Sensitivity to New Physics in Higgs Observables

based on work in progress (H. Bahl, J. Braathen, M. Gabelmann, S. Heinemeyer, K. R. , A. Verduras and G. Weiglein)

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KUTS15 @ KIT

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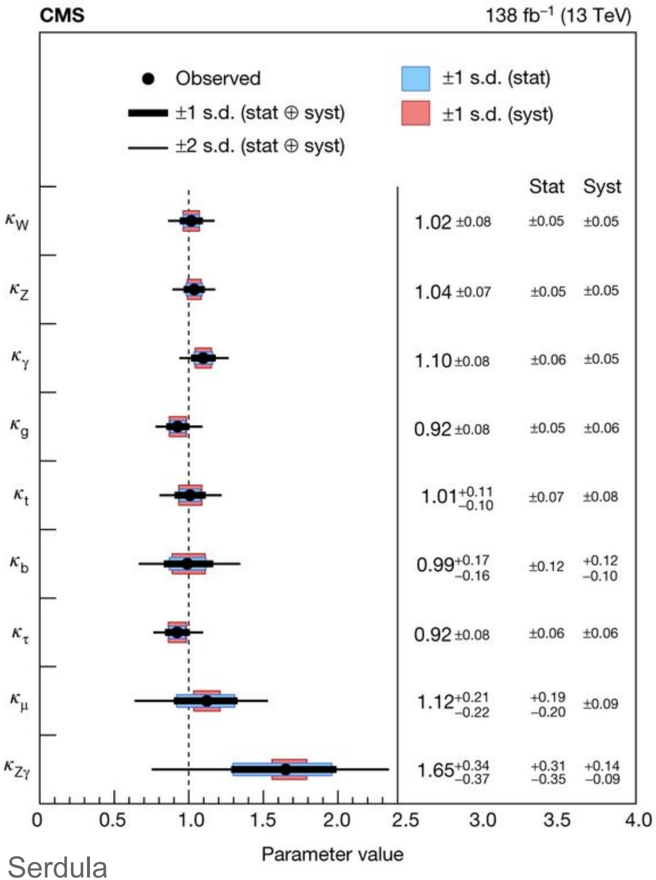
Obra Social Fundación "la Caixa"

Higgs properties

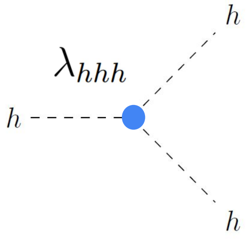


CMS: Nature 2022

The new particle seems to be **a** Higgs boson ... but is it **the SM** Higgs boson?

Without the measurement of the **trilinear Higgs coupling** the shape of the potential is unknown!

$$[-0.71 < \kappa_\lambda < 6.1]$$



ATLAS: arXiv 2602.23991

Notation:

$$\kappa_\lambda = \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}(0)}$$

Motivation: in which observable can we see new physics first?

Trilinear Higgs coupling κ_λ or single Higgs couplings such as g_{hZZ}?

Current limits:

ATLAS and CMS: arXiv 2602.23991

$[-0.71 < \kappa_\lambda < 6.1]$ at 95% C.L.

$[0.97 < \kappa_Z < 1.11]$ at 95% C.L.

Projected limits:

ATLAS and CMS: arXiv 2504.00672

HL-LHC

$[0.73 < \kappa_\lambda < 1.29]$ at 68% C.L. for κ_λ=1

$[0.982 < \kappa_Z < 1.018]$ at 68% C.L.

FCC-ee

$[0.7 \lesssim \kappa_\lambda \lesssim 1.3]$ at 68% C.L. Maura, Stefanek, You: arXiv: 2503.13719

$[0.9969 < \kappa_Z < 1.0031]$ at 95% C.L. FCC Collaboration

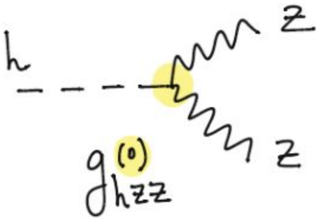
Notation:

$$\kappa_\lambda = \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}(0)}$$

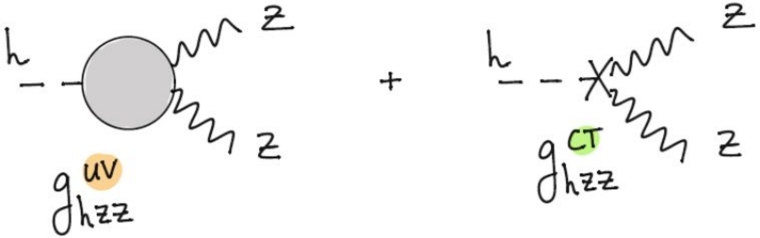
$$\kappa_Z = g_{hZZ}/g_{hZZ}^{\mathrm{SM}(0)}$$

hZZ coupling

* tree level



* one loop

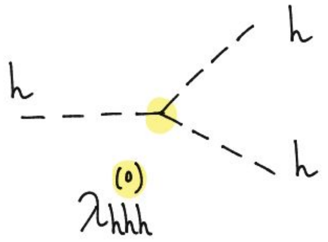


$$\Delta g_{hZZ}^{(1)} = g_{hZZ}^{UV} + g_{hZZ}^{CT}$$

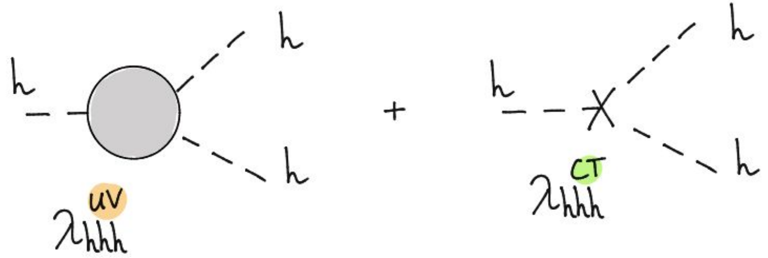
$$g_{hZZ}^{(1)} = g_{hZZ}^{(0)} + \Delta g_{hZZ}^{(1)} = g_{hZZ}^{(0)} \left(1 + \delta g_{hZZ}^{(1)}\right)$$

Trilinear coupling

* <u>tree level</u>



* <u>one loop</u>

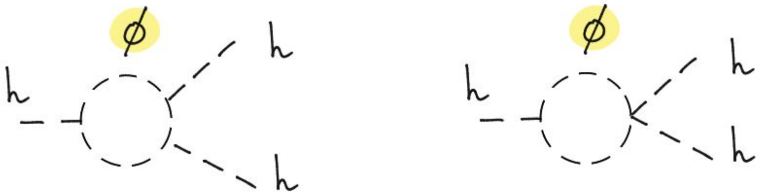


$$\Delta\lambda_{hhh}^{(1)} = \lambda_{hhh}^{UV} + \lambda_{hhh}^{CT}$$

$$\lambda_{hhh}^{(1)} = \lambda_{hhh}^{(0)} + \Delta\lambda_{hhh}^{(1)} = \lambda_{hhh}^{(0)}\left(1 + \delta\lambda_{hhh}^{(1)}\right)$$

Radiative corrections to the trilinear couplings

Large loop effects caused by **heavy New Physics:** ϕ



$$g_{hh\phi\phi} = \frac{2(m_\phi^2 - M_{BSM}^2)}{v^2}$$

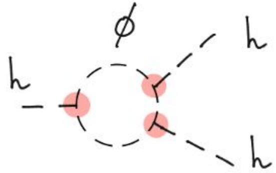
e.g. in the 2HDM: $\phi \in \{A, H, H^\pm\}$

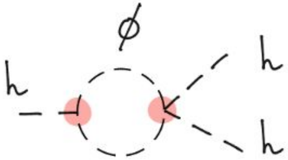
Kanemura, Kiyoura, Okada, Senaha, Yuan: arXiv: 0211308
Kanemura, Okada, Senaha, Yuan: arXiv:0408364

Power counting large BSM contributions: hhh

$\boxed{\lambda_{hhh}}$

$$\boxed{m_\phi^2 = \mathcal{M}^2_{BSM} + \frac{1}{2} g_{hh\phi\phi} v^2}$$





$$\propto (g_{hh\phi\phi} v)^3 \cdot C_0(\dots)$$

$$\sim \frac{(g_{hh\phi\phi} v)^3}{m_\phi^2} \longrightarrow \mathcal{O}(g^2_{hh\phi\phi})$$

$$g_{hh\phi\phi} v^2 \gg \mathcal{M}^2_{BSM}$$

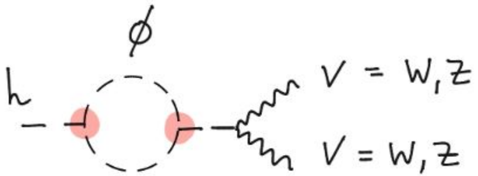
$$\propto g_{hh\phi\phi} v \cdot \underbrace{B_0(\dots)}_{\text{mass dim. } 0} \sim \mathcal{O}(g^2_{hh\phi\phi})$$

See also EFT arguments, e.g. talkby McCullough at ICHEP 2024

Power counting large BSM contributions: hVV

$\boxed{g_{hVV}}$

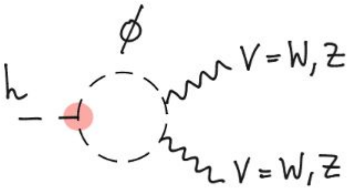
$$\boxed{m_\phi^2 = \mathcal{M}_{BSM}^2 + \frac{1}{2} g_{hh\phi\phi} v^2}$$



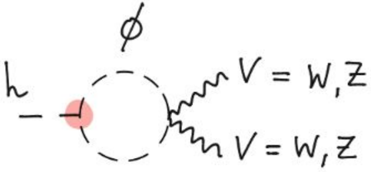
$$\propto (g_{hh\phi\phi} v)^2 \cdot g_{EW} \cdot B_0'(\ldots)$$

$$\sim \frac{(g_{hh\phi\phi} v)^2}{m_\phi^2} \longrightarrow \mathcal{O}(g_{hh\phi\phi})$$

$g_{hh\phi\phi} v^2 \gg \mathcal{M}_{BSM}^2$



or



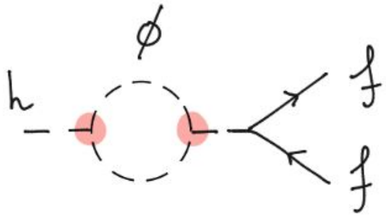
$$\propto g_{hh\phi\phi} v \cdot g_{EW}^2 \cdot \{ \underbrace{C_{\mu\nu}(\ldots) \text{ or } B_0(\ldots)}_{\text{mass dim. 0}} \} \sim \mathcal{O}(g_{hh\phi\phi})$$

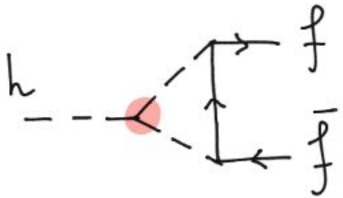
See also EFT arguments, e.g. talkby McCullough at ICHEP 2024

Power counting large BSM contributions: hff

$\boxed{g_{hf\bar{f}}}$

$\boxed{m_\phi^2 = M_{BSM}^2 + \frac{1}{2} g_{hh\phi\phi} v^2}$





$\propto (g_{hh\phi\phi} v)^2 \cdot y_f \cdot B_0'(\dots) \sim \mathcal{O}(g_{hh\phi\phi})$

$\sim \frac{(g_{hh\phi\phi} v)^2}{m_\phi^2} \longrightarrow \mathcal{O}(g_{hh\phi\phi})$

$g_{hh\phi\phi} v^2 \gg M_{BSM}^2$

$\propto g_{hh\phi\phi} v \cdot y_f^2 \cdot C_0(\dots)$

$\sim \frac{g_{hh\phi\phi} m_f v}{m_\phi^2} \longrightarrow \mathcal{O}(g_{hh\phi\phi}^0)$

$g_{hh\phi\phi} v^2 \gg M_{BSM}^2$

See also EFT arguments, e.g. talkby McCullough at ICHEP 2024

Two Higgs Doublet Model (2HDM)

T. D. Lee (1973) Phys. Rev. D
Branco, Ferreira et al: arXiv: 1106.0034

- two complex doublets: $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$

$$V_{2\mathrm{HDM}}^{\mathrm{tree}} = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}\left((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right)$$

- CP conserving 2HDM
- softly broken $\mathbb{Z}_2$ symmetry: $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$
- entails 4 Yukawa types (how Higgses couple to fermions)

Two Higgs Doublet Model (2HDM)

T. D. Lee (1973) Phys. Rev. D
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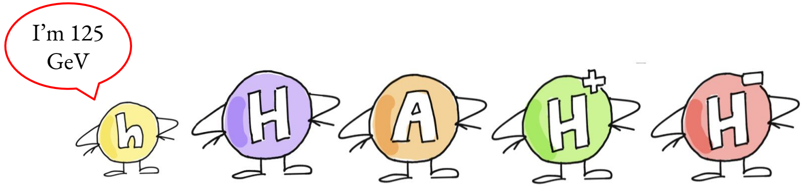


Free parameters
5 unkown: $\boxed{m_{12}^2}$ or $M \equiv m_{12}/\sqrt{\sin\beta\cos\beta}$

$\boxed{m_H}$, $\boxed{m_A}$, $\boxed{m_{H^\pm}}$

$\boxed{\tan\beta} \equiv v_2/v_1$, $\boxed{\cos(\beta-\alpha)} \longrightarrow 0$

alignment limit :  = SM at tree level

2 known: $\boxed{v} = \sqrt{v_1^2 + v_2^2} \simeq 246\,\mathrm{GeV}$, $\boxed{m_h} \simeq 125\,\mathrm{GeV}$

hZZ coupling in the 2HDM

* tree level

$$g_{hZZ}^{(0)} = \frac{e \cdot M_W}{\sin\theta \cos^2\theta} \sin(\alpha-\beta) = g_{hZZ}^{SM(0)} \sin(\alpha-\beta)$$

$$g_{HZZ}^{(0)} = \frac{e \cdot M_W}{\sin\theta \cos^2\theta} \cos(\alpha-\beta) = g_{HZZ}^{SM(0)} \cos(\alpha-\beta)$$

* one loop

$$\delta g_{hZZ}^{(1)} = \frac{1}{g_{hZZ}^{(0)}} \Bigg(\frac{\partial g_{hZZ}^{(0)}}{\partial e} \delta Z_e + \frac{\partial g_{hZZ}^{(0)}}{\partial \sin\theta} \delta s_\theta + \frac{\partial g_{hZZ}^{(0)}}{\partial M_W} \delta M_W + \underbrace{g_{hZZ}^{(0)} \delta Z_{ZZ} + g_{hZZ}^{(0)} \frac{\delta Z_{hh}}{2}}_{\text{WFR}} \Bigg\} \text{SM-like}$$

$$+ \frac{\partial g_{hZZ}^{(0)}}{\partial \alpha} \delta\alpha + \frac{\partial g_{hZZ}^{(0)}}{\partial \beta} \cdot \delta\beta + \underbrace{g_{HZZ}^{(0)} \delta Z_{Hh}}_{\text{WFR}} \Bigg) \Bigg\} \text{BSM}$$

SM-like counterterms

$$\boxed{g_{hZZ}^{(1)} \propto \left(\frac{\partial g_{hZZ}^{(0)}}{\partial e} \delta Z_e + \frac{\partial g_{hZZ}^{(0)}}{\partial \sin\theta} \delta s_\theta + \frac{\partial g_{hZZ}^{(0)}}{\partial M_W} \delta M_W + g_{hZZ}^{(0)} \delta Z_{ZZ} + g_{hZZ}^{(0)} \frac{\delta Z_{hh}}{2} \right)}$$

- $$\delta Z_e = -\frac{1}{2} \delta Z_{AA} - \frac{\sin\theta}{\cos\theta} \frac{1}{2} \delta Z_{ZA} = \frac{1}{2} \frac{\partial \Sigma_T^{AA}(p^2)}{\partial p^2}\bigg|_{p^2=0} - \frac{\sin\theta}{\cos\theta} \frac{\Sigma_T^{AZ}(0)}{M_Z^2}$$
- $$\frac{\delta s_\theta}{\sin\theta} = \frac{-\cos^2\theta}{\sin^2\theta} \frac{\delta c_\theta}{\cos\theta} = -\frac{1}{2} \frac{\cos^2\theta}{\sin^2\theta} \left(\frac{\Sigma_T^W(M_W^2)}{M_W^2} - \frac{\Sigma_T^Z(M_Z^2)}{M_Z^2} \right)$$
- $$\delta M_W^2 = \Sigma_T^W(M_W^2)$$
- $$\delta Z_{ZZ} = \frac{-\partial \Sigma_{ZZ}(p^2)}{\partial p^2}\bigg|_{p^2=M_Z^2}$$
- $$\delta Z_{hh} = \frac{-\partial \Sigma_{hh}(p^2)}{\partial p^2}\bigg|_{p^2=m_h^2}$$

Denner: arXiv: 0709.1075

BSM counterterms

$$\boxed{g_{hZZ}^{(1)} \propto \frac{\partial g_{hZZ}^{(0)}}{\partial \alpha}\,\delta\alpha + \frac{\partial g_{hZZ}^{(0)}}{\partial \beta}\,\delta\beta + g_{HZZ}^{(0)}\,\delta Z_{Hh}\;)}$$

- $$\delta\alpha = \frac{\Sigma_{Hh}(m_h^2) + \Sigma_{Hh}(m_h^2)}{2(m_h^2 - m_H^2)}$$
- $$\delta\beta = \frac{\Sigma_{G^\pm H^\pm}(m_{G^\pm}^2) + \Sigma_{G^\pm H^\pm}(m_{H^\pm}^2)}{2(m_{G^\pm}^2 - m_{H^\pm}^2)}$$
- $$\delta Z_{Hh} = \frac{\Sigma_{Hh}(m_h^2)}{(m_h^2 - m_H^2)}$$

→ this is a version of an OS scheme, see also:

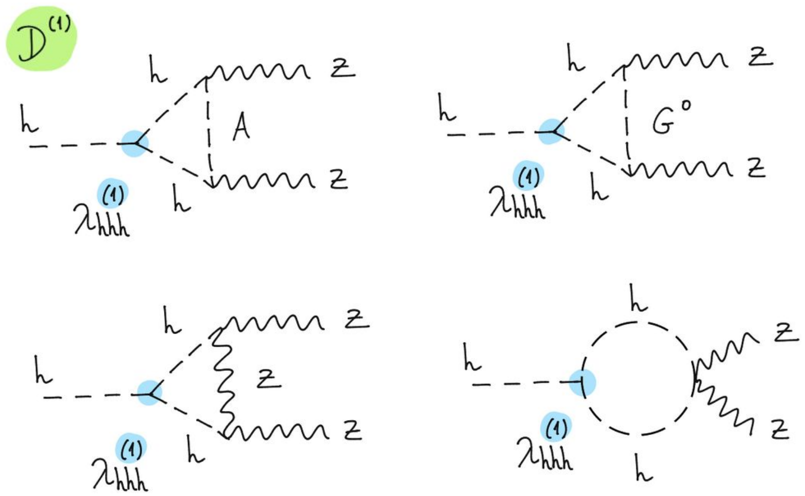
Kanemura et al. arXiv: 0408364

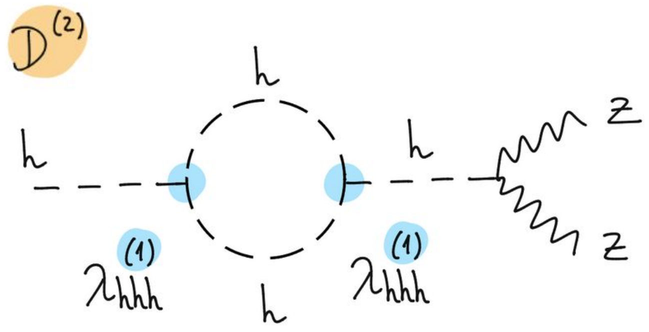
Krause et al. arXiv: 1605.04853

Denner et al. arXiv: 1808.03466

Kanemura et al. arXiv: 1705.05399

Higher order effects

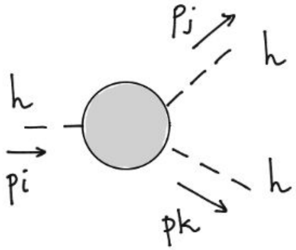




* <u>higher order corrections</u> $g_{hZZ}^{(eff)} = g_{hZZ}^{(0)} + \Delta g_{hZZ}^{(1)} + \left(\frac{\lambda_{hhh}^{(1)}}{\lambda_{hhh}^{(0)}} - 1\right) D^{(1)} + \left(\left(\frac{\lambda_{hhh}^{(1)}}{\lambda_{hhh}^{(0)}}\right)^2 - 1\right) D^{(2)}$

Both are UV-finite contributions

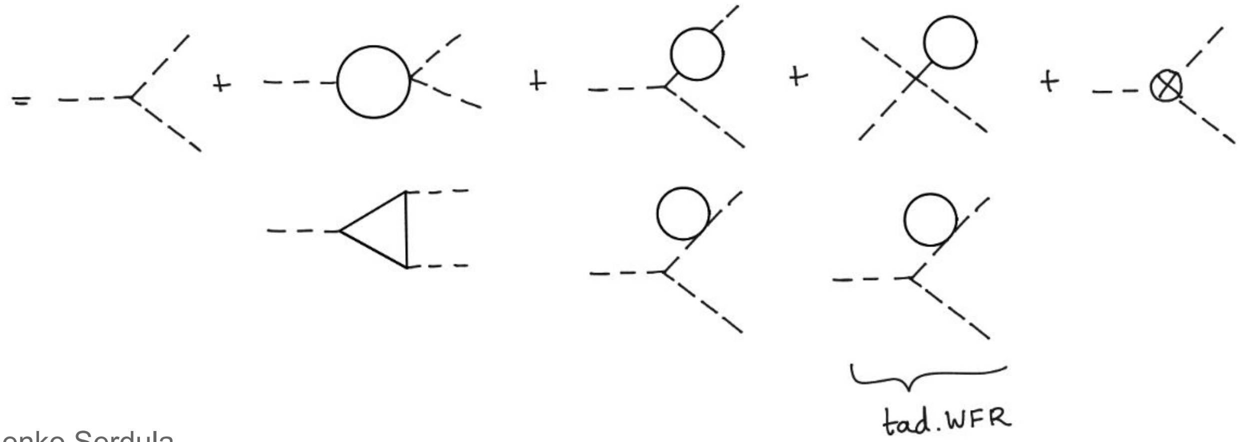
Contributions to the one-loop trilinear coupling



Automatized and computed in anyH3:

Bahl, Braathen, Gabelmann, Weiglein: arXiv: 2305.03015
Bahl, Braathen, Gabelmann, R. , Weiglein: TBP

$$= \lambda_{hhh}^{(0)} + \delta_{gen}^{(1)} \lambda_{hhh} + \delta_{WFR}^{(1)} \lambda_{hhh} + \delta_{tad}^{(1)} \lambda_{hhh} + \delta_{CT}^{(1)} \lambda_{hhh}$$



hhh coupling in the 2HDM

* tree level

$$\lambda_{hhh}^{(0)} = \frac{-1}{4v}\frac{3}{\sin\beta\cos\beta}\left[(M^2-m_h^2)\cos(3\alpha-\beta)+(2M^2-3m_h^2)\cos(\alpha-\beta)+M^2\cos(\alpha-3\beta)\right]+\text{tad.}$$

$$\lambda_{hhH}^{(0)} = \frac{1}{2v}\frac{\cos(\alpha-\beta)}{\sin\beta\cos\beta}\left[\sin(2\alpha)\cdot(-3M^2+2m_h^2+m_H^2)+M^2\sin(2\beta)\right]+\text{tad.}$$

* one loop

$$v = 2M_W\sin\theta/e$$

$$\delta\lambda_{hhh}^{(1)} = \frac{1}{\lambda_{hhh}^{(0)}}\left(\overbrace{\delta Z_e-\frac{\delta s_\theta}{\sin\theta}-\frac{1}{2}\frac{\delta M_W^2}{M_W^2}}+\frac{3}{2}\delta Z_{hh}\right)+3\lambda_{hhH}^{(0)}\frac{\delta Z_{Hh}}{2}$$

$$+\frac{\partial\lambda_{hhh}^{(0)}}{\partial m_h^2}\delta m_h^2+\frac{\partial\lambda_{hhh}^{(0)}}{\partial M^2}\delta M^2+\frac{\partial\lambda_{hhh}^{(0)}}{\partial\alpha}\delta\alpha+\frac{\partial\lambda_{hhh}^{(0)}}{\partial\beta}\delta\beta+\frac{\partial\lambda_{hhh}^{(0)}}{\partial t_h}\delta t_h+\frac{\partial\lambda_{hhh}^{(0)}}{\partial t_H}\delta t_H$$

OS renormalization conditions in the 2HDM

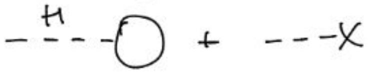
① Renormalize the tadpoles:

Condition:

- $\hat{T}_h = \underbrace{\text{tad}h}_{=0 \text{ at tree level}} + T_h + \delta t \overset{!}{=} 0 \Rightarrow \text{CT}: \; \delta t_h^{OS} = -T_h$

renormalized 1 point function

unrenormalized one poin function



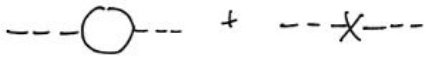
- $\hat{T}_H = \underbrace{\text{tad}H}_{=0} + T_H + \delta t \overset{!}{=} 0 \Rightarrow \text{CT}: \; \delta t_H^{OS} = -T_H$

In anyH3 they need to be rotated from the mass basis to the interaction basis

OS renormalization conditions in the 2HDM

(2) Renormalize the masses :

TPF: $$\hat{\Sigma}_{hh}(p^2) = \Sigma_{hh}(p^2) - \delta m_h^2 + (p^2 - m_h^2)\,\delta Z_{hh}$$



Condition :

- $\mathrm{Re}\,\hat{\Sigma}_{hh}(m_h^2) \stackrel{!}{=} 0 \Rightarrow$ CT : $\delta m_h^{2\,OS} = \mathrm{Re}\left(\Sigma_{hh}(m_h^2)\right)$

- $\mathrm{Re}\,\hat{\Sigma}_{HH}(m_H^2) \stackrel{!}{=} 0 \Rightarrow$ CT : $\delta m_H^{2\,OS} = \mathrm{Re}\left(\Sigma_{HH}(m_H^2)\right)$

Automatic in anyH3

OS renormalization conditions in the 2HDM

③ Renormalize the fields

Condition :

- $\left.\frac{\partial \hat{\Sigma}_{hh} = 0}{\partial p^2}\right|_{p^2 = m_h^2} \stackrel{!}{=} 0 \Rightarrow$ CT : $\delta Z_{hh}^{OS} = \left.\frac{- \partial \Sigma_{hh}(p^2)}{\partial p^2}\right|_{p^2 = m_h^2}$

- $\left.\frac{\partial \hat{\Sigma}_{HH} = 0}{\partial p^2}\right|_{p^2 = m_H^2} \stackrel{!}{=} 0 \Rightarrow$ CT : $\delta Z_{HH}^{OS} = \left.\frac{- \partial \Sigma_{HH}(p^2)}{\partial p^2}\right|_{p^2 = m_H^2}$

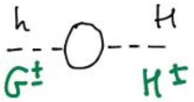
Automatic in anyH3

OS renormalization conditions in the 2HDM

- off diagonal field renormalization: α / β

KOSY: arXiv:0408364

$$\hat{\Sigma}_{hH}(p^2) = \Sigma_{hH}(p^2) + (p^2 - m_h^2)\frac{\delta Z_{hH}}{2} + (p^2 - m_H^2)\frac{\delta Z_{Hh}}{2}$$



[Defining $\frac{\delta Z_{Hh}}{2} \equiv \delta C_h + \delta\alpha$; $\frac{\delta Z_{hH}}{2} = \delta C_h - \delta\alpha$]

- $\hat{\Sigma}_{hH}(p^2 = m_h^2) \stackrel{!}{=} 0 \Rightarrow 0 = \Sigma_{hH}(m_h^2) + (m_h^2 - m_H^2)\delta C_h + (m_h^2 - m_H^2)\delta\alpha$

- $\hat{\Sigma}_{hH}(p^2 = m_H^2) \stackrel{!}{=} 0 \Rightarrow 0 = \Sigma_{hH}(m_H^2) - (m_h^2 - m_H^2)\delta C_h + (m_h^2 - m_H^2)\delta\alpha$

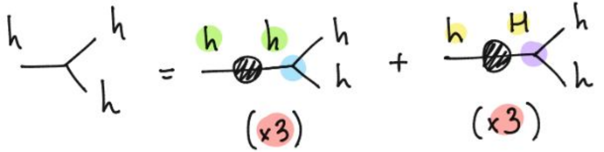
OS renormalization conditions in the 2HDM

- off diagonal field renormalization: α / β

KOSY: arXiv:0408364

$$\delta\alpha = \frac{\left(\Sigma_{Hh}(m_h^2) + \Sigma_{Hh}(m_H^2)\right)}{2(m_h^2 - m_H^2)}$$

$$\delta\beta = \frac{\Sigma_{H^\pm G^\pm}(m_{G^\pm}^2) + \Sigma_{H^\pm G^\pm}(m_{H^\pm}^2)}{2(m_{G^\pm}^2 - m_{H^\pm}^2)}$$



$$\delta Z_{Hh} = \frac{\Sigma_{Hh}(m_h^2)}{(m_h^2 - m_H^2)}$$

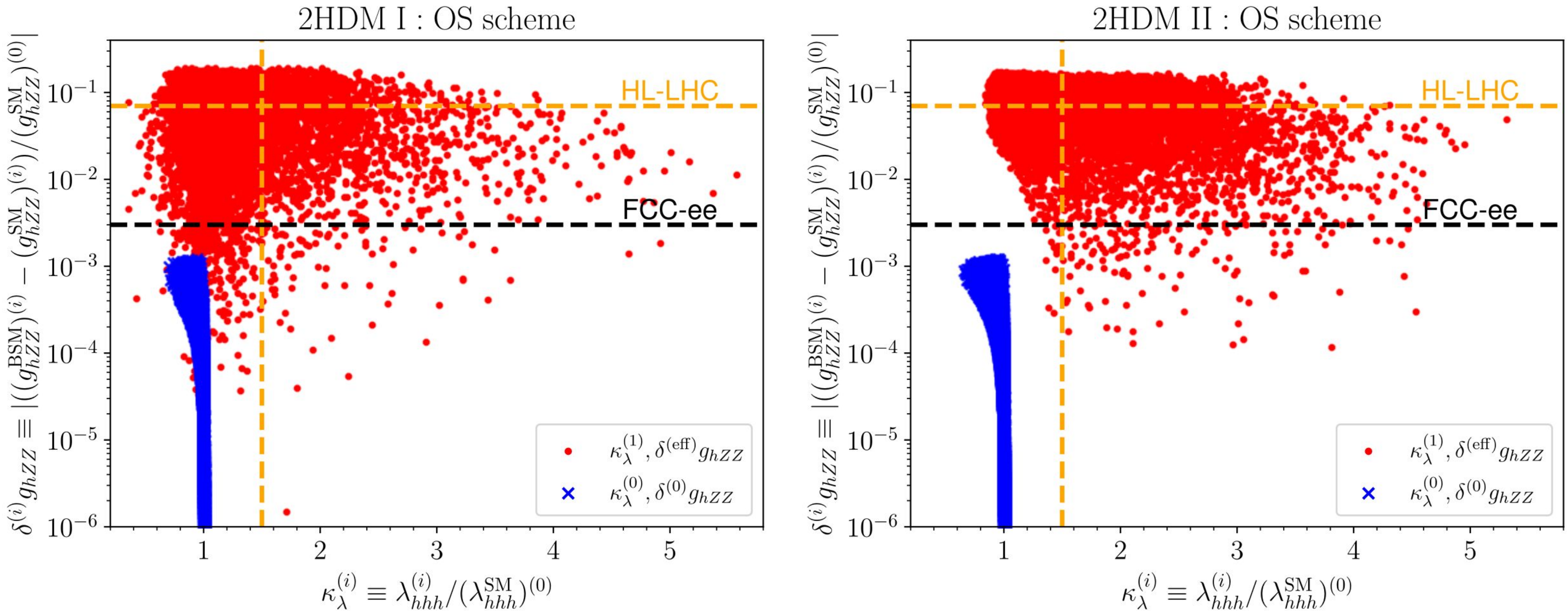
$$\delta Z_{hH} = \frac{\Sigma_{hH}(m_H}{(m_H^2 - m_h}$$

$$\delta\lambda_{hhh}^{WFR} = 3 \cdot \frac{1}{2} Z_{hh}(m_h^2)\lambda_{hhh} + 3 \cdot \frac{1}{2} Z_{hH}(m_h^2)\lambda_{hhH}$$

- Counterterm for M in $\overline{\text{MS}}$-scheme to cancel UV divergencies in the trilinear coupling

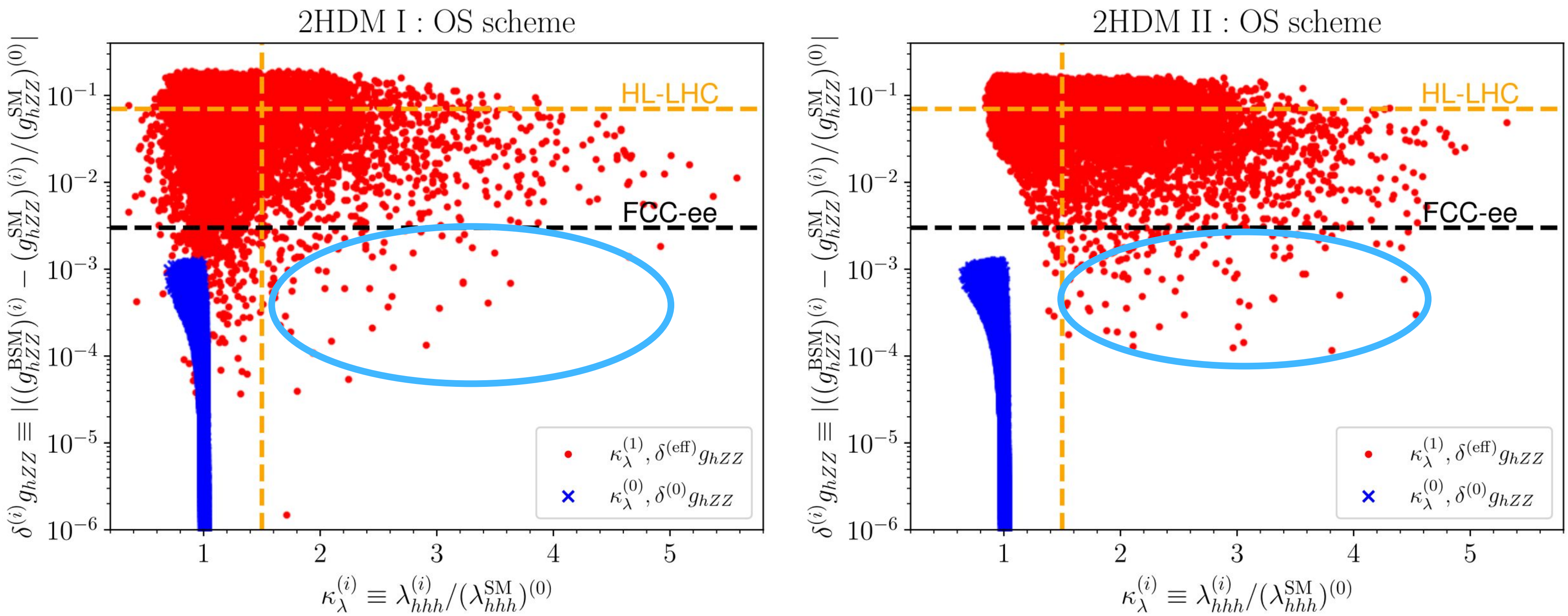
Self-energies are automatic, mixing angles and other parameters are user defined in anyH3

2HDM general scan



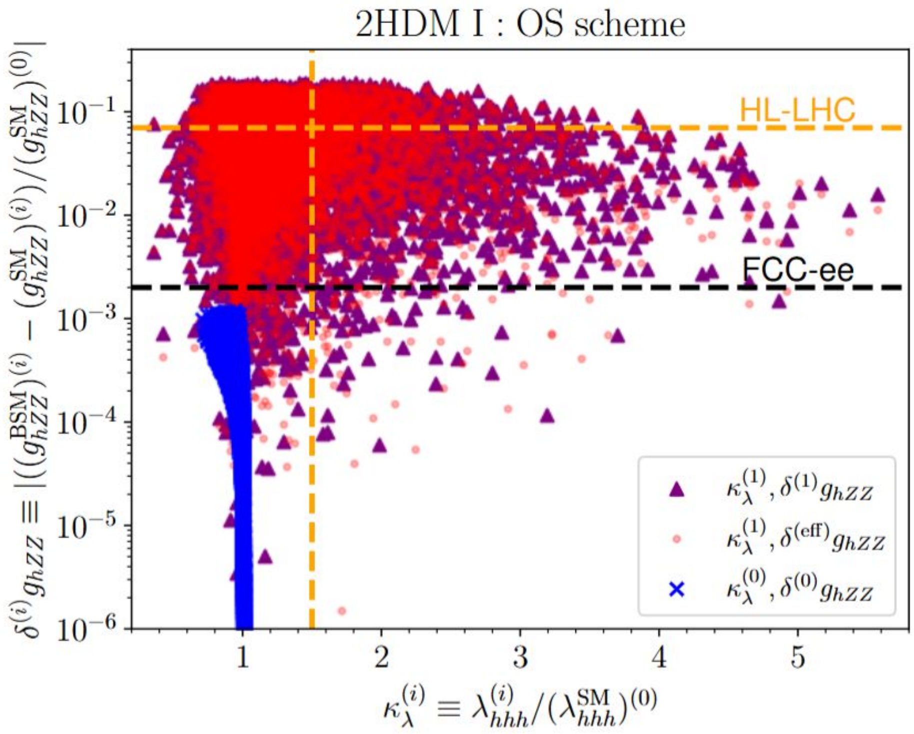
Vertical lines are the projected HL-LHC sensitivity assuming $\kappa_\lambda = 1$

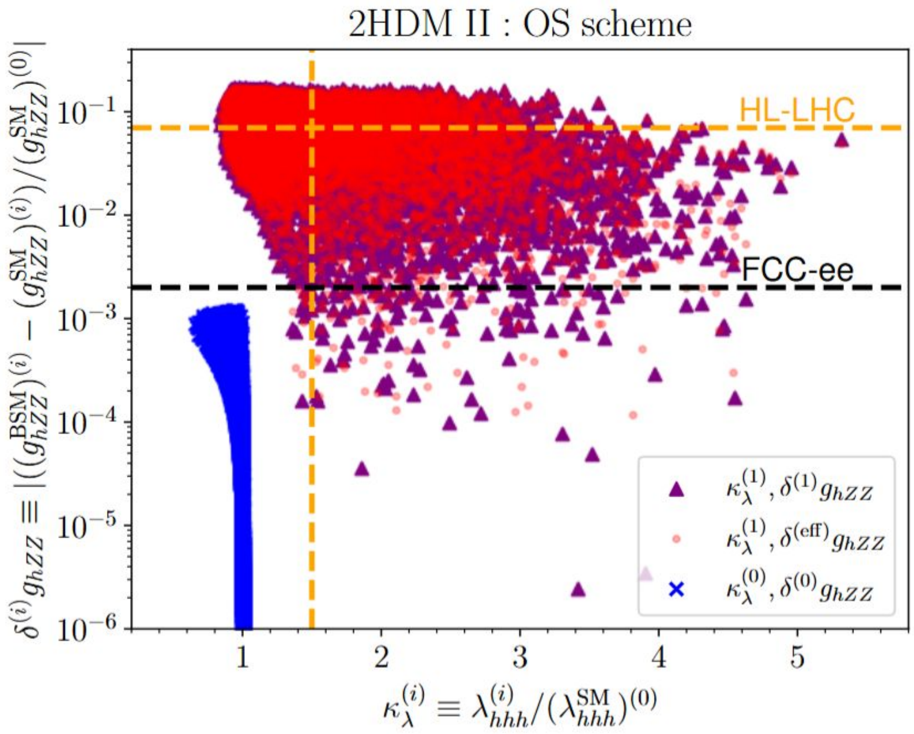
2HDM general scan



Vertical lines are the projected HL-LHC sensitivity assuming $\kappa_\lambda = 1$

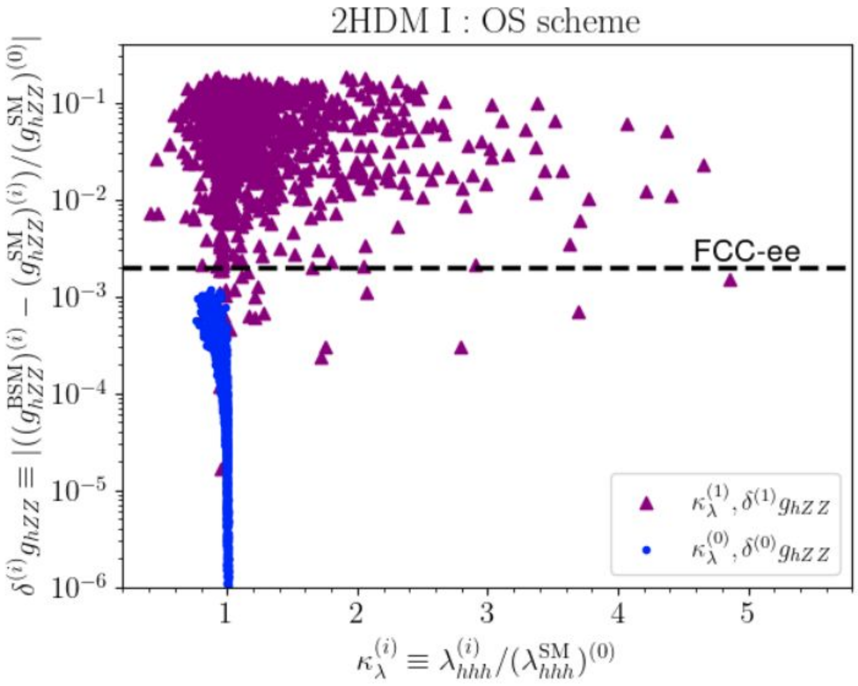
2HDM one loop VS higher order effects

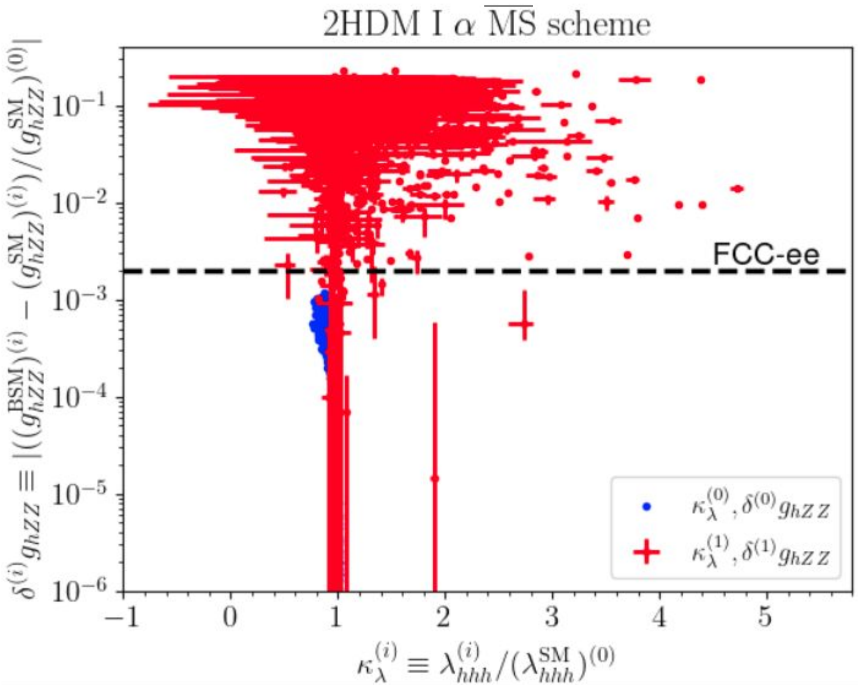




Vertical lines are the projected HL-LHC sensitivity assuming $\kappa_\lambda = 1$

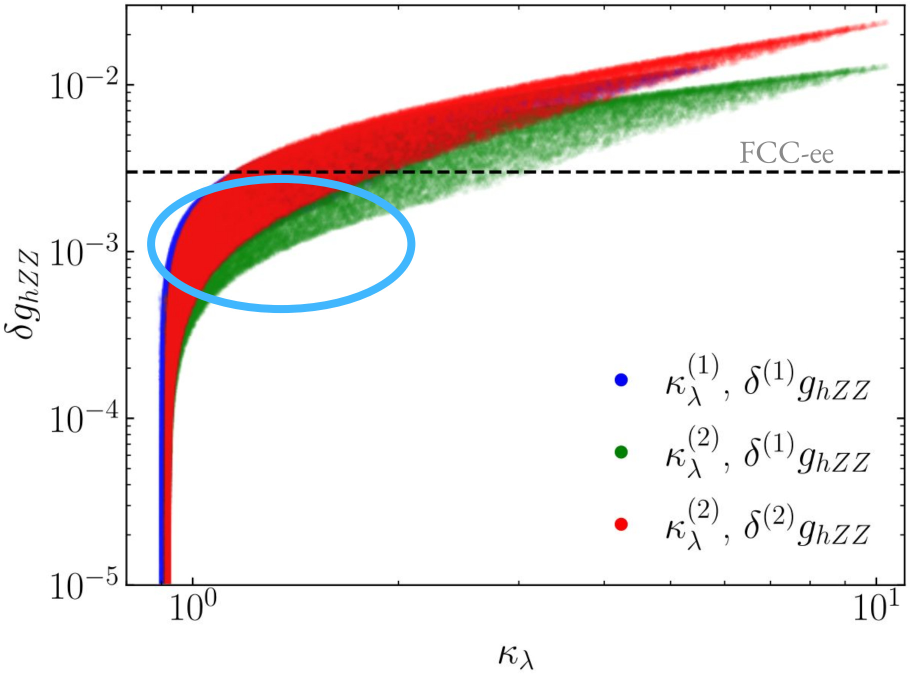
2HDM scheme comparison





$\mathbb{Z}_2$SSM

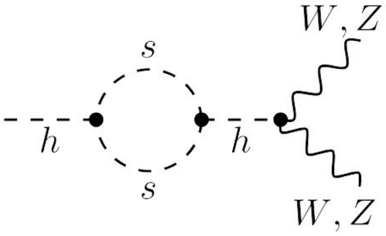
$\mathbb{Z}_2$ -symmetric real singlet extension of the SM: $V_{\mathrm{SSM}-\mathbf{Z}_2}(\Phi, S) = V_{\mathrm{SM}}(\Phi) + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \lambda_{S\Phi} S^2 \Phi^\dagger \Phi$



$$\boxed{m_S^2 = \mu_S^2 + \lambda_{S\Phi} v^2} \qquad \lambda_\Phi = \frac{m_H^2}{v^2}$$

$$\Delta\kappa_\lambda^{(1)} = \frac{\lambda_{hhh}^{(1)}}{\lambda_{hhh}^{\mathrm{SM}}} - 1 = \frac{1}{(4\pi)^2} \frac{4}{3} \frac{m_S^4}{v^4 \lambda_\Phi} \left(1 - \frac{\mu_S^2}{m_S^2}\right)^3$$

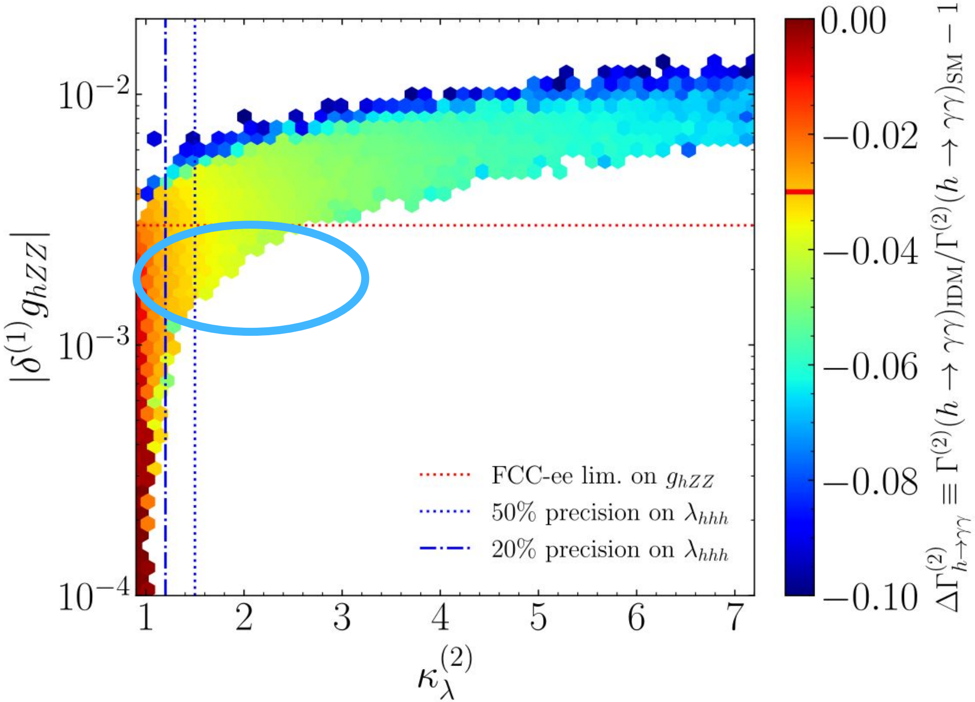
$$c_{\mathrm{eff}}^{(1)} = \frac{g_{hXX}}{g_{hXX}^{\mathrm{SM}}} - 1 = -\frac{1}{(4\pi)^2} \frac{m_S^2}{6v^2} \left(1 - \frac{\mu_S^2}{m_S^2}\right)^2$$

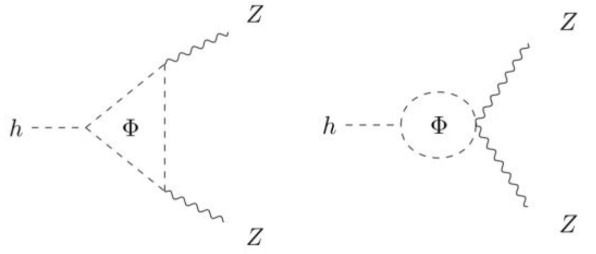


Compact expressions at 2 loops in backup

IDM

Inert Doublet Model: $V_{\rm IDM} = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\left[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right]$





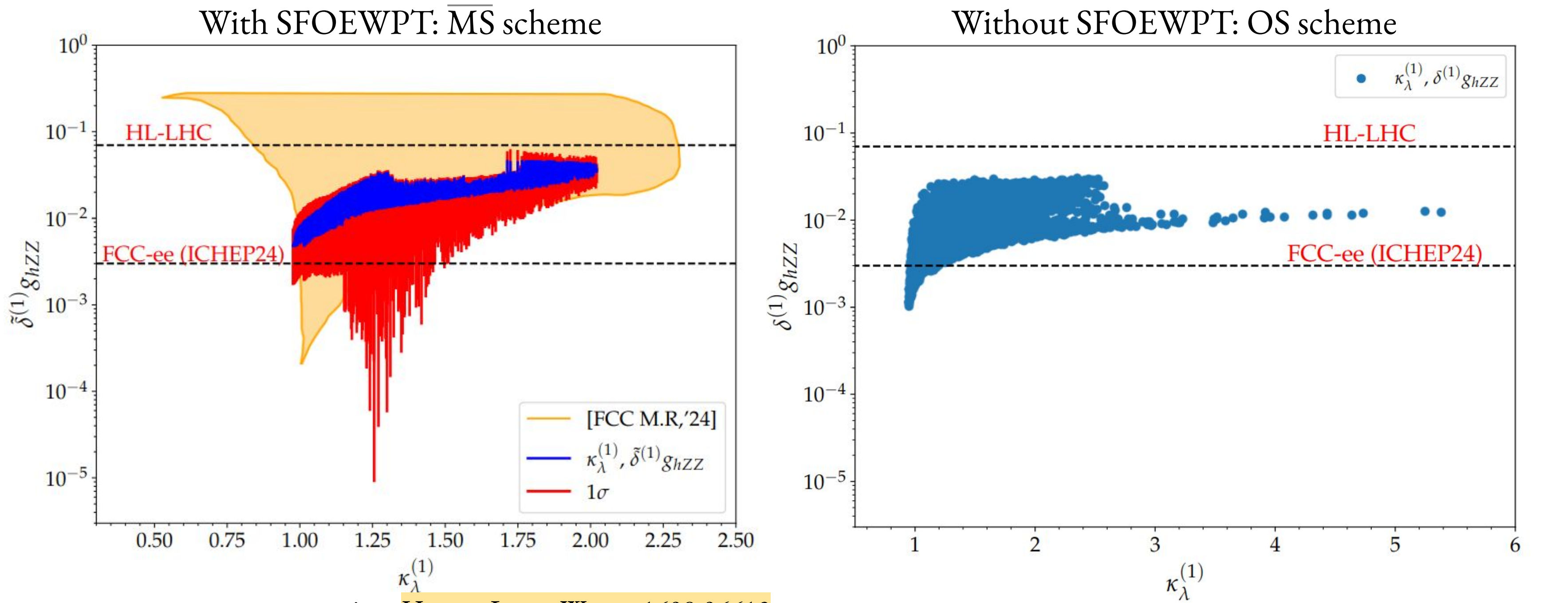
$\phi \in \{A, H, H^\pm\}$

$$\boxed{m_\phi^2 = \mu_2^2 + \lambda_\phi v^2}$$

Vertical lines are the projected HL-LHC sensitivity assuming $\kappa_\lambda = 1$

RxSM

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

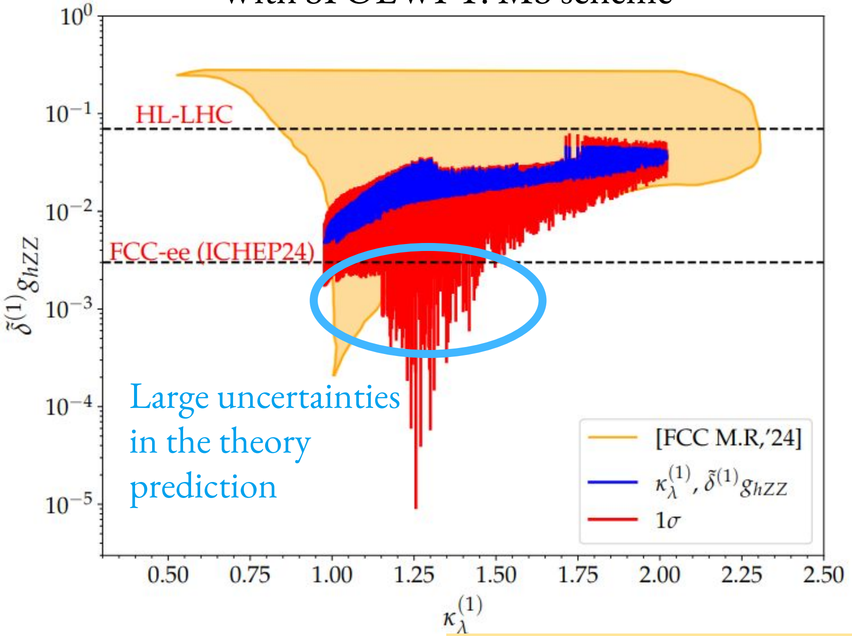


orange region: Huang, Long, Wang.: 1608.06619

RxSM

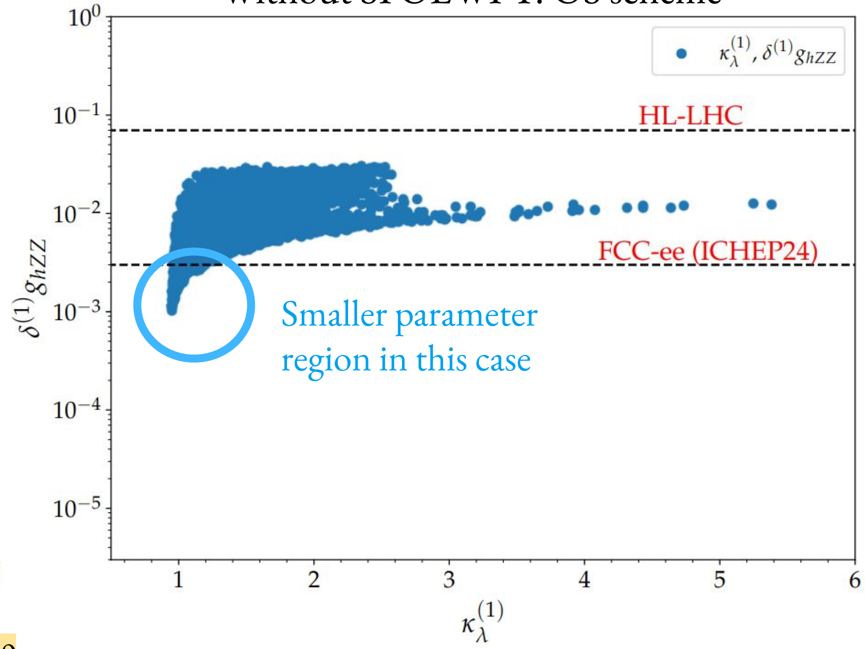
Real singlet extension: $V(\Phi, S) = \mu^2|\Phi|^2 + \frac{\lambda}{2}|\Phi|^4 + \kappa_{SH}|\Phi|^2 S + \frac{\lambda_{SH}}{2}|\Phi|^2 S^2 + \frac{M_S^2}{2} S^2 + \frac{\kappa_S}{3} S^3 + \frac{\lambda_S}{2} S^4$

With SFOEWPT: $\overline{\text{MS}}$ scheme



orange region: Huang, Long, Wang.: 1608.06619

Without SFOEWPT: OS scheme



Conclusions

- In typical **BSM frameworks**, deviations in **single-Higgs couplings** (e.g. g_{hZZ}) can be **too small** to be observed at **future e^+e^- colliders**.

- In contrast, **deviations in the Higgs self-coupling** (κ_λ) can be **significant** and **potentially detectable** at the **HL-LHC**.

- This highlights the importance of **direct and model-independent measurements** of the **trilinear Higgs coupling**.

- The **next-generation Higgs factory** should aim for the **highest possible precision** in probing this key parameter.

Back up

Higgs self-coupling measurements

Observable: **Higgs pair production (**at LHC: **gluon fusion)**

Exp. limits :
(95% CL at LHC Run II)

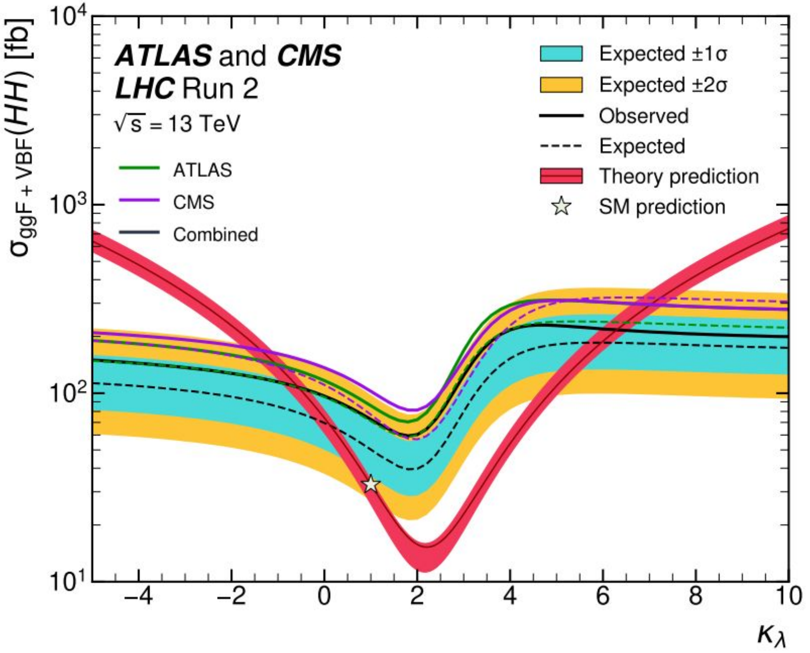
ATLAS and CMS: arXiv 2602.23991

Obs. $[-0.71 < \kappa_\lambda < 6.1]$

Exp. $[-1.3 < \kappa_\lambda < 6.7]$

Notation:

$$\kappa_\lambda = \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}(0)}$$

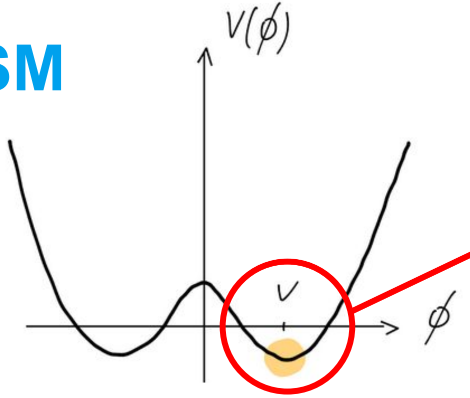


Motivation: unravel the scalar potential

$$V(\boxed{h}) \propto \frac{m_h^2}{2}\boxed{h^2} + \frac{m_h^2}{2v}\boxed{h^3} + \frac{m_h^2}{8v^2}\boxed{h^4}$$

$$\propto \lambda_{hhh}^{\mathrm{SM}(0)}$$

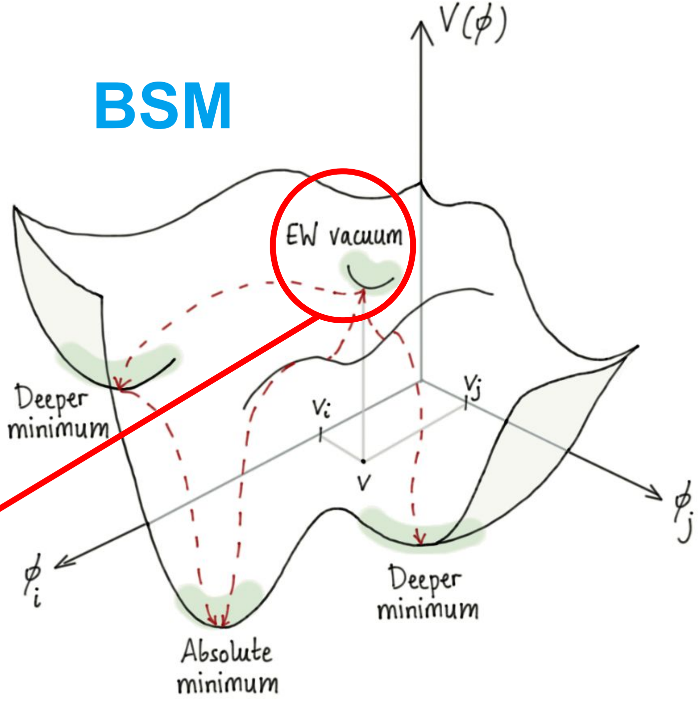
SM



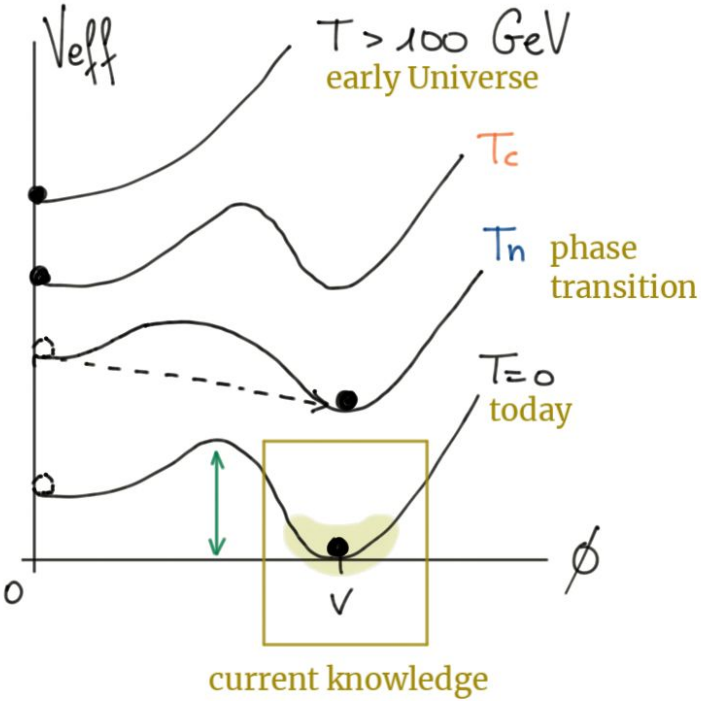
$v \simeq 246\,\mathrm{GeV}$

$m_h \simeq 125\,\mathrm{GeV}$

BSM



Evolution of the scalar potential



T= 0

$$V_{\text{eff}} = \boxed{V_{\text{tree}} + V_{\text{CW}} + V_{\text{CT}}} + V_{\text{T}} + V_{\text{daisy}}$$

Coleman, Weinberg: (1973) Phys. Rev. D

Dolan, Jackiw: (1974) Phys. Rev. D

Arnold, Espinosa: arXiv:9212235

Depending on the type of transition we can dynamically explain matter-antimatter asymmetry

Electroweak baryogenesis (EWBG)

First order = spontaneous bubble nucleation

Strong = $\xi_n = \dfrac{v_n(T_n)}{T_n} \gtrsim 1$ (n: nucleation)

See also talk by G. Weiglein on Monday

Electroweak baryogenesis

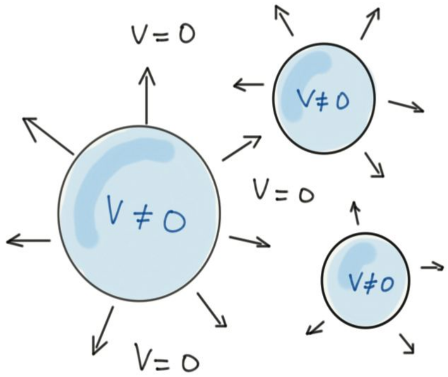
Requirements for a successful baryogenesis: Sakharov: (1967) JETP Letters

EWBG

1. B violation → Sphaleron processes
2. C/CP violation → BSM C/CP violation sources
3. Out of equilibrium dynamics → Strong First Order EW Phase Transition (SFOEWPT)

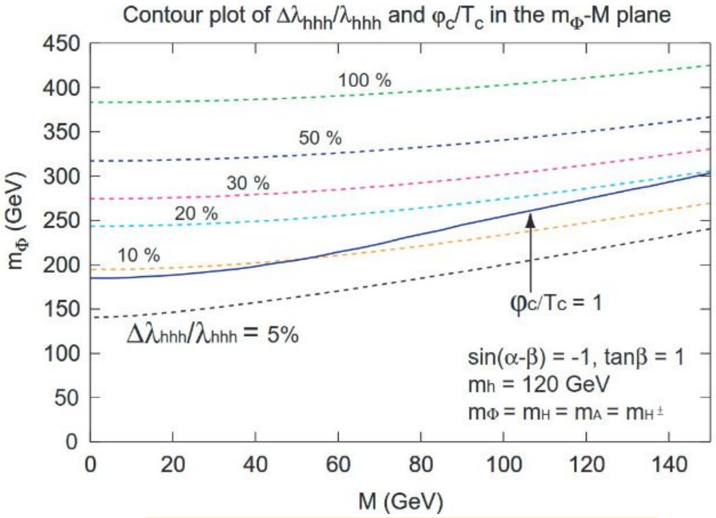
First order = spontaneous bubble nucleation:

Strong = $\xi_n = \dfrac{v_n(T_n)}{T_n} \gtrsim 1$ (n: nucleation)

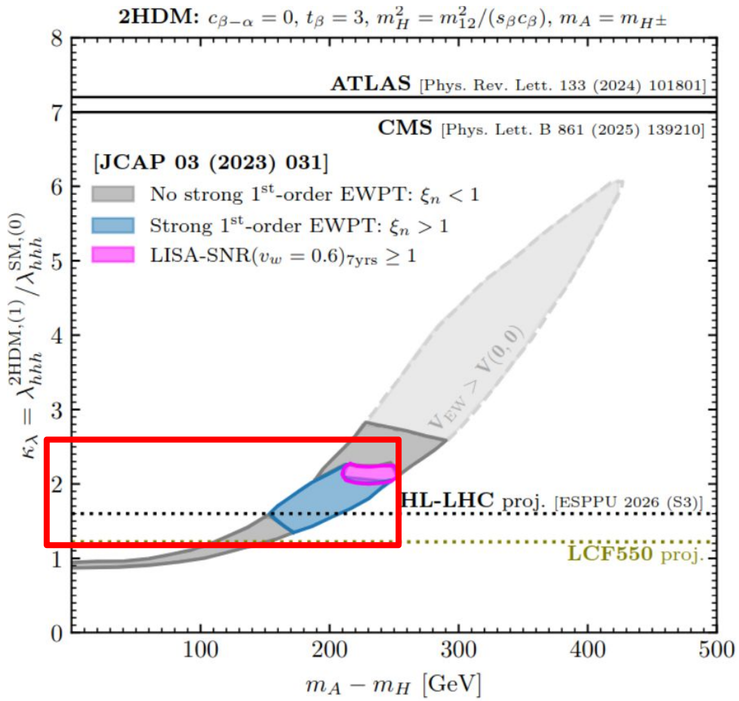


κ_λ at T ≠ 0 and T = 0

A **strong first order electroweak phase transition** is a requirement for successful baryogenesis and is typically correlated with a deviation in $\boldsymbol{\kappa_\lambda}$ **to values ~ 2**
If the transition happens in "one-step" the energy barrier needs a deviation of the trilinear couplings from the SM prediction



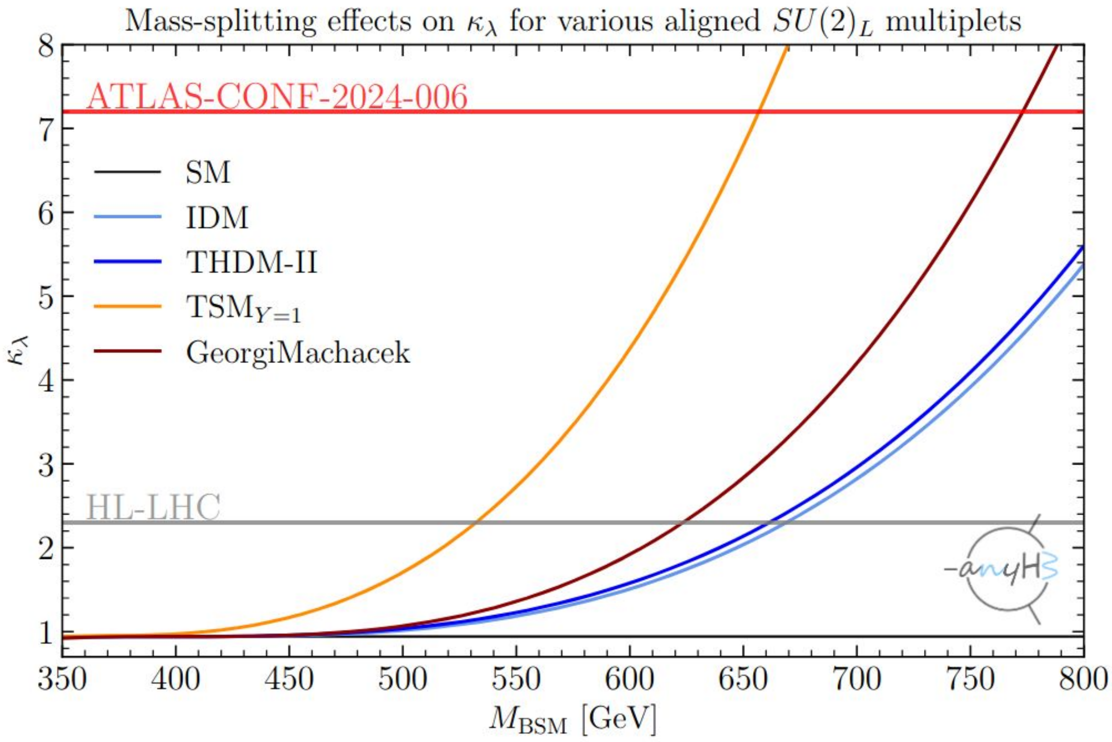
Kanemura, Okada, Senaha: arxiv:0411354



Biekötter, Heinemeyer, No, Olea, Weiglein: arxiv:2208.14466 (plot updated in 2025)

Corrections to the trilinears in BSM models

They play an important role in many BSM models even in the alignment limit (i.e. the other couplings are SM like)



Bahl, Braathen, Gabelmann, Weiglein: arXiv: 2305.03015

Decoupling limit

A cross-check: the decoupling limit

Slide by J. Braathen

- Consider the decoupling limit in several BSM models

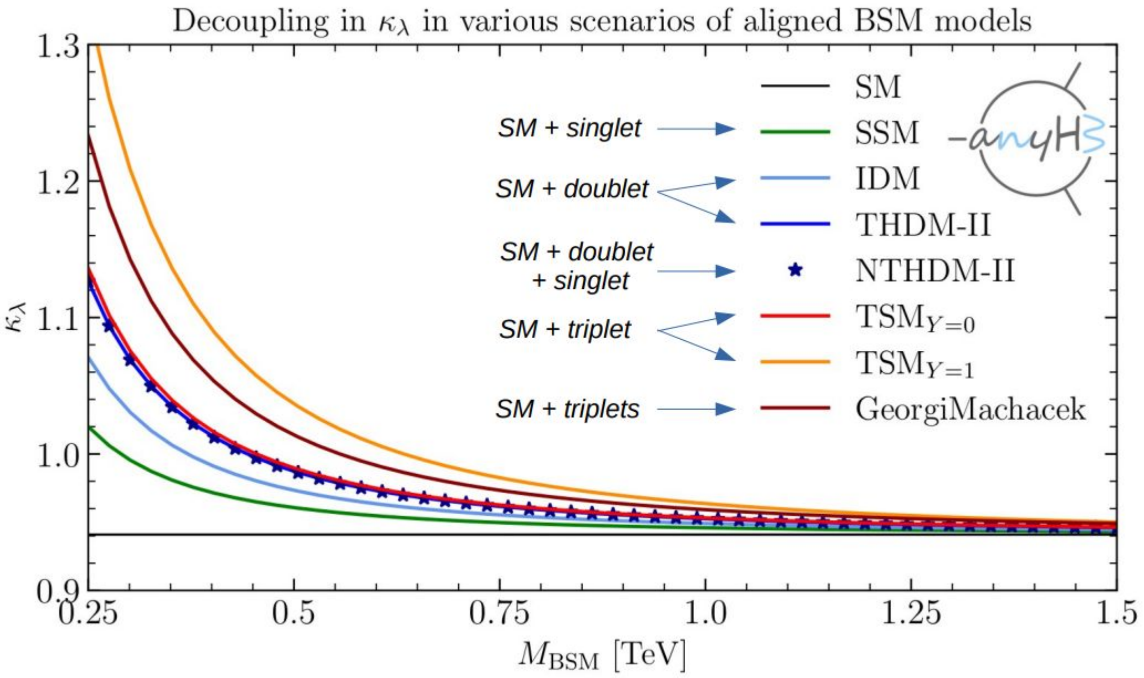
$$M^2_{\text{BSM}} = \mathcal{M}^2 + \tilde{\lambda} v^2$$

$\mathcal{M}$: BSM mass scale
$\tilde{\lambda}$: Quartic couplings

- Increase BSM mass scale

$$\mathcal{M} \to \infty$$

- BSM corrections to should vanish (c.f. decoupling theorem [Appelquist, Carrazone '75])



thdmTools: a python package to explore the 2HDM

- **EWPO**: impose a condition on the Higgs boson masses: $(m_{H\pm}-m_H) \sim 0$ and/or $(m_{H\pm}-m_A) \sim 0$
  in our scenarios $m_{H\pm} = m_A$

- Theoretical:
  (N)LO Unitarity: from the 2 → 2 processes scattering amplitude
  Cacchio, Chowdhury, Eberhardt, Murphy: arXiv:1609.01290
  Stability: tree level boundedness from below of the potential
  Bhattacharyya, Das: arXiv:1507.06424

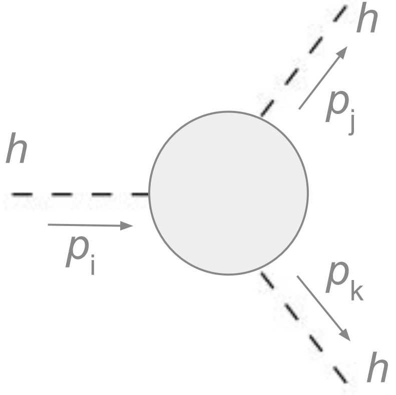
- Collider searches and measurements:
  HiggsBounds: experimental limits from direct searches
  HiggsSignals: signal strength of the 125 GeV Higgs
  HiggsTools Collaboration: arXiv: 2210.09332

- **Flavour observables**: $B \to X_s\gamma$ and $B_s \to \mu\mu$ (SuperIso)
  Mahmoudi: arXiv:0808.3144

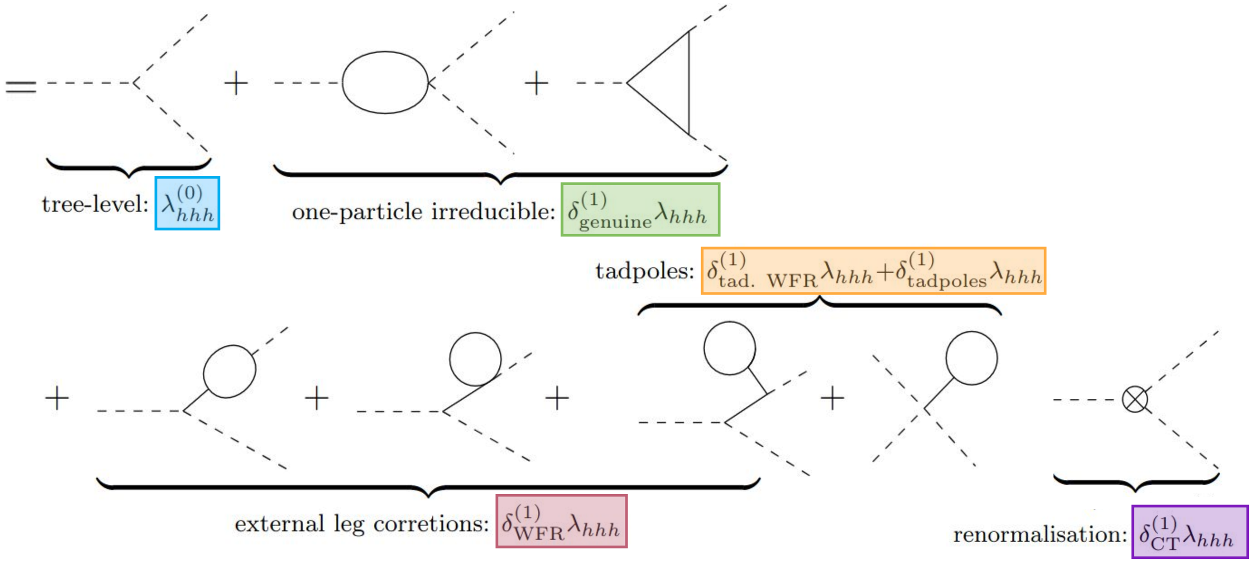
Allowed regions of the 2HDM parameter space are scanned with the python package **thdmTools**
Biekötter, Heinemeyer, No, K.R., Olea, Weiglein: arxiv:2309.17431

Trilinear Higgs couplings (generic approach)

Trilinear couplings = renormalized three point functions: $\lambda_{hhh} = -\hat{\Gamma}_{hhh}(p_1^2, p_2^2, p_3^2)$



$$= \boxed{\lambda^{(0)}_{hhh}} + \boxed{\delta^{(1)}_{\text{genuine}}\lambda_{hhh}} + \boxed{\delta^{(1)}_{\text{tadpoles}}\lambda_{hhh}} + \boxed{\delta^{(1)}_{\text{WFR}}\lambda_{hhh}} + \boxed{\delta^{(1)}_{\text{CT}}\lambda_{hhh}}$$



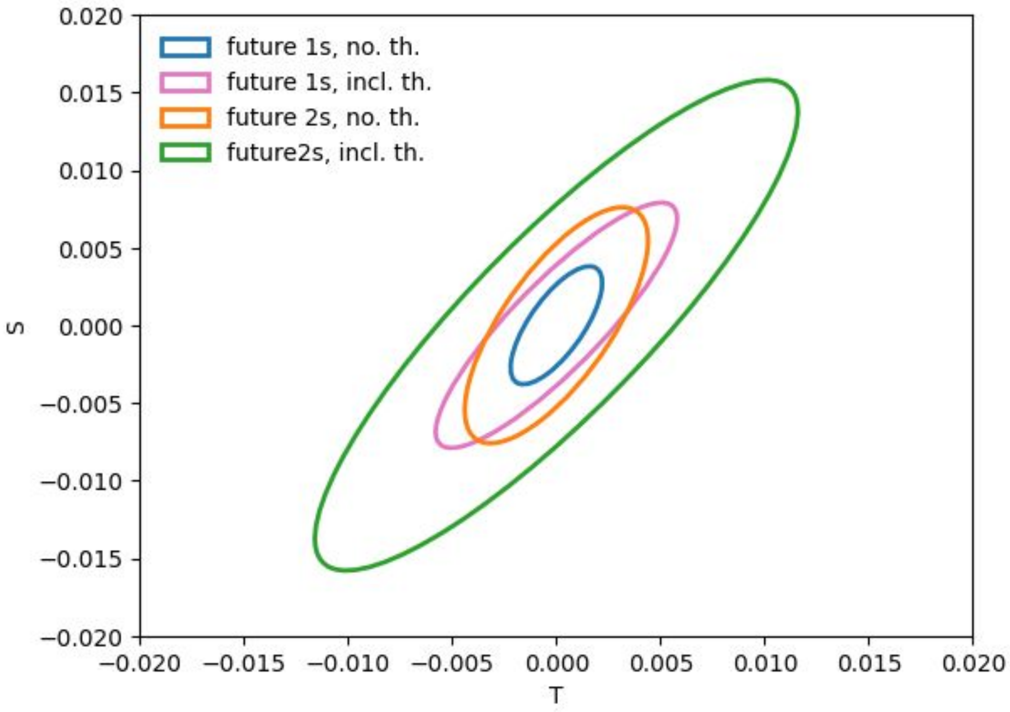
note: solid line = generic field

$\mathbb{Z}_2$SSM at 2 loops

$$\Delta\kappa_\lambda^{(2)} = \frac{1}{(4\pi)^4}\frac{1}{3}\left[48\frac{m_S^6}{v^6\lambda_\Phi}\left(1-\frac{\mu_S^2}{m_S^2}\right)^4 + 72\lambda_S\frac{m_S^4}{v^4\lambda_\Phi}\left(1-\frac{\mu_S^2}{m_S^2}\right)^3 - 2\frac{m_S^6}{v^6\lambda_\Phi}\left(1-\frac{\mu_S^2}{m_S^2}\right)^5\right]$$

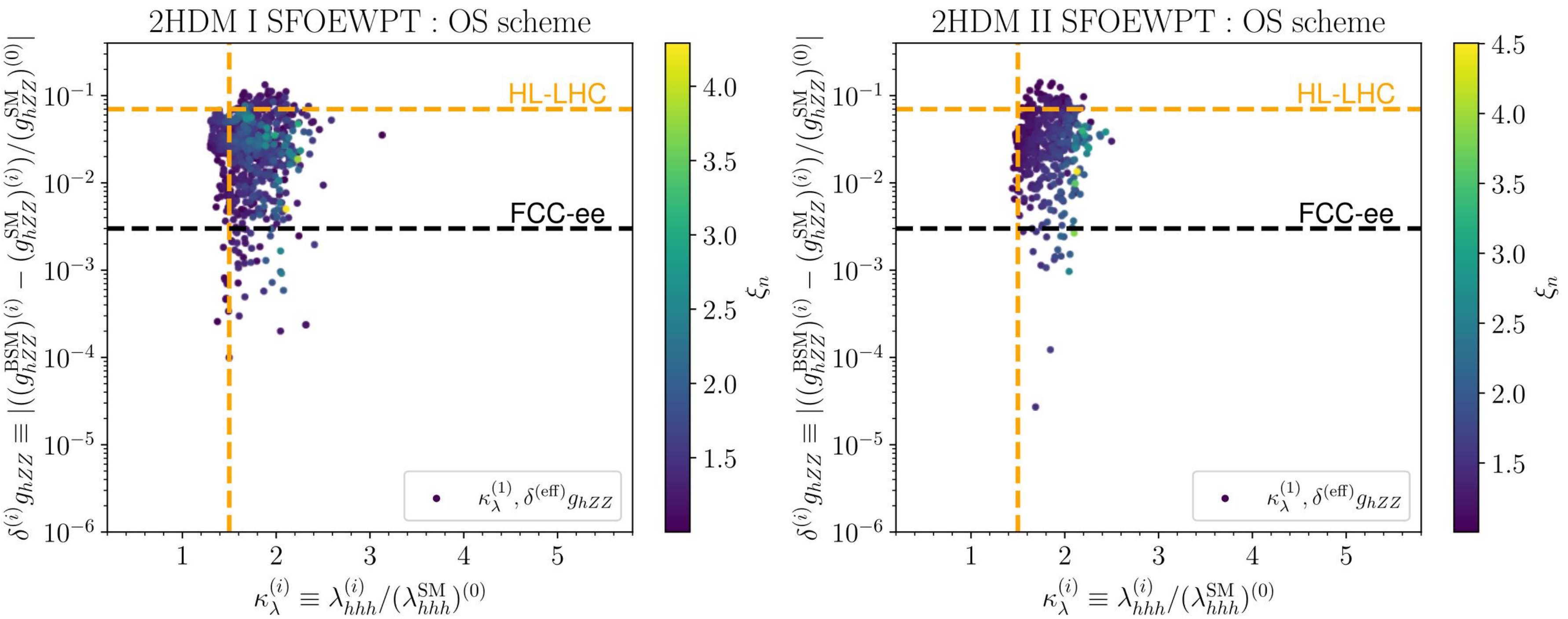
$$c_{\text{eff}}^{(2)} = c_{\text{eff}}^{(1)} - \frac{1}{(4\pi)^4}\left[\frac{m_S^4}{24v^4}\left(1-\frac{\mu_S^2}{m_S^2}\right)^3\left(43+5\frac{\mu_S^2}{m_S^2}\right) + 2\lambda_S\frac{m_S^2}{v^2}\left(1-\frac{\mu_S^2}{m_S^2}\right)^2\right]$$

STU in the THDM



J. de Blas et al.: arXiv: 1905.03764

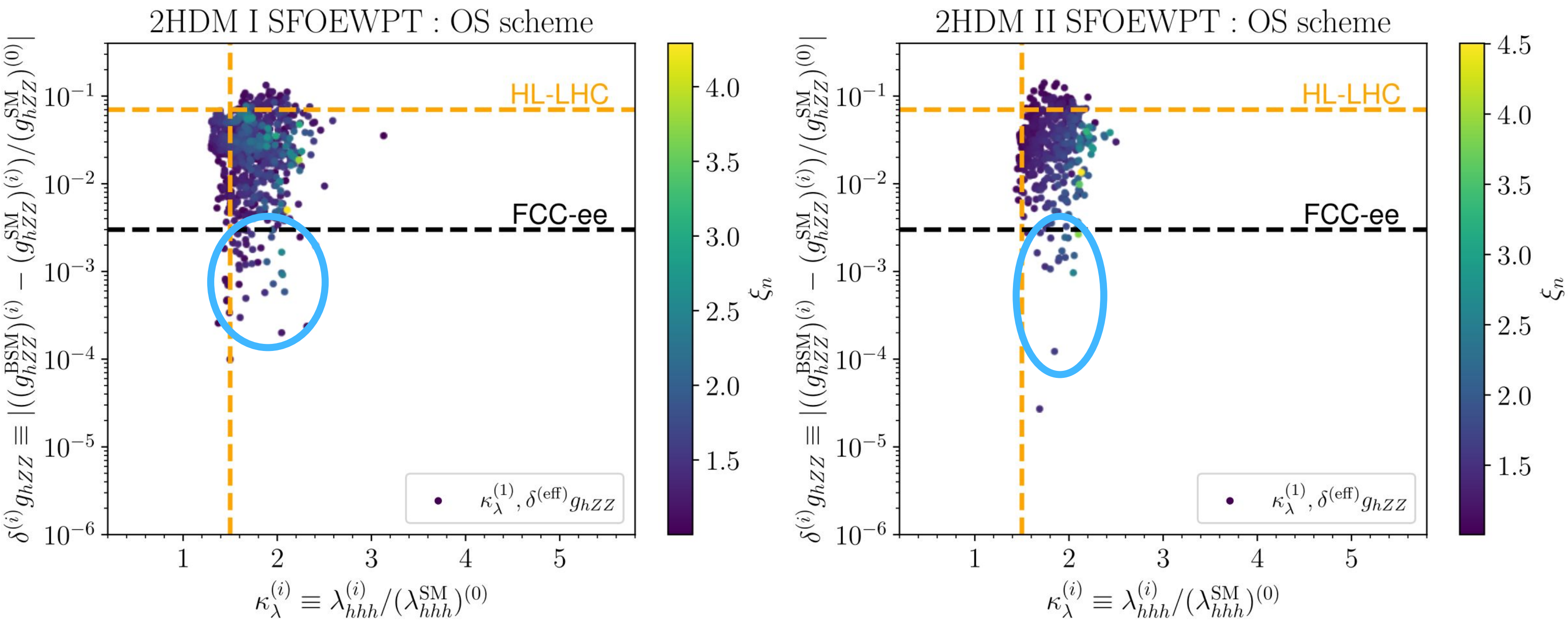
2HDM with a SFOEWPT



Vertical lines are the projected HL-LHC sensitivity assuming $\kappa_\lambda = 1$

Phase transition dynamics computed using the code developed in Biekötter, Heinemeyer, No, Olea, Weiglein: arxiv:2208.14466

2HDM with a SFOEWPT



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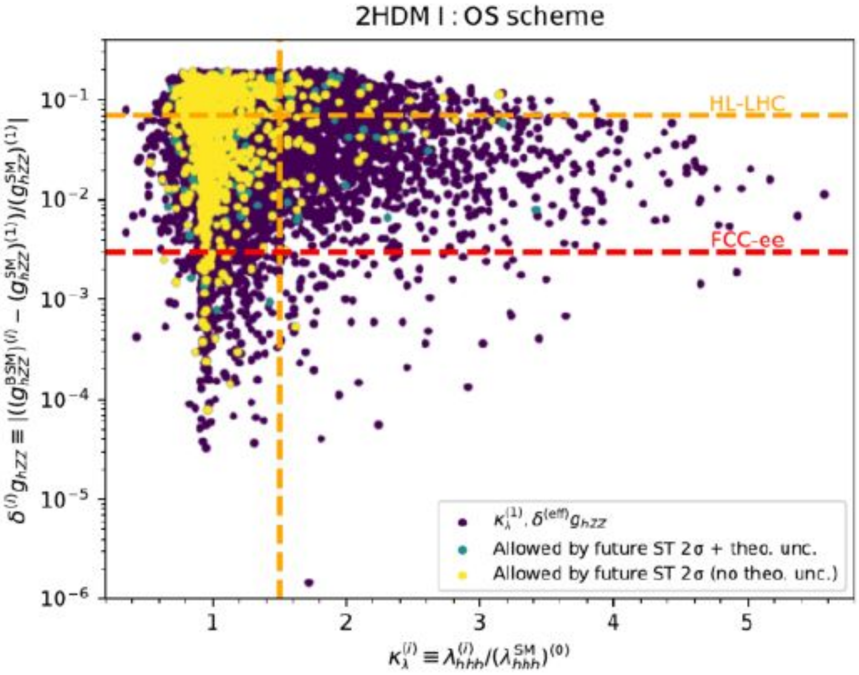
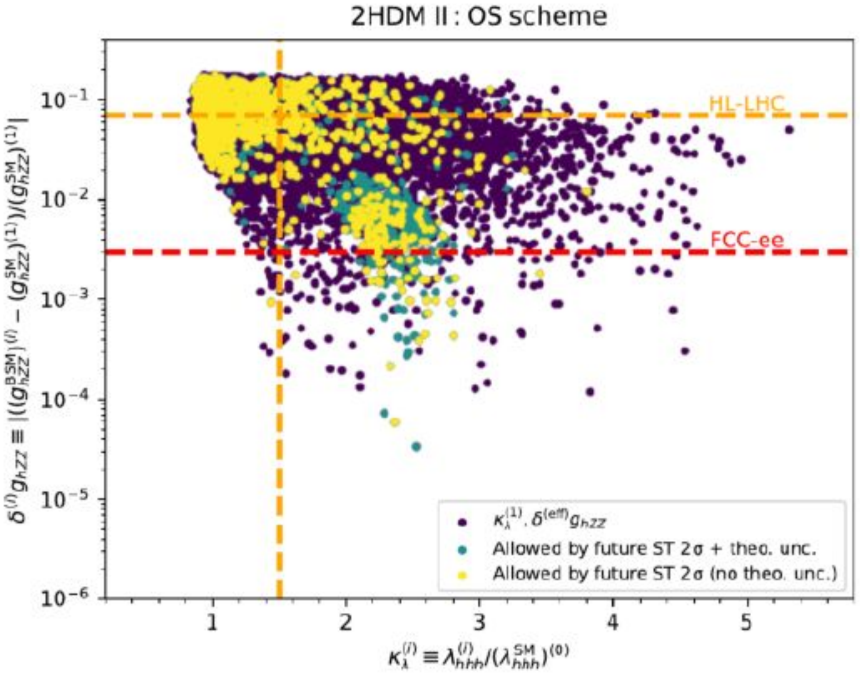
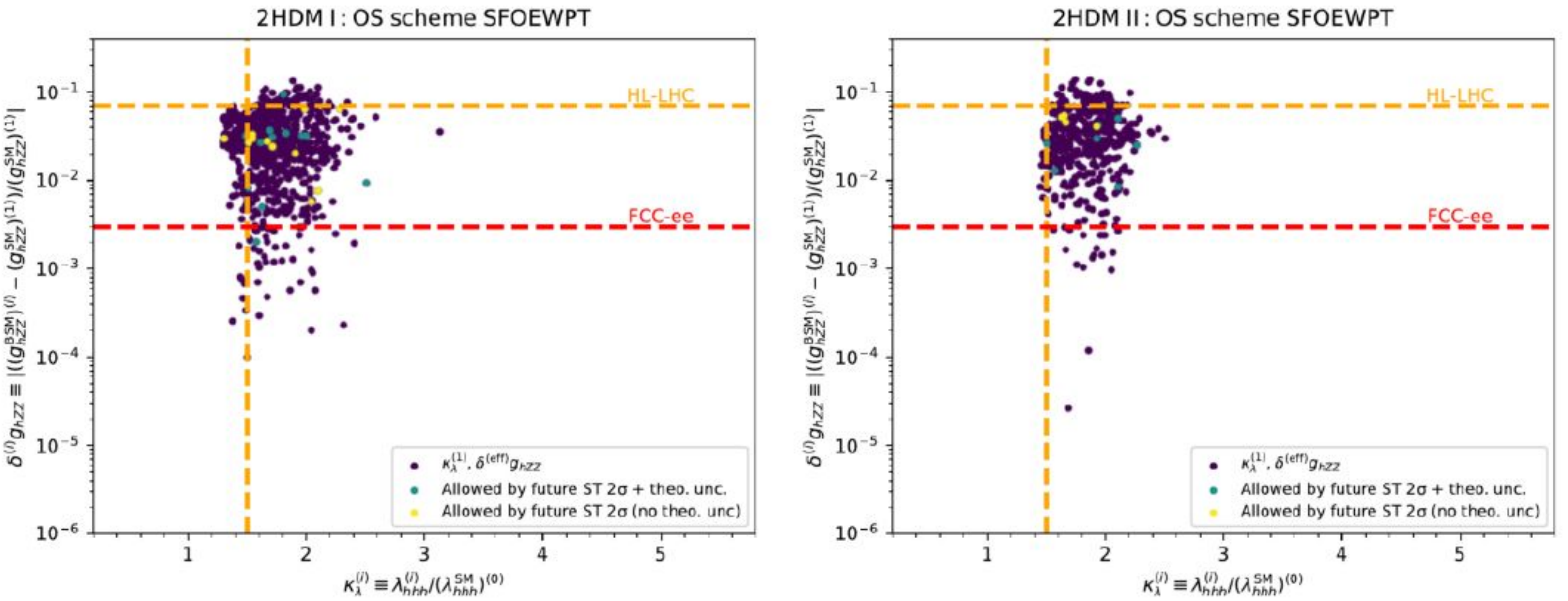
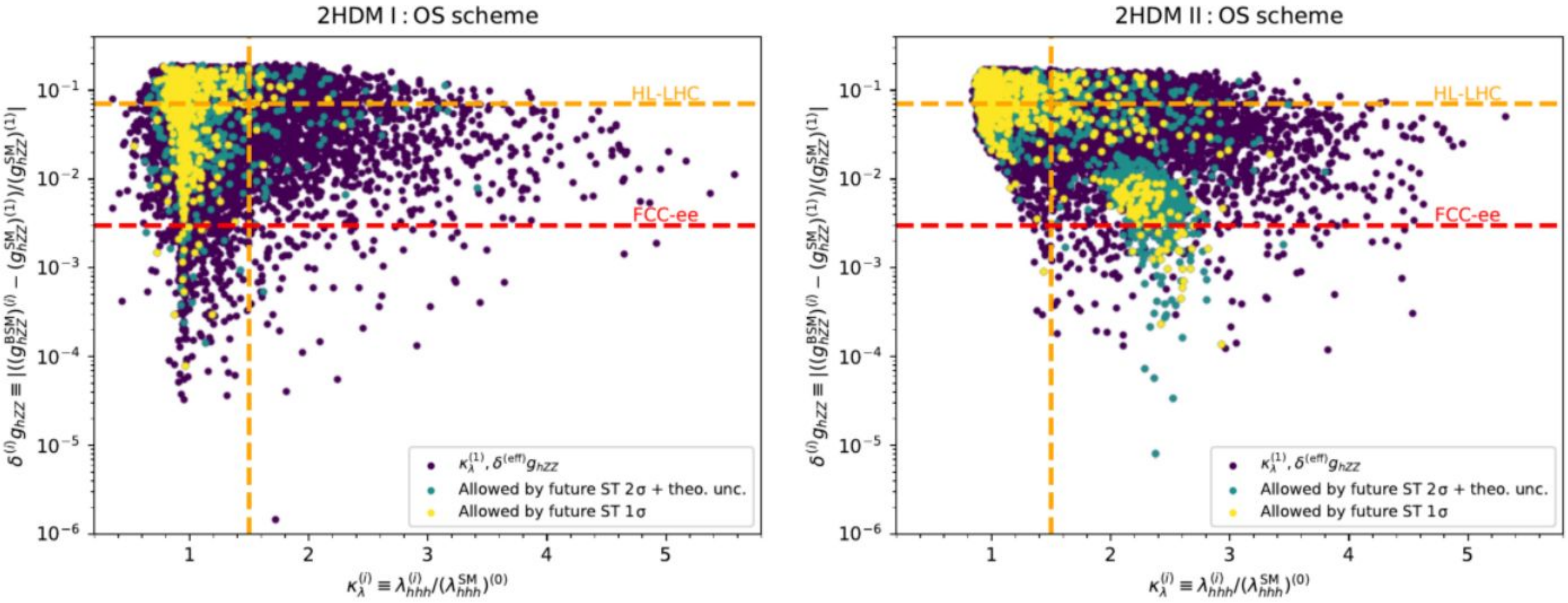




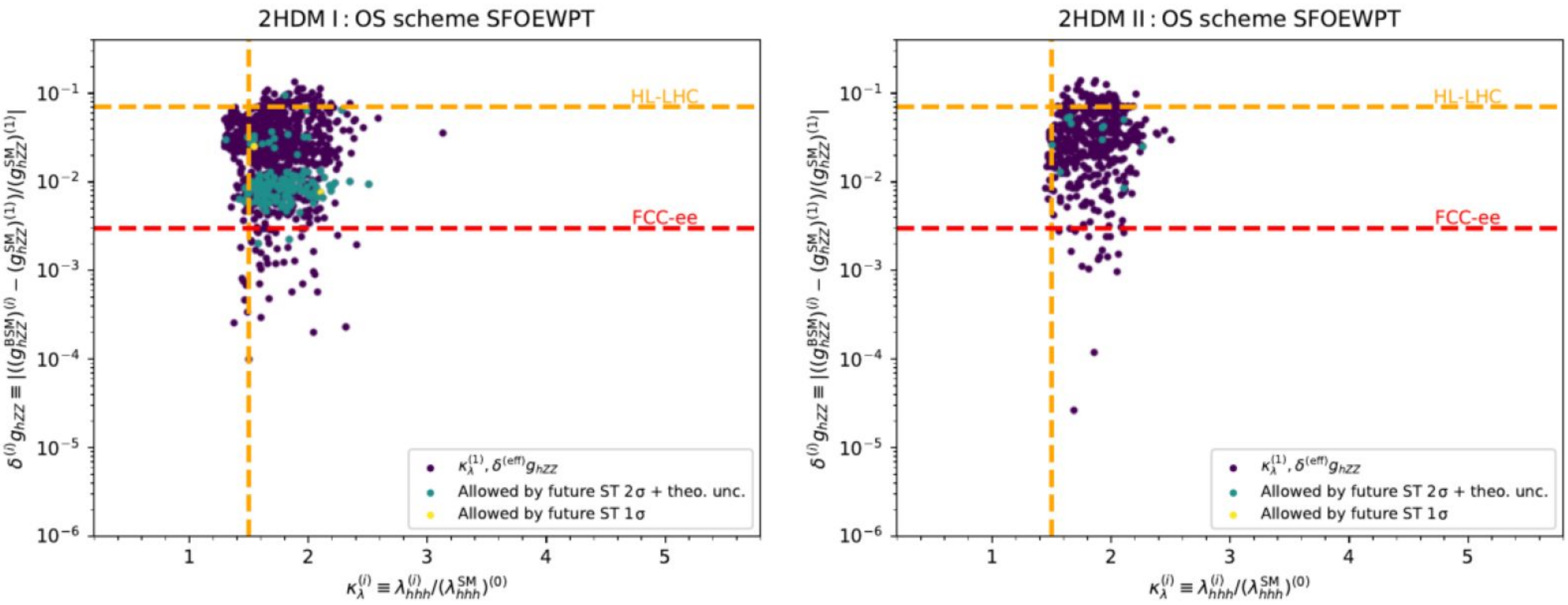
STU in the THDM



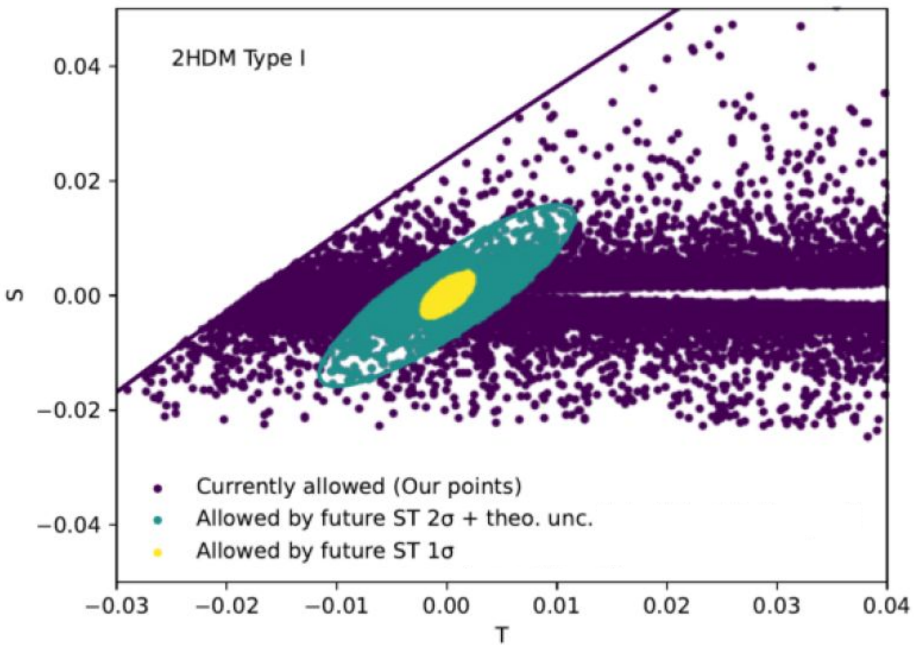
STU in the THDM

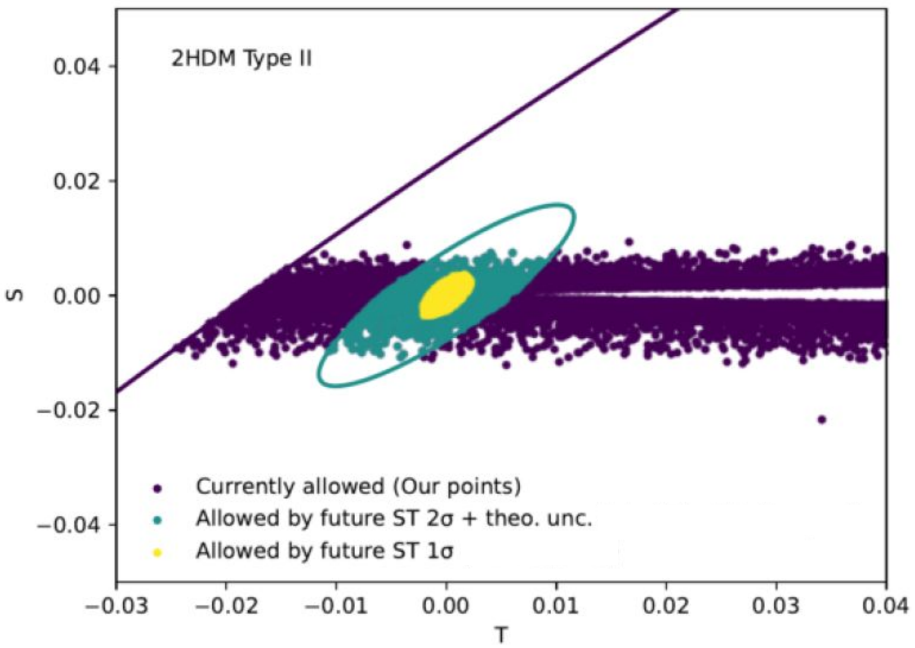


STU in the THDM

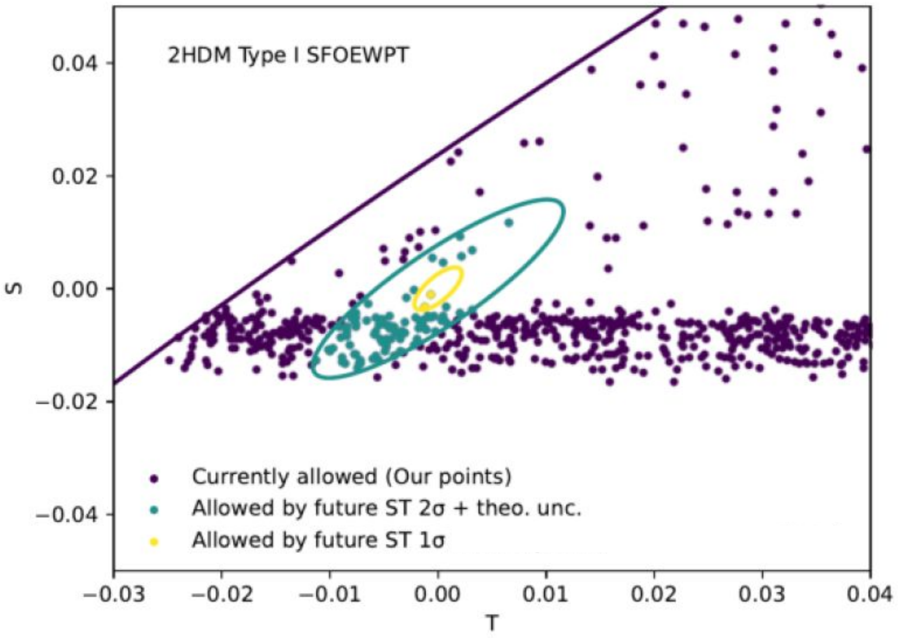


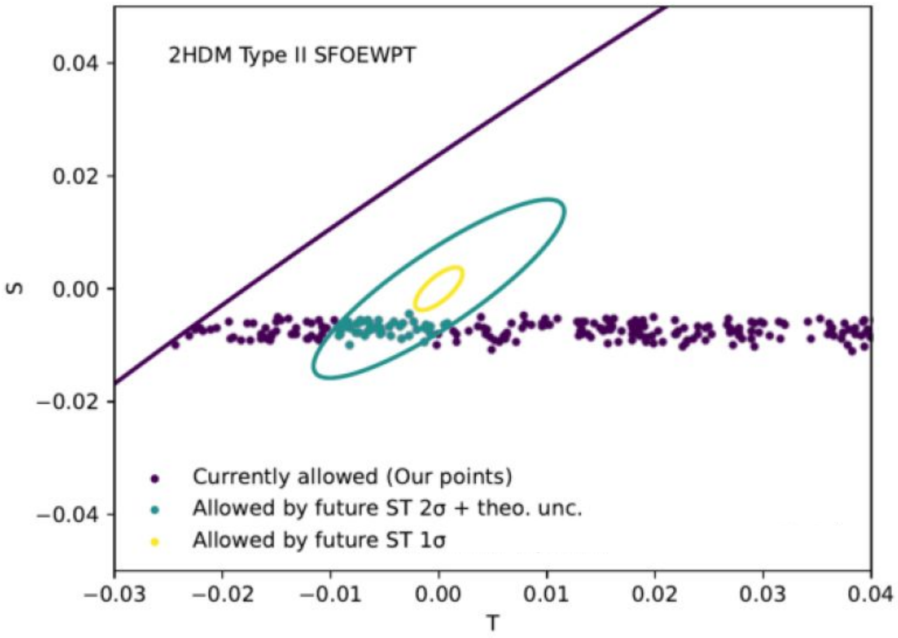
STU in the THDM





STU in the THDM





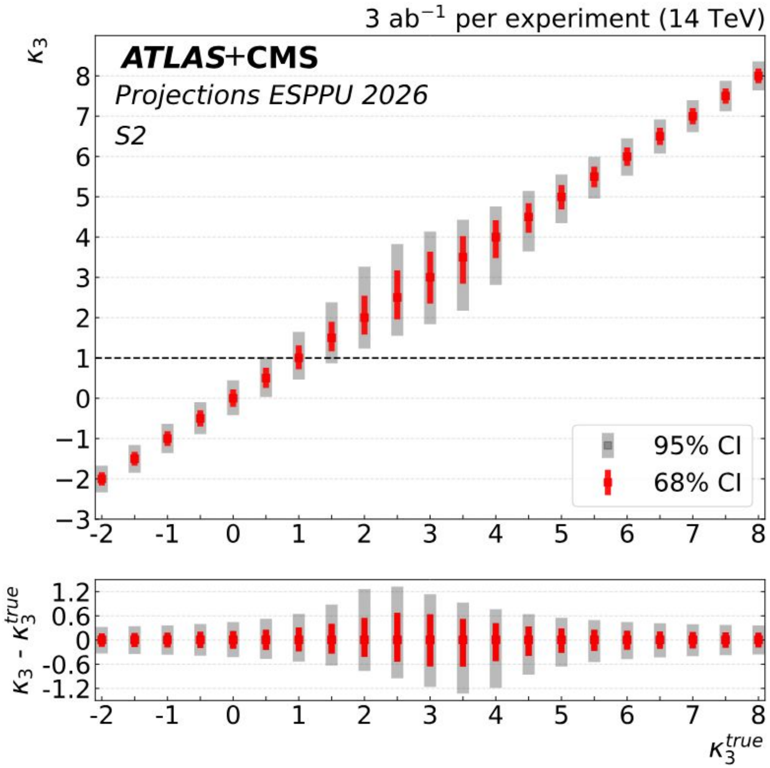
WFR definition in anyH3

$$\hat{\Sigma}^{\mathrm{OS}}_{ij}(p^2) = \Sigma_{ij}(p^2) + \delta^{(1)} Z^{\mathrm{OS}}_{ij}(m_j^2 - p^2) + \delta^{(1)} Z^{\mathrm{OS}}_{ji}(m_i^2 - p^2) + \delta^{(1)} m^2_{ij}$$
$$= \Sigma_{ij}(p^2) + (p^2 - m_i^2)\frac{\Sigma_{ij}(m_j^2)}{m_i^2 - m_j^2} + (p^2 - m_j^2)\frac{\Sigma_{ij}(m_i^2)}{m_j^2 - m_i^2}\,.$$

Counterterm for M in the THDM

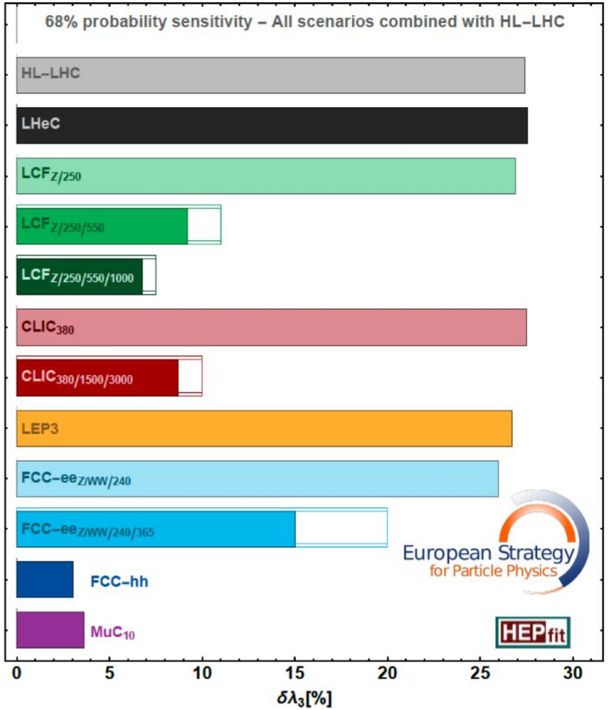
$$\delta M^{\overline{MS}} = \frac{-M}{32\pi^2 v^2}\Big(-3\,(2M_W^2 + M_Z^2) + 6\big((m_u^2 + m_c^2 + m_t^2)\cot\beta^2 + (m_d^2 + m_s^2 + m_b^2)\tan\beta^2\big) + 2\tan\beta^2(m_e^2 + m_\tau^2 + m_\mu^2) + 4M^2 - 2m_{H^\pm}^2 - m_A^2 - \frac{\sin(2\alpha)}{\sin(2\beta)}(m_h^2 - m_H^2)\Big)\frac{1}{\epsilon}$$

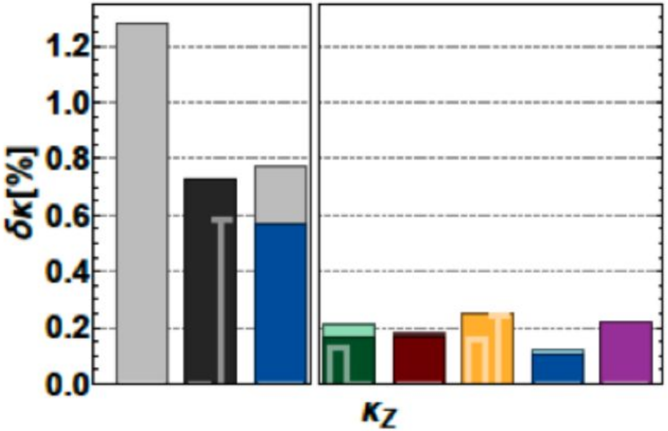
κ_λ sensitivity at the HL-LHC



CMS and ATLAS: arXiv: 2504.00672

Sensitivity at other colliders





See talk by K. Jakobs