Renormalisation of the 2HDM and of the N2HDM (just the highlights)

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Preamble

This work started many years ago

2015 Robin Lorenz - Full One-loop Electroweak Corrections to the Decays $H^+ \to W^+ h/H$ in the Two-Higgs-Doublet-Model

2016 Marcel Krause - On the Renormalization of the Two-Higgs-Doublet Model

2016 Hanna Ziesche - Higher-Order Corrections in Extended Higgs Sectors

2019 Marcel Krause - Higher-Order Corrections in the 2HDM, N2HDM and NMSSM

Krause, Mühlleitner, CPC (2019) ewN2HDECAY.

Krause, Mühlleitner, Spira, CPC (2019) 2HDECAY.

Krause, Lopez-Val, Mühlleitner, RS, JHEP 1712 (2017) 077.

Krause, Mühlleitner, RS, Ziesche, PRD95 (2017) 075019.

Krause, Lorenz, Mühlleitner, RS, Ziesche, JHEP 1609 (2016) 143.

Outline

- The models
- Tadpoles
- Mixing angles
- Comparing schemes
- Conclusions

The softly broken Z_2 symmetric 2HDM

Z_2 symmetry (two complex doublets)

$$\Phi_1 \to \Phi_1; \quad \Phi_2 \to -\Phi_2$$

Extended to the fermions - no FCNC at tree-level

leads to the potential

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

and CP is conserved because VEVs are

$$<\Phi_1> = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \qquad <\Phi_2> = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

and all parameters in the potential are real. Complex doublets defined as

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$$

The softly broken Z_2 symmetric N2HDM

Z_2 symmetries (two complex doublets plus one real singlet)

$$\Phi_1 \to \Phi_1; \quad \Phi_2 \to -\Phi_2; \quad \Phi_S \to \Phi_S$$

Same as for the 2HDM (softly broken)

$$\Phi_1 \to \Phi_1; \quad \Phi_2 \to \Phi_2; \quad \Phi_S \to -\Phi_S$$

Spontaneously broken - no singlet dark matter

leads to the potential

$$V = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{m_S^2}{2}\Phi_S^2$$
$$+ \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+ \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2) + h.c.\right] + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2$$

with the real singlet

$$\Phi_S = v_S + \rho_S$$

and a CP-conserving minimum because all VEVs and all parameters are real.

Mixing between the three CP-even states

Similarities and differences

Common:

- $\tan\beta = \frac{v_2}{v_1}$ ratio of vacuum expectation values of the doublets
- 2 charged, $H^{\pm}$, and 1 neutral CP-odd
- soft breaking parameter m^2_{12}
- 2 VEVs v_1 and v_2 (from the doublets)

Different:

- Extra VEV from the singlet v_S
- rotation angles in the neutral sector $[h_i]_{mass} = [R_{ij}][h_j]_{gauge}$

2HDM - α h, H $[R_{ij}] = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}$

N2HDM - α_1, α_2 and α_3 h_1, h_2 and h_3

$$[R_{ij}] = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

h_{125} couplings

$$g_{2HDM}^{hVV} = \sin(\beta - \alpha) g_{SM}^{hVV}$$

2HDM

$$g_{N2HDM}^{hVV} = \cos\alpha_2 \, g_{2HDM}^{hVV}$$

N2HDM

This is the structure of the couplings when h_{125} is the lightest CP-even scalar with rotation matrices as defined previously.

SINGLET COMPONENT

Type I $\kappa_U^I = \kappa_D^I = \kappa_L^I = \dfrac{\cos\alpha}{\sin\beta}$

Type II $\kappa_U^{II} = \dfrac{\cos\alpha}{\sin\beta}$ $\kappa_D^{II} = \kappa_L^{II} = -\dfrac{\sin\alpha}{\cos\beta}$

Type F(Y) $\kappa_U^F = \kappa_L^F = \dfrac{\cos\alpha}{\sin\beta}$ $\kappa_D^F = -\dfrac{\sin\alpha}{\cos\beta}$

Type LS(X) $\kappa_U^{LS} = \kappa_D^{LS} = \dfrac{\cos\alpha}{\sin\beta}$ $\kappa_L^{LS} = -\dfrac{\sin\alpha}{\cos\beta}$

$$Y_{N2HDM} = \cos\alpha_2 Y_{2HDM}$$

Different Yukawa types are obtained by extending the discrete symmetry to the fermions.

What is the problem?

➡ We want to renormalise the models. We want the renormalisation scheme to lead to gauge independent results and to moderate NLO corrections.

➡ We have renormalisation schemes for the SM and they work just fine. So now we just have to understand how to deal with the extra parameters.

➡ Most of the extra parameters are just the masses of the new particles. They are renormalised on-shell, and since they are independent parameters, this is a simple generalisation.

➡ Since the new chosen independent parameters are the rotation angles: two in the 2HDM: α, β and four in the N2HDM: $\alpha_1, \alpha_2, \alpha_3, \beta$ and the soft breaking parameter m_{12}^2, these are the ones we need to worry about.

➡ Besides, instead of one tadpole, we have two (2HDM) or three (N2HDM).

➡ So we will start with the tadpoles, changing from the standard scheme to a scheme proposed by Fleischer and Jegerlehner (PRD23 (1981) 2001). This will allow to move the gauge dependences in a way that makes them easy to control.

Renormalisation - on-shell conditions

Two scalar fields with the same quantum numbers, ϕ_1 and ϕ_2. Field strength renormalisation

$$\begin{pmatrix}\phi_1\\ \phi_2\end{pmatrix}_0 = \sqrt{Z_\phi}\begin{pmatrix}\phi_1\\ \phi_2\end{pmatrix} \approx \left(I + \frac{\delta Z_\phi}{2}\right)\begin{pmatrix}\phi_1\\ \phi_2\end{pmatrix}, \qquad \delta Z_\phi = \begin{pmatrix}\delta Z_{\phi_1\phi_1} & \delta Z_{\phi_1\phi_2}\\ \delta Z_{\phi_2\phi_1} & \delta Z_{\phi_2\phi_2}\end{pmatrix}$$

Two point correlation functions

$$\hat{\Gamma}_\phi(p^2) = \begin{pmatrix}\hat{\Gamma}_{\phi_1\phi_1}(p^2) & \hat{\Gamma}_{\phi_1\phi_2}(p^2)\\ \hat{\Gamma}_{\phi_2\phi_1}(p^2) & \hat{\Gamma}_{\phi_2\phi_2}(p^2)\end{pmatrix} = i\sqrt{Z_\phi}^{\dagger}\left[p^2 I - D_\phi^2 + \Sigma_\phi(p^2) - \delta D_\phi^2\right]\sqrt{Z_\phi} \approx i\left[p^2 I - D_\phi^2 + \hat{\Sigma}_\phi(p^2)\right]$$

Mass matrix (D for diagonal)

Mass CTs

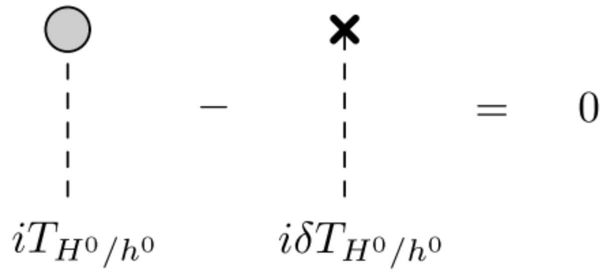
On-shell conditions

- residue of the propagator at its pole is equal to i $\qquad \delta Z_{\phi_i\phi_i} = -\,\mathrm{Re}\left[\frac{\partial \Sigma_{\phi_i\phi_i}}{\partial p^2}(m_{\phi_i}^2)\right]$
- field mixing vanishes for $p^2=m^2$ $\qquad \delta Z_{\phi_i\phi_j} = \frac{2}{m_{\phi_i}^2 - m_{\phi_j}^2}\mathrm{Re}\left[\Sigma_{\phi_i\phi_j}(m_{\phi_j}^2) - \delta D_{\phi_i\phi_j}^2\right], \quad i \neq j$
- masses are the real parts of the poles of the propagator $\qquad \mathrm{Re}\left[\delta D_{\phi_i\phi_i}^2\right] = \mathrm{Re}\left[\Sigma_{\phi_i\phi_i}(m_{\phi_i}^2)\right]$

Specific form of mass counterterms depends on tadpole scheme

Tadpole Renormalisation

Renormalisation condition for the tadpole is



Renormalisation condition is always the same

to restore the minimum condition of the potential at NLO. Two schemes

➡ standard (std)

Renormalisation constant is T_i — no tadpole diagrams at NLO

➡ alternative (alt)

Renormalisation constant is v_i — tadpoles reintroduced via v_i variation

Tadpole Renormalisation (Standard to Alternative)

In the standard scheme the tadpole renormalisation constants appear in the mass matrix counterterms

$$\delta D_\phi^2 \approx \begin{pmatrix} \delta m_{\phi_1}^2 & 0 \\ 0 & \delta m_{\phi_2}^2 \end{pmatrix} + \begin{pmatrix} \delta T_{\phi_1\phi_1} & \delta T_{\phi_1\phi_2} \\ \delta T_{\phi_2\phi_1} & \delta T_{\phi_2\phi_2} \end{pmatrix}$$

and this leads to mass counterterms that are gauge dependent. Going from the standard to the alternative scheme amounts to (SM)

$$v_{bare} = v_{ren} + \delta v$$

with

$$v_{ren} = v_{tree}$$

and therefore gauge independent.

We now just have to repeat the procedure with two tadpole conditions for the 2HDM and three conditions for the N2HDM.

Tadpole Renormalisation (Alternative)

From the practical point of view this is how it works.

Fleischer, Jegerlehner, PRD23 (1981) 2001

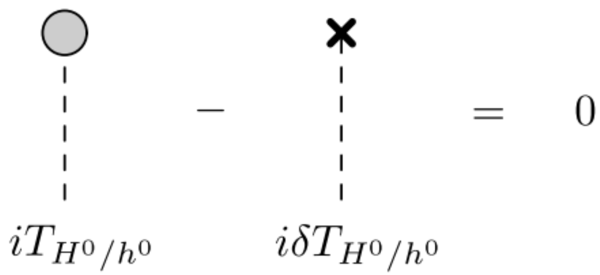
Since the VEVs are the renormalisation constants we have to define the corresponding CTs

$$v_1 \to v_1 + \delta v_1, \quad v_2 \to v_2 + \delta v_2$$

for the 2HDM case. The shifts can be expressed as a function of Tadpole variations

$$\begin{pmatrix} \delta v_1 \\ \delta v_2 \end{pmatrix} = \begin{pmatrix} \frac{\delta T_H}{m_H^2} c_\alpha - \frac{\delta T_h}{m_h^2} s_\alpha \\ \frac{\delta T_H}{m_H^2} s_\alpha + \frac{\delta T_h}{m_h^2} c_\alpha \end{pmatrix} \qquad \begin{pmatrix} \delta v_H \\ \delta v_h \end{pmatrix} = \begin{pmatrix} \frac{\delta T_H}{m_H^2} \\ \frac{\delta T_h}{m_h^2} \end{pmatrix}$$

and are <u>calculated with the exact same conditions</u>



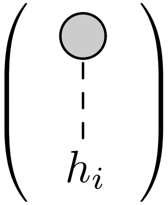
Tadpoles shifts are just for bookkeeping purposes.

The shifts have to be included in all counterterms.

Tadpole Renormalisation (Alternative)

Diagrammatically (a shift in VEV corresponds to an extra tadpole diagram)

$$\delta v_{h_i} = \frac{-i}{m_{h_i}^2} i\delta T_{h_i} = \frac{-i}{m_{h_i}^2}$$



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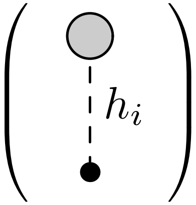
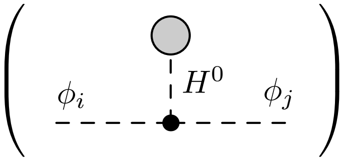


for the 2HDM case. The shifts can be expressed as a function of Tadpole variations

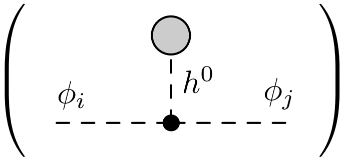
$$\begin{pmatrix} \delta v_1 \\ \delta v_2 \end{pmatrix} = \begin{pmatrix} \frac{\delta T_H}{m_H^2} c_\alpha - \frac{\delta T_h}{m_h^2} s_\alpha \\ \frac{\delta T_H}{m_H^2} s_\alpha + \frac{\delta T_h}{m_h^2} c_\alpha \end{pmatrix}$$

$$\delta D_\phi^2 = \begin{pmatrix} \delta m_{\phi_1}^2 & 0 \\ 0 & \delta m_{\phi_2}^2 \end{pmatrix} + \begin{pmatrix} \Delta D_{\phi_1\phi_1} & \Delta D_{\phi_1\phi_2} \\ \Delta D_{\phi_1\phi_2} & \Delta D_{\phi_2\phi_2} \end{pmatrix}$$

$$\Delta D_{\phi_i\phi_j} = i$$



$+ i$



and therefore

$$i\Sigma^{\text{tad}}_{\phi_i\phi_j}(p^2) := i\Sigma_{\phi_i\phi_j}(p^2) - i\Delta D_{\phi_i\phi_j}$$

which in practice removes the tadpoles from the definition of the counterterms.

We define the UV-divergent integral (V = W, Z)

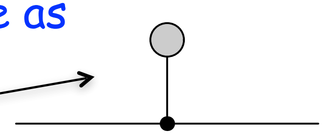
$$\alpha_V = \frac{16\pi^2}{i}\int \frac{d^Dk}{(2\pi)^D}\frac{1}{[k^2-m_V^2][k^2-\xi_V m_V^2]} = \frac{1}{\lambda_V m_i^2}[A_0(m_V^2) - A_0(\xi_V m_V^2)]; \qquad \lambda_V = 1-\xi_V$$

We can write the terms of the HH self-energy that are gauge dependent in the standard tadpole scheme

$$\Sigma_{HH}(m_H^2)|_{g.d.} = \lambda_Z \frac{g^2}{128\pi^2 c_W^2}\left[\left(\frac{4m_{12}^2}{s_{2\beta}} - \frac{s_{2\alpha}}{s_{2\beta}}(m_H^2 - m_h^2)\right)s_{\beta-\alpha}^2 - 3m_H^2\right]\alpha_Z$$
$$+\lambda_W \frac{g^2}{64\pi^2}\left[\left(\frac{4m_{12}^2}{s_{2\beta}} - \frac{s_{2\alpha}}{s_{2\beta}}(m_H^2 - m_h^2)\right)s_{\beta-\alpha}^2 - 3m_H^2\right]\alpha_W$$

We define the new self-energy, in the alternative tadpole scheme as

$$\Sigma_{HH}^{tad}(q^2) = \Sigma_{HH}(q^2) + \Sigma_{HH}^{add}(q^2)$$



$$\Sigma_{HH}^{add}(m_H^2)|_{g.d.} = -\lambda_Z \frac{g^2}{128\pi^2 c_W^2}\left[\left(\frac{4m_{12}^2}{s_{2\beta}} - \frac{s_{2\alpha}}{s_{2\beta}}(m_H^2 - m_h^2)\right)s_{\beta-\alpha}^2 - 3m_H^2\right]\alpha_Z$$
$$-\lambda_W \frac{g^2}{64\pi^2}\left[\left(\frac{4m_{12}^2}{s_{2\beta}} - \frac{s_{2\alpha}}{s_{2\beta}}(m_H^2 - m_h^2)\right)s_{\beta-\alpha}^2 - 3m_H^2\right]\alpha_W$$

and therefore the tadpole self-energy is gauge independent.

To compare the mass counterterms in the two schemes we just need the tadpole contributions

$$\delta T_{HH}|_{g.d.} = -\lambda_Z \frac{g^2}{128\pi^2 c_W^2} \left[\frac{s_{2\alpha}}{s_{2\beta}} s_{\beta-\alpha}^2 m_h^2 - \frac{2(c_\alpha^3 s_\beta + s_\alpha^2 c_\beta)}{s_{2\beta}} c_{\beta-\alpha} m_H^2 \right] \alpha_Z$$
$$-\lambda_W \frac{g^2}{64\pi^2} \left[\frac{s_{2\alpha}}{s_{2\beta}} s_{\beta-\alpha}^2 m_h^2 - \frac{2(c_\alpha^3 s_\beta + s_\alpha^2 c_\beta)}{s_{2\beta}} c_{\beta-\alpha} m_H^2 \right] \alpha_W$$

In the standard scheme the mass counterterm is

$$(\delta m_H^2)^{std}|_{g.d.} = \Sigma_{HH}(m_H^2)|_{g.d.} - \delta T_{HH}|_{g.d.}$$
$$= \lambda_Z \frac{g^2}{128\pi^2 c_W^2} \left[\frac{4m_{12}^2}{s_{2\beta}} - 2m_H^2 \right] \alpha_Z + \lambda_W \frac{g^2}{64\pi^2} \left[\frac{4m_{12}^2}{s_{2\beta}} - 2m_H^2 \right] \alpha_W$$

and in the alternative tadpole scheme

$$(\delta m_H^2)^{tad}|_{g.d.} = \Sigma_{HH}^{tad}(m_H^2)|_{g.d.} = \Sigma_{HH}(m_H^2)|_{g.d.} + \Sigma_{HH}^{add}(m_H^2)|_{g.d.} = (\delta m_H^2)^{std}|_{g.d.} + \Sigma_{HH}^{add}(m_H^2)|_{g.d.} + \delta T_{HH}|_{g.d.}$$
$$= \lambda_Z \frac{g^2}{128\pi^2 c_W^2} \left[\frac{4m_{12}^2}{s_{2\beta}} - 2m_H^2 \right] \alpha_Z + \lambda_W \frac{g^2}{64\pi^2} \left[\frac{4m_{12}^2}{s_{2\beta}} - 2m_H^2 \right] \alpha_W$$
$$= -\lambda_Z \frac{g^2}{128\pi^2 c_W^2} \left[\frac{4m_{12}^2}{s_{2\beta}} - 2m_H^2 \right] \alpha_Z - \lambda_W \frac{g^2}{64\pi^2} \left[\frac{4m_{12}^2}{s_{2\beta}} - 2m_H^2 \right] \alpha_W$$
$$= 0$$

The gauge dependent pieces are shifted in a way that the mass renormalisation constants become gauge independent

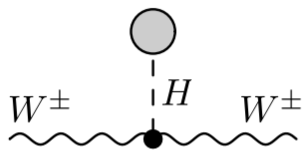
Tadpole Renormalisation (Alternative)

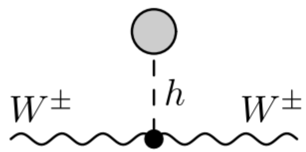
This is true for all masses. The W boson mass in the two schemes

$$m_W^2 \to m_W^2 + g^2 \frac{v_1 \delta v_1 + v_2 \delta v_2}{2}$$

for the 2HDM case. The shifts can be expressed as a function of Tadpole variations

$$m_W^2 + i \left(\right) + i \left(\right)$$

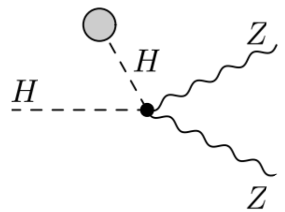




We also need to take into account this variation for the vertices - we need to see where the VEVs are (not the rotation angles)

$$i g_{HZZ} = \frac{i g^2}{2 c_W^2} \left(c_\alpha v_1 + s_\alpha v_2 \right) \quad , \qquad i g_{HHZZ} = \frac{i g^2}{2 c_W^2}$$

$$i g_{HZZ} \;\to\; i g_{HZZ} + \frac{i g^2}{2 c_W^2} \left(c_\alpha \delta v_1 + s_\alpha \delta v_2 \right) = i g_{HZZ} + \left(\right)_{\text{trunc}}$$



There are no tadpoles in the scalar sector. There are new tadpoles whenever a VEV is present.

Renormalisation of mixing angles

In the 2HDM there are two mixing angles α and β. In the N2HDM all 3 CP-even scalars mix and we end up with four angles α_1 , α_2 , α_3 and β. Let us start with the 2HDM.

The simplest approach would be to either use a physical process or $\overline{MS}$. As we will see this often leads to large NLO corrections.

It was shown that for the MSSM that a renormalisation scheme for $\tan\beta$ may not be simultaneously gauge-independent, process-independent and "numerically stable" (moderate NLO corrections)

Freitas, Stöckinger, PRD66 (2002) 095014

So our question is if we can find renormalisation schemes for the angles that satisfy these criteria.

Note that the wave function renormalisation constants are gauge dependent

Renormalisation of mixing angles

Mixing angle is renormalised via

Pilaftsis, NPB504, 61 (1997)

Kanemura, Okada, Senaha, Yuan, PRD70 115002 (2004)

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R\,(\alpha + \delta\alpha)\,\sqrt{Z_\Phi}\begin{pmatrix} \Phi_H \\ \Phi_S \end{pmatrix}$$

Gauge to mass eigenstates

$$R\,(\alpha + \delta\alpha)\,\sqrt{Z_\Phi}\begin{pmatrix} \Phi_H \\ \Phi_S \end{pmatrix} = \underbrace{R(\delta\alpha)R(\alpha)\sqrt{Z_\Phi}R(\alpha)^T}_{\stackrel{!}{=}\sqrt{Z_H}}\,R(\alpha)\begin{pmatrix} \Phi_H \\ \Phi_S \end{pmatrix} + \mathcal{O}(\delta\alpha^2) = \sqrt{Z_H}\begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

$$\sqrt{Z_H} = R(\delta\alpha)\begin{pmatrix} 1 + \frac{\delta Z_{h_1 h_1}}{2} & \delta C_h \\ \delta C_h & 1 + \frac{\delta Z_{h_2 h_2}}{2} \end{pmatrix} \approx \begin{pmatrix} 1 + \frac{\delta Z_{h_1 h_1}}{2} & \delta C_h + \delta\alpha \\ \delta C_h - \delta\alpha & 1 + \frac{\delta Z_{h_2 h_2}}{2} \end{pmatrix}$$

Expand in the rotation angle

$$\frac{\delta Z_{h_1 h_2}}{2} \stackrel{!}{=} \delta C_h + \delta\alpha \quad \text{and} \quad \frac{\delta Z_{h_2 h_1}}{2} \stackrel{!}{=} \delta C_h - \delta\alpha$$

$$\begin{aligned} \delta\alpha &= \frac{1}{4}\left(\delta Z_{h_1 h_2} - \delta Z_{h_2 h_1}\right) \\ &= \frac{1}{2(m_{h_1}^2 - m_{h_2}^2)}\mathrm{Re}\big(\Sigma_{h_1 h_2}(m_{h_1}^2) + \Sigma_{h_1 h_2}(m_{h_2}^2) - 2\delta T_{h_1 h_2}\big)\ . \end{aligned}$$

Using on-shell conditions

Renormalisation of mixing angles (2HDM)

The renormalisation conditions in the standard scheme are

$$\delta\alpha = \frac{1}{2\left(m_{H^0}^2 - m_{h^0}^2\right)} \mathrm{Re}\Big[\Sigma_{H^0h^0}(m_{H^0}^2) + \Sigma_{H^0h^0}(m_{h^0}^2) - 2\delta T_{H^0h^0}\Big] ,$$

$$\delta\beta^{(1)} = -\frac{1}{2m_{A^0}^2} \mathrm{Re}\Big[\Sigma_{G^0A^0}(m_{A^0}^2) + \Sigma_{G^0A^0}(0) - 2\delta T_{G^0A^0}\Big] ,$$

$$\delta\beta^{(2)} = -\frac{1}{2m_{H^\pm}^2} \mathrm{Re}\Big[\Sigma_{G^\pm H^\pm}(m_{H^\pm}^2) + \Sigma_{G^\pm H^\pm}(0) - 2\delta T_{G^\pm H^\pm}\Big] .$$

And using the alternative scheme we get

$$\delta\alpha = \frac{1}{2\left(m_{H^0}^2 - m_{h^0}^2\right)} \mathrm{Re}\Big[\Sigma^{\mathrm{tad}}_{H^0h^0}(m_{H^0}^2) + \Sigma^{\mathrm{tad}}_{H^0h^0}(m_{h^0}^2)\Big] ,$$

$$\delta\beta^{(1)} = -\frac{1}{2m_{A^0}^2} \mathrm{Re}\Big[\Sigma^{\mathrm{tad}}_{G^0A^0}(m_{A^0}^2) + \Sigma^{\mathrm{tad}}_{G^0A^0}(0)\Big] ,$$

$$\delta\beta^{(2)} = -\frac{1}{2m_{H^\pm}^2} \mathrm{Re}\Big[\Sigma^{\mathrm{tad}}_{G^\pm H^\pm}(m_{H^\pm}^2) + \Sigma^{\mathrm{tad}}_{G^\pm H^\pm}(0)\Big] .$$

β counterterms lead to gauge dependencies in the finite partes; α counterterm leads to gauge dependencies in the infinite part (too big to show)

$$\begin{aligned}\delta\beta^{(2)} = {} & \delta\beta^{(2)}\Big|_{\xi=1} \\ & + (1-\xi_W)\,\frac{g^2 \mathrm{c}_{\beta-\alpha}\mathrm{s}_{\beta-\alpha}}{128\pi^2}\Big\{ m_{h^0}^2\Big[\beta_{Wh^0}(m_{H^\pm}^2) - \beta_{Wh^0}(0)\Big] \\ & + m_{H^\pm}^2\Big[\beta_{WH^0}(m_{H^\pm}^2) - \beta_{Wh^0}(m_{H^\pm}^2)\Big] + m_{H^0}^2\Big[\beta_{WH^0}(0) - \beta_{WH^0}(m_{H^\pm}^2)\Big]\Big\} ,\end{aligned}$$

$$\frac{i}{16\pi^2}\,\beta_{V\mathrm{j}}(p^2) := \int_k \frac{1}{\left[k^2 - m_V^2\right]\left[k^2 - \xi_V m_V^2\right]\Big[(k+p)^2 - m_{\mathrm{j}}^2\Big]}$$

So now we would like to have a definition of the angle couterterms that is gauge independent and at the same time preferably leading to moderate NLO corrections.

Renormalisation of mixing angles (2HDM)

We choose to isolate the gauge dependent parts using the pinch technique (PT): the self-energies obtained by this procedure will be called pinched self-energies and the renormalisation conditions will be called pinched schemes.

CORNWALL, PAPAVASSILIOU, PRD40 (1989) 3474

The self energies can be written as

$$\Sigma^{\text{pinch}}_{\phi_1\phi_2}(p^2) = \left[\Sigma^{\text{tad}}_{\phi_1\phi_2}(p^2)\right]_{\xi=1} + \Sigma^{\text{add}}_{\phi_1\phi_2}(p^2)$$

The Background-Field Method seems to contain some of the results of PT for a particular choice of the gauge parameter: "Putting the quantum gauge parameter equal to one, we recover the pinch-technique results as a special case of the background-field method. "

DENNER, WEIGLEIN, DITTMAIER, PRLB333 (1994) 420

that is, the method gives us a term that is just the self-energy in the alternative tadpole scheme at $\xi = 1$, plus an additional term that depends on the model. In the case of the 2HDM

$$\Sigma^{\text{add}}_{H^0h^0}(p^2) = \frac{g^2 \mathrm{s}_{\beta-\alpha}\mathrm{c}_{\beta-\alpha}}{32\pi^2 c_{\mathrm{W}}^2}\left(p^2 - \frac{m_{H^0}^2 + m_{h^0}^2}{2}\right)\Big\{\left[B_0(p^2; m_Z^2, m_{A^0}^2) - B_0(p^2; m_Z^2, m_Z^2)\right] + 2\mathrm{c}_W^2\left[B_0(p^2; m_W^2, m_{H^\pm}^2) - B_0(p^2; m_W^2, m_W^2)\right]\Big\},$$

$$\Sigma^{\text{add}}_{G^0A^0}(p^2) = \frac{g^2 \mathrm{s}_{\beta-\alpha}\mathrm{c}_{\beta-\alpha}}{32\pi^2 c_{\mathrm{W}}^2}\left(p^2 - \frac{m_{A^0}^2}{2}\right)\left[B_0(p^2; m_Z^2, m_{H^0}^2) - B_0(p^2; m_Z^2, m_{h^0}^2)\right],$$

$$\Sigma^{\text{add}}_{G^\pm H^\pm}(p^2) = \frac{g^2 \mathrm{s}_{\beta-\alpha}\mathrm{c}_{\beta-\alpha}}{16\pi^2}\left(p^2 - \frac{m_{H^\pm}^2}{2}\right)\left[B_0(p^2; m_W^2, m_{H^0}^2) - B_0(p^2; m_W^2, m_{h^0}^2)\right] .$$

Renormalisation of mixing angles - definition of pinched schemes

Before defining the pinched schemes, note that importance of having a GFP-independent definition of the mixing angle CTs. The use of the alternative FJ tadpole scheme leads to one-loop decay amplitude which when setting the mixing angle CTs to zero, is already a manifestly GFP- independent quantity.

Consequently, by defining the mixing angle CTs in a GFP-independent scheme, the full partial decay width maintains the GFP independence as well.

The pOS pinched scheme leads to the following definition of the counterterms

$$\delta\alpha = \frac{\mathrm{Re}\Big[\left[\Sigma^{\mathrm{tad}}_{H^0h^0}(m^2_{H^0}) + \Sigma^{\mathrm{tad}}_{H^0h^0}(m^2_{h^0})\right]_{\xi=1} + \Sigma^{\mathrm{add}}_{H^0h^0}(m^2_{H^0}) + \Sigma^{\mathrm{add}}_{H^0h^0}(m^2_{h^0})\Big]}{2\left(m^2_{H^0} - m^2_{h^0}\right)} ,$$

$$\delta\beta^{(1)} = -\frac{\mathrm{Re}\Big[\left[\Sigma^{\mathrm{tad}}_{G^0A^0}(m^2_{A^0}) + \Sigma^{\mathrm{tad}}_{G^0A^0}(0)\right]_{\xi=1} + \Sigma^{\mathrm{add}}_{G^0A^0}(m^2_{A^0}) + \Sigma^{\mathrm{add}}_{G^0A^0}(0)\Big]}{2m^2_{A^0}} ,$$

$$\delta\beta^{(2)} = -\frac{\mathrm{Re}\Big[\left[\Sigma^{\mathrm{tad}}_{G^\pm H^\pm}(m^2_{H^\pm}) + \Sigma^{\mathrm{tad}}_{G^\pm H^\pm}(0)\right]_{\xi=1} + \Sigma^{\mathrm{add}}_{G^\pm H^\pm}(m^2_{H^\pm}) + \Sigma^{\mathrm{add}}_{G^\pm H^\pm}(0)\Big]}{2m^2_{H^\pm}}$$

while the p* pinched scheme leads to

$$\delta\alpha = \frac{1}{m^2_{H^0} - m^2_{h^0}} \mathrm{Re}\left[\Sigma^{\mathrm{tad}}_{H^0h^0}\left(\frac{m^2_{H^0} + m^2_{h^0}}{2}\right)\right]_{\xi=1} ,$$

$$\delta\beta^{(1)} = -\frac{1}{m^2_{A^0}} \mathrm{Re}\left[\Sigma^{\mathrm{tad}}_{G^0A^0}\left(\frac{m^2_{A^0}}{2}\right)\right]_{\xi=1} ,$$

$$\delta\beta^{(2)} = -\frac{1}{m^2_{H^\pm}} \mathrm{Re}\left[\Sigma^{\mathrm{tad}}_{G^\pm H^\pm}\left(\frac{m^2_{H^\pm}}{2}\right)\right]_{\xi=1} .$$

$$p^2_* = \frac{m^2_{\phi_1} + m^2_{\phi_2}}{2} .$$

Used for the MSSM in

Espinosa, Yamada, Phys. Rev. D67 (2003) 036003

Renormalisation of mixing angles (N2HDM)

In the N2HDM the charged and pseudo scalar sectors are exactly the same. So are the renormalisation conditions.

The CP-even sector has now three field, two from the doublets and one from the singlet

$$\sqrt{Z_{H_i}} = R(\delta\alpha_i)\begin{pmatrix} 1+\frac{\delta Z_{H_1H_1}}{2} & \delta C_{12} & \delta C_{13} \\ \delta C_{21} & 1+\frac{\delta Z_{H_2H_2}}{2} & \delta C_{23} \\ \delta C_{31} & \delta C_{32} & 1+\frac{\delta Z_{H_3H_3}}{2} \end{pmatrix} =$$

$$\begin{pmatrix} 1+\frac{\delta Z_{H_1H_1}}{2} & c_{\alpha_2}c_{\alpha_3}\delta\alpha_1+s_{\alpha_3}\delta\alpha_2+\delta C_{12} & c_{\alpha_3}\delta\alpha_2-s_{\alpha_3}c_{\alpha_2}\delta\alpha_1+\delta C_{13} \\ -c_{\alpha_2}c_{\alpha_3}\delta\alpha_1-s_{\alpha_3}\delta\alpha_2+\delta C_{21} & 1+\frac{\delta Z_{H_2H_2}}{2} & \delta\alpha_3+s_{\alpha_2}\delta\alpha_1+\delta C_{23} \\ -c_{\alpha_3}\delta\alpha_2+s_{\alpha_3}c_{\alpha_2}\delta\alpha_1+\delta C_{31} & -\delta\alpha_3-s_{\alpha_2}\delta\alpha_1+\delta C_{32} & 1+\frac{\delta Z_{H_3H_3}}{2} \end{pmatrix}$$

and this leads to the following definition of the rotation angles

$$\delta\alpha_1 = \frac{c_{\alpha_3}}{4\,c_{\alpha_2}}\left(\delta Z_{H_1H_2}-\delta Z_{H_2H_1}\right) - \frac{s_{\alpha_3}}{4\,c_{\alpha_2}}\left(\delta Z_{H_1H_3}-\delta Z_{H_3H_1}\right)$$

$$\delta\alpha_2 = \frac{c_{\alpha_3}}{4}\left(\delta Z_{H_1H_3}-\delta Z_{H_3H_1}\right) + \frac{s_{\alpha_3}}{4}\left(\delta Z_{H_1H_2}-\delta Z_{H_2H_1}\right)$$

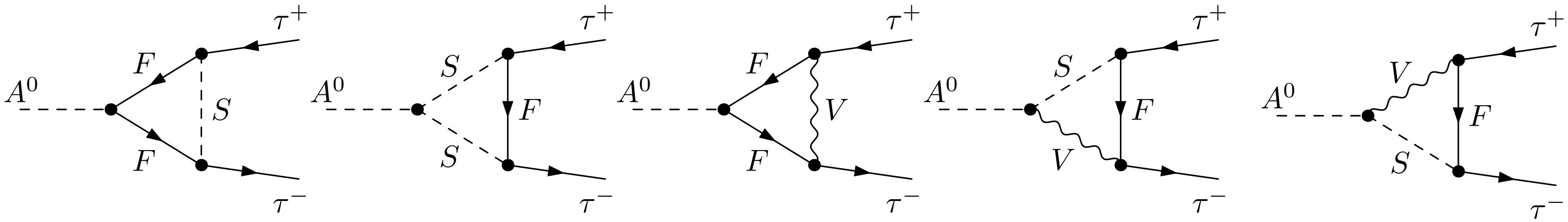
$$\delta\alpha_3 = \frac{1}{4}\left(\delta Z_{H_2H_3}-\delta Z_{H_3H_2}\right) + \frac{s_{\alpha_2}}{4c_{\alpha_2}}\left[s_{\alpha_3}\left(\delta Z_{H_1H_3}-\delta Z_{H_3H_1}\right) - c_{\alpha_3}\left(\delta Z_{H_1H_2}-\delta Z_{H_2H_1}\right)\right]$$

and then we just proceed as in the 2HDM.

Process dependent (for any of the models)

Process dependent: renormalisation of tanβ using the decay $A \to \tau^+\tau^-$ (that depends only on SM parameters and on tanβ)

Freitas, Stöckinger, PRD66 (2002) 095014



The process has the advantage that the QED corrections form a UV-finite subset by themselves. Since it is exactly the QED subset of the amplitude that contains the IR divergences, the idea is to isolate the purely weak corrections from the QED corrections and only use the former for the process dependent definition of the angle counterterm.

The one-loop amplitude for the process and the counterterms are

$$\mathcal{A}^{\text{1loop}}_{A^0\tau\tau} = \mathcal{A}^{\text{VC}}_{A^0\tau\tau} + \mathcal{A}^{\text{CT}}_{A^0\tau\tau} = \mathcal{A}^{\text{LO}}_{A^0\tau\tau}\left[\mathcal{F}^{\text{VC}}_{A^0\tau\tau} + \mathcal{F}^{\text{CT}}_{A^0\tau\tau}\right] \qquad \mathcal{F}^{\text{CT}}_{A^0\tau\tau} = \frac{\delta g}{g} + \frac{\delta m_\tau}{m_\tau} - \frac{\delta m_W^2}{2m_W^2} + \frac{1+Y_3^2}{Y_3}\delta\beta + \frac{\delta Z_{A^0A^0}}{2} - \frac{1}{Y_3}\frac{\delta Z_{G^0A^0}}{2} + \frac{\delta Z^{\text{L}}_{\tau\tau}}{2} + \frac{\delta Z^{\text{R}}_{\tau\tau}}{2}$$

The $\delta\beta$ counterterm is then fixed by the condition

$$\Gamma^{\text{LO}}_{A^0\tau\tau} \stackrel{!}{=} \Gamma^{\text{NLO,weak}}_{A^0\tau\tau}$$

giving

$$\delta\beta = \frac{-Y_3}{1+Y_3^2}\left[\mathcal{F}^{\text{VC}}_{A^0\tau\tau} + \frac{\delta g}{g} + \frac{\delta m_\tau}{m_\tau} - \frac{\delta m_W^2}{2m_W^2} + \frac{\delta Z_{A^0A^0}}{2} - \frac{1}{Y_3}\frac{\delta Z_{G^0A^0}}{2} + \frac{\delta Z^{\text{L}}_{\tau\tau}}{2} + \frac{\delta Z^{\text{R}}_{\tau\tau}}{2}\right]$$

2HDM type	Y_1	Y_2	Y_3
I	$\frac{c_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$-\frac{1}{t_\beta}$
II	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{c_\beta}$	t_β

Process dependent (for any of the models)

We can then use, for instance, the decay $H \to \tau^+\tau^-$ (that depends on SM parameters plus on α and β), using the previous definition of the angle β.

The one-loop amplitude for the process and the counterterms are

$$\mathcal{A}^{\rm 1loop}_{H^0\tau\tau} = \mathcal{A}^{\rm VC}_{H^0\tau\tau} + \mathcal{A}^{\rm CT}_{H^0\tau\tau} = \mathcal{A}^{\rm LO}_{H^0\tau\tau}\left[\mathcal{F}^{\rm VC}_{H^0\tau\tau} + \mathcal{F}^{\rm CT}_{H^0\tau\tau}\right]$$

$$\mathcal{F}^{\rm CT}_{H^0\tau\tau} = \frac{\delta g}{g} + \frac{\delta m_\tau}{m_\tau} - \frac{\delta m_W^2}{2m_W^2} + \frac{Y_1}{Y_2}\delta\alpha + Y_3\delta\beta + \frac{\delta Z_{H^0H^0}}{2} + \frac{Y_1}{Y_2}\frac{\delta Z_{h^0H^0}}{2} + \frac{\delta Z^{\rm L}_{\tau\tau}}{2} + \frac{\delta Z^{\rm R}_{\tau\tau}}{2} ,$$

The delta beta counterterm is then fixed by the condition

$$\Gamma^{\rm LO}_{H^0\tau\tau} \stackrel{!}{=} \Gamma^{\rm NLO,weak}_{H^0\tau\tau}$$

and

$$\delta\alpha = \frac{-Y_2}{Y_1}\left[\mathcal{F}^{\rm VC}_{H^0\tau\tau} + \frac{\delta g}{g} + \frac{\delta m_\tau}{m_\tau} - \frac{\delta m_W^2}{2m_W^2} + Y_3\delta\beta + \frac{\delta Z_{H^0H^0}}{2} + \frac{Y_1}{Y_2}\frac{\delta Z_{h^0H^0}}{2} + \frac{\delta Z^{\rm L}_{\tau\tau}}{2} + \frac{\delta Z^{\rm R}_{\tau\tau}}{2}\right]$$

The process dependent schemes that were chosen to be included in the 2HDECAY code are

Process 1 - define δβ via $A \to \tau^+\tau^-$ and subsequently δα via $H \to \tau^+\tau^-$

Process 2 - define δβ via $A \to \tau^+\tau^-$ and subsequently δα via $h \to \tau^+\tau^-$

Process 3 - define δα and δβ simultaneously via $H \to \tau^+\tau^-$ and $h \to \tau^+\tau^-$

KRAUSE, MÜHLLEITNER, SPIRA, CPC (2019) 2HDECAY.

Renormalisation of m_{12}^2 and the VEVs

The only remaining independent parameters which requires renormalisation are the soft-Z_2 breaking parameter m_{12}^2, and the VEVs.

Since m_{12}^2 appears in the trilinear and quartic Higgs couplings, the counterterm could be fix via a Higgs to Higgs decay process. We found this leads to huge NLO contributions.

So we fix the CT in the $\overline{MS}$ scheme. This implies that the value of the renormalisation scale μ_R has to be specified.

$$\delta m_{12}^2 = \frac{\alpha_{\rm em} m_{12}^2}{16\pi m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)}\Big[\frac{8m_{12}^2}{s_{2\beta}} - 2m_{H^\pm}^2 - m_A^2 + \frac{s_{2\alpha}}{s_{2\beta}}(m_H^2 - m_h^2) - 3(2m_W^2 + m_Z^2)$$
$$+ \sum_u 3m_u^2 \frac{1}{s_\beta^2} - \sum_d 6m_d^2 Y_3\left(-Y_3 - \frac{1}{t_{2\beta}}\right) - \sum_l 2m_l^2 Y_6\left(-Y_6 - \frac{1}{t_{2\beta}}\right)\Big]\Delta \,.$$

Infinite parte for the 2HDM

$$\delta m_{12}^2 = \frac{\alpha_{\rm em} m_{12}^2}{16\pi m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)}\Big[\frac{8m_{12}^2}{s_{2\beta}} - 2m_{H^\pm}^2 - m_A^2 + \sum_{i=1}^{3} R_{i1}R_{i2}m_{H_i}^2 - 3(2m_W^2 + m_Z^2)$$
$$+ \sum_u 3m_u^2 \frac{1}{s_\beta^2} + \sum_d 6m_d^2 Y_4^d\left(Y_4^d - \frac{1}{t_{2\beta}}\right) + \sum_l 2m_l^2 Y_4^l\left(Y_4^l - \frac{1}{t_{2\beta}}\right)\Big]\Delta$$

Infinite parte for the N2HDM

As for the VEVs, v_1 and v_2 are replaced by v and tanβ, while v_S is renormalised in the $\overline{MS}$ scheme (v_S infinity too big to show here).

Constraints

- Points generated with ScannerS requiring

  COIMBRA, SAMPAIO, SANTOS, EPJC73 (2013) 2428

  MÜHLLEITNER, SAMPAIO, RS, WITTBRODT, JHEP 03 (2017) 094

  - $m_{h_{SM}}$ =125.09 GeV (others 5 GeV away)
  - charged Higgs mass above 580 GeV in Type II and Flipped

    MISIAK, STEINHAUSER, EPJC77 NO. 3, (2017) 201
  - absolute minimum
  - boundedness from below
  - that perturbative unitarity holds
  - S,T and U

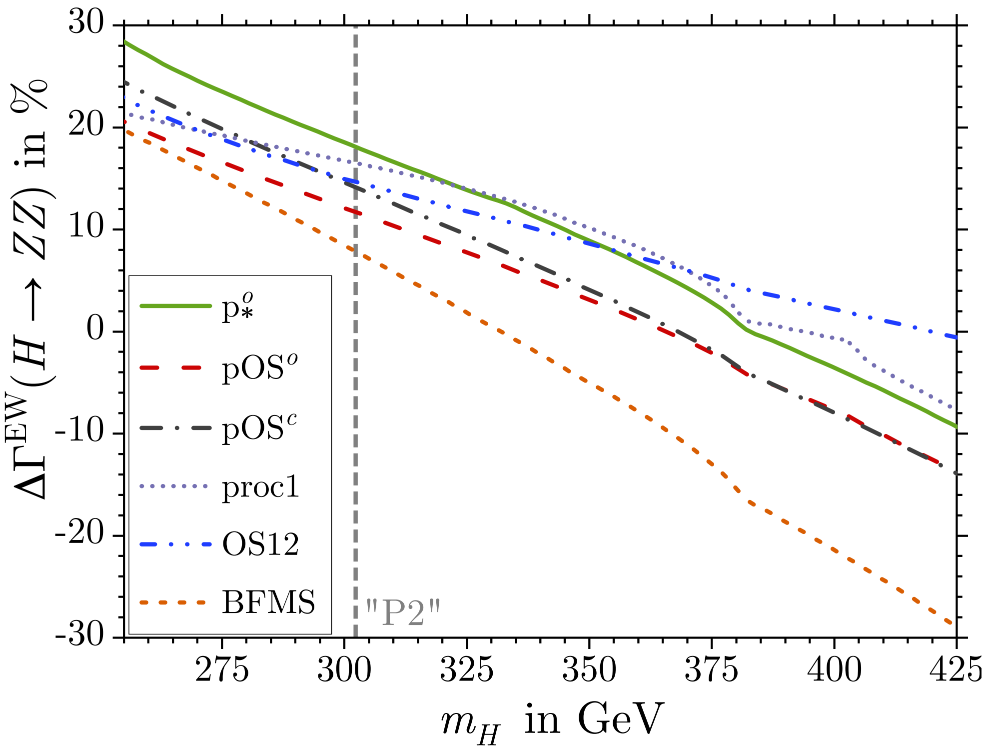
- The Higgs rates are checked with HiggsSignals 2.2.3

  BECHTLE, HEINEMEYER, STAL, STEFANIAK, WEIGLEIN, EPJC74 NO. 2, (2014) 2711

- The Higgs exclusion limits stemming from experiments at the LEP, Tevatron and LHC are checked with HiggsBounds 5.3.2.

  BECHTLE, BREIN, HEINEMEYER, STAL, STEFANIAK, WEIGLEIN, WILLIAMS, EPJC74 NO. 3, (2014) 2693

Comparison of schemes (2HDM)



Point P2

$$m_h = 125.09\,\text{GeV}\,, \quad m_H = 302.324\,\text{GeV}\,,$$
$$m_A = 494.618\,\text{GeV}\,, \quad m_{H^\pm} = 300.077\,\text{GeV}\,,$$
$$m_{12}^2(m_{h_{\rm SM}}) = 28\,328.8\,\text{GeV}^2\,, \quad \alpha|_{p_*^o} = -0.200\,175\,,$$
$$t_\beta|_{p_*^o} = 2.660\,82\,, \quad \text{2HDM type} = \text{I}\,,$$

relative size of electroweak one-loop corrections:

$$\Delta\Gamma^{\rm EW} = \frac{\Gamma^{\rm NLO,EW} - \Gamma^{\rm LO,EW}}{\Gamma^{\rm LO,EW}}$$

Krause, Mühlleitner, Spira, CPC (2019) 2HDECAY.

p* and pOS schemes as previously defined

proc 1: δβ viaA→τ+τ− and subsequently δα via H→τ+τ-

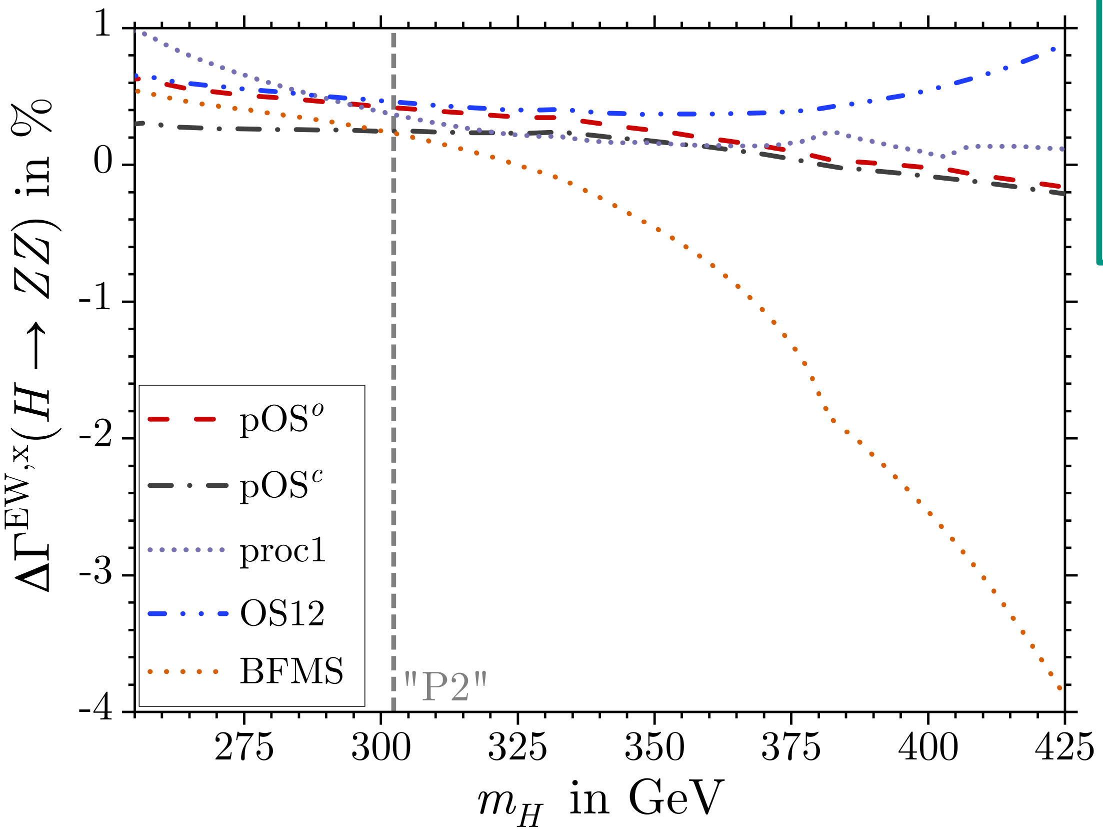
OS12 and BFMS in (and previous talk by S. Dittmaier)

Denner, Dittmaier, Lang, JHEP 11 (2018) 104.

Corrections for point P2 between 9% and 20%.

Comparison of schemes (2HDM)

Uncertainty estimate



Point P2

m_h	$=$	$125.09\,\mathrm{GeV}$,	m_H	$=$	$302.324\,\mathrm{GeV}$,
m_A	$=$	$494.618\,\mathrm{GeV}$,	$m_{H^\pm}$	$=$	$300.077\,\mathrm{GeV}$,
$m_{12}^2(m_{h_{\mathrm{SM}}})$	$=$	$28\,328.8\,\mathrm{GeV}^2$,	$\alpha\vert_{p_*^o}$	$=$	$-\,0.200\,175$,
$t_\beta\vert_{p_*^o}$	$=$	$2.660\,82$,	2HDM type	$=$	I ,

partial decay width for
$H \to ZZ$

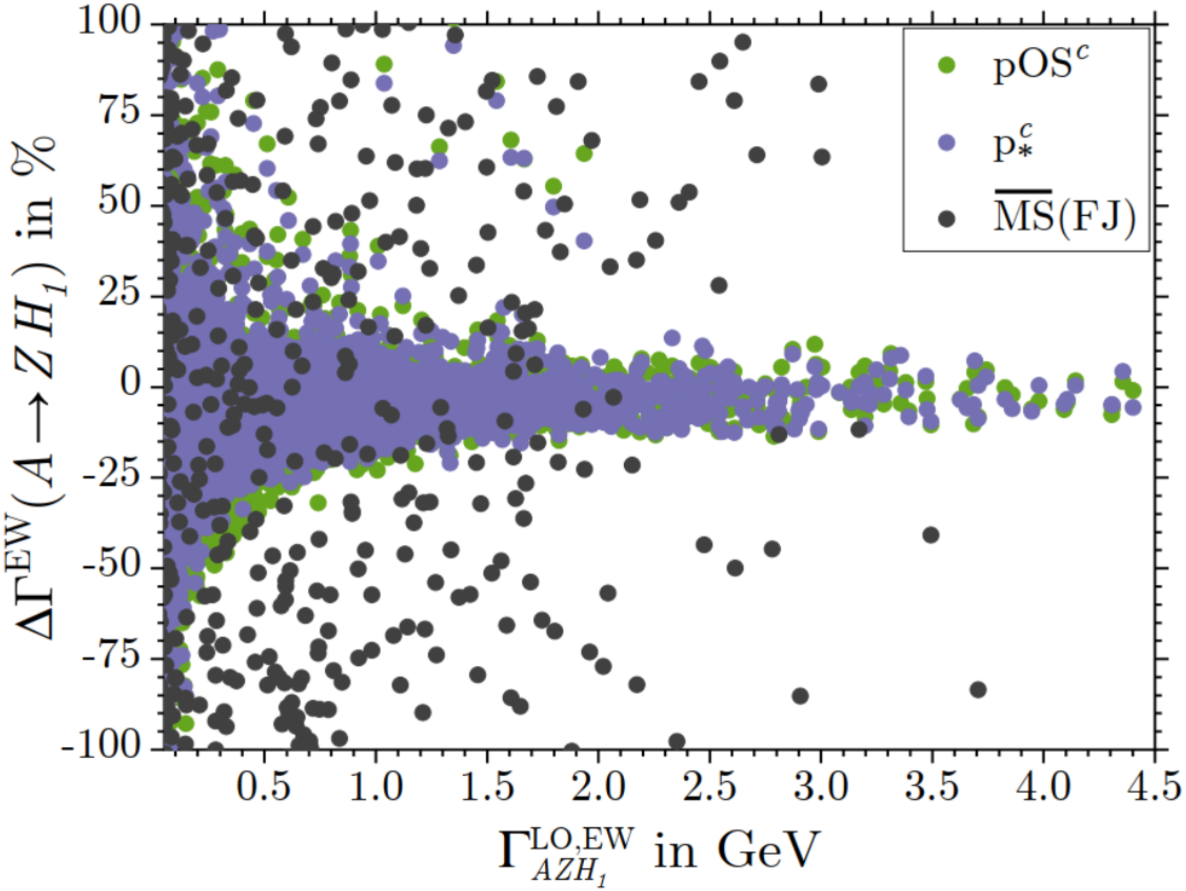
relative difference
between different schemes:

$$\Delta\Gamma^{\mathrm{EW},x} = \frac{\Gamma^{\mathrm{NLO,EW}}\big|_x - \Gamma^{\mathrm{NLO,EW}}\big|_{p_*^o}}{\Gamma^{\mathrm{NLO,EW}}\big|_{p_*^o}}$$

Relative difference over large range of the charged Higgs mass between -3.8% and 1.0%, and for point P2 the difference is of the order 0.5%.

Small uncertainty for the considered channel and parameters.

Comparison of schemes (N2HDM)



large range of input parameters
N2HDM type II

partial decay width for
$A \rightarrow Z H_1$

relative size of electroweak one-loop corrections:

$$\Delta\Gamma^{\mathrm{EW}} = \frac{\Gamma^{\mathrm{NLO,EW}} - \Gamma^{\mathrm{LO,EW}}}{\Gamma^{\mathrm{LO,EW}}}$$

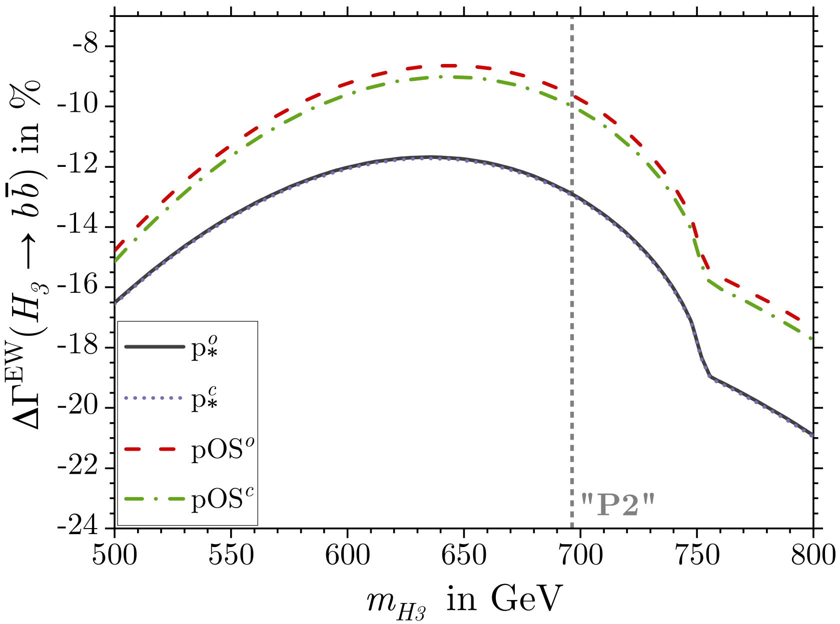
15 000 input parameter sets, that fulfil the most relevant theoretical and experimental constraints.

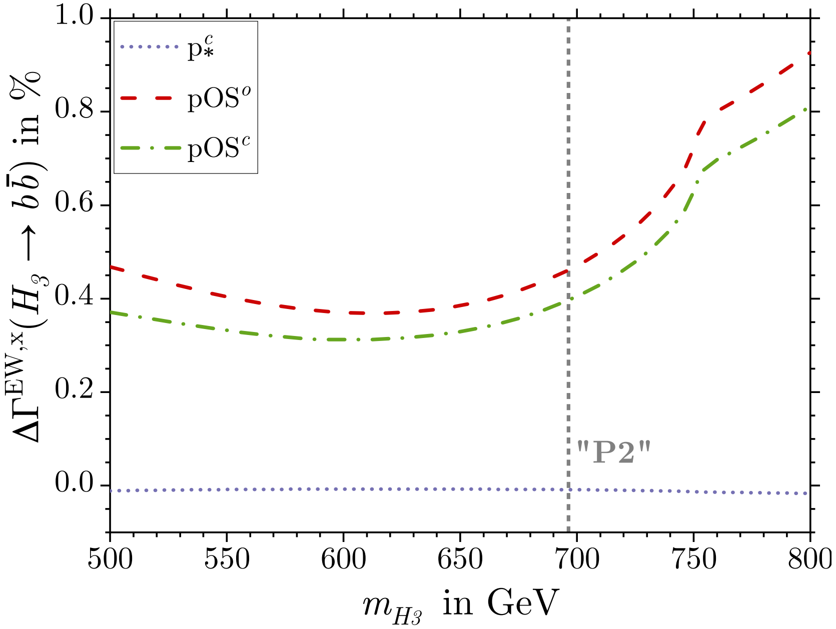
In this plot $\overline{MS}$ scheme refers to the renormalisation of the angles.

Although for large widths this scheme is the most unstable, it is also true that very large corrections also appear in the other schemes.

Comparison of schemes (N2HDM)

$H_3 \to b\bar{b}$





m_{H_1}	=	91.123 GeV ,	m_{H_2}	=	125.09 GeV ,
m_{H_3}	=	696.389 GeV ,	m_A	=	766.781 GeV ,
$m_{H^\pm}$	=	672.106 GeV ,	$m_{12}^2(m_{h_{\mathrm{SM}}})$	=	208 360.0 GeV^2 ,
$v_s(m_{h_{\mathrm{SM}}})$	=	2196.48 GeV ,	$\alpha_1\|_{p_*^o}$	=	0.697 912 ,
$\alpha_2\|_{p_*^o}$	=	− 1.459 21 GeV ,	$\alpha_3\|_{p_*^o}$	=	1.516 15 ,
$t_\beta\|_{p_*^o}$	=	0.950 614 ,	N2HDM type	=	II ,

Here again the corrections for point P2 vary just a few percent.

The uncertainty is below 1% for the entire range of masses shown.

Conclusions

- A renormalisation scheme for some of the most commonly used versions of the 2HDM and for the N2HDM was proposed.

- We have extended the scheme proposed by Fleischer and Jegerlehner to those models.

- New parameters: rotation angles and a mass term (soft breaking) appear.

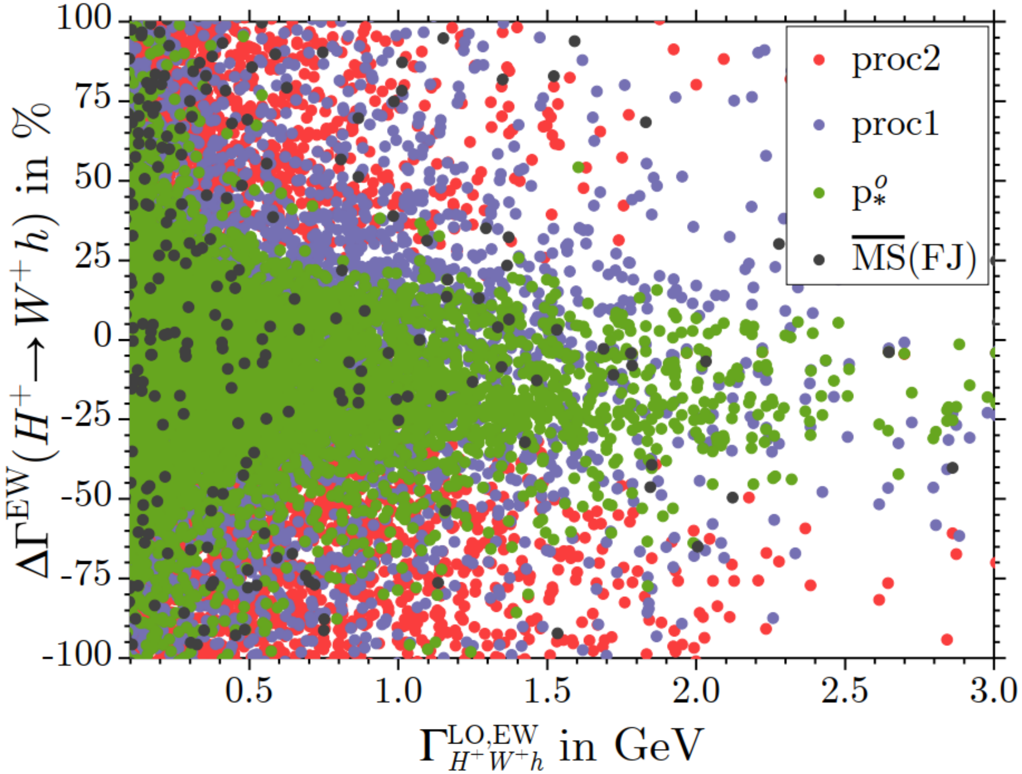
- Rotation angles are renormalised by an identification with the off-shell wave function renormalisation constants. As these are gauge dependent a procedure to remove the gauge dependencies was applied.

- The criteria of gauge independence was met and the one for moderate corrections was achieved in most cases.

- Good agreement with other proposed schemes.

Thank you

Comparison of schemes (2HDM)



large range of input parameters
2HDM type I

partial decay width for
$H^+ \to W^+ h$

relative size of electroweak one-loop corrections:

$$\Delta\Gamma^{\text{EW}} = \frac{\Gamma^{\text{NLO,EW}} - \Gamma^{\text{LO,EW}}}{\Gamma^{\text{LO,EW}}}$$

15 000 input parameter sets, that fulfil the most relevant theoretical and experimental constraints.

p* schemes as previously defined

proc 1: δβ viaA→τ+τ− and subsequently δα via H→τ+τ-

proc 2: δβ viaA→τ+τ− and subsequently δα via h→τ+τ-

For the full scan more stable seems to be the p* scheme