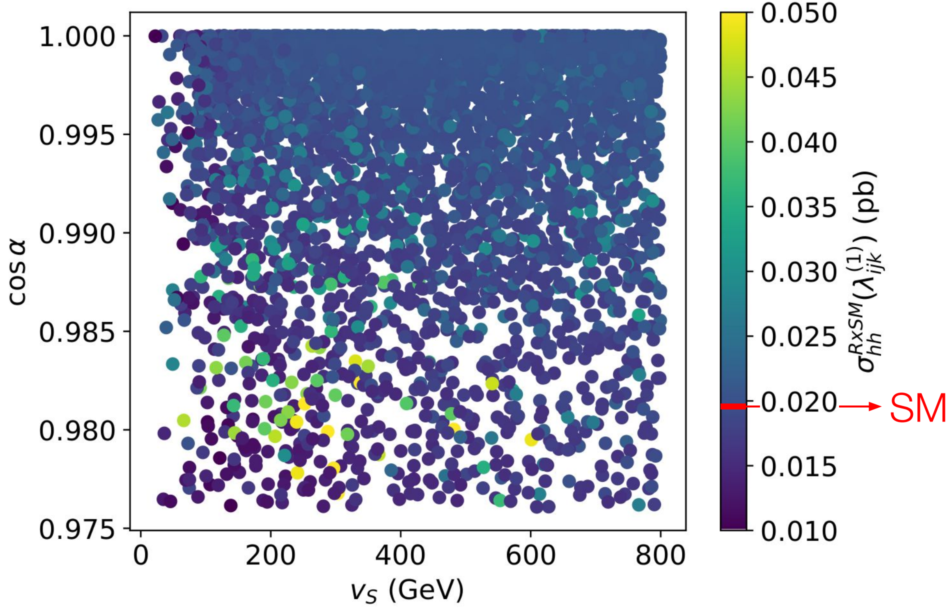


Total di-Higgs production cross section at HL-LHC

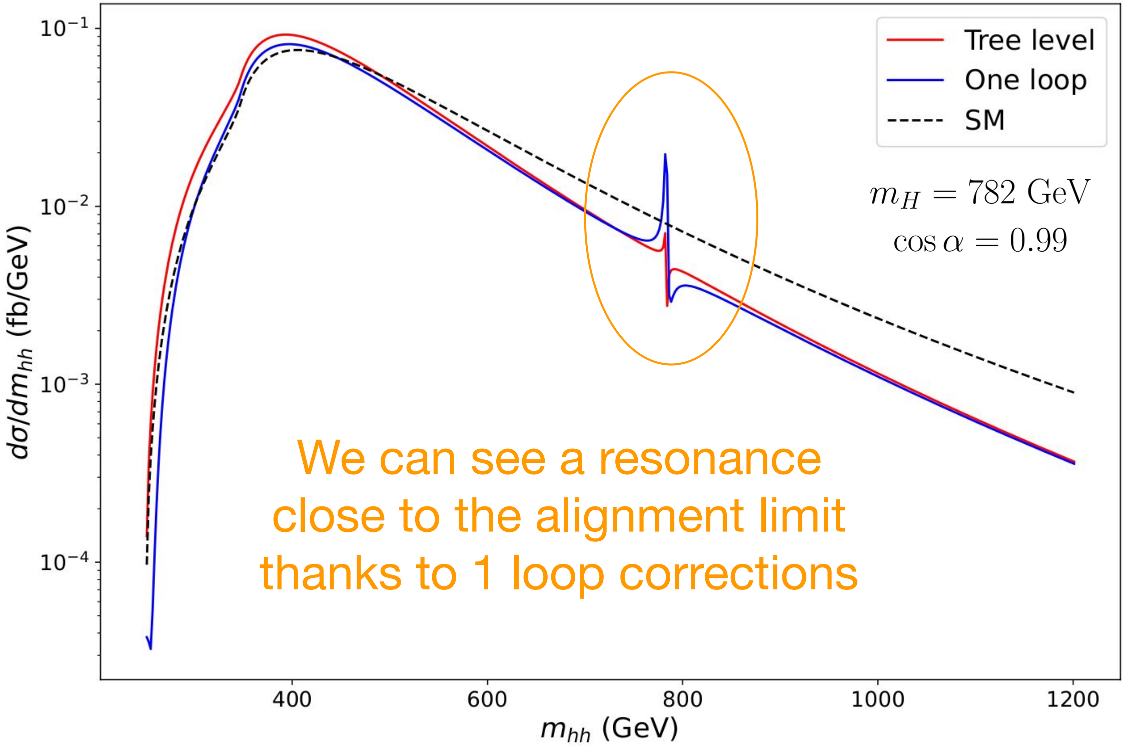
$$\Delta\sigma = \frac{\sigma_{hh}(\lambda^{(1)}_{ijk}) - \sigma_{hh}(\lambda^{(0)}_{ijk})}{\sigma_{hh}(\lambda^{(0)}_{ijk})}$$

Total cross-section value in the RxSM using one loop trilinears





Di-Higgs invariant mass distributions



Tree level

$$\kappa_\lambda^{(0)} = 1.01$$

$$\lambda_{hhH}^{(0)} = 32 \text{ GeV}$$

$$\sigma_{hh}^{(0)} = 19.5 \text{ fb}$$

One loop

$$\kappa_\lambda^{(1)} = 1.16$$

$$\lambda_{hhH}^{(1)} = 197 \text{ GeV}$$

$$\sigma_{hh}^{(1)} = 17.5 \text{ fb}$$

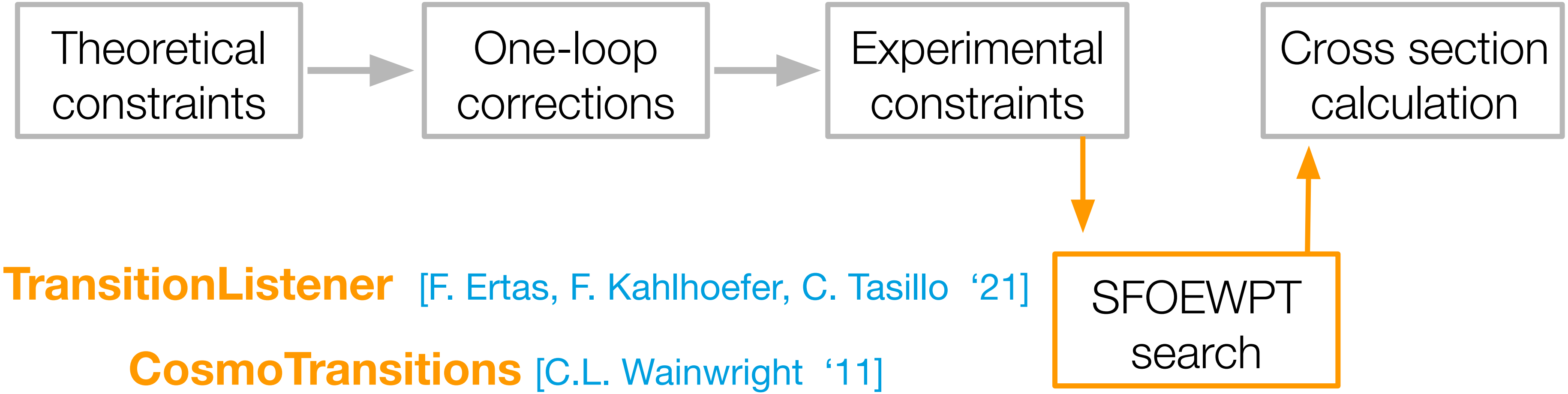
Previously seen in: [S. Heinemeyer, M. Muhlleitner, K. Radchenko, G. Weiglein '24] for 2HDM

SFOEWPT: Effective potential

$$V(\phi_i, T) = V_{\text{tree}} + V_{\text{CW}} + V_{\text{T}} + V_{\text{CT}} + V_{\text{daisy}}$$

- V_{tree} ➢ Tree level potential
- V_{CW} ➢ One loop contribution [S. Coleman, E. Weinberg, '73]
- V_{T} ➢ One loop thermal potential [P. Arnold, O. Espinosa, '93]
- V_{CT} ➢ One loop potential counter term [P. Basler et al., '17]
- V_{daisy} ➢ Daisy diagrams resummation term [P. Arnold, O. Espinosa, '93]

SFOEWPT scenario set-up

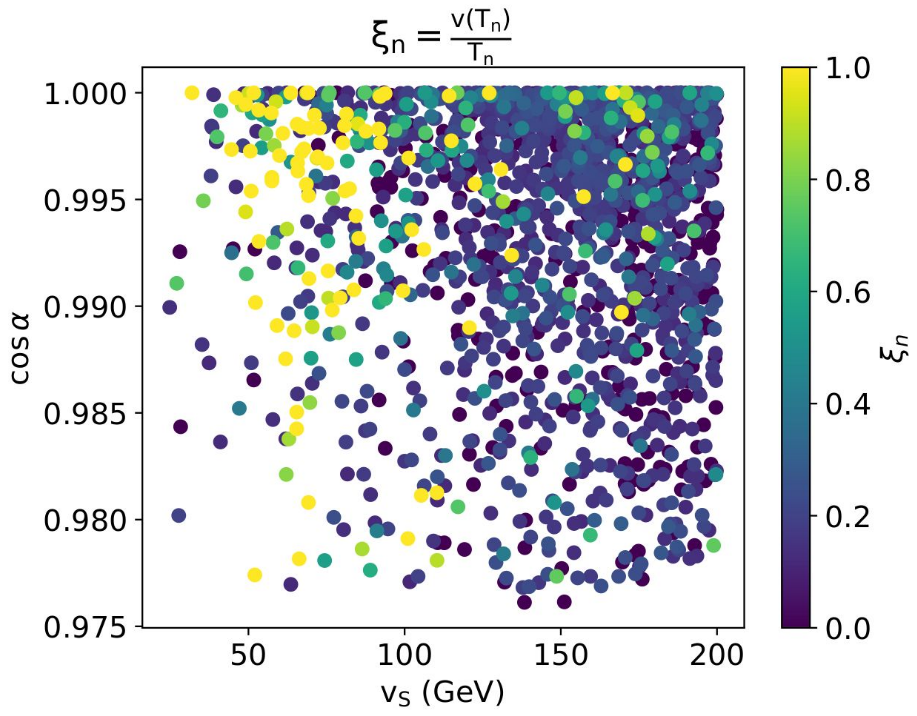


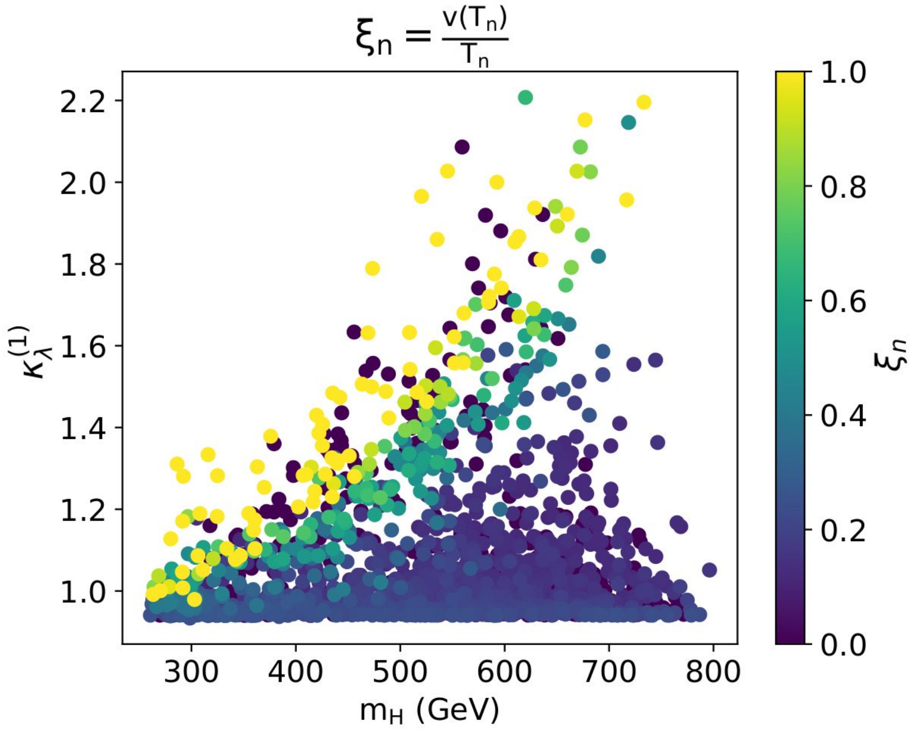
TransitionListener [F. Ertas, F. Kahlhoefer, C. Tasillo ‘21]

CosmoTransitions [C.L. Wainwright ‘11]

SFOEWPT result

We observe a SFOEWPT for values of $\xi_n \gtrsim 1$ [L. Susskind], [T. Biekötter et al. ‘22]

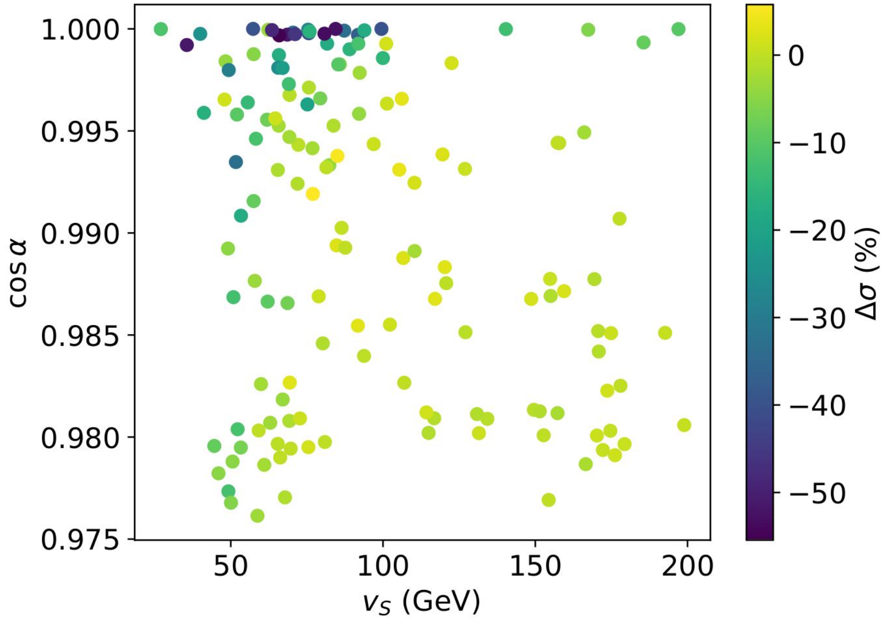


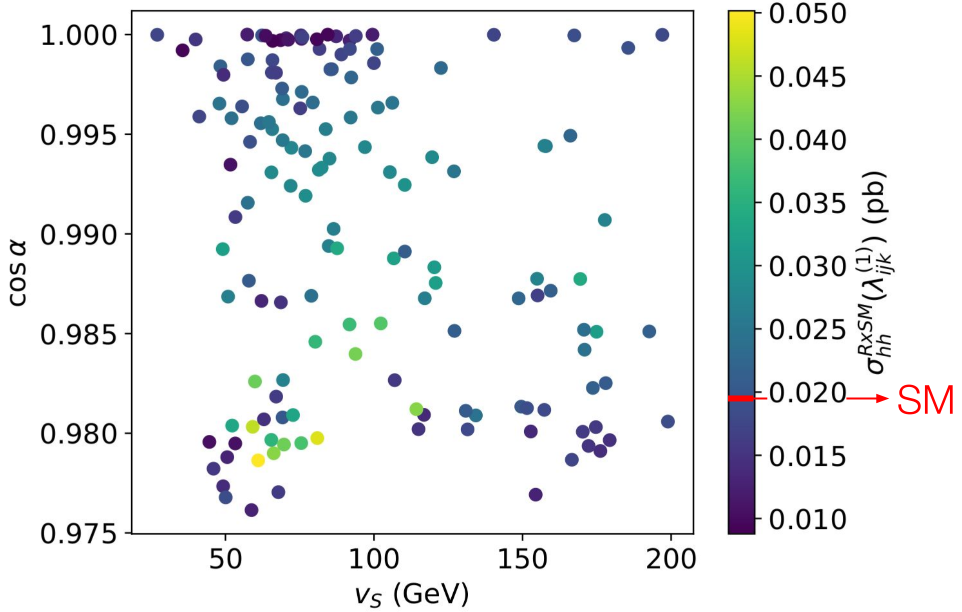


Total di-Higgs cross section in SFOEWPT

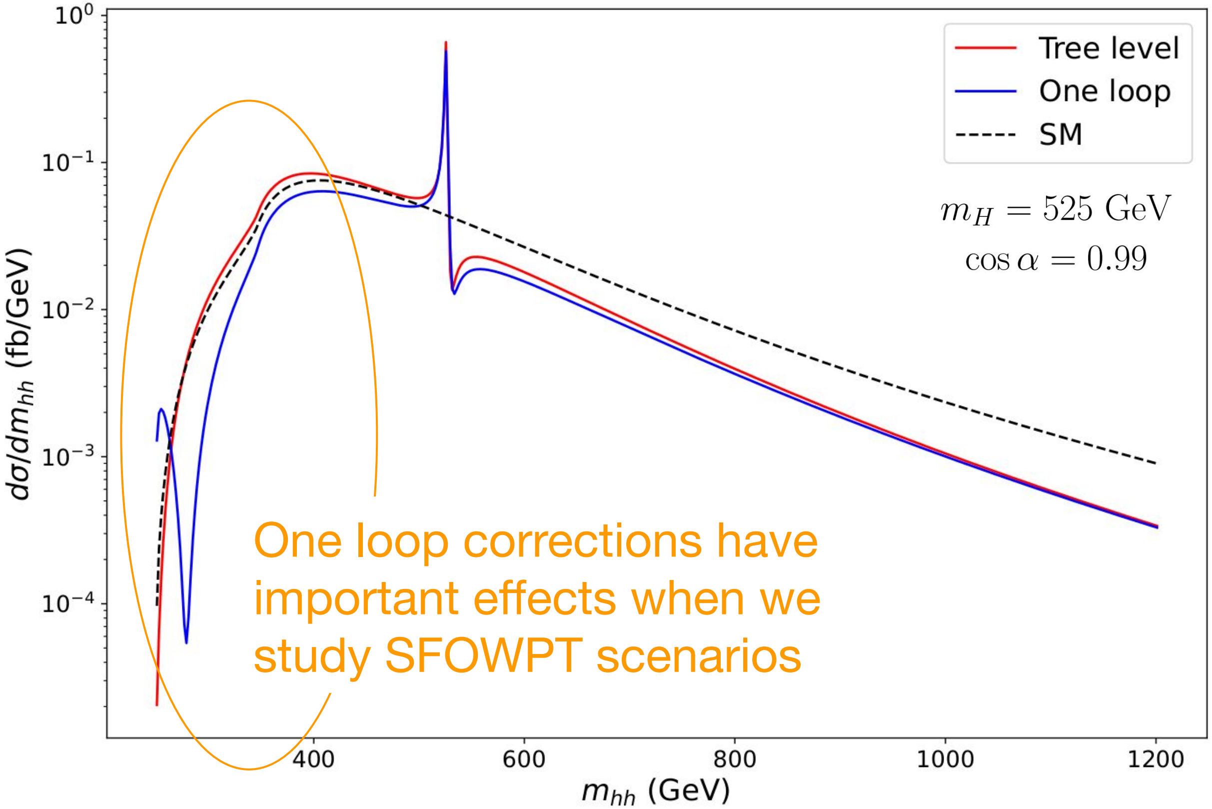
$$\Delta\sigma = \frac{\sigma_{hh}(\lambda^{(1)}_{ijk}) - \sigma_{hh}(\lambda^{(0)}_{ijk})}{\sigma_{hh}(\lambda^{(0)}_{ijk})}$$

Total cross-section value in the RxSM using one loop trilinears





Invariant mass distributions in SFOEWPT



Tree level

$$\kappa_\lambda^{(0)} = 1.10$$

$$\lambda_{hhH}^{(0)} = 158 \text{ GeV}$$

One loop

$$\kappa_\lambda^{(1)} = 1.46$$

$$\lambda_{hhH}^{(1)} = 182 \text{ GeV}$$

Conclusions

- For the RxSM we observe **positive deviations of a 20%** on the total di-Higgs production cross section from the tree level value and **negative deviations of a 50%**

- **One loop corrections to the trilinear Higgs couplings** have an important effect in the **differential di-Higgs cross section distributions** for the RxSM

WE NEED ONE LOOP CORRECTIONS TO THE TRILINEAR HIGGS COUPLINGS TO UNDERSTAND DI-HIGGS PRODUCTION PROPERLY

Conclusions SFOEWPT

- For the RxSM we observe **positive deviations of a 5%** on the total di-Higgs production cross section from the tree level value and **negative deviations of a 50% when we look for SFOEWPT scenario.**

- **One loop corrections to the trilinear Higgs couplings** have an important effect in the **differential di-Higgs cross section distributions** for the RxSM and **the corrections to κ_λ are especially important when we investigate the possibility of a SFOEWPT.**

WE NEED ONE LOOP CORRECTIONS TO THE TRILINEAR HIGGS COUPLINGS TO STUDY SFOEWPT THROUGH DI-HIGGS PRODUCTION PROPERLY

Thank you for your attention

Renormalization scheme: vev

$$v^2 = \frac{m_W^2}{\pi \alpha_{EM}} \left(1 - \frac{m_W^2}{m_Z^2}\right)$$

$$\frac{\delta v}{v} = \frac{1}{2}\left(\frac{s_W^2 - c_W^2}{s_W^2}\frac{\mathrm{Re}[\Sigma_{WW}(m_W^2)]}{m_W^2} + \frac{c_W^2}{s_W^2}\frac{\mathrm{Re}[\Sigma_{ZZ}(m_Z^2)]}{m_Z^2} - \frac{d}{dp^2}\Sigma_{\gamma\gamma}(p^2)\Big|_{p^2=0} - \frac{2 s_W}{c_W}\frac{\Sigma_{\gamma Z}(0)}{m_Z^2}\right)$$

Renormalization scheme: mixing angle

$$\begin{pmatrix} h \\ H \end{pmatrix}_0 = \mathrm{R}^{\mathrm{T}}_{\theta,0} \begin{pmatrix} s \\ h' \end{pmatrix}_0 \approx \mathrm{R}^{\mathrm{T}}_{\delta\theta}\mathrm{R}^{\mathrm{T}}_{\theta} \begin{pmatrix} s \\ h' \end{pmatrix}_0 = \mathrm{R}^{\mathrm{T}}_{\delta\theta}\mathrm{R}^{\mathrm{T}}_{\theta}\sqrt{Z_{h',s}} \begin{pmatrix} s \\ h' \end{pmatrix} = \mathrm{R}^{\mathrm{T}}_{\delta\theta}\mathrm{R}^{\mathrm{T}}_{\theta}\sqrt{Z_{h',s}}\mathrm{R}_{\theta}\mathrm{R}^{\mathrm{T}}_{\theta} \begin{pmatrix} s \\ h' \end{pmatrix} =$$

$$= \mathrm{R}^{\mathrm{T}}_{\delta\theta}\mathrm{R}^{\mathrm{T}}_{\theta}\sqrt{Z_{h',s}}\mathrm{R}_{\theta} \begin{pmatrix} h \\ H \end{pmatrix} = \sqrt{Z^{Kan}_{\phi}} \begin{pmatrix} h \\ H \end{pmatrix},$$

$$\sqrt{Z^{Kan}_{\phi}} = \mathrm{R}^{\mathrm{T}}_{\delta\theta}\mathrm{R}^{\mathrm{T}}_{\theta}\sqrt{Z_{h',s}}\mathrm{R}_{\theta} = \begin{pmatrix} 1 + \frac{\delta Z_{hh}}{2} & \delta C_{hH} - \delta\theta \\ \delta C_{Hh} + \delta\theta & 1 + \frac{\delta Z_{HH}}{2} \end{pmatrix}.$$

$$\delta C_{hH} - \delta\theta = 1 + \frac{\delta Z_{hH}}{2}$$

$$\delta C_{Hh} + \delta\theta = 1 + \frac{\delta Z_{Hh}}{2}$$

$$\delta\theta = \frac{1}{2(m_H^2 - m_h^2)}\mathrm{Re}[\Sigma_{hH}(m_h^2) + \Sigma_{hH}(m_H^2) - 2\delta D^2_{hH}]$$

Renormalization scheme: vs

It was shown in [arxiv: 1305.1548] that such an additional CT of the VEV can contain at most UV-finite contributions if the Lagrangian contains a rigid symmetry with respect to the field which corresponds to the VEV. In the RxSM, this is precisely the case for the $SU(2)_L$ gauge singlet S. Consequently, in the standard tadpole scheme δv_S is UV-finite and in this case, we choose to set the finite part of the CT to zero.

$$\delta v_S^{\overline{MS}}|_{fin} = 0. \tag{49}$$

SFOEWPT: Veff def

The CW potential is given in the $\overline{\mathrm{MS}}$ renormalisation scheme by

$$V_{\mathrm{CW}}(\phi_i) = \sum_j \frac{n_j}{64\pi^2}(-1)^{2s_j}\, m_j^4(\phi_i)\left[\ln\left(\frac{|m_j(\phi_i)^2|}{\mu^2}\right) - c_j\right],$$

UV-finite counterterm contribution V_{CT}, given by

$$V_{\mathrm{CT}} = \sum_i \frac{\partial V_0}{\partial p_i}\delta p_i + \sum_k (\phi_k + v_k)\delta T_k\ ,$$

$$\partial_{\phi_i} V_{\mathrm{CT}}(\phi)\Big|_{\langle\phi\rangle_{T=0}} = -\partial_{\phi_i} V_{\mathrm{CW}}(\phi)\Big|_{\langle\phi\rangle_{T=0}}$$

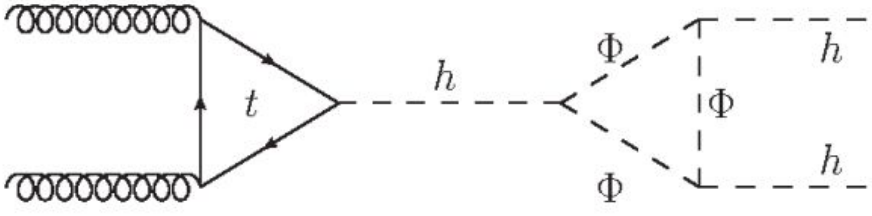
$$\partial_{\phi_i}\partial_{\phi_j} V_{\mathrm{CT}}(\phi)\Big|_{\langle\phi\rangle_{T=0}} = -\partial_{\phi_i}\partial_{\phi_j} V_{\mathrm{CW}}(\phi)\Big|_{\langle\phi\rangle_{T=0}}$$

SFOEWPT: Veff def

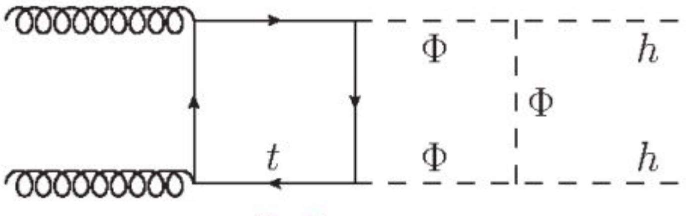
$$V_T(\phi_i, T) = \sum_j \frac{n_j\, T^4}{2\pi^2}\, J_\pm\left(\frac{m_j^2(\phi_i)}{T^2}\right)$$

$$J_\pm\left(\frac{m_j^2(\phi_i)}{T^2}\right) = \mp \int_0^\infty dx\, x^2\, \log\left[1 \pm \exp\left(-\sqrt{x^2 + \frac{m_j^2(\phi_i)}{T^2}}\right)\right]$$

$$V_{\text{daisy}}(\phi_i, T) = -\sum_i \frac{T}{12\pi}\text{Tr}\left[\left(m_i^2(\phi_i) + \Pi_i^2\right)^{\frac{3}{2}} - \left(m_i^2(\phi_i)\right)^{\frac{3}{2}}\right]$$



$\propto \mathcal{O}(y_t g^3_{hh\Phi\Phi})$ ***included***



$\propto \mathcal{O}(y_t^2 g^2_{hh\Phi\Phi})$ ***not included***

Taken from J. Braathen