Tools for BSM-Higgs physics:

Progress report

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Tools: Overview

sHDECAY

SusHi   HDECAY   N2HDECAY

vh@nnlo   C2HDECAY

HPAIR   eHDECAY

HAWK   RECOLA   NMSSMCALC

SloopS   NMSSMTools

FeynHiggs   GMCALC

MhEFT   Prophecy4f

CPsuperH

SOFTSUSY

HiggsBounds   SARAH/SPheno

HiggsSignals   ROSETTA

ScannerS   FlexibleSUSY   HEL@NLO

HEPfit

Higgs production: `SusHi`

Gluon fusion & bottom-quark annihilation in the SM, 2HDM, (N)MSSM

New in version 1.6.0 [Harlander, Liebler, Mantler 1605.03190]:

- N^3LO results in the heavy top-limit employing the threshold expansion [Anastasiou, Duhr, Dulat, Herzog, Mistelberger: + Furlan, Gehrmann 1411.3584, 1503.06056, + Furlan 1505.04110, + Furlan, Gehrmann, Lazopoulos 1602.00695]

- Top-quark mass corrections (expansion in $1/m_t^2$) at NNLO [Marzani, Ball, Del Duca, Forte, Vicini 0801.2544; Harlander, Mantler, Marzani, Ozeren 0912:2104; Harlander, Ozeren 0907.2997, 0909.3420; Pak, Rogal, Steinhauser 0907.2998, 0911.4662, 1107.3391]

- Matching to the high-energy limit for the s/m_t^2 terms [0801.2544, 0912:2104, 0909.3420]

- Implementation of dimension-5 operators

- Heavy quark annihilation (not just bb→h) [Harlander 1512.04901]

Higgs production: `SusHi`

: SusHi 1.7.0:

- Including SusHiMi extension for CP violation in the MSSM
  [Liebler, Patel, Weiglein 1611.09308]

- Employing Z factors for gluon fusion

Higgs production: `vh@NNLO`

Calculation of pp $\rightarrow$ HV at NNLO QCD incl. gg $\rightarrow$ HZ and bb $\rightarrow$ HZ

[Brein, Harlander, Zirke 1210.5347]

Upcoming:

- Extension to 2HDM and MSSM
  linking to 2HDMC and FeynHiggs

Higgs production: `HPAIR`: **A code for HH production**

- `HPAIR` computes cross section of Higgs pair production via gluon fusion at NLO QCD in infinite top mass limit in the SM and MSSM [Plehn, Spira, Zerwas hep-ph/9603205; Dawson, Dittmaier, Spira hep-ph/9805244]

- Also for dim-6 operators in linear and non-linear realisation [Gröber, Mühlleitner, Spira, Streicher 1504.06577]

  NEW! including CP-violating operators in future release [Gröber, Mühlleitner, Spira, 1705.05314]

$$\mathcal{L} = -m_t \bar{t} t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{2v^2} \right) - c_3 \frac{1}{6} \frac{3M_h^2}{v} h^3 + \frac{\alpha_s}{\pi} G^{a\,\mu\nu} G_{\mu\nu}^a \left(c_g \frac{h}{v} + c_{gg} \frac{h^2}{2v^2} \right)$$

$$- i m_t \bar{t} \gamma_5 t \left(\tilde{c}_t \frac{h}{v} + \tilde{c}_{tt} \frac{h^2}{2v^2} \right) + \frac{\alpha_s}{\pi} G^{a\,\mu\nu} \widetilde{G}_{\mu\nu}^a \left(\tilde{c}_g \frac{h}{v} + \tilde{c}_{gg} \frac{h^2}{2v^2} \right)$$

[Gröber, Mühlleitner, Spira '17]
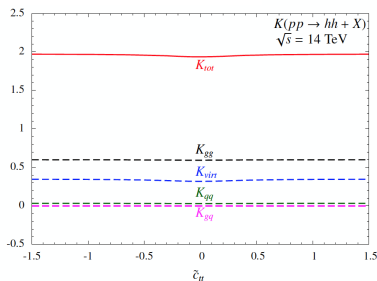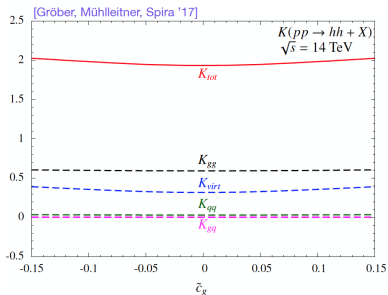
$\rightarrow$ Effect on K-factor is order few percent

slides by R. Gröber

Higgs (pair) production: `HPAIR`: For the C2HDM

- NEW! `HPAIR` for the complex 2HDM (at NLO QCD) [Gröber, Mühlleitner, Spira, 1705.05314]
- A heavier Higgs boson can be produced resonantly in 2HDM
  $\longrightarrow$ strong increase of cross section possible
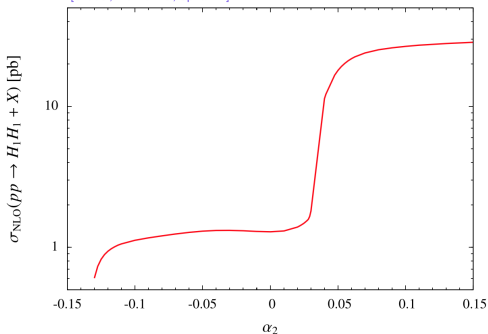
Starting scenario:
α_i denote the mixing angles between the 3 neutral Higgs bosons
m_{12} the mixing parameter between the two doublets

$\alpha_1 = 0.853$, $\alpha_2 = -0.103$, $\alpha_3 = 0.0072$, $\tan\beta = 0.969$, $\mathrm{Re}(m_{12}^2) = 70957 \ \mathrm{GeV}^2$,

$m_{H_1} = 125 \ \mathrm{GeV}$, $m_{H_2} = 377.6 \ \mathrm{GeV}$, $m_{H^\pm} = 709.7 \ \mathrm{GeV}$,

[Gröber, Mühlleitner, Spira '17]

slides by R. Gröber

Higgs production (& more): RECOLA2 for BSM physics

RECOLA2: REcursive Computation of One-Loop Amplitudes2

[Denner, Lang, Uccirati 1705.06053]

▶ Based on
  ▶ RECOLA for the tensor coefficient computation
    [Actis, Denner, Hofer, Scharf, Uccirati: 1211.6316, + Lang 1605.01090]
  ▶ COLLIER tensor integral evaluation
    [Denner, Dittmaier, Hofer; 1604.06792]

▶ <u>EW</u> and <u>QCD</u> amplitudes in BSM at NLO.
  RECOLA2 model files available:
  ▶ Two-Higgs-Doublet Model (Z_2 symmetry, all Yukawa types)
  ▶ Higgs-Singlet Extension of the SM (Z_2 symmetry)
  ▶ Anomalous couplings: VVV, HVV
  ▶ Formulation in Background-Field Method

▶ Soon publicly available at hepforge.org   slides by J.N. Lang

Higgs production (& more): RECOLA2 for BSM physics

RECOLA2 can compute any process at one-loop order for a given RECOLA2 model file.
Limitations: available memory/CPU power
(tested with up to 9 external particles at NLO)

As simple as:

```
use Recola
call define_process_rcl(1, "u u -> u u H", "NLO" )
call generate_processes_rcl
call compute_process_rcl(1, p)
```

▶ Dynamic process generation (in memory), no code generated.

▶ No intermediate intervention.
RECOLA2 can be used as black box.

▶ Dedicated interface of RECOLA2 to HAWK 2.0.
→ automated Higgs-boson production in VBF and
Higgs strahlung (no charged Higgs-boson production).

slides by
J.N. Lang

Higgs production (& more): RECOLA2 for BSM physics

Generation of renormalized model files for RECOLA2 via the tool
REPT1L [Denner, Lang, Uccirati 1705.06053]

▶ Fully automated, derived from tree-level UFO format.
  [Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter 1108.2040]

▶ Standard renormalization conditions for SM gauge-group.
  ▶ α: α_0 (in Thomson limit), G_F (Fermi scheme)
  ▶ α_s: Fixed or dynamical Nf-flavour scheme
  Simple framework for custom renormalization conditions.

▶ Models currently restricted to scalars, Dirac fermions and
  vector bosons. No SUSY yet.

▶ If you are interested in particular models, do not hesitate to
  contact the authors!   slides by J.N. Lang

Higgs decays: `HDECAY`: Extensions to BSM H sectors

- **General:** Based on implementation in `HDECAY`   slides by M. Mühlleitner

  [Douadi,Spira,Kalinowski+Mühlleitner(2010), Comput.Phys.Commun. 108 (1998) 56]

- **Features:** Stand-alone codes; relevant QCD corrections & off-shell decays included, EW corrections consistently neglected

  New!

- **sHDECAY**   http://www.itp.kit.edu/∼maggie/sHDECAY/

  [Costa, Mühlleitner, Sampaio, Santos, JHEP 06 (106) 034]

  ⋆ Real-extended SM in symmetric (dark) phase, RxSM-dark:
  $$1 \text{ Higgs} + 1 \text{ Dark } (\mathbb{Z}_2)$$

  ⋆ Real-extended SM in broken phase, RxSM-broken:
  $$2 \text{ mixing Higgs bosons } (\mathbb{Z}_2 \text{ spont. broken})$$

  ⋆ Complex-extended SM in symmetric (dark) phase, CxSM-dark:
  $$2 \text{ mixing Higgs} + 1 \text{ Dark}$$

  ⋆ Complex-extended SM in broken phase, CxSM-broken: 3 mixing Higgs bosons

Higgs decays: `HDECAY`: Extensions to BSM H sectors

- **N2HDECAY for N2HDM** http://www.itp.kit.edu/∼maggie/N2HDECAY/

  slides by M. Mühlleitner

  [Mühlleitner, Sampaio, Santos, Wittbrodt, JHEP 1703 (2017) 094]

  - ⋆ 2DHM + real singlet $\mathbb{Z}_2$ spont. broken: 3 scalars $H_{1,2,3}$, 1 pseudocalar A, charged pair $H^\pm$
  - ⋆ 2HDM + real singlet $\mathbb{Z}_2$: in preparation

- **C2HDECAY - to be released soon ← 2HDM already available**
  - ⋆ CP-violating 2DHM: 3 CP-mixing scalars $H_{1,2,3}$, charged Higgs pair $H^\pm$

  Further available

- **eHDECAY** http://www.itp.kit.edu/∼maggie/eHDECAY/

  [Contino, Ghezzi, Grojean, Mühlleitner, Spira, Comput.Phys.Commun. 185 (2014) 3412]

- SILH, minimal composite models MCHM4,5, non-linear parametrisation

- **NMSSMCALC** http://www.itp.kit.edu/∼maggie/NMSSMCALC/

  [Baglio, Gröber, Mühlleitner, Dao, Rzehak, Spira, Comput.Phys.Commun. 185 (2014) 12]

- CP-conserving & violating NMSSM: Mass corrections $\mathcal{O}(\alpha_t\alpha_s)$, branching ratios

Higgs decays: EW corrections beyond and with `HDECAY`

New code for Higgs decays with 2-particle-final state for the 2HDM:

Important ingredient: Renormalization of the 2HDM with focus on

- gauge independence
- process independence
- avoiding artificially large corrections

based on [Krause, Lorenz, Mühlleitner, Santos, Ziesche,1605.04853; Krause, Mühlleitner, Santos, Ziesche 1609.04185]

Features:

- 2 choices for mixing angles α and β, 2 scale choices ($+$ 1 process dep.)
- 2 choices for the parameter m_{12}^2
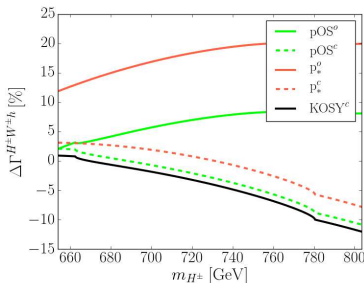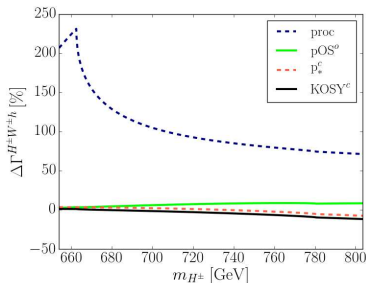- Masses and field-strength-renormalization constants on-shell

Private version available, public version with link to `HDECAY` in preparation

Higgs decays: EW corrections beyond and with `HDECAY`

slide by M. Mühlleitner

Example: $H^\pm \to W^\pm h$:

[Krause, Lorenz, Mühlleitner, Santos, Ziesche 1605.04853]

◇ $m_{H^\pm} = (654...804)$, $m_H = 743$, $m_A = 700$ GeV, $\text{tg}\beta = 1.46$, $\alpha = -0.57$, $m_{12}^2 = 2.1 \cdot 10^5$ GeV^2

◇ angular renorm.: 'c, o': β renorm. through charged/odd sector; '$\star$, OS': 2 different scales

◇ 'KOSY': gauge-dependent scheme [Kanemura, Okada, Senaha, Yuan, hep-ph/0408364]

Higgs decays: PROPHECY4F

PROPHECY4F: A Monte Carlo generator for a
    Proper description of the Higgs decay into 4 fermions
[Bredenstein, Denner, Dittmaier, Weber hep-ph/0604011; hep-ph/0607060; hep-ph/0611234]

New (available on request, soon on hepforge): [Altenkamp, Dittmaier, HR 1704.02645]

- Extension to the 2HDM:
  Features:

  ▶ 4 different renormalization schemes:
    ⋆ Different options for α/λ_3 and $\tan\beta$
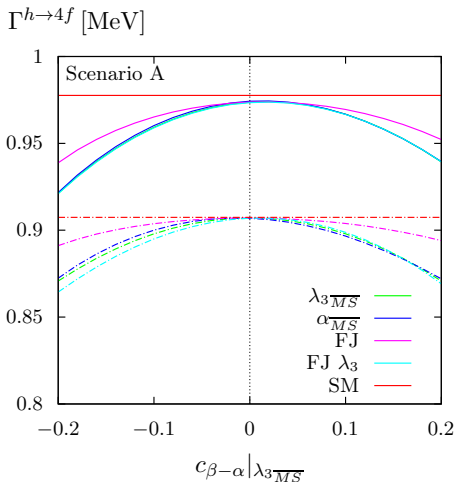   ⋆ Masses and field-strength-renormalization constants on-shell, λ_5 $\overline{\text{MS}}$
      Note: m_{12}^2 is not an input parameter

  ▶ Consistent conversion of parameters between the different ren. schemes

  ▶ Running of $\overline{\text{MS}}$ parameters

- Upcoming: SM Singlet extensions

Higgs decays: `PROPHECY4F`

$\cos(\beta - \alpha)$ dependence of $h \to 4f$ in the 2HDM:

$\Gamma^{h \to 4f}$ [MeV]

Scenario A

legend:
$\lambda_{3\overline{MS}}$
$\alpha_{\overline{MS}}$
FJ
FJ λ_3
SM

$c_{\beta-\alpha}|_{\lambda_{3\overline{MS}}}$

Scenario:
$M_h = 125$ GeV, $M_H = 300$ GeV,
$M_{A_0} = M_{H^+} = 460$ GeV,
$\lambda_5 = -1.9$, $\tan\beta = 2$,
$\mu_0 = (M_h + M_H + M_{A_0} + 2M_{H^+})/5$

LO: dashed
NLO: solid

• Scheme λ_3 $\overline{MS}$ used:

$$\Gamma^{h \to 4f}_{\text{2HDM, LO}}|_{\lambda_3,\overline{MS}} = s^2_{\beta-\alpha} \Gamma^{h \to 4f}_{\text{SM, LO}}$$

[Altenkamp, Dittmaier, HR 1704.02645]

Higgs decays: GMCALC

A calculator for the Georgi-Machacek model $\leftarrow$ scalar triplets:

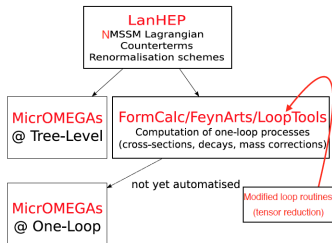[Hartling, Kumar, Logan 1412.7387]

- particle spectrum and tree-level couplings
- theoretical constraints
- branching ratios and total decay widths of the scalars
  (2-particle-final states)

Upcoming:

- Calculation of 1-loop decays including $H_5^+ \rightarrow W^+ \gamma$

$\uparrow$

particular important for $m_{H_5^+} < M_W + M_Z$

Higgs decays (and more): SloopS

LanHEP
NMSSM Lagrangian
Counterterms
Renormalisation schemes

MicrOMEGAs
@ Tree-Level

FormCalc/FeynArts/LoopTools
Computation of one-loop processes
(cross-sections, decays, mass corrections)

not yet automatised

MicrOMEGAs
@ One-Loop

Modified loop routines
(tensor reduction)

SLOOPS

An automatic code for calculation of loops diagrams for $\mathcal{SM}$ and $\mathcal{BSM}$ processes with application to colliders, astrophysics and cosmology.

- ▸ Automatic derivation of the CT Feynman rules and computation of the CT's
- ▸ Models renormalized: SM, MSSM, NMSSM, Wino DM, xSM (w/ & w/o v_s),
- ▸ Modularity between different renormalisation schemes.
- ▸ Non-linear gauge fixing.
- ▸ Checks: results UV,IR finite and gauge independent.

http://code.sloops.free.fr/

LPT Orsay

slide by G. Chalons

Higgs decays (and more): `SloopS`

Recent developments:

- Renormalization of the NMSSM
  [Bélanger, Bizouard, Boudjema, Chalons 1602.05495, 1705.02209]

- Application: 1-loop evaluation of Higgs decays to SUSY particles
  [Bélanger, Bizouard, Boudjema, Chalons 1705.02209]

Higgs decays (and more): NMSSMTools

[Ellwanger, Hugonie]

New features since v5.0.0:

- Treatment of the CP-violating NMSSM
  [Domingo 1503.07087]

- New improved treatment of
  light CP-even and CP-odd Higgs partial widths
  [Domingo 1612.06538]

- Continously updated constraints from Higgs measurements
  and dark matter searches

Higgs masses (and more): `FeynHiggs`

Most important new feature in v2.12.0:

- Log resummation via RGE improved: use loglevel [Bahl, Hollik 1608.01880]
  - ★ loglevel = 2: three high-mass scales: M_{stop}, M_{gluino}, $M_{\text{cha/neu}}$
    electroweak contributions taken into account in the RGEs
  - ★ loglevel = 3: RGE resummation at the 3-loop (NNLL) level;
    threshold effects at the 2-loop level.

New features since v2.13.0:

- looplevel = 0, 1 can be combined with loglevel (still beta-version)
  Note: looplevel = 0 ⇒ pure EFT calculation
- Interpolation of the EFT calculation in the case of complex parameters
- Higgs production cross sections for 13 TeV and 14 TeV updated
- Improvement of electroweak precision observables using
  [Awramik, Czakon, Freitas hep-ph/0608099;
  Heinemeyer, Hollik, Weiglein, Zeune 1311.1663]

Higgs masses (and more): `FeynHiggs`

[Bahl, Hahn, Heinemeyer, Hollik, Paßehr, HR, Weiglein]

Upcoming: (see also [Bahl, Heinemeyer, Hollik, Weiglein 1706.00346])

- $\overline{\text{DR}}$ renormalization of the top/stop sector
- Improved procedure for calculation of the pole masses/Z factors
- Some improvements of the resummation routines

Higgs masses (and more): `MhEFT`: Method Outline

slides by G. Lee

▶ Begin with SM couplings at M_t. [Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia 1307.3536]

▶ Use SM RGE's (possibly with EWkino contributions beginning at μ) to evolve $\{g_i, y_j, \lambda\}$ from M_t to m_A.

M_S ▶ Use THDM RGE's (in the $\lambda_i = 0$ approximation) to evolve $\{g_i, h_j, \tan\beta\}$ from m_A to M_S.

▶ Compute 1-loop threshold corrections to Yukawas h_j.

▶ Compute THDM quartic couplings $\lambda_i(M_S)$ in the MSSM (with 1-loop, select 2-loop corrections).

THDM(+EWkino)

▶ Use THDM RGE's to evolve $\{g_i, h_j, l_k\}$ from M_S to m_A.

m_A ▶ Compute λ_k combinations appearing in Higgs mass matrix $\mathcal{M}_{H^0}^2$ at m_A. [Gunion, Haber hep-ph/0207010]

SM(+EWkino)

μ ▶ Evolve $\{g_i, y_j, \lambda\}$ using SM RGE's in "Higgs basis", where λ corresponds to the Higgs doublet that receives a vev.

SM

M_t ▶ Diagonalize $\mathcal{M}_{H^0}^2$ at M_t.

▶ Compute masses, couplings, angles, etc.

Higgs masses (and more): MhEFT Package

▶ Mathematica notebook incorporating the calculations in [Lee, Wagner 1508.00576].

▶ It also incorporates approximate branching ratio and decay width calculations for the light SM-like Higgs.

  ▶ Use decay widths to $bb, \tau\tau, \mu\mu, cc, gg, \gamma\gamma, Z\gamma, WW^*, ZZ^*$ from LHCHXSWG tabulation for $M_h = 125$ GeV.
    [Denner, Heinemeyer, Puljak, Rebuzzi, Spira 1107.5909]

  ▶ Scale by computed couplings and Higgs masses according to formulae in, e.g., Djouadi reviews or Higgs Hunter's Guide.   [Djouadi hep-ph/0503172(3)]

  ▶ Include additional contributions to $\gamma\gamma, Z\gamma$ from charginos.

  ▶ Find good agreement in the SM case for masses $M_h \sim$ 110–150 GeV, e.g. within 5–10% for the decay to gauge bosons
    (worse at lower masses because we did not include 4-body decays).

▶ Numerical integration in Mathematica $\Rightarrow t \sim 1$ s for evaluation of one point.

▶ Functional inputs:

  ▶ $M_S, m_A, X_t, A_b, A_\tau, \tan\beta(m_A), \mu, M_1, M_2$,

  ▶ Can specify NLO, NNLO y_t.

Available at http://gabrlee.com/code

Higgs masses: MhEFT: M_h vs. X_t for different $\tan\beta$

slides by G. Lee
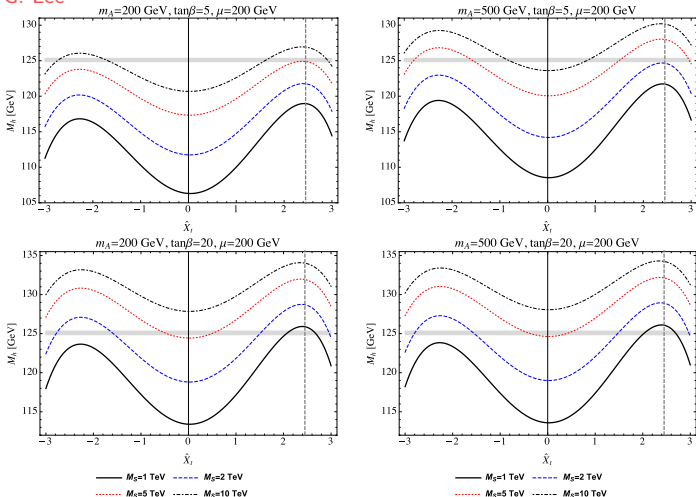
Significant effect of Higgs mixing at low t_β: For $t_\beta = 5$, the difference in M_h between curves for the same M_S is 2–3 GeV lower for $m_A = 200$ GeV compared to for $m_A = 500$ GeV ($\sim$ decoupling limit).

Higgs masses (and more): SOFTSUSY

[Allanach, Athron, Bednyakov, Bernhardt, Cridge, Grellscheid, Hanussek, Kom, Martin, Robertson, Ruiz de Austri, Slavich, Tunstall, Voigt and Williams]

Mass spectrum generator for

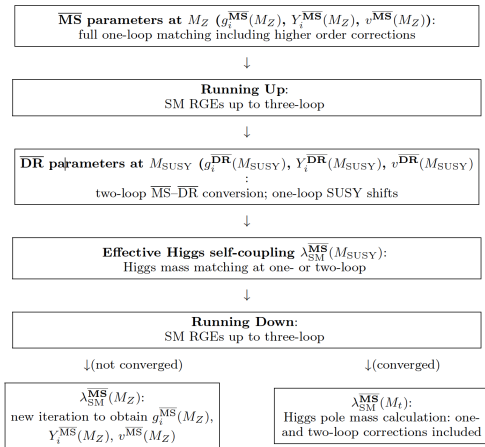- flavour-violating MSSM with/without R-parity
- NMSSM

New:

- MSSM/NMSSM decays added [Allanach, Cridge, 1703.09717]

Higgs masses (and more): `SARAH/SPheno`

New features:

- EFT calculation included
  [Porod, Staub 1703.03267]

- 1-loop two-body decays included
  [Goodsell, Liebler, Staub 1703.09237]

- Solution of the Goldstone boson catastrophe
  [Braathen, Goodsell, Staub 1706.05372]

$\overline{\text{MS}}$ parameters at M_Z ($g_i^{\overline{\text{MS}}}(M_Z)$, $Y_i^{\overline{\text{MS}}}(M_Z)$, $v^{\overline{\text{MS}}}(M_Z)$):
full one-loop matching including higher order corrections

↓

Running Up:
SM RGEs up to three-loop

↓

$\overline{\text{DR}}$ parameters at M_{SUSY} ($g_i^{\overline{\text{DR}}}(M_{\text{SUSY}})$, $Y_i^{\overline{\text{DR}}}(M_{\text{SUSY}})$, $v^{\overline{\text{DR}}}(M_{\text{SUSY}})$):
two-loop $\overline{\text{MS}}$–$\overline{\text{DR}}$ conversion; one-loop SUSY shifts

↓

Effective Higgs self-coupling $\lambda_{\text{SM}}^{\overline{\text{MS}}}(M_{\text{SUSY}})$:
Higgs mass matching at one- or two-loop

↓

Running Down:
SM RGEs up to three-loop

↓(not converged)   ↓(converged)

$\lambda_{\text{SM}}^{\overline{\text{MS}}}(M_Z)$:
new iteration to obtain $g_i^{\overline{\text{MS}}}(M_Z)$,
$Y_i^{\overline{\text{MS}}}(M_Z)$, $v^{\overline{\text{MS}}}(M_Z)$

$\lambda_{\text{SM}}^{\overline{\text{MS}}}(M_t)$:
Higgs pole mass calculation: one-
and two-loop corrections included

# Higgs masses (and more): `FlexibleSUSY`

- BSM particle mass spectrum at 1-loop for SUSY/ non-SUSY models
  (2-loop and 3-loop corrections included in the SM, MSSM, NMSSM)
  [Athron, Park, Stöckinger, Voigt 1406.2319]

- Many pre-defined models (MSSM, NMSSM, E6SSM, MRSSM, ...) and
  EFTs of the MSSM (HSSUSY, split-MSSM, THDM-II, ...)

- FlexibleEFTHiggs approach to predict Higgs mass in
  a combined EFT/fixed-order approach with (N)LL resummation
  [Athron, Park, Steudtner, Stöckinger, Voigt 1609.00371]

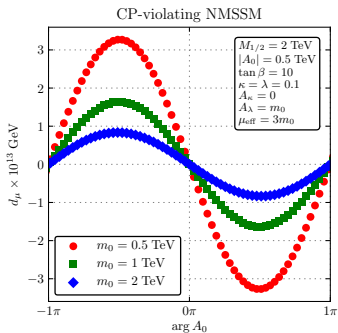 $\rightarrow$ improved in version 2.0

New in version 2.0:

- observables: effective hgg & $h\gamma\gamma$ couplings at NNNLO,
  $(g-2)_\mu$, EDMs, μ decay

- semi-analytic boundary value problem solver to solve full-constrained
  models (CNMSSM, CE6SSM, ...)
  $\rightarrow$ multiple solutions of constrained models

Higgs masses (and more): `FlexibleSUSY`: Predictions

Higgs mass in the MSSM:
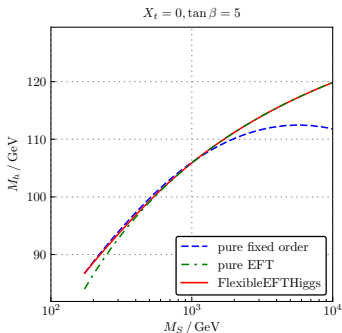
EDM in the NMSSM at 1-loop:

Improved resummation (NLL)

HiggsBounds/HiggsSignals

Testing parameter points of a model wrt Higgs search/measurement constraints

New beta versions:

- HiggsBounds-5 [Bechtle, Dercks, Heinemeyer, Stefaniak, Weiglein]
- HiggsSignals-2 [Bechtle, Heinemeyer, Stefaniak, Weiglein]

Features:

- New structure of "effective Couplings Approximation": Linear instead of squared scaling parameters
- New way for calculating $pp \to HZ$ from g_{hVV}, g_{htt}, g_{hbb} using vh@nnlo
- 13 TeV cross section input included
- Charged Higgs production cross section input included
- New branching ratio input (e.g. Higgs-to-Higgs decays, LFV decays)
- SM/BSM reference values $\leftarrow$ YR4
- HiggsSignals: estimated uncertainties $\leftarrow$ YR4
- New method for χ^2-calculation for comb. of ATLAS & CMS run-1 results

ScannerS alows general scalar potential with automatic:

- ▶ Analysis of tree level local minimum/stability
- ▶ Detection of tree level scalar spectrum and mixing
- ▶ Tree level unitarity test

Interfaces to:

- ▶ HDECAY, sHDECAY, N2HDECAY, C2HDECAY
- ▶ HiggsBounds/Signals (collider bounds/measurements)
- ▶ microOMEGAS (dark matter observables)
- ▶ SusHi (+ internal numerical tables for gluon fusion)
- ▶ SuperIso (flavour physics observables)

User/model defined functions to:

- ▶ Check boundedness from below
- ▶ Check global stability
- ▶ Implement phenomenological analysis for each point

ScannerS alows general scalar potential with automatic: slides by M.O.P. Sampaio

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- ▶ Detection of tree level scalar spectrum and mixing
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Interfaces to:

- ▶ HDECAY, sHDECAY, N2HDECAY, C2HDECAY
- ▶ HiggsBounds/Signals (collider bounds/measurements)
- ▶ microOMEGAS (dark matter observables)
- ▶ SusHi (+ internal numerical tables for gluon fusion)
- ▶ SuperIso (flavour physics observables)

User/model defined functions to:

- ▶ Check boundedness from below
- ▶ Check global stability
- ▶ Implement phenomenological analysis for each point

ScannerS: Overview (see also `scanners.hepforge.org`)

ScannerS alows general scalar potential with automatic:
slides by M.O.P. Sampaio

- ▶ Analysis of tree level local minimum/stability
- ▶ Detection of tree level scalar spectrum and mixing
- ▶ Tree level unitarity test

Interfaces to:

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ScannerS: **The currently available Models**

▶ Real and Complex Scalar Singlet Extensions: slides by M.O.P. Sampaio

R. Costa, M. Mühlleitner, M.O.P. Sampaio, R. Santos, JHEP 1606 (2016) 034 + see YR4
R. Coimbra, M.O.P. Sampaio, R. Santos, EPJ C73 (2013) 2428
R. Costa, A. Morais, M.O.P. Sampaio, R. Santos, Phys.Rev. D92 (2015) 2, 025024

  ▶ **RxSM-dark**: 1 Higgs + 1 Dark ($\mathbb{Z}_2$)
  ▶ **RxSM-broken**: 2 Higgs mixing ($\mathbb{Z}_2$ spont.broken)
  ▶ **CxSM-dark**: 2 Higgs mixing + 1 Dark
  ▶ **CxSM-broken**: 3 Higgs mixing

New: Input files allow *Scan* or *Check* point mode.

see → *How to run scalar singlet extensions in ScannerS* (indico.cern.ch/event/640710)

▶ Scalar Doublet Extensions:

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  P.M. Ferreira, R. Guedes, M.O.P. Sampaio, R. Santos, JHEP 12 (2014) 067

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HEPfit: **New fitting tool**

[de Blas Ciuchini, Chowdhury, Eberhardt, Fedele, Franco, Grilli di Cortona, Mishima, Paul, Pierini, Reina, Silvestrini, Valli, Yokozaki]

- Fit the model parameters to a given set of experimental observables including Higgs observables

  Models including SM, effective extensions,
  specific models e.g. 2HDM

- Obtain fit results for observables

- Obtain predictions for observables

  see http://hepfit.roma1.infn.it

ROSETTA **and** HEL@NLO

ROSETTA: EFT basis translation tool (see http://rosetta.hepforge.org)
includes modules e.g. interface to eHDECAY,
consistency check of parameter points

Ongoing work:

- Translations to other implementations of dimension 6-operators
  generated with FeynRules: [Alloul, Christensen, Duhr, Degrande, Fuks 1310.1921]
  - ⋆ HEL model [Alloul, Fuks, Sanz1310.5150]
  - ⋆ HEL@NLO model [Degrande, Fuks, Mawatari, Mimasu,Sanz 1609.04833]

- Implementation of the RGE running of the wilson coefficients via the
  anomalous dimensions matrix [Alonso, Jenkins, Manohar, Trott 1312.2014]

HEL@NLO model:

- small set of operators relevant for EW Higgs production at NLO in QCD
  (see http://feynrules.irmp.ucl.ac.be/wiki/HELatNLO)

- Ongoing: Increasing set of operators
  → towards a complete dimension-6 basis at NLO in QCD
  (no 4-fermions operators)

Overall

- Many aspects covered
  (cross sections, decay widths, mass spectra, scans and fits)

- Many models covered
  (extra singlets, extra doublets, SUSY models, triplets)

- Precision increased
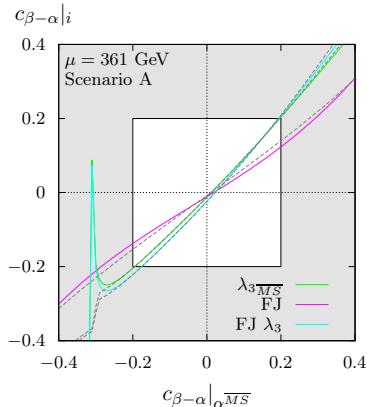 (higher-order QCD, EW corrections)

To discuss: Input scheme?

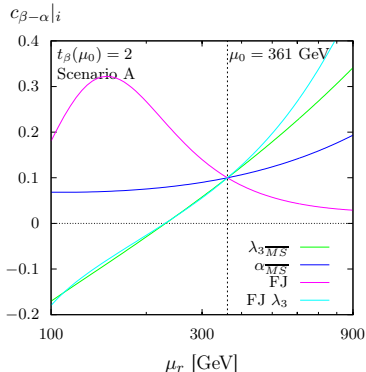Example: 2HDM: $\cos(\beta - \alpha)$ in different ren. schemes: [Altenkamp, Dittmaier, HR 1704.02645]

Scenario: $M_h = 125$ GeV, $M_H = 300$ GeV, $M_{A_0} = M_{H^+} = 460$ GeV, $\lambda_5 = -1.9$, $\tan\beta = 2$

Conversion:

Running ($\cos(\beta - \alpha) = 0.1$):

- A benchmark scenario depends on the chosen ren. scheme and the scale.

To discuss: Input scheme?

Example: 2HDM:

- First gauge-independent ren. scheme using pinch techniques and specific processes
  [Krause, Lorenz, Mühlleitner, Santos, Ziesche,1605.04853;

  Krause, Mühlleitner, Santos, Ziesche 1609.04185]
  $\rightarrow$ `New Code` for Higgs decays to 2-particle-final state
- Gauge-independent ren. scheme without use of pinch techniques and specific processes

  [Denner, Jenniches, Lang, Sturm 1607.07352]
  $\rightarrow$ `HAWK`
- Further ren. schemes with diff. options for λ_3/α, $\tan\beta$, m_{12}^2

  [Altenkamp, Dittmaier, HR 1704.02645]
  $\rightarrow$ `PROPHECY4F`

- $\Rightarrow$ No simple combination of results
- $\Rightarrow$ Discussion of choice of input scheme needed