FlexibleDecay:
An automated computation of scalar decays

Workshop on Automatic Phenomenology (2022)

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based on arXiv:2106.05038

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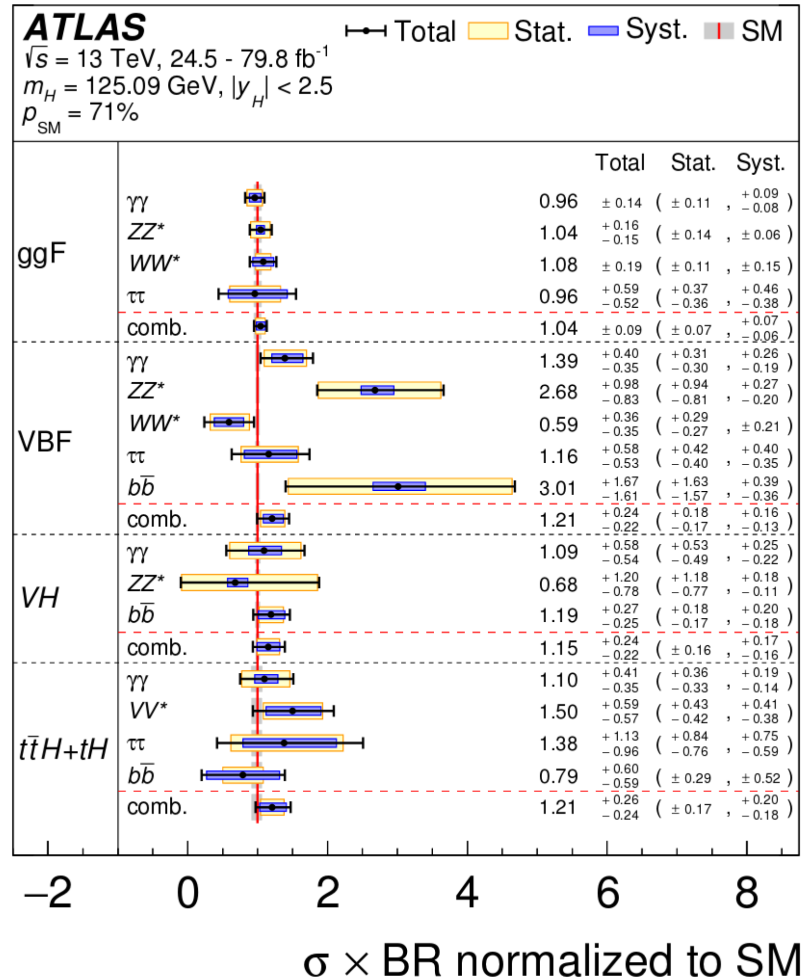
Motivation

- Many BSM models predict existence of new scalars. Their decay patterns are important for collider searches
- Realistic models must also contain a SM-like Higgs boson
- In lack of direct BSM signatures Higgs boson became our window to BSM physics
  - 125 GeV Higgs turned out to be very SM-like
  - strong constraints on BSM models
  - require accurate prediction of Higgs branching ratios in BSM models



FlexibleDecay overview

- Fully automated scalar decays evaluation in an almost arbitrary BSM model (see this page for a list of current limitations). Tested on SM, real singlet extended SM, type II THDM, MSSM/CMSSM, MRSSM and many more.
- Works as an add-on to FlexibleSUSY spectrum-generator generator (internally FlexibleSUSY utilises SARAH). Almost no extra configuration needed by a user.

```
FSCalculateDecays = True;
DecayParticles = {hh, Ah, Hpm, Su, Sd, Se, Sv};
```

turning on decays for the MSSM

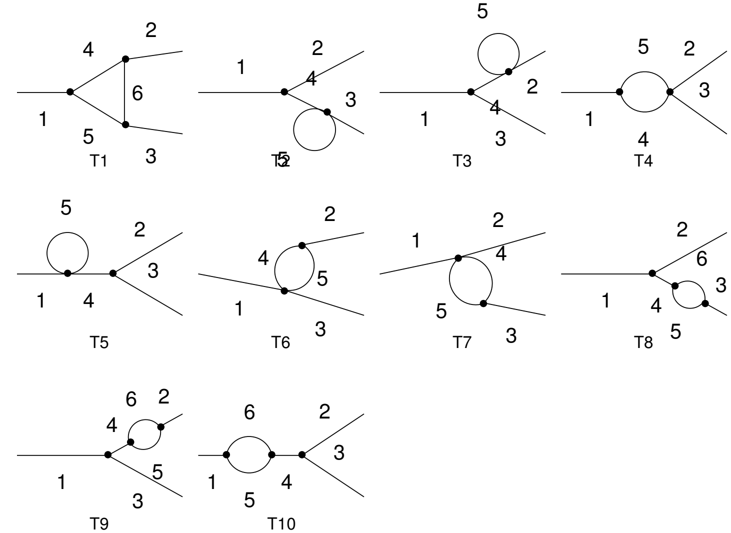
  You run FS as before.
- Generic decays are handled at the leading order (**both** tree-level and loop-induced processes are handled)
- Special treatment of scalar and pseudoscalar Higgs decays
  - higher order SM corrections from literature
  - precision comparable with state of the art codes like HDECAY

Tree-level decays

- Automatically generated $1 \longrightarrow 2$ amplitudes
- All final state types (and their combinations) are handled: scalar, fermion, vector (both massive and massless)
- Most colour representation are handled
- $\overline{\text{MS}}/\overline{\text{DR}}$ vertices with pole masses on external lines
- Example application of generic routines:
  - sfermion decays in SUSY
  - Higgs decays to non-SM particles
- Special treatment of Higgs decays into SM particles, including hand-coded single and double off-shell partial width for $h \longrightarrow VV$

Loop-induced decays

- 10 1-loop topologies



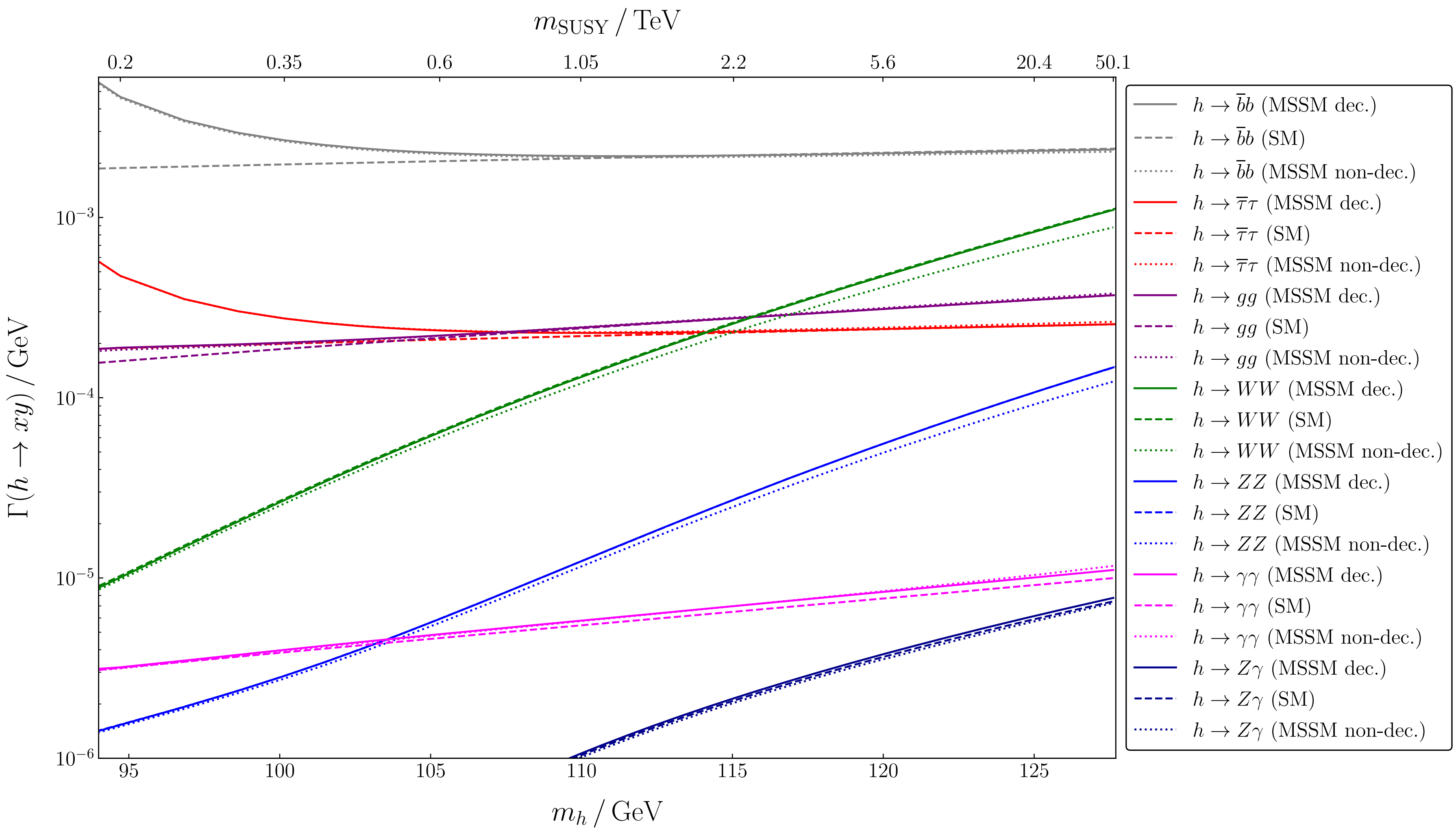
- Generic Analytical expression at the level of particle types like S, F, V, etc... created with FeynArts/FormCalc (4000+ lines of generated code)
- Strategy:
  - generate appropriate insertions at classes level during mathematica stage
  - map them to amplitudes at the C++ level
  - introduce colour factors using modified version of ColorMath package from Malin Sjödahl

Renormalization scheme

- Need for a dedicated renormalization scheme since BSM is (probably) heavy
  - On-shell scheme most natural but it's not how spectrum generators work
  - $\overline{\text{MS}}/\overline{\text{DR}}$ features non-decoupling effects
- Dedicated scheme with explicit decoupling properties
  - BSM equivalents of SM parameters are set to SM $\overline{\text{MS}}$ values by definition
  - actual BSM parameters are defined in the $\overline{\text{MS}}/\overline{\text{DR}}$ scheme
- Decay module is agnostic of the scheme. It can be selected at run time though higher order corrections are not applicable if one is not using the decoupling scheme.
- Side remark: using $\overline{\text{MS}}/\overline{\text{DR}}$ scheme for BSM parameters allows for an easy connection between Higgs branching ratios and observables like vacuum stability

Decoupling scheme in action

decoupling scheme "interpolates" between a BSM and the SM

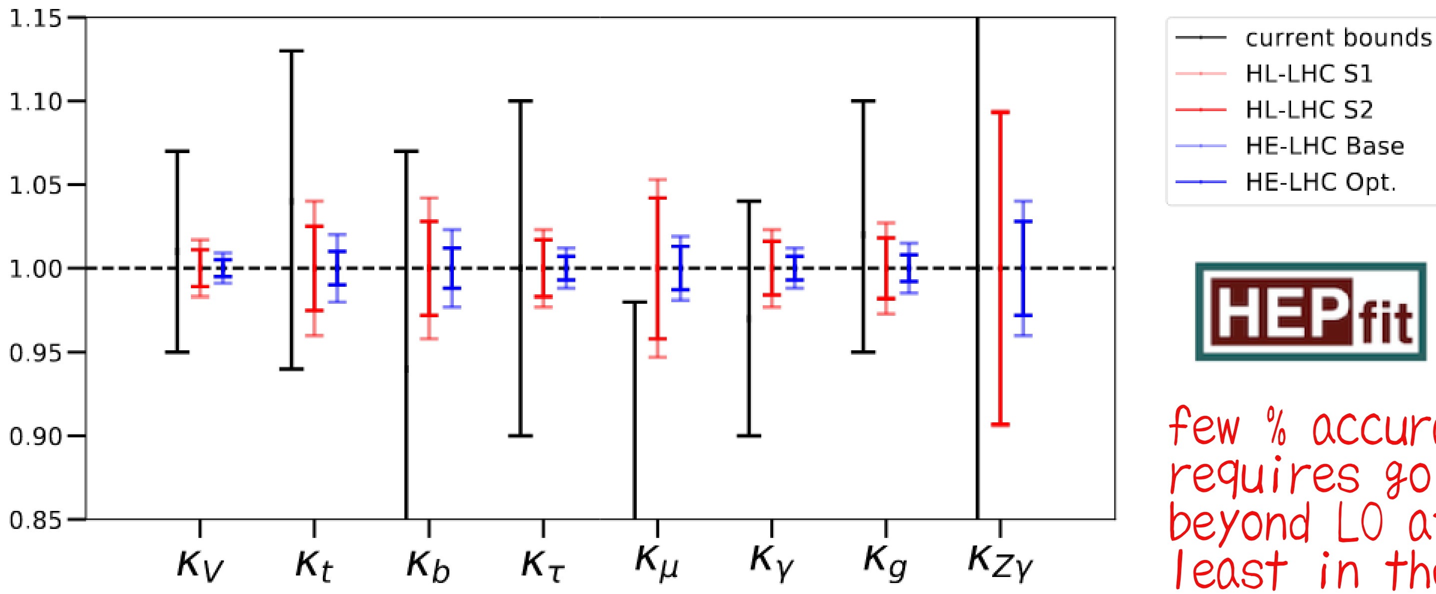


Expected experimental precision

- Kappa framework

$$\kappa_X^2 = \frac{\sigma(X_i \to h + X_f)}{\sigma(X_i \to h + X_f)_{\rm SM}}, \qquad \kappa_Y^2 = \frac{\Gamma(h \to Y)}{\Gamma(h \to Y)_{\rm SM}}$$

- Current and expected precision in measurement of Higgs (effective) couplings



HEPfit

few % accuracy requires going beyond LO at least in the SM part

Higher order SM corrections in FD

- $H \longrightarrow VV$
  - single/double off-shell decays into gauge bosons
- $\Phi \longrightarrow gg$
  - 2,3 and 4-loop SM QCD corrections to top triangle for $m_H/(2m_t) \lesssim 0.84$ with m_t dependence
  - 2 and 3-loop QCD, leading m_t corrections for A
- $\Phi \longrightarrow \gamma\gamma$
  - 2-loop QCD corrections to fermion loop for almost arbitrary m_Φ
  - 2-loop QCD corrections to scalar loops for $m_s/m_\Phi \ll 1$ and $\gg 1$
- $\Phi \longrightarrow q\bar{q}$
  - interpolation between an $\overline{\text{MS}}$ and an on-shell calculation (accurate for arbitrary ratios of m_q/m_Φ (HDECAY approach)
  - 4-loop QCD, 1-loop QED, 2-loop mixed QED$\otimes$QCD

Ward Identity

- Generic form of the $h\to\gamma\gamma$ amplitude

$$\mathcal{A}_{S\to V_1V_2} = \varepsilon^*_{1,\mu}\varepsilon^*_{2,\nu}\left(F_\eta\eta^{\mu\nu} + F_{11}p_1^\mu p_1^\nu + F_{12}p_1^\mu p_2^\nu + F_{21}p_1^\nu p_2^\mu + F_{22}p_2^\mu p_2^\nu + F_\epsilon\epsilon^{\mu\nu\alpha\beta}p_{1,\alpha}p_{2,\beta}\right)$$

- For physical photons (because of $\epsilon_i \cdot p_i=0$) and applying the Ward identity we get

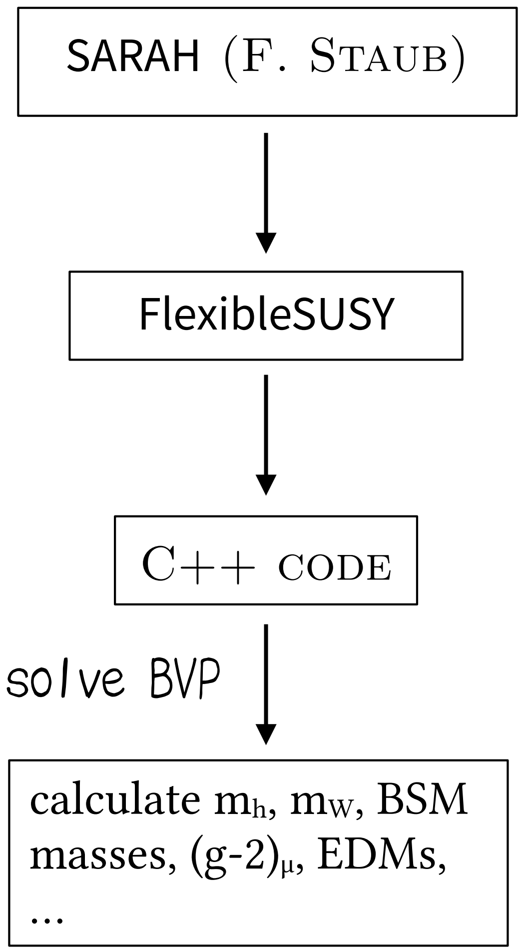
$$F_\eta = -p_1p_2\,F_{21}$$

  As a technical consequence this also ensures that $|\mathcal{A}_{S\to V_1V_2}|^2$ is positive.
- In gauges other than unitary and non-onshell renormalization schemes the above relation is broken by higher order effects
- 3 sets of diagrams
  - pure gauge boson loop (WI always fulfilled)
  - pure Goldstone boson loop (WI always fulfilled)
  - mixed one (WI broken)
- For example in the SM the mixed set has a single diagram dependent on hG^+G^- coupling containing $\lambda=m_h^2/v$ and WI hangs on whether $p_h^2=m_h^2$.

FlexibleSUSY in a nutshell

- FlexibleSUSY is a spectrum-generator generator. But what does it mean?
- There are codes like 2HDMC, SPheno, SOFTSUSY or SuSpect that calculate mass spectra and various observables for a predefined model (THDM in case of 2HDMC and MSSM/NMSSM in remaining cases).
- FlexibleSUSY creates a code analogue to such programs but for an arbitrary BSM model.
- Use known results for a generic QFT. Don't recalculate what you don't have to from the ground.
- Streamlining study of BSM phenomenology, reducing time needed to study a new model from years to weeks. No hand written code, less place for errors.

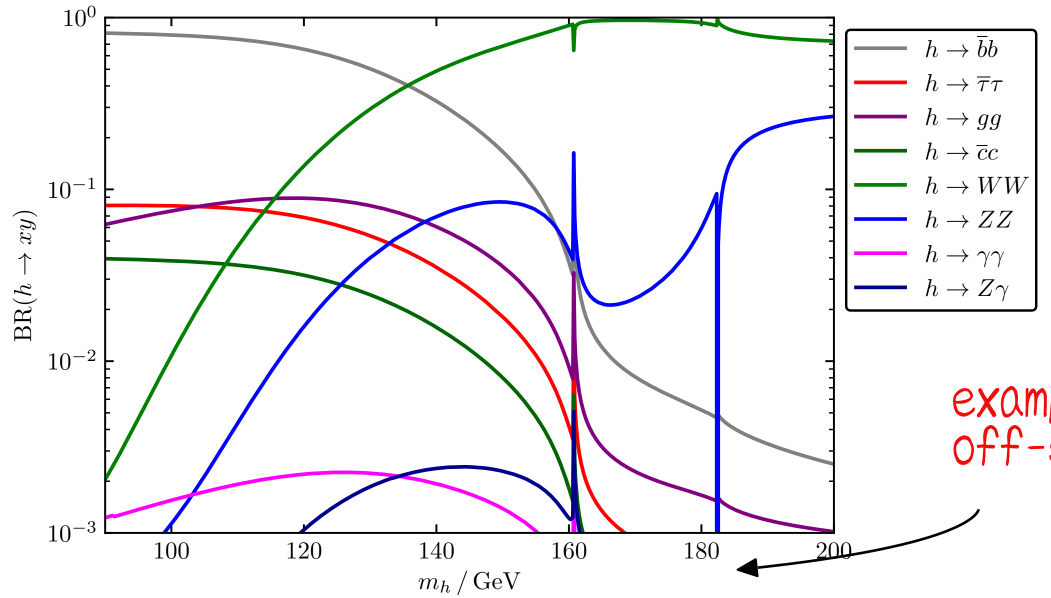
Program flow



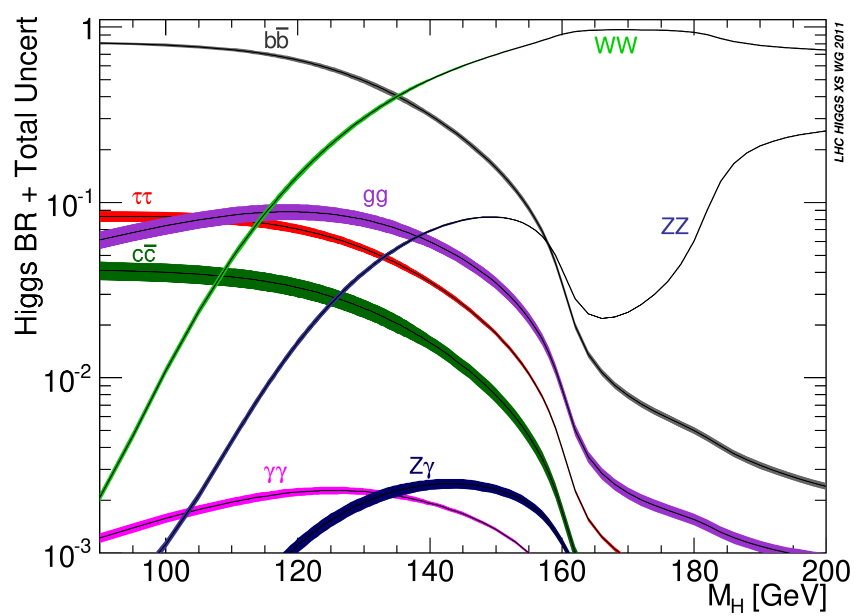
- Analytic calculation: particle content + Lagrangian $\Longrightarrow$ tadpole equations, self-energies, mass matrices, RGEs, vertices etc.

- Creates code for numerical evaluation of various observables
  - 1-loop pole masses and mixing matrices (in specific models higher corrections are available)
  - observables: muon $(g\text{-}2)_\mu$, lepton's EDMs, $l \to l'\gamma$, $b \to s\gamma$, scalar decays
  - soon: $l \to l'$ conversion in nuclei, $l \to 3l$

SM Higgs BR



example of 2-body - off-shell threshold



Example: Higgs decays in the CMSSM

large difference because of strict 1-loop on-shell calculation which has an explicit $\ln m_b^2/m_h^2$

overall good agreement between SUSY-HIT (SDECAY), SARAH+SPheno (DECAY) and FS

channel	SUSY-HIT	SOFTSUSY	SARAH/SPheno (DECAY)	SARAH/SPheno (DECAY1L)	FlexibleSUSY
$h \to b\bar{b}$	2.662	3.843	2.403	1.541	2.348
$h \to W^+W^-$	$8.342 \cdot 10^{-1}$	$6.751 \cdot 10^{-1}$	$5.887 \cdot 10^{-1}$	—	$8.141 \cdot 10^{-1}$
$h \to \tau\bar{\tau}$	$2.595 \cdot 10^{-1}$	$2.726 \cdot 10^{-1}$	$2.778 \cdot 10^{-1}$	$2.355 \cdot 10^{-1}$	$2.499 \cdot 10^{-1}$
$h \to c\bar{c}$	$1.183 \cdot 10^{-1}$	$2.235 \cdot 10^{-1}$	$1.031 \cdot 10^{-1}$	$1.073 \cdot 10^{-1}$	$1.160 \cdot 10^{-1}$
$h \to ZZ$	$1.060 \cdot 10^{-1}$	$7.606 \cdot 10^{-2}$	$5.882 \cdot 10^{-2}$	—	$1.032 \cdot 10^{-1}$
$h \to gg$	$2.731 \cdot 10^{-1}$	$2.760 \cdot 10^{-1}$	$2.993 \cdot 10^{-1}$	$9.555 \cdot 10^{-2}$	$3.434 \cdot 10^{-1}$
$h \to \gamma\gamma$	$9.439 \cdot 10^{-3}$	$1.052 \cdot 10^{-2}$	$8.580 \cdot 10^{-3}$	$1.024 \cdot 10^{-2}$	$9.940 \cdot 10^{-3}$
$h \to Z\gamma$	$6.316 \cdot 10^{-3}$	$6.779 \cdot 10^{-3}$	—	$4.303 \cdot 10^{-1}$	$6.098 \cdot 10^{-3}$
total width	4.272	5.386	3.741	—	3.993

note difference in the treatment of h→VV between codes

$h \to Z\gamma$ in SARAH+SPheno seems buggy

R-symmetry

- R-symmetry is an additional symmetry of the SUSY algebra allowed by the Haag - Łopuszański - Sohnius theorem
- For N=1 SUSY it is a global $U(1)_R$ symmetry under which the SUSY generators are charged
- implies that the spinorial coordinates are also charged

$$Q_R(\theta) = 1,\ \theta \to e^{\imath\alpha}\theta$$

- Lagrangian invariance
  - Kähler potential K term is automatically invariant
  - R-charge of the superpotential W must be 2

$Q_R(d^2\theta)=-2$

$$Q_R(\mathscr{L})=0 \longrightarrow \mathcal{L} \ni \int d^2\theta\, W$$

$Q_R(W)=+2$

  - soft-breaking terms must have R-charge 0

Low-energy R-symmetry realization

- Charges of component fields

$$\begin{array}{ccccccc} e^{\imath\alpha Q_R} & & e^{\imath\alpha Q_R} & & e^{\imath\alpha(Q_R-1)} & & \\ \Phi & = & \phi(y) & + & \sqrt{2}\theta\psi(y) & + & \theta\theta F(y) \end{array}$$

- "Natural" choice

Higgs	$Q_R = 1$	$Q_R = 1$	$Q_R = 0$
leptons and quarks	$Q_R = 0$	$Q_R = 0$	$Q_R = -1$

- Good: no barion and lepton number violating terms
- Bad: No Majorana masses for higgsinos and gauginos

One way to fix it: Dirac masses
Minimal R-Symmetric Supersymmetric Standardmodel (MRSSM)
Kribs et.al. arXiv:0712.2039

			$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_R$
Additional fields:	Singlet	$\hat{S}$	1	1	0	0
	Triplet	$\hat{T}$	1	3	0	0
	Octet	$\hat{O}$	8	1	0	0
	R-Higgses	$\hat{R}_u$	1	2	$-1/2$	2
		$\hat{R}_d$	1	2	$1/2$	2

$$\begin{aligned} W = & \mu_d \hat{R}_d \hat{H}_d + \mu_u \hat{R}_u \hat{H}_u \\ & + \Lambda_d \hat{R}_d \hat{T} \hat{H}_d + \Lambda_u \hat{R}_u \hat{T} \hat{H}_u + \lambda_d \hat{S} \hat{R}_d \hat{H}_d + \lambda_u \hat{S} \hat{R}_u \hat{H}_u \\ & - Y_d \hat{d} \hat{q} \hat{H}_d - Y_e \hat{e} \hat{l} \hat{H}_d + Y_u \hat{u} \hat{q} \hat{H}_u \end{aligned}$$

MSSM vs. MRSSM

- MSSM superpotencial

$$\mu \hat{H}_u \hat{H}_d$$

$$-Y_d\, \hat{d}\, \hat{q}\, \hat{H}_d \; - Y_e\, \hat{e}\, \hat{l}\, \hat{H}_d \; + Y_u\, \hat{u}\, \hat{q}\, \hat{H}_u$$

- MSSM soft-SUSY breaking terms
  - B_μ - term ✔
  - soft scalar masses ✔
  - Majorana gaugino masses !
  - A - terms !

- MRSSM superpotencial

$$\mu_d\, \hat{R}_d\, \hat{H}_d \; + \mu_u\, \hat{R}_u\, \hat{H}_u$$

$$-Y_d\, \hat{d}\, \hat{q}\, \hat{H}_d \; - Y_e\, \hat{e}\, \hat{l}\, \hat{H}_d \; + Y_u\, \hat{u}\, \hat{q}\, \hat{H}_u$$

$$\Lambda_d\, \hat{R}_d\, \hat{T}\, \hat{H}_d \; + \Lambda_u\, \hat{R}_u\, \hat{T}\, \hat{H}_u \; + \lambda_d\, \hat{S}\, \hat{R}_d\, \hat{H}_d \; + \lambda_u\, \hat{S}\, \hat{R}_u\, \hat{H}_u$$

- MRSSM soft-SUSY breaking terms
  - B_μ - term (though no B_{μ_u}, B_{μ_d})
  - soft scalar masses
  - Dirac gaugino masses
  - no A-terms

One way to fix it: Dirac masses
Minimal R-Symmetric Supersymmetric Standardmodel (MRSSM)
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			$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_R$
Additional fields:	Singlet	$\hat{S}$	1	1	0	0
	Triplet	$\hat{T}$	1	3	0	0
	Octet	$\hat{O}$	8	1	0	0
	R-Higgses	$\hat{R}_u$	1	2	$-1/2$	2
		$\hat{R}_d$	1	2	$1/2$	2

R-symmetry vs. matter parity

- Consider R-symmetric transformation of a generic supermultiplet

$$R : \Phi(x, \theta, \bar{\theta}) \to \Phi'(x, e^{\imath\varphi}\theta, e^{-\imath\varphi}\bar{\theta}) = e^{\imath\varphi R_\Phi}\Phi(x, \theta, \bar{\theta})$$

- In the MSSM one imposes the so-called matter parity

$$M_p = (-1)^{3(B-L)}$$

  - this is equivalent to R-pairity which is defined on components of a supermultiplet as $P_R = (-1)^{3(\mathrm{B}-\mathrm{L})+2s}$
  - This is also equivalent to R-symmetry $R = e^{\imath\varphi R_\Phi}$ with $\varphi = \pi$ and $R_\Phi = 3(B - L)$
- R-charges
  - MSSM: $R_\Phi = 0, 1$
  - MRSSM: $R_\Phi = 0, 1, 2$
- R-symmetry is more restrictive than matter parity

Particle content summary: MSSM vs. MRSSM

different number of physical state

completely new states

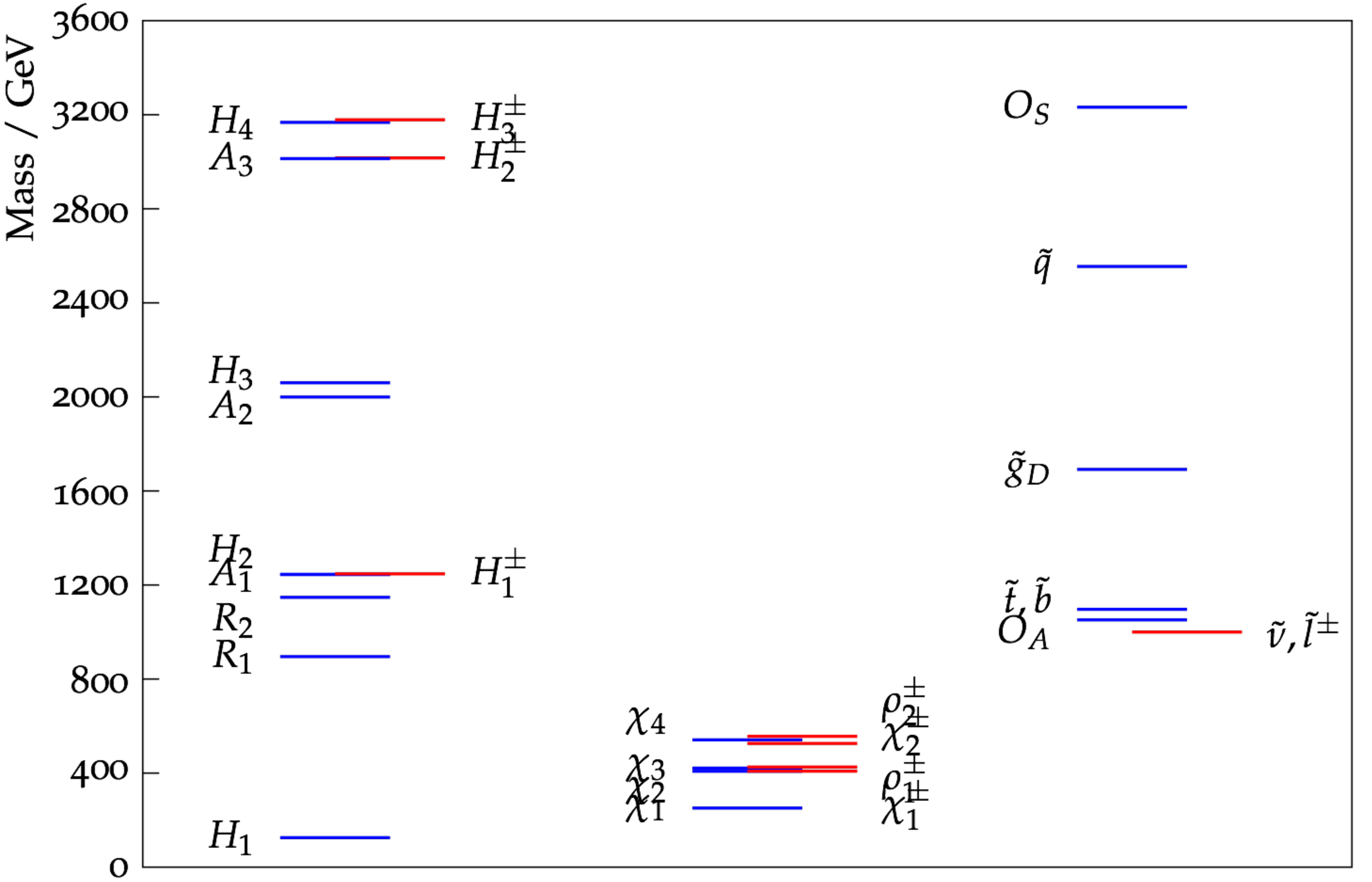
		Higgs			R-Higgs		
	CP-even	CP-odd	charged	charginos	neutral	charged	sgluon
MSSM	2	1	1	2	0	0	0
MRSSM	4	3	3	2+2	2	2	2

	neutralino	gluino
MSSM	4	1
MRSSM	4	1

Majorana fermions

Dirac fermions

Exemplary mass spectrum



Example: Higgs decays in the MRSSM

only 2 codes are capable of computing Higgs decays in a "non-standard" model like the MRSSM

channel	SARAH/SPheno (DECAY)	SARAH/SPheno (DECAY1L)	FlexibleSUSY
$h \to b\bar{b}$	2.460	2.079	2.433
$h \to W^+W^-$	$7.234 \cdot 10^{-1}$	—	$7.856 \cdot 10^{-1}$
$h \to \tau\bar{\tau}$	$2.851 \cdot 10^{-1}$	$2.601 \cdot 10^{-1}$	$2.587 \cdot 10^{-1}$
$h \to c\bar{c}$	$1.046 \cdot 10^{-1}$	$1.273 \cdot 10^{-1}$	$1.158 \cdot 10^{-1}$
$h \to ZZ$	$7.686 \cdot 10^{-2}$	—	$9.987 \cdot 10^{-2}$
$h \to gg$	$3.186 \cdot 10^{-1}$	$1.353 \cdot 10^{-1}$	$3.462 \cdot 10^{-1}$
$h \to \gamma\gamma$	$8.402 \cdot 10^{-3}$	$1.007 \cdot 10^{-2}$	$9.140 \cdot 10^{-3}$
$h \to \gamma Z$	—	$1.671 \cdot 10^{-1}$	$5.588 \cdot 10^{-3}$
total width	3.979	—	4.056

good agreement between SARAH+SPheno (DECAY) and FS

$h \to Z\gamma$ in SARAH+SPheno seems buggy

Example: squark decays in the CMSSM

SDECAY contains some higher order corrections which we manually disable

SoftSUSY, old SARAH+SPheno and FS work on tree-level

channel	SUSY-HIT	SOFTSUSY	SARAH/SPheno (DECAY)	FlexibleSUSY
$\tilde{b}_1 \to \tilde{\chi}_1^- t$	26.931	26.569	27.061	26.380
$\tilde{b}_1 \to \tilde{\chi}_2^- t$	26.690	33.160	25.931	26.371
$\tilde{b}_1 \to \tilde{t}_1 W^-$	23.434	23.906	23.903	23.635
$\tilde{b}_1 \to \tilde{\chi}_2^0 b$	13.389	13.318	13.419	13.239
$\tilde{b}_1 \to \tilde{\chi}_1^0 b$	$7.617 \cdot 10^{-1}$	$7.635 \cdot 10^{-1}$	$6.807 \cdot 10^{-1}$	$7.650 \cdot 10^{-1}$
$\tilde{b}_1 \to \tilde{\chi}_4^0 b$	$3.420 \cdot 10^{-1}$	$4.308 \cdot 10^{-1}$	$3.927 \cdot 10^{-1}$	$3.575 \cdot 10^{-1}$
$\tilde{b}_1 \to \tilde{\chi}_3^0 b$	$3.078 \cdot 10^{-1}$	$4.010 \cdot 10^{-1}$	$3.404 \cdot 10^{-1}$	$3.311 \cdot 10^{-1}$
total width	91.856	98.548	91.728	91.079

overall good agreement between codes

Runtime configuration

Entry number in FlexibleDecay SLHA block

Index	`Mathematica` symbol	Default	Description
0	–	1	calculate decays (0 = no, 1 = yes)
1	`minBRtoPrint`	10^{-5}	minimum BR to print
2	`maxHigherOrderCorrections`	4	include higher order corrections in decays (0 = LO, 1 = NLO, 2 = NNLO, 3 = NNNLO, 4 = N^{4}LO)
3	`alphaThomson`	1	use $\hat{\alpha}(m)$ or Thomson $\alpha(0)$ in decays to $\gamma\gamma$ and γZ ($0 = \hat{\alpha}(m)$, $1 = \alpha(0)$)
4	`offShellVV`	2	decays into off-shell VV pair (0 = no off-shell decays, 1 = single off-shell decays if $m_V < m_H < 2m_H$, double off-shell if $m_H < m_V$, 2 = double off-shell decays if $m_H < 2m_V$)

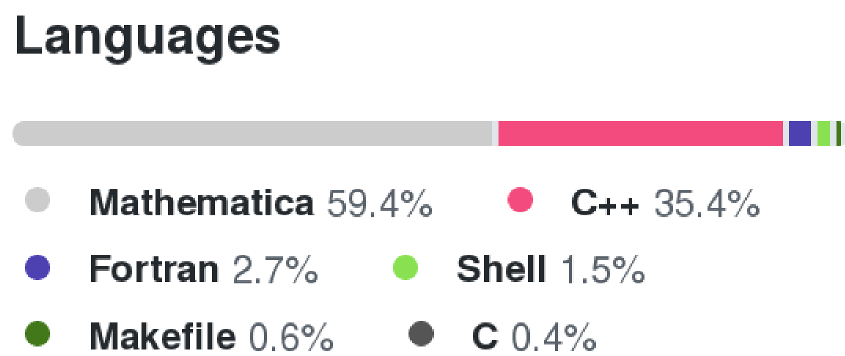
If used via the mathematica interface

Current limitations

- Decays of fermions and vector bosons currently not supported
- Decays of colour octets into pair of colour octets are broken. Other combinations, like for example $8 \longrightarrow 3 \otimes 3$ or $3 \longrightarrow 8 \otimes 3$ work correctly.
- Decays containing vertices which cannot be decomposed into a single product of Lorentz and colour structure, e.g. quartic-gluon vertex
- Only $1 \longrightarrow 2$ decays are possible. The exception is decay of scalar Higgses to ZZ and W^+W^- pairs where we include single and double off-shell decays assuming SM decays of W and Z bosons.

FlexibleSUSY development and support

- The code is written exploiting relatively modern features of C++ (C++14) with use of template metaprograming to reduce runtime overhead



- Development is done in public on github

- Large collection of unit tests, triggered by every commit to the main repository

- In case of any problems, please file an issue. We'll be happy to assist you.

Conclusions and outlook

- FlexibleDecay is a powerful tool capable of computing decays of scalars in user defined models
- Higgs decays are treated in special way, bringing in that case precision of FlexibleDecay close to state of the art codes like HDECAY.
- You can get it today, just visit FlexibleSUSY github page (current version is *2.7.1*). Send me a message if you have any problems.
- Future plans:
  - finish implementation of decays of fermions and vectors
  - 1-loop corrections to tree-level decays

Hope you'll use and like FlexibleDecay. Writing generic code is hard. We can only hope to squash all bugs if we have actual users with real world problem. And If you do, I'm here to help. Thanks!