FlexibleDecay: From Lagrangian to Higgs physics constraints with high precision

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Goal: high precision prediction of Higgs properties

- Mass
  - fixed order/EFT/hybrid aproaches
  - need for at least some 2-loop corrections (+/-)
- Partial widths of neutral na charged Higgses
  - higher order SM corrections (+)
  - higher order BSM corrections (+/-)
- Checking the validity of a BSM Higgs sector (+)
  - link with HiggsTools and Lilith

FlexibleDecay overview

- Fully automated scalar decays evaluation in an almost arbitrary BSM model. 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. 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.

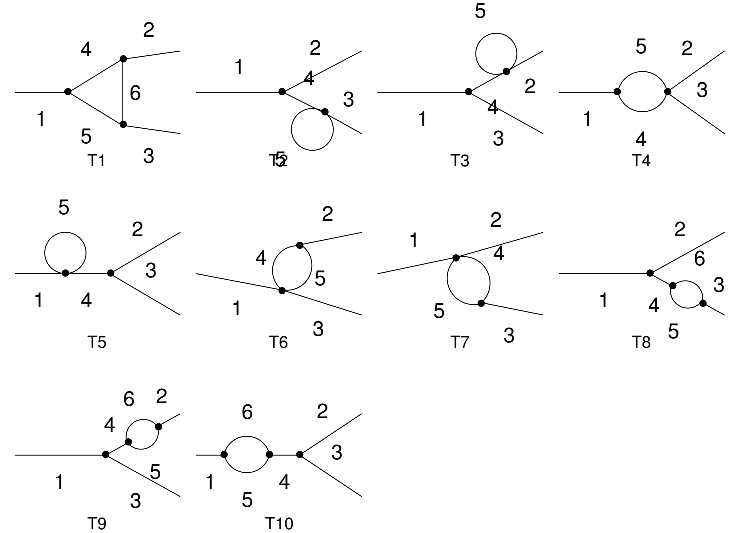
- Generic decays are handled at the leading order (**both** tree-level and loop-induced processes are handled)
- Special treatment of scalar and pseudoscalar Higgs decays
  - higher order SM corrections from literature
  - precision comparable with state of the art codes like HDECAY

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



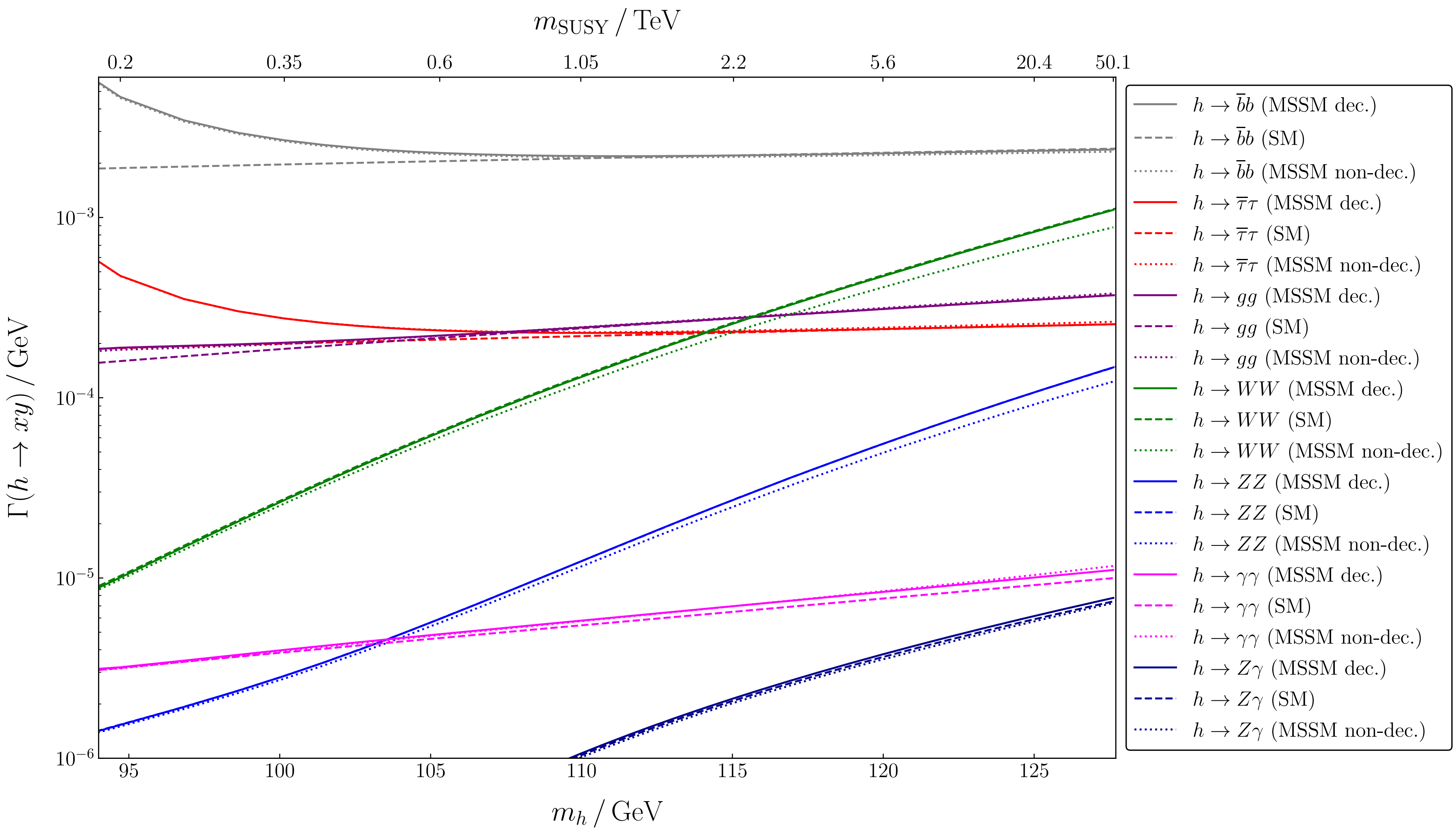
- Generic Analytical expression at the level of particle types like S, F, V, etc... created with FeynArts/FormCalc (4000+ lines of generated code)
- Strategy:
  - generate appropriate insertions at classes level during mathematica stage
  - map them to amplitudes at the C++ level
  - introduce colour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

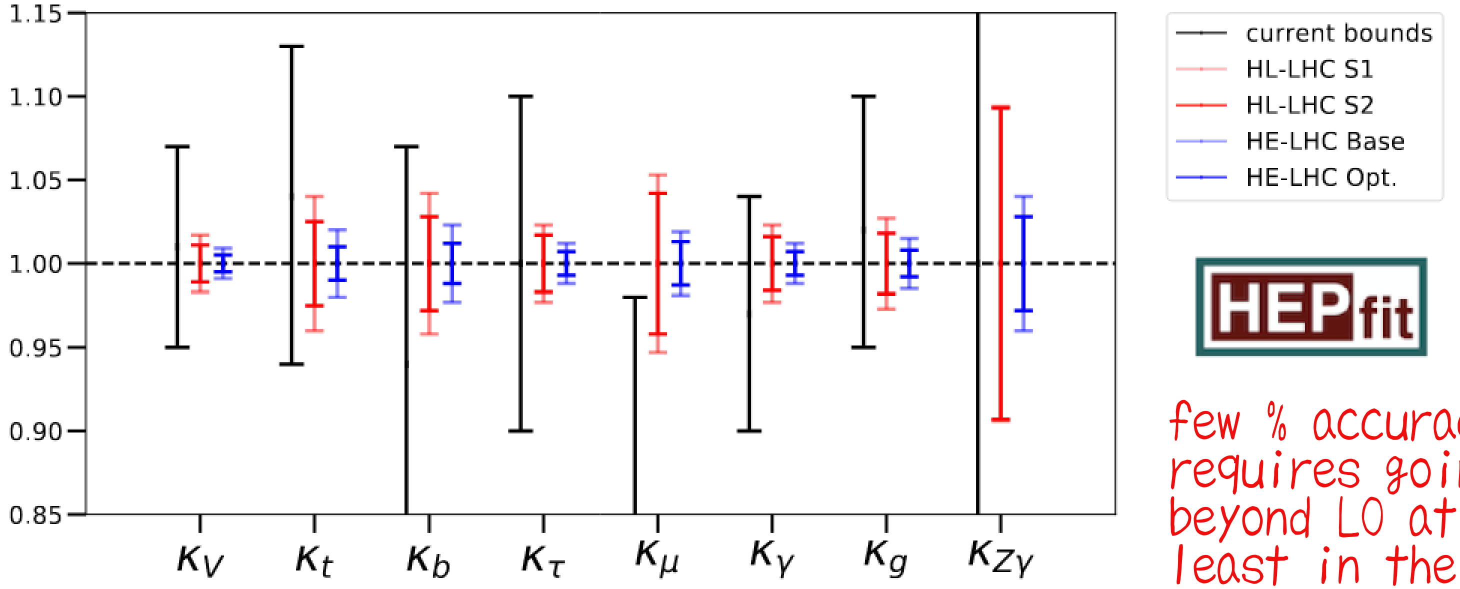


Expected experimental precision

- 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

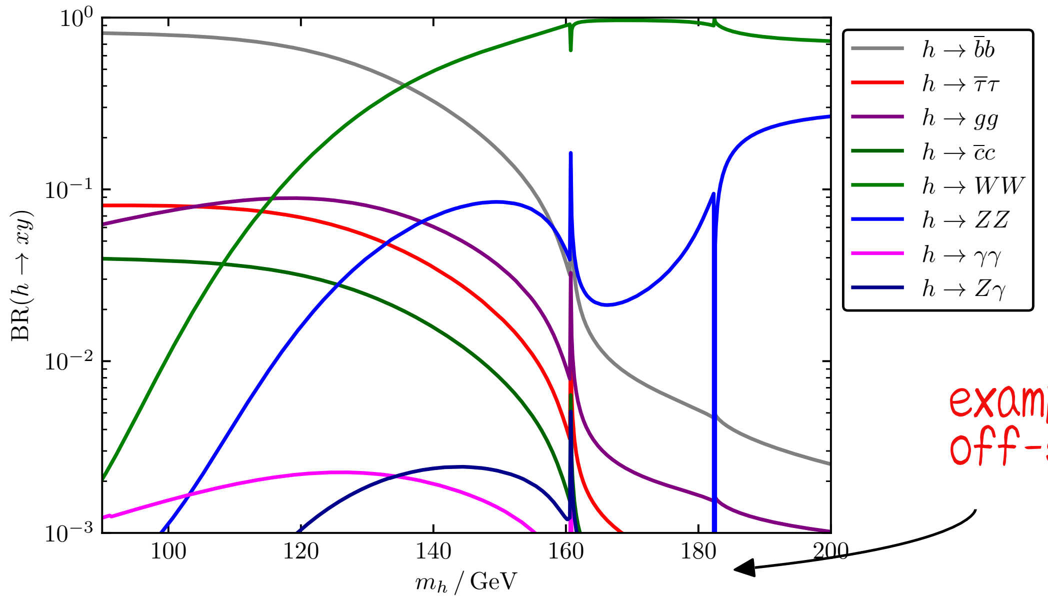


few % accuracy requires going beyond LO at least in the SM part

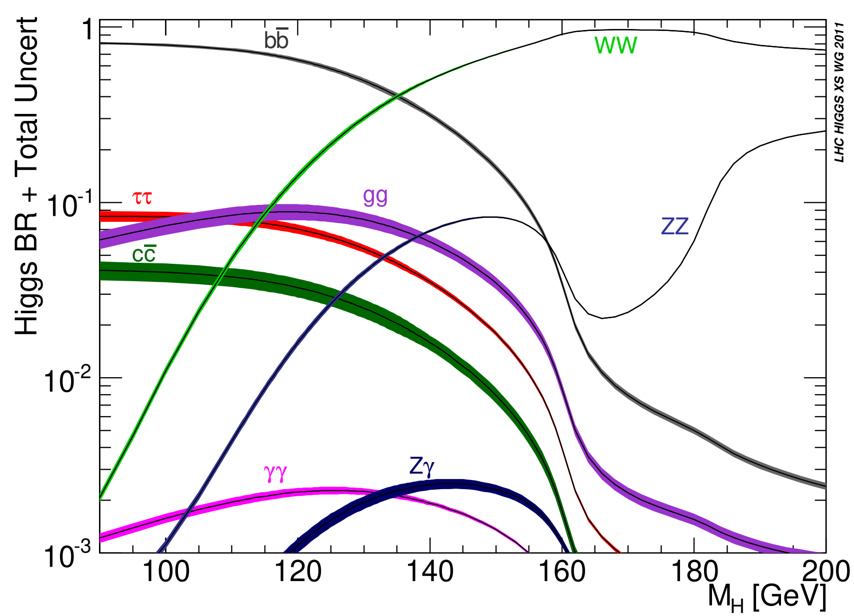
Higher order SM corrections in FD

- $H \longrightarrow VV$
  - 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

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

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

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.

Partial widths by themselves are not enough

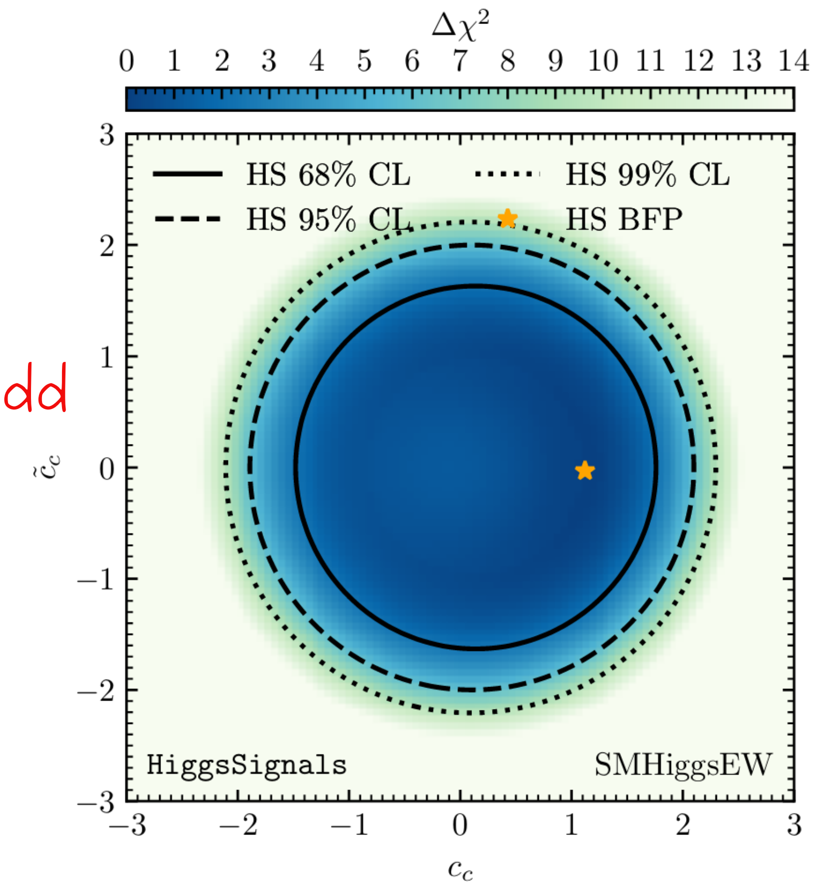
```
...
Block DCINFO
     1   FlexibleSUSY
     2   2.6.1
     5   SSMMhInput
     9   4.14.3
DECAY        25     3.20846016E-03   # hh(1) decays
     5.82089643E-01   2           -5          5  # BR(hh(1) -> barFd(3) Fd(3))
     2.10479150E-01   2          -24         24  # BR(hh(1) -> conjVWp VWp)
     8.56684916E-02   2           21         21  # BR(hh(1) -> VG VG)
     6.19432803E-02   2          -15         15  # BR(hh(1) -> barFe(3) Fe(3))
     2.87673651E-02   2           -4          4  # BR(hh(1) -> barFu(2) Fu(2))
     2.67950080E-02   2           23         23  # BR(hh(1) -> VZ VZ)
     2.29059815E-03   2           22         22  # BR(hh(1) -> VP VP)
     1.48172847E-03   2           22         23  # BR(hh(1) -> VP VZ)
     2.64726402E-04   2           -3          3  # BR(hh(1) -> barFd(2) Fd(2))
     2.19292886E-04   2          -13         13  # BR(hh(1) -> barFe(2) Fe(2))
DECAY        35     8.56617420E-01   # hh(2) decays
...
```

HiggsTools

Bahl, Biekötter, Heinemeyer, Li, Paasch, Weiglein, Wittbrod

- Succesor of HiggsBounds and HiggsSignals
- Consists of two parts:
  - HiggsSignals: checks SM-like Higgs
  - HiggsBounds: checks BSM Higgses
- Example: SM-like Higgs with perturbed coupling to charm quarks
- Some care needed in interpreting χ^2 from HiggSignals
- Latest databases (HS v1.1, HB v1.6). Latest HS has 159 dof

CP–odd



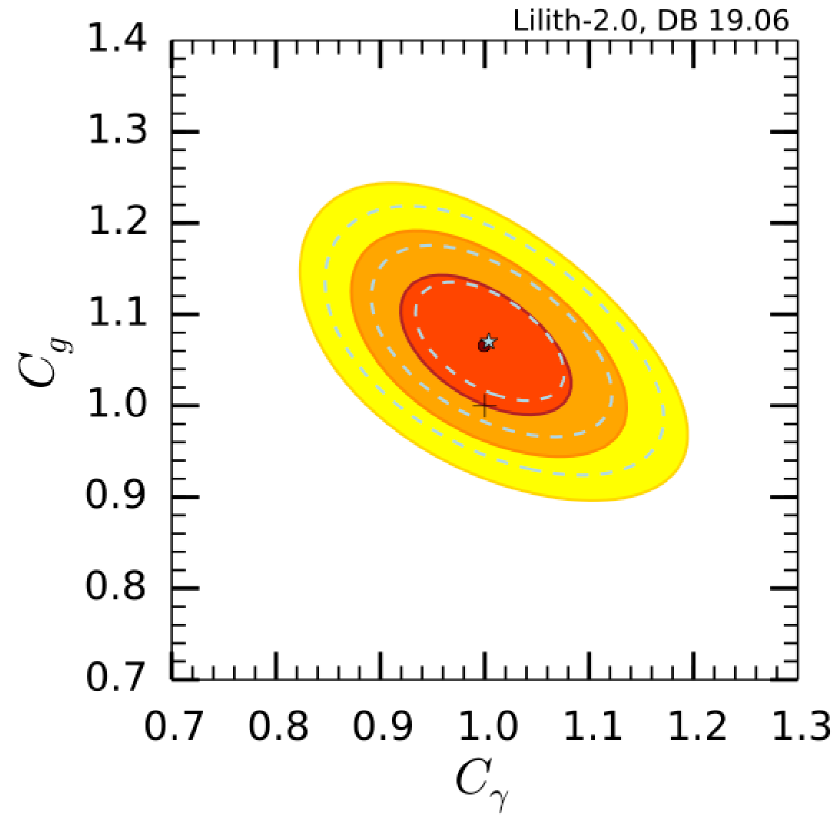
CP–even

Bahl et al. [arXiv:2210.09332]

Lilith

Kraml, Loc, Nhung and Ninh

- A Python library for constraining new physics from Higgs signal strength measurements.
- It is similar in spirit to HiggsTools (even allows for the same input).
- There's a difference in implemented analysis. The latest database (called latestRun2 contains analysis from 36 and 137 fb^{-1} data samples).
- LatestRun2 has 53 dof.



Construction of effective couplings

- Effective couplings (normalised to SM) are constructed from partial widths

$$\kappa^2 \equiv \frac{\Gamma(H \to AB)_{\mathrm{BSM}}}{\Gamma(h \to AB)_{\mathrm{SM},m_h=m_H}}$$

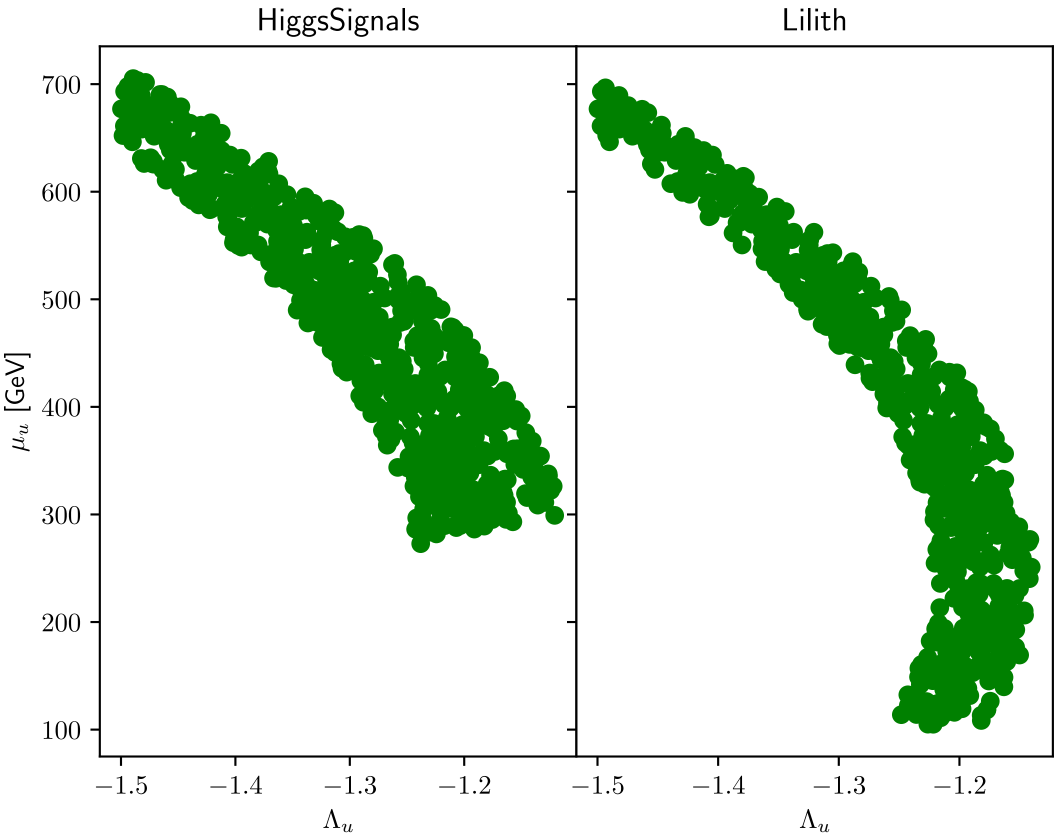
$$\kappa \equiv \frac{\Gamma^{CP-even,1/2}(H \to AB)_{\mathrm{BSM}} + \imath\Gamma^{CP-odd,1/2}(H \to AB)_{\mathrm{BSM}}}{\Gamma(h \to AB)^{1/2}_{\mathrm{SM},m_h=m_H}}$$

meaning we lose information about the sign. The CP properties are correctly tracked. Limited to masses between ~1 and ~650 GeV.

The input chain

HiggsTools vs. Lilith

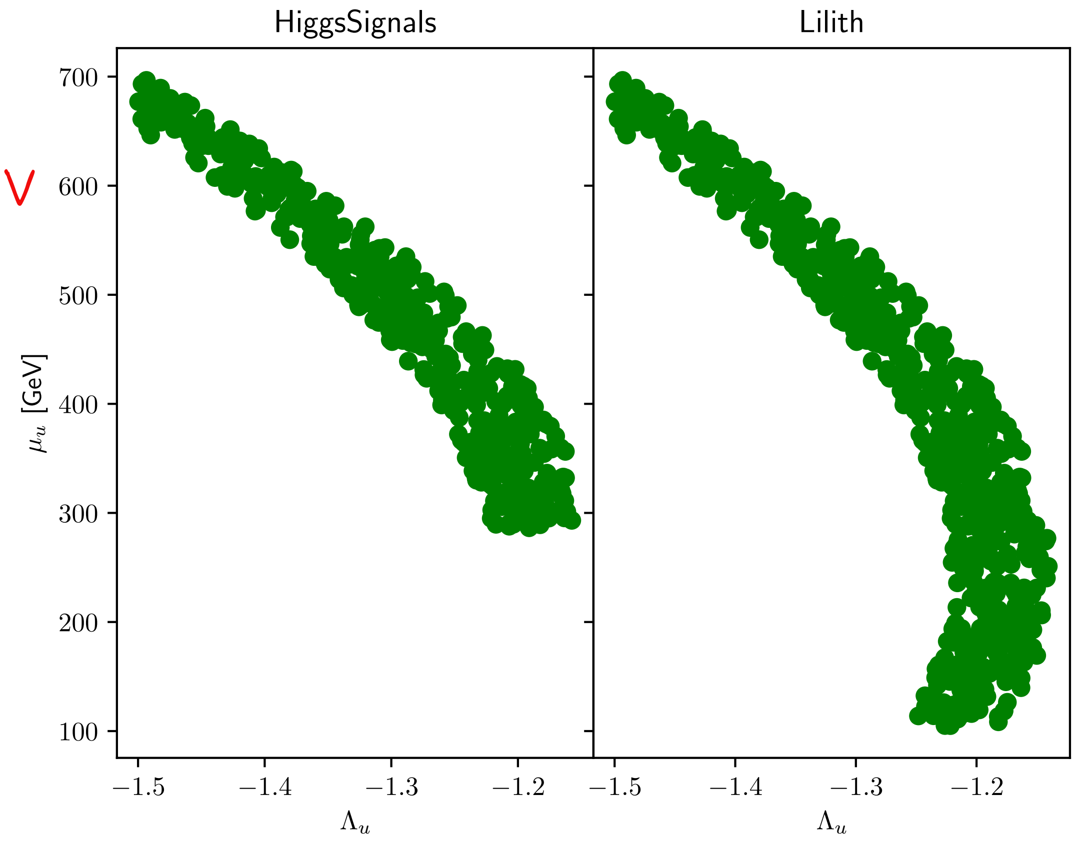
We set 3% mass uncertainty for HT



Lilith has a hardcoded limit $m_h \in [123, 128]$ GeV

HiggsTools vs. Lilith

after artificially restricting HT to $m_h \in [123, 128]$ GeV



a genuine effect from differnce in implemented experimental analyses

Constraining charged Higgses

- Lilith constraints only neutral Higgses but HiggsBounds can check also the charged ones (both single and double charged)
- The effective coupling input doesn't make sense in this case – need to specify production cross-sections and branching ratios directly or $BR(t \to bH^+)$
- HiggsTools has some helper functions to compute charged Higgs production processes based on masses and couplings in the model. For example $pp \to H^\pm t(b)$ or $pp \to H^\pm \phi$
- Higher order corrections to some charged Higgs decays or to $t \to bH^+$ can be take over from literature as we did for the neutral Higgses

Higher order BSM corrections

- Higher order BSM corrections to tree-level decays in the decoupling scheme

pure SM
taken from
literature

$$\Gamma^{\text{full BSM}}(H \to XY) = \Gamma^{\text{SM}}(H \to XY) + \Gamma^{\text{only BSM}}(H \to XY)$$

pure BSM

- Required property

$$\Gamma^{\text{only BSM}}(H \to XY) \to 0 \quad \text{for} \quad m_{\text{BSM}} \to 0$$

- Application/tests in simplified models
  - $h \to \mu^+\mu^-$ in S1 leptoquark model
  - singlet extended SM

In preparation: FS 3.0 manual

Conclusions and outlook

- Goal: state of the art code going directly from Lagrangian to experimental exclussions
  - high precision Higgs mass calculation (~60% done)
  - high precision decay calculation (~50% done)
  - experimental constraints (~90% done)
- Further improvements:
  - constaining charged (singly and doubly) Higgses (only HiggsBounds)
  - higher order BSM corrections to SM-like Higgs decays are under implementation
  - 2-loop corrections in the 0-momentum approximation to Higgs boson mass (from SARAH)