Two-Loop Renormalization in the 2HDM and Applications

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Introduction

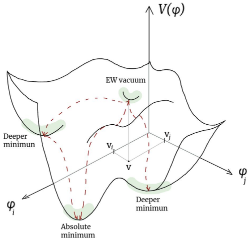
Introduction

Motivation

- Trilinear Higgs coupling(s) have not been measured yet

⇒ Potential portal into new physics

- Impact on di-Higgs production and early universe physics (electroweak phase transition)
- Higher order corrections can be large, are needed for precise predictions



[Drawing from K. Radchenko]

Setup

- Follow up on [Braathen and Kanemura 2019, 2020]
- Renormalize the Two-Higgs-doublet model (2HDM) at two loops in the alignment limit using the Higgs basis + calculate all CP-even trilinear Higgs coupings at two-loop order
- Leading two-loop results: gaugeless limit (i.e. $m_W, m_Z \to 0$) and neglect light Higgs mass ($m_h \to 0$), include top quark contributions

2HDM in the Higgs Basis

2HDM in the Higgs Basis

2HDM Lagrangian [Branco et al. 2012]

$$\Phi_{\text{SM}} = \begin{pmatrix} G'^{+} \\ \frac{1}{\sqrt{2}}(v + \phi_{\text{SM}} + iG'^{0}) \end{pmatrix}, \quad \Phi_{\text{BSM}} = \begin{pmatrix} H'^{+} \\ \frac{1}{\sqrt{2}}(v_{\text{BSM}} + \phi_{\text{BSM}} + iA') \end{pmatrix},$$

$$\begin{aligned} V(\Phi_{\text{SM}}, \Phi_{\text{BSM}}) = {} & M_{11}^2 |\Phi_{\text{SM}}|^2 + M_{22}^2 |\Phi_{\text{BSM}}|^2 - M_{12}^2 (\Phi_{\text{BSM}}^\dagger \Phi_{\text{SM}} + \text{h.c.}) \\ & + \frac{\Lambda_1}{2} |\Phi_{\text{SM}}|^4 + \frac{\Lambda_2}{2} |\Phi_{\text{BSM}}|^4 + \Lambda_3 |\Phi_{\text{SM}}|^2 |\Phi_{\text{BSM}}|^2 + \Lambda_4 |\Phi_{\text{BSM}}^\dagger \Phi_{\text{SM}}|^2 \\ & + \left[\frac{\Lambda_5}{2} (\Phi_{\text{BSM}}^\dagger \Phi_{\text{SM}})^2 + (\Lambda_6 |\Phi_{\text{SM}}|^2 + \Lambda_7 |\Phi_{\text{BSM}}|^2) \Phi_{\text{SM}}^\dagger \Phi_{\text{BSM}} + \text{h.c.} \right], \end{aligned}$$

$$\mathcal{L}_{\text{Yuk}} \supset -\bar{Q}_{\text{L}} Y_{\text{SM}}^t \tilde{\Phi}_{\text{SM}} t_{\text{R}} - \bar{Q}_{\text{L}} Y_{\text{BSM}}^t \tilde{\Phi}_{\text{BSM}} t_{\text{R}} \qquad \left(Q_{\text{L}} = \begin{pmatrix} t_{\text{L}} & b_{\text{L}} \end{pmatrix}^{\text{T}}, \; Y_{\text{BSM}}^t = \zeta_t Y_{\text{SM}}^t \right)$$

- Higgs basis: $v_{\text{BSM}} = 0$

2HDM in the Higgs Basis

Rotations

$$\begin{pmatrix} H \\ h \end{pmatrix} = R^{\mathsf{T}}_{\alpha'} \begin{pmatrix} \phi_{\text{SM}} \\ \phi_{\text{BSM}} \end{pmatrix}, \begin{pmatrix} G^0 \\ A \end{pmatrix} = R^{\mathsf{T}}_{\beta'} \begin{pmatrix} G'^0 \\ A' \end{pmatrix}, \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = R^{\mathsf{T}}_{\beta'} \begin{pmatrix} G'^\pm \\ H'^\pm \end{pmatrix}, \tan\beta' = \frac{v_{\text{BSM}}}{v}$$

- Higgs basis: $\tan\beta' = 0$ ($v_{\text{BSM}} = 0$)
- Alignment limit: $\alpha' = -\frac{\pi}{2}$ ($\Lambda_6 = 0$)
- These are tree level conditions (not symmetry-protected), have to introduce $\delta\alpha'$ ($\leftrightarrow \delta\Lambda_6$) and $\delta\beta'$ ($\leftrightarrow \delta v_{\text{BSM}}$)
- Alternatively, do not introduce mixing angles α', β' [Degrassi and Slavich 2023], renormalize Λ_6 and v_{BSM} to keep alignment and Higgs basis condition at loop level

$\Rightarrow$ $\phi_{SM}, G'^0, G'^\pm, A', H'^\pm \to h, G^0, G^\pm, A, H^\pm$ but $\phi_{BSM} \to -H$

- Can connect parameters to $\mathbb{Z}_2$ symmetric parameters (but do not have to)

2HDM in the Higgs Basis

$\mathbb{Z}_2$ basis to Higgs basis [Davidson and Haber 2005; Haber and Stål 2015; Bernon et al. 2015]

$$\Lambda_1 = \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + \frac{1}{2}\lambda_{345} s_{2\beta}^2$$

$$\Lambda_2 = \lambda_1 s_\beta^4 + \lambda_2 c_\beta^4 + \frac{1}{2}\lambda_{345} s_{2\beta}^2$$

$$\Lambda_i = \frac{1}{4} s_{2\beta}^2 (\lambda_1 + \lambda_2 - 2\lambda_{345}) + \lambda_i \; (i = 3, 4, 5)$$

$$\Lambda_6 = -\frac{1}{2} s_{2\beta} (\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - \lambda_{345} c_{2\beta})$$

$$\Lambda_7 = -\frac{1}{2} s_{2\beta} (\lambda_1 s_\beta^2 - \lambda_2 c_\beta^2 + \lambda_{345} c_{2\beta})$$

$$M_{11}^2 = m_{11}^2 c_\beta^2 + m_{22}^2 s_\beta^2 - m_{12}^2 s_{2\beta}$$

$$M_{12}^2 = m_{11}^2 s_\beta^2 + m_{22}^2 c_\beta^2 + m_{12}^2 s_{2\beta}$$

$$M_{22}^2 = \frac{1}{2}(m_{22}^2 - m_{11}^2) s_{2\beta} - m_{12}^2 c_{2\beta}$$

$$\Lambda_2 = \Lambda_1 + 2(\Lambda_6 + \Lambda_7) \cot 2\beta$$

$$\Lambda_3 + \Lambda_4 + \Lambda_5 = \Lambda_1 + 2\Lambda_6 \cot 2\beta - \frac{(\Lambda_6 - \Lambda_7)}{\cot 2\beta}$$

Yukawa Couplings

$$Y_{\text{SM}}^t = \frac{m_t\sqrt{2}}{v} \frac{1}{1 + \zeta_t \frac{v_{\text{BSM}}}{v}}, \quad Y_{\text{BSM}}^t = \frac{m_t\sqrt{2}}{v} \frac{\zeta_t}{1 + \zeta_t \frac{v_{\text{BSM}}}{v}} \qquad \Rightarrow \zeta_t = \cot\beta$$

2HDM in the Higgs Basis

Input Parameters

- Input parameters: v, m_h, m_H, $m_{H^\pm}$, m_A, M_{22}^2,Λ_2 Λ_7, ζ_t ($v_{\text{BSM}} = 0$, $\Lambda_6 = 0$)
- If we want to connect to $\mathbb{Z}_2$ basis, use equations

$$\Lambda_2 = \Lambda_1 + 2(\Lambda_6 + \Lambda_7)\,\cot 2\beta\,,$$

$$\Lambda_3 + \Lambda_4 + \Lambda_5 = \Lambda_1 + 2\Lambda_6 \cot 2\beta - \frac{(\Lambda_6 - \Lambda_7)}{\cot 2\beta}\,.$$

- Can also use $\mathbb{Z}_2$-basis input (M and $\tan\beta$) and convert to the Higgs basis

Renormalization

Renormalization

Previous Work

- Previous calculations at one loop done by [Kanemura, Okada, et al. 2004; Kanemura, Kikuchi, and Yagyu 2015; Kanemura, Kikuchi, Sakurai, et al. 2017], [Krause, Lorenz, et al. 2016; Krause, Muhlleitner, et al. 2017], [Ansgar Denner, Jenniches, et al. 2016] and [Altenkamp, Dittmaier, and Rzehak 2017; Ansgar Denner, Dittmaier, and Lang 2018]

Our Approach

- Two loop calculation of trilinears, our work is based on [Braathen and Kanemura 2019, 2020] and we follow the approach in [Degrassi and Slavich 2023] (comparing also to [Degrassi, Gröber, and Slavich 2025])
- Several approaches of renormalization, especially the mixing angles, worked out, focus in this talk on one scheme

Renormalization

Definitions

- Introduce WRC and mass counterterms for h, H (similarly for $H^\pm, A$):

$$\begin{pmatrix} H \\ h \end{pmatrix} \to \sqrt{1+\delta Z_\mathsf{S}} \begin{pmatrix} H \\ h \end{pmatrix} \approx \left(1 + \frac{\delta Z_\mathsf{S}}{2} - \frac{\delta Z_\mathsf{S}^2}{8}\right) \begin{pmatrix} H \\ h \end{pmatrix} , \delta Z_\mathsf{S} = \begin{pmatrix} \delta Z_{HH} & \delta Z_{Hh} \\ \delta Z_{hH} & \delta Z_{hh} \end{pmatrix} ,$$

$$m_{h/H}^2 \to m_{h/H}^2 + \delta m_{h/H}^2$$

- Introduce counterterms for all input parameters up to two loop order
- In the following: Focus on 2HDM specific parameters

Tadpole Scheme

- Renormalize tadpoles in the parameter renormalized scheme (PRTS), renormalized tadpoles vanish, $\hat{T}_h = \hat{T}_H = 0$

$\Rightarrow$ Tadpoles cancel in the calculation

Mixing Angle Relations

Mixing Angle Relations

$$\mathcal{M}_{\phi_{\text{SM}}\phi_{\text{BSM}}} = \begin{pmatrix} \mathcal{M}_{11} & \mathcal{M}_{12} \\ \mathcal{M}_{12} & \mathcal{M}_{22} \end{pmatrix} \quad \Rightarrow \tan 2\alpha' = \frac{2\mathcal{M}_{12}}{\mathcal{M}_{11} - \mathcal{M}_{22}}\,, \quad \tan\beta' = \frac{v_{\text{BSM}}}{v}\,,$$

and thus ($v_{\text{BSM}} = 0\ \alpha' = -\frac{\pi}{2},\ \Lambda_6 = 0$):

$$\delta v_{\text{BSM}}^{(1)} = \delta\beta'^{(1)} v\,,$$

$$\delta v_{\text{BSM}}^{(2)} = \delta\beta'^{(2)} v + \delta\beta'^{(1)}\delta v^{(1)}\,,$$

$$\delta\Lambda_6^{(1)} = \frac{\delta\beta'^{(1)}(2M_{22}^2 - m_H^2)}{v} + \frac{\delta\alpha'^{(1)}(m_h^2 - m_H^2)}{v^2}$$

$$\delta\Lambda_6^{(2)} = 3(\delta\beta'^{(1)})^2\Lambda_7 + \delta\beta'^{(1)}\left(\frac{\delta v^{(1)}(2m_H^2 - 4M_{22}^2)}{v^3} + \frac{2(\delta M_{22}^2)^{(1)}}{v^2} - \frac{(\delta m_H^2)^{(1)}}{v^2}\right)$$
$$+ \delta\alpha'^{(1)}\left(\frac{2\delta v^{(1)}(m_H^2 - m_h^2)}{v^3} + \frac{(\delta m_h^2)^{(1)}}{v^2} - \frac{(\delta m_H^2)^{(1)}}{v^2}\right) + \frac{\delta\beta'^{(2)}(2M_{22}^2 - m_H^2)}{v} + \frac{\delta\alpha'^{(2)}(m_h^2 - m_H^2)}{v^2}$$

Renormalization of the Mixing Angles

Rigid Symmetry Approach [Ansgar Denner, Jenniches, et al. 2016; Altenkamp, Dittmaier, and Rzehak 2017]

- Diagonal δZ factors for the gauge fields are sufficient for renormalization,

$$\Phi_1 \to \sqrt{Z_{\Phi_1}}\Phi_1$$
$$\Phi_2 \to \sqrt{Z_{\Phi_2}}\Phi_2$$

  (Φ_1 and Φ_2 in the $\mathbb{Z}_2$ basis).
- Rotate into Higgs basis with β and then into mass basis with α' (similar for β'),

$$\sqrt{Z_\mathrm{S}}\begin{pmatrix} H \\ h \end{pmatrix} = R^\mathsf{T}_{\beta+\alpha'+\delta\alpha'}\begin{pmatrix} \sqrt{Z_{\Phi_1}} & 0 \\ 0 & \sqrt{Z_{\Phi_2}} \end{pmatrix} R_{\beta+\alpha'}\begin{pmatrix} H \\ h \end{pmatrix} .$$

Renormalization of the Mixing Angles

Rigid Symmetry (RS) Approach [Ansgar Denner, Jenniches, et al. 2016; Altenkamp, Dittmaier, and Rzehak 2017]

- Relations:

$$\begin{aligned}
\delta Z_{hh}^{(1)} &= c_\beta^2 \delta Z_{\Phi_1}^{(1)} + s_\beta^2 \delta Z_{\Phi_2}^{(1)}\,, \\
\delta Z_{HH}^{(1)} &= s_\beta^2 \delta Z_{\Phi_1}^{(1)} + c_\beta^2 \delta Z_{\Phi_2}^{(1)}\,, \\
\delta Z_{hH}^{(1)} + \delta Z_{Hh}^{(1)} &= 2 s_\beta c_\beta (\delta Z_{\Phi_1}^{(1)} - \delta Z_{\Phi_2}^{(1)})\,, \\
\delta Z_{Hh}^{(1)} - \delta Z_{hH}^{(1)} &= 4 \delta \alpha'^{(1)}\,, \\
\delta \alpha'^{(2)} &= \frac{(\delta Z_{hh}^{(1)} + \delta Z_{HH}^{(1)})(\delta Z_{hH}^{(1)} - \delta Z_{Hh}^{(1)})}{16} + \frac{\delta Z_{Hh}^{(2)} - \delta Z_{hH}^{(2)}}{4} - \frac{\delta \alpha'^{(1)}}{4} (\delta Z_{\Phi_1}^{(1)} + \delta Z_{\Phi_2}^{(1)})\,,
\end{aligned}$$

- Relations hold only for UV divergent parts, can demand to define a finite counterterm for $\delta\alpha'^{(1)}$

Renormalization of the Mixing Angles

Rigid Symmetry (RS) Approach [Ansgar Denner, Jenniches, et al. 2016; Altenkamp, Dittmaier, and Rzehak 2017]

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\delta Z_{Hh}^{(1)} - \delta Z_{hH}^{(1)} &= 4 \delta \alpha'^{(1)} \,, \\
\delta \alpha'^{(2)} &= \frac{(\delta Z_{hh}^{(1)} + \delta Z_{HH}^{(1)})(\delta Z_{hH}^{(1)} - \delta Z_{Hh}^{(1)})}{16} + \frac{\delta Z_{Hh}^{(2)} - \delta Z_{hH}^{(2)}}{4} - \frac{\delta \alpha'^{(1)}}{4} (\delta Z_{\Phi_1}^{(1)} + \delta Z_{\Phi_2}^{(1)}) \,,
\end{aligned}
$$

- Relations hold only for UV divergent parts, can demand to define a finite counterterm for $\delta\alpha'^{(1)}$
- Using these relations OS does not result in the correct $\frac{1}{\epsilon}$ behaviour for $\delta\alpha'^{(2)}$

Renormalization of the Mixing Angles

More General Approach

$$\sqrt{Z_\mathsf{S}}\begin{pmatrix}H\\h\end{pmatrix} = R^\mathsf{T}_{\beta+\alpha'+\delta\beta+\delta\alpha'}\begin{pmatrix}\sqrt{Z_{\Phi_1}} & \delta C+\delta D\\ \delta C & \sqrt{Z_{\Phi_2}}\end{pmatrix} R_{\beta+\alpha'}\begin{pmatrix}H\\h\end{pmatrix}.$$

- δC, δD, $\delta\beta$ apriori undetermined counterterms

$$\begin{aligned}
\delta Z^{(1)}_{hh} &= \delta Z^{(1)}_{\Phi_1} c^2_\beta + \delta Z^{(1)}_{\Phi_2} s^2_\beta + (\delta D^{(1)} + 2\delta C^{(1)}) c_\beta s_\beta\,,\\
\delta Z^{(1)}_{HH} &= \delta Z^{(1)}_{\Phi_1} c^2_\beta + \delta Z^{(1)}_{\Phi_2} s^2_\beta - (\delta D^{(1)} + 2\delta C^{(1)}) c_\beta s_\beta\,,\\
\delta Z^{(1)}_{hH} + \delta Z^{(1)}_{Hh} &= -(2\delta C^{(1)} + \delta D^{(1)}) c_{2\beta} + (\delta Z^{(1)}_{\phi_1} - \delta Z^{(1)}_{\Phi_2}) s_{2\beta}\,,\\
\delta Z^{(1)}_{Hh} - \delta Z^{(1)}_{hH} &= 4\delta\alpha'^{(1)} + 4\delta\beta^{(1)} - \delta D^{(1)}\,,
\end{aligned}$$

$$\delta\alpha'^{(2)} = -\delta\beta^{(2)} + \frac{1}{4}\delta D^{(2)} + \frac{1}{8}(\delta Z^{(1)}_{hh} + \delta Z^{(1)}_{HH})(\delta Z^{(1)}_{hH} - \delta Z^{(1)}_{Hh}) - \frac{1}{8}\delta D^{(1)}(\delta Z^{(1)}_{hh} + \delta Z^{(1)}_{HH}) + \frac{1}{4}(\delta Z^{(2)}_{Hh} - \delta Z^{(2)}_{hH})\,,$$

- Definition of δD changes $\frac{1}{\epsilon}$ dependence of $\delta\alpha'$

Renormalization of the Mixing Angles

More General Approach

$$\sqrt{Z_\mathsf{S}}\begin{pmatrix} H \\ h \end{pmatrix} = R^\mathsf{T}_{\beta+\alpha'+\delta\beta+\delta\alpha'}\begin{pmatrix} \sqrt{Z_{\Phi_1}} & \delta C + \delta D \\ \delta C & \sqrt{Z_{\Phi_2}} \end{pmatrix} R_{\beta+\alpha'}\begin{pmatrix} H \\ h \end{pmatrix} .$$

- δC, δD, $\delta\beta$ apriori undetermined counterterms

$$\begin{aligned}
\delta Z^{(1)}_{hh} &= \delta Z^{(1)}_{\Phi_1} c^2_\beta + \delta Z^{(1)}_{\Phi_2} s^2_\beta + (\delta D^{(1)} + 2\delta C^{(1)}) c_\beta s_\beta \, , \\
\delta Z^{(1)}_{HH} &= \delta Z^{(1)}_{\Phi_1} c^2_\beta + \delta Z^{(1)}_{\Phi_2} s^2_\beta - (\delta D^{(1)} + 2\delta C^{(1)}) c_\beta s_\beta \, , \\
\delta Z^{(1)}_{hH} + \delta Z^{(1)}_{Hh} &= -(2\delta C^{(1)} + \delta D^{(1)}) c_{2\beta} + (\delta Z^{(1)}_{\phi_1} - \delta Z^{(1)}_{\Phi_2}) s_{2\beta} \, , \\
\delta Z^{(1)}_{Hh} - \delta Z^{(1)}_{hH} &= 4\delta\alpha'^{(1)} + 4\delta\beta^{(1)} - \delta D^{(1)} \, ,
\end{aligned}$$

$$\delta\alpha'^{(2)} = -\delta\beta^{(2)} + \frac{1}{4}\delta D^{(2)} + \frac{1}{8}(\delta Z^{(1)}_{hh} + \delta Z^{(1)}_{HH})(\delta Z^{(1)}_{hH} - \delta Z^{(1)}_{Hh}) - \frac{1}{8}\delta D^{(1)}(\delta Z^{(1)}_{hh} + \delta Z^{(1)}_{HH}) + \frac{1}{4}(\delta Z^{(2)}_{Hh} - \delta Z^{(2)}_{hH}) \, ,$$

- Definition of δD changes $\frac{1}{\epsilon}$ dependence of $\delta\alpha'$
- We use for now another prescription for $\delta\alpha'$

VEV Renormalization

"VEV" scheme [Sperling, Stöckinger, and Voigt 2013]

- Rotate the VEVs (v_h and v_H: mass eigenstate VEVs)

$$\begin{pmatrix} v \\ v_{\text{BSM}} \end{pmatrix} = R'_\alpha \begin{pmatrix} v_H \\ v_h \end{pmatrix} ,$$

$$\sqrt{Z_{\text{S}}} \begin{pmatrix} v_H \\ v_h \end{pmatrix} = R^{\mathsf{T}}_{\alpha'+\delta\alpha'} \begin{pmatrix} v+\delta v \\ v_{\text{BSM}}+\delta v_{\text{BSM}} \end{pmatrix} ,$$

- Solve for the VEV counterterms ($v_{\text{BSM}} = v_H = 0, \alpha' = -\frac{\pi}{2}$)

$$\begin{aligned}
\delta v^{(1)} &= \frac{v}{2}\delta Z^{(1)}_{hh} \\
\delta v^{(1)}_{\text{BSM}} &= \frac{v}{2}(2\delta\alpha - \delta Z^{(1)}_{Hh}) \\
\delta v^{(2)} &= -\delta\alpha^{(1)}\delta v^{(1)}_{\text{BSM}} + \frac{v}{2}(\delta\alpha^{(1)})^2 - \frac{v}{8}(\delta Z^{(1)}_{hh})^2 + \frac{v}{2}\delta Z^{(2)}_{hh} - \frac{v}{8}\delta Z^{(1)}_{hH}\delta Z^{(1)}_{Hh} , \\
\delta v^{(2)}_{\text{BSM}} &= \delta\alpha^{(1)}\delta v^{(1)} + \delta\alpha^{(2)} v + \frac{v}{8}\delta Z^{(1)}_{hh}\delta Z^{(1)}_{Hh} - \frac{v}{2}\delta Z^{(2)}_{Hh} + \frac{v}{8}\delta Z^{(1)}_{Hh}\delta Z^{(1)}_{HH} .
\end{aligned}$$

VEV renormalization

"VEV" scheme [Sperling, Stöckinger, and Voigt 2013]

- δv is fixed, introduce additional counterterm Δv_h for more flexibility

$$\sqrt{Z_\text{S}} \begin{pmatrix} v_H \\ v_h + \Delta v_h \end{pmatrix} = R^\text{T}_{\alpha'+\delta\alpha'} \begin{pmatrix} v + \delta v \\ v_\text{BSM} + \delta v_\text{BSM} \end{pmatrix} ,$$

$$\begin{aligned} \delta v^{(1)} &= \frac{v}{2} \delta Z^{(1)}_{hh} + \Delta v^{(1)}_h \\ \delta v^{(1)}_\text{BSM} &= \frac{v}{2} (2\delta\alpha - \delta Z^{(1)}_{Hh}) \\ \delta v^{(2)} &= \Delta v^{(2)}_h + \frac{\delta Z^{(1)}_{hh}}{2} \Delta v^{(1)}_h - \delta\alpha^{(1)} \delta v^{(1)}_\text{BSM} + \frac{v}{2} (\delta\alpha^{(1)})^2 - \frac{v}{8} (\delta Z^{(1)}_{hh})^2 + \frac{v}{2} \delta Z^{(2)}_{hh} - \frac{v}{8} \delta Z^{(1)}_{hH} \delta Z^{(1)}_{Hh} , \\ \delta v^{(2)}_\text{BSM} &= -\frac{\delta Z^{(1)}_{Hh}}{2} \Delta v^{(1)}_h + \delta\alpha^{(1)} \delta v^{(1)} + \delta\alpha^{(2)} v + \frac{v}{8} \delta Z^{(1)}_{hh} \delta Z^{(1)}_{Hh} - \frac{v}{2} \delta Z^{(2)}_{Hh} + \frac{v}{8} \delta Z^{(1)}_{Hh} \delta Z^{(1)}_{HH} . \end{aligned}$$

- By setting Δv_h accordingly, we can freely renormalize δv and obtain a suitable expression for δv_BSM.

Renormalization of Λ_7 and Λ_2

$\mathbb{Z}_2$ relations

$$\Lambda_2 = \Lambda_1 + 2(\Lambda_6 + \Lambda_7)\cot 2\beta\,,$$
$$\Lambda_3 + \Lambda_4 + \Lambda_5 = \Lambda_1 + 2\Lambda_6 \cot 2\beta - \frac{(\Lambda_6 - \Lambda_7)}{\cot 2\beta}\,.$$

- Use relations at loop level (apply $\delta\beta = 0$) to obtain counterterms for Λ_2 and Λ_7 ($i = 1, 2$):

$$\cot 2\beta = \frac{\Lambda_7}{-\Lambda_1 + \Lambda_3 + \Lambda_4 + \Lambda_5}\,,$$
$$\Lambda_2 = -\frac{\Lambda_1^2 - \Lambda_1(\Lambda_3 + \Lambda_4 + \Lambda_5) - 2\Lambda_7^2}{-\Lambda_1 + \Lambda_3 + \Lambda_4 + \Lambda_5}$$
$$\delta\Lambda_2^{(i)} = \delta\Lambda_1^{(i)} - 2\cot(2\beta)^2\delta\Lambda_1^{(i)} + 2\cot 2\beta(\cot 2\beta(\delta\Lambda_3^{(i)} + \delta\Lambda_4^{(i)} + \delta\Lambda_5^{(i)}) + 2\delta\Lambda_6^{(i)} - 2\cot(2\beta)^2\delta\Lambda_6^{(i)})$$
$$\delta\Lambda_7^{(i)} = \cot 2\beta(-\delta\Lambda_1^{(i)} + \delta\Lambda_3^{(i)} + \delta\Lambda_4^{(i)} + \delta\Lambda_5^{(i)}) + \delta\Lambda_6^{(i)} - 2\cot(2\beta)^2\delta\Lambda_6^{(i)}\,,$$

Renormalization of δM_{22}^2

Decoupling Renormalization [Braathen and Kanemura 2019, 2020; Degrassi and Slavich 2023]

- Define δM_{22}^2 by demanding:

$$\lambda_{hhh}^{\text{2-loop,BSM}} \xrightarrow{M_{22}\to\infty} 0\,, \text{ where } m_\Phi^2 = M_{22}^2 + \lambda_\Phi v^2 \; (\Phi = H, A, H^\pm)$$

$$\Rightarrow \; (\delta M_{22}^2)^{\text{finite}} = \frac{3M_{22}^2}{16\pi^2}\left(\Lambda_2(1-\log(M_{22}^2/Q^2)) + \frac{2\zeta_t^2 m_t^2}{v^2}(2-\log(M_{22}^2/Q^2))\right)$$

- Only one-loop counterterm obtained, need other prescription for two-loop counterterm
- Potential difference in decoupling with M_{22} or M

Renormalization with CP-odd Trilinear Couplings

Counterterm definitions

- In order to obtain (two-loop) counterterms for M_{22}^2, Λ_7, α', we use the trilinear couplings λ_{hAA}, λ_{HAA}
- $\lambda_{hAA}^{(1)} = 0$, $\lambda_{hAA}^{(2)} = 0 \Rightarrow$ solve for $(\delta M_{22}^2)^{(1)}$, $(\delta M_{22}^2)^{(2)}$ (hAA scheme)
- $\lambda_{HAA}^{(1)} = 0$, $\lambda_{HAA}^{(2)} = 0 \Rightarrow$ solve for $\delta\Lambda_7^{(1)}/\delta\alpha'^{(1)}$, $\delta\Lambda_7^{(2)}/\delta\alpha'^{(2)}$ (HAA scheme)
- If these couplings are used for renormalization of M_{22}^2 and Λ_7, in all CP-even trilinears the dependence on $\delta\alpha'^{(2)}$ cancels, no explicit expression for $\delta\alpha'^{(2)}$ needed
- Alternatively, use HAA for $\delta\alpha'^{(2)}$ and define $\delta\Lambda_7$ via the $\mathbb{Z}_2$ relations

Renormalization Summary

Renormalization Scheme Choices

Parameter	Scheme
$m_h, m_H, m_A, m_{H\pm}, m_t$	OS
Tadpoles	PRTS
v	VEV, G_μ scheme
v_{BSM} (β')	RS, VEV
α' (Λ_6)	RS, HAA
M_{22}^2	decoupling, hAA
Λ_7	HAA, $\mathbb{Z}_2$
Λ_2	$\mathbb{Z}_2$

- Rigid Symmetry (RS) scheme and decoupling scheme for M_{22}^2 only implemented at one-loop
- $\overline{\text{MS}}$ also possible for all parameters

Counterterms needed for Trilinears

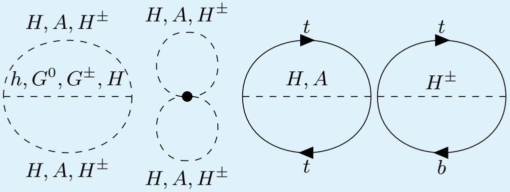
Trilinear Coupling	Counterterms
λ_{hhh}	$(\delta m_h^2)^{(2)}$, $(\delta m_H^2)^{(1)}$, $(\delta m_A^2)^{(1)}$, $(\delta m_{H\pm}^2)^{(1)}$, $\delta m_t^{(1)}$, $\delta\alpha'^{(1)}$, $\delta v_{\text{BSM}}^{(1)}$, $(\delta M_{22}^2)^{(1)}$
λ_{hhH}	$(\delta m_h^2)^{(1)}$, $(\delta m_H^2)^{(1)}$, $(\delta m_A^2)^{(1)}$, $(\delta m_{H\pm}^2)^{(1)}$, $\delta m_t^{(1)}$, $\delta\alpha'^{(2)}$, $\delta v_{\text{BSM}}^{(2)}$, $(\delta M_{22}^2)^{(1)}$, $\delta\Lambda_7^{(1)}$
$\lambda_{hHH}, \lambda_{hAA}$	$(\delta m_h^2)^{(1)}$, $(\delta m_H^2)^{(2)}$, $(\delta m_A^2)^{(2)}$, $(\delta m_{H\pm}^2)^{(1)}$, $\delta m_t^{(1)}$, $\delta\alpha'^{(2)}$, $\delta v_{\text{BSM}}^{(2)}$, $(\delta M_{22}^2)^{(2)}$, $\delta\Lambda_7^{(1)}$, $\delta\Lambda_2^{(1)}$
$\lambda_{HHH}, \lambda_{HAA}$	$(\delta m_h^2)^{(1)}$, $(\delta m_H^2)^{(2)}$, $(\delta m_A^2)^{(2)}$, $(\delta m_{H\pm}^2)^{(1)}$, $\delta m_t^{(1)}$, $\delta\alpha'^{(2)}$, $\delta v_{\text{BSM}}^{(2)}$, $(\delta M_{22}^2)^{(1)}$, $\delta\Lambda_7^{(2)}$, $\delta\Lambda_2^{(1)}$

Calculation of Trilinear Couplings at Two-Loops

Two-Loop Corrections to Trilinear Couplings

Effective Potential Approach

- Diagrams to consider (BSM contributions):

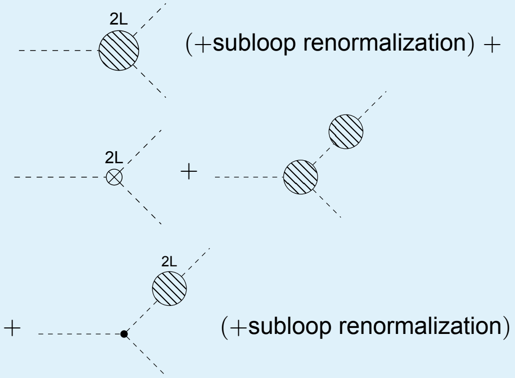


$\Rightarrow$ $\overline{\text{MS}}$ renormalized expressions

- Include finite shifts of parameters to obtain OS result

Diagrammatic Approach

- Two-loop corrections:



IR Divergences

Handling of IR Divergences

- Massless particles (m_h, m_G) in our calculation: Potential issue of IR divergences (”Goldstone-Boson Catastrophe”)
- Regularize expressions with finite masses, set them to zero at the end of the calculation
- Final result should be independent of regulators

Technical Details

- Need mass expansion for one- and two-loop integrals, can be found in the literature (e.g. from [Martin 2002]) or rederived using relations from [Martin 2003]
- For two-loop mass counterterms: Need expansion or certain U integrals, have been derived

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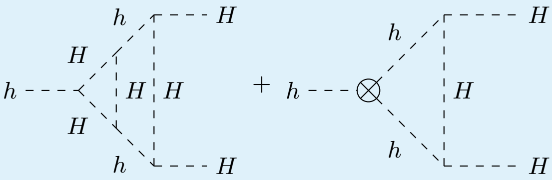
Result

- All counterterms and the 2-loop corrections for hhh and hhH are IR finite
- However, issues arise for hHH and HHH

IR Divergences

The hHH and HHH case

- Check IR divergences topologywise, consider e.g.:



- IR divergence above does not cancel (left side: $(M_{22})^{10}$ from 5 hHH couplings, right side: only $(M_{22})^8$), also other contributions do not cancel $\Rightarrow$ remaining $\log(m_h^2)$ dependence

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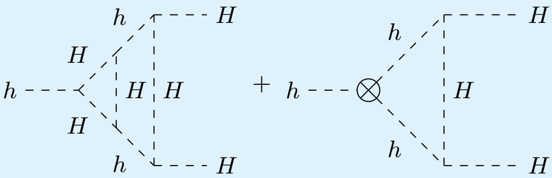


- IR divergence above does not cancel (left side: $(M_{22})^{10}$ from 5 hHH couplings, right side: only $(M_{22})^8$), also other contributions do not cancel $\Rightarrow$ remaining $\log(m_h^2)$ dependence

Possible solutions

- In our setup: IR divergence proportional to $m_H - m_A$, vanishes in the degenerate mass case
- Other possible patchwork solutions (usage of effective couplings,..)
- Proper solution: Introduce finite momentum to regulate IR divergences (out of the scope of this project)

Implementation and Checks

Details on the Calculation

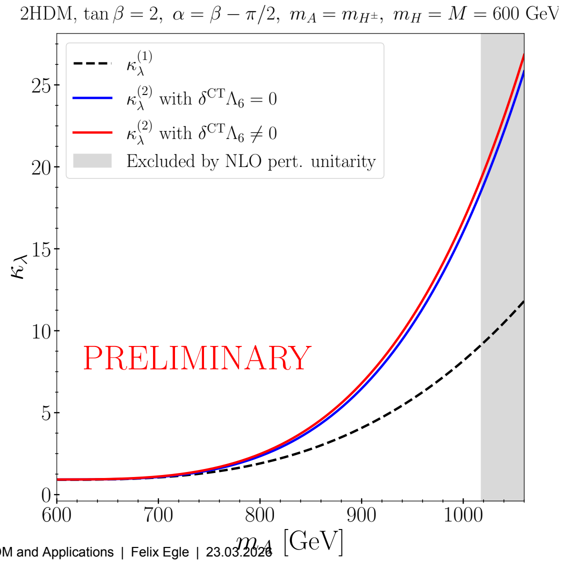
- Use of `Feynarts` [Hahn 2001], `Feyncalc` [R. Mertig, Böhm, and A. Denner 1991; Shtabovenko, Rolf Mertig, and Orellana 2016, 2020, 2025] and `TARCER` [R. Mertig and Scharf 1998] to calculate and simplify two-loop results
- Use of [Martin 2003] for two-loop integral relations
- Comparison of results from diagrammatic and effective potential approaches
- Comparison of counterterms with RGE relations from `SARAH` [Staub 2014]
- Cancellation of renormalization scale dependence, UV finiteness of final result

Code Implementation

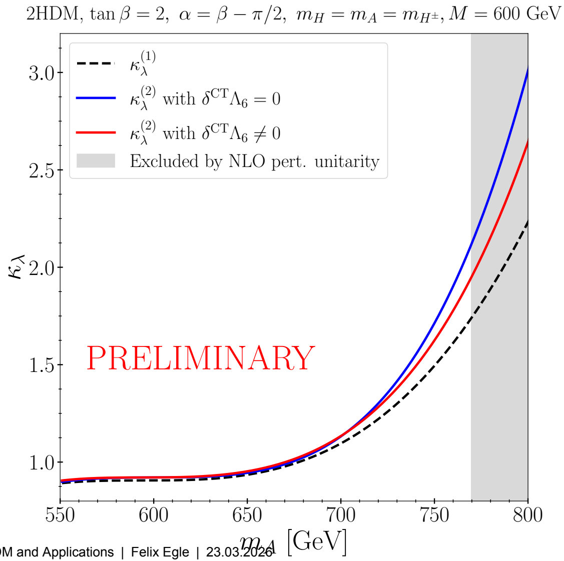
- Implementation of all results in a python code
- Input parameters and renormalization schemes can be varied
- Usage of `TSIL` [Martin and Robertson 2006] for the numerical evaluation of two-loop integrals

Results

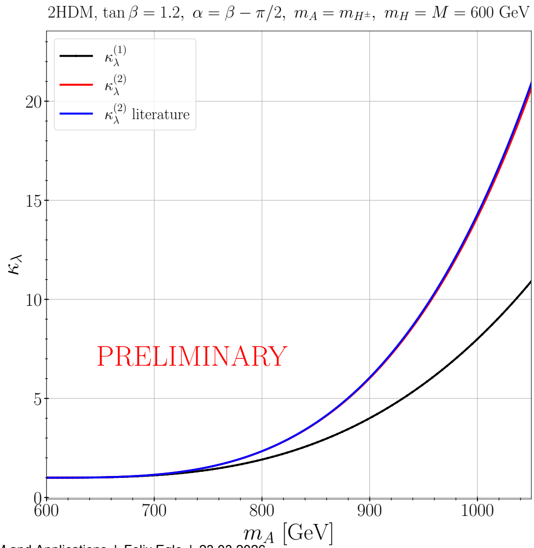
Comparison with [Braathen and Kanemura 2019, 2020]



Comparison with [Braathen and Kanemura 2019, 2020]



Comparison with [Degrassi, Gröber, and Slavich 2025]



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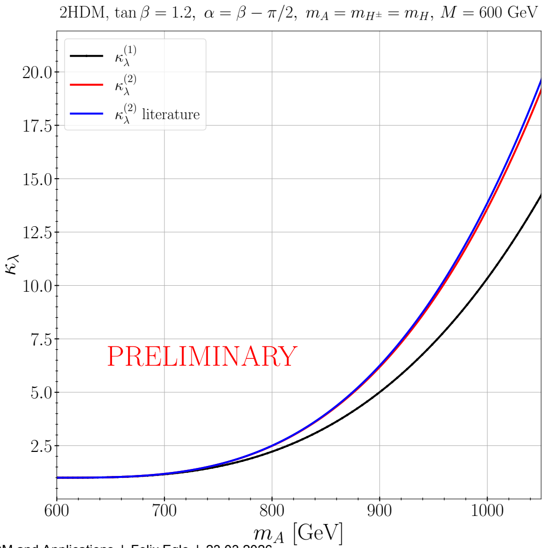
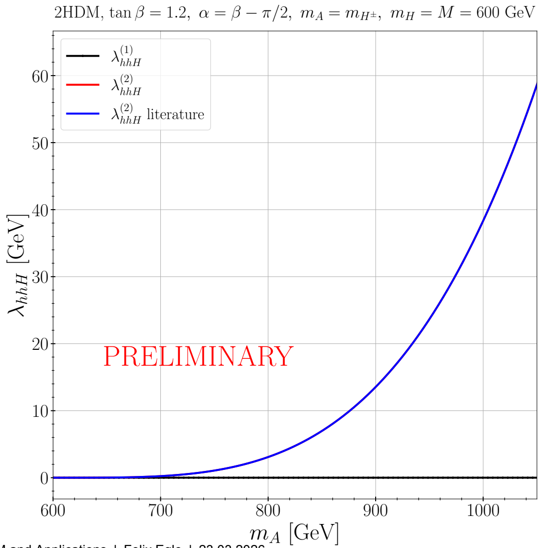
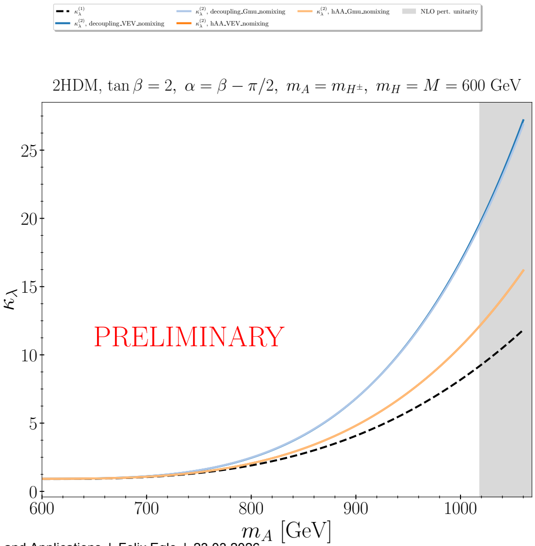


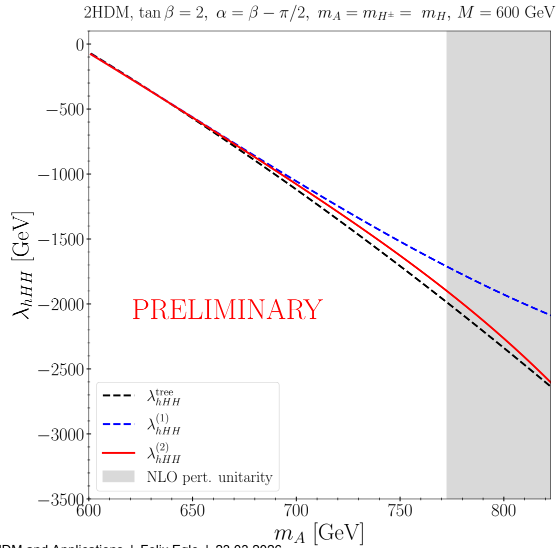
Comparison with [Degrassi, Gröber, and Slavich 2025]



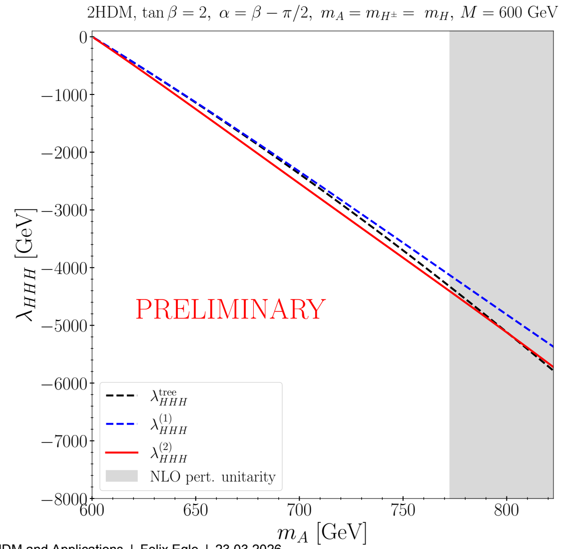
Comparison of Different Schemes



Two loop Corrections to hHH and HHH



Two loop Corrections to hHH and HHH



Conclusion

Summary

- Renormalization of all 2HDM parameters at two loops
- Calculation of scalar trilinear couplings at two loops
- Comparison with existing results

Outlook

- Further comparison, check with viable benchmark points, impact on phenomenology?
- Check of different scheme choices, impact on results
- Resolve IR issue

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2HDM in the Higgs Basis

2HDM $\mathbb{Z}_2$-symmetric Lagrangian [Branco et al. 2012]

$$\Phi_1 = \begin{pmatrix} \phi_a^+ \\ \frac{1}{\sqrt{2}}(v_a + \rho_a + i\eta_a) \end{pmatrix}, \quad a = 1, 2\,,$$

$$V(\Phi_1, \Phi_2) = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_2^\dagger \Phi_1 + \text{h.c.})$$
$$+ \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_2^\dagger \Phi_1|^2 + \frac{\lambda_5}{2} \left[(\Phi_2^\dagger \Phi_1)^2 + \text{h.c.} \right],$$

$$\mathcal{L}_{\text{Yuk}} \supset -\bar{Q}_{\text{L}} Y^t \tilde{\Phi}_2 t_{\text{R}} \qquad \left(Q_{\text{L}} = \begin{pmatrix} t_{\text{L}} & b_{\text{L}} \end{pmatrix}^{\text{T}}\right)$$

Higgs basis input in terms of $\mathbb{Z}_2$-basis input (in the alignment limit)

$$\tan\beta = \frac{v_2}{v_1}\,, \quad M^2 = \frac{2m_{12}^2}{\sin 2\beta}\,, \quad M_{22}^2 = M^2 - \frac{m_h^2}{2}\,, \quad \Lambda_7 = \frac{2(m_H^2 - M^2)\cot 2\beta}{v^2}$$

2HDM in the Higgs Basis

Tadpole Equations

$$\left.\frac{\partial V_{\text{2HDM}}}{\partial \phi}\right|_{\{\phi\}=0} \overset{!}{=} T_\phi \quad (\phi = \phi_{\text{SM}}, \phi_{\text{BSM}}, G'^0, A'^0, G'^\pm, H'^\pm)$$

$$\Rightarrow M_{11}^2 = \frac{1}{2v^2}(2T_1 v - \Lambda_1 v^4 + v_{\text{BSM}}(-2T_2 - 2\Lambda_6 v^3 + 2M_{22}^2 v_{\text{BSM}} + 2\Lambda_7 v v_{\text{BSM}}^2 + \Lambda_2 v_{\text{BSM}}^3)$$

$$M_{12}^2 = \frac{1}{2v}(-2T_2 + \Lambda_6 v^3 + v_{\text{BSM}}(2M_{22}^2 + (\Lambda_3 + \Lambda_4 + \Lambda_5)v^2 + 3\Lambda_7 v v_{\text{BSM}} + \Lambda_2 v_{\text{BSM}}^2)$$

$$T_1 = T_{\phi_{\text{SM}}}\,, \quad T_2 = T_{\phi_{\text{BSM}}}$$

$$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix} = R_{\alpha'} \begin{pmatrix} T_H \\ T_h \end{pmatrix}, R_{\alpha'} = \begin{pmatrix} \cos\alpha' & -\sin\alpha' \\ \sin\alpha' & \cos\alpha' \end{pmatrix}$$

2HDM in the Higgs Basis

Mass Matrices

$$\mathcal{M}_{\phi_{\text{SM}}\phi_{\text{BSM}}} = \begin{pmatrix} \frac{2\Lambda_1 v^4 + v_{\text{BSM}}(4\Lambda_6 v^3 + v_{\text{BSM}}(2M_{22}^2 + (\Lambda_3+\Lambda_4+\Lambda_5)v^2 + 2\Lambda_7 v v_{\text{BSM}} + \Lambda_2 v_{\text{BSM}}^2))}{2v^2} & \frac{2\Lambda_6 v^3 + v_{\text{BSM}}(-2M_{22}^2 + (\Lambda_3+\Lambda_4+\Lambda_5)v^2 - \Lambda_2 v_{\text{BSM}}^2)}{2v} \\ \frac{2\Lambda_6 v^3 + v_{\text{BSM}}(-2M_{22}^2 + (\Lambda_3+\Lambda_4+\Lambda_5)v^2 - \Lambda_2 v_{\text{BSM}}^2)}{2v} & \frac{1}{2}(2M_{22}^2 + (\Lambda_3 + \Lambda_4 + \Lambda_5)v^2 + 6\Lambda_7 v v_{\text{BSM}} + 3\Lambda_2 v_{\text{BSM}}^2) \end{pmatrix}$$

$$\mathcal{M}_{G'^0 A'} = \begin{pmatrix} \frac{1}{2v^2}(v_{\text{BSM}}^2(2M_{22}^2 + (\Lambda_3 + \Lambda_4 - \Lambda_5)v^2 + 2\Lambda_7 v v_{\text{BSM}} + \Lambda_2 v_{\text{BSM}}^2)) & -\frac{v_{\text{BSM}}}{2v}(2M_{22}^2 + (\Lambda_3 + \Lambda_4 - \Lambda_5)v^2 + 2\Lambda_7 v v_{\text{BSM}} + \Lambda_2 v_{\text{BSM}}^2) \\ -\frac{v_{\text{BSM}}}{2v}(2M_{22}^2 + (\Lambda_3 + \Lambda_4 - \Lambda_5)v^2 + 2\Lambda_7 v v_{\text{BSM}} + \Lambda_2 v_{\text{BSM}}^2) & \frac{1}{2}(2M_{22}^2 + (\Lambda_3 + \Lambda_4 - \Lambda_5)v^2 + 2\Lambda_7 v v_{\text{BSM}} + \Lambda_2 v_{\text{BSM}}^2) \end{pmatrix}$$

$$\mathcal{M}_{G'^\pm H'^\pm} = \begin{pmatrix} \frac{1}{2}(v_{\text{BSM}}^2(2M_{22}^2 + \Lambda_3 v^2 + 2\Lambda_7 v v_{\text{BSM}} + \Lambda_2 v_{\text{BSM}}^2) & -\frac{v_{\text{BSM}}}{2v}(2M_{22}^2 + \Lambda_3 v^2 + 2\Lambda_7 v v_{\text{BSM}} + \Lambda_2 v_{\text{BSM}}^2) \\ -\frac{v_{\text{BSM}}}{2v}(2M_{22}^2 + \Lambda_3 v^2 + 2\Lambda_7 v v_{\text{BSM}} + \Lambda_2 v_{\text{BSM}}^2) & M_{22}^2 + \frac{1}{2}(\Lambda_3 v^2 + v_{\text{BSM}}(2\Lambda_7 v + \Lambda_2 v_{\text{BSM}})) \end{pmatrix}$$

$$T_{\phi_{\text{SM}}\phi_{\text{BSM}}} = T_{G'^0 A'} = T_{G'^\pm H'^\pm} = \begin{pmatrix} \frac{T_1 v - T_2 v_{\text{BSM}}}{v^2} & \frac{T_2}{v} \\ \frac{T_2}{v} & 0 \end{pmatrix}$$

$$\mathcal{M}_{\phi_{\text{SM}}\phi_{\text{BSM}}} = \begin{pmatrix} \mathcal{M}_{11} & \mathcal{M}_{12} \\ \mathcal{M}_{12} & \mathcal{M}_{22} \end{pmatrix} \Rightarrow \tan 2\alpha' = \frac{2\mathcal{M}_{12}}{\mathcal{M}_{11} - \mathcal{M}_{22}}, \qquad \tan\beta' = \frac{v_{\text{BSM}}}{v}$$

2HDM in the Higgs Basis

Replacement Rules

$$\Lambda_1 = \frac{-1}{2v^4}(-(m_h^2 + m_H^2)v^2 + 2\Lambda_6 v^3 v_{\text{BSM}} + 4M_{22}^2 v_{\text{BSM}}^2 + 2\Lambda_7 v v_{\text{BSM}}^3 + 2\Lambda_2 v_{\text{BSM}}^4 + v\sqrt{S})$$

$$\Lambda_3 = \frac{-2M_{22}^2}{v^2} - \frac{v_{\text{BSM}}(2\Lambda_7 v + \Lambda_2 v_{\text{BSM}})}{v^2} + \frac{(2m_{H\pm}^2)}{v^2 + v_{\text{BSM}}^2}$$

$$\Lambda_4 = \frac{1}{2v^2(v^2 + v_{\text{BSM}}^2)}((2m_A^2 + m_h^2 + m_H^2 - 4m_{H\pm}^2)v^2 - 2\Lambda_6 v^3 v_{\text{BSM}} - 4\Lambda_7 v^3 v_{\text{BSM}} + 4M_{22}^2 v_{\text{BSM}}^2$$
$$- 2\Lambda_2 v^2 v_{\text{BSM}}^2 + 2\Lambda_7 v v_{\text{BSM}}^3 + 2\Lambda_2 v_{\text{BSM}}^4 + v\sqrt{S})$$

$$\Lambda_5 = \frac{1}{2v^2(v^2 + v_{\text{BSM}}^2)}((-2m_A^2 + m_h^2 + m_H^2)v^2 - 2\Lambda_6 v^3 v_{\text{BSM}} - 4\Lambda_7 v^3 v_{\text{BSM}} + 4M_{22}^2 v_{\text{BSM}}^2$$
$$- 2\Lambda_2 v^2 v_{\text{BSM}}^2 + 2\Lambda_7 v v_{\text{BSM}}^3 + 2\Lambda_2 v_{\text{BSM}}^4 + v\sqrt{S})$$

$$S \equiv (m_h^4 + m_H^4)v^2 - 4(\Lambda_6 v^3 - v_{\text{BSM}}(2M_{22}^2 + v_{\text{BSM}}(3\Lambda_7 v + 2\Lambda_2 v_{\text{BSM}})))^2 + 4m_H^2 v_{\text{BSM}}(-\Lambda_6 v^3$$
$$+ v_{\text{BSM}}(2M_{22}^2 + v_{\text{BSM}}(3\Lambda_7 v + 2\Lambda_2 v_{\text{BSM}}))) - 2m_h^2(2\Lambda_6 v^3 v_{\text{BSM}} + m_H^2(v^2 + 2v_{\text{BSM}}^2)$$
$$- 2v_{\text{BSM}}^2(2M_{22}^2 + v_{\text{BSM}}(3\Lambda_7 v + 2\Lambda_2 v_{\text{BSM}})))$$

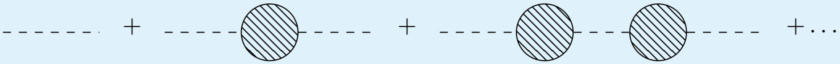
Mixed Propagator Resummation [Frank et al. 2007; Fuchs 2015]

Propagator Mixing

- Mixing of fields, introduce ($\hat{\Sigma} = \hat{\Sigma}(p^2)$):

$$\mathbf{P} = \begin{pmatrix} P_1 & 0 \\ 0 & P_2 \end{pmatrix}, \quad P_i = \frac{1}{p^2 - m_i^2} \ (i = 1, 2) \quad \hat{\boldsymbol{\Sigma}} = \begin{pmatrix} \hat{\Sigma}_{11} & \hat{\Sigma}_{12} \\ \hat{\Sigma}_{21} & \hat{\Sigma}_{22} \end{pmatrix}.$$

- $\mathbf{P}$: the tree level propagators, $\hat{\boldsymbol{\Sigma}}$: scalar self-energies



$$= i\mathbf{P} - i\mathbf{P}\hat{\boldsymbol{\Sigma}}\mathbf{P} + i\mathbf{P}\hat{\boldsymbol{\Sigma}}\mathbf{P}\hat{\boldsymbol{\Sigma}}\mathbf{P} + \cdots = i\mathbf{P}\sum_{k=0}^{\infty}(-\hat{\boldsymbol{\Sigma}}\mathbf{P})^k = \mathbf{P}\frac{1}{1 + \hat{\boldsymbol{\Sigma}}\mathbf{P}} \equiv \hat{\mathbf{P}}.$$

- $\hat{\mathbf{P}}$: resummed propagator matrix

Mixed Propagator Resummation [Frank et al. 2007; Fuchs 2015]

Resummed Propagator

- $\hat{\mathbf{P}}$: resummed propagator matrix

$$\hat{\mathbf{P}}_{11} = i\frac{(m_2^2 - \hat{\Sigma}_{22} - p^2)}{\hat{\Sigma}_{12}^2 + (m_1^2 - \hat{\Sigma}_{11} - p^2)(-m_2^2 + \hat{\Sigma}_{22} + p^2)} = \frac{i}{p^2 - m_1^2 + \hat{\Sigma}_{11}^{\text{eff}}}$$

$$\hat{\mathbf{P}}_{22} = i\frac{(m_1^2 - \hat{\Sigma}_{11} - p^2)}{\hat{\Sigma}_{12}^2 + (m_1^2 - \hat{\Sigma}_{11} - p^2)(-m_2^2 + \hat{\Sigma}_{22} + p^2)} = \frac{i}{p^2 - m_2^2 + +\hat{\Sigma}_{22}^{\text{eff}}}$$

$$\hat{\mathbf{P}}_{12} = i\frac{\hat{\Sigma}_{12}}{(\hat{\Sigma}_{12}^2 + (m_1^2 - \hat{\Sigma}_{11} - p^2)(-m_2^2 + \hat{\Sigma}_{22} + p^2)}\,,$$

$$\hat{\Sigma}_{11}^{\text{eff}} = \hat{\Sigma}_{11} - \frac{\hat{\Sigma}_{12}^2}{p^2 - m_2^2 + \hat{\Sigma}_{22}}\,,$$

$$\hat{\Sigma}_{22}^{\text{eff}} = \hat{\Sigma}_{22} - \frac{\hat{\Sigma}_{12}^2}{p^2 - m_1^2 + \hat{\Sigma}_{11}}\,.$$

OS Renormalization with Mixing Propagators [Frank et al. 2007; Fuchs 2015]

OS Conditions

- OS conditions:

$$\mathrm{Re}\hat{\Sigma}^{\mathrm{eff}}_{ii}(m_i^2) = 0\,, \qquad \frac{\partial}{\partial p^2}\mathrm{Re}\hat{\Sigma}^{\mathrm{eff}}_{ii}(p^2)\bigg|_{p^2=m_i^2} = 0$$

$$\mathrm{Re}\,\frac{\hat{\mathbf{P}}_{12}}{\hat{\mathbf{P}}_{11}} \xrightarrow{p^2\to m_1^2} 0\,,$$

$$\mathrm{Re}\,\frac{\hat{\mathbf{P}}_{12}}{\hat{\mathbf{P}}_{22}} \xrightarrow{p^2\to m_2^2} 0\,.$$

Mass Matrix Renormalization

CP-even Scalar Matrix

$$D_{(Hh)} = R_{\alpha'}^{\mathsf{T}} \mathcal{M} R_{\alpha'} = \begin{pmatrix} m_H^2 & 0 \\ 0 & m_h^2 \end{pmatrix} + R_{\alpha'}^{\mathsf{T}} \begin{pmatrix} \frac{T_1}{v} - \frac{T_2 v_{\mathsf{BSM}}}{v^2} & \frac{T_2}{v} \\ \frac{T_2}{v} & 0 \end{pmatrix} R_{\alpha}' \,,$$

$$\delta D_{(Hh)} = \begin{pmatrix} \delta m_H^2 & 0 \\ 0 & \delta m_h^2 \end{pmatrix}$$

$$+ \underbrace{(R_{\alpha'} + R_{\delta\alpha'})^{\mathsf{T}} \begin{pmatrix} \frac{\delta T_1}{v+\delta v} - \frac{\delta T_2 (v_{\mathsf{BSM}} + \delta v_{\mathsf{BSM}})}{(v+\delta v)^2} & \frac{\delta T_2}{v+\delta v} \\ \frac{\delta T_2}{v+\delta v} & 0 \end{pmatrix} (R_{\alpha'} + R_{\delta\alpha'})}_{\begin{pmatrix} \delta T_{HH} & \delta T_{hH} \\ \delta T_{hH} & \delta T_{hh} \end{pmatrix}} \,.$$

Mass Matrix Renormalization

Tadpole Counterterms

Tadpole counterterm matrix ($\alpha' = -\frac{\pi}{2}, \beta' = 0$):

$$\delta T_{hh} = \left(\frac{\delta T_h^{(1)}}{v}\right) + \left(-\frac{\delta T_h^{(1)}\delta v^{(1)}}{v^2} + \frac{\delta T_h^{(2)}}{v} - \frac{\delta T_H^{(1)}\delta\alpha'^{(1)}}{v} + \frac{\delta\beta'^{(1)}\delta T_H^{(1)}}{v}\right),$$

$$\delta T_{hH} = \left(\frac{\delta T_H^{(1)}}{v}\right) + \left(-\frac{\delta T_H^{(1)}\delta v^{(1)}}{v^2} + \frac{\delta T_H^{(2)}}{v}\right),$$

$$\delta T_{HH} = (0) + \left(\frac{2\delta T_H^{(1)}\delta\alpha'^{(1)}}{v}\right).$$

OS Renormalization

Counterterm Expressions

$$\delta T_h^{(1)} = t_h^{(1)} \,,$$

$$\delta T_h^{(2)} = t_h^{(2)} - \delta T_h^{(1)} \frac{\delta Z_{hh}^{(1)}}{2} - \delta T_H^{(1)} \frac{\delta Z_{Hh}^{(1)}}{2} \,,$$

$$\delta T_H^{(1)} = t_H^{(1)} \,,$$

$$\delta T_H^{(2)} = t_H^{(2)} - \delta T_H^{(1)} \frac{\delta Z_{HH}^{(1)}}{2} - \delta T_h^{(1)} \frac{\delta Z_{hH}^{(1)}}{2} \,,$$

$$(\delta m_h^2)^{(1)} = \text{Re}\Sigma_{hh}^{(1)}(m_h^2) - \delta T_{hh}^{(1)} \,,$$

$$(\delta m_h^2)^{(2)} = \text{Re}\Sigma_{hh}^{(2)}(m_h^2) - \frac{(\text{Im}\Sigma_{hH}^{(1)}(m_h^2))^2}{m_H^2 - m_h^2} - \delta T_{hh}^{(2)} - \delta D_{hh}^{(1)} \delta Z_{hh}^{(1)} - \delta D_{hH}^{(1)} \delta Z_{Hh}^{(1)} + \frac{1}{4} (\delta Z_{Hh}^{(1)})^2 (m_h^2 - m_H^2) \,,$$

$$(\delta m_H^2)^{(1)} = \text{Re}\Sigma_{HH}^{(1)}(m_H^2) - \delta T_{HH}^{(1)} \,,$$

$$(\delta m_H^2)^{(2)} = \text{Re}\Sigma_{HH}^{(2)}(m_H^2) - \frac{(\text{Im}\Sigma_{hH}^{(1)}(m_H^2))^2}{m_h^2 - m_H^2} - \delta T_{HH}^{(2)} - \delta D_{HH}^{(1)} \delta Z_{HH}^{(1)} - \delta D_{hH}^{(1)} \delta Z_{hH}^{(1)} + \frac{1}{4} (\delta Z_{hH}^{(1)})^2 (m_H^2 - m_h^2) \,,$$

OS Renormalization

Counterterm Expressions

$$\delta Z^{(1)}_{hh} = -\text{Re}\Sigma'^{(1)}_{hh}(m_h^2)\,, \quad \delta Z^{(1)}_{HH} = -\text{Re}\Sigma'^{(1)}_{HH}(m_H^2)\,,$$

$$\delta Z^{(1)}_{hH} = \frac{2}{m_h^2 - m_H^2}\left(\text{Re}\Sigma^{(1)}_{hH}(m_H^2) - \delta T^{(1)}_{hH}\right)\,, \quad \delta Z^{(1)}_{Hh} = \frac{2}{m_H^2 - m_h^2}\left(\text{Re}\Sigma^{(1)}_{hH}(m_h^2) - \delta T^{(1)}_{hH}\right)\,,$$

$$\delta Z^{(2)}_{hh} = -\text{Re}\Sigma'^{(2)}_{hh}(m_h^2) + \frac{(\text{Im}\Sigma^{(1)}_{hH}(m_h^2))^2}{(m_h^2 - m_H^2)^2} + 2\frac{\text{Im}\Sigma^{(1)}_{hH}(m_h^2)\text{Im}\Sigma'^{(1)}_{hH}(m_h^2)}{m_H^2 - m_h^2} - \frac{1}{4}\delta Z^{(1)}_{Hh}(\delta Z^{(1)}_{Hh} - \delta Z^{(1)}_{hH})\,,$$

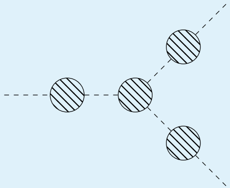
$$\delta Z^{(2)}_{HH} = -\text{Re}\Sigma'^{(2)}_{HH}(m_H^2) + \frac{(\text{Im}\Sigma^{(1)}_{hH}(m_H^2))^2}{(m_h^2 - m_H^2)^2} + 2\frac{\text{Im}\Sigma^{(1)}_{hH}(m_H^2)\text{Im}\Sigma'^{(1)}_{hH}(m_H^2)}{m_h^2 - m_H^2} - \frac{1}{4}\delta Z^{(1)}_{hH}(\delta Z^{(1)}_{hH} - \delta Z^{(1)}_{Hh})\,,$$

$$\delta Z^{(2)}_{hH} = \frac{2}{m_h^2 - m_H^2}\Bigg(\text{Re}\Sigma^{(2)}_{hH}(m_H^2) - \frac{\text{Im}\Sigma^{(1)}_{hH}(m_H^2)\text{Im}\Sigma^{(1)}_{hh}(m_H^2)}{m_h^2 - m_H^2} - \delta T^{(2)}_{hH} - \frac{1}{2}\delta D^{(1)}_{hh}\delta Z^{(1)}_{hH} - \frac{1}{2}\delta D^{(1)}_{HH}\delta Z^{(1)}_{Hh}$$
$$-\delta D^{(1)}_{hH}\left(\frac{\delta Z^{(1)}_{hh} + \delta Z^{(1)}_{HH}}{2}\right) - \frac{1}{8}\delta Z^{(1)}_{hh}\delta Z^{(1)}_{hH}(m_h^2 - m_H^2) - \frac{1}{8}\delta Z^{(1)}_{HH}\delta Z^{(1)}_{hH}(m_H^2 - m_h^2)\Bigg)\,,$$

$$\delta Z^{(2)}_{Hh} = \frac{2}{m_H^2 - m_h^2}\Bigg(\text{Re}\Sigma^{(2)}_{hH}(m_h^2) - \frac{\text{Im}\Sigma^{(1)}_{hH}(m_h^2)\text{Im}\Sigma^{(1)}_{HH}(m_h^2)}{m_H^2 - m_h^2} - \delta T^{(2)}_{hH} - \frac{1}{2}\delta D^{(1)}_{hh}\delta Z^{(1)}_{hH} - \frac{1}{2}\delta D^{(1)}_{HH}\delta Z^{(1)}_{Hh}$$
$$-\delta D^{(1)}_{hH}\left(\frac{\delta Z^{(1)}_{hh} + \delta Z^{(1)}_{HH}}{2}\right) - \frac{1}{8}\delta Z^{(1)}_{hh}\delta Z^{(1)}_{Hh}(m_h^2 - m_H^2) - \frac{1}{8}\delta Z^{(1)}_{HH}\delta Z^{(1)}_{Hh}(m_H^2 - m_h^2)\Bigg)\,.$$

Leg Corrections

LSZ Reduction



$$=< 0|T\Phi_a\Phi_b\Phi_c|0 >= \hat{\mathsf{P}}_{ia}\hat{\mathsf{P}}_{jb}\hat{\mathsf{P}}_{kc}\lambda_{ijk} = \hat{\mathsf{P}}_{aa}\hat{\mathsf{P}}_{bb}\hat{\mathsf{P}}_{cc}R_{ia}R_{jb}R_{kc}\lambda_{ijk} \,, \quad R_{ia} \equiv \frac{\hat{\mathsf{P}}_{ia}}{\hat{\mathsf{P}}_{aa}}$$

- $\hat{\mathsf{P}}_{ia}$: resummed external propagator corrections, λ_{ijk}: amputated vertex correction
- In the spirit of the LSZ reduction:

$$< 0|T\Phi_a\Phi_b\Phi_c|0 >\sim \frac{\widetilde{Z}_a}{p^2-m_a^2}\frac{\widetilde{Z}_b}{p^2-m_b^2}\frac{\widetilde{Z}_c}{p^2-m_c^2}R_{ia}R_{jb}R_{kc}\lambda_{ijk} \,,$$

Leg Corrections

LSZ Reduction

- Define the leg-corrected trilinear as:

$$\widetilde{\lambda}_{abc} = \sqrt{\widetilde{Z}_a}\sqrt{\widetilde{Z}_b}\sqrt{\widetilde{Z}_c} R_{ia} R_{jb} R_{kc} \lambda_{ijk} \,.$$

- Determine the $\widetilde{Z}$ at zero external momentum:

$$\left.\frac{\widetilde{Z}_a}{p^2 - m_a^2}\right|_{p^2\to 0} = \left.\hat{\mathbf{P}}_{aa}\right|_{p^2\to 0} , \qquad R_{ia} = \left.\frac{\hat{\mathbf{P}}_{ia}}{\hat{\mathbf{P}}_{aa}}\right|_{p^2\to 0} .$$

- We obtain ($m_h \to 0$):

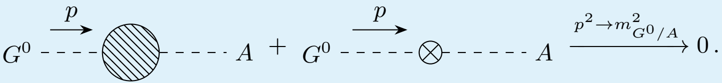
$$\widetilde{Z}_h = 1 \,, \qquad R_{hh} = R_{HH} = 1 \,, R_{Hh} = 0 \,,$$

$$\widetilde{Z}_H = \frac{1}{1 - \frac{\hat{\Sigma}_{HH}(0)}{m_H^2}} \,, \qquad R_{hH} = -\hat{\Sigma}'_{hH}(0) \,,$$

Renormalization without Mixing Angles

Renormalization of v_{BSM}

- Use δv_{BSM} to renormalize the pseudoscalar mixing self energy:´



- Result is already UV finite, can set $\delta v_{\text{BSM}} = 0$.

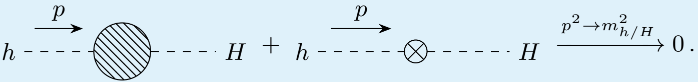
Renormalization without Mixing Angles

Renormalization of Λ_6

- Scalar mass matrix:

$$D_{Hh} = \begin{pmatrix} m_H^2 & -\Lambda_6 v^2 \\ -\Lambda_6 v^2 & m_h^2 \end{pmatrix} + \begin{pmatrix} 0 & \frac{T_H}{v} \\ \frac{T_H}{v} & \frac{T_h}{v} \end{pmatrix}$$

- Use $\delta\Lambda_6$ to renormalize the scalar mixing self energy:´



- Redundancy between $\delta\Lambda_6$ and δZ_{Hh}: We choose $\delta Z_{Hh} = 0$

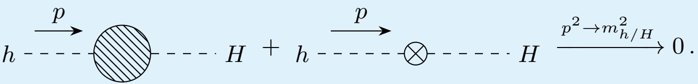
Renormalization without Mixing Angles

Renormalization of Λ_6

- Scalar mass matrix:

$$D_{Hh} = \begin{pmatrix} m_H^2 & -\Lambda_6 v^2 \\ -\Lambda_6 v^2 & m_h^2 \end{pmatrix} + \begin{pmatrix} 0 & \frac{T_H}{v} \\ \frac{T_H}{v} & \frac{T_h}{v} \end{pmatrix}$$

- Use $\delta\Lambda_6$ to renormalize the scalar mixing self energy:´



- Redundancy between $\delta\Lambda_6$ and δZ_{Hh}: We choose $\delta Z_{Hh} = 0$

$$\delta\Lambda_6^{(1)} = -\frac{1}{v^2}\left(\Sigma_{hH}^{(1)}(m_h^2) - \delta T_{hH}^{(1)}\right),$$

$$\delta\Lambda_6^{(2)} = -\frac{1}{v^2}\left(\Sigma_{hH}^{(2)}(m_h^2) - \delta T_{hH}^{(2)} - \left(-v^2\delta\Lambda_6^{(1)} + \delta T_{hH}^{(1)}\right)\left(\frac{\delta Z_{hh}^{(1)} + \delta Z_{HH}^{(1)}}{2}\right) - \frac{1}{2}\delta D_{hh}^{(1)}\delta Z_{hH}^{(1)} + 2\delta\Lambda_6^{(1)}\delta v^{(1)} v\right)$$

$$\delta Z_{hH}^{(1)} = \frac{2}{m_h^2 - m_H^2}\left(\Sigma_{hH}^{(1)}(m_H^2) + \delta\Lambda_6 v^2 - \delta T_{hH}^{(1)}\right) = \frac{2}{m_h^2 - m_H^2}\left(\Sigma_{hH}^{(1)}(m_H^2) - \Sigma_{hH}^{(1)}(m_h^2)\right)$$

Renormalization without Mixing Angles

Renormalization of Λ_7

$$\Lambda_2 = \Lambda_1 + 2(\Lambda_6 + \Lambda_7)\cot 2\beta\,,$$

$$\Lambda_3 + \Lambda_4 + \Lambda_5 = \Lambda_1 + 2\Lambda_6 \cot 2\beta - \frac{(\Lambda_6 - \Lambda_7)}{\cot 2\beta}\,.$$

- Use relations at loop level to obtain counterterm relations

$$\delta\Lambda_7^{(1)} = \delta\Lambda_6^{(1)} - 2\cot^2 2\beta\delta\Lambda_6^{(1)} - (2\delta\beta^{(1)}\Lambda_7)\tan 2\beta + \cot 2\beta(-\delta\Lambda_1^{(1)} + \delta\Lambda_3^{(1)} + \delta\Lambda_4^{(1)} + \delta\Lambda_5^{(1)} - 2\delta\beta^{(1)}\Lambda_7)$$

- Given $\delta\beta$, we obtain an expression for $\delta\Lambda_7$

Renormalization without Mixing Angles

Renormalization of β [Altenkamp, Dittmaier, and Rzehak 2017; Ansgar Denner, Dittmaier, and Lang 2018]

- Introduce diagonal δZ factors for the gauge fields in the $\mathbb{Z}_2$ basis:

$$\Phi_1 \to \sqrt{Z_{\Phi_1}}\Phi_1$$
$$\Phi_2 \to \sqrt{Z_{\Phi_2}}\Phi_2$$

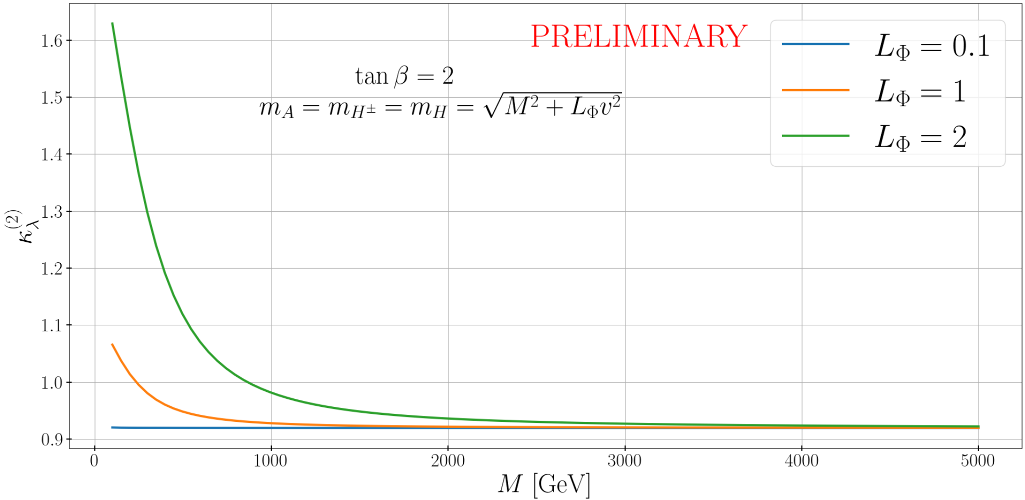
- Relate WFR constants to the OS constants δZ_S via a rotation:

$$\sqrt{Z_S}\begin{pmatrix} H \\ h \end{pmatrix} = R^{\mathsf{T}}_{-\frac{\pi}{2}+\beta+\delta\beta}\begin{pmatrix} \sqrt{Z_{\Phi_1}} & 0 \\ 0 & \sqrt{Z_{\Phi_2}} \end{pmatrix} R_{-\frac{\pi}{2}+\beta}\begin{pmatrix} H \\ h \end{pmatrix},$$

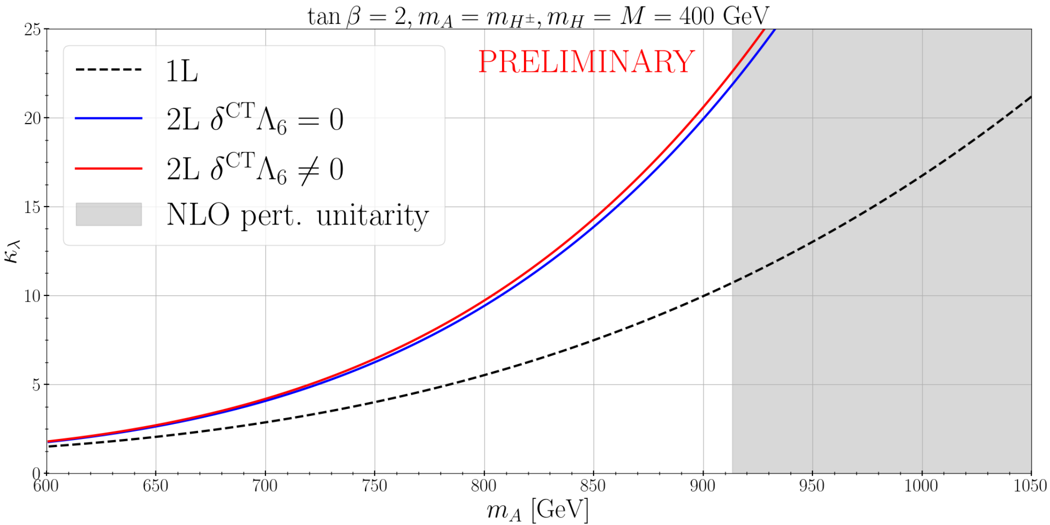
- We obtain

$$\begin{aligned} \delta Z^{(1)}_{hh} &= c^2_\beta \delta Z^{(1)}_{\Phi_1} + s^2_\beta \delta Z^{(1)}_{\Phi_2} \\ \delta Z^{(1)}_{HH} &= s^2_\beta \delta Z^{(1)}_{\Phi_1} + c^2_\beta \delta Z^{(1)}_{\Phi_2} \\ \delta Z^{(1)}_{hH} + \delta Z^{(1)}_{Hh} &= 2 s_\beta c_\beta (\delta Z^{(1)}_{\Phi_1} - \delta Z^{(1)}_{\Phi_2}) \\ \delta Z^{(1)}_{Hh} - \delta Z^{(1)}_{hH} &= 4\delta\beta^{(1)} . \end{aligned}$$

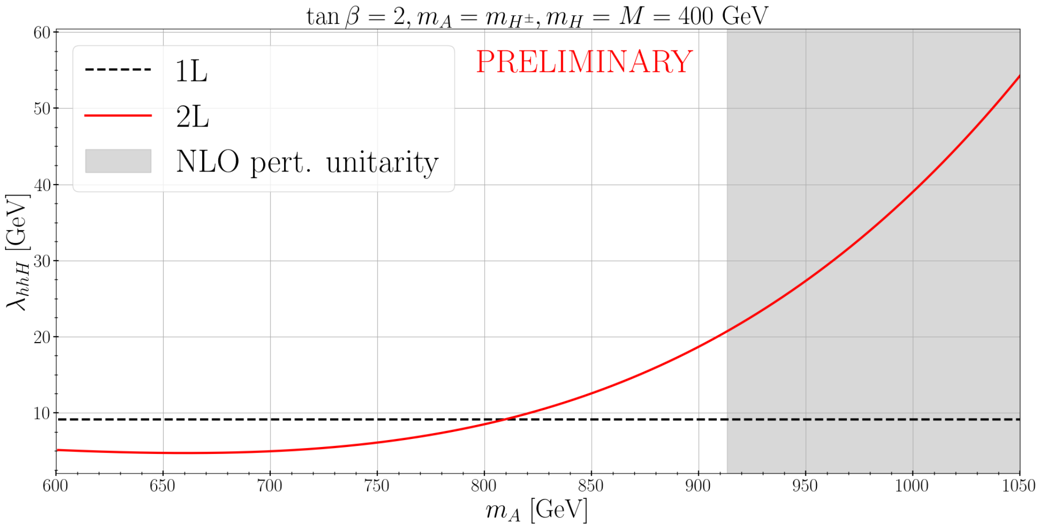
M_{22} Decoupling



Results Scenario I



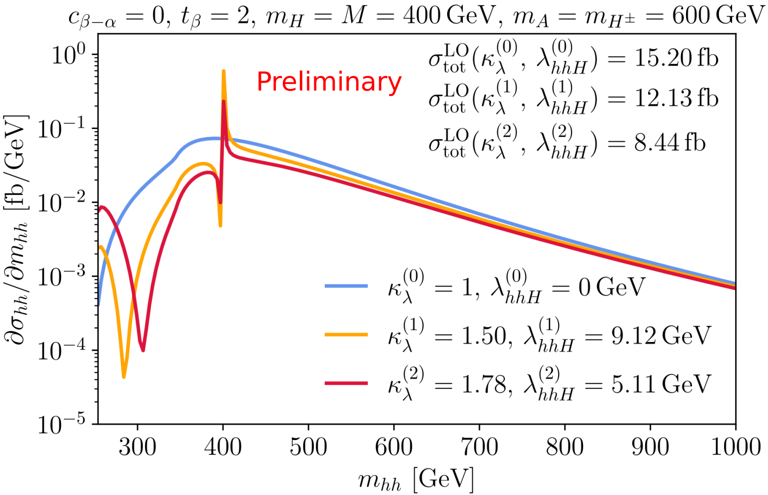
Results Scenario I



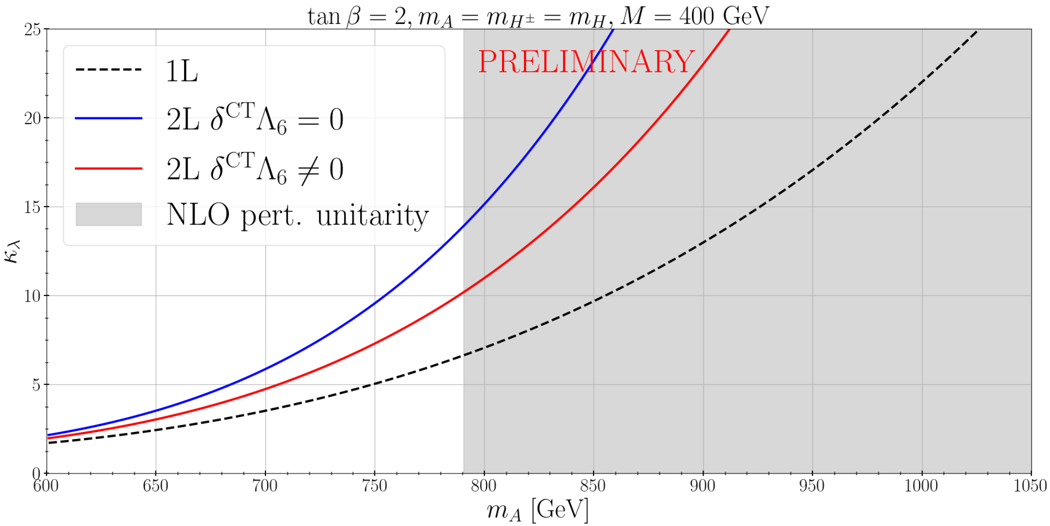
Results Scenario I

Cross-sections and distributions obtained with `anyHH` [Bahl, Braathen, Gabelmann, Radchenko, Weiglein WIP]

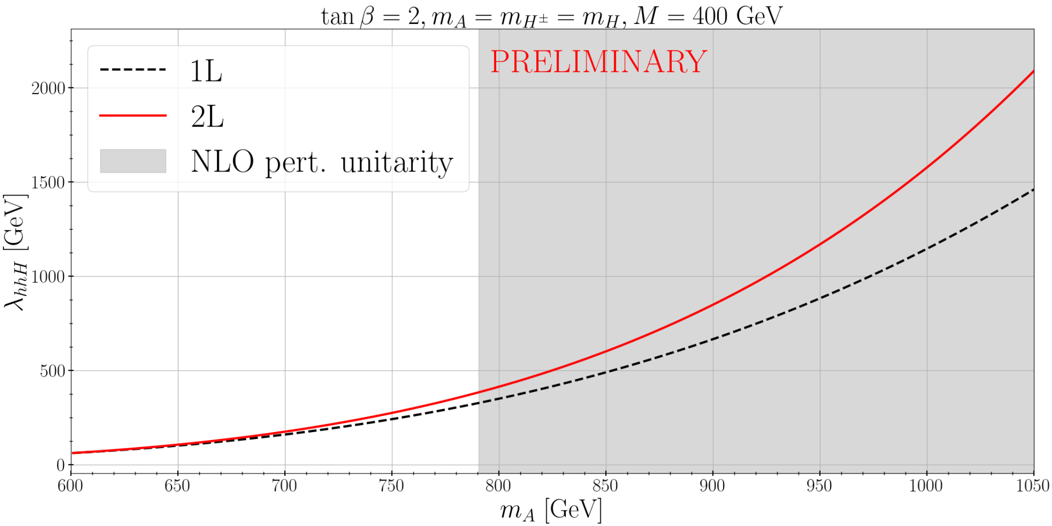
Thanks to Kateryna for providing this plot!



Results Scenario II



Results Scenario II



Results Scenario II

Cross-sections and distributions obtained with `anyHH` [Bahl, Braathen, Gabelmann, Radchenko, Weiglein WIP]

Thanks to Kateryna for providing this plot!