Looking for a SFOEWPT in the RxSM at the HL-LHC and LISA

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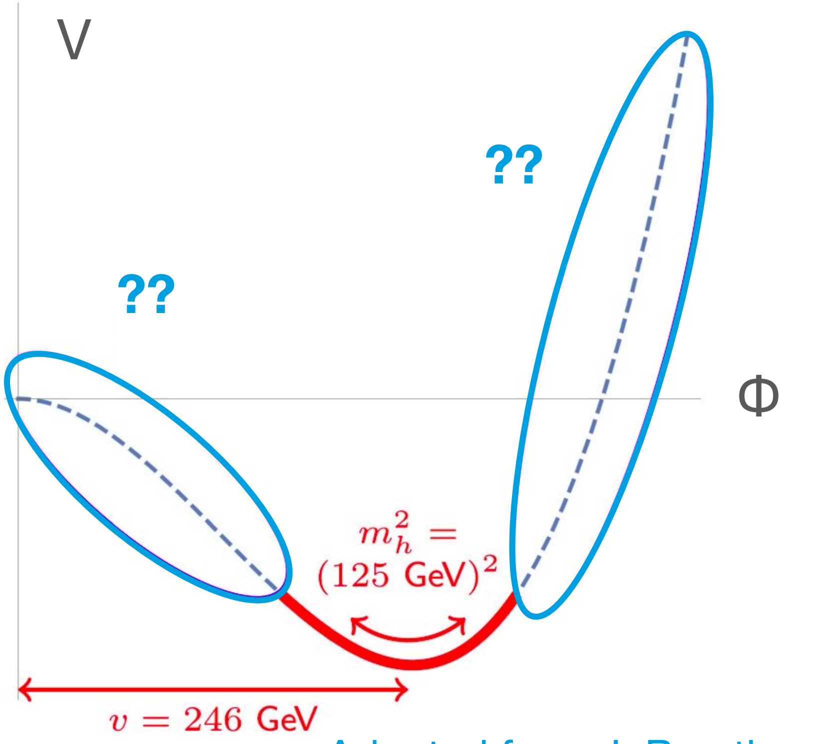
Extended Scalar Sectors From All Angles

CERN, 24-10-24

Motivation

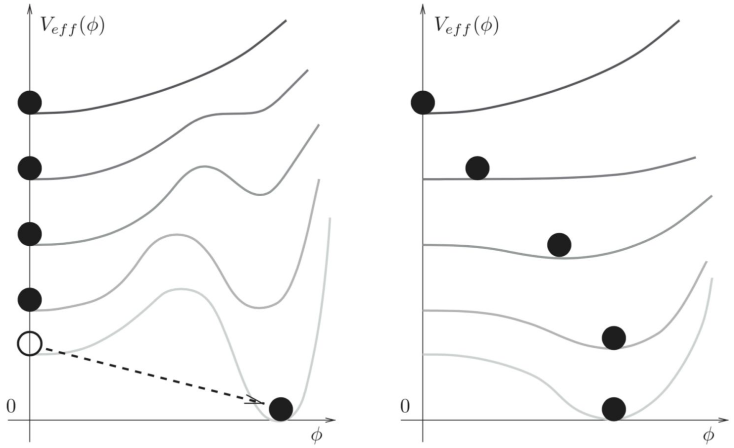
- Why SFOEWPT? (Strong First Order Electroweak Phase Transition)
  - Explain BAU with EW baryogenesis
- Why BSM models?
  - No SFOEWPT in the SM
- Why Trilinear Higgs Couplings (THC)?
  - We don't know the shape of the Higgs potential
  - PT dynamics are determined by THC
  - Di-Higgs production is sensitive to them

Di-Higgs production as a tool to look for SFOEWPT scenarios in BSM models

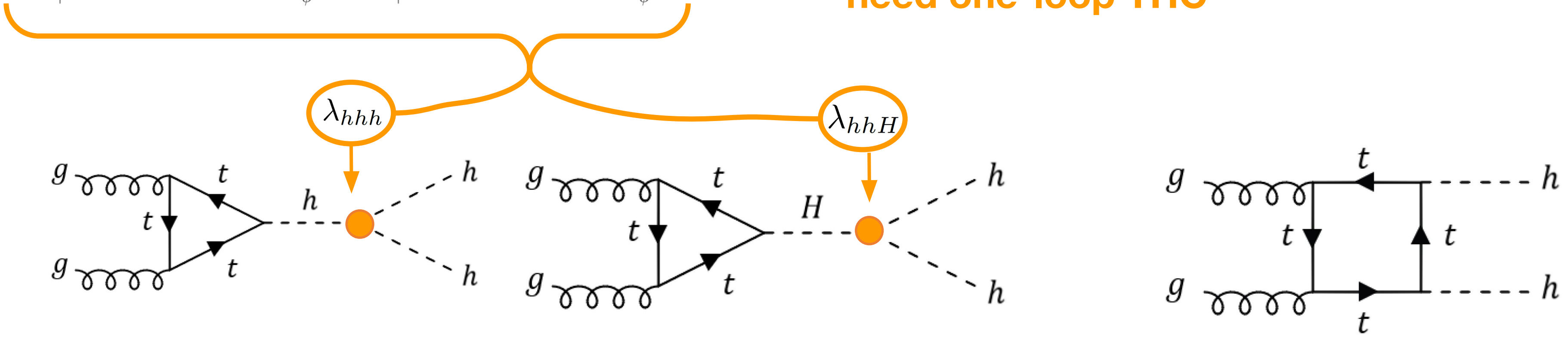


Adapted from J. Braathen

Motivation



- THC determine the formation of the barrier
- The computation of the **EWPT dynamics is done at the one-loop level**
- To capture the same order of BSM contributions in di-Higgs production **we need one-loop THC**



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:

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

Gauge eigenstates:

$$\phi, \; s$$

Mass eigenstates:

$$h, \; H$$

Masses & mixing angle:

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

Tree level triple Higgs couplings in RxSM

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

$$\lambda_{hhh} = \frac{1}{4v^2 v_S^2}\{-3v_S\left[\kappa_{SH}v^3 + 3(t_\phi - m_h^2 v)v_S\right]c_\alpha + 3v_S\left[\kappa_{SH}v^3 - t_\phi v_S + m_h^2 v v_S\right]c_{3\alpha} + \\ + 2v^2\left[-6t_S + 3\kappa_{SH}v^2 + 6m_h^2 v_S - 2\kappa_S v_S^2\right]s_\alpha^3\}$$

$$\lambda_{hhH} = \frac{1}{4v^2 v_S^2}s_\alpha\{-2v_S\left[\kappa_{SH}v^3 - 3t_\phi v_S + (2m_h^2 + m_H^2)v v_S\right] - 2v_S[3\kappa_{SH}v^3 - 3t_\phi v_S + \\ + (2m_h^2 + m_H^2)v v_S]c_{2\alpha} + v^2\left[-6t_S + 3\kappa_{SH}v^2 + 2v_S\left(2m_h^2 + m_H^2 - \kappa_S v_S\right)\right]s_{2\alpha}\}$$

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_ϕ, t_s — OS/Standard scheme
- Kappas: κ_S, κ_{SH} — $\hat{\lambda}^{(1)}_{hHH} \stackrel{!}{=} \lambda^{(0)}_{hHH} \quad \hat{\lambda}^{(1)}_{HHH} \stackrel{!}{=} \lambda^{(0)}_{HHH}$

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 Coleman-Weinberg (T=0) [S. Coleman, E. Weinberg, '73]
- V_{T} ➢ One loop thermal potential
- V_{CT} ➢ One loop potential counter term [P. Basler et al., '17]
- V_{daisy} ➢ Daisy diagrams resummation term [P. Arnold, O. Espinosa, '93]

Set-up of analysis, including loop corrections

Theoretical constraints → One-loop corrections to λ_{ijk} → Experimental constraints → SFOEWPT analysis → Di-Higgs cross section calc.

Potential stability
Pertubativity
[Li, Ramsey-Musolf, Willocq, '19]
Unitarity
[Braathen, Goodsell, Krauss, Opferkuch, Staub, '17]

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]

Transition Listener
[F. Ertas, F. Kahlhoefer, C. Tasillo '21]
Cosmo Transitions
[C.L. Wainwright '11]

HPAIR
[T. Plehn, M. Spira, P.M. Zerwas, '96] [S.Dawson, S. Dittmaier, M.Spira, '98] [Abouabid et al., '22]

SFOEWPT benchmark plane

We observe a SFOEWPT for values of $\xi_n \gtrsim 1$

Phenomenological constraint to maximise the di-Higgs cross-section

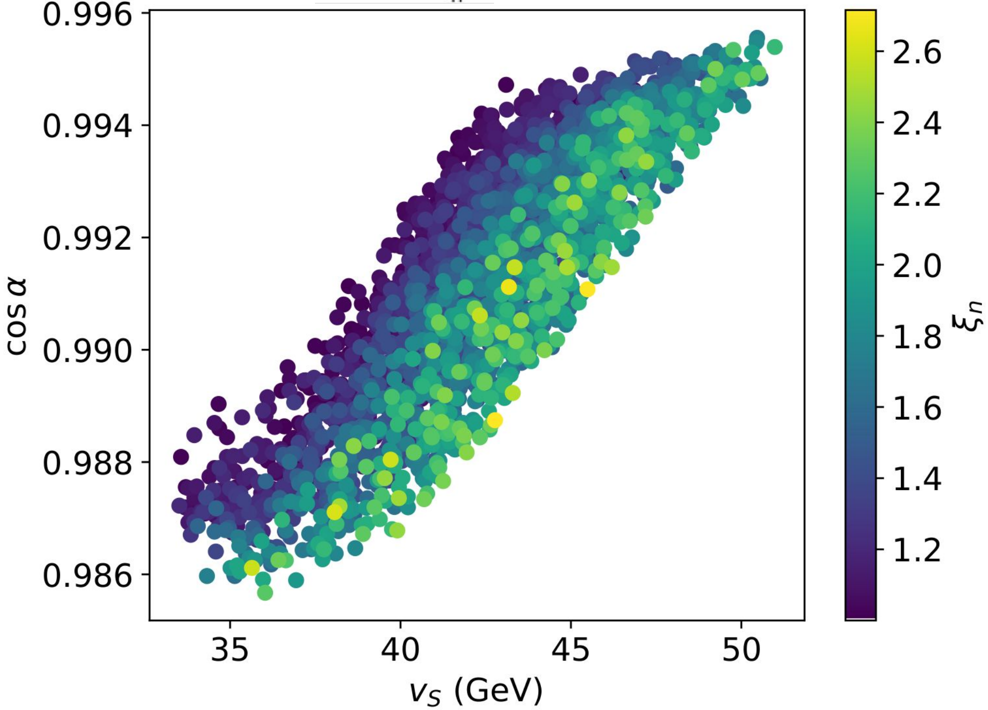
$$2\pi < \frac{\lambda_{SH}}{2} < 4\pi$$

Phenomenological constraint to increase the probability of realising a SFOEWPT

$$\kappa_S = \kappa_{SH}$$

$$\xi_n = \frac{v(T_n)}{T_n}$$

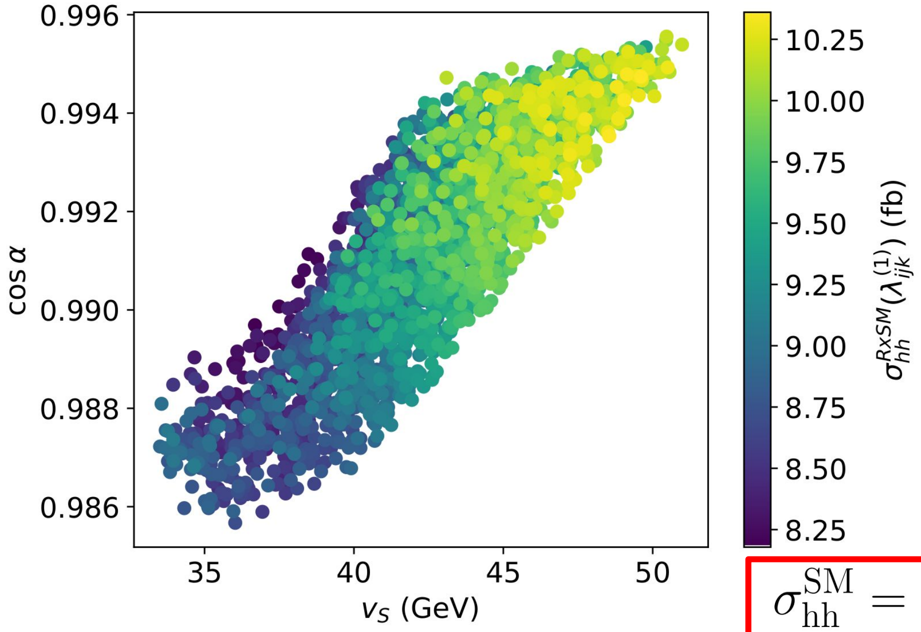
T_n: Nucleation temperature



LO result

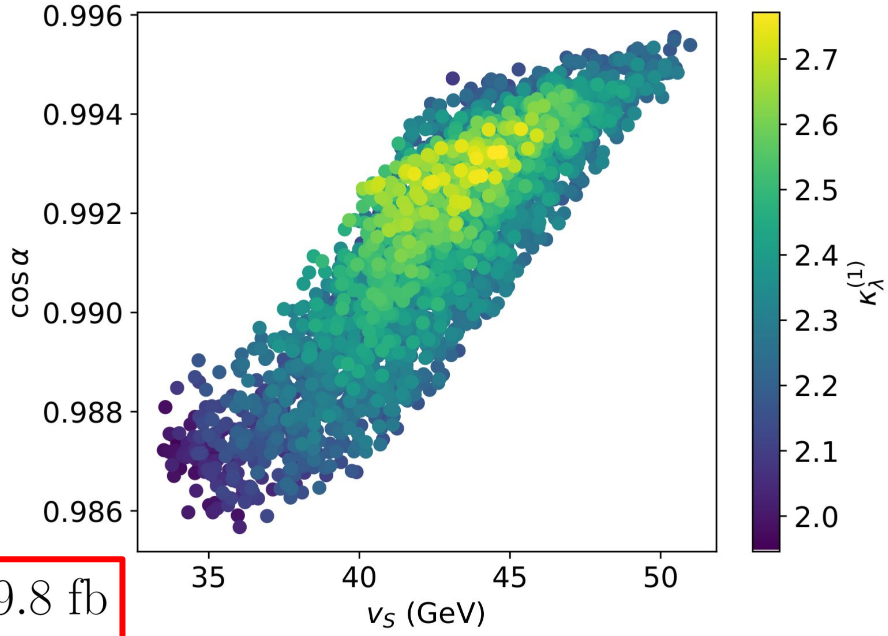
SFOEWPT BP result

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



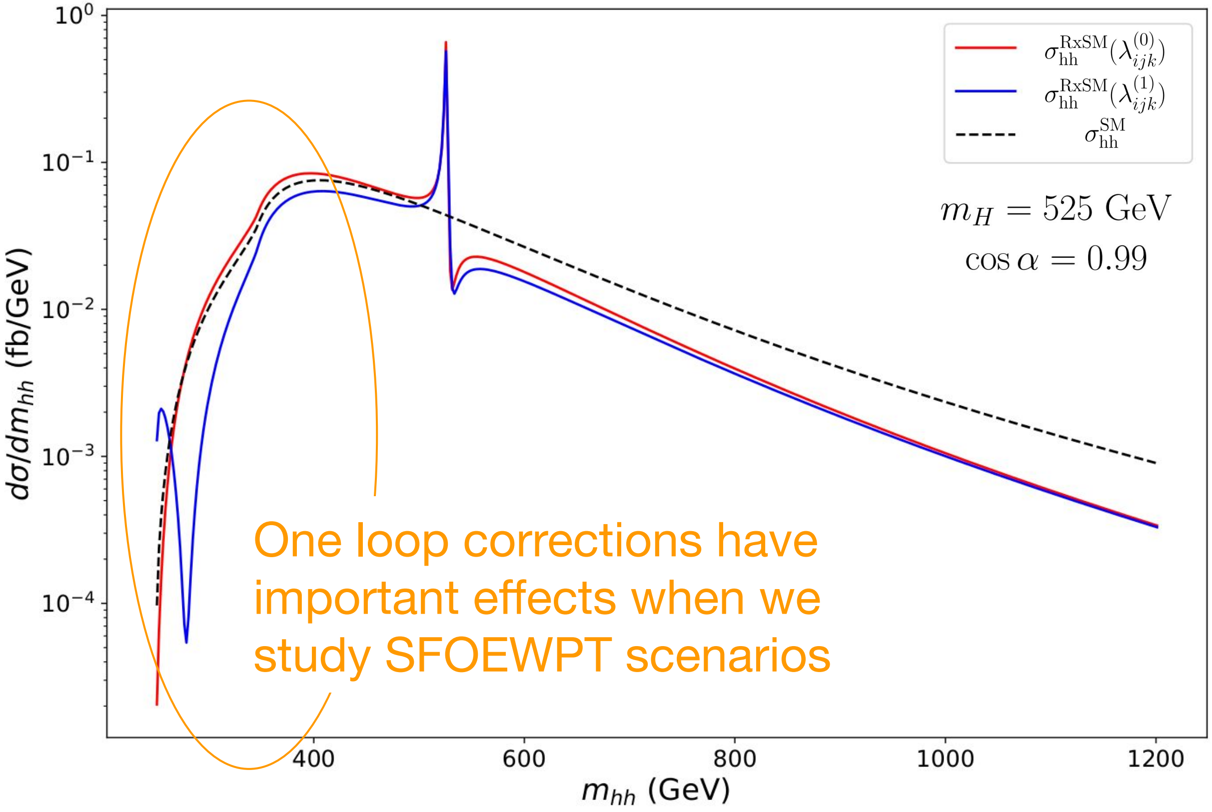
$$\sigma_{\mathrm{hh}}^{\mathrm{SM}} = 19.8 \text{ fb}$$

Kappa lambda one loop value in the RxSM



Low di-Higgs production cross section in the parameter region with SFOEWPT

Invariant mass distributions in SFOEWPT



Tree level

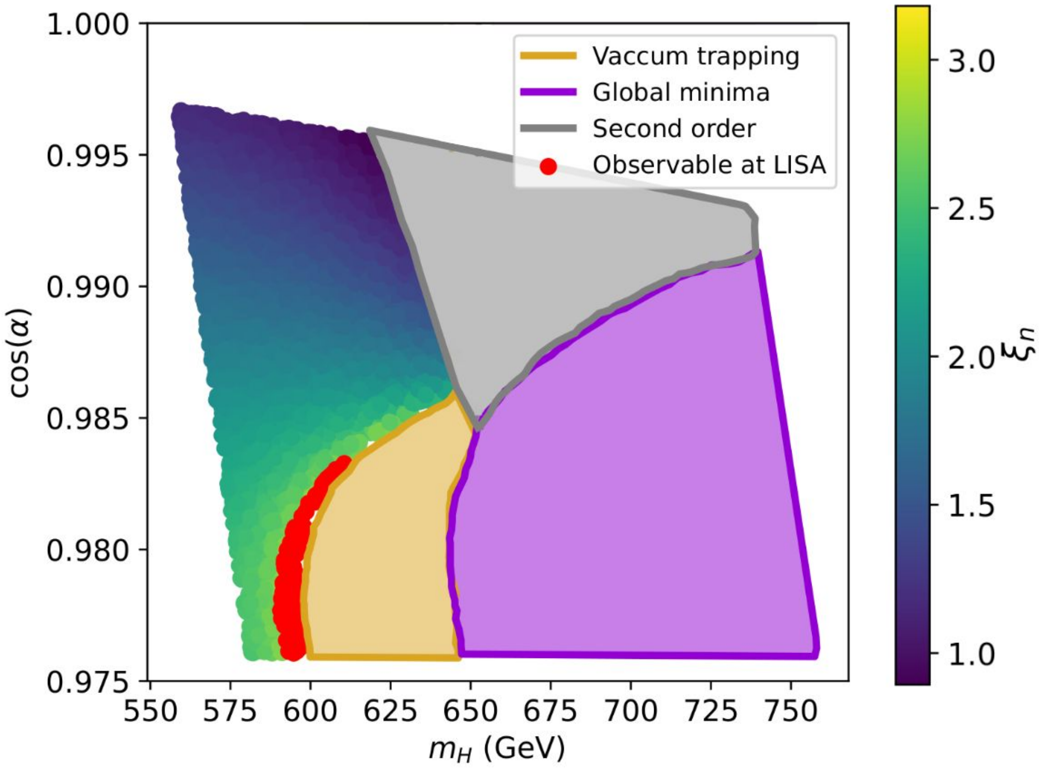
$$\kappa_\lambda^{(0)} = 1.10$$
$$\lambda_{hhH}^{(0)} = 158 \text{ GeV}$$
$$\sigma_{\rm hh}(\lambda_{ijk}^{(0)}) = 25.2 \text{ fb}$$

One loop

$$\kappa_\lambda^{(1)} = 1.46$$
$$\lambda_{hhH}^{(1)} = 182 \text{ GeV}$$
$$\sigma_{\rm hh}(\lambda_{ijk}^{(1)}) = 21.4 \text{ fb}$$

Are there other ways of investigating SFOEWPT in the RxSM?

SFOEWPT GW signal



$$v_S = 50 \text{ GeV}$$

Phenomenological constraint to look for SFOEWPT

$$\kappa_S = \kappa_{SH} = -m_H$$

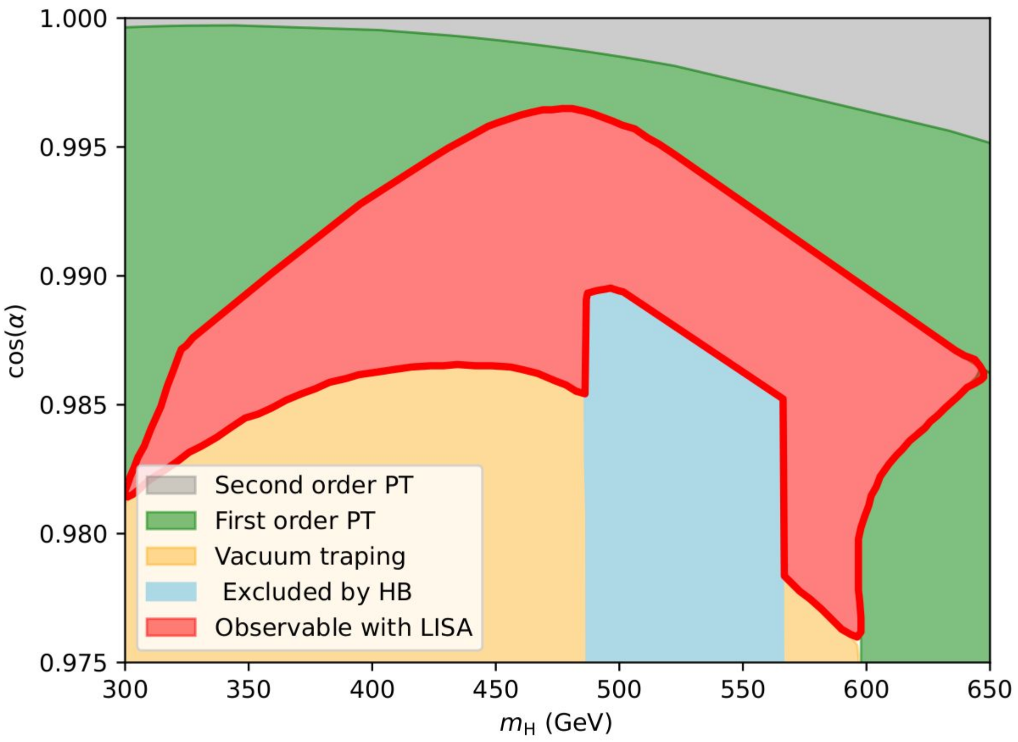
Scanned region

$$m_H \in [250, 1000] \text{ GeV}$$

$$\cos\alpha \in [0.97, 1]$$

Parameter space observable at LISA in the RxSM!

SFOEWPT GW signal



Phenomenological constraint to look for SFOEWPT

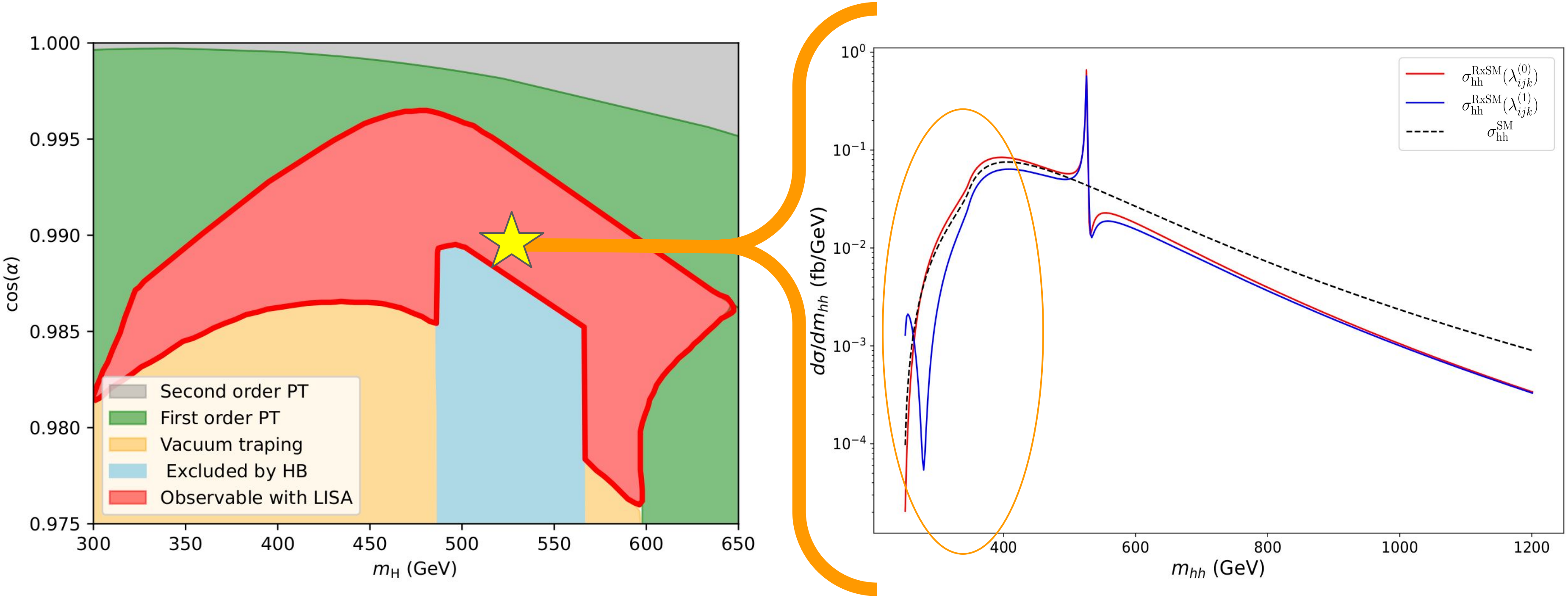
$$\kappa_S = \kappa_{SH} = -m_H$$

Scanned region

$$v_S \in [45, 80]\ \text{GeV}$$
$$m_H \in [250, 1000]\ \text{GeV}$$
$$\cos\alpha \in [0.97, 1]$$

Parameter space observable at LISA in the RxSM!

Combining: LISA + HL-LHC



One-loop trilinear Higgs coupling are a portal to SFOEWPT at colliders!

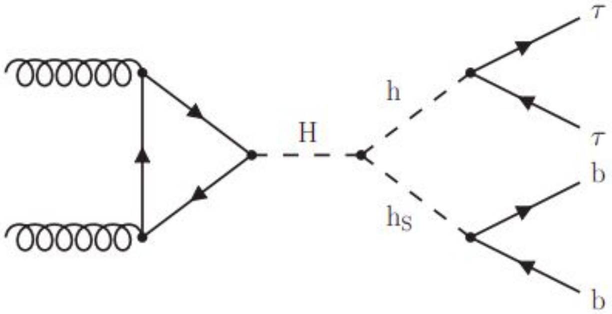
Conclusions

- **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.**
- **Differential di-Higgs cross section distributions** can be used to investigate **SFOEWPT scenarios** at the HL-LHC
- The RxSM has a **parameter region with a SFOEWPT** in the early Universe which generates a stochastic background of **gravitational waves observable at LISA**
- **Loop corrected trilinear Higgs couplings are a portal to SFOEWPT at the HL-LHC**

Thank you for your attention

Search for a heavy Higgs boson decaying into two lighter Higgs bosons in the $\tau\tau bb$ final state at 13 TeV

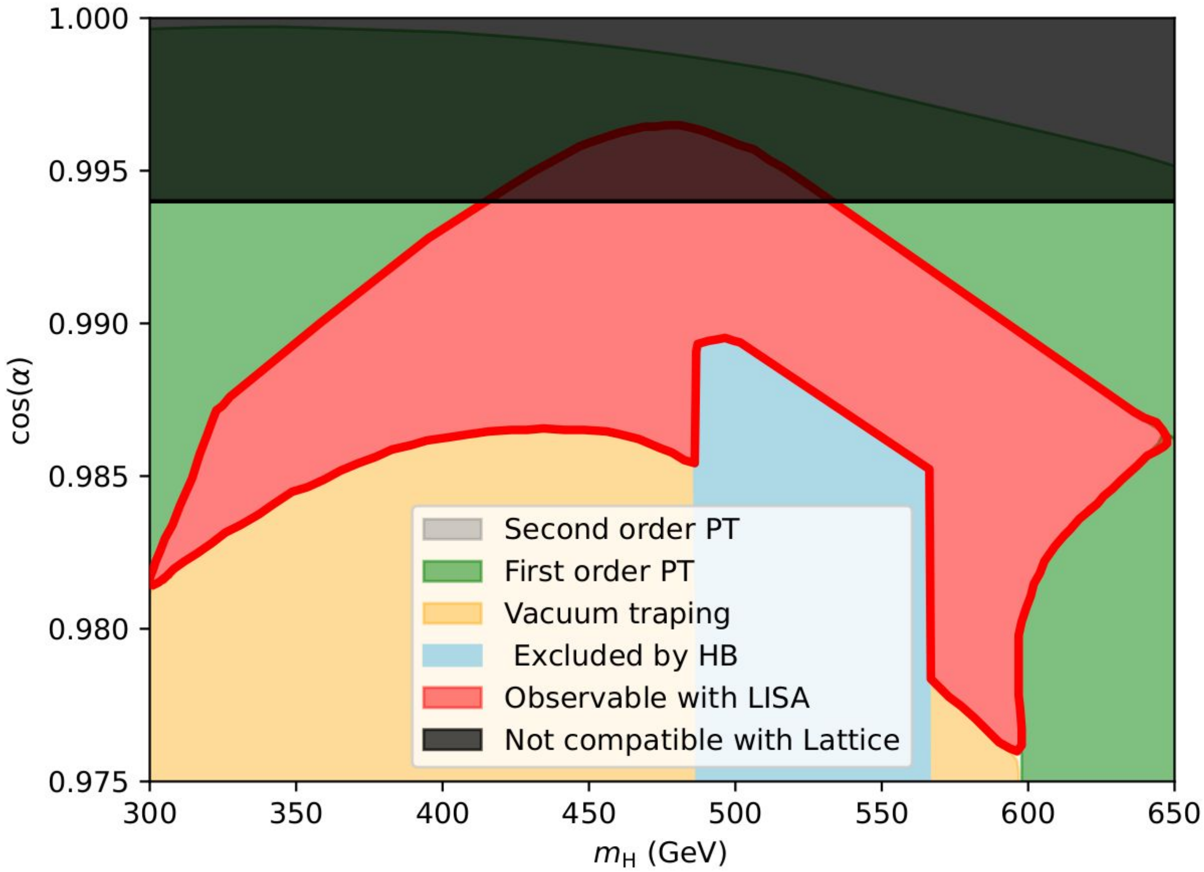
Considered signal:



NO INTERFERENCE

KAPPA LAMBDA = 1

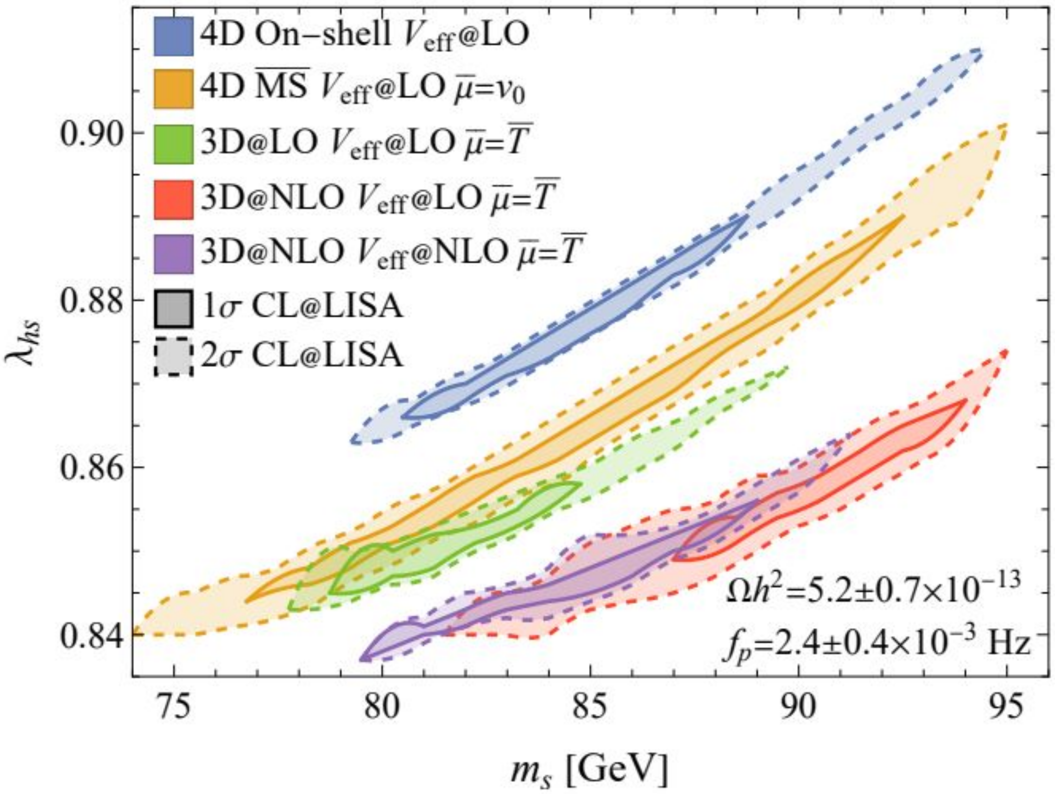
CMS collaboration 2021: [arxiv: 2106.10361]



One-step phase transition in the non Z2-symmetric RxSM

Two-loop loop dimensionally reduced effective field theory with lattice simulations

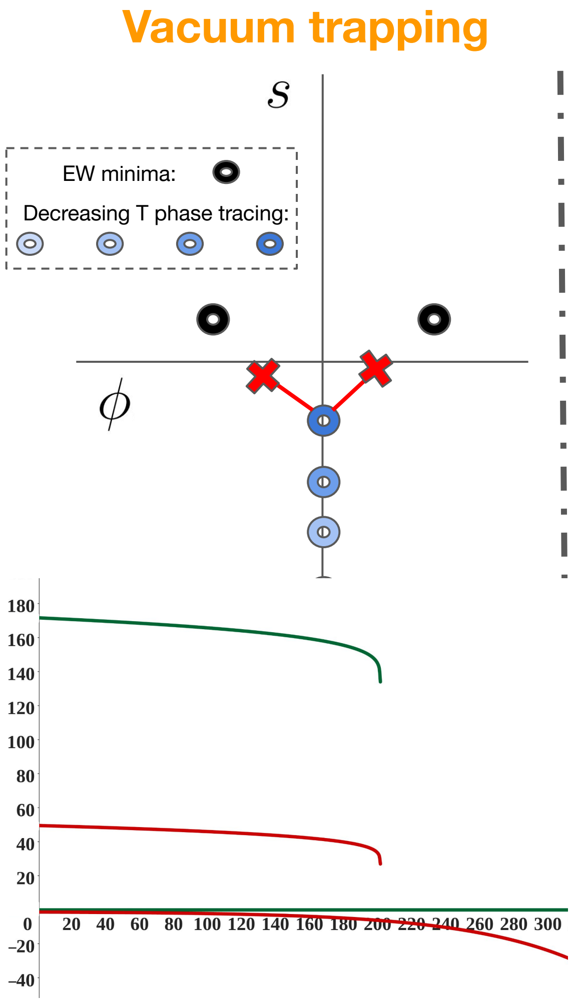
Lattice result: [Niemi, Ramsey-Musolf, Xia, '24] [arxiv: 22405.01191]

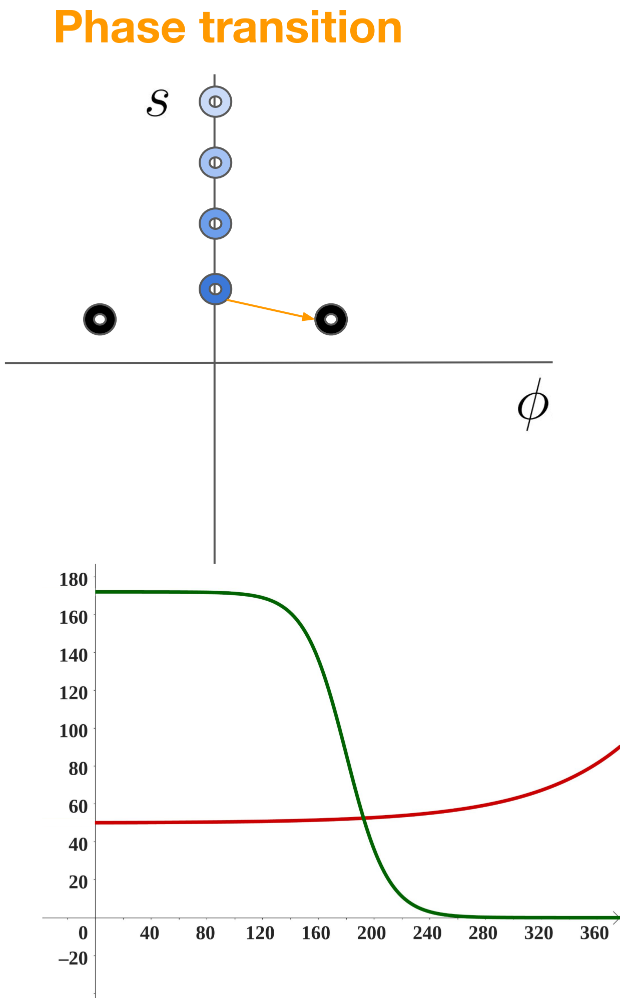


Two-step phase transition in a Z2-symmetric RxSM

The observable region is sifted but it is still in a similar parameter region

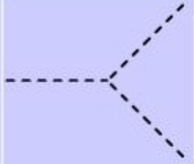
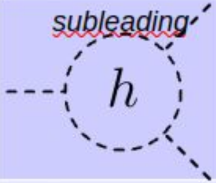
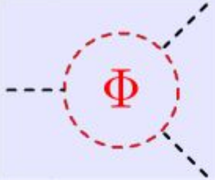
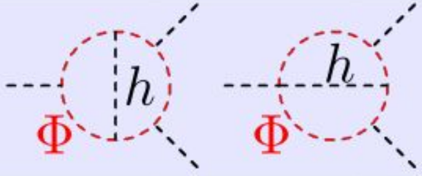
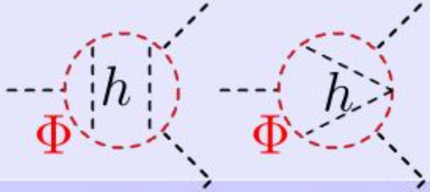
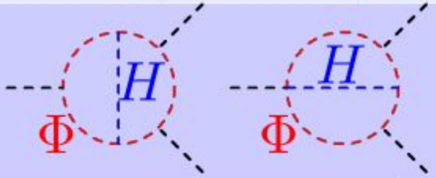
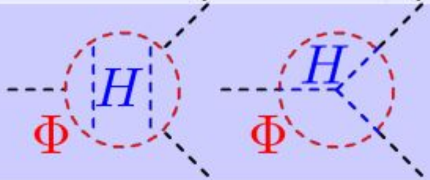
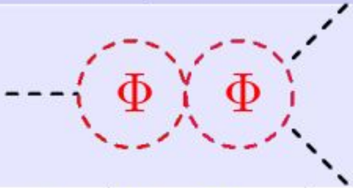
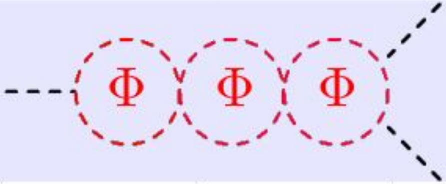
[Lewicki , Merchand, Sagunski, Schicho, Schmitt, ‘24] [arxiv: 2403.03769


Vacuum trapping
s
EW minima:
Decreasing T phase tracing:
ϕ
180
160
140
120
100
80
60
40
20
0
–20
–40
20 40 60 80 100 120 140 160 180 200 220 240 260 280 300


Phase transition
s
ϕ
180
160
140
120
100
80
60
40
20
0
–20
40 80 120 160 200 240 280 320 360

Examples of scalar contributions to λ_{hhh} in aligned 2HDM

BSM scalars:
$\Phi \in \{H, A, H^{\pm}\}$
$m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2$

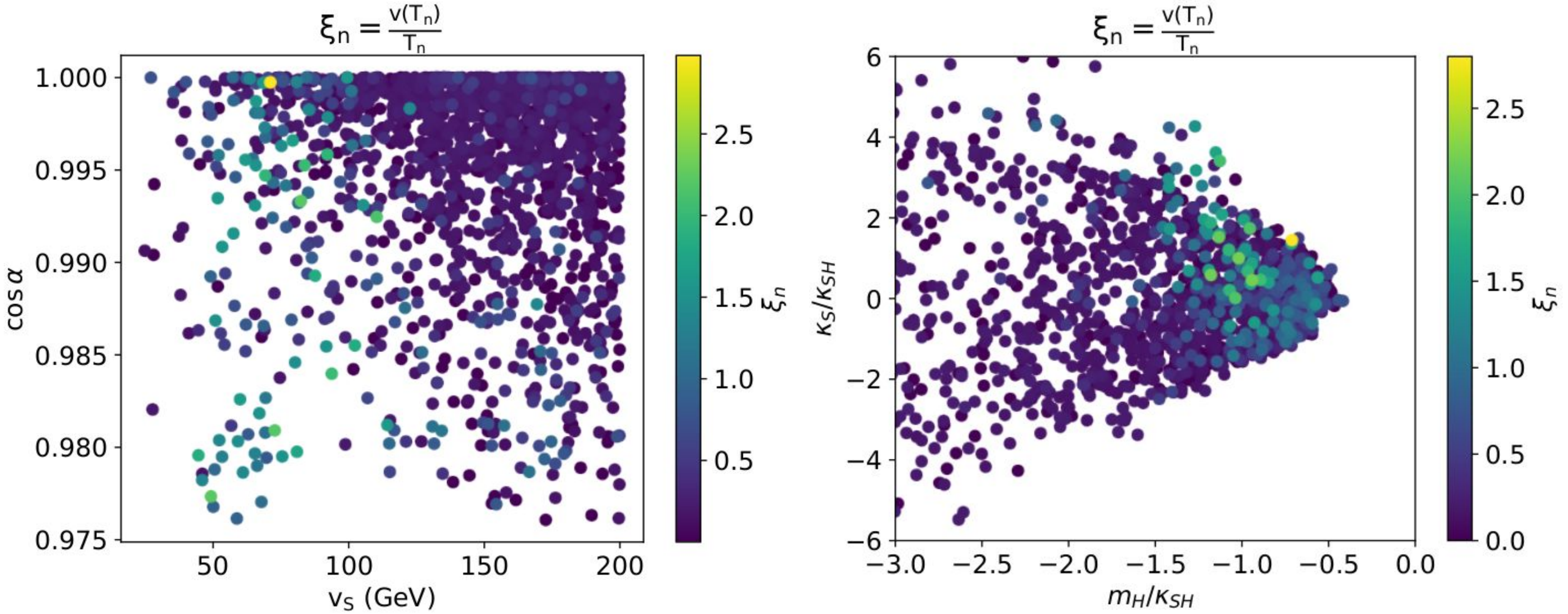
Coupling/Order	0L	1L	2L	3L
g_{hhhh}			*subleading*	*subleading*
$g_{(h)h\Phi\Phi}$ $\left[g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}\right]$	-			
$g_{(h)H\Phi\Phi'}$ [$g_{(h)G\Phi\Phi'}$ case similar]	-	-		
$g_{\Phi\Phi\Phi'\Phi'}$ [2 BSM scalars of species Φ, 2 of species Φ']	-	-		

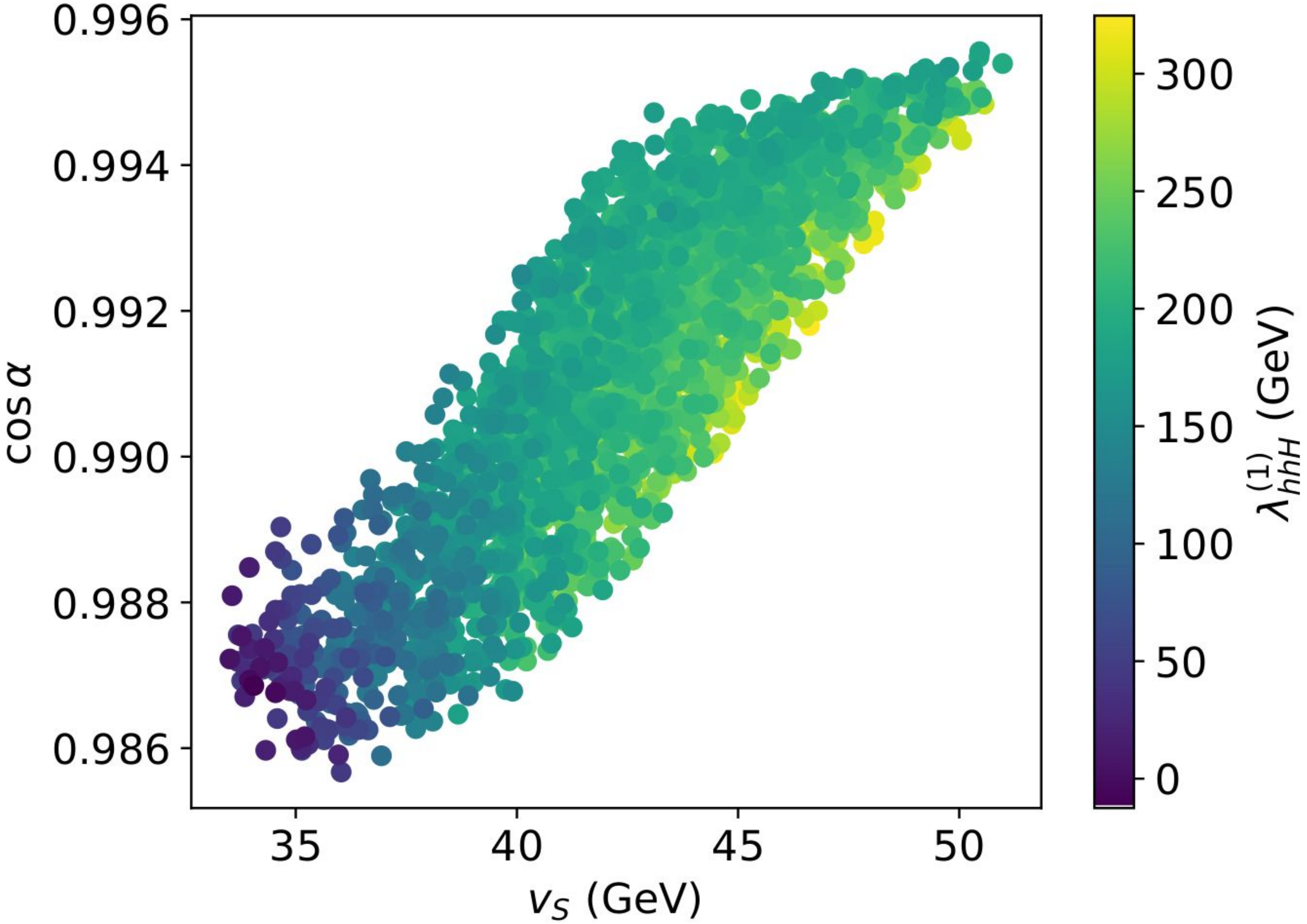
[NB: 1 h can be replaced by a VEV]

→ *no further type of coupling entering after 2L*
→ *for each class of diagrams, perturbative convergence can be checked!*

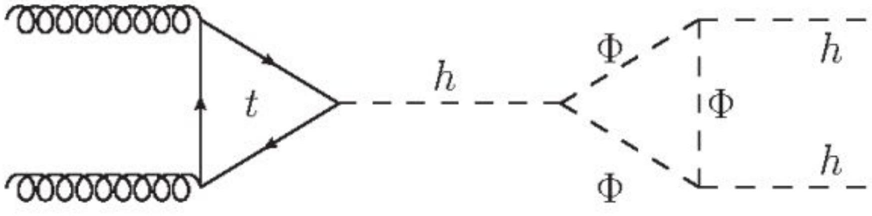
SFOEWPT result

We observe a SFOEWPT for values of $\xi_n \gtrsim 1$

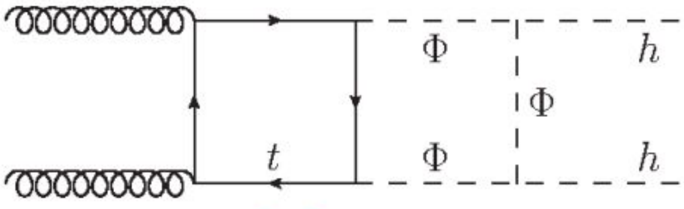




0.996
0.994
0.992
0.990
0.988
0.986
cos α
35
40
45
50
v_S (GeV)
300
250
200
150
100
50
0
$\lambda_{hhH}^{(1)}$ (GeV)



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



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

Taken from J. Braathen

Renormalization scheme: κ_S, κ_{SH}

Our choice of renormalization conditions:

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

$$\underbrace{\lambda^{(0)}_{hHH}}_{\text{Tree level}} + \underbrace{\delta\lambda^{(1)}_{hHH}}_{\text{Genuine one-loop contribution}} + \underbrace{\delta\lambda^{m^2}_{hHH} + \delta\lambda^{v}_{hHH} + \delta\lambda^{tad}_{hHH} + \delta\lambda^{wfr}_{hHH} + \delta\kappa_S^{\text{CT}}\frac{\partial\lambda^{(0)}_{hHH}}{\partial\kappa_S} + \delta\kappa_{SH}^{\text{CT}}\frac{\partial\lambda^{(0)}_{hHH}}{\partial\kappa_S H}}_{\text{Contribution from renormalization of different parameters and WFR}} = \lambda^{(0)}_{hHH}$$

Tree level

Genuine one-loop contribution

Contribution from renormalization of different parameters and WFR

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

Renormalization scheme: κ_S, κ_{SH}

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

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

Renormalization scheme: v

Definition of the EW vev:

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

The vector boson masses and the fine structure constant are automatically renormalized OS by anyH3

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

Renormalization scheme: α

[S.Kanemura, Y. Okada,E. Senaha, C.P. Yuan, ‘04]

[S. Kanemura, M. Kikuchi, K. Yagyu, ‘15]

KOSY scheme

- Rotate the bare fields and switch to the renormalize fields:

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \mathrm{R}^{\mathrm{T}}_{\alpha^0} \begin{pmatrix} s^0 \\ \phi^0 \end{pmatrix} \to \mathrm{R}^{\mathrm{T}}_{\delta\alpha^{\mathrm{CT}}} \mathrm{R}^{\mathrm{T}}_{\hat{\alpha}} \begin{pmatrix} s^0 \\ \phi^0 \end{pmatrix} = \mathrm{R}^{\mathrm{T}}_{\delta\alpha^{\mathrm{CT}}} \mathrm{R}^{\mathrm{T}}_{\hat{\alpha}} \sqrt{Z_{\phi,s}} \begin{pmatrix} \hat{s} \\ \hat{\phi} \end{pmatrix} = \mathrm{R}^{\mathrm{T}}_{\delta\alpha^{\mathrm{CT}}} \mathrm{R}^{\mathrm{T}}_{\hat{\alpha}} \sqrt{Z_{\phi,s}} \mathrm{R}_{\hat{\alpha}} \mathrm{R}^{\mathrm{T}}_{\hat{\alpha}} \begin{pmatrix} \hat{s} \\ \hat{\phi} \end{pmatrix} =$$

$$= \mathrm{R}^{\mathrm{T}}_{\delta\alpha^{\mathrm{CT}}} \mathrm{R}^{\mathrm{T}}_{\hat{\alpha}} \sqrt{Z_{\phi,s}} \mathrm{R}_{\hat{\alpha}} \begin{pmatrix} \hat{h} \\ \hat{H} \end{pmatrix} = \sqrt{\tilde{Z}} \begin{pmatrix} \hat{h} \\ \hat{H} \end{pmatrix} = \sqrt{Z} \begin{pmatrix} \hat{h} \\ \hat{H} \end{pmatrix}$$

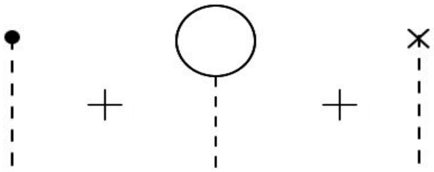
- Equate the fields renormalization matrices:

$$\sqrt{\tilde{Z}} = \mathrm{R}^{\mathrm{T}}_{\delta\alpha^{\mathrm{CT}}} \mathrm{R}^{\mathrm{T}}_{\hat{\alpha}} \sqrt{Z_{\phi,s}} \mathrm{R}_{\hat{\alpha}} = \begin{pmatrix} 1 + \frac{\delta Z_{hh}}{2} & \delta C_{hH} - \delta\alpha^{\mathrm{CT}} \\ \delta C_{Hh} + \delta\alpha^{\mathrm{CT}} & 1 + \frac{\delta Z_{HH}}{2} \end{pmatrix} = \sqrt{Z}$$

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

Renormalization scheme: t_ϕ, t_s

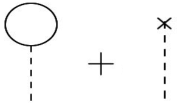
$$\hat{t}_i^{(1)} = t_i^{(0)} + \delta t_i^{(1)} + \delta t_i^{CT} = 0$$



OS:

$$t_i^{(0)} = 0$$

$$\delta t_i^{(1)} + \delta t_i^{CT} = 0$$



$$\delta^{CT} t_\phi = -(\cos(\alpha)\delta^{(1)} t_h|^{\text{FIN}} - \sin(\alpha)\delta^{(1)} t_H|^{\text{FIN}})$$
$$\delta^{CT} t_s = -(\sin(\alpha)\delta^{(1)} t_h|^{\text{FIN}} + \cos(\alpha)\delta^{(1)} t_H|^{\text{FIN}})$$

SFOEWPT: Veff def

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

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

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

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

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

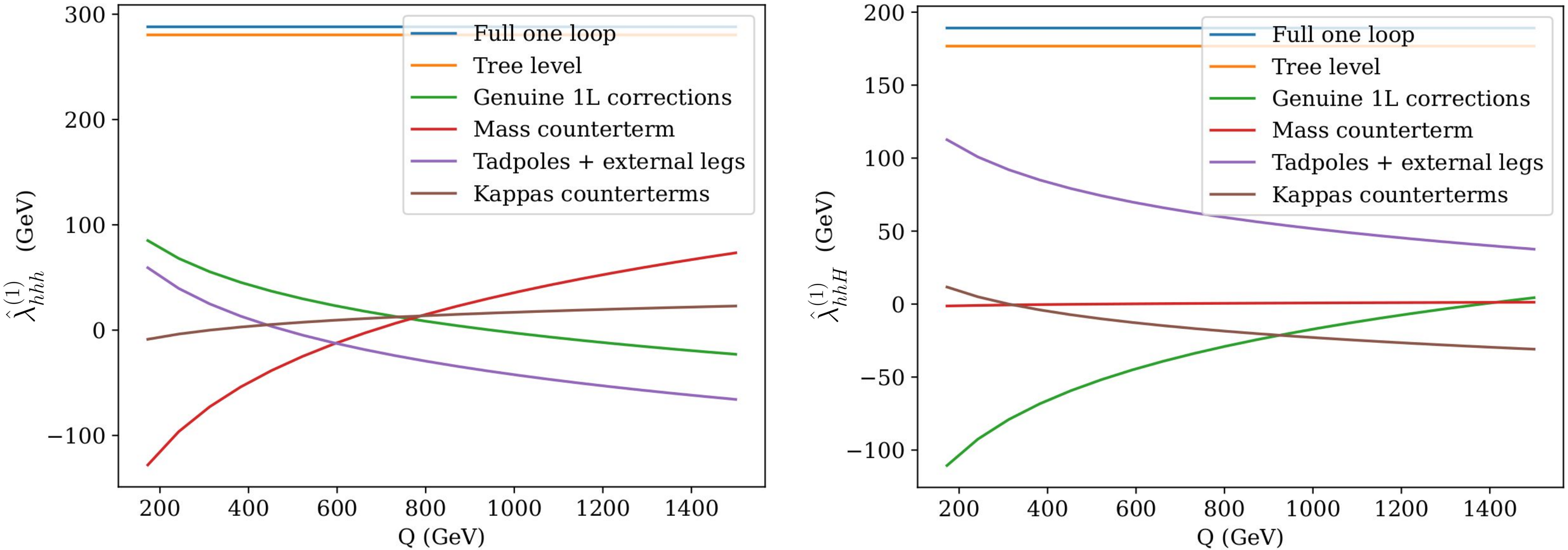
$$\partial_{\phi_i}\partial_{\phi_j} V_{\text{CT}}(\phi)\Big|_{\langle\phi\rangle_{T=0}} = -\partial_{\phi_i}\partial_{\phi_j} V_{\text{CW}}(\phi)\Big|_{\langle\phi\rangle_{T=0}}$$

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.

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

Renormalization scheme: Q dependence



No Q dependence in the OS results

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

SFOEWPT: Veff def

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

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

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