Automatizing the path from Lagrangian to Higgs physics constraints

Scalars 2025

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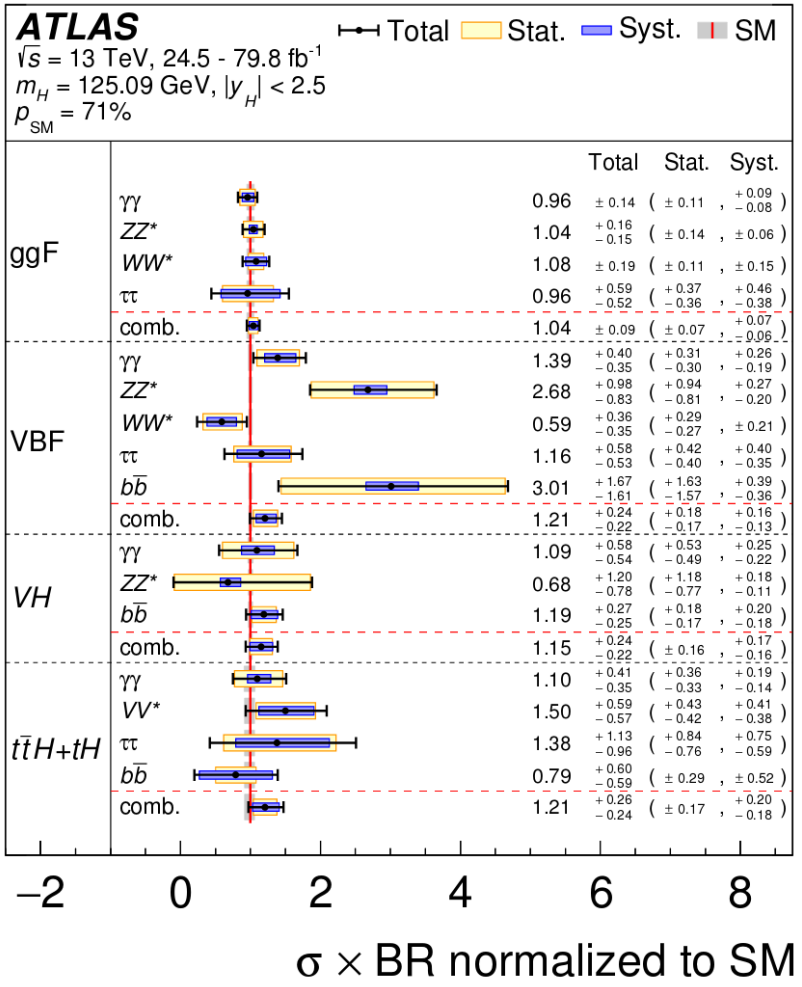
Motivation

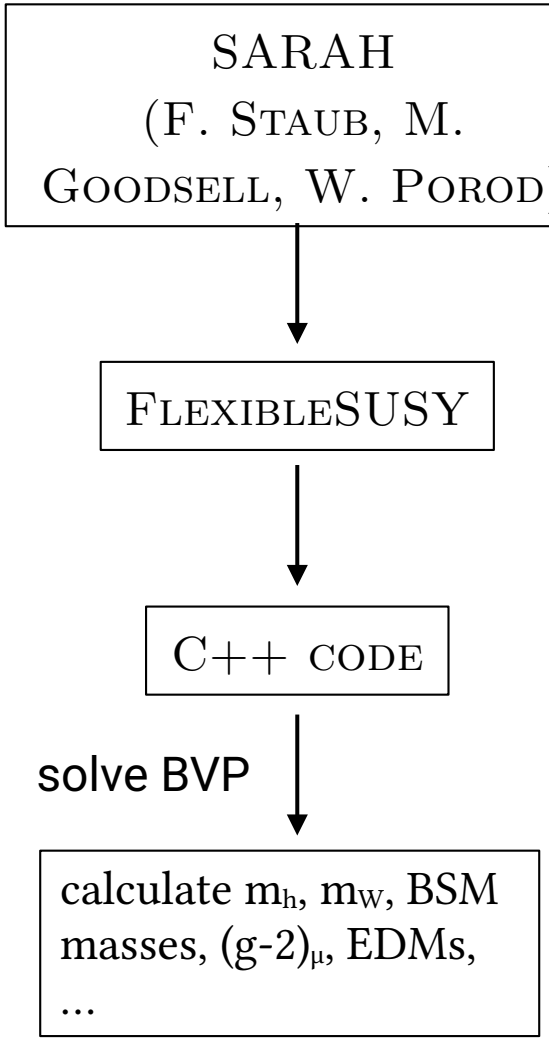
- Many BSM models predict existence of new scalars, especially “Higgses”
- Realistic models must also contain a SM-like Higgs boson
- In lack of direct BSM signatures Higgs boson(s) might become our only handle on BSM physics
  - strong constraints on BSM models
  - requirement for an accurate prediction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



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, $l \longrightarrow l'\gamma$, $b \longrightarrow s\gamma$, scalar decays
  - soon: $l \longrightarrow l'$ conversion in nuclei, $l \longrightarrow 3l$

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
  - genuine 1L BSM corrections in the decoupling renormalization scheme in preparation (see talks by J. Lang and J. Wuensche)
  - precision comparable with state of the art codes like HDECAY

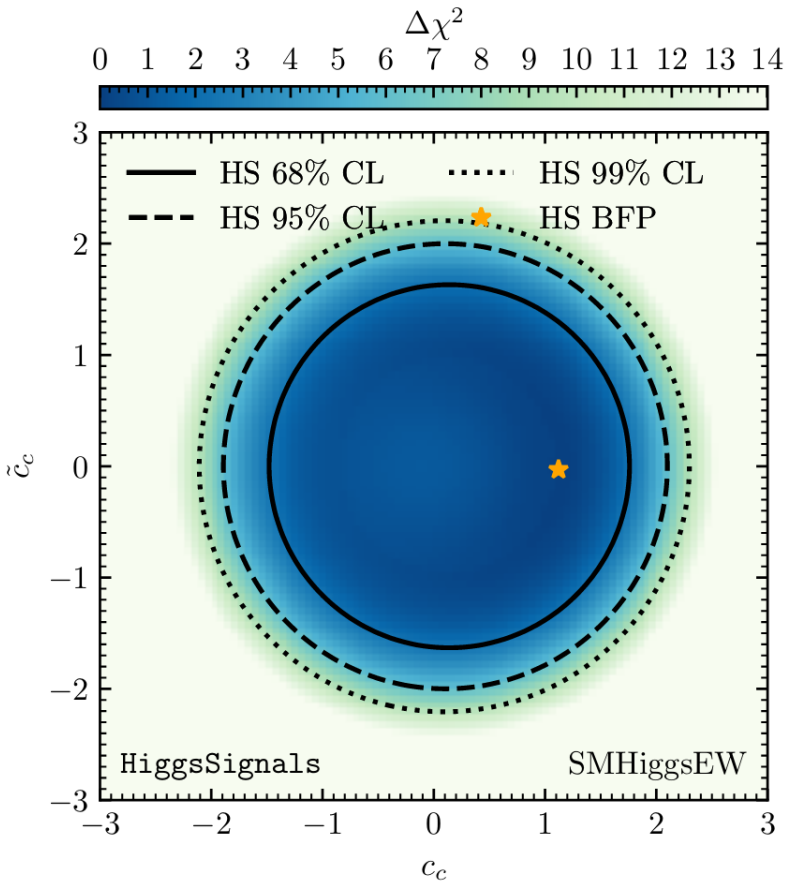
What you get (singlet+SM example)

```
...
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 detabases (HS v1.2, HB v1.6). Latest HS has 159 dof



CP-odd

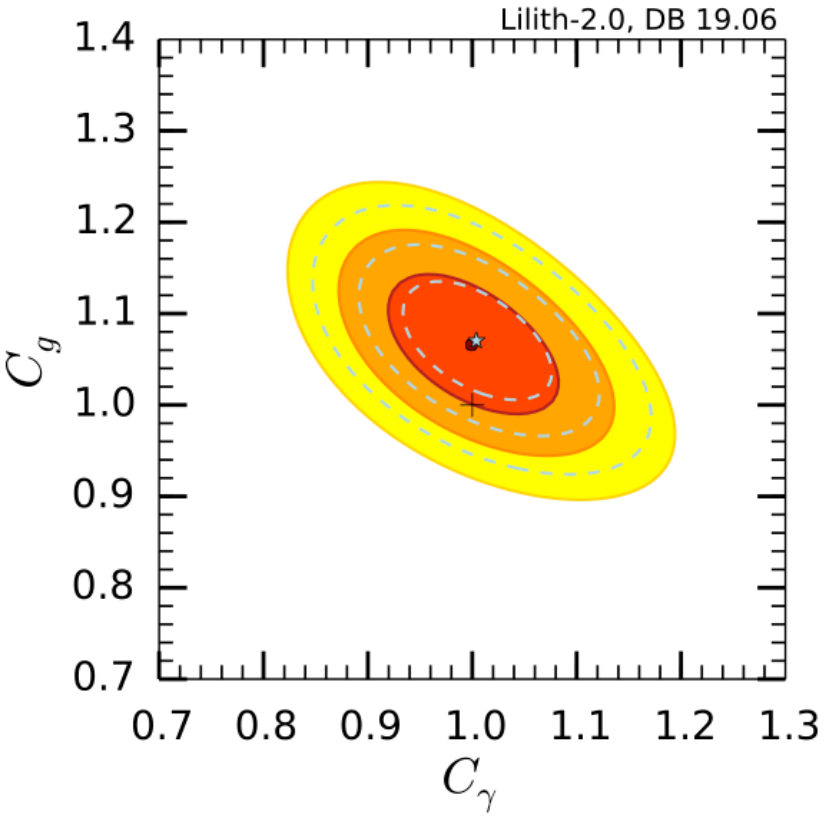
CP-even

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

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

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

- 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

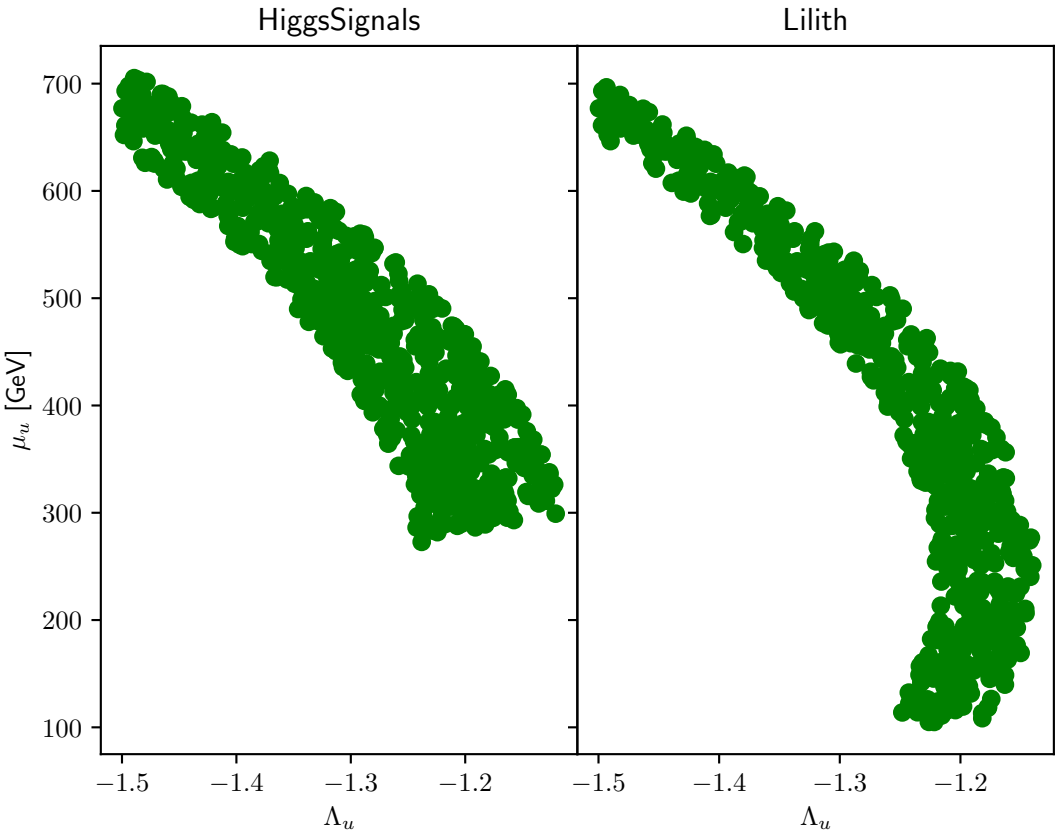
```
Block HIGGSSIGNALS
     1     1.59000000E+02   # number of degrees of freedom
     2     1.57662766E+02   # χ²
     3     1.51551655E+02   # SM χ² for mh = 125.250000 GeV
     4     4.70965484E-02   # p-value
Block HIGGSBOUNDS
 25  1     2.38307377E-01   # LHC13 [vbfH,HW,Htt,H,HZ]>[gamgam] from 1811.0845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

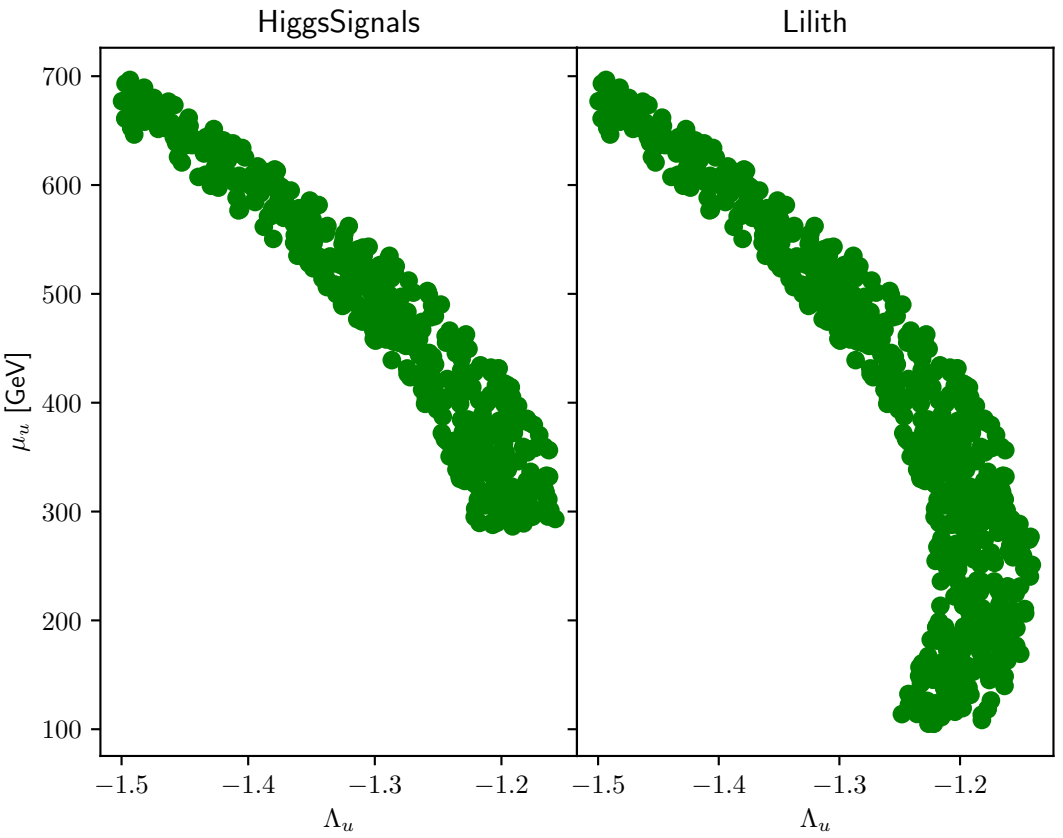
We set 3% mass uncertainty for HT



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 difference 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:
  - constraining charged (singly and doubly) Higgses (only HiggsBounds)
  - higher order BSM corrections to SM-like Higgs decays will be available soon
  - 2-loop corrections in the 0-momentum approximation to Higgs boson mass (from SARAH)