Automatizing the path from Lagrangian to Higgs physics constraints

SUSY 2024

Theory meets Experiment

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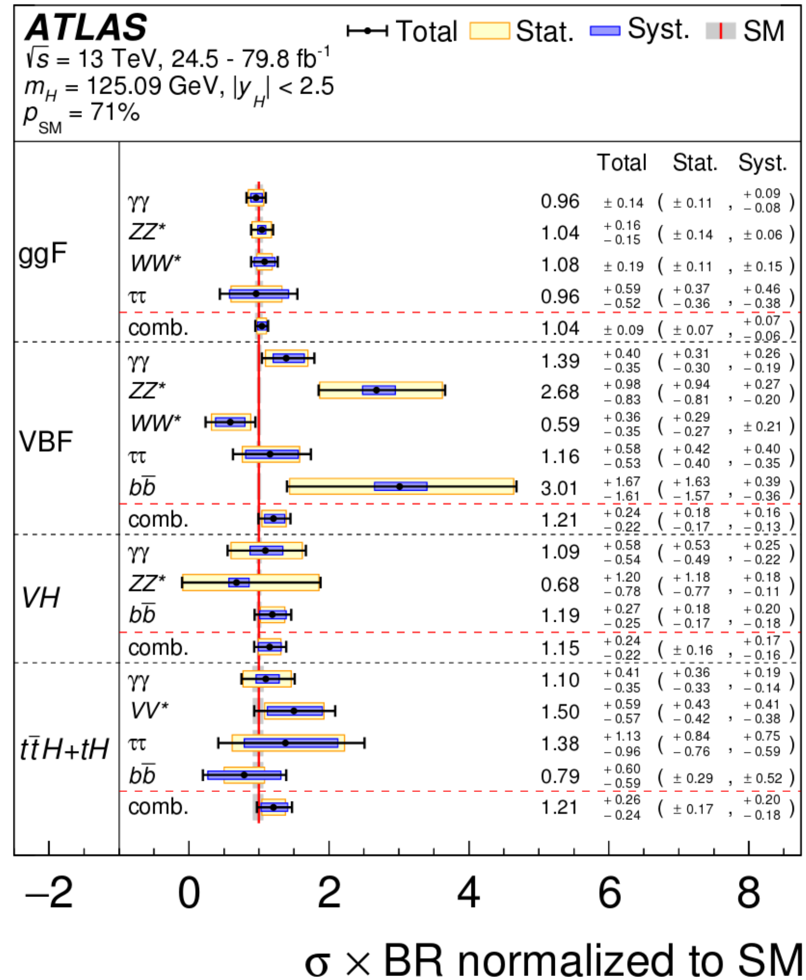
Motivation

- Many BSM models predict existence of new scalars, especially “Higgses”
- Realistic models must also contain a SM-like Higgs boson
- In lack of direct BSM signatures Higgs boson(s) might become our only handle on BSM physics
  - strong constraints on BSM models
  - requirement for an accurate prediction of Higgs boson properties in BSM models
  - and an easy way to compare them with experimental data



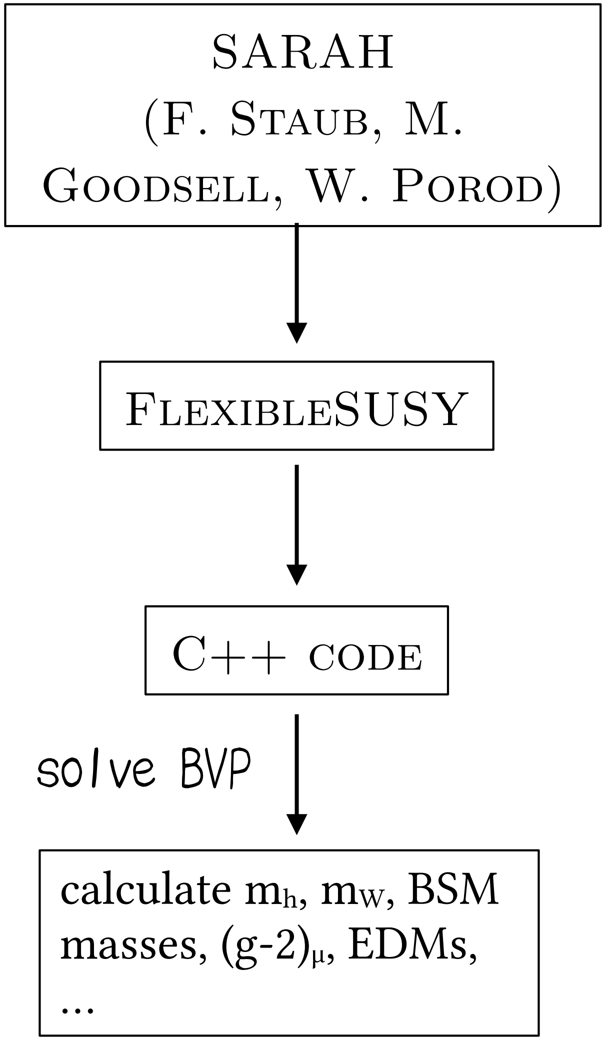
Predicting Higgs boson properties

- Mass
  - fixed order
  - effective field theory
  - hybrid (fixed order + EFT)
- Decays
- Production
- Many tools (see for example a great overview by H. Rzehak from the “TOOLS” workshop)
  - model specific
  - generic (SAHAH+SPheno, FlexibleSUSY)

FlexibleSUSY in a nutshell

- 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 is a spectrum-generator generator - creates a code analogue to abovementioned 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 $(g-2)_\mu$, lepton's EDMs, $l \rightarrow l'\gamma$, $b \rightarrow s\gamma$, scalar decays
  - soon: $l \rightarrow l'$ conversion in nuclei, $l \rightarrow 3l$

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

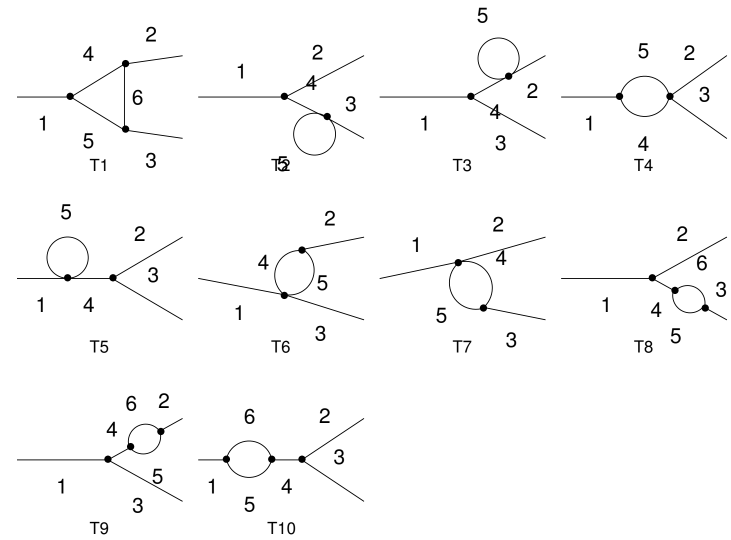
  You run FS as before.
- Generic decays are handled at the leading order (**both** tree-level and loop-induced processes are handled)
- Special treatment of scalar and pseudoscalar Higgs decays
  - higher order SM corrections from literature
  - precision comparable with state of the art codes like HDECAY

Tree-level decays

- Automatically generated 1⟶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⟶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

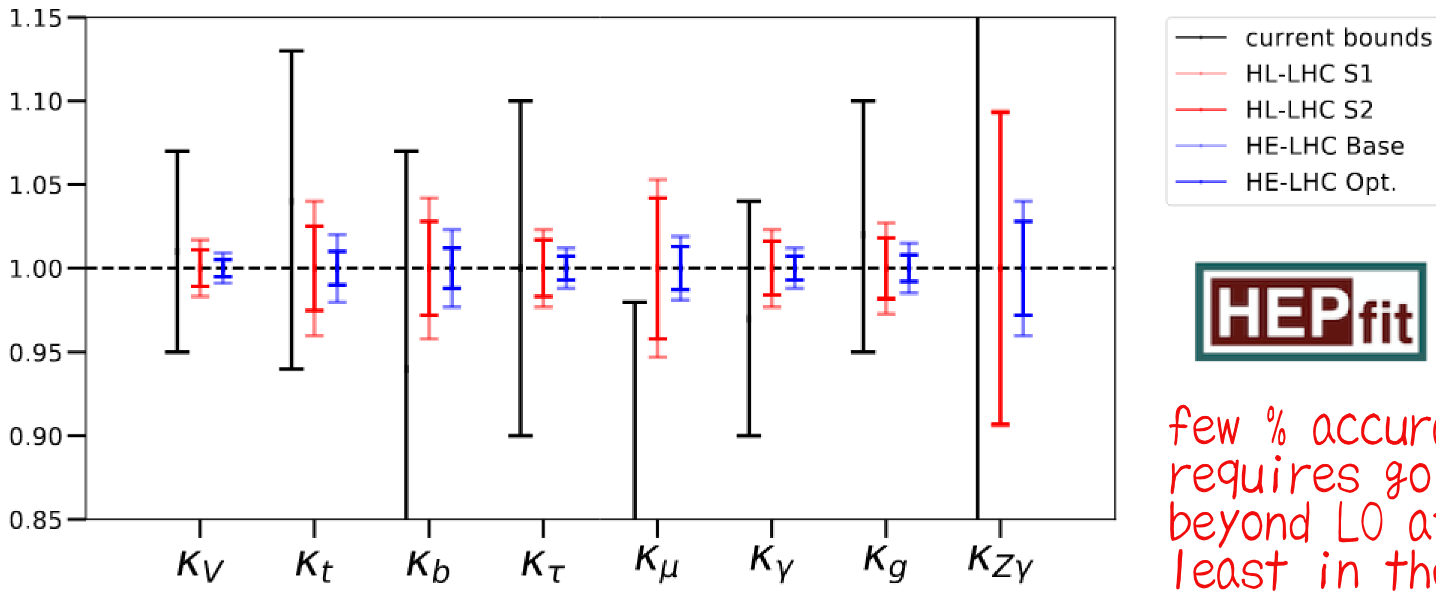
- Need for a dedicated renormalization scheme since BSM is (probably) heavy
  - On-shell scheme most natural but it's not how spectrum generators work
  - $\overline{\text{MS}}/\overline{\text{DR}}$ features non-decoupling effects
- Dedicated scheme with explicit decoupling properties
  - BSM equivalents 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

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

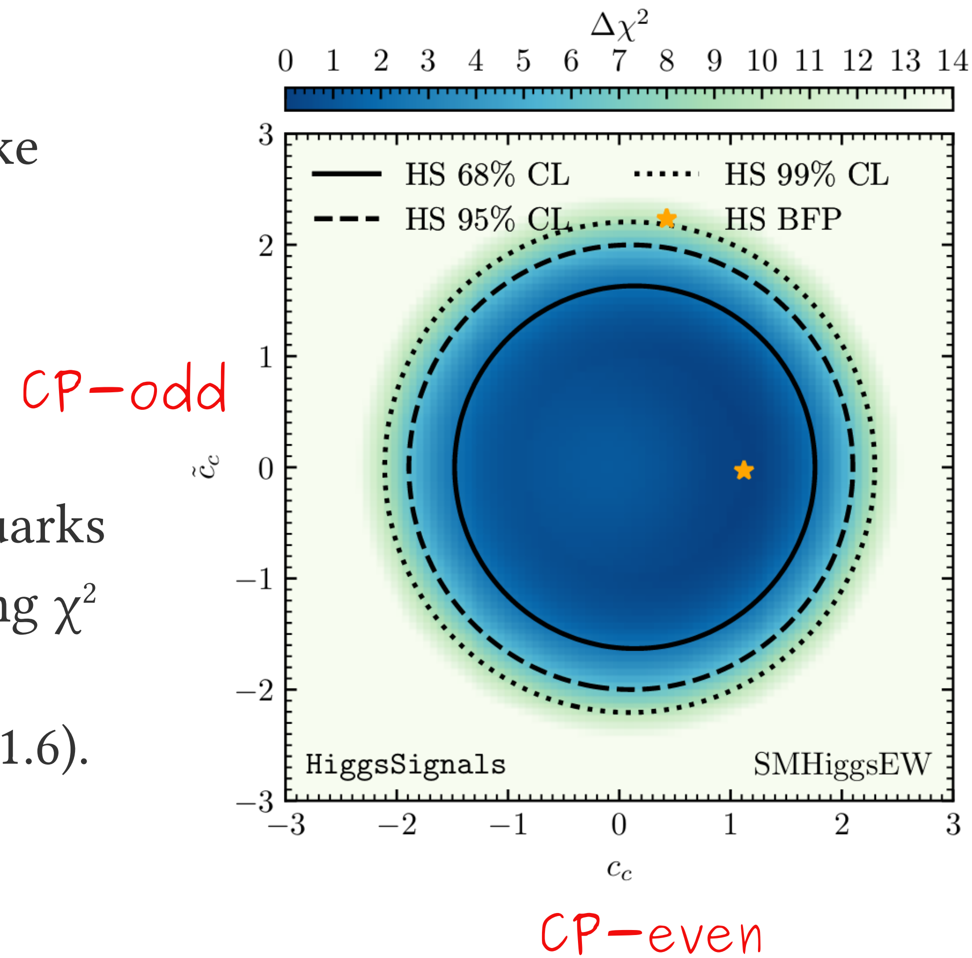
What you get (singlet+SM example)

```
...
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

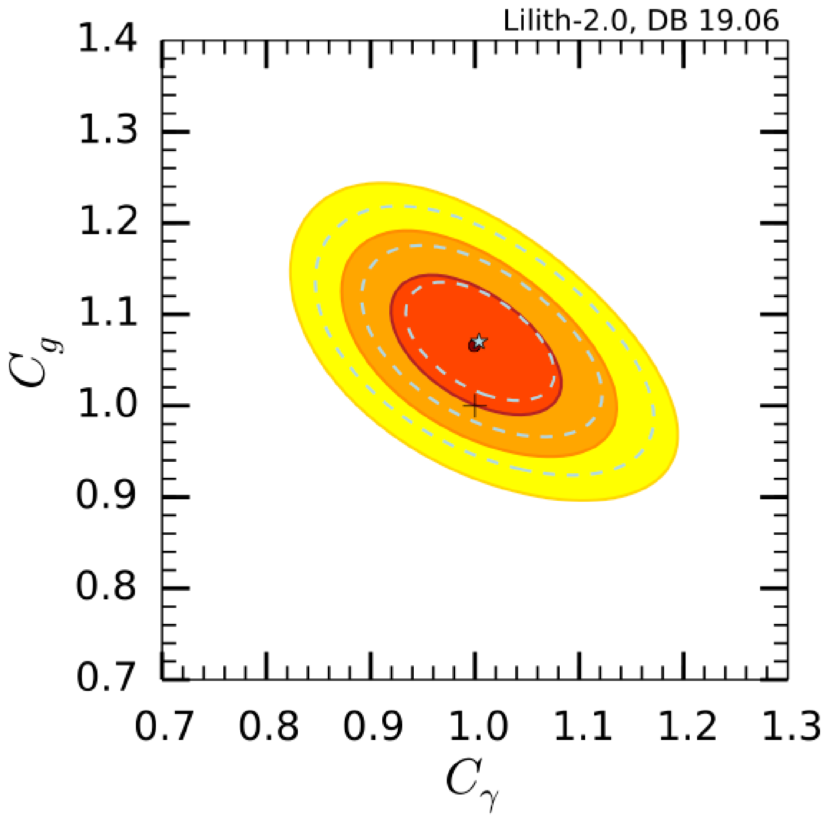


Barh et al. [arXiv:2210.09332]

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

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

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

- New output block

PDG 0 0 contains a partial width for a SM-like Higgs with a given BSM mass

```
Block NORMALIZEDEFFHIGGSCOUPLINGS
  25          0          0      2.33429130E-03
  25         -1          1      2.60004739E-01
  25         -2          2      3.60808433E-01
  25         -3          3      2.58715570E-01
  25         -4          4      3.60805762E-01
  25         -5          5      2.57589220E-01
  25         -6          6      3.60800617E-01
  25        -11         11      2.57231012E-01
  ...
```

The input chain

HiggsTools/Lilith interface

- Using HiggsTools or Limith from FlexibleSUSY is totally transparent to the user
- Howto:
  - install HiggsTools and/or Lilith
  - point FlexibleSUSY to their location during configuration
  - you're good to go

```
models/MRSSM2/run_MRSSM2.x --slha-input-file=BMP1.in \
--higgsbounds-dataset=hbdataset-master \
--higgssignals-dataset=hsdataset-main \
--lilith-db=Lilith/data/latestRun2.list
```

HiggsTools/Lilith output

- HiggsTools output

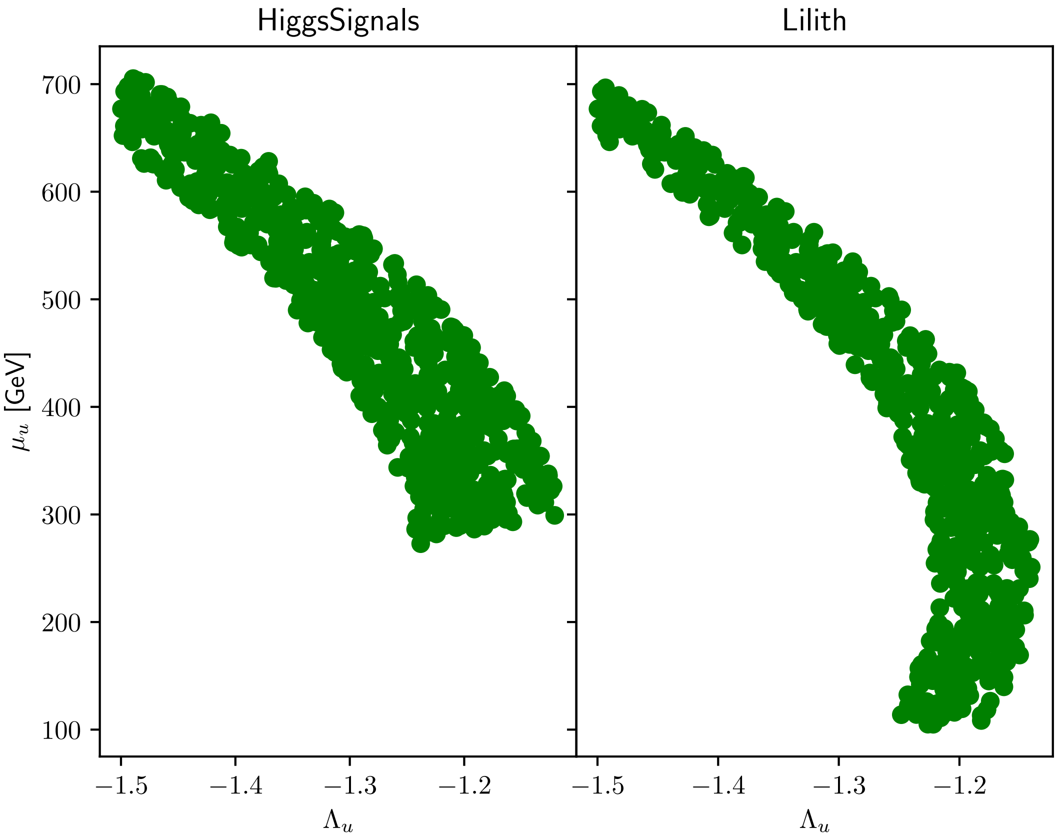
```
Block HIGGSSIGNALS
     1      1.59000000E+02   # number of degrees of freedom
     2      1.57662766E+02   # χ²
     3      1.51551655E+02   # SM χ² for mh = 125.250000 GeV
     4      4.70965484E-02   # p-value
Block HIGGSBOUNDS
 25  1      2.38307377E-01   # LHC13 [vbfH,HW,Htt,H,HZ]>[gamgam] from 1811.0845
 25  2      5.84526557E-01   # expRatio
 35  1      7.11468251E-01   # LHC8 [vbfH,HW,Htt,H,HZ]>[bb,tautau,WW,ZZ,gamgam]
 35  2      3.57914871E+00   # expRatio
```

- Lilith output

```
Block LILITH
     1      5.30000000E+01   # number of degrees of freedom
     2      6.06908417E+01   # χ²
     3      5.47825089E+01   # SM χ² for mh = 125.090000 GeV
     4      5.21220908E-02   # p-value
```

HiggsTools vs. Lilith

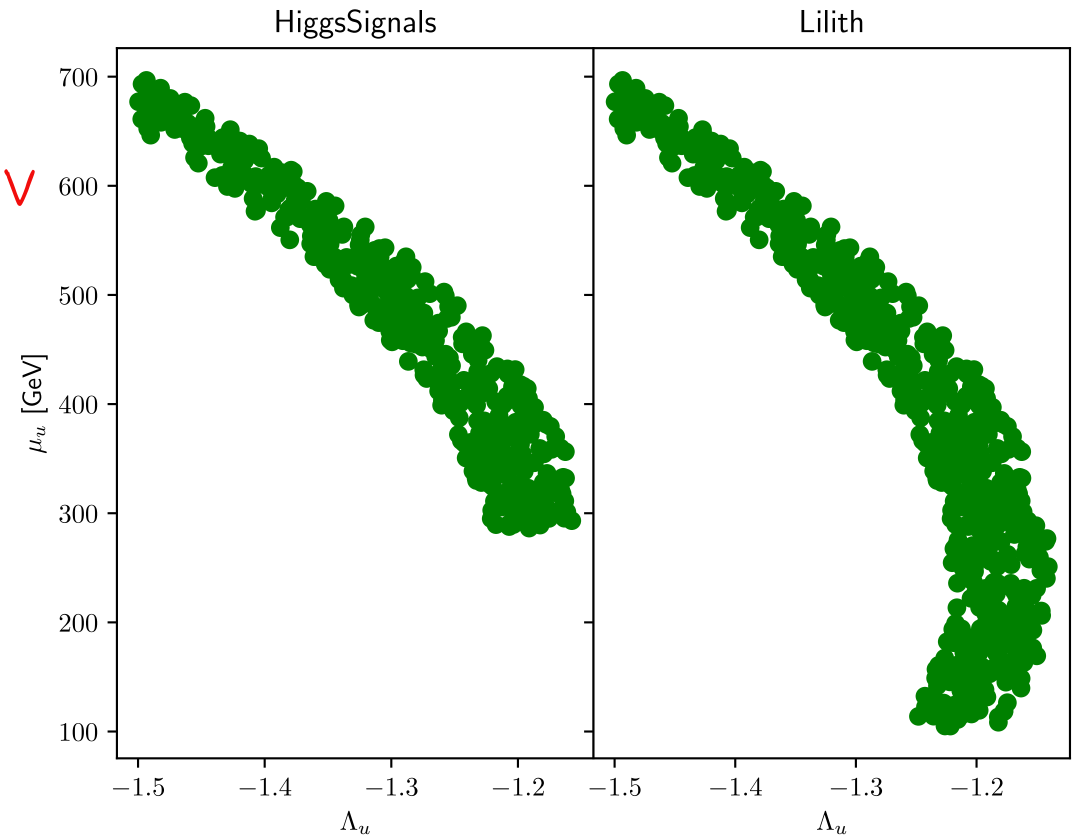
We set 3% mass uncertainty for HT



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

Conclusions and outlook

- Streamlining comparison of Higgs sector of **your** favourite model with experimental data
- The publication documenting the code will appear this month. In the meantime, you can grab the code from here.
- We are happy to assist you in setting the code up for your particular model.
- 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)