# PROPHECY4F 3.0: A Monte Carlo program for Higgs-boson decays into four-fermion final states in and beyond the Standard Model

Ansgar Denner<sup>a</sup>, Stefan Dittmaier<sup>b</sup>, Alexander Mück<sup>c,\*</sup>

<sup>a</sup>Universität Würzburg, Institut für Theoretische Physik und Astrophysik, D-97074 Würzburg, Germany <sup>b</sup>Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, D-79104 Freiburg, Germany <sup>c</sup>RWTH Aachen University, Institut für Theoretische Teilchenphysik und Kosmologie, D-52056 Aachen, Germany

# Abstract

The Monte Carlo generator PROPHECY4F provides a <u>PROP</u>er description of the <u>Higgs dECaY</u> into <u>4</u> Fermions within the Standard Model, the Standard Model with a fourth fermion generation, a simple Higgs-singlet extension of the Standard Model, and the Two-Higgs-Doublet Model. The fully differential predictions include the full QCD and electroweak next-to-leading-order corrections, all interference contributions between different WW/ZZ channels, and all off-shell effects of intermediate W/Z bosons. PROPHECY4F computes the inclusive partial decay widths and allows for the computation of binned differential distributions of the decay products. For leptonic final states also unweighted events are provided.

*Keywords:* Higgs physics, radiative corrections, Monte Carlo integration

# PROGRAM SUMMARY

Manuscript Title: PROPHECY4F 3.0: A Monte Carlo program for Higgs-boson decays into four-fermion final states in and beyond the Standard Model

Authors: Ansgar Denner, Stefan Dittmaier, Alexander Mück

Preprint submitted to Computer Physics Communications

December 5, 2019

<sup>\*</sup>Corresponding author.

*E-mail address:* mueck@physik.rwth-aachen.de

Program Title: PROPHECY4F, version 3.0

Journal Reference:

Catalogue identifier:

Licensing provisions: none

Programming language: Fortran 77, Fortran 95

Computer: Any computer with a Fortran 95 compiler

Operating system: Linux, Mac OS

RAM: less than 1 GB

Keywords: Higgs physics, radiative corrections, Monte Carlo integration

*Classification:* 4.4 Feynman Diagrams, 11.1 General, High Energy Physics and Computing, 11.2 Phase Space and Event Simulation.

External routines/libraries: COLLIER (https://collier.hepforge.org/).

*Nature of problem:* Precision calculation of partial decay widths and differential distributions for Higgs-boson decays into four-fermion final states as described in Refs. [1–7].

*Solution method:* Multi-channel Monte Carlo integration of perturbative matrix elements including higher-order QCD and electroweak corrections which are based on a Feynman-diagrammatic calculation.

Restrictions: No unweighted events for semileptonic and hadronic final states.

*Running time:* For  $10^7$  weighted events the program will roughly run 10–90 minutes depending on the final state, hardware, and compilers. The production of  $10^6$  unweighted events will take about 1–2 days.

- A. Bredenstein, A. Denner, S. Dittmaier and M. M. Weber, Phys. Rev. D 74 (2006) 013004 [hep-ph/0604011].
- [2] A. Bredenstein, A. Denner, S. Dittmaier and M. M. Weber, Nucl. Phys. Proc. Suppl. 160 (2006) 131 [hep-ph/0607060].
- [3] A. Bredenstein, A. Denner, S. Dittmaier and M. M. Weber, JHEP 0702 (2007) 080 [hep-ph/0611234].
- [4] L. Altenkamp, S. Dittmaier and H. Rzehak, JHEP 1709 (2017) 134 [arXiv:1704.02645 [hep-ph]].
- [5] L. Altenkamp, S. Dittmaier and H. Rzehak, JHEP 1803 (2018) 110 [arXiv:1710.07598 [hep-ph]].

- [6] L. Altenkamp, M. Boggia and S. Dittmaier, JHEP 1804 (2018) 062 [arXiv:1801.07291 [hep-ph]].
- [7] A. Denner, S. Dittmaier and J. N. Lang, JHEP 1811 (2018) 104 [arXiv:1808.03466 [hep-ph]].

#### 1. Introduction

Presently, one of the main objectives of the experiments at CERN's Large Hadron Collider (LHC) is the precise investigation of the Higgs boson. Pinning down its nature and searching for deviations from the predictions of the Standard Model (SM) requires precise theoretical predictions. In a coordinated effort between the theory community and the LHC experiments, theoretical predictions and recommendations are compiled by the LHC Higgs Cross Section Working Group (LHCHXSWG) [8–11].

A crucial role for the accurate investigation of the properties of the Higgs boson is played by the Higgs branching ratios and decay widths. The SM Higgs-boson branching ratios used by the LHC experiments are provided by the LHCHXSWG [8–11] based on the codes HDECAY [12–14] for the two-particle decays and PROPHECY4F [1–3] for the Higgs decays into four fermions. While both codes were initially constructed for the SM, they have been extended to models beyond. Recent versions [14, 15] of HDECAY include the SM with four generations of fermions, a general Two-Higgs-Doublet Model (THDM), and the minimal supersymmetric Standard Model (MSSM). Moreover, an extension to the SM effective field theory exists [16].

PROPHECY4F is a state-of-the-art tool to predict the SM Higgs-boson decay widths into four arbitrary fermions (i.e. quarks or leptons) via W and/or Z pairs, including full electroweak (EW) and QCD next-to-leading order (NLO) corrections. These processes have played a central role in the discovery of the Higgs boson, and are very important channels in Higgs coupling analyses (see Refs. [10, 11] and references therein). Originally, PROPHECY4F had been designed for Higgs-boson decays in the SM, but in recent years it has been extended to the Standard Model with a fourth fermion generation and to the corresponding decays of CP-even, neutral Higgs bosons in the THDM [17, 18] and in a simple Higgs-singlet extension of the SM (SESM) [19–21], as described in Refs. [24], [4, 5], and [6], respectively. As a particular strength of our THDM and SESM implementations, PROPHECY4F supports many different renormalization schemes, even different types of schemes based on  $\overline{\rm MS}$ , on-shell, or symmetry-inspired renormalization conditions [7]. This allows for an assessment of uncertainties in predictions due to residual renormalization scale and renormalization scheme dependences. We consider this feature important, since many examples in the literature have shown that individual renormalization schemes might produce unreliable results in specific regions of parameter space of model extensions (see, e.g., Refs. [4, 5, 7] for such examples of  $H \rightarrow 4f$  decays in the THDM). On the technical side, the internal library of PROPHECY4F for one-loop integrals is now replaced by the public integral library COLLIER [22, 23].

An alternative to PROPHECY4F for the simulation of the SM Higgs-boson decays into four charged leptons is the Monte Carlo event generator HTO4L [25]. Besides the complete NLO EW corrections, it includes also multiple-photon effects in a matched-to-NLO Parton Shower framework. The SM results of HTO4L are fully equivalent to those of PROPHECY4F for the inclusive partial decay widths and branching ratios. The effects of multi-photon emissions on distributions provided by HTO4L are typically below one percent. The code HTO4L has been extended to the SM effective field theory [26].

The purpose of this paper is to describe version 3.0 of PROPHECY4F including all of its extensions and to document its use.

This paper is organized as follows: In Section 2 we describe the basic features of PROPHECY4F and highlight some important details. Section 3 provides all information how to use and run the code, and Section 4 describes the output of the code and the sample runs. Concluding remarks are contained in Section 5.

# 2. PROPHECY4F description

PROPHECY4F provides predictions for decays of on-shell Higgs bosons via a pair of virtual W/Z bosons into four fermions in the SM, the SM with a fourth fermion generation, a simple Higgs-singlet extension of the SM, and the Two-Higgs-Doublet Model. External fermions are considered in the massless limit. In the non-standard models, PROPHECY4F only deals with the decays of the CP-even, neutral Higgs bosons, and possible fourfermion decay channels via Higgs-boson pairs are not considered (in line with the massless limit of the external fermions). PROPHECY4F produces fully differential predictions in the Higgs-boson rest frame, including the full QCD and electroweak next-to-leading-order corrections, all interference

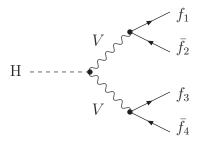


Figure 1: Generic lowest-order diagram for  $H \rightarrow 4f$  where V = W, Z.

contributions between different WW/ZZ channels at leading order (LO) and NLO, and all off-shell effects of intermediate W/Z bosons. For decays within the SM also an improved Born approximation (IBA) is implemented.

#### 2.1. Process definition

The considered processes are of the form

$$H(p) \to f_1(k_1) + \bar{f}_2(k_2) + f_3(k_3) + \bar{f}_4(k_4), \qquad (1)$$

where the momenta are indicated in parentheses. The generic LO Feynman diagram is shown in Fig. 1. The external fermions are assumed to be massless; their masses only serve as regulators in case of logarithmic mass singularities, which arise for instance if final-state fermions and photons are not recombined. While the order of fermions in the input is arbitrary, the produced distributions are based on a canonical order of the final-state fermions in (1), where the fermion–antifermion pairs  $f_1 \bar{f}_2$  and  $f_3 \bar{f}_4$  are related to the virtual W/Z bosons. For processes, where both virtual WW and ZZ pairs are possible,  $f_1 \bar{f}_2$  and  $f_3 \bar{f}_4$  are associated to the W bosons, as further explained in Section 4.2.

#### 2.2. EW input-parameter scheme

For the electromagnetic coupling constant, we use the  $G_{\rm F}$  scheme, i.e. the coupling constant  $\alpha$  is derived from the Fermi constant according to

$$\alpha_{G_{\rm F}} = \frac{\sqrt{2}G_{\rm F}M_{\rm W}^2}{\pi} \left(1 - \frac{M_{\rm W}^2}{M_{\rm Z}^2}\right).$$
 (2)

This procedure takes into account some higher-order effects, related to the running of the electromagnetic coupling and to the  $\rho$  parameter, already at tree level.

#### 2.3. Complex-mass scheme, input masses and widths

Gauge-boson resonances are treated using the complex-mass scheme [27, 28], i.e. all corresponding decay and off-shell effects are supported at NLO accuracy in the full phase space. As input, the program expects the on-shell W/Z masses and widths. From these it calculates internally the real parts of the complex pole masses using

$$M_V^{\text{pole}} = \frac{M_V^{\text{on-shell}}}{\sqrt{1 + (\Gamma_V^{\text{on-shell}}/M_V^{\text{on-shell}})^2}} \,. \tag{3}$$

The imaginary parts of the complex pole masses, i.e. the vector-boson widths are calculated as described below. These pole masses are then used in propagators, the complex weak mixing angle, and other couplings for the evaluation of the Higgs-boson decays.

The decay widths of the W and Z bosons that enter the complex pole masses are calculated from the pole masses and the other input parameters as follows: If only LO results are requested, the LO widths are used. For NLO results and the IBA we employ the NLO widths (also for the LO subcontribution). This ensures that the effective branching fractions for the Wand Z-boson decays in both LO and NLO add up to one.

Since the NLO W and Z widths in the SESM and the THDM are almost identical to the corresponding SM NLO widths, the SM widths are used employing a SM Higgs mass set to the mass of the decaying Higgs boson.

# 2.4. Total width

The total width is calculated according to

$$\Gamma_{\mathrm{H}\to 4f} = \Gamma^{\mathrm{total}} = \Gamma^{\mathrm{leptonic}} + \Gamma^{\mathrm{semi-leptonic}} + \Gamma^{\mathrm{hadronic}} \tag{4}$$

with

$$\Gamma^{\text{leptonic}} = 3\Gamma^{\nu_{e}\bar{\nu}_{e}\nu_{\mu}\bar{\nu}_{\mu}} + 3\Gamma^{e^{-}e^{+}\mu^{-}\mu^{+}} + 6\Gamma^{\nu_{e}\bar{\nu}_{e}\mu^{-}\mu^{+}} + 6\Gamma^{\nu_{e}e^{+}\mu^{-}\bar{\nu}_{\mu}} + 3\Gamma^{\nu_{e}\bar{\nu}_{e}\nu_{e}\bar{\nu}_{e}} + 3\Gamma^{e^{-}e^{+}e^{-}e^{+}} + 3\Gamma^{\nu_{e}e^{+}e^{-}\bar{\nu}_{e}},$$

$$\Gamma^{\text{hadronic}} = \Gamma^{u\bar{u}c\bar{c}} + 3\Gamma^{d\bar{d}s\bar{s}} + 4\Gamma^{u\bar{u}s\bar{s}} + 2\Gamma^{u\bar{d}s\bar{c}} + 2\Gamma^{u\bar{u}u\bar{u}} + 3\Gamma^{d\bar{d}d\bar{d}} + 2\Gamma^{u\bar{d}d\bar{u}},$$

 $\Gamma^{\text{semi-leptonic}} = 6\Gamma^{\nu_{e}\bar{\nu}_{e}u\bar{u}} + 9\Gamma^{\nu_{e}\bar{\nu}_{e}d\bar{d}} + 6\Gamma^{u\bar{u}e^{-}e^{+}} + 9\Gamma^{d\bar{d}e^{-}e^{+}} + 12\Gamma^{\nu_{e}e^{+}d\bar{u}}.$  (5)

The total width can be split into decays via ZZ, WW and the interference,

$$\Gamma_{\mathrm{H}\to 4f} = \Gamma_{\mathrm{H}\to\mathrm{W}^*\mathrm{W}^*\to 4f} + \Gamma_{\mathrm{H}\to\mathrm{Z}^*\mathrm{Z}^*\to 4f} + \Gamma_{\mathrm{WW}/\mathrm{ZZ}\text{-interference}},\tag{6}$$

where the individual terms are defined in terms of partial widths with specific final states as

$$\Gamma_{\mathrm{H}\to\mathrm{W}^{*}\mathrm{W}^{*}\to4f} = 9\Gamma^{\nu_{e}\mathrm{e}^{+}\mu^{-}\bar{\nu}_{\mu}} + 12\Gamma^{\nu_{e}\mathrm{e}^{+}\mathrm{d}\bar{\mathrm{u}}} + 4\Gamma^{\mathrm{u}\bar{\mathrm{d}}\mathrm{s}\bar{\mathrm{c}}},$$

$$\Gamma_{\mathrm{H}\to\mathrm{Z}^{*}\mathrm{Z}^{*}\to4f} = 3\Gamma^{\nu_{e}\bar{\nu}_{e}\nu_{\mu}\bar{\nu}_{\mu}} + 3\Gamma^{\mathrm{e}^{-}\mathrm{e}^{+}\mu^{-}\mu^{+}} + 9\Gamma^{\nu_{e}\bar{\nu}_{e}\mu^{-}\mu^{+}}$$

$$+ 3\Gamma^{\nu_{e}\bar{\nu}_{e}\nu_{e}\bar{\nu}_{e}} + 3\Gamma^{\mathrm{e}^{-}\mathrm{e}^{+}\mathrm{e}^{-}\mathrm{e}^{+}}$$

$$+ 6\Gamma^{\nu_{e}\bar{\nu}_{e}\mathrm{u}\bar{\mathrm{u}}} + 9\Gamma^{\nu_{e}\bar{\nu}_{e}\mathrm{d}\bar{\mathrm{d}}} + 6\Gamma^{\mathrm{u}\bar{\mathrm{u}}\mathrm{e}^{-}\mathrm{e}^{+}} + 9\Gamma^{\mathrm{d}\bar{\mathrm{d}}\mathrm{e}^{-}\mathrm{e}^{+}}$$

$$+ \Gamma^{\mathrm{u}\bar{\mathrm{u}}\mathrm{c}\bar{\mathrm{c}}} + 3\Gamma^{\mathrm{d}\bar{\mathrm{d}}\mathrm{s}\bar{\mathrm{s}}} + 6\Gamma^{\mathrm{u}\bar{\mathrm{u}}\mathrm{s}\bar{\mathrm{s}}} + 2\Gamma^{\mathrm{u}\bar{\mathrm{u}}\mathrm{u}} + 3\Gamma^{\mathrm{d}\bar{\mathrm{d}}\mathrm{d}\bar{\mathrm{d}}},$$

$$\Gamma_{\mathrm{WW}/\mathrm{ZZ}\text{-interference}} = 3\Gamma^{\nu_{e}\mathrm{e}^{+}\mathrm{e}^{-}\bar{\nu}_{e}} - 3\Gamma^{\nu_{e}\bar{\nu}_{e}\mu^{-}\mu^{+}} - 3\Gamma^{\nu_{e}\mathrm{e}^{+}\mu^{-}\bar{\nu}_{\mu}}$$

$$+ 2\Gamma^{\mathrm{u}\bar{\mathrm{d}}\mathrm{d}\bar{\mathrm{u}}} - 2\Gamma^{\mathrm{u}\bar{\mathrm{u}}\mathrm{s}\bar{\mathrm{s}}} - 2\Gamma^{\mathrm{u}\bar{\mathrm{d}}\mathrm{s}\bar{\mathrm{c}}}.$$
(7)

# 2.5. Extended Higgs models

The conventions for the implementation of the SESM and THDM in PRO-PHECY4F follow Ref. [7], where the Higgs potentials are specified and the renormalized parameters are defined. More details on the SESM, though with slightly different conventions, can be found in Refs. [6, 29], and more details on the THDM are provided in Refs. [4, 5, 29, 30]. The renormalization of mixing angles in extended Higgs sectors has recently been studied by various authors both in the SESM [6, 29, 31, 32] and the THDM [4, 29, 30, 33– 36]. PROPHECY4F employs various renormalization schemes as defined in Refs. [4, 5, 7].

The renormalization schemes are defined via the choice of renormalization conditions. In particular,  $\overline{\text{MS}}$  schemes depend on the choice of the renormalized parameters, e.g. whether a mixing angle  $(\alpha, \beta)$  or a coupling  $(\lambda_{12}, \lambda_1, \ldots)$  is used for renormalization, and in addition on the treatment of tadpoles. The renormalization schemes used in PROPHECY4F are based on the tadpole schemes of Refs. [37] and [38] dubbed FJTS and PRTS, respectively, in Ref. [7]. More details on these tadpole schemes can be found in Refs. [7, 30].

For a comparison of predictions based on different renormalization schemes, a conversion of renormalized input parameters is needed. PRO-PHECY4F automatically provides this conversion and the running of  $\overline{\text{MS}}$  parameters based on the values for the scale of the input parameters (start renormalization scale) and the scale of the parameters used in the calculation (target renormalization scale). In particular, this can be used to evaluate the

renormalization-scale variation with respect to parameters of the extended Higgs sectors renormalized in the  $\overline{\text{MS}}$  scheme (which is unrelated to the scale dependence of  $\alpha_s$ ). More details on the parameter conversion can be found in Refs. [4, 6, 7].

# 3. The usage of PROPHECY4F

#### 3.1. PROPHECY4F installation

PROPHECY4F has been tested under various different Linux distributions and MAC OS. It should be compilable with any standard Fortran compiler and has been successfully tested using GNU Fortran (GCC), the Intel Fortran Compiler, and Intel's MPI for parallel execution.

PROPHECY4F depends on COLLIER [22, 23, 39–41] for the evaluation of loop integrals. The COLLIER library (libcollier.so or libcollier.a for dynamic or static linking, respectively) can be compiled following the COLLIER instructions [22].

For installation, download PROPHECY4F from HEPForge [42] and issue

```
tar -xzvf Prophecy4f-3.0.tar.gz
cd Prophecy4f-3.0
make COLLIERDIR=path FC=compiler
```

from the command line where path has to be the path to the COLLIER library and FC is an optional argument that allows to use the Fortran compiler compiler instead of the default one. Both variables COLLIERDIR and FC can also be set in the makefile. The make command generates the executable ./Prophecy4f. The PROPHECY4F directory contains the README-3.0 file as a manual and a default input file defaultinput. The source code is contained in the subdirectory src, and several example runs can be found in the subdirectory example-runs. The subdirectories HISTOGRAMS, HISTUNWEIGHTED, and UNWEIGHTEDEVENTS are empty and are used at runtime to store the results as discussed in Section 4.1. The empty subdirectory obj is used to store the object files after compilation.

#### 3.2. PROPHECY4F execution

PROPHECY4F is executed using

```
./Prophecy4f < inputfile
```

where the file inputfile specifies all the input for the current run. If no input

file is provided via standard input, PROPHECY4F does not start. Output is written to standard output. If an output file is specified in the input file, most output is redirected to the output file. Note that the path to the COLLIER library has to be known (e.g. by including it in the LD\_LIBRARY\_PATH variable) if the dynamic library is linked.

The general format of the input file is given in the default input file defaultinput and the input files of the subdirectories containing the example runs. While defaultinput specifies all relevant parameters, it is sufficient to specify those values that differ from the default. As a general remark, do not forget the d0 after double precision quantities.

# 3.3. PROPHECY4F input

In the following sections, all input options for PROPHECY4F are discussed along with the underlying physics. We follow the structure of the default input file defaultinput which is provided with the PROPHECY4F distribution.

#### 3.3.1. Input for calculations within the SM

In this section, we discuss all the input that is necessary for predictions within the Standard Model:

outputfile: a character string that specifies the name of the output file.

outputfile=' '	: For a blank character string (default) all
	output is written to standard output.
<pre>outputfile='filename'</pre>	: Any other string usable as a file name
	redirects the output to a file with the
	given filename.

The plot data will be written to files named plot.\* in directory HISTOGRAMS. The string plot is replaced by the file name of the output file if provided. Unweighted events are written to the directory UNWEIGHTEDEVENTS (\*.lhe files) in the same manner. To allow for consistency checks, unweighted events are also binned into distributions written to the directory HISTUNWEIGHTED.

nevents: integer that selects the number of generated weighted events.

nevents=10000000 : is the default value.

We recommend to use at least  $10^7$  events for the integrated partial decay width, for histograms about  $5 \cdot 10^7$  should be used.

nunwevents: integer that selects the number of unweighted events.

The unweighted events are produced in the Les Houches event file format [46] after the generation of **nevents** weighted events to find the maximal weights used for unweighting. Unweighted events have weight 1 or very rarely weight -1. For **nunwevents**>0 one has to use **qsoftcoll=2** (slicing, see below) and **qrecomb=0** (no recombination, see below). For **nunwevents**>0 the two parameters are set accordingly.

model: integer that selects the model used for the calculation.

model=0 : the Standard Model (SM) (default), model=1 : a Higgs-Singlet Extension of the Standard Model (SESM), model=2 : the Two-Higgs-Doublet-Model (THDM), model=4 : the SM with a fourth fermion generation (SM4).

Additional input that specifies the models beyond the Standard Model are discussed from Section 3.3.2 to Section 3.3.5.

- contrib: integer that specifies how radiative corrections are included when calculating the partial decay width.

  - contrib=2 : use the Improved Born Approximation (IBA) (see Ref. [1] for details),
  - contrib=3 : calculate only leading-order result, i.e. no radiative corrections are included.

Note that the option contrib=2 is only available in the SM (model=0).

qqcd: integer that specifies whether to use only EW corrections, both EW and QCD corrections, or only QCD corrections.

qqcd=0 : only EW corrections are included, qqcd=1 : EW and QCD corrections are included (default), qqcd=2 : only QCD corrections are included. Note that for purely leptonic final states only EW corrections contribute.

**qsoftcoll**: integer that specifies whether soft and collinear singularities are treated with the subtraction or the slicing method.

qsoftcoll=1 : the subtraction method is used (default), qsoftcoll=2 : the slicing method is used.

For calculations of partial decay widths, subtraction is the preferred option, while for the production of unweighted events slicing has to be used.

channel: string that specifies the final state for which the width is to be calculated.

channel= e anti-e mu anti-mu : is the default.

The final state has to be specified using e for the electron, mu for the muon, nue and num for the corresponding neutrinos, dq, uq, sq, cq for the down, up, strange, and charm quark, respectively, and the corresponding antiparticles, e.g. anti-e, anti-num, anti-dq, etc. The four final-state particles have to be separated by spaces. If more than one channel is specified by including several channel lines in the input file, PROPHECY4F will calculate the different channels consecutively.

Since final-state fermions are treated in the massless limit, integrated partial widths usually do not differ between different generations of fermions. For example, the integrated partial decay width for  $H \rightarrow e$  anti-e e anti-e is the same as for  $H \rightarrow mu$  anti-mu mu anti-mu. Symmetric final states are an exception, here effects of identical particles are taken into account, i.e.  $H \rightarrow e$  anti-e e anti-e is different from  $H \rightarrow e$  anti-e mu anti-mu. Moreover, in distributions (or unweighted events) fermion-mass logarithms do show up if no photon recombination is applied, i.e. fermions of different generations will in general yield different results. Third generation fermions cannot be used as input. However, the partial widths including third generation particles like bottom quarks, tau leptons or tau neutrinos do not differ significantly in the massless approximation from those into fermions of the first and second generation, i.e. use e.g.  $H \rightarrow mu$  anti-mu sq

anti-sq to calculate the  $H \rightarrow mu$  anti-mu bq anti-bq partial width. Top quarks in the final state are not supported. The old input format of Version 1.0 is also still supported.

In addition one can choose the special cases [see (5) and (7)]:

channel=	total	:	the total width is calculated,
channel=	leptonic	:	the leptonic width is calculated,
channel=	semi-leptonic	:	the semi-leptonic width is calculated,
channel=	hadronic	:	the hadronic width is calculated,
channel=	WW	:	$\Gamma_{\mathrm{H}\to\mathrm{W}^*\mathrm{W}^*\to4f}$ is calculated,
channel=	ZZ	:	$\Gamma_{\mathrm{H}\to\mathrm{Z}^*\mathrm{Z}^*\to 4f}$ is calculated,
channel=	interference	:	$\Gamma_{\rm WW/ZZ\text{-interference}}$ is calculated.

If one of the above options is used, PROPHECY4F calculates the necessary partial widths consecutively. For channel= total, also the results for channel= WW, channel= ZZ, and channel= interference are automatically calculated.

qrecomb: integer that specifies whether to use a recombination procedure.

qrecomb=0 : photons and fermions are not recombined,

qrecomb=1 : the photon and the fermion with the smallest invariant mass are recombined if their invariant mass in GeV is smaller than invrecomb (see below), i.e. their 4momenta are added and attributed to the fermion (default).

Note that we cannot use a proper jet-algorithm for recombination since the lab frame of the Higgs decay is not specified; this would require the embedding of the Higgs decay process into a full production process. For inclusive partial widths recombination does not affect the result. Independent of qrecomb, we always recombine the two QCD partons with the smallest invariant mass in events with gluon emission to form two jets in semileptonic decays or four jets in hadronic decays. When producing unweighted events for leptonic final states one has to use qrecomb=0, in order to create the flexibility to perform the recombination on the event files after production.

invrecomb: double precision number that is used in the recombination procedure for qrecomb=1 (see above).

- invrecomb=5d0 : is the default, i.e. the photon-fermion pair with the smallest invariant mass is recombined if the invariant mass is smaller than 5 GeV.
- **qrecombcolle:** integer that specifies whether to use a specific recombination procedure for electrons.

In the slicing approximation these recombined electron-photon pairs are strictly collinear. This option for recombination might be useful to avoid large fractions of negative unweighted events for electron final states. The idea is that photons and electrons are always recombined within a small cone in a physical analysis, i.e. electrons are used as dressed leptons in contrast to bare muons which can also be defined without recombination. The technical slicing cone should always be smaller than the physical cone size, so that this recombination is not in conflict with the physical treatment, i.e. the full flexibility of the unweighted event sample is not spoiled if dressed electrons are assumed. The internal slicing parameters are set so that the ratio of the energies of an unrecombined photon and the Higgs boson fulfils  $E_{\gamma}/E_{\rm H} > \delta_E = 4 \times 10^{-4}$  and each angle between the three-momentum of an unrecombined photon and the three-momentum of any fermion is larger than  $\Delta \theta = 3 \times 10^{-2}$ . All quantities refer to the Higgs-boson rest frame.

randomseed: integer that specifies how random numbers are generated.

randomseed = -1 : use internal random numbers as in PRO-PHECY4F version 2.0 (default),

 $randomseed \geq 0$ : use RANLUX [43] for random number generation, where randomseed is used as a seed for the random number generator to obtain statistically independent samples. The following input parameters can be specified with double-precision values. Here, we also state the corresponding default values:

mh = 125d0	: Higgs-boson mass in the SM or SM4 in GeV,
alphas = 0.118d0	: strong coupling constant,
gf = 1.1663787d-5	: Fermi constant $G_{\rm F}$ in ${\rm GeV}^{-2}$ ,
mz = 91.1876d0	: on-shell Z-boson mass in GeV,
mw = 80.385d0	: on-shell W-boson mass in GeV,
gammaz = 2.4952d0	: on-shell Z-boson width in GeV,
gammaw = 2.085d0	: on-shell W-boson width in GeV,
me = 0.510998928d-3	: electron mass in GeV,
mmu = 105.6583715d-3	: muon mass in GeV,
mtau = 1.77682d0	: tau mass in GeV,
md = 0.100d0	: d-quark mass in GeV,
mu = 0.100d0	: u-quark mass in GeV,
ms = 0.100d0	: s-quark mass in GeV,
mc = 1.51d0	: c-quark mass in GeV,
mb = 4.92d0	: b-quark mass in GeV,
mt = 172.5d0	: t-quark mass in GeV.

The values of the fermion masses are needed, but the results are practically independent of the specific values in the  $\alpha_{G_{\rm F}}$  scheme for inclusive quantities. Only if photons and fermions are not recombined, logarithms of the fermion masses may appear in distributions.

The gauge-boson resonances are described in the complex-mass scheme as discussed in Section 2.3. The values of the on-shell gauge-boson masses and widths, as given in the input, are only used to calculate the pole masses of the gauge bosons according to (3). For the actual evaluation of the Higgs decay, the gauge-boson widths are calculated from the gauge-boson pole masses and the remaining input as discussed in Section 2.3: If only LO results are requested (i.e. for contrib=3) the LO gauge-boson widths are used. For NLO results and the IBA (contrib=1 or contrib=2) we apply the NLO gauge-boson widths (also for the LO sub-contribution). Note that in Refs. [1–3] we have presented the LO results with NLO gauge-boson widths. At LO, the difference is, of course, only a higher-order effect.

In the SESM and the THDM, the NLO W and Z widths are almost identical to the corresponding SM NLO widths. Hence, the SM widths are used employing a SM Higgs mass set to the mass of the decaying Higgs boson.

#### 3.3.2. Additional input for calculations within SM4

In PROPHECY4F a 4th fermion generation of massive fermions can be optionally included upon setting model=4. In the following, we specify the additional input needed for a calculation in the model SM4. The following options have no effect unless model=4 is used.

qsm4: integer that specifies which corrections are included.

- qsm4=1 : the full mass dependence of the additional closed fermion loops is taken into account at NLO, comprising the HWW/HZZ/HZA/HAA vertex corrections as well as all gauge-boson self-energies (default),
- qsm4=2: in addition to the corrections used for qsm4=1, the leading corrections  $\propto G_{\rm F}^2 m_{f,4}^4$  and  $\propto \alpha_s G_{\rm F} m_{f,4}^2$  to the HVV vertices are taken in to account, which are taken from Refs. [44] and [45], respectively. Here,  $m_{f,4}$  refers to the masses of the fourth generation fermions.

The masses of the two additional leptons and two additional quarks are specified as double precision numbers, stated in the following along with their default values:

ml4 = 600d0	: mass of the charged lepton in the 4th generation,
mn4 = 600d0	: mass of the neutrino in the 4th generation,
md4 = 600d0	: mass of the down-type quark in the 4th generation,
mu4 = 600d0	: mass of the up-type quark in the 4th generation.

3.3.3. Additional input for calculations within the SESM or THDM

PROPHECY4F can perform calculations for the partial widths of the CPeven neutral Higgs bosons in the SESM (model=1) or the THDM (model=2). Here and in the following sections, we discuss the additional input for these models which is irrelevant for calculations within the SM or SM4.

First of all, one has to specify the Higgs boson in the initial state for which the calculation has to be performed:

hboson: string that specifies the decaying Higgs boson.

hboson=h0 : light Higgs boson in the SESM or THDM (default), hboson=hh : heavy Higgs boson in the SESM or THDM. The SESM/THDM input parameters and the available renormalization schemes are discussed in the following sections. The SESM/THDM input parameters of  $\overline{\text{MS}}$  type are defined at the renormalization scale mrenbsm1 in the renormalization scheme specified by renscheme and evolved to the renormalization scale mrenbsm2 by solving the renormalization group equations numerically. The corresponding parameters at the target scale mrenbsm2 are used in the calculation within the scheme renscheme. In particular, this can be used to evaluate the scale variation with respect to the BSM  $\overline{\text{MS}}$  parameters ( $\alpha_s$  is not varied).

#### 3.3.4. Additional input for calculations within the SESM

In this section, we discuss the input specific for the SESM (see Section 2.5). We follow the notation and the conventions of Ref. [7].

**renscheme**: integer that specifies the renormalization scheme for the input parameters.

renscheme = 0 : $\alpha \overline{\text{MS}}$ (running $\lambda_{12}$ ), i.e. $\overline{\text{MS}}$ of Ref. [6],
renscheme = 1 : $\alpha \overline{\text{MS}}$ à la FJ (running $\lambda_{12}$ ), i.e. FJ of Ref. [6],
renscheme = 2 : $\alpha$ on-shell (running $\lambda_{12}$ ), i.e. OS of Ref. [7] for $\alpha$ ,
renscheme = 3 : $\alpha \overline{\text{MS}}$ (running $\lambda_1$ ), i.e. $\overline{\text{MS}}$ (PRTS) of Ref. [7],
renscheme = 4 : $\alpha$ $\overline{MS}$ à la FJ (running $\lambda_1$ ), i.e. $\overline{MS}$ (FJTS) of
Ref. [7],
renscheme = 5 : $\alpha$ on-shell (running $\lambda_1$ ), i.e. OS of Ref. [7] (de-
fault),
renscheme = $6$ : BFM-inspired scheme based on Eqs. (3.41) and
(3.64) of Ref. [7],
renscheme = 7 : BFM-inspired scheme BFMS of Ref. [7] based on
Eqs. $(3.41)$ and $(3.68)$ of Ref. [7].

The masses of the Higgs bosons, the Higgs-boson mixing angle  $\alpha$ , the additional Higgs-sector coupling  $\lambda_{12}$ , and the renormalization scales have to be specified as double precision numbers, stated in the following along with their default values:

mrenbsm1 = 125.1d0	: start renormalization scale for $\overline{\mathrm{MS}}$ param-
	eters (we usually use mrenbsm1 = mh0),
mrenbsm2 = 125.1d0	: target renormalization scale for $\overline{\mathrm{MS}}$ pa-
	rameters (we usually use mrenbsm2 =
	mhO),

sa = 0.29d0	$: \sin \alpha,$
!ta = 0.303d0	: $\tan \alpha$ , as alternative to define $\alpha$
mh0 = 125.1d0	: mass of the light Higgs boson,
mhh = 200d0	: mass of the heavy Higgs boson,
112 = 0.07d0	: coupling $\lambda_{12}$ .

The mixing angle  $\alpha$  can vary in the range  $-\pi/2 < \alpha < \pi/2$ . The line for setting ta is an alternative for defining the angle  $\alpha$ ; the parameter  $\alpha$ , however, should only be set once. Our model parametrization requires the relation  $s_{\alpha}\lambda_{12} \geq 0$  for consistency.

3.3.5. Additional input for calculations within the THDM

In this section, we discuss the input specific for the THDM (see Section 2.5). We follow the notation and the conventions of Ref. [7].

<pre>modeltype: integer that specifies the variant of the THDM, as defined in Ref. [5].</pre>
modeltype = 1 : type I: all fermions couple to Higgs doublet $\Phi_2$ only (default),
modeltype = 2 : type II: down-type fermions couple to $\Phi_1$ , up-type fermions to $\Phi_2$ ,
modeltype = 3 : lepton specific: quarks couple to $\Phi_2$ , leptons to $\Phi_1$ ,
modeltype = 4 : flipped: down-type quarks couple to $\Phi_1$ , up-type quarks and charged leptons couple to $\Phi_2$ .

**renscheme**: integer that specifies the renormalization scheme for the input parameters.

renscheme = 0 : $\alpha/\beta$ $\overline{\text{MS}}$ , i.e. $\overline{\text{MS}}(\alpha)$ of Refs. [4, 5] = $\overline{\text{MS}}(\text{PRTS})$
of Ref. [7],
renscheme = 1 : $\alpha/\beta$ MS à la FJ, i.e. FJ( $\alpha$ ) of Refs. [4, 5] = MS
(FJTS) of Ref. [7],
renscheme = 2 : $\lambda_3/\beta$ $\overline{\text{MS}}$ , i.e. $\overline{\text{MS}}$ ( $\lambda_3$ ) of Refs. [4, 5],
renscheme = 3 : $\lambda_3/\beta$ MS à la FJ, i.e. FJ( $\lambda_3$ ) of Refs. [4, 5],
renscheme = 4 : $\alpha/\beta$ on-shell ( $\nu_2$ ), i.e. OS2 of Ref. [7],
renscheme = 5 : $\alpha/\beta$ on-shell $(\nu_1, \nu_2)$ , i.e. OS12 of Ref. [7] (default),
renscheme = 6 : $\alpha/\beta$ on-shell ( $\nu_1$ ), i.e. OS1 of Ref. [7],
renscheme = $7$ : BFM-inspired scheme based on Eqs. $(3.41)$ and
(3.74) of Ref. [7],
renscheme = 8 : BFM-inspired scheme BFMS of Ref. [7] based on
Eqs. $(3.41)$ and $(3.76)$ of Ref. [7].

The masses of the Higgs bosons, the mixing angles  $\alpha$ ,  $\beta$ , the additional Higgssector coupling  $\lambda_5$ , and the renormalization scales have to be specified as double precision numbers, stated in the following along with their default values:

mrenbsm1 = 361d0	: start renormalization scale for MS parame- ters (we usually use mrenbsm1=(mh0+mhh+ma0+2mhp)/5),
mrenbsm2 = 361d0	<pre>: target renormalization scale for MS parame- ters (we usually use mrenbsm2=(mh0+mhh+ma0+2mhp)/5),</pre>
sa = -0.355d0	$\sin \alpha$ ,
!ta = -0.380d0	: $\tan \alpha$ , as alternative to define $\alpha$
!cba = 0.1d0	: $\cos(\beta - \alpha)$ , as alternative to define $\alpha$
!sgnsba = +1	: $\operatorname{sgn}[\sin(\beta - \alpha)]$ , required if cba is input
tb = 2d0	$: \tan eta,$
!sb = 0.894d0	: $\sin(\beta)$ , as alternative to define $\beta$ ,
!cb = 0.447d0	: $\cos(\beta)$ , as alternative to define $\beta$ ,
mh0 = 125d0	: mass of the light CP-even Higgs boson,
mhh = 300d0	: mass of the heavy CP-even Higgs boson,
ma0 = 460d0	: mass of the CP-odd Higgs boson,
mhp = 460d0	: mass of the charged Higgs boson,
lam5 = -1.9d0	: coupling $\lambda_5$ .

The mixing angles  $\alpha$  and  $\beta$  can vary in the ranges  $-\pi/2 < \alpha < \pi/2$  and  $0 < \beta < \pi/2$ . The lines for setting **sb** and **cb** are alternatives for defining the angle  $\beta$ , the ones for setting **ta** and **cba** are alternatives for defining the angle  $\alpha$ . Again the parameters  $\alpha$  and  $\beta$  should only be set once. If **cba** is chosen as input, the parameter **sgnsba** has to be set as well, in order to define  $\alpha$  uniquely.

#### 3.4. Parallel execution using the MPI standard

PROPHECY4F supports parallel execution using MPI. To use the parallel version, one has to compile the program using the preprocessor flag -Dmpiuse and make sure that proper MPI libraries are linked. The program will produce nevents weighted events in total and nunwevents unweighted events per core. The parallel version of PROPHECY4F has been tested using Intel's Fortran compiler with Intel's MPI.

# 4. PROPHECY4F output and sample runs

All output by PROPHECY4F is written to standard output or the output file specified in the input. Information about the COLLIER library is always written to standard output and the COLLIER output directory. In the output, the model under consideration is given along with the initial-state Higgs boson and the four-fermion final state for which the partial width and corresponding differential distributions are calculated. The input parameters are listed along with derived parameters, in particular the gauge-boson pole masses and widths (see Section 3.3.1).

For the SESM and the THDM, also information to define the model input is given, i.e. the renormalization scheme and the renormalization scale (see Sections 3.3.4 and 3.3.5). For convenience, PROPHECY4F also converts the employed model parameters to the corresponding values of the model parameters in other renormalization schemes, based on two different parameter conversion techniques (see Refs. [4–7]), and provides them in the output.

The relevant options, which are available as input (see Section 3.3.1), are also listed, in particular the number of requested events, the radiative corrections included in the calculation and the options for lepton-photon recombination.

During the Monte Carlo integration, PROPHECY4F provides intermediate results for the integrated partial width under consideration which allows one to monitor the progress of the calculation. Once the calculation is finished, the full result containing all radiative corrections is provided in the output along with an estimate of the Monte Carlo integration error. Subcontributions of the full result such as the LO result or the EW and QCD corrections are also given if they are included and non-zero.

If unweighted events are requested, the output includes information how many unweighted events have been already produced. After the production is finished, we include information if and how often the largest weight used for the unweighting procedure has been exceeded. If this number becomes large, the number of weighted events **nevents** should be increased. We also give the number of unweighted events with a negative weight. If this number exceeds a few percent for final states with electrons, one should consider to use **qrecombcolle=1** (see Section 3.3.1).

If more than one final state is requested in the input file, PROPHECY4F lists all requested channels at the beginning of the output. Then, the output for the different final states is provided consecutively as the calculation is performed in complete analogy to a run with only one final state. After finishing the calculation for all requested final states, a summary of all results is printed.

If channel=total, channel=leptonic, channel=semi-leptonic, or channel=hadronic is used to request the corresponding width of the Higgs boson, all required four-fermion final states are listed in the beginning. Output for each channel is created along with the calculation. In the end, the corresponding width is calculated according to Eqs. (4) and (5). For channel=total, i.e. the Higgs-boson width for decays into all four-fermion final states, we additionally give the Higgs-boson width for the decays  $H \rightarrow$ WW and  $H \rightarrow ZZ$  along with the corresponding interference contribution as defined in Eq. (7).

#### 4.1. Unweighted events

Unweighted events are written to the directory UNWEIGHTEDEVENTS in the Les Houches event file format (\*.lhe) [46]. For each run, we provide Born-level unweighted events and unweighted events including radiative corrections. These files contain also the complete output in their headers. As a cross check the unweighted events are binned into distributions (see Section 4.2) and written to the directory HISTUNWEIGHTED. These histograms are equivalent to histograms obtained by binning the events in the \*.lhe files accordingly. Note that the unweighted events are not suitable for a subsequent partonshower simulation for multi-photon emissions from the Higgs-boson decay products. Showering the unweighted events provided by PROPHECY4F would lead to a partial double counting of the photon-emission from the final-state leptons.

In unweighting runs with more than  $10^6$  unweighted events in a single run it is possible that fewer unweighted events are generated than requested. This is caused by a 32bit integer overflow and can be solved by using 64bit integers everywhere. The default size of all integers can be controlled using the following compiler options for the Fortran compiler:

```
gfortran: -fdefault-integer-8
ifort: -integer-size 64
```

These options are the default in the supplied makefile.

#### 4.2. Differential distributions

For leptonic or semi-leptonic final states, a few default histograms corresponding to the distributions presented in Refs. [1-3] are produced in the directory HISTOGRAMS. They can be modified in the subroutine create\_histo in the file src/public.F. There, a subroutine called histogram is called. Its first two parameters correspond to the range of the histogram, the third parameter to the variable of the distribution, and the number 50 refers to the number of bins. The output format of the histograms is detailed in the corresponding output files.

If one is interested in differential distributions it is not useful to specify more than one decay channel for a given PROPHECY4F run. The results for one channel would be simply overwritten by the next channel.

By default, PROPHECY4F provides histograms for invariant masses around the W- and Z-boson resonances. The invariant masses refer to the first two or the last two particles listed in the output for the final state under consideration, as indicated by the file names. Note that the particle ordering can vary between the input file and the output since particles are always ordered so that the first two and the last two particles correspond to the gauge-boson resonances. Note that the distributions do not necessarily have direct physical significance if identical or invisible particles are present in the final state. The following invariant-mass distributions are provided by default:

outputfile.inv12.5090 inv. mass  $m_{12}$  between 50 and 90 GeV,

outputfile.inv12.7585 inv. mass  $m_{12}$  between 75 and 85 GeV, outputfile.inv12.60100 inv. mass  $m_{12}$  between 60 and 100 GeV, outputfile.inv12.8595 inv. mass  $m_{12}$  between 85 and 95 GeV, outputfile.inv34.5090 inv. mass  $m_{34}$  between 50 and 90 GeV, outputfile.inv34.7585 inv. mass  $m_{34}$  between 75 and 85 GeV, outputfile.inv34.60100 inv. mass  $m_{34}$  between 60 and 100 GeV, outputfile.inv34.8595 inv. mass  $m_{34}$  between 85 and 95 GeV,

where  $m_{ij}$  denotes the invariant mass of the fermion pair  $f_i \bar{f}_j$ .

In addition, the following distributions are available, where again the particle numbering refers the to the final state as printed in the output and, for example,  $k_3$  denotes the four-momentum of the third particle:

outputfile.cthv2f2	the cosine of the angle between $(k_3 + k_4)$ and $k_2$ in the Higgs rest frame, see e.g. Fig. 12 in Ref. [3] (however, the particle numbering is different there),
outputfile.cthv2f3	the cosine of the angle of $k_3$ with respect to $(k_3 + k_4)$ in the $(k_3 + k_4)$ rest frame, see e.g. Fig. 14 in Ref. [1],
outputfile.phitrf2f3	angle between particle 2 and 3 in the transverse plane according to Fig. 15 in Ref. [1],
outputfile.cthf1f3	the cosine of the angle between particle 1 and 3 according to Fig. 16 in Ref. [1],
outputfile.phi	the angle between the decay planes ac- cording to Eq. (7.9) of Ref. [1] (only pro- vided for fully leptonic final states),
outputfile.cphihad	the absolute value of the cosine of the an- gle between the decay planes (one plane spanned by particles 1 and 2, the second plane spanned by particles 3 and 4), as defined in Eq. (4.2) of Ref. [3] (only pro- vided for semi-leptonic final states).

The present version of PROPHECY4F does not provide histograms for hadronic final states.

# 4.3. Sample runs

Examples for input files and the resulting output are given in the directory example-runs. It contains subdirectories which are discussed in the following:

# example-paper:

This directory contains input files for the decay modes  $H \rightarrow ZZ \rightarrow e^-e^+\mu^-\mu^+$ ,  $H \rightarrow ZZ \rightarrow e^-e^+e^-e^+$ ,  $H \rightarrow WW \rightarrow \nu_e e^+\mu^-\bar{\nu}_\mu$ , and  $H \rightarrow WW \rightarrow \nu_e e^+e^-\bar{\nu}_e$  in the SM with Higgs masses of 140, 170, and 200 GeV for the input parameters of Ref. [1]. For reference the corresponding output files are provided in out.\* and the histograms in the directory example-paper/HISTOGRAMS. The results for the WW-mediated channels differ by up to 0.5% from those given in Table 1 of Ref. [1] due to a bug in the renormalization of the (complex) W-boson mass which has been removed in the meanwhile. The ZZ-mediated channels give slightly different results from those in Refs. [1–3] since the top-mass effects in the Z width calculation are treated in an improved manner in the recent version of PROPHECY4F.

#### example-channels:

This directory contains input and corresponding output files for all final states in the SM for a Higgs mass of 125 GeV for the default input parameter set.

#### example-unweighted:

This directory contains input and corresponding output files for the production of unweighted events for leptonic final states in the SM, a Higgs mass of 125 GeV, and the default input parameter set along with the corresponding distributions. The files with the unweighted events are not part of the distribution due to their size.

#### example-SESM:

This directory contains input files for the decay mode  $h \to WW \to \nu_{\mu}\mu^+e^-\bar{\nu}_e$ of the light CP-even Higgs boson of the SESM scenario BHM200 of Refs. [6, 7].

# example-THDM:

This directory contains input files for the decay mode  $h \to WW \to \nu_{\mu}\mu^{+}e^{-}\bar{\nu}_{e}$ of the light CP-even Higgs boson of the THDM scenario Aa of Refs. [4, 5], which is identical to A1 of Ref. [7].

#### 5. Conclusions

The Monte Carlo program PROPHECY4F calculates predictions for Higgsboson decays into four-fermion final states via  $H \rightarrow WW/ZZ \rightarrow 4f$  including the full set of next-to-leading order corrections of the strong and electroweak interactions. In addition to predictions within the Standard Model, PRO-PHECY4F provides the partial decay widths of the CP-even, neutral Higgs bosons in several extensions of the Standard Model, i.e. the Standard Model extended by a fourth fermion generation, a simple Higgs-singlet extension of the SM, and the Two-Higgs-Doublet Model. For these SM extensions, PRO-PHECY4F supports different types of renormalization schemes based on  $\overline{\text{MS}}$ , on-shell, or symmetry-inspired renormalization conditions and different variants thereof. This allows for important checks on the perturbative stability and, thus, reliability of predictions by estimating residual renormalization scale and renormalization scheme dependences.

In the past, state-of-the-art predictions for SM Higgs decay widths have been produced by the program HDECAY in tandem with PROPHECY4F. With the new versions of the two programs, both supporting various common renormalization schemes, uniform predictions within the THDM and SESM become possible, which is an important step towards Higgs precision physics in models with extended Higgs sectors.

# Acknowledgements

We are indebted to A. Bredenstein and M.M. Weber for constructing the first versions of PROPHECY4F. We thank L. Altenkamp, M. Boggia, J.N. Lang, and H. Rzehak for their contributions to the extension of PROPHECY4F for extended Higgs sectors. A.D. acknowledges financial support by the German Research Foundation (DFG) under reference number DE 623/5-1. S.D. gratefully acknowledges support by the German Bundesministerium für Bildung und Forschung (BMBF) under contract no. 05H18VFCA1. A.M. is supported in part by the DFG through the CRC/Transregio "P3H: Particle Physics Phenomenology after the Higgs Discovery" (TRR257).

- A. Bredenstein, A. Denner, S. Dittmaier and M. M. Weber, Phys. Rev. D 74 (2006) 013004 [hep-ph/0604011].
- [2] A. Bredenstein, A. Denner, S. Dittmaier and M. M. Weber, Nucl. Phys. Proc. Suppl. 160 (2006) 131 [hep-ph/0607060].
- [3] A. Bredenstein, A. Denner, S. Dittmaier and M. M. Weber, JHEP 0702 (2007) 080 [hep-ph/0611234].

- [4] L. Altenkamp, S. Dittmaier and H. Rzehak, JHEP **1709** (2017) 134
   [arXiv:1704.02645 [hep-ph]].
- [5] L. Altenkamp, S. Dittmaier and H. Rzehak, JHEP 1803 (2018) 110 [arXiv:1710.07598 [hep-ph]].
- [6] L. Altenkamp, M. Boggia and S. Dittmaier, JHEP 1804 (2018) 062
   [arXiv:1801.07291 [hep-ph]].
- [7] A. Denner, S. Dittmaier and J. N. Lang, JHEP 1811 (2018) 104
   [arXiv:1808.03466 [hep-ph]].
- [8] S. Dittmaier, C. Mariotti, G. Passarino and R. Tanaka *et al.* [LHC Higgs Cross Section Working Group], CERN-2011-002, arXiv:1101.0593 [hepph].
- [9] S. Dittmaier, C. Mariotti, G. Passarino and R. Tanaka *et al.* [LHC Higgs Cross Section Working Group], CERN-2012-002, arXiv:1201.3084 [hepph].
- [10] S. Heinemeyer, C. Mariotti, G. Passarino and R. Tanaka *et al.* [LHC Higgs Cross Section Working Group], CERN-2013-004, arXiv:1307.1347 [hep-ph].
- [11] D. de Florian *et al.* [LHC Higgs Cross Section Working Group], CERN-2017-002-M, arXiv:1610.07922 [hep-ph].
- [12] A. Djouadi, J. Kalinowski and M. Spira, Comput. Phys. Commun. 108 (1998) 56 [hep-ph/9704448].
- [13] A. Djouadi, M. M. Mühlleitner and M. Spira, Acta Phys. Polon. B 38 (2007) 635 [hep-ph/0609292].
- [14] A. Djouadi, J. Kalinowski, M. Mühlleitner and M. Spira, Comput. Phys. Commun. 238 (2019) 214 [arXiv:1801.09506 [hep-ph]].
- [15] M. Krause, M. Mühlleitner and M. Spira, Comput. Phys. Commun. 246 (2020) 106852 [arXiv:1810.00768 [hep-ph]].
- [16] R. Contino, M. Ghezzi, C. Grojean, M. Mühlleitner and M. Spira, Comput. Phys. Commun. 185 (2014) 3412 [arXiv:1403.3381 [hep-ph]].

- [17] J. F. Gunion and H. E. Haber, Phys. Rev. D 67 (2003) 075019 [hepph/0207010].
- [18] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher and J. P. Silva, Phys. Rept. 516 (2012) 1 [arXiv:1106.0034 [hep-ph]].
- [19] R. M. Schabinger and J. D. Wells, Phys. Rev. D 72 (2005) 093007 [hepph/0509209].
- [20] B. Patt and F. Wilczek, hep-ph/0605188.
- [21] M. Bowen, Y. Cui and J. D. Wells, JHEP 0703 (2007) 036 [hepph/0701035].
- [22] A. Denner, S. Dittmaier, and L. Hofer, Collier, https://collier.hepforge.org/.
- [23] A. Denner, S. Dittmaier and L. Hofer, Comput. Phys. Commun. 212 (2017) 220 [arXiv:1604.06792 [hep-ph]].
- [24] A. Denner, S. Dittmaier, A. Mück, G. Passarino, M. Spira, C. Sturm, S. Uccirati and M. M. Weber, Eur. Phys. J. C 72 (2012) 1992 [arXiv:1111.6395 [hep-ph]].
- [25] S. Boselli, C. M. Carloni Calame, G. Montagna, O. Nicrosini and F. Piccinini, JHEP 1506 (2015) 023 [arXiv:1503.07394 [hep-ph]].
- [26] S. Boselli, C. M. Carloni Calame, G. Montagna, O. Nicrosini, F. Piccinini and A. Shivaji, JHEP 1801 (2018) 096 [arXiv:1703.06667 [hep-ph]].
- [27] A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, Nucl. Phys. B 560 (1999) 33 [hep-ph/9904472].
- [28] A. Denner, S. Dittmaier, M. Roth and L. H. Wieders, Nucl. Phys. B 724 (2005) 247 [Erratum-ibid. B 854 (2012) 504] [hep-ph/0505042].
- [29] A. Denner, J. N. Lang and S. Uccirati, JHEP **1707** (2017) 087 [arXiv:1705.06053 [hep-ph]].
- [30] A. Denner, L. Jenniches, J. N. Lang and C. Sturm, JHEP 1609 (2016) 115 [arXiv:1607.07352 [hep-ph]].

- [31] S. Kanemura, M. Kikuchi and K. Yagyu, Nucl. Phys. B 907 (2016) 286 [arXiv:1511.06211 [hep-ph]].
- [32] F. Bojarski, G. Chalons, D. Lopez-Val and T. Robens, JHEP 1602 (2016) 147 [arXiv:1511.08120 [hep-ph]].
- [33] S. Kanemura, Y. Okada, E. Senaha and C.-P. Yuan, Phys. Rev. D 70 (2004) 115002 [hep-ph/0408364].
- [34] D. Lopez-Val and J. Sola, Phys. Rev. D 81 (2010) 033003 [arXiv:0908.2898 [hep-ph]].
- [35] S. Kanemura, M. Kikuchi and K. Yagyu, Phys. Lett. B 731 (2014) 27 [arXiv:1401.0515 [hep-ph]].
- [36] M. Krause, R. Lorenz, M. Mühlleitner, R. Santos and H. Ziesche, JHEP 1609 (2016) 143 [arXiv:1605.04853 [hep-ph]].
- [37] J. Fleischer and F. Jegerlehner, Phys. Rev. D 23 (1981) 2001.
- [38] A. Denner, Fortsch. Phys. **41** (1993) 307 [arXiv:0709.1075 [hep-ph]].
- [39] A. Denner and S. Dittmaier, Nucl. Phys. B 658 (2003) 175 [hepph/0212259].
- [40] A. Denner and S. Dittmaier, Nucl. Phys. B 734 (2006) 62 [hepph/0509141].
- [41] A. Denner and S. Dittmaier, Nucl. Phys. B 844 (2011) 199 [arXiv:1005.2076 [hep-ph]].
- [42] A. Denner, S. Dittmaier, and A. Mück, PROPHECY4F, https://prophecy4f.hepforge.org/.
- [43] M. Lüscher, Comput. Phys. Commun. **79** (1994) 100 [hep-lat/9309020].
- [44] A. Djouadi, P. Gambino and B. A. Kniehl, Nucl. Phys. B 523 (1998) 17 [hep-ph/9712330].
- [45] B. A. Kniehl, Phys. Rev. D 53 (1996) 6477 [hep-ph/9602304].
- [46] J. Alwall *et al.*, Comput. Phys. Commun. **176** (2007) 300 [hepph/0609017].