2HDECAY - A program for the Calculation of Electroweak One-Loop Corrections to Higgs Decays in the Two-Higgs-Doublet Model Including State-of-the-Art QCD Corrections

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Abstract

We present the program package 2HDECAY for the calculation of the partial decay widths and branching ratios of the Higgs bosons of a general CP-conserving 2-Higgs doublet model (2HDM). The tool includes the full electroweak one-loop corrections to all two-body on-shell Higgs decays in the 2HDM that are not loop-induced. It combines them with the state-of-the-art QCD corrections that are already implemented in the program HDECAY. For the renormalization of the electroweak sector an on-shell scheme is implemented for most of the renormalization parameters. Exceptions are the soft-$\mathbb{Z}_2$-breaking squared mass scale m_{12}^2, where an $\overline{\text{MS}}$ condition is applied, as well as the 2HDM mixing angles α and β, for which several distinct renormalization schemes are implemented. The tool 2HDECAY can be used for phenomenological analyses of the branching ratios of Higgs decays in the 2HDM. Furthermore, the separate output of the electroweak contributions to the tree-level partial decay widths for several different renormalization schemes allows for an efficient analysis of the impact of the electroweak corrections and the remaining theoretical error due to missing higher-order corrections. The latest version of the program package 2HDECAY can be downloaded from the URL https://github.com/marcel-krause/2HDECAY.

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1 Introduction

The discovery of the Higgs particle, announced on 4 July 2012 by the LHC experiments ATLAS [1] and CMS [2] marked a milestone for particle physics. It structurally completed the Standard Model (SM) providing us with a theory that remains weakly interacting all the way up to the Planck scale. While the SM can successfully describe numerous particle physics phenomena at the quantum level at highest precision, it leaves open several questions. Among these are *e.g.* the one for the nature of Dark Matter (DM), the baryon asymmetry of the universe or the hierarchy problem. This calls for physics beyond the SM (BSM). Models beyond the SM usually entail enlarged Higgs sectors that can provide candidates for Dark Matter or guarantee successful baryogenesis. Since the discovered Higgs boson with a mass of 125.09 GeV [3] behaves SM-like any BSM extension has to make sure to contain a Higgs boson in its spectrum that is in accordance with the LHC Higgs data. Moreover, the models have to be tested against theoretical and further experimental constraints from electroweak precision tests, *B*-physics, low-energy observables and the negative searches for new particles that may be predicted by some of the BSM theories.

The lack of any direct sign of new physics renders the investigation of the Higgs sector more and more important. The precise investigation of the discovered Higgs boson may reveal indirect signs of new physics through mixing with other Higgs bosons in the spectrum, loop effects due to the additional Higgs bosons and/or further new states predicted by the model, or decays into non-SM states or Higgs bosons, including the possibility of invisible decays. Due to the SM-like nature of the 125 GeV Higgs boson indirect new physics effects on its properties are expected to be small. Moreover, different BSM theories can lead to similar effects in the Higgs sector. In order not to miss any indirect sign of new physics and to be able to identify the underlying theory in case of discovery, highest precision in the prediction of the observables and sophisticated experimental techniques are therefore indispensable. The former calls for the inclusion of higher-order corrections at highest possible level, and theorists all over the world have spent enormous efforts to improve the predictions for Higgs observables [4].

Among the new physics models supersymmetric (SUSY) extensions [5–17] certainly belong to the best motivated and most thoroughly investigated models beyond the SM, and numerous higher-order predictions exist for the production and decay cross sections as well as the Higgs potential parameters, *i.e.* the masses and Higgs self-couplings [4]. The Higgs sector of the minimal supersymmetric extension (MSSM) [17–20] is a 2-Higgs doublet model (2HDM) of type II [21, 22]. While due to supersymmetry the MSSM Higgs potential parameters are given in terms of gauge couplings this is not the case for general 2HDMs so that the 2HDM entails an interesting and more diverse Higgs phenomenology and is also affected differently by higher-order electroweak (EW) corrections. Moreover, 2HDMs allow for successful baryogenesis [23–41] and in their inert version provide a Dark Matter candidate [42–56].

The situation with respect to EW corrections in non-SUSY models is not as advanced as for SUSY extensions. While the QCD corrections can be taken over to those models with a minimum effort from the SM and the MSSM by applying appropriate changes, this is not the case for the EW corrections. Moreover, some issues arise with respect to renormalization. Thus, only recently a renormalization procedure has been proposed by authors of this paper for the mixing angles of the 2HDM that ensures explicitly gauge-independent decay amplitudes, [57,58]. Subsequent groups have confirmed this in different Higgs channels [59–62]. In [63] we completed the renormalization of the 2HDM and calculated the higher-order corrections to Higgs-to-Higgs decays. We have applied and extended this renormalization procedure in [64] to the next-to-

2HDM (N2HDM) which includes an additional real singlet. The computation of the (N)2HDM EW corrections has shown that the corrections can become very large for certain areas of the parameters space. There can be several reasons for this. The corrections can be parametrically enhanced due to involved couplings that can be large [63–66]. This is in particular the case for the trilinear Higgs self-couplings that in contrast to SUSY are not given in terms of the gauge couplings of the theory and that are so far only weakly constrained by the LHC Higgs data. The corrections can be large due to light particles in the loop in combination with not too small couplings, *e.g.* light Higgs states of the extended Higgs sector. Also an inapt choice of the renormalization scheme can artificially enhance loop corrections. Thus we found for our investigated processes that process-dependent renormalization schemes or $\overline{\text{MS}}$ renormalization of the scalar mixing angles can blow up the one-loop corrections due to an insufficient cancellation of the large finite contributions from wave function renormalization constants [58,63]. Moreover, counterterms can blow up in certain parameter regions because of small leading-order couplings, *e.g.* in the 2HDM the coupling of the heavy non-SM-like CP-even Higgs boson to gauge bosons, which in the limit of a light SM-like CP-even Higgs boson is almost zero. The same effects are observed for supersymmetric theories where a badly chosen parameter set for the renormalization can lead to very large counterterms and hence enhanced loop corrections, *cf.* Ref. [67] for a recent analysis.

This discussion shows that the renormalization of the EW corrections to BSM Higgs observables is a highly non-trivial task. In addition, there may be no unique best renormalization scheme for the whole parameter space of a specific model, and the user has to decide which scheme to choose to obtain trustworthy predictions. With the publication of the new tool 2HDECAY we aim to give an answer to this problematic task.

The program 2HDECAY computes, for 14 different renormalization schemes, the EW corrections to the Higgs decays of the 2HDM Higgs bosons into all possible on-shell two-particle final states of the model that are not loop-induced. It is combined with the widely used Fortran code HDECAY version 6.52 [68,69] which provides the loop-corrected decay widths and branching ratios for the SM, the MSSM and 2HDM incorporating the state-of-the-art higher-order QCD corrections including also loop-induced and off-shell decays. Through the combination of these corrections with the 2HDM EW corrections 2HDECAY becomes a code for the prediction of the 2HDM Higgs boson decay widths at the presently highest possible level of precision. Additionally, the separate output of the leading order (LO) and next-to-leading order (NLO) EW corrected decay widths allows to perform studies on the importance of the relative EW corrections (as function of the parameter choices), comparisons with the relative EW corrections within the MSSM or investigations on the most suitable renormalization scheme for specific parameter regions. The comparison of the results for different renormalization schemes moreover permits to estimate the remaining theoretical error due to missing higher-order corrections. With this tool we contribute to the effort of improving the theory predictions for BSM Higgs physics observables so that in combination with sophisticated experimental techniques Higgs precision physics becomes possible and the gained insights may advance us in our understanding of the mechanism of electroweak symmetry breaking (EWSB) and the true underlying theory.

The program package was developed and tested under `Windows 10`, `openSUSE Leap 15.0` and `macOS Sierra 10.12`. It requires an up-to-date version of `Python 2` or `Python 3` (tested with versions `2.7.14` and `3.5.0`), the `FORTRAN` compiler `gfortran` and the `GNU C` compilers `gcc` (tested for compatibility with versions `6.4.0` and `7.3.1`) and `g++`. The latest version of the package can be downloaded from

https://github.com/marcel-krause/2HDECAY .

The paper is organized as follows. The subsequent Sec. 2 forms the theoretical background for our work. We briefly introduce the 2HDM, all relevant parameters and particles and set our notation. We give a summary of all counterterms that are needed for the computation of the EW corrections and state them explicitly. The relevant formulae for the computation of the partial decay widths at one-loop level are presented and the combination of the electroweak corrections with the QCD corrections already implemented in `HDECAY` is described. In Sec. 3, we introduce `2HDECAY` in detail, describe the structure of the program package and the input and output file formats. Additionally, we provide installation and usage manuals. We conclude with a short summary of our work in Sec. 4. As reference for the user, we list exemplary input and output files in Appendices A and B, respectively.

2   One-Loop Electroweak and QCD Corrections in the 2HDM

In the following, we briefly set up our notation and introduce the 2HDM along with the input parameters used in our parametrization. We give details on the EW one-loop renormalization of the 2HDM. We discuss how the calculation of the one-loop partial decay widths is performed. At the end of the section, we explain how the EW corrections are combined with the existing state-of-the-art QCD corrections already implemented in `HDECAY`.

2.1   Introduction of the 2HDM

For our work, we consider a general CP-conserving 2HDM [21, 22] with a global discrete $\mathbb{Z}_2$ symmetry that is softly broken. The model consists of two complex $SU(2)_L$ doublets Φ_1 and Φ_2, both with hypercharge $Y = +1$. The electroweak part of the 2HDM can be described by the Lagrangian

$$\mathcal{L}_{2\text{HDM}}^{\text{EW}} = \mathcal{L}_{\text{YM}} + \mathcal{L}_{\text{F}} + \mathcal{L}_{\text{S}} + \mathcal{L}_{\text{Yuk}} + \mathcal{L}_{\text{GF}} + \mathcal{L}_{\text{FP}} \ . \tag{2.1}$$

in terms of the Yang-Mills Lagrangian $\mathcal{L}_{\text{YM}}$ and the fermion Lagrangian $\mathcal{L}_{\text{F}}$ containing the kinetic terms of the gauge bosons and fermions and their interactions, the Higgs Lagrangian $\mathcal{L}_{\text{S}}$, the Yukawa Lagrangian $\mathcal{L}_{\text{yuk}}$ with the Higgs-fermion interactions, the gauge-fixing and the Fadeev-Popov Lagrangian, $\mathcal{L}_{\text{GF}}$ and $\mathcal{L}_{\text{FP}}$, respectively. Explicit forms of $\mathcal{L}_{\text{YM}}$ and $\mathcal{L}_{\text{F}}$ can be found *e.g.* in [70,71] and of the general 2HDM Yukawa Lagrangian *e.g.* in [22,72]. We do not give them explicitly here. For the renormalization of the 2HDM, we follow the approach of Ref. [73] and apply the gauge-fixing only *after* the renormalization of the theory, *i.e.* $\mathcal{L}_{\text{GF}}$ contains only fields that are already renormalized. For the purpose of our work we do not present $\mathcal{L}_{\text{GF}}$ nor $\mathcal{L}_{\text{FP}}$ since their explicit forms are not needed in the following.

The scalar Lagrangian $\mathcal{L}_{\text{S}}$ introduces the kinetic terms of the Higgs doublets and their scalar potential. With the the covariant derivative

$$D_\mu = \partial_\mu + \frac{i}{2} g \sum_{a=1}^{3} \sigma^a W_\mu^a + \frac{i}{2} g' B_\mu \ , \tag{2.2}$$

where W_μ^a and B_μ are the gauge bosons of the $SU(2)_L$ and $U(1)_Y$ respectively, g and g' are the corresponding coupling constants of the gauge groups and σ^a are the Pauli matrices, the scalar Lagrangian is given by

$$\mathcal{L}_S = \sum_{i=1}^{2} (D_\mu \Phi_i)^\dagger (D^\mu \Phi_i) - V_{2\text{HDM}} \ . \tag{2.3}$$

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The scalar potential of the CP-conserving 2HDM reads [22]

$$V_{\text{2HDM}} = m_{11}^2 \left|\Phi_1\right|^2 + m_{22}^2 \left|\Phi_2\right|^2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + h.c.\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2$$
$$+ \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + h.c.\right] . \tag{2.4}$$

Since we consider a CP-conserving model, the 2HDM potential can be parametrized by three real-valued mass parameters m_{11}, m_{22} and m_{12} as well as five real-valued dimensionless coupling constants λ_i $(i = 1, ..., 5)$. For later convenience, we define the frequently appearing combination of three of these coupling constants as

$$\lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5 . \tag{2.5}$$

For $m_{12}^2 = 0$, the potential V_{2HDM} exhibits a discrete $\mathbb{Z}_2$ symmetry under the simultaneous field transformations $\Phi_1 \to -\Phi_1$ and $\Phi_2 \to \Phi_2$. This symmetry, implemented in the scalar potential in order to avoid flavour-changing neutral currents (FCNC) at tree level, is softly broken by a non-zero mass parameter m_{12}.

After EWSB the neutral components of the Higgs doublets develop vacuum expectation values (VEVs) which are real in the CP-conserving case. After expanding about the real VEVs v_1 and v_2, the Higgs doublets Φ_i $(i = 1, 2)$ can be expressed in terms of the charged complex field ω_i^+ and the real neutral CP-even and CP-odd fields ρ_i and η_i, respectively as

$$\Phi_1 = \begin{pmatrix} \omega_1^+ \\ \frac{v_1 + \rho_1 + i\eta_1}{\sqrt{2}} \end{pmatrix} , \quad \Phi_2 = \begin{pmatrix} \omega_2^+ \\ \frac{v_2 + \rho_2 + i\eta_2}{\sqrt{2}} \end{pmatrix} , \tag{2.6}$$

where

$$v^2 = v_1^2 + v_2^2 \approx (246.22 \text{ GeV})^2 \tag{2.7}$$

is the SM VEV obtained from the Fermi constant G_F and we define the ratio of the VEVs through the mixing angle β as

$$\tan \beta = \frac{v_2}{v_1} \tag{2.8}$$

so that

$$v_1 = vc_\beta \quad \text{and} \quad v_2 = vs_\beta . \tag{2.9}$$

Insertion of Eq. (2.6) in the kinetic part of the scalar Lagrangian in Eq. (2.3) yields after rotation to the mass eigenstates the tree-level relations for the masses of the electroweak gauge bosons

$$m_W^2 = \frac{g^2 v^2}{4} \tag{2.10}$$

$$m_Z^2 = \frac{(g^2 + g'^2)v^2}{4} \tag{2.11}$$

$$m_\gamma^2 = 0 . \tag{2.12}$$

The electromagnetic coupling constant e is connected to the fine-structure constant α_{em} and to the gauge boson coupling constants through the tree-level relation

$$e = \sqrt{4\pi\alpha_{\text{em}}} = \frac{gg'}{\sqrt{g^2 + g'^2}} , \tag{2.13}$$

which allows to replace g' in favor of e or α_{em}. In our work, we use the fine-structure constant α_{em} as an independent input. Alternatively, one could use the tree-level relation to the Fermi constant

$$G_F \equiv \frac{\sqrt{2}g^2}{8m_W^2} = \frac{\alpha_{\mathrm{em}}\pi}{\sqrt{2}m_W^2\left(1 - \frac{m_W^2}{m_Z^2}\right)} \tag{2.14}$$

to replace one of the parameters of the electroweak sector in favor of G_F. Since G_F is used as an input value for HDECAY, we present the formula here explicitly and explain the conversion between the different parametrizations in Sec. 2.4.

Inserting Eq. (2.6) in the scalar potential in Eq. (2.4) leads to

$$V_{\mathrm{2HDM}} = \frac{1}{2}\begin{pmatrix}\rho_1 & \rho_2\end{pmatrix} M_\rho^2 \begin{pmatrix}\rho_1\\\rho_2\end{pmatrix} + \frac{1}{2}\begin{pmatrix}\eta_1 & \eta_2\end{pmatrix} M_\eta^2 \begin{pmatrix}\eta_1\\\eta_2\end{pmatrix} + \frac{1}{2}\begin{pmatrix}\omega_1^\pm & \omega_2^\pm\end{pmatrix} M_\omega^2 \begin{pmatrix}\omega_1^\pm\\\omega_2^\pm\end{pmatrix}$$
$$+ T_1\rho_1 + T_2\rho_2 + \quad\cdots \tag{2.15}$$

where the terms T_1 and T_2 and the matrices M_ω^2, M_ρ^2 and M_η^2 are defined below. By requiring the VEVs of Eq. (2.6) to represent the minimum of the potential, the minimum conditions for the potential can be expressed as

$$\left.\frac{\partial V_{\mathrm{2HDM}}}{\partial \Phi_i}\right|_{\langle\Phi_j\rangle} = 0 \; . \tag{2.16}$$

This is equivalent to the statement that the two terms linear in the CP-even fields ρ_1 and ρ_2, the tadpole terms,

$$\frac{T_1}{v_1} \equiv m_{11}^2 - m_{12}^2\frac{v_2}{v_1} + \frac{v_1^2\lambda_1}{2} + \frac{v_2^2\lambda_{345}}{2} \tag{2.17}$$

$$\frac{T_2}{v_2} \equiv m_{22}^2 - m_{12}^2\frac{v_1}{v_2} + \frac{v_2^2\lambda_2}{2} + \frac{v_1^2\lambda_{345}}{2} \; , \tag{2.18}$$

have to vanish at tree level:

$$T_1 = T_2 = 0 \quad \text{(at tree level)} \; . \tag{2.19}$$

The tadpole equations can be solved for m_{11}^2 and m_{22}^2 in order to replace these two parameters by the tadpole parameters T_1 and T_2.

The terms bilinear in the fields given in Eq. (2.15) define the scalar mass matrices

$$M_\rho^2 \equiv \begin{pmatrix} m_{12}^2\frac{v_2}{v_1} + \lambda_1 v_1^2 & -m_{12}^2 + \lambda_{345}v_1v_2 \\ -m_{12}^2 + \lambda_{345}v_1v_2 & m_{12}^2\frac{v_1}{v_2} + \lambda_2 v_2^2 \end{pmatrix} + \begin{pmatrix} \frac{T_1}{v_1} & 0 \\ 0 & \frac{T_2}{v_2} \end{pmatrix} \tag{2.20}$$

$$M_\eta^2 \equiv \left(\frac{m_{12}^2}{v_1v_2} - \lambda_5\right)\begin{pmatrix} v_2^2 & -v_1v_2 \\ -v_1v_2 & v_1^2 \end{pmatrix} + \begin{pmatrix} \frac{T_1}{v_1} & 0 \\ 0 & \frac{T_2}{v_2} \end{pmatrix} \tag{2.21}$$

$$M_\omega^2 \equiv \left(\frac{m_{12}^2}{v_1v_2} - \frac{\lambda_4 + \lambda_5}{2}\right)\begin{pmatrix} v_2^2 & -v_1v_2 \\ -v_1v_2 & v_1^2 \end{pmatrix} + \begin{pmatrix} \frac{T_1}{v_1} & 0 \\ 0 & \frac{T_2}{v_2} \end{pmatrix} \; , \tag{2.22}$$

where Eqs. (2.17) and (2.18) have already been applied to replace the parameters m_{11}^2 and m_{22}^2 in favor of T_1 and T_2. Keeping the latter explicitly in the expressions of the mass matrices is

crucial for the correct renormalization of the scalar sector, as explained in Sec. 2.2. By means of two mixing angles α and β which define the rotation matrices[1]

$$R(x) \equiv \begin{pmatrix} c_x & -s_x \\ s_x & c_x \end{pmatrix} , \tag{2.23}$$

the fields ω_i^+, ρ_i and η_i are rotated to the mass basis according to

$$\begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ h \end{pmatrix} \tag{2.24}$$

$$\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = R(\beta) \begin{pmatrix} G^0 \\ A \end{pmatrix} \tag{2.25}$$

$$\begin{pmatrix} \omega_1^\pm \\ \omega_2^\pm \end{pmatrix} = R(\beta) \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} , \tag{2.26}$$

with the two CP-even Higgs bosons h and H, the CP-odd Higgs boson A, the CP-odd Goldstone boson G^0 and the charged Higgs bosons $H^\pm$ as well as the charged Goldstone bosons $G^\pm$. In the mass basis, the diagonal mass matrices are given by

$$D_\rho^2 \equiv \begin{pmatrix} m_H^2 & 0 \\ 0 & m_h^2 \end{pmatrix} \tag{2.27}$$

$$D_\eta^2 \equiv \begin{pmatrix} m_{G^0}^2 & 0 \\ 0 & m_A^2 \end{pmatrix} \tag{2.28}$$

$$D_\omega^2 \equiv \begin{pmatrix} m_{G^\pm}^2 & 0 \\ 0 & m_{H^\pm}^2 \end{pmatrix} , \tag{2.29}$$

with the diagonal entries representing the squared masses of the respective particles. The Goldstone bosons are massless,

$$m_{G^0}^2 = m_{G^\pm}^2 = 0 . \tag{2.30}$$

The squared masses expressed in terms of the potential parameters and the mixing angle α can be cast into the form [66]

$$m_H^2 = c_{\alpha-\beta}^2 M_{11}^2 + s_{2(\alpha-\beta)} M_{12}^2 + s_{\alpha-\beta}^2 M_{22}^2 \tag{2.31}$$

$$m_h^2 = s_{\alpha-\beta}^2 M_{11}^2 - s_{2(\alpha-\beta)} M_{12}^2 + c_{\alpha-\beta}^2 M_{22}^2 \tag{2.32}$$

$$m_A^2 = \frac{m_{12}^2}{s_\beta c_\beta} - v^2 \lambda_5 \tag{2.33}$$

$$m_{H^\pm}^2 = \frac{m_{12}^2}{s_\beta c_\beta} - \frac{v^2}{2} (\lambda_4 + \lambda_5) , \quad \text{with} \tag{2.34}$$

$$t_{2(\alpha-\beta)} = \frac{2 M_{12}^2}{M_{11}^2 - M_{22}^2} , \tag{2.35}$$

where we have introduced

$$M_{11}^2 \equiv v^2 \left(c_\beta^4 \lambda_1 + s_\beta^4 \lambda_2 + 2 s_\beta^2 c_\beta^2 \lambda_{345} \right) \tag{2.36}$$

$$M_{12}^2 \equiv s_\beta c_\beta v^2 \left(-c_\beta^2 \lambda_1 + s_\beta^2 \lambda_2 + c_{2\beta} \lambda_{345} \right) \tag{2.37}$$

$$M_{22}^2 \equiv \frac{m_{12}^2}{s_\beta c_\beta} + \frac{v^2}{8} (1 - c_{4\beta}) (\lambda_1 + \lambda_2 - 2\lambda_{345}) . \tag{2.38}$$

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[1]Here and in the following, we use the short-hand notation $s_x \equiv \sin(x)$, $c_x \equiv \cos(x)$, $t_x \equiv \tan(x)$ for convenience.

	u-type	d-type	leptons
I	Φ_2	Φ_2	Φ_2
II	Φ_2	Φ_1	Φ_1
lepton-specific	Φ_2	Φ_2	Φ_1
flipped	Φ_2	Φ_1	Φ_2

Table 1: The four Yukawa types of the $\mathbb{Z}_2$-symmetric 2HDM defined by the Higgs doublet that couples to each kind of fermions.

2HDM type	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
I	$\frac{c_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$-\frac{1}{t_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$-\frac{1}{t_\beta}$
II	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{c_\beta}$	t_β	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{c_\beta}$	t_β
lepton-specific	$\frac{c_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$-\frac{1}{t_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{c_\beta}$	t_β
flipped	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{c_\beta}$	t_β	$\frac{c_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$-\frac{1}{t_\beta}$

Table 2: Parametrization of the Yukawa coupling parameters in terms of six parameters Y_i ($i = 1, ..., 6$) for each 2HDM type.

Inverting these relations, the quartic couplings λ_i ($i = 1, ..., 5$) can be expressed in terms of the mass parameters m_h^2, m_H^2, m_A^2, $m_{H^\pm}^2$ and the CP-even mixing angle α as [66]

$$\lambda_1 = \frac{1}{v^2 c_\beta^2} \left(c_\alpha^2 m_H^2 + s_\alpha^2 m_h^2 - \frac{s_\beta}{c_\beta} m_{12}^2 \right) \tag{2.39}$$

$$\lambda_2 = \frac{1}{v^2 s_\beta^2} \left(s_\alpha^2 m_H^2 + c_\alpha^2 m_h^2 - \frac{c_\beta}{s_\beta} m_{12}^2 \right) \tag{2.40}$$

$$\lambda_3 = \frac{2 m_{H^\pm}^2}{v^2} + \frac{s_{2\alpha}}{s_{2\beta} v^2} \left(m_H^2 - m_h^2 \right) - \frac{m_{12}^2}{s_\beta c_\beta v^2} \tag{2.41}$$

$$\lambda_4 = \frac{1}{v^2} \left(m_A^2 - 2 m_{H^\pm}^2 + \frac{m_{12}^2}{s_\beta c_\beta} \right) \tag{2.42}$$

$$\lambda_5 = \frac{1}{v^2} \left(\frac{m_{12}^2}{s_\beta c_\beta} - m_A^2 \right) . \tag{2.43}$$

In order to avoid tree-level FCNC currents, as introduced by the most general 2HDM Yukawa Lagrangian, one type of fermions is allowed to couple only to one Higgs doublet by imposing a global $\mathbb{Z}_2$ symmetry under which $\Phi_{1,2} \to \mp \Phi_{1,2}$. Depending on the $\mathbb{Z}_2$ charge assignments, there are four phenomenologically different types of 2HDMs summarized in Tab. 1. For the four 2HDM types considered in this work, all Yukawa couplings can be parametrized through six different Yukawa coupling parameters Y_i ($i = 1, ..., 6$) whose values for the different types are presented in Tab. 2. They are introduced here for later convenience.

We conclude this section with an overview over the full set of independent parameters that is used as input for the computations in 2HDECAY. Additionally to the parameters defined by $\mathcal{L}_{2HDM}^{EW}$, HDECAY requires the electromagnetic coupling constant α_{em} in the Thomson limit for the calculation of the loop-induced decays into a photon pair and into $Z\gamma$, the strong coupling constant α_s for the loop-induced decay into gluons and the QCD corrections as well as the total decay widths of the W and Z bosons, Γ_W and Γ_Z, for the computation of the off-shell decays into massive gauge boson final states. In the mass basis of the scalar sector, the set of independent

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parameters is given by

$$\{G_F, \alpha_s, \Gamma_W, \Gamma_Z, \alpha_{\text{em}}, m_W, m_Z, m_f, V_{ij}, t_\beta, m_{12}^2, \alpha, m_h, m_H, m_A, m_{H^\pm}\} \ . \qquad (2.44)$$

Here m_f denote the fermion masses of the strange, charm, bottom and top quarks and of the μ and τ leptons ($f = s, c, b, t, \mu, \tau$). All other fermion masses are assumed to be zero in HDECAY and will also be assumed to be zero in our computation of the EW corrections to the decay widths. The fermion and gauge boson masses are defined in accordance with the recommendations of the LHC Higgs cross section working group [74]. The V_{ij} denote the CKM mixing matrix elements. All HDECAY decay widths are computed in terms of the Fermi constant G_F except for processes involving on-shell external photon vertices that are expressed by α_{em} in the Thomson limit. In the computation of the EW corrections, however, we require the on-shell masses m_W and m_Z and the electromagnetic coupling at the Z boson mass scale, $\alpha_{\text{em}}(m_Z^2)$ (not to be confused with the mixing angle α in the Higgs sector), as input parameters for our renormalization conditions. We will come back to this point later.

Alternatively, the original parametrization of the scalar potential in the interaction basis can be used[2]. In this case, the set of independent parameters is given by

$$\{G_F, \alpha_s, \Gamma_W, \Gamma_Z, \alpha_{\text{em}}, m_W, m_Z, m_f, V_{ij}, t_\beta, m_{12}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5\} \ . \qquad (2.45)$$

Actually, also the tadpole parameters T_1 and T_2 should be included in the two sets as independent parameters of the Higgs potential. However, as described in Sec. 2.2, the treatment of the minimum of the Higgs potential at higher orders requires special care, and in an alternative treatment of the minimum conditions, the tadpole parameters disappear as independent parameters. In any case, after the renormalization procedure is completely performed, the tadpole parameters vanish again and hence, do not count as input parameters for 2HDECAY.

2.2 Renormalization

We focus on the calculation of EW one-loop corrections to decay widths of Higgs particles in the 2HDM. Since the higher-order (HO) corrections of these decay widths are in general ultraviolet (UV)-divergent, a proper regularization and renormalization of the UV divergences is required. In the following, we briefly present the definition of the counterterms (CTs) needed for the calculation of the EW one-loop corrections. For a thorough derivation and presentation of the gauge-independent renormalization of the 2HDM, we refer the reader to [57,58,63].[3]

All input parameters that are renormalized for the calculation of the EW corrections (apart from the mixing angles α and β and the soft-$\mathbb{Z}_2$-breaking scale m_{12}) are renormalized in the on-shell (OS) scheme. For the physical fields, we employ the conditions that any mixing of fields with the same quantum numbers shall vanish on the mass shell of the respective particles and that the fields are normalized by fixing the residue of their corresponding propagators at their poles to unity. Mass CTs are fixed through the condition that the masses are defined as the real parts of the poles of the renormalized propagators. These OS conditions suffice to renormalize most of the parameters of the 2HDM necessary for our work. The renormalization of the mixing angles α and β follows an OS-motivated approach, as discussed in Sec. 2.2.4, while m_{12} is renormalized via an $\overline{\text{MS}}$ condition as discussed in Sec. 2.2.6.

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[2]HDECAY internally translates the parameters from the interaction to the mass basis, in terms of which the decay widths are implemented.

[3]See also Refs. [59–61] for a discussion of the renormalization of the 2HDM. For recent works discussing gauge-independent renormalization within multi-Higgs models, see [62,75].

2.2.1 Tadpole Renormalization

As shown for the 2HDM for the first time in [57,58], the proper treatment of the tadpole terms at one-loop order is crucial for the gauge-independent definition of the CTs of the mixing angles α and β. This allows for the calculation of one-loop partial decay widths with a manifestly gauge-independent relation between input variables and the physical observable. In the following, we briefly repeat the different renormalization conditions for the tadpoles that can be employed in the 2HDM.

The *standard tadpole scheme* is a commonly used renormalization scheme for the tadpoles (*cf. e.g.* [71] for the SM or [66,76] for the 2HDM). While the tadpole parameters vanish at tree level, as stated in Eq. (2.19), they are in general non-vanishing at higher orders in perturbation theory. Since the tadpole terms, being the terms linear in the Higgs potential, define the minimum of the potential, it is necessary to employ a renormalization of the tadpoles in such a way that the ground state of the potential still represents the minimum at higher orders. In the standard tadpole scheme, this condition is imposed on the loop-corrected potential. By replacing the tree-level tadpole terms at one-loop order with the physical (*i.e.* renormalized) tadpole terms and the tadpole CTs δT_i,

$$T_i \;\rightarrow\; T_i + \delta T_i \quad (i = 1, 2) \; , \tag{2.46}$$

the correct minimum of the loop-corrected potential is obtained by demanding the renormalized tadpole terms T_i to vanish. This directly connects the tadpole CTs δT_i with the corresponding one-loop tadpole diagrams,

$$i\delta T_{H/h} = \begin{pmatrix} \vcenter{\hbox{\includegraphics{tadpole}}} \\ H/h \end{pmatrix} , \tag{2.47}$$

where we switched the tadpole terms from the interaction basis to the mass basis by means of the rotation matrix $R(\alpha)$, as indicated in Eq. (2.24). Since the tadpole terms explicitly appear in the mass matrices in Eqs. (2.20)-(2.22), their CTs explicitly appear in the mass matrices at one-loop order. The rotation from the interaction to the mass basis yields nine tadpole CTs in total which depend on the two tadpole CTs $\delta T_{H/h}$ defined by the one-loop tadpole diagrams in Eq. (2.47):

Tadpole renormalization (standard scheme)

$$\delta T_{HH} = \frac{c_\alpha^3 s_\beta + s_\alpha^3 c_\beta}{v s_\beta c_\beta} \delta T_H - \frac{s_{2\alpha} s_{\beta-\alpha}}{v s_{2\beta}} \delta T_h \tag{2.48}$$

$$\delta T_{Hh} = -\frac{s_{2\alpha} s_{\beta-\alpha}}{v s_{2\beta}} \delta T_H + \frac{s_{2\alpha} c_{\beta-\alpha}}{v s_{2\beta}} \delta T_h \tag{2.49}$$

$$\delta T_{hh} = \frac{s_{2\alpha} c_{\beta-\alpha}}{v s_{2\beta}} \delta T_H - \frac{s_\alpha^3 s_\beta - c_\alpha^3 c_\beta}{v s_\beta c_\beta} \delta T_h \tag{2.50}$$

$$\delta T_{G^0 G^0} = \frac{c_{\beta-\alpha}}{v} \delta T_H + \frac{s_{\beta-\alpha}}{v} \delta T_h \tag{2.51}$$

$$\delta T_{G^0 A} = -\frac{s_{\beta-\alpha}}{v} \delta T_H + \frac{c_{\beta-\alpha}}{v} \delta T_h \tag{2.52}$$

$$\delta T_{AA} = \frac{c_\alpha s_\beta^3 + s_\alpha c_\beta^3}{v s_\beta c_\beta} \delta T_H - \frac{s_\alpha s_\beta^3 - c_\alpha c_\beta^3}{v s_\beta c_\beta} \delta T_h \tag{2.53}$$

$$\delta T_{G^\pm G^\pm} = \frac{c_{\beta-\alpha}}{v} \delta T_H + \frac{s_{\beta-\alpha}}{v} \delta T_h \tag{2.54}$$

$$\delta T_{G^\pm H^\pm} = -\frac{s_{\beta-\alpha}}{v} \delta T_H + \frac{c_{\beta-\alpha}}{v} \delta T_h \tag{2.55}$$

$$\delta T_{H^\pm H^\pm} = \frac{c_\alpha s_\beta^3 + s_\alpha c_\beta^3}{v s_\beta c_\beta} \delta T_H - \frac{s_\alpha s_\beta^3 - c_\alpha c_\beta^3}{v s_\beta c_\beta} \delta T_h \tag{2.56}$$

Since the minimum of the potential is defined through the loop-corrected scalar potential, which in general is a gauge-dependent quantity, the CTs defined through this minimum (*e.g.* the CTs of the scalar or gauge boson masses) become manifestly gauge-dependent themselves. This is no problem as long as all gauge dependences arising in a fixed-order calculation cancel against each other. In the 2HDM, however, an improper renormalization condition for the mixing angle CTs within the standard tadpole scheme can lead to uncanceled gauge dependences in the calculation of partial decay widths. This is discussed in more detail in Sec. 2.2.4. Apart from the appearance of the tadpole diagrams in Eqs. (2.48)-(2.56), and subsequently in the CTs and the wave function renormalization constants (WFRCs) defined through these, the renormalization condition in Eq. (2.47) ensures that all other appearances of tadpoles are canceled in the one-loop calculation, *i.e.* tadpole diagrams in the self-energies or vertex corrections do not have to be taken into account.

An alternative treatment of the tadpole renormalization was proposed by J. Fleischer and F. Jegerlehner in the SM [77]. It was applied to the extended scalar sector of the 2HDM for the first time in [57, 58] and is called *alternative (FJ) tadpole scheme* in the following. In this alternative approach, the VEVs $v_{1,2}$ are considered as the fundamental quantities instead of the tadpole terms. The *proper* VEVs are the renormalized all-order VEVs of the Higgs fields which represent the true ground state of the theory and which are connected to the particle masses and the couplings of the electroweak sector. Since the alternative approach relies on the minimization of the gauge-independent tree-level scalar potential, the mass CTs defined in this framework become manifestly gauge-independent quantities by themselves. Moreover, the alternative tadpole scheme connects the all-order renormalized VEVs directly to the corresponding tree-level VEVs. Since the tadpoles are not the fundamental quantities of the Higgs minimum in this framework, they do not receive CTs. Instead, CTs for the VEVs are introduced by replacing
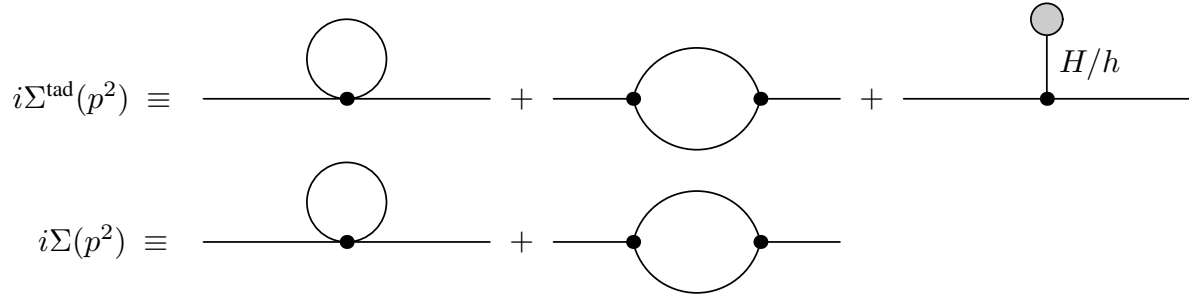
Figure 1: Generic definition of the self-energies Σ and Σ^{tad} as function of the external momentum p^2 used in our CT definitions of the 2HDM. While Σ is the textbook definition of the one-particle irreducible self-energy, the self-energy Σ^{tad} additionally contains tadpole diagrams, indicated by the gray blob. For the actual calculation, the full particle content of the 2HDM has to be inserted into the self-energy topologies depicted here.

the VEVs with the renormalized VEVs and their CTs,

$$v_i \ \rightarrow \ v_i + \delta v_i \tag{2.57}$$

and by fixing the latter in such a way that it is ensured that the renormalized VEVs represent the proper tree-level minima to all orders. At one-loop level, this leads to the following connection between the VEV CTs in the interaction basis and the one-loop tadpole diagrams in the mass basis,

$$\delta v_1 = \frac{-i c_\alpha}{m_H^2} \left(\begin{array}{c} \bullet \\ \vdots \\ H \end{array} \right) - \frac{-i s_\alpha}{m_h^2} \left(\begin{array}{c} \bullet \\ \vdots \\ h \end{array} \right) , \quad \delta v_2 = \frac{-i s_\alpha}{m_H^2} \left(\begin{array}{c} \bullet \\ \vdots \\ H \end{array} \right) + \frac{-i c_\alpha}{m_h^2} \left(\begin{array}{c} \bullet \\ \vdots \\ h \end{array} \right) . \tag{2.58}$$

The renormalization of the VEVs in the alternative tadpole scheme effectively shifts the VEVs by tadpole contributions. As a consequence, tadpole diagrams have to be considered wherever they can appear in the 2HDM. For the self-energies, this means that the fundamental self-energies used to define the CTs are the ones defined as Σ^{tad} in Fig. 1 instead of the usual one-particle irreducible self-energies Σ. Additionally, tadpole diagrams have to be considered in the calculation of the one-loop vertex corrections to the Higgs decays. In summary, the renormalization of the tadpoles in the alternative scheme leads to the following conditions:

Tadpole renormalization (alternative FJ scheme)

$$\delta T_{ij} = 0 \tag{2.59}$$

$$\Sigma(p^2) \ \rightarrow \ \Sigma^{\text{tad}}(p^2) \tag{2.60}$$

Tadpole diagrams have to be considered in the vertex corrections.

2.2.2 Renormalization of the Gauge Sector

For the renormalization of the gauge sector, we introduce CTs and WFRCs for all parameters and fields of the electroweak sector of the 2HDM by applying the shifts

$$m_W^2 \;\rightarrow\; m_W^2 + \delta m_W^2 \tag{2.61}$$

$$m_Z^2 \;\rightarrow\; m_Z^2 + \delta m_Z^2 \tag{2.62}$$

$$\alpha_{\rm em} \;\rightarrow\; \alpha_{\rm em} + \delta\alpha_{\rm em} \equiv \alpha_{\rm em} + 2\alpha_{\rm em}\delta Z_e \tag{2.63}$$

$$W_\mu^\pm \;\rightarrow\; \left(1 + \frac{\delta Z_{WW}}{2}\right) W_\mu^\pm \tag{2.64}$$

$$\begin{pmatrix} Z \\ \gamma \end{pmatrix} \;\rightarrow\; \begin{pmatrix} 1 + \frac{\delta Z_{ZZ}}{2} & \frac{\delta Z_{Z\gamma}}{2} \\ \frac{\delta Z_{\gamma Z}}{2} & 1 + \frac{\delta Z_{\gamma\gamma}}{2} \end{pmatrix} \begin{pmatrix} Z \\ \gamma \end{pmatrix} , \tag{2.65}$$

where for convenience, we additionally introduced the shift

$$e \;\rightarrow\; e(1 + \delta Z_e) \tag{2.66}$$

for the electromagnetic coupling constant by using Eq. (2.13). Applying OS conditions to the gauge sector of the 2HDM leads to equivalent expressions for the CTs as derived in Ref. [71] for the SM[4], for the standard and alternative tadpole scheme, respectively,

---

Renormalization of the gauge sector (standard scheme)

$$\delta m_W^2 = {\rm Re}\left[\Sigma_{WW}^T\left(m_W^2\right)\right] \tag{2.67}$$

$$\delta m_Z^2 = {\rm Re}\left[\Sigma_{ZZ}^T\left(m_Z^2\right)\right] \tag{2.68}$$

Renormalization of the gauge sector (alternative FJ scheme)

$$\delta m_W^2 = {\rm Re}\left[\Sigma_{WW}^{{\rm tad},T}\left(m_W^2\right)\right] \tag{2.69}$$

$$\delta m_Z^2 = {\rm Re}\left[\Sigma_{ZZ}^{{\rm tad},T}\left(m_Z^2\right)\right] \tag{2.70}$$

The WFRCs are the same in both tadpole schemes,

---

[4]In contrast to Ref. [71], however, we choose a different sign for the $SU(2)_L$ term of the covariant derivative, which subsequently leads to a different sign in front of the second term of Eq. (2.71).

> **Renormalization of the gauge sector (standard and alternative FJ scheme)**
>
> $$\delta Z_e(m_Z^2) = \frac{1}{2} \left. \frac{\partial \Sigma_{\gamma\gamma}^T(p^2)}{\partial p^2} \right|_{p^2=0} + \frac{s_W}{c_W} \frac{\Sigma_{\gamma Z}^T(0)}{m_Z^2} - \frac{1}{2}\Delta\alpha(m_Z^2) \qquad (2.71)$$
>
> $$\delta Z_{WW} = -\text{Re}\left[\frac{\partial \Sigma_{WW}^T(p^2)}{\partial p^2} \right]_{p^2=m_W^2} \qquad (2.72)$$
>
> $$\begin{pmatrix} \delta Z_{ZZ} & \delta Z_{Z\gamma} \\ \delta Z_{\gamma Z} & \delta Z_{\gamma\gamma} \end{pmatrix} = \begin{pmatrix} -\text{Re}\left[\frac{\partial \Sigma_{ZZ}^T(p^2)}{\partial p^2}\right]_{p^2=m_Z^2} & \frac{2}{m_Z^2}\Sigma_{Z\gamma}^T(0) \\ -\frac{2}{m_Z^2}\text{Re}\left[\Sigma_{Z\gamma}^T(m_Z^2)\right] & -\text{Re}\left[\frac{\partial \Sigma_{\gamma\gamma}^T(p^2)}{\partial p^2}\right]_{p^2=0} \end{pmatrix} \qquad (2.73)$$

The superscript T indicates that only the transverse parts of the self-energies are taken into account. The CT for the electromagnetic coupling $\delta Z_e(m_Z^2)$ is defined at the scale of the Z boson mass instead of the Thomson limit. For this, the additional term

$$\Delta\alpha(m_Z^2) = \left. \frac{\partial \Sigma_{\gamma\gamma}^{\text{light},T}(p^2)}{\partial p^2} \right|_{p^2=0} - \frac{\Sigma_{\gamma\gamma}^T(m_Z^2)}{m_Z^2} \qquad (2.74)$$

is required, where the transverse photon self-energy $\Sigma_{\gamma\gamma}^{\text{light},T}(p^2)$ in Eq. (2.74) contains solely light fermion contributions (*i.e.* contributions from all fermions apart from the t quark). This ensures that the results of our EW one-loop computations are independent of large logarithms due to light fermion contributions [71].

For later convenience, we additionally introduce the shift of the weak coupling constant

$$g \ \rightarrow \ g + \delta g \ . \qquad (2.75)$$

Since g is not an independent parameter in our approach, *cf.* Eq. (2.13), the CT δg is not independent either and can be expressed through the other CTs derived in this subsection as

$$\frac{\delta g}{g} = \delta Z_e(m_Z^2) + \frac{1}{2(m_Z^2 - m_W^2)}\left(\delta m_W^2 - \frac{m_W^2}{m_Z^2}\delta m_Z^2 \right) \ . \qquad (2.76)$$

2.2.3 Renormalization of the Scalar Sector

In the scalar sector of the 2HDM, the masses and fields of the scalar particles are shifted as

$$m_H^2 \ \rightarrow \ m_H^2 + \delta m_H^2 \tag{2.77}$$

$$m_h^2 \ \rightarrow \ m_h^2 + \delta m_h^2 \tag{2.78}$$

$$m_A^2 \ \rightarrow \ m_A^2 + \delta m_A^2 \tag{2.79}$$

$$m_{H^\pm}^2 \ \rightarrow \ m_{H^\pm}^2 + \delta m_{H^\pm}^2 \tag{2.80}$$

$$\begin{pmatrix} H \\ h \end{pmatrix} \ \rightarrow \ \begin{pmatrix} 1 + \frac{\delta Z_{HH}}{2} & \frac{\delta Z_{Hh}}{2} \\ \frac{\delta Z_{hH}}{2} & 1 + \frac{\delta Z_{hh}}{2} \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix} \tag{2.81}$$

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} \ \rightarrow \ \begin{pmatrix} 1 + \frac{\delta Z_{G^0 G^0}}{2} & \frac{\delta Z_{G^0 A}}{2} \\ \frac{\delta Z_{A G^0}}{2} & 1 + \frac{\delta Z_{AA}}{2} \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix} \tag{2.82}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} \ \rightarrow \ \begin{pmatrix} 1 + \frac{\delta Z_{G^\pm G^\pm}}{2} & \frac{\delta Z_{G^\pm H^\pm}}{2} \\ \frac{\delta Z_{H^\pm G^\pm}}{2} & 1 + \frac{\delta Z_{H^\pm H^\pm}}{2} \end{pmatrix} \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} \ . \tag{2.83}$$

Applying OS renormalization conditions leads to the following CT definitions [57],

---

Renormalization of the scalar sector (standard scheme)

$$\delta Z_{Hh} = \frac{2}{m_H^2 - m_h^2} \mathrm{Re}\Big[\Sigma_{Hh}(m_h^2) - \delta T_{Hh}\Big] \tag{2.84}$$

$$\delta Z_{hH} = -\frac{2}{m_H^2 - m_h^2} \mathrm{Re}\Big[\Sigma_{Hh}(m_H^2) - \delta T_{Hh}\Big] \tag{2.85}$$

$$\delta Z_{G^0 A} = -\frac{2}{m_A^2} \mathrm{Re}\Big[\Sigma_{G^0 A}(m_A^2) - \delta T_{G^0 A}\Big] \tag{2.86}$$

$$\delta Z_{A G^0} = \frac{2}{m_A^2} \mathrm{Re}\Big[\Sigma_{G^0 A}(0) - \delta T_{G^0 A}\Big] \tag{2.87}$$

$$\delta Z_{G^\pm H^\pm} = -\frac{2}{m_{H^\pm}^2} \mathrm{Re}\Big[\Sigma_{G^\pm H^\pm}(m_{H^\pm}^2) - \delta T_{G^\pm H^\pm}\Big] \tag{2.88}$$

$$\delta Z_{H^\pm G^\pm} = \frac{2}{m_{H^\pm}^2} \mathrm{Re}\Big[\Sigma_{G^\pm H^\pm}(0) - \delta T_{G^\pm H^\pm}\Big] \tag{2.89}$$

$$\delta m_H^2 = \mathrm{Re}\Big[\Sigma_{HH}(m_H^2) - \delta T_{HH}\Big] \tag{2.90}$$

$$\delta m_h^2 = \mathrm{Re}\Big[\Sigma_{hh}(m_h^2) - \delta T_{hh}\Big] \tag{2.91}$$

$$\delta m_A^2 = \mathrm{Re}\Big[\Sigma_{AA}(m_A^2) - \delta T_{AA}\Big] \tag{2.92}$$

$$\delta m_{H^\pm}^2 = \mathrm{Re}\Big[\Sigma_{H^\pm H^\pm}(m_{H^\pm}^2) - \delta T_{H^\pm H^\pm}\Big] \tag{2.93}$$

Renormalization of the scalar sector (alternative FJ scheme)

$$\delta Z_{Hh} = \frac{2}{m_H^2 - m_h^2} \text{Re}\Big[\Sigma_{Hh}^{\text{tad}}(m_h^2)\Big] \tag{2.94}$$

$$\delta Z_{hH} = -\frac{2}{m_H^2 - m_h^2} \text{Re}\Big[\Sigma_{Hh}^{\text{tad}}(m_H^2)\Big] \tag{2.95}$$

$$\delta Z_{G^0 A} = -\frac{2}{m_A^2} \text{Re}\Big[\Sigma_{G^0 A}^{\text{tad}}(m_A^2)\Big] \tag{2.96}$$

$$\delta Z_{AG^0} = \frac{2}{m_A^2} \text{Re}\Big[\Sigma_{G^0 A}^{\text{tad}}(0)\Big] \tag{2.97}$$

$$\delta Z_{G^\pm H^\pm} = -\frac{2}{m_{H^\pm}^2} \text{Re}\Big[\Sigma_{G^\pm H^\pm}^{\text{tad}}(m_{H^\pm}^2)\Big] \tag{2.98}$$

$$\delta Z_{H^\pm G^\pm} = \frac{2}{m_{H^\pm}^2} \text{Re}\Big[\Sigma_{G^\pm H^\pm}^{\text{tad}}(0)\Big] \tag{2.99}$$

$$\delta m_H^2 = \text{Re}\Big[\Sigma_{HH}^{\text{tad}}(m_H^2)\Big] \tag{2.100}$$

$$\delta m_h^2 = \text{Re}\Big[\Sigma_{hh}^{\text{tad}}(m_h^2)\Big] \tag{2.101}$$

$$\delta m_A^2 = \text{Re}\Big[\Sigma_{AA}^{\text{tad}}(m_A^2)\Big] \tag{2.102}$$

$$\delta m_{H^\pm}^2 = \text{Re}\Big[\Sigma_{H^\pm H^\pm}^{\text{tad}}(m_{H^\pm}^2)\Big] \tag{2.103}$$

Renormalization of the scalar sector (standard and alternative FJ scheme)

$$\delta Z_{HH} = -\text{Re}\left[\frac{\partial \Sigma_{HH}\left(p^2\right)}{\partial p^2}\right]_{p^2 = m_H^2} \tag{2.104}$$

$$\delta Z_{hh} = -\text{Re}\left[\frac{\partial \Sigma_{hh}\left(p^2\right)}{\partial p^2}\right]_{p^2 = m_h^2} \tag{2.105}$$

$$\delta Z_{G^0 G^0} = -\text{Re}\left[\frac{\partial \Sigma_{G^0 G^0}\left(p^2\right)}{\partial p^2}\right]_{p^2 = 0} \tag{2.106}$$

$$\delta Z_{AA} = -\text{Re}\left[\frac{\partial \Sigma_{AA}\left(p^2\right)}{\partial p^2}\right]_{p^2 = m_A^2} \tag{2.107}$$

$$\delta Z_{G^\pm G^\pm} = -\text{Re}\left[\frac{\partial \Sigma_{G^\pm G^\pm}\left(p^2\right)}{\partial p^2}\right]_{p^2 = 0} \tag{2.108}$$

$$\delta Z_{H^\pm H^\pm} = -\text{Re}\left[\frac{\partial \Sigma_{H^\pm H^\pm}\left(p^2\right)}{\partial p^2}\right]_{p^2 = m_{H^\pm}^2} \tag{2.109}$$

with the tadpole CTs in the standard scheme defined in Eqs. (2.48)-(2.56).

2.2.4 Renormalization of the Scalar Mixing Angles

In the following, we describe the renormalization of the scalar mixing angles α and β in the 2HDM. In our approach, we perform the rotation from the interaction to the mass basis, *cf.* Eqs. (2.24)-(2.26), before renormalization so that the mixing angles need to be renormalized. At one-loop level, the bare mixing angles are replaced by their renormalized values and counterterms as

$$\alpha \;\to\; \alpha + \delta\alpha \tag{2.110}$$

$$\beta \;\to\; \beta + \delta\beta \;. \tag{2.111}$$

The renormalization of the mixing angles in the 2HDM is a non-trivial task and several different schemes have been proposed in the literature. In the following, we only briefly present the definition of the mixing angle CTs in all different schemes that are implemented in `2HDECAY` and refer to [57,58] for details on the derivation of these schemes. It was shown in [57,78] that an $\overline{\text{MS}}$ condition for $\delta\alpha$ and $\delta\beta$ can lead to one-loop corrections that are orders of magnitude larger than the LO result[5]. We therefore do not implement $\overline{\text{MS}}$ conditions for the mixing angle CTs in `2HDECAY`.

KOSY scheme. The KOSY scheme (denoted by the authors' initials) was suggested in [66]. It combines the standard tadpole scheme with the definition of the counterterms through off-diagonal wave function renormalization constants. As shown in [57,58], the KOSY scheme not only implies a gauge-dependent definition of the mixing angle CTs but also leads to explicitly gauge-dependent decay amplitudes. The CTs are derived by temporarily switching from the mass to the gauge basis. Since β diagonalizes both the charged and CP-odd sector not all scalar fields can be defined OS at the same time, unless a systematic modification of the $SU(2)$ relations is performed which we do not do here. We implemented two different CT definitions where $\delta\beta$ is defined through the CP-odd or the charged sectors, indicated by superscripts o and c, respectively. The KOSY scheme is implemented in `2HDECAY` both in the standard and in the alternative FJ scheme as a benchmark scheme for comparison with other schemes, but for actual computations, we do not recommend to use it due to the explicit gauge dependence of the decay amplitudes. In the KOSY scheme, the mixing angle CTs are defined as

---

Renormalization of $\delta\alpha$ and $\delta\beta$: KOSY scheme (standard scheme)

$$\delta\alpha = \frac{1}{2(m_H^2 - m_h^2)} \text{Re} \left[\Sigma_{Hh}(m_H^2) + \Sigma_{Hh}(m_h^2) - 2\delta T_{Hh} \right] \tag{2.112}$$

$$\delta\beta^o = -\frac{1}{2m_A^2} \text{Re} \left[\Sigma_{G^0 A}(m_A^2) + \Sigma_{G^0 A}(0) - 2\delta T_{G^0 A} \right] \tag{2.113}$$

$$\delta\beta^c = -\frac{1}{2m_{H^\pm}^2} \text{Re} \left[\Sigma_{G^\pm H^\pm}(m_{H^\pm}^2) + \Sigma_{G^\pm H^\pm}(0) - 2\delta T_{G^\pm H^\pm} \right] \tag{2.114}$$

---

[5]In [59], an $\overline{\text{MS}}$ condition for the scalar mixing angles in certain processes led to corrections that are numerically well-behaving due to a partial cancellation of large contributions from tadpoles. In the decays considered in our work, an $\overline{\text{MS}}$ condition of $\delta\alpha$ and $\delta\beta$ in general leads to very large corrections, however.

Renormalization of $\delta\alpha$ and $\delta\beta$: KOSY scheme (alternative FJ scheme)

$$\delta\alpha = \frac{1}{2(m_H^2 - m_h^2)}\text{Re}\left[\Sigma_{Hh}^{\text{tad}}(m_H^2) + \Sigma_{Hh}^{\text{tad}}(m_h^2)\right] \qquad (2.115)$$

$$\delta\beta^o = -\frac{1}{2m_A^2}\text{Re}\left[\Sigma_{G^0 A}^{\text{tad}}(m_A^2) + \Sigma_{G^0 A}^{\text{tad}}(0)\right] \qquad (2.116)$$

$$\delta\beta^c = -\frac{1}{2m_{H^\pm}^2}\text{Re}\left[\Sigma_{G^\pm H^\pm}^{\text{tad}}(m_{H^\pm}^2) + \Sigma_{G^\pm H^\pm}^{\text{tad}}(0)\right] \qquad (2.117)$$

p_*-**pinched scheme.** One possibility to avoid gauge-dependent mixing angle CTs was suggested in [57, 58]. The main idea is to maintain the OS-based definition of $\delta\alpha$ and $\delta\beta$ of the KOSY scheme, but instead of using the usual gauge-dependent off-diagonal WFRCs, the WFRCs are defined through pinched self-energies in the alternative FJ scheme by applying the pinch technique (PT) [79–86]. As worked out for the 2HDM for the first time in [57, 58], the pinched scalar self-energies are equivalent to the usual scalar self-energies in the alternative FJ scheme, evaluated in Feynman-'t Hooft gauge ($\xi = 1$), up to additional UV-finite self-energy contributions $\Sigma_{ij}^{\text{add}}(p^2)$. The mixing angle CTs depend on the scale where the pinched self-energies are evaluated. In the p_*-pinched scheme, we follow the approach of [87] in the MSSM, where the self-energies $\Sigma_{ij}^{\text{tad}}(p^2)$ are evaluated at the scale

$$p_*^2 \equiv \frac{m_i^2 + m_j^2}{2} \ . \qquad (2.118)$$

At this scale, the additional contributions $\Sigma_{ij}^{\text{add}}(p^2)$ vanish. Using the p_*-pinched scheme at one-loop level yields explicitly gauge-independent partial decay widths. The mixing angle CTs are defined as

Renormalization of $\delta\alpha$ and $\delta\beta$: p_*-pinched scheme (alternative FJ scheme)

$$\delta\alpha = \frac{1}{m_H^2 - m_h^2}\text{Re}\left[\Sigma_{Hh}^{\text{tad}}\left(\frac{m_H^2 + m_h^2}{2}\right)\right]_{\xi=1} \qquad (2.119)$$

$$\delta\beta^o = -\frac{1}{m_A^2}\text{Re}\left[\Sigma_{G^0 A}^{\text{tad}}\left(\frac{m_A^2}{2}\right)\right]_{\xi=1} \qquad (2.120)$$

$$\delta\beta^c = -\frac{1}{m_{H^\pm}^2}\text{Re}\left[\Sigma_{G^\pm H^\pm}^{\text{tad}}\left(\frac{m_{H^\pm}^2}{2}\right)\right]_{\xi=1} \qquad (2.121)$$

OS-pinched scheme. In order to allow for the analysis of the effects of different scale choices of the mixing angle CTs, we implemented another OS-motivated scale choice, which is

called the OS-pinched scheme. Here, the additional terms do not vanish and are given by [57]

$$\Sigma_{Hh}^{\mathrm{add}}(p^2) = \frac{\alpha_{\mathrm{em}} m_Z^2 \mathrm{s}_{\beta-\alpha} \mathrm{c}_{\beta-\alpha}}{8\pi m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right)} \left(p^2 - \frac{m_H^2 + m_h^2}{2}\right) \left\{ \left[B_0(p^2; m_Z^2, m_A^2) - B_0(p^2; m_Z^2, m_Z^2)\right] \right.$$

$$\left. + 2\frac{m_W^2}{m_Z^2} \left[B_0(p^2; m_W^2, m_{H^\pm}^2) - B_0(p^2; m_W^2, m_W^2)\right] \right\} \tag{2.122}$$

$$\Sigma_{G^0 A}^{\mathrm{add}}(p^2) = \frac{\alpha_{\mathrm{em}} m_Z^2 \mathrm{s}_{\beta-\alpha} \mathrm{c}_{\beta-\alpha}}{8\pi m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right)} \left(p^2 - \frac{m_A^2}{2}\right) \left[B_0(p^2; m_Z^2, m_H^2) - B_0(p^2; m_Z^2, m_h^2)\right] \tag{2.123}$$

$$\Sigma_{G^\pm H^\pm}^{\mathrm{add}}(p^2) = \frac{\alpha_{\mathrm{em}} \mathrm{s}_{\beta-\alpha} \mathrm{c}_{\beta-\alpha}}{4\pi \left(1 - \frac{m_W^2}{m_Z^2}\right)} \left(p^2 - \frac{m_{H^\pm}^2}{2}\right) \left[B_0(p^2; m_W^2, m_H^2) - B_0(p^2; m_W^2, m_h^2)\right] \ . \tag{2.124}$$

The mixing angle CTs in the OS-pinched scheme are then defined as

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Renormalization of $\delta\alpha$ and $\delta\beta$: OS-pinched scheme (alternative FJ scheme)

$$\delta\alpha = \frac{\mathrm{Re}\left[\left[\Sigma_{Hh}^{\mathrm{tad}}(m_H^2) + \Sigma_{Hh}^{\mathrm{tad}}(m_h^2)\right]_{\xi=1} + \Sigma_{Hh}^{\mathrm{add}}(m_H^2) + \Sigma_{Hh}^{\mathrm{add}}(m_h^2)\right]}{2\left(m_H^2 - m_h^2\right)} \tag{2.125}$$

$$\delta\beta^o = -\frac{\mathrm{Re}\left[\left[\Sigma_{G^0 A}^{\mathrm{tad}}(m_A^2) + \Sigma_{G^0 A}^{\mathrm{tad}}(0)\right]_{\xi=1} + \Sigma_{G^0 A}^{\mathrm{add}}(m_A^2) + \Sigma_{G^0 A}^{\mathrm{add}}(0)\right]}{2 m_A^2} \tag{2.126}$$

$$\delta\beta^c = -\frac{\mathrm{Re}\left[\left[\Sigma_{G^\pm H^\pm}^{\mathrm{tad}}(m_{H^\pm}^2) + \Sigma_{G^\pm H^\pm}^{\mathrm{tad}}(0)\right]_{\xi=1} + \Sigma_{G^\pm H^\pm}^{\mathrm{add}}(m_{H^\pm}^2) + \Sigma_{G^\pm H^\pm}^{\mathrm{add}}(0)\right]}{2 m_{H^\pm}^2} \tag{2.127}$$

Process-dependent schemes. The definition of the mixing angle CTs through observables, like *e.g.* partial decay widths of Higgs bosons, was proposed for the MSSM in [88, 89] and for the 2HDM in [90]. This scheme leads to explicitly gauge-independent partial decay widths per construction. Moreover, the connection of the mixing angle CTs with physical observables allows for a more physical interpretation of the unphysical mixing angles α and β. However, as it was shown in [57, 58], process-dependent schemes can in general lead to very large one-loop corrections. We implemented three different process-dependent schemes for $\delta\alpha$ and $\delta\beta$ in 2HDECAY. The schemes differ in the processes that are used for the definition of the CTs. In all cases we have chosen leptonic Higgs boson decays. For these, the QED corrections can be separated in a UV-finite way from the rest of the EW corrections and therefore be excluded from the counterterm definition. This is necessary to avoid the appearance of infrared (IR) divergences in the CTs [89]. The NLO corrections to the partial decay widths of the leptonic decay of a Higgs particle ϕ_i into a pair of leptons f_j, f_k can then be cast into the form

$$\Gamma_{\phi_i f_j f_k}^{\mathrm{NLO,weak}} = \Gamma_{\phi_i f_j f_k}^{\mathrm{LO}} \left(1 + 2\mathrm{Re}\left[\mathcal{F}_{\phi_i f_j f_k}^{\mathrm{VC}} + \mathcal{F}_{\phi_i f_j f_k}^{\mathrm{CT}}\right]\right) \ , \tag{2.128}$$

where $\mathcal{F}_{\phi_i f_j f_k}^{\mathrm{VC}}$ and $\mathcal{F}_{\phi_i f_j f_k}^{\mathrm{CT}}$ are the form factors of the vertex corrections and the CT, respectively, and the superscript weak indicates that in the vertex corrections IR-divergent QED contributions are excluded. The form factor $\mathcal{F}_{\phi_i f_j f_k}^{\mathrm{CT}}$ contains either $\delta\alpha$ or $\delta\beta$ or both simultaneously as well

as other CTs that are fixed as described in the other subsections of Sec. 2.2. Employing the renormalization condition

$$\Gamma^{\text{LO}}_{\phi_i f_j f_k} \equiv \Gamma^{\text{NLO,weak}}_{\phi_i f_j f_k} \tag{2.129}$$

for two different decays then allows for a process-dependent definition of the mixing angle CTs. For more details on the calculation of the CTs in process-dependent schemes in the 2HDM, we refer to [57, 58]. In 2HDECAY, we have chosen the following three different combinations of processes as definition for the CTs,

1. $\delta\beta$ is first defined by $A \to \tau^+\tau^-$ and $\delta\alpha$ is subsequently defined by $H \to \tau^+\tau^-$.

2. $\delta\beta$ is first defined by $A \to \tau^+\tau^-$ and $\delta\alpha$ is subsequently defined by $h \to \tau^+\tau^-$.

3. $\delta\beta$ and $\delta\alpha$ are simultaneously defined by $H \to \tau^+\tau^-$ and $h \to \tau^+\tau^-$.

Employing these renormalization conditions yields the following definitions of the mixing angle CTs[6]:

Renormalization of $\delta\alpha$ and $\delta\beta$: process-dependent scheme 1 (both schemes)

$$\delta\alpha = \frac{-Y_5}{Y_4}\left[\mathcal{F}^{\text{VC}}_{H\tau\tau} + \frac{\delta g}{g} + \frac{\delta m_\tau}{m_\tau} - \frac{\delta m_W^2}{2m_W^2} + Y_6\delta\beta + \frac{\delta Z_{HH}}{2} + \frac{Y_4}{Y_5}\frac{\delta Z_{hH}}{2} + \frac{\delta Z_{\tau\tau}^{\text{L}}}{2}\right. \tag{2.130}$$
$$\left. + \frac{\delta Z_{\tau\tau}^{\text{R}}}{2}\right]$$

$$\delta\beta = \frac{-Y_6}{1+Y_6^2}\left[\mathcal{F}^{\text{VC}}_{A\tau\tau} + \frac{\delta g}{g} + \frac{\delta m_\tau}{m_\tau} - \frac{\delta m_W^2}{2m_W^2} + \frac{\delta Z_{AA}}{2} - \frac{1}{Y_6}\frac{\delta Z_{G^0 A}}{2} + \frac{\delta Z_{\tau\tau}^{\text{L}}}{2} + \frac{\delta Z_{\tau\tau}^{\text{R}}}{2}\right] \tag{2.131}$$

Renormalization of $\delta\alpha$ and $\delta\beta$: process-dependent scheme 2 (both schemes)

$$\delta\alpha = \frac{Y_4}{Y_5}\left[\mathcal{F}^{\text{VC}}_{h\tau\tau} + \frac{\delta g}{g} + \frac{\delta m_\tau}{m_\tau} - \frac{\delta m_W^2}{2m_W^2} + Y_6\delta\beta + \frac{\delta Z_{hh}}{2} + \frac{Y_5}{Y_4}\frac{\delta Z_{Hh}}{2} + \frac{\delta Z_{\tau\tau}^{\text{L}}}{2}\right. \tag{2.132}$$
$$\left. + \frac{\delta Z_{\tau\tau}^{\text{R}}}{2}\right]$$

$$\delta\beta = \frac{-Y_6}{1+Y_6^2}\left[\mathcal{F}^{\text{VC}}_{A\tau\tau} + \frac{\delta g}{g} + \frac{\delta m_\tau}{m_\tau} - \frac{\delta m_W^2}{2m_W^2} + \frac{\delta Z_{AA}}{2} - \frac{1}{Y_6}\frac{\delta Z_{G^0 A}}{2} + \frac{\delta Z_{\tau\tau}^{\text{L}}}{2} + \frac{\delta Z_{\tau\tau}^{\text{R}}}{2}\right] \tag{2.133}$$

Renormalization of $\delta\alpha$ and $\delta\beta$: process-dependent scheme 3 (both schemes)

$$\delta\alpha = \frac{Y_4 Y_5}{Y_4^2 + Y_5^2}\left[\mathcal{F}^{\text{VC}}_{h\tau\tau} - \mathcal{F}^{\text{VC}}_{H\tau\tau} + \frac{\delta Z_{hh}}{2} - \frac{\delta Z_{HH}}{2} + \frac{Y_5}{Y_4}\frac{\delta Z_{Hh}}{2} - \frac{Y_4}{Y_5}\frac{\delta Z_{hH}}{2}\right] \tag{2.134}$$

$$\delta\beta = \frac{-1}{Y_6(Y_4^2+Y_5^2)}\left[(Y_4^2+Y_5^2)\left(\frac{\delta g}{g} + \frac{\delta m_\tau}{m_\tau} - \frac{\delta m_W^2}{2m_W^2} + \frac{\delta Z_{\tau\tau}^{\text{L}}}{2} + \frac{\delta Z_{\tau\tau}^{\text{R}}}{2}\right)\right. \tag{2.135}$$
$$\left. + Y_4 Y_5\left(\frac{\delta Z_{Hh}}{2} + \frac{\delta Z_{hH}}{2}\right) + Y_4^2\left(\frac{\delta Z_{hh}}{2} + \mathcal{F}^{\text{VC}}_{h\tau\tau}\right) + Y_5^2\left(\frac{\delta Z_{HH}}{2} + \mathcal{F}^{\text{VC}}_{H\tau\tau}\right)\right]$$

---

[6]While the definition of the CTs is generically the same for both tadpole schemes, their actual analytic forms differ in both schemes since some of the CTs used in the definition differ in the two schemes, as well.

Note that for the process-dependent schemes, decays have to be chosen that are experimentally accessible. This may not be the case for certain parameter configurations, in which case the user has to choose, if possible, the decay combination that leads to large enough decay widths to be measurable.

2.2.5 Renormalization of the Fermion Sector

The masses m_f, where f generically stands for any fermion of the 2HDM, the CKM matrix elements V_{ij} $(i, j = 1, 2, 3)$, the Yukawa coupling parameters Y_k $(k = 1, ..., 6)$ and the fields of the fermion sector are replaced by the renormalized quantities and the respective CTs and WFRCs as

$$m_f \rightarrow m_f + \delta m_f \tag{2.136}$$

$$V_{ij} \rightarrow V_{ij} + \delta V_{ij} \tag{2.137}$$

$$Y_k \rightarrow Y_k + \delta Y_k \tag{2.138}$$

$$f_i^L \rightarrow \left(\delta_{ij} + \frac{\delta Z_{ij}^{f,L}}{2}\right) f_j^L \tag{2.139}$$

$$f_i^R \rightarrow \left(\delta_{ij} + \frac{\delta Z_{ij}^{f,R}}{2}\right) f_j^R , \tag{2.140}$$

where we use Einstein's sum convention in the last two lines. The superscripts L and R denote the left- and right-chiral component of the fermion fields, respectively. The Yukawa coupling parameters Y_i are not independent input parameters, but functions of α and β, *cf.* Tab. 2. Their one-loop counterterms are therefore given in terms of $\delta\alpha$ and $\delta\beta$ defined in Sec. 2.2.4 by the following formulae which are independent of the 2HDM type,

$$\delta Y_1 = Y_1 \left(-\frac{Y_2}{Y_1}\delta\alpha + Y_3\delta\beta\right) \tag{2.141}$$

$$\delta Y_2 = Y_2 \left(\frac{Y_1}{Y_2}\delta\alpha + Y_3\delta\beta\right) \tag{2.142}$$

$$\delta Y_3 = \left(1 + Y_3^2\right)\delta\beta \tag{2.143}$$

$$\delta Y_4 = Y_4 \left(-\frac{Y_5}{Y_4}\delta\alpha + Y_6\delta\beta\right) \tag{2.144}$$

$$\delta Y_5 = Y_5 \left(\frac{Y_4}{Y_5}\delta\alpha + Y_6\delta\beta\right) \tag{2.145}$$

$$\delta Y_6 = \left(1 + Y_6^2\right)\delta\beta . \tag{2.146}$$

Before presenting the renormalization conditions of the mass CTs and WFRCs, we shortly discuss the renormalization of the CKM matrix. In [71] the renormalization of the CKM matrix is connected to the renormalization of the fields, which in turn are renormalized in an OS approach, leading to the definition $(i, j, k = 1, 2, 3)$

$$\delta V_{ij} = \frac{1}{4}\left[\left(\delta Z_{ik}^{u,L} - \delta Z_{ik}^{u,L\dagger}\right)V_{kj} - V_{ik}\left(\delta Z_{kj}^{d,L} - \delta Z_{kj}^{d,L\dagger}\right)\right] , \tag{2.147}$$

where the superscripts u and d denote up-type and down-type quarks, respectively. This definition of the CKM matrix CTs leads to uncanceled explicit gauge dependences when used in

the calculation of EW one-loop corrections, however, [91–96]. Since the CKM matrix is approximately a unit matrix [97], the numerical effect of this gauge dependence is typically very small, but the definition nevertheless introduces uncanceled explicit gauge dependences into the partial decay widths, which should be avoided. In our work, we follow the approach of Ref. [95] and use pinched fermion self-energies for the definition of the CKM matrix CT. An analytic analysis shows that this is equivalent with defining the CTs in Eq. (2.147) in the Feynman-'t Hooft gauge.

Apart from the CKM matrix CT, all other CTs of the fermion sector are defined through OS conditions. The resulting forms of the CTs are analogous to the ones presented in [71] and given by

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Renormalization of the fermion sector (standard scheme)

$$\delta m_{f,i} = \frac{m_{f,i}}{2} \text{Re} \left(\Sigma_{ii}^{f,L}(m_{f,i}^2) + \Sigma_{ii}^{f,R}(m_{f,i}^2) + 2\Sigma_{ii}^{f,S}(m_{f,i}^2) \right) \tag{2.148}$$

$$\delta Z_{ij}^{f,L} = \frac{2}{m_{f,i}^2 - m_{f,j}^2} \text{Re} \Big[m_{f,j}^2 \Sigma_{ij}^{f,L}(m_{f,j}^2) + m_{f,i} m_{f,j} \Sigma_{ij}^{f,R}(m_{f,j}^2) \tag{2.149}$$

$$+ (m_{f,i}^2 + m_{f,j}^2)\Sigma_{ij}^{f,S}(m_{f,j}^2) \Big] , \qquad (i \neq j)$$

$$\delta Z_{ij}^{f,R} = \frac{2}{m_{f,i}^2 - m_{f,j}^2} \text{Re} \Big[m_{f,j}^2 \Sigma_{ij}^{f,R}(m_{f,j}^2) + m_{f,i} m_{f,j} \Sigma_{ij}^{f,L}(m_{f,j}^2) \tag{2.150}$$

$$+ 2m_{f,i} m_{f,j} \Sigma_{ij}^{f,S}(m_{f,j}^2) \Big] , \qquad (i \neq j)$$

Renormalization of the fermion sector (alternative FJ scheme)

$$\delta m_{f,i} = \frac{m_{f,i}}{2} \text{Re} \left(\Sigma_{ii}^{f,L}(m_{f,i}^2) + \Sigma_{ii}^{f,R}(m_{f,i}^2) + 2\Sigma_{ii}^{\text{tad},f,S}(m_{f,i}^2) \right) \tag{2.151}$$

$$\delta Z_{ij}^{f,L} = \frac{2}{m_{f,i}^2 - m_{f,j}^2} \text{Re} \Big[m_{f,j}^2 \Sigma_{ij}^{f,L}(m_{f,j}^2) + m_{f,i} m_{f,j} \Sigma_{ij}^{f,R}(m_{f,j}^2) \tag{2.152}$$

$$+ (m_{f,i}^2 + m_{f,j}^2)\Sigma_{ij}^{\text{tad},f,S}(m_{f,j}^2) \Big] , \qquad (i \neq j)$$

$$\delta Z_{ij}^{f,R} = \frac{2}{m_{f,i}^2 - m_{f,j}^2} \text{Re} \Big[m_{f,j}^2 \Sigma_{ij}^{f,R}(m_{f,j}^2) + m_{f,i} m_{f,j} \Sigma_{ij}^{f,L}(m_{f,j}^2) \tag{2.153}$$

$$+ 2m_{f,i} m_{f,j} \Sigma_{ij}^{\text{tad},f,S}(m_{f,j}^2) \Big] , \qquad (i \neq j)$$

<div>

Renormalization of the fermion sector (standard and alternative FJ scheme)

$$\delta V_{ij} = \frac{1}{4} \left[\left(\delta Z_{ik}^{u,L} - \delta Z_{ik}^{u,L\dagger} \right) V_{kj} - V_{ik} \left(\delta Z_{kj}^{d,L} - \delta Z_{kj}^{d,L\dagger} \right) \right]_{\xi=1} \qquad (2.154)$$

$$\delta Z_{ii}^{f,L} = -\mathrm{Re}\left[\Sigma_{ii}^{f,L}(m_{f,i}^2) \right] - m_{f,i}^2 \mathrm{Re}\left[\frac{\partial \Sigma_{ii}^{f,L}(p^2)}{\partial p^2} + \frac{\partial \Sigma_{ii}^{f,R}(p^2)}{\partial p^2} + 2\frac{\partial \Sigma_{ii}^{f,S}(p^2)}{\partial p^2} \right]_{p^2=m_{f,i}^2}$$
$$(2.155)$$

$$\delta Z_{ii}^{f,R} = -\mathrm{Re}\left[\Sigma_{ii}^{f,R}(m_{f,i}^2) \right] - m_{f,i}^2 \mathrm{Re}\left[\frac{\partial \Sigma_{ii}^{f,L}(p^2)}{\partial p^2} + \frac{\partial \Sigma_{ii}^{f,R}(p^2)}{\partial p^2} + 2\frac{\partial \Sigma_{ii}^{f,S}(p^2)}{\partial p^2} \right]_{p^2=m_{f,i}^2}$$
$$(2.156)$$

</div>

where as before, the superscripts L and R denote the left- and right-chiral parts of the self-energies, while the superscript S denotes the scalar part.

2.2.6 Renormalization of the Soft-$\mathbb{Z}_2$-Breaking Parameter m_{12}^2

The last remaining parameter of the 2HDM that needs to be renormalized is the soft-$\mathbb{Z}_2$-breaking parameter m_{12}^2. As before, we replace the bare parameter by the renormalized one and its corresponding CT,

$$m_{12}^2 \;\to\; m_{12}^2 + \delta m_{12}^2 \;. \qquad (2.157)$$

In order to fix δm_{12}^2 in a physical way, one could use a process-dependent scheme analogous to Sec. 2.2.4 for the scalar mixing angles. Since m_{12}^2 only appears in trilinear Higgs couplings, a Higgs-to-Higgs decay width would have to be chosen as observable that fixes the CT. However, as discussed in [63], a process-dependent definition of δm_{12}^2 can lead to very large one-loop corrections in Higgs-to-Higgs decays. We therefore employ an $\overline{\mathrm{MS}}$ condition in 2HDECAY to fix the CT. This is done by calculating the off-shell decay process $h \to hh$ at one-loop order and by extracting all UV-divergent terms, *i.e.* all terms proportional to

$$\Delta \equiv \frac{1}{\varepsilon} - \gamma_E + \ln(4\pi) \;, \qquad (2.158)$$

that are left in the amplitude after all parameters apart from m_{12}^2 are renormalized. Here, γ_E is the Euler-Mascheroni constant and ε the dimensional shift when switching from 4 to $D = 4 - 2\varepsilon$ dimensions in the framework of dimensional regularization [98–100]. This fixes the CT of m_{12}^2 to

<div>

Renormalization of m_{12}^2 (standard and alternative FJ scheme)

$$\delta m_{12}^2 = \frac{\alpha_{\mathrm{em}} m_{12}^2}{16\pi m_W^2 \left(1 - \frac{m_W^2}{m_Z^2} \right)} \left[\frac{8m_{12}^2}{s_{2\beta}} - 2m_{H^\pm}^2 - m_A^2 + \frac{s_{2\alpha}}{s_{2\beta}}(m_H^2 - m_h^2) - 3(2m_W^2 + m_Z^2) \right.$$
$$\left. + \sum_u 3m_u^2 \frac{1}{s_\beta^2} - \sum_d 6m_d^2 Y_3 \left(-Y_3 - \frac{1}{t_{2\beta}} \right) - \sum_l 2m_l^2 Y_6 \left(-Y_6 - \frac{1}{t_{2\beta}} \right) \right] \Delta \qquad (2.159)$$
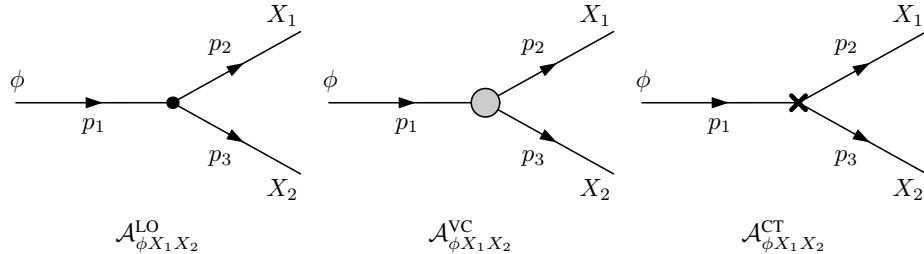
</div>

Figure 2: Decay amplitudes at LO and NLO. The LO decay amplitude $\mathcal{A}^{\text{LO}}_{\phi X_1 X_2}$ simply consists of the trilinear coupling of the three particles ϕ_1, X_1 and X_2, while the one-loop amplitude is given by the sum of the genuine vertex corrections $\mathcal{A}^{\text{VC}}_{\phi X_1 X_2}$, indicated by a grey blob, and the vertex counterterm $\mathcal{A}^{\text{CT}}_{\phi X_1 X_2}$ which also includes all WFRCs necessary to render the NLO amplitude UV-finite. We do not show corrections on the external legs since in the decays we consider, they vanish either due to OS renormalization conditions or due to Slavnov-Taylor identities. In the case of the alternative tadpole scheme, the vertex corrections $\mathcal{A}^{\text{VC}}_{\phi X_1 X_2}$ also in general contain tadpole diagrams.

where the sum indices u, d and l indicate a summation over all up-type and down-type quarks and charged leptons, respectively. The result in Eq. (2.159) is in agreement with the formula presented in [76].

Choosing to renormalize m_{12}^2 in an $\overline{\text{MS}}$ scheme automatically leads to a dependence of the partial decay widths of the Higgs-to-Higgs decays on the renormalization scale μ_R. This scale should be chosen appropriately in order to avoid the appearance of large logarithms in the EW one-loop corrections. A typical choice of μ_R is *e.g.* the mass scale of the decaying Higgs boson. In 2HDECAY, the scale μ_R can either be set to a global fixed value for all decay channels or it can be chosen equal to the mass of the decaying Higgs boson of the respective decay channel.

2.3 Electroweak Decay Processes at LO and NLO

Figure 2 shows the topologies that contribute to the tree-level and one-loop corrected decay of a scalar particle ϕ with four-momentum p_1 into two other particles X_1 and X_2 with four-momenta p_2 and p_3, respectively. We emphasize that for the EW corrections, we restrict ourselves to OS decays, *i.e.* we demand

$$p_1^2 \geq (p_2 + p_3)^2 \,, \tag{2.160}$$

with $p_i^2 = m_i^2$ $(i = 1, 2, 3)$ where m_i denote the masses of the three particles. Moreover, we do not calculate EW corrections to loop-induced Higgs decays, which are of two-loop order. In particular, we do not provide EW corrections to Higgs boson decays into two-gluon, two-photon or $Z\gamma$ final states. Note, however, that the decay widths implemented in HDECAY include also loop-induced decay widths as well as off-shell decays into heavy-quark, massive gauge boson, neutral Higgs pair as well as Higgs and gauge boson final states. We come back to this point in Sec. 2.4. The LO and NLO partial decay widths were calculated by first generating all Feynman diagrams and the corresponding amplitudes for all decay modes that exist for the 2HDM, shown topologically in Fig. 2, with help of the tool FeynArts 3.9 [101]. To that end, we used the 2HDM model file that is implemented in FeynArts, but modified the Yukawa couplings to implement all four 2HDM types. Diagrams that account for NLO corrections on the external legs were not calculated since for all decay modes that we considered, they either vanish due to OS renormalization conditions or due to Slavnov-Taylor identities. All amplitudes were then calculated analytically with FeynCalc 8.2.0 [102,103], together with all self-energy amplitudes needed for the CTs.

The LO partial decay width is obtained from the LO amplitude $\mathcal{A}^{\mathrm{LO}}_{\phi X_1 X_2}$, while the NLO amplitude is given by the sum of all amplitudes stemming from the vertex correction and the necessary CTs as defined in Sec. 2.2,

$$\mathcal{A}^{\mathrm{1loop}}_{\phi X_1 X_2} \equiv \mathcal{A}^{\mathrm{VC}}_{\phi X_1 X_2} + \mathcal{A}^{\mathrm{CT}}_{\phi X_1 X_2} . \tag{2.161}$$

By introducing the Källén phase space function

$$\lambda(x,y,z) \equiv \sqrt{x^2 + y^2 + z^2 - 2xy - 2xz - 2yz} , \tag{2.162}$$

the LO and NLO partial decay widths can be cast into the form

$$\Gamma^{\mathrm{LO}}_{\phi X_1 X_2} = S \frac{\lambda(m_1^2, m_2^2, m_3^2)}{16\pi m_1^3} \sum_{\mathrm{d.o.f.}} \left| \mathcal{A}^{\mathrm{LO}}_{\phi X_1 X_2} \right|^2 \tag{2.163}$$

$$\Gamma^{\mathrm{NLO}}_{\phi X_1 X_2} = \Gamma^{\mathrm{LO}}_{\phi X_1 X_2} + S \frac{\lambda(m_1^2, m_2^2, m_3^2)}{8\pi m_1^3} \sum_{\mathrm{d.o.f.}} \mathrm{Re}\left[\left(\mathcal{A}^{\mathrm{LO}}_{\phi X_1 X_2} \right)^* \mathcal{A}^{\mathrm{1loop}}_{\phi X_1 X_2} \right] + \Gamma_{\phi X_1 X_2 + \gamma} , \tag{2.164}$$

where the symmetry factor S accounts for identical particles in the final state and the sum extends over all degrees of freedom of the final-state particles, *i.e.* over spins or polarizations. The partial decay width $\Gamma_{\phi X_1 X_2 + \gamma}$ accounts for real corrections that are necessary for removing IR divergences in all decays that involve charged particles in the initial or final state. For this, we implemented the results given in [104] for generic one-loop two-body partial decay widths. Since the involved integrals are analytically solvable for two-body decays [71], the IR corrections that are implemented in 2HDECAY are given in analytic form as well and do not require numerical integration. Additionally, since the implemented integrals account for the full phase-space of the radiated photon, *i.e.* both the "hard" and "soft" parts, our results do not depend on arbitrary cuts in the photon phase-space.

In the following, we present all decay channels for which the EW corrections were calculated at one-loop order:

- $h/H/A \to f\bar{f}$ $(f = u, d, c, s, t, b, e, \mu, \tau)$

- $h/H \to VV$ $(V = W^\pm, Z)$

- $h/H \to VS$ $(V = Z, W^\pm, \ S = A, H^\pm)$

- $h/H \to SS$ $(S = A, H^\pm)$

- $H \to hh$

- $H^\pm \to VS$ $(V = W^\pm, \ S = h, H, A)$

- $H^+ \to f\bar{f}$ $(f = u, c, t, \nu_e, \nu_\mu, \nu_\tau \ , \ \bar{f} = \bar{d}, \bar{s}, \bar{b}, e^+, \mu^+, \tau^+)$

- $A \to VS$ $(V = Z, W^\pm, \ S = h, H, H^\pm)$

All analytic results of these decay processes are stored in subdirectories of 2HDECAY. For a consistent connection with HDECAY, *cf.* also Sec. 2.4, not all of these decay processes are used for the calculation of the decay widths and branching ratios, however. Decays containing pairs of first-generation fermions are neglected, *i.e.* in 2HDECAY, the EW corrections of the following processes are not used for the calculation of the partial decay widths and branching ratios: $h/H/A \to f\bar{f}$ $(f = u, d, e)$ and $H^+ \to f\bar{f}$ $(f\bar{f} = u\bar{d}, \nu_e e^+)$. The reason is that they are overwhelmed by the Dalitz decays $\Phi \to f\bar{f}^{(')}\gamma$ $(\Phi = h, H, A, H^\pm)$ that are induced *e.g.* by off-shell $\gamma^* \to f\bar{f}$ splitting.

2.4   Link to HDECAY, Calculated Higher-Order Corrections and Caveats

The EW one-loop corrections to the Higgs decays in the 2HDM derived in this work are combined with HDECAY version 6.52 [68, 69][7] in form of the new tool 2HDECAY. The Fortran code HDECAY provides the LO and QCD corrected decay widths. As outlined in Sec. 2.2.2 the EW corrections use $\alpha_{\rm em}$ at the Z boson mass scale as input parameter instead of G_F as used in HDECAY. For a consistent combination of the EW corrected decay widths with the HDECAY implementation in the G_F scheme we would have to convert between the $\{\alpha_{\rm em}, m_W, m_Z\}$ and the $\{G_F, m_W, m_Z\}$ scheme including 2HDM higher-order corrections in the conversion formulae. Since these conversion formulae are not implemented yet, we chose a pragmatic approximate solution:

In the configuration of 2HDECAY with OMIT ELW2=0 being set (*cf.* the input file format described in Sec. 3.5), the EW corrections to the decay widths are calculated automatically. This setting also overwrites the value that the user chooses for the input 2HDM. If *e.g.* the user does not choose the 2HDM by setting 2HDM=0 but at the same time chooses OMIT ELW2=0 in order to calculate the EW corrections, then a warning is printed and 2HDM=1 is automatically set internally. In this configuration, the value of G_F given in the input file of 2HDECAY is ignored by the part of the program that calculates the EW corrections. Instead, $\alpha_{\rm em}(m_Z^2)$, given in line 26 of the input file, is taken as independent input. This $\alpha_{\rm em}(m_Z^2)$ is used for the calculation of all electroweak corrections. Subsequently, for the consistent combination with the decay widths of HDECAY computed in terms of the Fermi constant G_F, the latter decay widths are adapted to the input scheme of the EW corrections by rescaling the HDECAY decay widths with $G_F^{\rm calc}/G_F$, where $G_F^{\rm calc}$ is calculated by means of the tree-level relation Eq. (2.14) as a function of $\alpha_{\rm em}(m_Z^2)$. We expect the differences between the observables within these two schemes to be small.

On the other hand, if OMIT ELW2=1 is set, no EW corrections are computed and 2HDECAY reduces to the original program code HDECAY, including (where applicable) the QCD corrections in the decay widths, the off-shell decays and the loop-induced decays. In this case, the value of G_F given in line 27 of the input file is used as input parameter instead of being calculated through the input value of $\alpha_{\rm em}(m_Z^2)$, and no rescaling with $G_F^{\rm calc}$ is performed. We note in particular that therefore the QCD corrected decay widths, printed out separately by 2HDECAY, will be different in the two input options OMIT ELW2=0 and OMIT ELW2=1.

Another comment is at order in view of the fact that we implemented EW corrections to OS decays only, while HDECAY also features the computation of off-shell decays. More specifically, HDECAY includes off-shell decays into final states with an off-shell top-quark t^*, *i.e.* $\phi \to t^*\bar{t}$ ($\phi = h, H, A$), $H^+ \to t^* + \bar{d}, \bar{s}, \bar{b}$, into gauge and Higgs boson final states with an off-shell gauge boson, $h/H \to Z^*A, A \to Z^*h/H, \phi \to H^-W^{+*}, H^+ \to \phi W^{+*}$, and into neutral Higgs pairs with one off-shell Higgs boson that is assumed to predominantly decay into the $b\bar{b}$ final state, $h/H \to AA^*, H \to hh^*$. The top quark total width within the 2HDM, required for the off-shell decays with top final states, is calculated internally in HDECAY. In 2HDECAY, we combine the EW and QCD corrections in such a way that HDECAY still computes the decay widths of off-shell decays, while the electroweak corrections are added only to OS decay channels. It is important to keep this restriction in mind when performing the calculation for large varieties of input data. If *e.g.* the lighter Higgs boson h is chosen to be the SM-like Higgs boson, then the OS decay $h \to W^+W^-$ would be kinematically forbidden while the heavier Higgs boson decay $H \to W^+W^-$ might be OS. In such cases, 2HDECAY calculates the EW NLO corrections only for the latter decay channel, while the LO (and QCD decay widths where applicable) are

---

[7]The program code for HDECAY can be downloaded from the URL http://tiger.web.psi.ch/hdecay/.

IELW2=0	QCD-corrected	QCD&EW-corrected
on-shell and non-loop induced	$\Gamma^{\mathrm{HD,QCD}}\frac{G_F^{\mathrm{calc}}}{G_F}$	$\Gamma^{\mathrm{HD,QCD}}[1+\delta^{\mathrm{EW}}]\frac{G_F^{\mathrm{calc}}}{G_F}$
off-shell or loop-induced	$\Gamma^{\mathrm{HD,QCD}}\frac{G_F^{\mathrm{calc}}}{G_F}$	$\Gamma^{\mathrm{HD,QCD}}\frac{G_F^{\mathrm{calc}}}{G_F}$

Table 3: The QCD-corrected and the QCD&EW-corrected decay widths as calculated by `2HDECAY` for `IELW2=0`. The label QCD is in the sense that the QCD corrections are included where applicable.

calculated for both. The same is true for any other decay channel for which we implemented EW corrections but which are off-shell in certain input scenarios.

For the combination of the QCD and EW corrections finally, we assume that these corrections factorize. We denote by δ^{QCD} and δ^{EW} the relative QCD and EW corrections, respectively. Here δ^{QCD} is normalized to the LO width $\Gamma^{\mathrm{HD,LO}}$, calculated internally by `HDECAY`. This means for example in the case of quark pair final states that the LO width includes the running quark mass in order to improve the perturbative behaviour. The relative EW corrections δ^{EW} on the other hand are obtained by normalization to the LO width with on-shell particle masses. With these definitions the QCD and EW corrected decay width into a specific final state, $\Gamma^{\mathrm{QCD\&EW}}$, is given by

$$\Gamma^{\mathrm{QCD\&EW}} = \frac{G_F^{\mathrm{calc}}}{G_F}\Gamma^{\mathrm{HD,LO}}[1+\delta^{\mathrm{QCD}}][1++\delta^{\mathrm{EW}}] \equiv \frac{G_F^{\mathrm{calc}}}{G_F}\Gamma^{\mathrm{HD,QCD}}[1+\delta^{\mathrm{EW}}]\,. \qquad (2.165)$$

We have included the rescaling factor G_F^{calc}/G_F which is necessary for the consistent connection of our EW corrections with the decay widths obtained from `HDECAY`, as outline above.

QCD&EW-corrected branching ratios: The program code will provide the branching ratios calculated originally by `HDECAY`, which, however, for `OMIT ELW2=0` are rescaled by G_F^{calc}/G_F. They include all loop decays, off-shell decays and QCD corrections where applicable. We summarize these branching ratios under the name 'QCD-corrected' branching ratios and call their associated decay widths $\Gamma^{\mathrm{HD,QCD}}$, keeping in mind that the QCD corrections are included only where applicable. Furthermore, the EW and QCD corrected branching ratios will be given out. Here, we add the EW corrections to the decay widths calculated internally by `HDECAY` where possible, i.e. for non-loop induced and OS decay widths. We summarize these branching ratios under the name 'QCD&EW-corrected' branching ratios and call their associated decay widths $\Gamma^{\mathrm{QCD\&EW}}$. In Table 3 we summarize all details and caveats on their calculation that we described here above. All these branching ratios are written to the output file carrying the suffix '_BR' with its filename, see also end of section 3.5 for details.

NLO EW-corrected decay widths: For $\mathrm{IELW2}=0$, we additionally give out the LO and the EW-corrected NLO decay widths as calculated by the new addition to `HDECAY`. Here the LO widths do not include any running of the quark masses in the case of quark final states, but are obtained for OS masses. They can hence differ quite substantially from the LO widths as calculated in the original `HDECAY` version. These LO and EW-corrected NLO widths are computed in the $\{\alpha_{\mathrm{em}}, m_W, m_Z\}$ scheme and therefore obviously do not need the inclusion of the rescaling factor G_F^{calc}/G_F. The decay widths are written to the output file carrying the suffix '_EW' with its filename. While the widths given out here are not meant to be applied in Higgs observables as they do not include the important QCD corrections, the study of the NLO EW-corrected decay widths for various renormalization schemes, as provided by `2HDECAY`, allows to

analyze the importance of the EW corrections and estimate the remaining theoretical error due to missing higher-order EW corrections. The decay widths can also be used for phenomenological studies like *e.g.* the comparison with the EW-corrected decay widths in the MSSM in the limit of large supersymmetric particle masses, or the investigation of specific 2HDM parameter regions at LO and NLO as *e.g.* the alignment limit, the non-decoupling limit or the wrong-sign limit.

Caveats: We would like to point out to the user that it can happen that the EW-corrected decay widths become negative because of too large negative EW corrections compared to the LO width. There can be several reasons for this: (*i*) The LO width may be very small in parts of the parameter space due to suppressed couplings. For example the decay of the heavy Higgs boson H into massive vector bosons is very small in the region where the lighter h becomes SM-like and takes over almost the whole coupling to massive gauge bosons. If the NLO EW width is not suppressed by the same power of the relevant coupling or if at NLO there are cancellations between the various terms that remove the suppression, the NLO width can largely exceed the LO width. (*ii*) The EW corrections are artificially enhanced due to a badly chosen renormalization scheme, *cf.* Refs. [58,63,64] for investigations on this subject. The choice of a different renormalization scheme may cure this problem, but of course raises also the question for the remaining theoretical error due to missing higher-order corrections. (*iii*) The EW corrections are parametrically enhanced due to involved couplings that are large, because of small coupling parameters in the denominator or due to light particles in the loop, see also Refs. [58,63,64] for discussions. This would call for the resummation of EW corrections beyond NLO to improve the behaviour. It is obvious that the EW corrections should not be trusted in case of extremely large positive or negative corrections and rather be discarded, in particular in the comparison with experimental observables, unless some of the suggested measures are taken to improve the behaviour.

3   Program Description

In the following, we describe the system requirements needed for compiling and running 2HDECAY, the installation procedure and the usage of the program. Additionally, we describe the input and output file formats in detail.

3.1   System Requirements

The `Python/FORTRAN` program code 2HDECAY was developed under `Windows 10` and `openSUSE Leap 15.0`. The supported operating systems are:

- `Windows 7` and `Windows 10` (tested with `Cygwin 2.10.0`)

- `Linux` (tested with `openSUSE Leap 15.0`)

- `macOS` (tested with `macOS Sierra 10.12`)

In order to compile and run 2HDECAY on Windows, you need to install `Cygwin` first (together with the packages `cURL`, `find`, `gcc`, `g++` and `gfortran`, which also are required to be installed on `Linux` and `macOS`). For the compilation, the `GNU C` compilers `gcc` (tested with versions `6.4.0` and `7.3.1`), `g++` and the `FORTRAN` compiler `gfortran` are required. Additionally, an up-to-date version of `Python 2` or `Python 3` is required (tested with versions `2.7.14` and `3.5.0`). For an optimal performance of 2HDECAY, we recommend that the program is installed on a solid state drive (SSD) with high reading and writing speeds.

3.2 License

2HDECAY is released under the GNU General Public License (GPL) (`GNU GPL-3.0-or-later`).
2HDECAY is free software, which means that anyone can redistribute it and/or modify it under
the terms of the GNU GPL as published by the Free Software Foundation, either version 3 of
the License, or any later version. 2HDECAY is distributed without any warranty. A copy of the
GNU GPL is included in the `LICENSE.md` file in the root directory of 2HDECAY.

3.3 Download

The latest version of the program as well as a short quick-start documentation is given at
https://github.com/marcel-krause/2HDECAY. To obtain the code either the repository is cloned
or the zip archive is downloaded and unzipped to a directory of the user's choice, which here
and in the following will be referred to as `$2HDECAY`. The main folder of 2HDECAY consists of
several subfolders:

`BuildingBlocks` Contains the analytic electroweak one-loop corrections for all decays con-
sidered, as well as the real corrections and CTs needed to render the decay widths UV-
and IR-finite.

`Documentation` Contains this documentation.

`HDECAY` This subfolder contains a modified version of `HDECAY` 6.52 [68, 69], needed for the
computation of the LO and (where applicable) QCD corrected decay widths. `HDECAY`
also provides off-shell decay widths and the loop-induced decay widths into gluon and
photon pair final states and into $Z\gamma$. `HDECAY` is furthermore used for the computation of
the branching ratios.

`Input` In this subfolder, at least one or more input files can be stored that shall be used
for the computation. The format of the input file is explained in Sec. 3.5. In the Github
repository, the `Input` folder contains an exemplary input file which is printed in App. A.

`Results` All results of a successful run of 2HDECAY are stored as output files in this subfolder
under the same name as the corresponding input files in the `Input` folder, but with the
file extension `.in` replaced by `.out` and a suffix "_BR" and "_EW" for the branching
ratios and electroweak partial decay widths, respectively. In the Github repository, the
`Results` folder contains two exemplary output files which are given in App. B.

The main folder `$2HDECAY` itself also contains several files:

`2HDECAY.py` Main program file of 2HDECAY. It serves as a wrapper file for calling `HDECAY` in
order to convert the charm and bottom quark masses from the $\overline{\text{MS}}$ input values to the
corresponding OS values and to calculate the LO widths, QCD corrections, off-shell and
loop-induced decays, the branching ratios as well as `electroweakCorrections` for the
calculation of the EW one-loop corrections.

`Changelog.md` Documentation of all changes made in the program since version
2HDECAY 1.0.0.

`CommonFunctions.py` Function library of 2HDECAY, providing functions frequently used in
the different files of the program.

Config.py Main configuration file. If `LoopTools` is not installed automatically by the installer of 2HDECAY, the paths to the `LoopTools` executables and libraries have to be set manually in this file.

constants.F90 Library for all constants used in 2HDECAY.

counterterms.F90 Definition of all fundamental CTs necessary for the EW one-loop renormalization of the Higgs boson decays. The CTs defined in this file require the analytic results saved in the `BuildingBlocks` subfolder.

electroweakCorrections.F90 Main file for the calculation of the EW one-loop corrections to the Higgs boson decays. It combines the EW one-loop corrections to the decay widths with the necessary CTs and IR corrections and calculates the EW contributions to the tree-level decay widths that are then combined with the QCD corrections in `HDECAY`.

getParameters.F90 Routine to read in the input values given by the user in the input files that are needed by 2HDECAY.

LICENSE.md Contains the full GNU General Public License (`GNU GPL-3.0-or-later`) agreement under which 2HDECAY is published.

README.md Provides an overview over basic information about the program as well as a quick-start guide.

setup.py Main setup and installation file of 2HDECAY. For a guided installation, this file should be called after downloading the program.

3.4 Installation

We highly recommend to use the automatic installation script `setup.py` that is part of the 2HDECAY download. The script guides the user through the installation and asks what components should be installed. For an installation under Windows, the user should open the configuration file `$2HDECAY/Config.py` and check that the path to the `Cygwin` executable in line 36 is set correctly before starting the installation. In order to initiate the installation, the user navigates to the `$2HDECAY` folder and executes the following in the command-line shell:

```
python setup.py
```

The script first asks the user if `LoopTools` should be downloaded and installed. By entering `y`, the installer downloads the `LoopTools` version that is specified in the `$2HDECAY/Config.py` file in line 37 and starts the installation automatically. `LoopTools` is then installed in a subdirectory of 2HDECAY. Further information about the installation of the program can be found in [105].

If the user already has a working version of `LoopTools` on the system, this step of the installation can be skipped. In this case, the user has to open the file `$2HDECAY/Config.py` in an editor and change the lines 33-35 to the absolute path of the `LoopTools` root directory and to the `LoopTools` executables and libraries on the system. Additionally, line 32 has to be changed to

```
useRelativeLoopToolsPath = False
```

Line	Input name	Allowed values and meaning
6	OMIT ELW2	0: electroweak corrections (2HDM) are calculated
		1: electroweak corrections (2HDM) are neglected
9	2HDM	0: considered model is not the 2HDM
		1: considered model is the 2HDM
56	PARAM	1: 2HDM Higgs masses and α (lines 64-68) are given as input
		2: 2HDM potential parameters (lines 70-74) are given as input
57	TYPE	1: 2HDM type I
		2: 2HDM type II
		3: 2HDM lepton-specific
		4: 2HDM flipped
58	RENSCHEM	0: all renormalization schemes are calculated
		1-14: only the chosen scheme (*cf.* Tab. 6) is calculated

Table 4: Input parameters for the basic control of 2HDECAY. The line number corresponds to the line of the input file where the input value can be found. In order to calculate the EW corrections for the 2HDM, the input parameter OMIT ELW2 has to be set to 0. In this case, the given input value of 2HDM is ignored and 2HDM=1 is set automatically, independent of the chosen input value. All input values presented in this table have to be entered as integer values.

This step is important if LoopTools is not installed automatically with the install script, since otherwise, 2HDECAY will not be able to find the necessary executables and libraries for the calculation of the EW one-loop corrections.

As soon as LoopTools is installed (or alternatively, as soon as paths to the LoopTools libraries and executables on the user's system are being set manually in $2HDECAY/Config.py), the installation script asks whether it should automatically create the makefile and the main EW corrections file electroweakCorrections.F90 and whether the program shall be compiled. For an automatic installation, the user should type y for all these requests to compile the main program as well as to compile the modified version of HDECAY that is included in 2HDECAY. The compilation may take several minutes to finish. At the end of the installation the user has the choice to 'make clean' the installation. This is optional.

In order to test if the installation was successful, the user can type

```
python 2HDECAY.py
```

in the command-line shell, which runs the main program. The exemplary input file provided by the default 2HDECAY version is used for the calculation. In the command window, the output of several steps of the computation should be printed, but no errors. If the installation was successful, 2HDECAY terminates with no errors and the existing output files in $2HDECAY/Results are overwritten by the newly created ones, which, however, are equivalent to the exemplary output files that are provided with the program.

3.5 Input File Format

The format of the input file is adopted from HDECAY [68, 69], with minor modifications to account for the EW corrections that are implemented. The file has to be stored as a text-only file in UTF-8 format. Since 2HDECAY is a program designed for the calculation of higher-order corrections solely for the 2HDM, only a subset of input parameters in comparison to the original HDECAY input file is actually used (*e.g.* SUSY-related input parameters are not needed for

2HDECAY). The input file nevertheless contains the full set of input parameters from HDECAY to make 2HDECAY fully backwards-compatible, *i.e.* HDECAY 6.52 is fully contained in 2HDECAY. The input file contains two classes of input parameters. The first class are input values that control the main flow of the program (*e.g.* whether corrections for the SM or the 2HDM are calculated). The control parameters relevant for 2HDECAY are shown in Tab. 4, together with their line numbers in the input file, their allowed values and the meaning of the input values. In order to choose the 2HDM as the model that is considered, the input value 2HDM = 1 has to be chosen. By setting OMIT ELW2 = 0, the EW and QCD corrections are calculated for the 2HDM, whereas for OMIT ELW2 = 1, only the QCD corrections are calculated. The latter choice corresponds to the corrections for the 2HDM that are already implemented in HDECAY 6.52. If the user sets OMIT ELW2 = 0 in the input file, then 2HDM = 1 is automatically set internally, independent of the input value of 2HDM that the user provides. The input value PARAM determines which parametrization of the Higgs sector shall be used. For PARAM = 1, the Higgs boson masses and mixing angle α are chosen as input, while for PARAM = 2, the Higgs potential parameters λ_i are used as input. As described at the end of Sec. 2.1, however, it should be noted that the EW corrections in 2HDECAY are in both cases parametrized through the Higgs masses and mixing angle. Hence, if PARAM = 2 is chosen, the masses and mixing angle are calculated as functions of λ_i by means of Eqs. (2.31)-(2.35). The input value TYPE sets the type of the 2HDM, as described in Sec. 2.1, and RENSCHEM determines the renormalization schemes that are used for the calculation. By setting RENSCHEM = 0, the EW corrections to the Higgs boson decays are calculated for all 14 implemented renormalization schemes. This allows for analyses of the renormalization scheme dependence and for an estimate of the effects of missing higher-order EW corrections, but this setting has the caveat of increasing the computation time and output file size rather significantly. A specific integer value of RENSCHEME between 1 and 14 sets the renormalization scheme to the chosen one. An overview of all implemented schemes and their identifier values between 1 and 14 is presented in Tab. 6. All input values of the first class must be entered as integers.

The second class of input values in the input file are the physical input parameters shown in Tab. 5, together with their line numbers in the input file, their allowed input values and the meaning of the input values. This is the full set of input parameters needed for the calculation of the electroweak and QCD corrections. All other input parameters present in the input file that are not shown in Tab. 5 are neglected for the calculation of the QCD and EW corrections in the 2HDM. We want to emphasize again that depending on the choice of PARAM (*cf.* Tab. 4), either the Higgs masses and mixing angle α or the Higgs potential parameters λ_i are chosen as independent input, but never both simultaneously, *i.e.* if PARAM = 1 is chosen, then the input values for λ_i are ignored, while for PARAM = 2, the input values of the Higgs masses and α are ignored and instead calculated by means of Eqs. (2.31)-(2.35). All input values of the second class are entered in FORTRAN double-precision format, *i.e.* valid input formats are *e.g.* MT = 1.732e+02 or MHH = 258.401D0. Due to the $\overline{\text{MS}}$ renormalization of m_{12}^2, the partial decay widths of Higgs-to-Higgs decays depend on the renormalization scale μ_R, which should be chosen appropriately to avoid artificially enhanced corrections. The input value INSCALE of μ_R can be entered either as a double-precision number or it can be expressed in terms of the mass scale MIN of the decaying Higgs boson, *i.e.* setting *e.g.* INSCALE=MIN sets $\mu_R = m_1$ for each decay channel, where m_1 is the mass of the decaying Higgs boson in the respective channel. Note finally, that the input masses for the W and Z gauge bosons must be the on-shell values for consistency with the renormalization conditions applied in the EW corrections. The amount of input files that can be stored in the input folder is not limited. The input files can have arbitrary non-empty names and

Line	Input name	Name in Sec. 2	Allowed values and meaning
18	ALS(MZ)	$\alpha_s(m_Z)$	strong coupling constant (at m_Z)
19	MSBAR(2)	$m_s(2\,\text{GeV})$	s-quark $\overline{\text{MS}}$ mass at 2 GeV in GeV
20	MCBAR(3)	$m_c(3\,\text{GeV})$	c-quark $\overline{\text{MS}}$ mass at 3 GeV in GeV
21	MBBAR(MB)	$m_b(m_b)$	b-quark $\overline{\text{MS}}$ mass at m_b in GeV
22	MT	m_t	t-quark pole mass in GeV
23	MTAU	m_τ	τ-lepton pole mass in GeV
24	MMUON	m_μ	μ-lepton pole mass in GeV
25	1/ALPHA	$\alpha_{\text{em}}^{-1}(0)$	inverse fine-structure constant (Thomson limit)
26	ALPHAMZ	$\alpha_{\text{em}}(m_Z)$	fine-structure constant (at m_Z)
29	GAMW	Γ_W	partial decay width of the W boson
30	GAMZ	Γ_Z	partial decay width of the Z boson
31	MZ	m_Z	Z boson on-shell mass in GeV
32	MW	m_W	W boson on-shell mass in GeV
33-41	Vij	V_{ij}	CKM matrix elements ($i \in \{u,c,t\}$, $j \in \{d,s,b\}$)
60	TGBET2HDM	t_β	ratio of the VEVs in the 2HDM
61	M_12^2	m_{12}^2	squared soft-$\mathbb{Z}_2$-breaking scale in GeV^2
62	INSCALE	μ_R	renormalization scale in GeV or in terms of MIN
64	ALPHA_H	α	CP-even Higgs mixing angle in radians
65	MHL	m_h	light CP-even Higgs boson mass in GeV
66	MHH	m_H	heavy CP-even Higgs boson mass in GeV
67	MHA	m_A	CP-odd Higgs boson mass in GeV
68	MH+-	$m_{H^\pm}$	charged Higgs boson mass in GeV
70-74	LAMBDAi	λ_i	Higgs potential parameters [see Eq. (2.4)]

Table 5: Shown are all relevant physical input parameters of 2HDECAY that are necessary for the calculation of the QCD and EW corrections. The line number corresponds to the line of the input file where the input value can be found. Depending on the chosen value of PARAM (*cf.* Tab. 4), either the Higgs masses and mixing angle α (lines 64-68) or the 2HDM potential parameters (lines 70-74) are chosen as input, but never both simultaneously. The value INSCALE is entered either as a double-precision number or as MIN, representing the mass scale of the decaying Higgs boson. All other input values presented in this table are entered as double-precision numbers.

filename extensions[8]. The output files are saved in the $2HDECAY/Results subfolder under the same name as the corresponding input files, but with their filename extension replaced by .out. For each input file, two output files are generated. The output file containing the branching ratios is indicated by the filename suffix '_BR', while the output file containing the electroweak partial decay widths is indicated by the filename suffix '_EW'.

3.6 Structure of the Program

As briefly mentioned in Sec. 3.3, the main program 2HDECAY combines the already existing QCD corrections from HDECAY with the full EW one-loop corrections. Depicted in Fig. 3 is the flowchart of 2HDECAY which shows how the QCD and EW corrections are combined by the main wrapper file 2HDECAY.py. First, the wrapper file generates a list of all input files that the user

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[8]On some systems, certain filename extensions should be avoided when naming the input files, as they are reserved for certain types of files (*e.g.* under Windows, the .exe file extension is automatically connected to executables by the operating system, which can under certain circumstances lead to runtime problems when trying to read the file). Choosing text file extensions like .in, .out, .dat or .txt should in general be unproblematic.

Input ID	Tadpole scheme	$\delta\alpha$	$\delta\beta$	Gauge-indep. Γ
1	standard	KOSY	KOSY (odd)	✗
2	standard	KOSY	KOSY (charged)	✗
3	alternative (FJ)	KOSY	KOSY (odd)	✗
4	alternative (FJ)	KOSY	KOSY (charged)	✗
5	alternative (FJ)	p_*-pinched	p_*-pinched (odd)	✓
6	alternative (FJ)	p_*-pinched	p_*-pinched (charged)	✓
7	alternative (FJ)	OS-pinched	OS-pinched (odd)	✓
8	alternative (FJ)	OS-pinched	OS-pinched (charged)	✓
9	standard	proc.-dep. 1	proc.-dep. 1	✓
10	alternative (FJ)	proc.-dep. 1	proc.-dep. 1	✓
11	standard	proc.-dep. 2	proc.-dep. 2	✓
12	alternative (FJ)	proc.-dep. 2	proc.-dep. 2	✓
13	standard	proc.-dep. 3	proc.-dep. 3	✓
14	alternative (FJ)	proc.-dep. 3	proc.-dep. 3	✓

Table 6: Overview over all renormalization schemes for the mixing angles α and β that are implemented in 2HDECAY. By setting RENSCHEM in the input file, *cf.* Tab. 4, equal to the Input ID the renormalization scheme is chosen. In case of 0 the results for all renormalization schemes are given out. The definition of the CTs $\delta\alpha$ and $\delta\beta$ in each scheme is explained in Sec. 2.2.4. The crosses and check marks in the column for gauge independence indicate whether the chosen scheme in general yields explicitly gauge-independent partial decay widths or not.

provides in $2HDECAY/Input. The user can provide an arbitrary non-zero amount of input files with arbitrary filenames, as described in Sec. 3.5. For any input file in the list, the wrapper file first calls HDECAY in a so-called minimal run, technically by calling HDECAY in the subfolder $2HDECAY/HDECAY with an additional flag "1":

```
run 1
```

With this flag, HDECAY reads the selected input file from the input file list and uses the input values only to convert the $\overline{\text{MS}}$ values of the *c*- and *b*-quark masses, as given in the input file, to the corresponding pole masses, but no other computations are performed at this step.

The wrapper file then calls the subprogram electroweakCorrections, which reads the selected input file as well as the OS values of the quark masses. With these input values, the full EW one-loop corrections are calculated for all decays that are kinematically allowed, as described in Sec. 2.3, and the value of G_F^{calc} at the Z mass is calculated, as described in Sec. 2.4. Subsequently, a temporary new input file is created, which consists of a copy of the selected input file with the calculated OS quark masses, the calculated value of G_F^{calc} and all EW corrections being appended.

Lastly, the wrapper file calls HDECAY without the minimal flag. In this configuration, HDECAY reads the temporary input file and calculates the LO widths and QCD corrections to the decays. Moreover, the program calculates off-shell decay widths as well as the loop-induced decays to final-state pairs of gluons or photons and $Z\gamma$. Furthermore, the branching ratios are calculated by HDECAY. The results of these computations are consistently combined with the electroweak corrections, as described in Sec. 2.4. The results are saved in an output file in the $2HDECAY/Results subfolder.

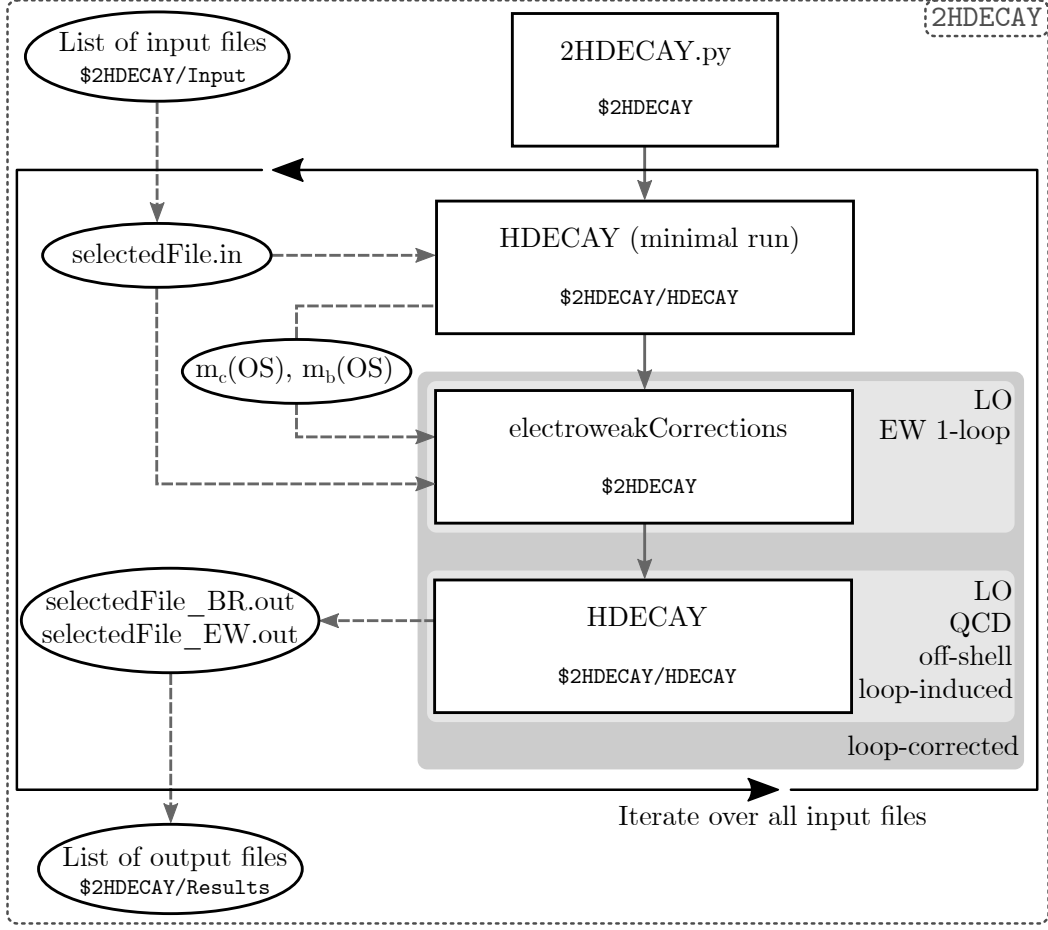The wrapper file repeats these steps for each file in the input file list until the end of the list is reached.

Figure 3: Flowchart of 2HDECAY. The main wrapper file 2HDECAY.py generates a list of input files, provided by the user in the subfolder $2HDECAY/Input, and iterates over the list. For each selected input file in the list, the wrapper calls HDECAY and the subprogram electroweakCorrections. The computed branching ratios including the EW and QCD corrections as described in the text are written to the output file with suffix '_BR', the calculated LO and NLO EW-corrected partial decay widths are given out in the output file with suffix '_EW'. For further details, we refer to the text.

3.7 Usage

Before running the program, the user should check that all input files for which the computation shall be performed are stored in the subfolder $2HDECAY/Input. The input files have to be formatted exactly as described in 3.5 or otherwise the input values are not read in correctly and the program might crash with a segmentation error. The exemplary input file printed in App. A that is part of the 2HDECAY repository can be used as a template for generating other input files in order to avoid formatting problems.

The user should check the output subfolder $2HDECAY/Results for any output files of previous runs of 2HDECAY. These previously created output files are overwritten if in a new run input files with the same names as the already stored output files are used. Hence, the user is advised to create backups of the output files before starting a new run of 2HDECAY.

In order to run the program, open a terminal, navigate to the $2HDECAY folder and execute the following command:

35

```
python 2HDECAY.py
```

If `2HDECAY` was installed correctly according to Sec. 3.4 and if the input files have the correct format, the program should now compute the EW and/or QCD corrections according to the flowchart shown in Fig. 3. Several intermediate results and information about the computation are printed in the terminal. As soon as the computation for all input files is done, `2HDECAY` is terminated and the resulting output files can be found in the `$2HDECAY/Results` subfolder.

3.8 Output File Format

For each input file, two output files with the suffices '_QCD' and '_EW' for the branching ratios and electroweak partial decay widths, respectively, are generated in an SLHA format, as described in Sec. 2.4. The SLHA output format [106–108] in its strict and original sense has only been designed for supersymmetric models. We have modified the format to account for the EW corrections that are implemented in `2HDECAY` in the 2HDM. As a reference for the following description, exemplary output files are given in App. B. These modified SLHA output files are only generated if `OMIT ELW2=0` is set in the input file, *i.e.* only if the electroweak corrections to the 2HDM decays are taken into account. In the following we describe the changes that we have applied.

The first block `BLOCK DCINFO` contains basic information about the program itself, while the subsequent three blocks `SMINPUTS`, `2HDMINPUTS` and `VCKMIN` contain the input parameters used for the calculation that were already described in Sec. 3.5. As explained in Sec. 2.4, the value of G_F printed in the output file is not necessarily the same as the one given in the input file if `OMIT ELW2=0` is set, since in this case, G_F is calculated from the input value $\alpha_{\mathrm{em}}(m_Z^2)$ instead, and this value is then given out. These four blocks are given out in both output files.

In the output file containing the branching ratios, indicated by the suffix '_BR', subsequently two blocks follow for each Higgs boson (h, H, A and $H^\pm$). They are called `DECAY QCD` and `DECAY QCD&EW`. The block `DECAY QCD` contains the total decay width and the branching ratios of the decays of the respective Higgs boson, as implemented in `HDECAY`. These are in particular the LO (loop-induced for the gg, $\gamma\gamma$ and $Z\gamma$ final states) decay widths including the relevant and state-of-the art QCD corrections where applicable (*cf.* [68, 69] for further details). For decays into heavy quarks, massive vector bosons, neutral Higgs pairs as well as gauge and Higgs boson final states also off-shell decays are computed if necessary. We want to emphasize again that the partial and total decay widths differ from the ones of the original `HDECAY` version if `OMIT ELW2=0` is set, as for consistency with the computed EW corrections in this case the `HDECAY` decay widths are rescaled by G_F^{calc}/G_F, as explained in Sec. 2.4. If `OMIT ELW2=1` is set, no EW corrections are computed and the `HDECAY` decay widths are computed with G_F as in the original `HDECAY` version.

The block `DECAY QCD&EW` contains the total decay width and branching ratios of the respective Higgs boson including both the QCD corrections (provided by `HDECAY`) and the EW corrections (computed by `2HDECAY`) to the LO decay widths. Note that the LO decay widths are also computed by `2HDECAY`. As an additional cross-check, we internally compare the respective `HDECAY` LO decay width (rescaled by G_F^{calc}/G_F and calculated with OS masses for this comparison) with the one computed by `2HDECAY`. If they differ (which they should not), a warning is printed on the screen. As described in Sec. 2.4, we emphasize again that the EW corrections are calculated and included only for OS decay channels that are kinematically allowed and for non-loop-induced decays. Therefore, some of the branching ratios given out may be QCD-, but

not EW-corrected. The total decay width given out in this block is the sum of all accordingly computed partial decay widths.

The last block at the end of the file with the branching ratios contains the QCD-corrected branching ratios of the top-quark calculated in the 2HDM. It is required for the computation of the Higgs decays into final states with an off-shell top.

In the output file with the EW corrected NLO decay widths, indicated by the suffix '_EW', the first four blocks described above are instead followed by the two blocks `LO DECAY WIDTH` and `NLO DECAY WIDTH` for each Higgs boson (h, H, A and $H^{\pm}$). In these blocks, the partial decay widths at LO and including the one-loop EW corrections are given out, respectively. These values are particularly useful for studies of the relative size of the EW corrections and for studying the renormalization scheme dependence of the EW corrections. This allows for a rough estimate of the remaining theoretical error due to missing higher-order EW corrections. Since the EW corrections are calculated only for OS decays and additionally only for decays that are not loop-induced, these two blocks do not contain all final states written out in the blocks `DECAY QCD` and `DECAY QCD&EW`. Hence, depending on the input values that are chosen, it can happen that the two blocks `DECAY QCD` and `DECAY QCD&EW` contain decays that are not printed out in the blocks `LO DECAY WIDTH` and `NLO DECAY WIDTH`, since for the calculation of the branching ratios, off-shell and loop-induced decays are considered by `HDECAY` as well.

4 Summary

We have presented the program package `2HDECAY` for the calculation of the Higgs boson decays in the 2HDM. The tool computes the NLO EW corrections to all 2HDM Higgs boson decays into OS final states that are not loop-induced. The user can choose among 14 different renormalization schemes that have been specified in the manual. They are based on different renormalization schemes for the mixing angles α and β, an $\overline{\text{MS}}$ condition for the soft-$\mathbb{Z}_2$-breaking scale m_{12}^2 and an OS scheme for all other counterterms and wave function renormalization constants of the 2HDM necessary for calculating the EW corrections. The EW corrections are combined with the state-of-the-art QCD corrections obtained from `HDECAY`. The EW&QCD-corrected total decay widths and branching ratios are given out in an SLHA-inspired output file format. Moreover, the tool provides separately an SLHA-inspired output for the LO and EW NLO partial decay widths to all OS and non-loop-induced decays. This separate output enables *e.g.* an efficient analysis of the size of the EW corrections in the 2HDM or the comparison with the relative EW corrections in the MSSM as a SUSY benchmark model. The implementation of several different renormalization schemes additionally allows for the investigation of the numerical effects of the different schemes and an estimate of the residual theoretical uncertainty due to missing higher-order EW corrections. Being fast, our new tool enables efficient phenomenological studies of the 2HDM Higgs sector at high precision. The latter is necessary to reveal indirect new physics effects in the Higgs sector and to identify the true underlying model in case of the discovery of additional Higgs bosons. This brings us closer to our goal of understanding electroweak symmetry breaking and deciphering the physics puzzle in fundamental particle physics.

Florian Staub for helpful discussions. MK and MM acknowledge financial support from the DFG project Precision Calculations in the Higgs Sector - Paving the Way to the New Physics Landscape (ID: MU 3138/1-1).

A   Exemplary Input File

In the following, we present an exemplary input file `2hdecay.in` as it is included in the subfolder `$2HDECAY/Input` in the `2HDECAY` repository. The first integer in each line represents the line number and is not part of the actual input file, but printed here for convenience. The meaning of the input parameters is specified in Sec. 3.5. In comparison to the input file format of the unmodified `HDECAY` program [68,69], the lines 6, 26, 28, 58 and 62 are new, but the rest of the input file format is unchanged. We want to emphasize again that the value `GFCALC` in the input file is overwritten by the program and thus not an input value that is provided by the user, but it is calculated by `2HDECAY` internally. The sample 2HDM parameter point has been checked against all relevant theoretical and experimental constraints. In particular it features a SM-like Higgs boson with a mass of 125.09 GeV which is given by the lightest CP-even neutral Higgs boson h. For details on the applied constraints, we refer to Refs. [38,109].

```
 1  SLHAIN    = 1
 2  SLHAOUT   = 1
 3  COUPVAR   = 1
 4  HIGGS     = 5
 5  OMIT ELW  = 1
 6  OMIT ELW2 = 0
 7  SM4       = 0
 8  FERMPHOB  = 0
 9  2HDM      = 1
10  MODEL     = 1
11  TGBET     = 5.07403e+01
12  MABEG     = 4.67967e+02
13  MAEND     = 4.67967e+02
14  NMA       = 1
15  ******************** hMSSM (MODEL = 10) ********************************
16  MHL       = 125.D0
17  **********************************************************************
18  ALS(MZ)   = 1.18000e−01
19  MSBAR(2)  = 9.50000e−02
20  MCBAR(3)  = 0.98600e+00
21  MBBAR(MB) = 4.18000e+00
22  MT        = 1.73200e+02
23  MTAU      = 1.77682e+00
24  MMUON     = 1.056583715e−01
25  1/ALPHA   = 1.37036e+02
26  ALPHAMZ   = 7.754222173973729e−03
27  GF        = 1.1663787e−05
28  GFCALC    = 0.000000000
29  GAMW      = 2.08500e+00
30  GAMZ      = 2.49520e+00
31  MZ        = 9.11876e+01
32  MW        = 8.0385e+01
33  VTB       = 9.9910e−01
34  VTS       = 4.040e−02
35  VTD       = 8.67e−03
36  VCB       = 4.12e−02
```

```
37   VCS        =  9.7344e−01
38   VCD        =  2.252e−01
39   VUB        =  3.51e−03
40   VUS        =  2.2534e−01
41   VUD        =  9.7427e−01
42   ******************** 4TH GENERATION *************************************
43     SCENARIO FOR ELW. CORRECTIONS TO H −> GG (EVERYTHING IN GEV):
44     GG_ELW = 1: MTP = 500      MBP = 450      MNUP = 375      MEP = 450
45     GG_ELW = 2: MBP = MNUP = MEP = 600      MTP = MBP+50*(1+LOG(M_H/115)/5)
46
47   GG_ELW     =  1
48   MTP        =  500.D0
49   MBP        =  450.D0
50   MNUP       =  375.D0
51   MEP        =  450.D0
52   *********************** 2 Higgs Doublet Model ************************
53     TYPE: 1 (I), 2 (II), 3 (lepton−specific), 4 (flipped)
54     PARAM: 1 (masses), 2 (lambda_i)
55
56   PARAM      =  1
57   TYPE       =  1
58   RENSCHEM   =  7
59   *******************
60   TGBET2HDM=  4.23635D0
61   M_12^2     =  28505.5D0
62   INSCALE    =  MIN
63   ******************* PARAM=1:
64   ALPHA_H    = −0.189345D0
65   MHL        =  125.09D0
66   MHH        =  381.767D0
67   MHA        =  350.665D0
68   MH+−       =  414.114D0
69   ******************* PARAM=2:
70   LAMBDA1    =  6.368674377530086700D0
71   LAMBDA2    =  0.235570240072350970D0
72   LAMBDA3    =  1.780416490847621700D0
73   LAMBDA4    = −1.52623758540479430D0
74   LAMBDA5    =  0.074592764717552856D0
75   *************************************************************************
76   SUSYSCALE=  2.22449e+03
77   MU         = −1.86701e+03
78   M2         = −2.39071e+02
79   MGLUINO    =  7.32754e+02
80   MSL1       =  1.49552e+03
81   MER1       =  1.62210e+03
82   MQL1       =  9.30379e+01
83   MUR1       =  2.77029e+03
84   MDR1       =  1.76481e+03
85   MSL        =  1.97714e+03
86   MER        =  9.29678e+02
87   MSQ        =  2.68124e+03
88   MUR        =  1.85939e+03
89   MDR        =  2.28235e+03
90   AL         = −4.62984e+03
91   AU         =  5.31164e+03
92   AD         =  2.54430e+03
93   ON−SHELL = 0
94   ON−SH−WZ = 0
```

```
 95   IPOLE    = 0
 96   OFF–SUSY = 0
 97   INDIDEC  = 0
 98   NF–GG    = 5
 99   IGOLD    = 0
100   MPLANCK  = 2.40000 e+18
101   MGOLD    = 1.00000 e−13
102   ****************** VARIATION OF HIGGS COUPLINGS ************************
103   ELWK     = 1
104   CW       = 1.D0
105   CZ       = 1.D0
106   Ctau     = 1.D0
107   Cmu      = 1.D0
108   Ct       = 1.D0
109   Cb       = 1.D0
110   Cc       = 1.D0
111   Cs       = 1.D0
112   Cgaga    = 0.D0
113   Cgg      = 0.D0
114   CZga     = 0.D0
115   ******************** 4TH GENERATION ************************************
116   Ctp      = 0.D0
117   Cbp      = 0.D0
118   Cnup     = 0.D0
119   Cep      = 0.D0
```

B Exemplary Output Files

In the following, we present exemplary output files `2hdecay_BR.out` and `2hdecay_EW.out` as they are generated from the sample input file `2hdecay.in` and included in the subfolder `$2HDECAY/Results` in the `2HDECAY` repository. The suffices "_BR" and "_EW" stand for the branching ratios and electroweak partial decay widths, respectively. The first integer in each line represents the line number and is not part of the actual output file, but printed here for convenience. The output file format is explained in detail in Sec. 3.8. The exemplary output file was generated for a specific choice of the renormalization scheme, *i.e.* we have set `RENSCHEM =` `7` in line 58 of the input file, *cf.* App. A. For `RENSCHEM = 0`, the output file becomes considerably longer, since the electroweak corrections are calculated for all 14 implemented renormalization schemes.

B.1 Exemplary Output File for the Branching Ratios

The exemplary output file `2hdecay_BR.out` contains the branching ratios without and with the electroweak corrections. The content of the file is presented in the following.

```
 1  #
 2  BLOCK DCINFO   # Decay Program information
 3       1   2HDECAY        # decay calculator
 4       2   1.0.0          # version number
 5  #
 6  BLOCK SMINPUTS  # Standard Model inputs
 7           2     1.19596488E−05   # G_F [GeV^−2]
 8           3     1.18000000E−01   # alpha_S(M_Z)^MSbar
 9           4     9.11876000E+01   # M_Z on−shell mass
10           5     4.18000000E+00   # mb(mb)^MSbar
```

11	6	1.73200000E+02	# mt pole mass
12	7	1.77682000E+00	# mtau pole mass
13	8	4.84141297E+00	# mb pole mass
14	9	1.43141297E+00	# mc pole mass
15	10	1.05658372E−01	# muon mass
16	11	8.03850000E+01	# M_W on−shell mass
17	12	2.08500000E+00	# W boson total width
18	13	2.49520000E+00	# Z boson total width
19	#		
20	BLOCK 2HDMINPUTS	# 2HDM inputs	
21	1	1	# 2HDM parametrization
22	2	1	# 2HDM type
23	3	4.23635000E+00	# tan(beta)
24	4	2.85055000E+04	# M_12^2
25	5	−1.89345000E−01	# alpha
26	6	1.25090000E+02	# M_h
27	7	3.81767000E+02	# M_H
28	8	3.50665000E+02	# M_A
29	9	4.14114000E+02	# M_CH
30	10	6.53022117E+00	# LAMBDA1 calc. from masses/alpha
31	11	2.41545678E−01	# LAMBDA2 calc. from masses/alpha
32	12	1.82557826E+00	# LAMBDA3 calc. from masses/alpha
33	13	−1.56495189E+00	# LAMBDA4 calc. from masses/alpha
34	14	7.64848730E−02	# LAMBDA5 calc. from masses/alpha
35	15	7	# renormalization scheme EW corrs
36	16	MIN	# input scale
37	#		
38	BLOCK VCKMIN	# CKM mixing	
39	1	9.99100000E−01	# V_tb
40	1	4.04000000E−02	# V_ts
41	1	8.67000000E−03	# V_td
42	1	4.12000000E−02	# V_cb
43	1	9.73440000E−01	# V_cs
44	1	2.25200000E−01	# V_cd
45	1	3.51000000E−03	# V_ub
46	1	2.25340000E−01	# V_us
47	1	9.74270000E−01	# V_ud
48	#		
49	#	PDG	Width QCD Only
50	DECAY QCD	25	4.23079767E−03	# h decays with QCD corrections only
51	#	BR	NDA	ID1	ID2
52		5.94057260E−01	2	5	−5	# BR(h −> b | bb |)
53		6.38910135E−02	2	−15	15	# BR(h −> tau+ | tau− |)
54		2.26195956E−04	2	−13	13	# BR(h −> mu+ | mu− |)
55		2.24336368E−04	2	3	−3	# BR(h −> s | sb |)
56		2.90834784E−02	2	4	−4	# BR(h −> c | cb |)
57		7.77041237E−02	2	21	21	# BR(h −> g | g |)
58		2.19287204E−03	2	22	22	# BR(h −> gam | gam |)
59		1.50138640E−03	2	22	23	# BR(h −> Z | gam |)
60		2.05453788E−01	2	24	−24	# BR(h −> W+ | W− |)
61		2.56655457E−02	2	23	23	# BR(h −> Z | Z |)
62	#		
63	#	PDG	Width QCD and EW
64	DECAY QCD&EW	25	4.10902403E−03	# h decays with QCD and EW corrections
65		7	# Renormalization Scheme Number
66	#	BR	NDA	ID1	ID2
67		5.85629854E−01	2	5	−5	# BR(h −> b | bb |)
68		6.30484763E−02	2	−15	15	# BR(h −> tau+ | tau− |)

	BR	NDA	ID1	ID2				
69	2.18338629E−04	2	−13	13	# BR(h −> mu+	mu−	)
70	2.25852423E−04	2	3	−3	# BR(h −> s	sb	)
71	2.90980943E−02	2	4	−4	# BR(h −> c	cb	)
72	8.00069367E−02	2	21	21	# BR(h −> g	g	)
73	2.25785925E−03	2	22	22	# BR(h −> gam	gam	)
74	1.54588098E−03	2	22	23	# BR(h −> Z	gam	)
75	2.11542547E−01	2	24	−24	# BR(h −> W+	W−	)
76	2.64261611E−02	2	23	23	# BR(h −> Z	Z	)

```
77 #
78 #               PDG      Width QCD Only
79 DECAY QCD    35     1.91770641E−01    # H decays with QCD corrections only
80 #         BR         NDA       ID1       ID2
```

	BR	NDA	ID1	ID2				
81	1.19192593E−03	2	5	−5	# BR(H −> b	bb	)
82	1.58161473E−04	2	−15	15	# BR(H −> tau+	tau−	)
83	5.59342612E−07	2	−13	13	# BR(H −> mu+	mu−	)
84	4.49422613E−07	2	3	−3	# BR(H −> s	sb	)
85	5.83220675E−05	2	4	−4	# BR(H −> c	cb	)
86	5.20107902E−01	2	6	−6	# BR(H −> t	tb	)
87	4.07509451E−03	2	21	21	# BR(H −> g	g	)
88	1.78393866E−05	2	22	22	# BR(H −> gam	gam	)
89	1.07062881E−05	2	22	23	# BR(H −> Z	gam	)
90	1.35039668E−01	2	24	−24	# BR(H −> W+	W−	)
91	6.26636468E−02	2	23	23	# BR(H −> Z	Z	)
92	1.21461206E−10	2	36	36	# BR(H −> A	A	)
93	2.76517470E−01	2	25	25	# BR(H −> h	h	)
94	1.58255247E−04	2	23	36	# BR(H −> Z	A	)

```
95 #
96 #               PDG      Width QCD and EW
97 DECAY QCD&EW   35     2.08614540E−01    # H decays with QCD and EW corrections
98                        7                # Renormalization Scheme Number
99 #         BR         NDA       ID1       ID2
```

	BR	NDA	ID1	ID2				
100	1.04478374E−03	2	5	−5	# BR(H −> b	bb	)
101	1.31703579E−04	2	−15	15	# BR(H −> tau+	tau−	)
102	4.55027271E−07	2	−13	13	# BR(H −> mu+	mu−	)
103	3.85379375E−07	2	3	−3	# BR(H −> s	sb	)
104	4.95282635E−05	2	4	−4	# BR(H −> c	cb	)
105	4.69367675E−01	2	6	−6	# BR(H −> t	tb	)
106	3.74606433E−03	2	21	21	# BR(H −> g	g	)
107	1.63990036E−05	2	22	22	# BR(H −> gam	gam	)
108	9.84184384E−06	2	22	23	# BR(H −> Z	gam	)
109	1.29180073E−01	2	24	−24	# BR(H −> W+	W−	)
110	7.16362911E−02	2	23	23	# BR(H −> Z	Z	)
111	1.11654218E−10	2	36	36	# BR(H −> A	A	)
112	3.24671322E−01	2	25	25	# BR(H −> h	h	)
113	1.45477444E−04	2	23	36	# BR(H −> Z	A	)

```
114 #
115 #               PDG      Width QCD Only
116 DECAY QCD    36     4.27152737E−01    # A decays with QCD corrections only
117 #         BR         NDA       ID1       ID2
```

	BR	NDA	ID1	ID2				
118	7.25746347E−04	2	5	−5	# BR(A −> b	bb	)
119	9.71815207E−05	2	−15	15	# BR(A −> tau+	tau−	)
120	3.43658327E−07	2	−13	13	# BR(A −> mu+	mu−	)
121	2.60392190E−07	2	3	−3	# BR(A −> s	sb	)
122	3.66923493E−05	2	4	−4	# BR(A −> c	cb	)
123	9.60042117E−01	2	6	−6	# BR(A −> t	tb	)
124	9.61480220E−03	2	21	21	# BR(A −> g	g	)
125	3.96441723E−05	2	22	22	# BR(A −> gam	gam	)
126	6.57435803E−06	2	22	23	# BR(A −> Z	gam	)

127	2.94366379E−02	2	23	25	# BR(A −> Z	h	)
128	#						
129	#	PDG	Width QCD and EW				
130	DECAY QCD&EW	36	4.24433777E−01		# A decays with QCD and EW correction s		
131			7		# Renormalization Scheme Number		
132	#	BR	NDA	ID1	ID2		
133	6.82493672E−04	2	5	−5	# BR(A −> b	bb	)
134	8.62127699E−05	2	−15	15	# BR(A −> tau+	tau−	)
135	2.97643093E−07	2	−13	13	# BR(A −> mu+	mu−	)
136	2.37952864E−07	2	3	−3	# BR(A −> s	sb	)
137	3.32024128E−05	2	4	−4	# BR(A −> c	cb	)
138	9.69089576E−01	2	6	−6	# BR(A −> t	tb	)
139	9.67639546E−03	2	21	21	# BR(A −> g	g	)
140	3.98981363E−05	2	22	22	# BR(A −> gam	gam	)
141	6.61647394E−06	2	22	23	# BR(A −> Z	gam	)
142	2.03850692E−02	2	23	25	# BR(A −> Z	h	)
143	#						
144	#	PDG	Width QCD Only				
145	DECAY QCD	37	9.85202061E−01		# H+ decays with QCD corrections only		
146	#	BR	NDA	ID1	ID2		
147	6.37168323E−07	2	4	−5	# BR(H+ −> c	bb	)
148	4.97594276E−05	2	−15	16	# BR(H+ −> tau+	nu_tau	)
149	1.75959317E−07	2	−13	14	# BR(H+ −> mu+	nu_mu	)
150	4.40906799E−09	2	2	−5	# BR(H+ −> u	bb	)
151	6.72128061E−09	2	2	−3	# BR(H+ −> u	sb	)
152	8.82535052E−07	2	4	−1	# BR(H+ −> c	db	)
153	1.66151916E−05	2	4	−3	# BR(H+ −> c	sb	)
154	9.68313852E−01	2	6	−5	# BR(H+ −> t	bb	)
155	1.58162332E−03	2	6	−3	# BR(H+ −> t	sb	)
156	7.28404834E−05	2	6	−1	# BR(H+ −> t	db	)
157	2.81079832E−02	2	24	25	# BR(H+ −> W+	h	)
158	4.73997465E−05	2	24	35	# BR(H+ −> W+	H	)
159	1.80821952E−03	2	24	36	# BR(H+ −> W+	A	)
160	#						
161	#	PDG	Width QCD and EW				
162	DECAY QCD&EW	37	9.48017110E−01		# H+ decays with QCD and EW correctios		
163			7		# Renormalization Scheme Number		
164	#	BR	NDA	ID1	ID2		
165	5.93596259E−07	2	4	−5	# BR(H+ −> c	bb	)
166	4.70821612E−05	2	−15	16	# BR(H+ −> tau+	nu_tau	)
167	1.62670592E−07	2	−13	14	# BR(H+ −> mu+	nu_mu	)
168	3.64051049E−09	2	2	−5	# BR(H+ −> u	bb	)
169	6.54232264E−09	2	2	−3	# BR(H+ −> u	sb	)
170	8.52909834E−07	2	4	−1	# BR(H+ −> c	db	)
171	1.60586860E−05	2	4	−3	# BR(H+ −> c	sb	)
172	9.63902996E−01	2	6	−5	# BR(H+ −> t	bb	)
173	1.57661387E−03	2	6	−3	# BR(H+ −> t	sb	)
174	7.29483674E−05	2	6	−1	# BR(H+ −> t	db	)
175	3.24542779E−02	2	24	25	# BR(H+ −> W+	h	)
176	4.92589505E−05	2	24	35	# BR(H+ −> W+	H	)
177	1.87914498E−03	2	24	36	# BR(H+ −> W+	A	)
178	#						
179	#	PDG	Width				
180	DECAY	6	1.33570599E+00		# top decays		
181	#	BR	NDA	ID1	ID2		
182	1.00000000E+00	2	5	24	# BR(t −> b	W+	)

In the following, we make some comments on the output files that partly pick up hints and

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caveats made in the main text of the manual. First of all, notice that indeed the branching ratios of the lightest CP-even Higgs boson h are SM-like. All branching ratios presented in the blocks DECAY QCD can be compared to the ones generated by the program code HDECAY version 6.52. The user will notice that the partial widths related to the branching ratios generated by 2HDECAY and HDECAY, respectively, differ by the rescaling factor $G_F^{\text{calc}}/G_F = 1.026327$, which is applied in 2HDECAY for the consistent combination of the EW-corrected decay widths with the decay widths generated by HDECAY. The comparison furthermore shows an additional difference between the decay widths for the heavy CP-even Higgs boson H into massive vector bosons, $\Gamma(H \to VV)$ ($V = W, Z$), of around 2%. The reason is that HDECAY throughout computes these decay widths using the double off-shell formula while 2HDECAY uses the on-shell formula for Higgs boson masses above the threshold. Let us also note some phenomenological features of the chosen parameter point. The H boson with a mass of 382 GeV is heavy enough to decay on-shell into WW and ZZ, and also into the 2-Higgs boson final state hh. It decays off-shell into AA and the gauge plus Higgs boson final state ZA with branching ratios of $\mathcal{O}(10^{-10})$ and $\mathcal{O}(10^{-4})$, respectively. The pseudoscalar with a mass of 351 GeV decays on-shell into the gauge plus Higgs boson final state Zh with a branching ratio at the per cent level. The charged Higgs boson has a mass of 414 GeV allowing it to decay on-shell in the gauge plus Higgs boson final state W^+h with a branching ratio at the per cent level. It decays off-shell into the final states W^+H and W^+A with branching ratios of $\mathcal{O}(10^{-5})$ and $\mathcal{O}(10^{-3})$, respectively.

B.2 Exemplary Output File for the Electroweak Partial Decay Widths

The exemplary output file 2hdecay_EW.out contains the LO and electroweak NLO partial decay widths. The content of the file is presented in the following.

```
 1  #
 2  BLOCK DCINFO    # Decay Program information
 3          1    2HDECAY        # decay calculator
 4          2    1.0.0          # version number
 5  #
 6  BLOCK SMINPUTS   # Standard Model inputs
 7              2      1.19596488E−05   # G_F [GeV^−2]
 8              3      1.18000000E−01   # alpha_S(M_Z)^MSbar
 9              4      9.11876000E+01   # M_Z pole mass
10              5      4.18000000E+00   # mb(mb)^MSbar
11              6      1.73200000E+02   # mt pole mass
12              7      1.77682000E+00   # mtau pole mass
13              8      4.84141297E+00   # mb pole mass
14              9      1.43141297E+00   # mc pole mass
15             10      1.05658372E−01   # muon mass
16             11      8.03850000E+01   # M_W mass
17             12      2.08500000E+00   # W boson total width
18             13      2.49520000E+00   # Z boson total width
19  #
20  BLOCK 2HDMINPUTS   # 2HDM inputs
21              1                 1     # 2HDM parametrization
22              2                 1     # 2HDM type
23              3      4.23635000E+00   # tan(beta)
24              4      2.85055000E+04   # M_12^2
25              5     −1.89345000E−01   # alpha
26              6      1.25090000E+02   # M_h
27              7      3.81767000E+02   # M_H
28              8      3.50665000E+02   # M_A
```

```
29              9      4.14114000E+02    # M_CH
30             10      6.53022117E+00    # LAMBDA1 calc. from masses/alpha
31             11      2.41545678E−01    # LAMBDA2 calc. from masses/alpha
32             12      1.82557826E+00    # LAMBDA3 calc. from masses/alpha
33             13     −1.56495189E+00    # LAMBDA4 calc. from masses/alpha
34             14      7.64848730E−02    # LAMBDA5 calc. from masses/alpha
35             15                    7    # renormalization scheme EW corrs
36             16     MIN               # input scale
37   #
38   BLOCK VCKMIN   # CKM mixing
39              1      9.99100000E−01    # V_tb
40              1      4.04000000E−02    # V_ts
41              1      8.67000000E−03    # V_td
42              1      4.12000000E−02    # V_cb
43              1      9.73440000E−01    # V_cs
44              1      2.25200000E−01    # V_cd
45              1      3.51000000E−03    # V_ub
46              1      2.25340000E−01    # V_us
47              1      9.74270000E−01    # V_ud
48   #
49   #                      PDG
50   LO DECAY WIDTH     25    # h non−zero LO decay widths of on−shell and non−loop
            induced decays
51   #        WIDTH      NDA       ID1       ID2
52      5.97381239E−03    2         5        −5   # GAM(h −> b        bb     )
53      2.70309951E−04    2       −15        15   # GAM(h −> tau+     tau−   )
54      9.56989322E−07    2       −13        13   # GAM(h −> mu+      mu−    )
55      2.32096231E−06    2         3        −3   # GAM(h −> s        sb     )
56      5.26515301E−04    2         4        −4   # GAM(h −> c        cb     )
57   #
58   #                      PDG
59   NLO DECAY WIDTH     25    # h non−zero NLO EW decay widths of on−shell and non−loop
            induced decays
60                       7    # Renormalization Scheme Number
61   #        WIDTH      NDA       ID1       ID2
62      5.71956373E−03    2         5        −5   # GAM(h −> b        bb     )
63      2.59067704E−04    2       −15        15   # GAM(h −> tau+     tau−   )
64      8.97158672E−07    2       −13        13   # GAM(h −> mu+      mu−    )
65      2.26939232E−06    2         3        −3   # GAM(h −> s        sb     )
66      5.11617771E−04    2         4        −4   # GAM(h −> c        cb     )
67   #
68   #                      PDG
69   LO DECAY WIDTH     35    # H non−zero LO decay widths of on−shell and non−loop
            induced decays
70   #        WIDTH      NDA       ID1       ID2
71      6.74992142E−04    2         5        −5   # GAM(H −> b        bb     )
72      3.03307270E−05    2       −15        15   # GAM(H −> tau+     tau−   )
73      1.07265491E−07    2       −13        13   # GAM(H −> mu+      mu−    )
74      2.60148127E−07    2         3        −3   # GAM(H −> s        sb     )
75      5.90563953E−05    2         4        −4   # GAM(H −> c        cb     )
76      6.42270681E−02    2         6        −6   # GAM(H −> t        tb     )
77      2.58966436E−02    2        24       −24   # GAM(H −> W+       W−     )
78      1.20170477E−02    2        23        23   # GAM(H −> Z        Z      )
79      5.30279324E−02    2        25        25   # GAM(H −> h        h      )
80   #
81   #                      PDG
82   NLO DECAY WIDTH     35    # H non−zero NLO EW decay widths of on−shell and non−loop
            induced decays
```

83		7	# Renormalization Scheme Number		

	WIDTH	NDA	ID1	ID2	
83		7	# Renormalization Scheme Number		
84	# WIDTH	NDA	ID1	ID2	
85	6.43633010E−04	2	5	−5	# GAM(H −> b bb)
86	2.74752816E−05	2	−15	15	# GAM(H −> tau+ tau−)
87	9.49253048E−08	2	−13	13	# GAM(H −> mu+ mu−)
88	2.42670344E−07	2	3	−3	# GAM(H −> s sb)
89	5.45568867E−05	2	4	−4	# GAM(H −> c cb)
90	6.30522048E−02	2	6	−6	# GAM(H −> t tb)
91	2.69488415E−02	2	24	−24	# GAM(H −> W+ W−)
92	1.49443719E−02	2	23	23	# GAM(H −> Z Z)
93	6.77311584E−02	2	25	25	# GAM(H −> h h)
94	#				
95	#	PDG			
96	LO DECAY WIDTH 36		# A non−zero LO decay widths of on−shell and non−loop induced decays		
97	# WIDTH	NDA	ID1	ID2	
98	9.24277129E−04	2	5	−5	# GAM(A −> b bb)
99	4.15113526E−05	2	−15	15	# GAM(A −> tau+ tau−)
100	1.46794595E−07	2	−13	13	# GAM(A −> mu+ mu−)
101	3.56016986E−07	2	3	−3	# GAM(A −> s sb)
102	8.08237531E−05	2	4	−4	# GAM(A −> c cb)
103	1.84002229E−01	2	6	−6	# GAM(A −> t tb)
104	1.25739404E−02	2	23	25	# GAM(A −> Z h)
105	#				
106	#	PDG			
107	NLO DECAY WIDTH 36		# A non−zero NLO EW decay widths of on−shell and non−loop induced decays		
108		7	# Renormalization Scheme Number		
109	# WIDTH	NDA	ID1	ID2	
110	8.63659833E−04	2	5	−5	# GAM(A −> b bb)
111	3.65916116E−05	2	−15	15	# GAM(A −> tau+ tau−)
112	1.26329782E−07	2	−13	13	# GAM(A −> mu+ mu−)
113	3.23266311E−07	2	3	−3	# GAM(A −> s sb)
114	7.26707905E−05	2	4	−4	# GAM(A −> c cb)
115	1.84554001E−01	2	6	−6	# GAM(A −> t tb)
116	8.65211194E−03	2	23	25	# GAM(A −> Z h)
117	#				
118	#	PDG			
119	LO DECAY WIDTH 37		# H+ non−zero LO decay widths of on−shell and no−loop induced decays		
120	# WIDTH	NDA	ID1	ID2	
121	2.01499994E−06	2	4	−5	# GAM(H+ −> c bb)
122	4.90230906E−05	2	−15	16	# GAM(H+ −> tau+ nu_tau)
123	1.73355482E−07	2	−13	14	# GAM(H+ −> mu+ nu_mu)
124	1.34490261E−08	2	2	−5	# GAM(H+ −> u bb)
125	2.13488662E−08	2	2	−3	# GAM(H+ −> u sb)
126	4.84069114E−06	2	4	−1	# GAM(H+ −> c db)
127	9.08443168E−05	2	4	−3	# GAM(H+ −> c sb)
128	9.50609568E−01	2	6	−5	# GAM(H+ −> t bb)
129	1.55272618E−03	2	6	−3	# GAM(H+ −> t sb)
130	7.15105580E−05	2	6	−1	# GAM(H+ −> t db)
131	2.76920430E−02	2	24	25	# GAM(H+ −> W+ h)
132	#				
133	#	PDG			
134	NLO DECAY WIDTH 37		# H+ non−zero NLO EW decay widths of on−shell an non−loop induced decays		
135		7	# Renormalization Scheme Number		
136	# WIDTH	NDA	ID1	ID2	

137	1.80635406E−06	2	4	−5	# GAM(H+ −> c	b b	)
138	4.46346944E−05	2	−15	16	# GAM(H+ −> tau+	nu_tau	)
139	1.54214504E−07	2	−13	14	# GAM(H+ −> mu+	nu_mu	)
140	1.06855576E−08	2	2	−5	# GAM(H+ −> u	b b	)
141	1.99961142E−08	2	2	−3	# GAM(H+ −> u	s b	)
142	4.50162585E−06	2	4	−1	# GAM(H+ −> c	d b	)
143	8.44876595E−05	2	4	−3	# GAM(H+ −> c	s b	)
144	9.10563486E−01	2	6	−5	# GAM(H+ −> t	b b	)
145	1.48938859E−03	2	6	−3	# GAM(H+ −> t	s b	)
146	6.89134176E−05	2	6	−1	# GAM(H+ −> t	d b	)
147	3.07672108E−02	2	24	25	# GAM(H+ −> W+	h	)

The inspection of the output file shows that the EW corrections reduce the h decay widths, and the relative NLO EW corrections, $\Delta^{\mathrm{EW}} = (\Gamma^{\mathrm{EW}} - \Gamma^{\mathrm{LO}})/\Gamma^{\mathrm{LO}}$, range between -6.3 and -2.2% for the decays $\Gamma(h \to \mu^+\mu^-)$ and $\Gamma(h \to s\bar{s})$, respectively. Regarding H, the corrections can both enhance and reduce the decay widths. The relative corrections range between -11.5 and 27.7% for the decays $\Gamma(H \to \mu^+\mu^-)$ and $\Gamma(H \to hh)$, respectively. The relative corrections to the A decay widths vary between -31.2 and 0.3% for the decays $\Gamma(A \to Zh)$ and $\Gamma(A \to t\bar{t})$, respectively. And those for the $H^\pm$ decays between -20.6 and 11.1% for the decays $\Gamma(H^+ \to u\bar{b})$ and $\Gamma(H^+ \to W^+h)$, respectively. The EW corrections (for the renormalization scheme number 7) of the chosen parameter point can hence be sizeable. Finally, note also that only LO and NLO EW-corrected decay widths are given out for on-shell and non-loop induced decays.

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