$\mathcal{O}$n the $\mathcal{R}$enormalization of the 2HDM

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$\mathcal{O}$utline

◇ Introduction and Model

◇ Renormalization

◇ Tadpole Treatment

◇ Mixing Angle and v_S renormalization

◇ Numerical Analysis

◇ Conclusions

Introduction

$\mathcal{I}$ntroduction

◇ Flaws of Standard Model call for New Physics (NP) - no direct hint for NP so far $\rightsquigarrow$

◇ Precision measurements in the Higgs sector increasingly important for NP searches

- ∗ requires precise experimental measurements and
- ∗ precise theoretical predictions for parameters and observables

◇ Precision calls for inclusion of higher order corrections

- ∗ prerequisite: proper **renormalization scheme**

$\mathcal{R}$equirements for $\mathcal{R}$enormalization $\mathcal{S}$cheme

◇ Gauge independence:

- as many parameters as possible renormalized such that interpretable as physical quantities $\rightsquigarrow$
- must not depend on renormalization scale or gauge fixing parameter
- aim for gauge-independent expression for S-matrix element

◇ Process independence:

- otherwise non-universality introduced for renormalized parameters
- possibly very much restricted selection of processes due to allowed parameter range

◇ Numerical stability:

- avoid artifically huge radiative corrections

Requirements for Renormalization Scheme

- **Status:**
  - ◇ simultaneous gauge-independent, process-independent and numerically stable renormalization of $\tan\beta$ in the MSSM not possible [Freitas,Stöckinger]
  - ◇ full renormalization of the 2HDM:
    Krause,Lorenz,MM,Santos,Ziesche, JHEP **1609** (2016) 43
    Krause,MM,Santos,Ziesche, Phys. Rev. **D95** (2017) no.7, 075019
    - ∗ α, β renormalization in tadpole-pinched scheme: gauge-independent, process-independent and numerically stable
    - ∗ m_{12}^2 renormalization: $\overline{\text{MS}}$ and process-dependent
  - ◇ 2HDM: $\overline{\text{MS}}$ renormalization for α and β [Denner,Jenniches,Lang,Sturm]
  - ◇ 2HDM: based on OS scheme as far as possible, $\overline{\text{MS}}$ renormalization for remaining parameters [Altenkamp,Dittmaier,Rzehak]

- **Renormalization of N2HDM:**
  - ◇ Proceed analoguously to 2HDM
  - ◇ N2HDM-specific: more mixing angles, renormalization of v_S (VEV of the singlet field) required

The Model

$\mathcal{T}$he $\mathcal{N}$2HDM

- **The Next-to-Minimal 2HDM:**
  Extension of 2HDM by real singlet field S with a $\mathbb{Z}_2$ parity symmetry

- **Features**
  - not subject to SUSY relations $\rightsquigarrow$ more freedom in parameter space and phenomenology $\rightsquigarrow$ [MM,Sampaio,Santos,Wittbrodt '16]
  - interesting benchmark model for Higgs sector with doublet and singlet fields
  - features light Higgs bosons ($\leftarrow$ singlet admixture $\rightsquigarrow$ escaped detection)
  - various different Higgs-to-Higgs decay modes possible
  - contains viable Dark Matter candidate in its symmetric phase

$\mathcal{M}$odel and $\mathcal{P}$arameters I

- **CP-conserving N2HDM Potential**

$$
\begin{aligned}
V \quad = \quad & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\
& +\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\
& +\frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{2}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2
\end{aligned}
$$

- **Expansion about VEVs**

$$
\Phi_1 = \left(\phi_1^+, \frac{\rho_1 + i\eta_1 + v_1}{\sqrt{2}}\right)^T , \quad \Phi_2 = \left(\phi_2^+, \frac{\rho_2 + i\eta_2 + v_2}{\sqrt{2}}\right)^T , \quad \Phi_S = \rho_S + v_S
$$

- **Minimum Conditions**

$$
\left\langle \frac{\partial V}{\partial \Phi_1} \right\rangle = \left\langle \frac{\partial V}{\partial \Phi_2} \right\rangle = \left\langle \frac{\partial V}{\partial \Phi_S} \right\rangle = 0
$$

- **Lead to Tadpole Conditions** $(T_3 \equiv T_S)$

$$
\begin{aligned}
T_{1/2} \quad &= \quad m_{11/22}^2 v_{1/2} - m_{12}^2 v_{2/1} + \frac{\lambda_{1/2} v_{1/2}^3}{2} + \frac{\lambda_{345} v_{1/2} v_{2/1}^2}{2} = 0 \\
T_3 \quad &= \quad m_S^2 v_S + \frac{1}{2}(v_1^2\lambda_7 + v_2^2\lambda_8 + v_S^2\lambda_6)v_S = 0
\end{aligned}
$$

$\mathcal{M}$odel and $\mathcal{P}$arameters II

- **Terms bilinear in fields lead to mass matrices**

$$M_\rho^2 = \begin{pmatrix} \lambda_1 c_\beta^2 v^2 + t_\beta m_{12}^2 & \lambda_{345} c_\beta s_\beta v^2 - m_{12}^2 & \lambda_7 c_\beta v v_S \\ \lambda_{345} c_\beta s_\beta v^2 - m_{12}^2 & \lambda_2 s_\beta^2 v^2 + m_{12}^2/t_\beta & \lambda_8 s_\beta v v_S \\ \lambda_7 c_\beta v v_S & \lambda_8 s_\beta v v_S & \lambda_6 v_S^2 \end{pmatrix} + \begin{pmatrix} \frac{T_1}{v_1} & 0 & 0 \\ 0 & \frac{T_2}{v_2} & 0 \\ 0 & 0 & \frac{T_3}{v_S} \end{pmatrix}$$

$$M_\eta^2 = \left(\frac{m_{12}^2}{v_1 v_2} - \lambda_5\right) \begin{pmatrix} v_2^2 & -v_1 v_2 \\ -v_1 v_2 & v_1^2 \end{pmatrix} + \begin{pmatrix} \frac{T_1}{v_1} & 0 \\ 0 & \frac{T_2}{v_2} \end{pmatrix}$$

$$M_{\phi^\pm}^2 = \left(\frac{m_{12}^2}{v_1 v_2} - \frac{\lambda_4 + \lambda_5}{2}\right) \begin{pmatrix} v_2^2 & -v_1 v_2 \\ -v_1 v_2 & v_1^2 \end{pmatrix} + \begin{pmatrix} \frac{T_1}{v_1} & 0 \\ 0 & \frac{T_2}{v_2} \end{pmatrix}$$

- **Diagonalization with four mixing angles, $\alpha_{1,2,3}$ and β:**

$$D_\rho^2 = R(\alpha_i)^T M_\rho^2 R(\alpha_i) \ , \quad D_\eta^2 = R(\beta)^T M_\eta^2 R(\beta) \ , \quad D_{\phi^\pm}^2 = R(\beta)^T M_{\phi^\pm}^2 R(\beta)$$

$\mathcal{M}$odel and $\mathcal{P}$arameters III

- **Mass basis: 6 physical Higgs bosons with masses:**

  3 CP-even Higgses: $m_{H_1}, m_{H_2}, m_{H_3}$, 1 CP-odd Higgs: m_A 2 charged Higgs bosons: $m_{H^\pm}$

- **N2HDM parameters in the gauge basis:**

$$\{\lambda_1 ... \lambda_8, m_{11}^2, m_{22}^2, m_S^2, m_{12}^2, v_1, v_2, v_S, g, g', y_\psi\}$$

- **For renormalization: choose as many 'physical' parameters as possible** $\leadsto$

$$\{m_{H_{1,2,3}}, m_A, m_{H^\pm}, \alpha_1, \alpha_2, \alpha_3, T_1, T_2, T_3, m_{12}^2, v_S, t_\beta, e, M_Z^2, M_W^2, m_\psi\}$$

$\mathcal{R}$enormalization

$\mathcal{R}$enormalization of the N2HDM $\mathcal{P}$arameters

- **Tadpole Terms T_1, T_2, T_3:**

  We choose *alternative* (Fleischer, Jegerlehner 'FJ') tadpole scheme

- **Masses $m_{H_{1,2,3}}, m_A, m_{H^\pm}, M_W, M_Z, m_\psi$:** on-shell

- **Field Strength Renormalization Constants Z_i:** on-shell

- **Electric Charge e:**

  full electron-positron photon coupling for OS external particles in the Thomson limit

- **Mixing angles α_i, β:** see in the following

- **Mass parameter m_{12}^2:** $\overline{\text{MS}}$ scheme

- **Singlet VEV v_S:** process-dependent

$\mathcal{T}$adpole $\mathcal{T}$reatment

$\mathcal{A}$lternative $\mathcal{T}$adpole $\mathcal{S}$cheme

- **Alternative Tadpole Scheme:** [Jegerlehner,Fleischer, Phys. Rev. D **23** (1981) 2001]

  * Bare masses expressed through gauge-independent tree-level VEVs $\rightsquigarrow$ bare masses gauge-independent

  * Correct minimum at NLO requires shift in the VEVs: $v_i \to v_i + \delta v_i \ , \quad i = 1, 2, S$

  * Shift affects counterterms, not bare masses

  * Fixation of shifts by applying the tadpole conditions:

$$\begin{pmatrix} \delta v_1 \\ \delta v_2 \\ \delta v_S \end{pmatrix} = R(\alpha_i)^T \begin{pmatrix} \frac{T_{H_1}^{\text{loop}}}{m_{H_1}^2} \\ \frac{T_{H_2}^{\text{loop}}}{m_{H_2}^2} \\ \frac{T_{H_3}^{\text{loop}}}{m_{H_3}^2} \end{pmatrix} ,$$

  where $T_{H_i}^{\text{loop}}$ is the tadpole loop contribution in the mass basis.
  Tadpole conditions chosen such that minimum conditions of potential restored at NLO

$\mathcal{A}$lternative $\mathcal{T}$adpole $\mathcal{S}$cheme

- **Gauge Dependence:**
  - ◇ Gauge dependence in VEV shifts cancels gauge dependence of counterterms $\rightsquigarrow$ counterterms gauge independent
  - ◇ Note: gauge-independent bare masses and counterterms $\rightsquigarrow$ gauge-independent OS renormalized masses
  - ◇ In practice: shifts tanslate into every counterterm, wave function renormalization constants and Feynman rules

$\mathcal{M}$ixing $\mathcal{A}$ngle and v_S $\mathcal{R}$enormalization

$\mathcal{G}$auge-$\mathcal{I}$ndependent$\mathcal{R}$enormalization of the $\mathcal{S}$calar $\mathcal{M}$ixing $\mathcal{A}$ngles

- **Gauge-independent Approach:**
  - ◇ Combine virtues of tadpole scheme with unambiguous extraction of truly gauge-independent parts of angular counterterms [Baro,Boudjema(+Semenov);Yamada;Espinosa,Yamada;Pilaftsis]
  - ◇ we use Pinch Technique (PT) [Cornwall,Papavassiliou;Degrassi,Sirlin;Watson;Binosi,Papavassiliou;Papavassiliou,Pilaftsis;Pilaftsis]

- **Consistent Application of PT:** requires alternative tadpole scheme [Binosi;Espinosa,Yamada]

$$\text{Pinched self-energy:} \quad \overline{\Sigma}(p^2) = \Sigma^{\text{tad}}(p^2)\big|_{\xi=1} + \Sigma^{\text{add}}(p^2)$$

- **Schemes for Angular Counterterms based on PT:**
  - ∗ On-Shell Tadpole-Pinched: in $\overline{\Sigma}(p^2)$: $p^2 = m_\phi^2$
  - ∗ $p_\star$ Tadpole-Pinched: $p^2 = p_\star^2 = \frac{m_{\phi_1}^2 + m_{\phi_2}^2}{2}$

$\mathcal{A}$ngular $\mathcal{C}$ounterterms OS $\mathcal{T}$adpole-$\mathcal{P}$inched $\mathcal{S}$cheme

$$\delta\alpha_1 = \frac{c_{\alpha_3}}{2c_{\alpha_2}} \frac{\text{Re}\left(\left[\Sigma^{\text{tad}}_{H_1H_2}(m^2_{H_2}) + \Sigma^{\text{tad}}_{H_2H_1}(m^2_{H_1})\right]_{\xi_V=1} + \Sigma^{\text{add}}_{H_1H_2}(m^2_{H_2}) + \Sigma^{\text{add}}_{H_2H_1}(m^2_{H_1})\right)}{m^2_{H_1} - m^2_{H_2}}$$

$$- \frac{s_{\alpha_3}}{2c_{\alpha_2}} \frac{\text{Re}\left(\left[\Sigma^{\text{tad}}_{H_1H_3}(m^2_{H_3}) + \Sigma^{\text{tad}}_{H_3H_1}(m^2_{H_1})\right]_{\xi_V=1} + \Sigma^{\text{add}}_{H_1H_3}(m^2_{H_3}) + \Sigma^{\text{add}}_{H_3H_1}(m^2_{H_1})\right)}{m^2_{H_1} - m^2_{H_3}}$$

$$\delta\alpha_2 = \frac{c_{\alpha_3}}{2} \frac{\text{Re}\left(\left[\Sigma^{\text{tad}}_{H_1H_3}(m^2_{H_3}) + \Sigma^{\text{tad}}_{H_3H_1}(m^2_{H_1})\right]_{\xi_V=1} + \Sigma^{\text{add}}_{H_1H_3}(m^2_{H_3}) + \Sigma^{\text{add}}_{H_3H_1}(m^2_{H_1})\right)}{m^2_{H_1} - m^2_{H_3}}$$

$$+ \frac{s_{\alpha_3}}{2} \frac{\text{Re}\left(\left[\Sigma^{\text{tad}}_{H_1H_2}(m^2_{H_2}) + \Sigma^{\text{tad}}_{H_2H_1}(m^2_{H_1})\right]_{\xi_V=1} + \Sigma^{\text{add}}_{H_1H_2}(m^2_{H_2}) + \Sigma^{\text{add}}_{H_2H_1}(m^2_{H_1})\right)}{m^2_{H_1} - m^2_{H_2}}$$

$$\delta\alpha_3 = \frac{1}{2} \frac{\text{Re}\left[\Sigma^{\text{tad}}_{H_2H_3}(m^2_{H_3}) + \Sigma^{\text{tad}}_{H_3H_2}(m^2_{H_2})\right]_{\xi_V=1} + \Sigma^{\text{add}}_{H_2H_3}(m^2_{H_3}) + \Sigma^{\text{add}}_{H_3H_2}(m^2_{H_2})}{m^2_{H_2} - m^2_{H_3}}$$

$$+ \frac{s_{\alpha_2}}{2c_{\alpha_2}} \left\{ \frac{s_{\alpha_3}\,\text{Re}\left(\left[\Sigma^{\text{tad}}_{H_1H_3}(m^2_{H_3}) + \Sigma^{\text{tad}}_{H_3H_1}(m^2_{H_1})\right]_{\xi_V=1} + \Sigma^{\text{add}}_{H_1H_3}(m^2_{H_3}) + \Sigma^{\text{add}}_{H_3H_1}(m^2_{H_1})\right)}{m^2_{H_1} - m^2_{H_3}} \right.$$

$$\left. - \frac{c_{\alpha_3}\,\text{Re}\left(\left[\Sigma^{\text{tad}}_{H_1H_2}(m^2_{H_2}) + \Sigma^{\text{tad}}_{H_2H_1}(m^2_{H_1})\right]_{\xi_V=1} + \Sigma^{\text{add}}_{H_1H_2}(m^2_{H_2}) + \Sigma^{\text{add}}_{H_2H_1}(m^2_{H_1})\right)}{m^2_{H_1} - m^2_{H_2}} \right\} .$$

$\mathcal{A}$ngular $\mathcal{C}$ounterterms OS $\mathcal{T}$adpole-$\mathcal{P}$inched $\mathcal{S}$cheme

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

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

(1) - renormalization via charged Higgs sector

(2) - renormalization via CP-odd Higgs sector

$\mathcal{A}$ngular $\mathcal{C}$ounterterms OS $\mathcal{T}$adpole-$\mathcal{P}$inched $\mathcal{S}$cheme

- Σ^{add}_{Hh} in MSSM [Espinosa,Yamada], Σ^{add} in 2HDM [Krause,Lorenz,MM,Santos,Ziesche]
- Σ^{add} in N2HDM [Krause,Lopez-Val,MM,Santos]

$$\begin{aligned}
\Sigma^{\text{add}}_{H_iH_j}(p^2) &= -\frac{g^2}{32\pi^2 c_W^2}\left(p^2 - \frac{m^2_{H_i}+m^2_{H_j}}{2}\right)\Big\{\mathcal{O}^{(1)}_{H_iH_j}\, B_0(p^2;m_Z^2,m_A^2) + \mathcal{O}^{(2)}_{H_iH_j}\, B_0(p^2;m_Z^2,m_Z^2) \\
&\quad +2c_W^2\left[\mathcal{O}^{(1)}_{H_iH_j}\, B_0(p^2;m_W^2,m^2_{H^\pm}) + \mathcal{O}^{(2)}_{H_iH_j}\, B_0(p^2;m_W^2,m_W^2)\right]\Big\} \\
\Sigma^{\text{add}}_{G^0A}(p^2) &= \frac{-g^2}{32\pi^2 c_W^2}\left(p^2 - \frac{m_A^2}{2}\right)\sum_{i=1}^{3}\mathcal{O}^{(3)}_{H_iH_i}\, B_0(p^2;m_Z^2,m^2_{H_i}) \\
\Sigma^{\text{add}}_{G^\pm H^\pm}(p^2) &= \frac{-g^2}{16\pi^2}\left(p^2 - \frac{m^2_{H^\pm}}{2}\right)\sum_{i=1}^{3}\mathcal{O}^{(3)}_{H_iH_i}\, B_0(p^2;m_W^2,m^2_{H_i})\ ,
\end{aligned}$$

B_0 scalar two-point function, $\mathcal{O}^{(i)}_{\phi_i\phi_j}$ coupling combinations in the Higgs-gauge sector

$\mathcal{A}$ngular $\mathcal{C}$ounterterms $p_\star$ $\mathcal{T}$adpole-$\mathcal{P}$inched $\mathcal{S}$cheme

$$\delta\alpha_1 = \frac{c_{\alpha_3}\,\overline{\Sigma}_{H_1H_2}(p^2_{\star,12})}{c_{\alpha_2}(m^2_{H_1}-m^2_{H_2})} - \frac{s_{\alpha_3}\,\overline{\Sigma}_{H_1H_3}(p^2_{\star,13})}{c_{\alpha_2}(m^2_{H_1}-m^2_{H_3})}$$

$$\delta\alpha_2 = \frac{c_{\alpha_3}\,\mathrm{Re}\,\overline{\Sigma}_{H_1H_3}(p^2_{\star,13})}{m^2_{H_1}-m^2_{H_3}} + \frac{s_{\alpha_3}\,\mathrm{Re}\,\overline{\Sigma}_{H_1H_2}(p^2_{\star,12})}{m^2_{H_1}-m^2_{H_2}}$$

$$\delta\alpha_3 = \frac{\mathrm{Re}\,\overline{\Sigma}_{H_2H_3}(p^2_{\star,23})}{m^2_{H_3}-m^2_{H_2}} + \frac{s_{\alpha_2}}{c_{\alpha_2}}\left\{\frac{s_{\alpha_3}\,\mathrm{Re}\,\overline{\Sigma}_{H_1H_3}(p^2_{\star,13})}{m^2_{H_1}-m^2_{H_3}} - \frac{c_{\alpha_3}\,\mathrm{Re}\,\overline{\Sigma}_{H_1H_2}(p^2_{\star,12})}{m^2_{H_1}-m^2_{H_2}}\right\}$$

$$\delta\beta^{(1)} = -\mathrm{Re}\left[\overline{\Sigma}_{G^\pm H^\pm}\left(\frac{m^2_{H^\pm}}{2}\right)\right]/m^2_{H^\pm}\,, \quad \delta\beta^{(2)} = -\mathrm{Re}\left[\overline{\Sigma}_{G^0 A}\left(\frac{m^2_A}{2}\right)\right]/m^2_A\,,$$

with

$$p^2_{\star,ij} = (m^2_{H_i}+m^2_{H_j})/2 \quad \text{and} \quad \overline{\Sigma}(p^2) = \Sigma^{\mathrm{tad}}(p^2)\big|_{\xi=1} + \Sigma^{\mathrm{add}}(p^2)$$

- **Properties of the Pinched Scheme:**
  - ∗ manifestly gauge independent by construction
  - ∗ process independent
  - ∗ numerically stable

$\mathcal{R}$enormalization of v_S

- **Higgs-to-Higgs Decays:** sensitive to v_S through Higgs self-coupling

- **Alternative/FJ Tadpole Scheme:** v_S needs to be renormalized, cancels part of UV poles genuinely appearing in one-loop amplitudes computed in the FJ-scheme

  Note: v_S not divergent in R_ξ scheme in standard tadpole scheme [Sperling,Stöckinger,Voigt]

- **Gauge-independent renormalization of v_S:**
  process-dependent through other Higgs-to-Higgs decay:
  $H_3 \to H_1 H_1$ for our sample processes $H_3 \to H_2 H_2$, $H_2 \to H_1 H_1$

  renormalization condition:

$$\Gamma^{\text{NLO}}_{H_3 \to H_1 H_1} \stackrel{!}{=} \Gamma^{\text{LO}}_{H_3 \to H_1 H_1}$$

- **Criteria for choice of process:** experimental feasibility and dependence on v_S

$\mathcal{N}$umerical $\mathcal{A}$nalysis

$\mathcal{C}$onsidered $\mathcal{P}$rocesses for $\mathcal{N}$umerical $\mathcal{A}$nalysis

- **Sample processes for:** N2HDM type I, $H_1 = H^{\mathrm{SM}}$

- **Considered Processes:**

  $*\ H_{2,3} \to ZZ$ depend on α_i, β

  $*\ H_{2,3} \to AA$ depend on α_i, β, m_{12}^2

  $*\ H_3 \to H_2 H_2$ depends on α_i, β, m_{12}^2, v_S

  $*\ H_2 \to H_1 H_1$ depends on α_i, β, m_{12}^2, v_S

- **Process for Process-Dependent Renormalization of v_S:**

  $*\ H_3 \to H_1 H_1$ depends on α_i, β, m_{12}^2, v_S

$\mathcal{P}$arameter $\mathcal{S}$can for $\mathcal{N}$umerical $\mathcal{A}$nalysis

- **Standard Model Parameters:** [ParticleDataGroup; LHCHXSWG-INT-2015-006; LHCHXSWG YR1]

$$
\begin{aligned}
\alpha(M_Z^2) &= \frac{1}{128.962}\,, & M_W &= 80.385\,, & M_Z &= 91.1876 \text{ GeV} \\
m_e &= 0.510998928 \text{ MeV}\,, & m_\mu &= 105.6583715 \text{ MeV}\,, & m_\tau &= 1.77682 \text{ GeV} \\
m_u &= 100 \text{ MeV}\,, & m_d &= 100 \text{ MeV}\,, & m_s &= 100 \text{ MeV} \\
m_t &= 172.5 \text{ GeV}\,, & m_c &= 1.51 \text{ GeV}\,, & m_b &= 4.92 \text{ GeV} \\
m_{H^{\text{SM}}} &= 125.09 \text{ GeV}
\end{aligned}
$$

[ATLAS,CMS 1503.07589]

V_{CKM} assumed to be unity

- **All Scenarios:** for N2HDM type I, $H_1 = H^{\text{SM}}$

$\mathcal{C}$onstraints on $\mathcal{P}$arameters for $\mathcal{N}$umerical $\mathcal{A}$nalysis

- **2HDM Scan:** Theoretical & Experimental Constraints
  - ◇ Data set generated with `ScannerS` [Coimbra,Sampaio,Santos]
  - ◇ CP-conserving vacuum is global minimum
  - ◇ N2HDM potential bounded from below
  - ◇ tree-level unitarity holds
  - ◇ EWP constraints fulfilled [Baak eal]
  - ◇ B physics constraints [Mahmoudi,Stal;Deschamps eal;Hermann eal;Misiak,Steinhauser], R_b [Deschamp eal;Haber,Logan]
  - ◇ Compatibility with LHC Higgs data: interface w/ `SusHi` (ggF, bb-F at NNLO QCD) [Harlander,Liebler,Mantler] , remaining σ_{prod} at NLO QCD [LHCHXSWG], N2HDM decays from `N2HDECAY` [MM,Sampaio.Santos,Wittbrodt]
  - ◇ Check of exclusion limits with `HiggsBounds` [Bechtle,Brein,Heinemeyer,Weiglein,Williams]
  - ◇ Compatibility with observed 125 GeV Higgs signal with `HiggsSignals` [Bechtle,Heinemeyer,Stal,Stefaniak,Weiglein]

Sample Numerical Results

- **Sample scenarios:** BRH2ZZ and BRH3ZZ with large LO BRs of 0.327 and 0.329, respectively
- **NLO corrections:** in OS and $p_\star$ tadpole pinched scheme with β renormalization through charged ('c') or CP-odd ('o') sector
- **Input scheme for mixing angles:** α_i – pOS, β – pOC^c
- **Scheme $a \to b$ conversion of parameter p:** $p^b = p^a + \delta p^a - \delta p^b$
- **Relative correction:** $\Delta\Gamma \equiv \frac{\Delta\Gamma^{\text{NLO}}}{\Gamma^{\text{LO}}} = \frac{\Gamma^{\text{NLO}} - \Gamma^{\text{LO}}}{\Gamma^{\text{LO}}}$

		pOS^c	pOS^o	p$_\star^c$	p$_\star^o$
BRH2ZZ	$\Gamma^{\text{LO}}(H_2 \to ZZ)$	0.989	0.989	1.008	1.008
	$\Gamma^{\text{NLO}}(H_2 \to ZZ)$	1.120	1.122	1.142	1.148
	$\Delta\Gamma^{H_2ZZ}$ [%]	13.2	13.4	13.3	14.0
BRH3ZZ	$\Gamma^{\text{LO}}(H_3 \to ZZ)$	0.755	0.755	0.782	0.782
	$\Gamma^{\text{NLO}}(H_3 \to ZZ)$	0.872	0.867	0.890	0.889
	$\Delta\Gamma^{H_3ZZ}$ [%]	15.6	14.9	13.9	13.7

$\mathcal{F}$eatures of $\mathcal{N}$umerical $\mathcal{R}$esults

- **Overall features of our sample processes:**
  - ◇ EW corrections can be sizeable and need to be taken into account
  - ◇ For broad range of phenomenologically representative scenarios: rather weak renormalization scale and scheme dependence
  - ◇ If LO width suppressed: NLO-corrected width effectively LO width $\rightsquigarrow$ sizeable corrections and renormalization scale/scheme dependence $\rightsquigarrow$ beyond NLO corrections required

- **Results in other N2HDM types:** Same overall results
  $\leftarrow$ only difference arises from fermion loops and
  Yukawa couplings in all types well-behaved functions of α_i, β

$\mathcal{C}$onclusions

◇ Renormalization scheme for N2HDM:

* along the lines of 2HDM renormalization
* new: more mixing angles and v_S renormalization

◇ Renormalization scheme for the mixing angles α and β

Tadpole-pinched schemes:

* gauge independent
* process independent
* numerically stable

◇ Renormalization scheme for v_S:

process-dependent scheme (Higgs-to-Higgs decay)

◇ Renormalization scheme for m_{12}^2

$\overline{\text{MS}}$ scheme (shows better numerical behaviour than process-dependent scheme)

Thank You For Your Attention!

$\mathcal{T}$he $\mathcal{M}$ixing $\mathcal{M}$atrix

- **Mass matrix in CP-even neutral sector diagonalized by R:**

$$D_\rho^2 \quad = \quad R(\alpha_i) M_\rho^2 R^T(\alpha_i)$$

- **Parameterization of R:**

$$R(\alpha_i) \quad = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix} .$$

with

$$-\frac{\pi}{2} \leq \alpha_{1,2,3} < \frac{\pi}{2}$$

Comments on Background Field Method and Pinch Technique

- **Relation BFM and PT:** Pinched self-energies of the gauge bosons obtainable from BFM [Honerkamp;Kluberg-Stern,Zuber;Arefa,Fadeev,Slavnov] for $\xi = 1$ [Binosi,Papavassiliou]
- **Discussion of PT versus BFM** [Denner,Weiglein,Dittmaier]

Criticism of PT	Our answer for PT
extension beyond 1l neither unique nor trivial	here: only 1l; 2l application in SM [Bauberger eal]; unambiguous generalization to all orders for EW SM sector [Binosi,Papavassiliou]
process independence not generally proven	applied to variety of toy processes yielding a universal result [Watson]
not generally applicable to all possible 1l Green's functions; technically involved	applicable to 2HDM, N2HDM as has been shown

- **Problems in BFM:**
  - ∗ not applicable for calc of current correlation functions or Wilson loops [Binosi,Papavassiliou]; possible w/ PT [Cornwalli,Papavassiliou;Binosi,Papavassiliou]
  - ∗ provides manifestly gauge-invariant n-point functions, however, still gauge-dependent; gauge dependence induces unphysical thresholds in BFM Green's functions for any BF gauge $\xi \neq 1$ in theories w/ SSB

Comments on Background Field Method and Pinch Technique

- **Conclusion:** PT and BFM complement each other

  If PT Green's functions coincide w/ BFM Green's functions for $\xi = 1$ gauge of BFs $\rightsquigarrow$ PT automatically process independent and gauge invariant

- **Further discussions on connection PT and BFM:**
  - ◇ QCD [Hashimoto eal]
  - ◇ SM EW sector [Binosi,Papavassiliou;Degrassi,Sirlin]
  - ◇ MSSM [Espinosa,Yamada;Degrassi,Slavich]