# HiggsTools: A Toolbox for BSM Scalar Phenomenology

Jonas Wittbrodt

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HiggsBounds

# A Phenomenological Perspective

*I have this awesome new model, it has dark matter, gravitational waves, and can do baryogenesis . . . now I just need to check if its 29 scalars are fine with the LHC data.*

Using all applicable search results, set a 95 % C.L. limit on the model parameter space.

- **quantity**: There are a lot of Higgs measurements and even more searches.
- **assumptions**: Is analysis X really applicable to my particle Y?
- **statistical interpretation**: Need a reasonable combination of all of those results applied to all of those particles.
- **channels**: Large and increasing number of channels that need model predictions.

# HiggsBounds and HiggsSignals — A Recap

## HiggsBounds-5

[Bechtle et al. **2006.06007**]

- exclusion bounds from over 200 analyses at LEP, Tevatron and the LHC
- determine most sensitive analyses to obtain a combined limit at $\sim 95\,\%$ C.L..
- use model-independent limits (if possible) or check analysis assumptions
- input framework for all relevant model predictions

## HiggsSignals-2

[Bechtle et al. **2012.09197**]

- LHC Run 1 combination + latest 13 TeV LHC results up to $139\,\text{fb}^{-1}$
- $\chi^2$ fit of model predictions to data including all available correlations
- uses HiggsBounds to handle model input

# HiggsTools — An Overhaul

HiggsTools is a complete rewrite of HiggsBounds and HiggsSignals in modern C++ with a native Python interface. It contains three parts:

## HiggsPredictions

- handles user input for model predictions
- tabulated cross sections and BRs (SM, effC, ...)
- common process definitions and clustering

## HiggsBounds

Compares experimental search results to provided model predictions.

## HiggsSignals

Compares experimental measurements to provided model predictions.

# HiggsPredictions — Overview

- stores model predictions for BSM particles in the BSMParticle class
  - quantum numbers: electric charge, CP, (potentially add spin)
  - all relevant production and decay modes for LEP and LHC
  - decays into pairs of other BSM particles, or mixed SM/BSM pairs (e.g. $H \to ZA$)
  - theoretical mass uncertainty
- Predictions class contains all BSM particles in a model and stores properties that depend on more than one BSM particle (e.g. non-resonant $pp \to h_1 h_2$)
- tabulated properties of reference particles, e.g. SMHiggs
- effective coupling input to set BSM properties relative to these reference models

# Providing Model Predictions

**The HiggsBounds-5 input framework was suboptimal to use and hard to extend.**

```
subroutine HiggsBounds_neutral_input_SMBR(BR_hjss, BR_hjcc, BR_hjbb, BR_hjtt,
                                          BR_hjmumu, BR_hjtautau, BR_hjWW, BR_hjZZ,
                                          BR_hjZga, BR_hjgaga, BR_hjgg)
```

Structure of arrays approach (each argument has one entry for each particle).

- every BR and cross section has to be provided for every particle
- adding new decay modes (e.g. $H \to jj$) breaks existing code

- object oriented interface where properties of all particles can be set independently, e.g. p.setBr("bb", 0.4)
- C++ interface for high performance, Python (and Mathematica) interface for ease of use

# Reference and Effective Coupling Tables

HiggsPredictions gives access to all YR-4 SM-Higgs cxns and BRs as well as

| channel | couplings | mass range [GeV] | source |
|---|---|---|---|
| VBF | $c_Z, c_W$ | LHC8: 1 — 1050, LHC13: 1 — 3050 | |
| $t\bar{t}H$ | $c_t, \tilde{c}_t$ | 25 — 1000 | `MadGraph` |
| $tH$ ($t$ channel) | $c_t, \tilde{c}_t, c_W$ | 25 — 1000 | `MadGraph` |
| $tWH$ | $c_t, \tilde{c}_t, c_W$ | 25 — 1000 | `MadGraph` |
| $WH$ | $c_W, c_t$ | 1 — 2950 | `vh@nnlo` |
| $qq \to ZH$ | $c_Z, c_t$ | 1 — 5000 | `vh@nnlo` |
| $gg \to ZH$ | $c_t, c_b, c_Z, \tilde{c}_t, \tilde{c}_b$ | 1 — 5000 | `vh@nnlo` |
| $b\bar{b} \to ZH$ | $c_b$ | 1 — 5000 | `vh@nnlo` |
| $q_i q_j \to H$ | $c_{q,ij}, \tilde{c}_{q,ij}$ | 1 — 5000 | `vh@nnlo` |
| $q_i q_j \to H^\pm$ | $c_{qL,ij}, c_{qR,ij}$ | 200 — 1150 | [Bahl et al. `2109.10366`] |
| $q_i q_j \to H + \gamma$ | $c_{q,ij}, \tilde{c}_{q,ij}$ | 200 — 1150 | [Bahl et al. `2109.10366`] |
| $q_i q_j \to H^\pm + \gamma$ | $c_{qL,ij}, c_{qR,ij}$ | 200 — 1150 | [Bahl et al. `2109.10366`] |
| $b\bar{b} \to ZH$ | $c_b$ | 200 — 1150 | [Bahl et al. `2109.10366`] |
| $pp \to H^\pm tb$ | $c_{L,tb}, c_{R,tb}$ | 145 — 2000 | [Degrande et al. `1507.02549`, `1607.05291`] |
| $pp \to H^\pm \phi$ | $c_{H^\pm \phi W^\mp}$ | $m_\phi$ : 10 — 500, $m_{H^\pm}$ : 100 — 500 | [Bahl et al. `2103.07484`] |

# HiggsPredictions — Example Model Input

```
pred = HP.Predictions()
h = pred.addParticle(HP.NeutralScalar("h"))
h.setMass(125.09)
HP.effectiveCouplingInput(h, HP.smLikeEffCouplings)
h.setDecayWidth("DM", "DM", 5e-2 / (1 - 5e-2) * h.totalWidth())

hp = pred.addParticle(HP.ChargedScalar("H+"))
hp.setMass(400)
hp.setCxn("LHC13", "Hptb", HP.EffectiveCouplingCxns.ppHpmtb(
        "LHC13", hp.mass(), cHpmtbR=0.9, cHpmtbL=0.6, brtHpb=0.0
    ))
hp.setDecayWidth("W", "h", 1.2)
hp.setDecayWidth("tb", 0.4)

hpp = pred.addParticle(HP.DoublyChargedScalar("H++"))
hpp.setMass(500)
hpp.setDecayWidth("WWsamesign", 0.8)
hpp.setDecayWidth("tautausamesign", 0.1)

pred.setBsmPairCxn( "LHC13", "h", "H+",
    HP.EffectiveCouplingCxns.ppHpmPhi("LHC13", hp.mass(), h.mass(), 0.2))
pred.setBsmPairCxn("LHC13", "H++", "H++", 0.6)
```

# HiggsBounds — Overview

For every implemented limit HiggsBounds performs the following steps:

1. check which particles in the model are *relevant* for each *role* in the process
2. find all *maximal clusters* for each *role* that fulfill the analysis assumptions
3. for all *assignments* of clusters to the process *roles* compute the model predictions
4. obtain the observed and expected ratios (model prediction/limit)

Then select the most sensitive limit for each particle based on the `expRatio`.
The parameter point is allowed if the observed ratio $< 1$ for all selected limits.

# Experimental Results from Higgs Searches

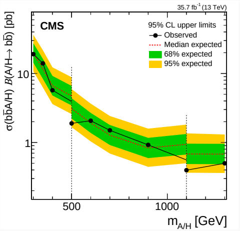
**In HiggsBounds-5, all process definitions were hard-coded in Fortran.**

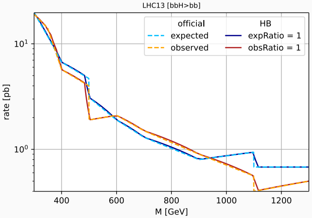
- ! maintainability: adding new limits requires non-trivial code changes
- ! consistency: implementations for similar processes can differ significantly

- fully define experimental search results through datafiles (`json` format)
- general class of constraints that can be used to verify analysis assumptions
- code changes only required for new process topologies, all topologies up to $xx \to \phi_i \to \phi_j \phi_k \to yyzz$ are implemented
- database of experimental results separate and independent of the main code
- public implementation and validation scripts for every analysis

# Experimental Results from Higgs Searches — Example


```
{
    "limitClass": "ChannelLimit",
    "id": 180512191,
    "reference": "1805.12191",
    "source": "Fig. 6/Tab. 1",
    "citeKey": "CMS:2018hir",
    "collider": "LHC13",
    "experiment": "CMS",
    "luminosity": 35.7,
    "process": {"channels": [["bbH", "bb"]]},
    "analysis": {
        "massResolution": {"absolute": 15, "relative": 0.15},
        "grid": {
            "mass": [300.0, 350.0, 400.0, 499.0,
                     500.0, 600.0, 700.0, 900.0, 1099.0,
                     1100.0, 1300.0]
        },
        "limit": {
            "observed": [19.1, 14.0, 5.7, 4.0, 1.9, 2.1,
                         1.5, 0.9, 0.56, 0.4, 0.5],
            "expected": [19.7, 11.7, 6.7, 4.7, 3.1, 1.9,
                         1.3, 0.8, 0.94, 0.68, 0.68]
        }
    }
}
```


[CMS 1805.12191]

# Experimental Results from Higgs Searches — The Dataset

HiggsBounds dataset at **`gitlab.com/higgsbounds/hbdataset`**.

## What is (currently) included?

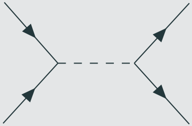
- 258 search results from 165 experimental publications
  - 25 LEP searches from 13 publications (mostly combinations)
  - 90 LHC Run 1 searches from 26 ATLAS and 37 CMS publications
  - 143 LHC Run 2 searches from 44 ATLAS and 45 CMS publications
- dataset strictly superior to the HB-5 dataset
  - full Run-2 results in many channels
  - doubly charged Higgs searches

## What is not (yet) included?

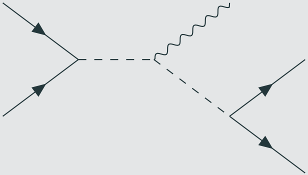
- 7 TeV LHC and Tevatron results
- $Z'/W'$ searches — *possible extension*

# Process Toplolgies

## channel

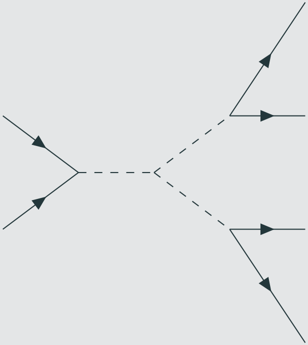


## chain decay



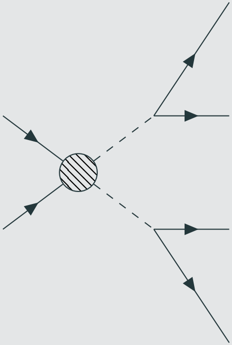
2 BSM particles

## pair decay



3 BSM particles

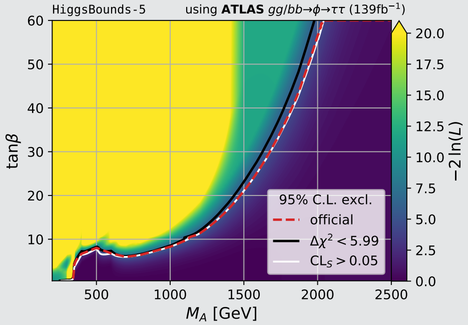
## pair production



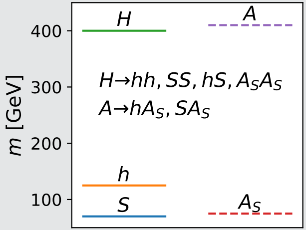
2 BSM particles

Multiple particles of similar mass could remain unresolved.

## MSSM $pp \to \{H, A\} \to \tau\tau$




## $pp \to \phi_i \to h_{125}\phi_j, h_{125} \to \tau\tau, \phi_j \to bb$




Clustering to $\{H, A\} \to \{h\}\,\{S, A_S\}$

# Clustering — Implementation

A cluster $C$ of particles with masses $m_i$ is valid if

$$\mathbf{max}(m_i) - \mathbf{min}(m_i) \leq r_{\text{abs}} + r_{\text{rel}} \cdot \mathbf{mean}(m_i)\,.$$

- mass resolutions given by experiment or estimated
- theoretical mass uncertainties $\Delta m_i$?

`cautious` only if entire $\pm\Delta m_i$ regions overlap

`eager` as soon as $\Delta m + r$ regions touch

`ignore` ignore $\Delta m$ for clustering

- clustering for all particle roles in all search topologies
- consistent treatment of all implemented searches

# HiggsSignals — Overview

HiggsSignals computes a $\chi^2$ of the model predictions compared to all of the available LHC Higgs measurements:

$$\chi^2 = (\mu - \hat{\mu})^{\mathrm{T}} \left[\Delta_{\mathrm{obs}}^{\mathrm{T}} \mathrm{Corr}_{\mathrm{obs}} \Delta_{\mathrm{obs}} + \Delta_{\mathrm{theo}}^{\mathrm{T}} \mathrm{Corr}_{\mathrm{theo}} \Delta_{\mathrm{theo}}\right]^{-1} (\mu - \hat{\mu})$$

where $\mu$ can refer to (normalized) signal rate, masse, or coupling measurements.

Plus additional $\chi^2$ contributions from

- partially resolve combinations of multiple particles $\rightarrow$ separation $\chi^2$
- public LLHs *if available in the future*

# Experimental Results — Measurements

Measurements in HiggsSignals-2 were already implemented through datafiles.

However, HiggsSignals-2 distinguished three observable types:

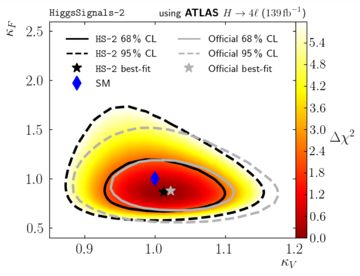
- peak observables
- the ATLAS/CMS Run 1 combinations
- STXS observables

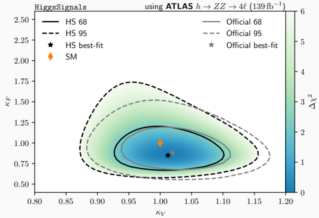
with subtly different implementations.

In HiggsTools, all HiggsSignals measurements are implemented through json files and treated equally.

# Experimental Results — Example


```
{
  "id": 200403447,
  "reference": "2004.03447",
  "source": "https://doi.org/10.17182/hepdata.94311.v1/t25",
  "citeKey": "ATLAS:2020rej",
  "collider": "LHC13",
  "experiment": "ATLAS",
  "luminosity": 139.0,
  "referenceMass": 125,
  "massResolution": 2.5,
  "bins": {
      "gg2H_0j_pTH_Low": {
          "exp": [0.151, 0.176, 0.201],
          "obs": [0.115, 0.17, 0.225],
          "process": {"channels": [["H", "ZZ"]]}
      },
      "gg2H_0j_pTH_High": {
          "exp": [0.51, 0.55, 0.59],
          "obs": [0.52, 0.63, 0.74],
          "process": {"channels": [["H", "ZZ"]]}
      },
      "VH_Lep": {
          "exp": [0.016, 0.0164, 0.0168],
          "obs": [0.004, 0.022, 0.05],
          "process": { "channels": [["HZ", "ZZ"], ["HW", "WW"]]},
          "channelWeights": [0.067316, 0.2172]
      }
```


[ATLAS 2004.03447]

# Experimental Results from Higgs Measurements – The Dataset

HiggsSignals dataset at `gitlab.com/higgsbounds/hbdataset`.

**What is (currently) included?**

- 22 measurements (11 ATLAS Run-2, 9 CMS Run-2 and 2 Run-1 Combination)
  - 136 individual observables
- dataset strictly superior to the HS-2 dataset
  - full Run-2 results in many channels
  - CMS measurement of the $\tau$-Yukawa CP-phase
  - updated mass measurements (WIP)

# Development Status

You can try out HiggsTools now. It is only missing some documentation polish and we are still validating the HiggsSignals dataset.

## Quick start guide

1. make sure you have a working C++17 compiler (gcc>=9, clang>=5), CMake>=3.17 and Python>=3.5
2. download the code from gitlab.com/higgsbounds/higgstools
3. in the code directory run `pip install .`
4. download the datasets (HBDataSet, HSDataSet) to a convenient location
5. done, try it out!