Probing Higgs Sectors with HiggsBounds and HiggsSignals

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Lund University, Theoretical Particle Physics

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.

Interpreting Higgs Searches with HiggsBounds

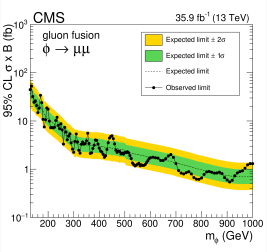
HiggsBounds

[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

To implement a new analysis we need:

- 95 % C.L. observed *and* expected limits as a function of *all* relevant kinematical parameters
- rates in reference model (if normalized)
- details about model assumptions
- machine readable format, ideally via HEPData



[CMS 1907.03152]

HiggsBounds — Phenomenological Perspective

Input

Model Predictions

- production @ LHC and Tevatron
  - ggF, bbh, Wh, Zh, VBF, tth, th, tWh, h_ih_j
  - $tbH^\pm$, $t \to H^\pm b$, $H^\pm h_i$
- production @ LEP
  - hZ, bbh, $\tau\tau h$, h_ih_j
  - $H^\pm H^\mp$
- decay
  - $h \to f\bar{f}$, VV, inv, h_ih_j, h_iZ, $H^\pm W$
  - $H^\pm \to tb$,cs, cb, $\tau\nu$, h_jW, WZ

alternative: effective coupling input

Output

Overall 95 % C.L. limit

1. judge the sensitivity of each search to each scalar using the expected limit
2. select the most sensitive limit *for each scalar*
3. apply the observed limits of the selected limits

Exclusion likelihoods can also be used directly in fits.

Assumptions in Model Independent Scalar Searches

Basic assumptions for a reinterpretation at the inclusive level:

- the narrow width approximation holds,
- background processes are not altered by the signal model,
- signal kinematics match the signal hypothesis.

What if the signal is comprised of different production/decay channels?

worst: limit without additional information and SM-like assumptions

- have to assume SM-like signal composition

$\Rightarrow$ only usable with a *model-likeness test*: for each channel $\mu_{\text{channel}} \approx \mu$

better: provide SM-like signal efficiencies for each channel

- efficiencies stay unchanged as long as the basic assumptions hold

best: exclusion likelihoods in the sub-channel rates

HiggsBounds — Exclusion Likelihoods

Simplified exclusion likelihood profiles are available for:

- LEP Higgs Combination [ALEPH, DELPHI, L3, OPAL `hep-ex/0602042`]
- ATLAS and CMS $H \to \tau\tau$ searches [CMS `HIG-14-029`; ATLAS `1709.07242`; CMS `1803.06553`; ATLAS `2002.12223`]

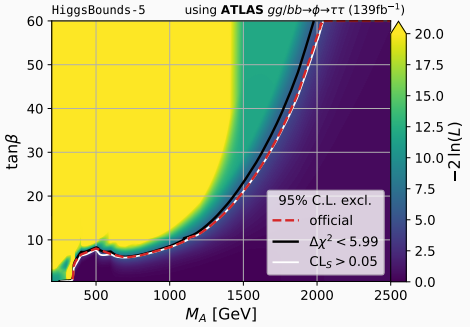
Likelihood profile as function of kinematical parameters and sub-channel rates.

$L(m_h, \sigma(ggF \to \tau\tau), \sigma(bbH \to \tau\tau))$

$\to$ construct 95 % C.L. CL_S limits

$\to$ as likelihood contribution in a fit

Contains full information for all sub-channel rates.



Interpreting Higgs Measurements

HiggsSignals [Bechtle et al. 2012.09197]

Fit model predictions to the latest measurements of h_{125} to obtain a χ^2 value for use in model fits or limit setting.

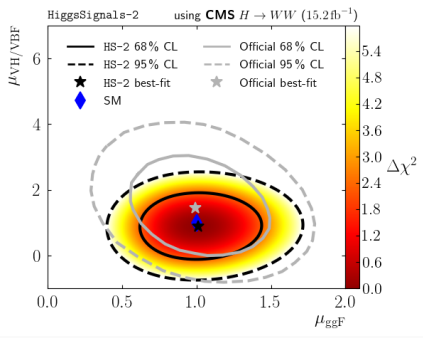
Observable sets of the latest LHC Higgs measurements:

- 7+8 TeV measurements covered by the Run 1 combination [ATLAS, CMS 1606.02266]
- 13 TeV results up to 139 fb^{-1}, updated as they come in

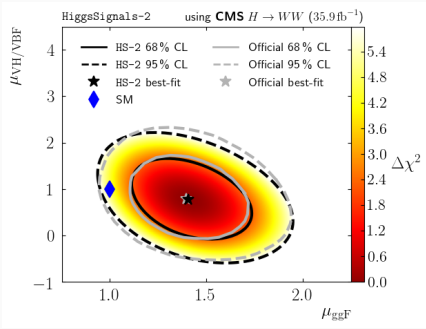
HiggsSignals uses HiggsBounds to handle theory input.
See the new manual for a detailed discussion on the statistical interpretation of the returned χ^2.

HiggsSignals — μ Measurements and Past Progress

CMS $H \to WW$ signal-strength measurements in sub-channels aimed at different production modes.



no signal efficiencies [CMS HIG-16-021]



signal efficiencies [CMS 1806.05246]

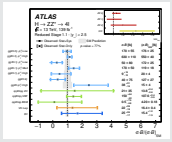
New 139 fb^{-1} analysis additionally includes inter-bin correlations but no usable validation plots. [CMS 2007.01984]

HiggsSignals — STXS Measurement

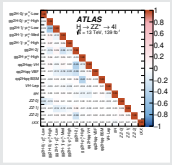
Example: ATLAS $H \to ZZ \to 4\ell$ [ATLAS 2004.03447]

HiggsSignals implementation

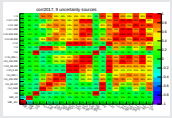
- measurements (12-bin STXS)



- experimental correlations

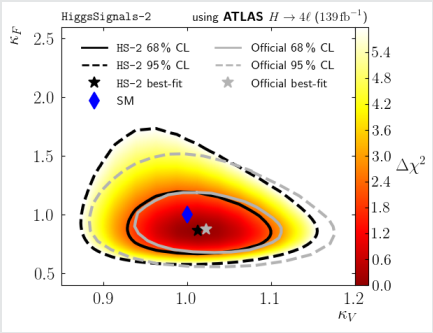


- theory correlations [2017 Scheme]



Performance of HiggsSignals

compared to official κ-fit.



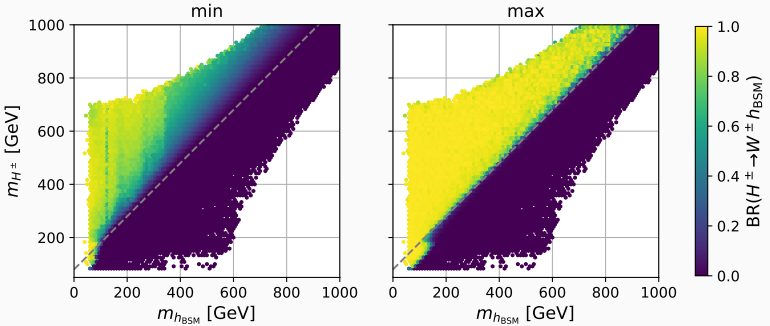
Current and Future Developments — Searches for Aligned Models

We observe rates of h_{125} very similar to the SM expectation $\Rightarrow$ alignment limit.

In the 2HDM:

$g(h_{125}H^{\pm}W^{\mp}), g(h_{125}AZ) \propto c(h_{\text{BSM}}VV) \to 0$ $\quad$ $g(h_{\text{BSM}}H^{\pm}W^{\mp}), g(h_{\text{BSM}}AZ) \propto c(h_{125}VV) \to 1$

Searches for $H^{\pm} \to W^{\pm}h_{\text{BSM}}$ to probe the alignment limit. [Bahl, Stefaniak, and JW 2103.07484]

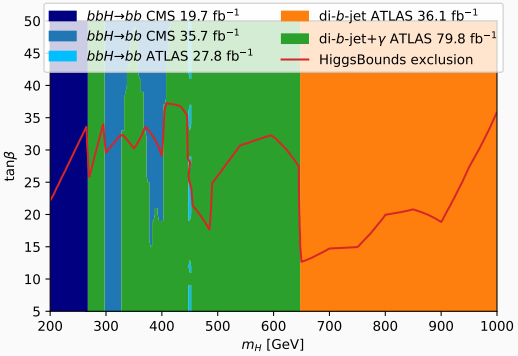


BSM scalars may have very different Yukawa couplings from h_{125} or may not have Higgs-like couplings (*i.e.* $\propto m$) at all $\Rightarrow$ di-jet and di-lepton searches.

Extend HiggsBounds by existing "exotics" searches. [Bahl, Lozano, Stefaniak, JW upcoming]

Example: flipped 2HDM

- dedicated $bbH \to bb$ searches [CMS 1506.08329; CMS 1805.12191; ATLAS 1907.02749]
- new: b-jet resonance searches [ATLAS 1805.09299, 1901.10917]



Current and Future Developments — Upcoming Code Updates

Upcoming major update of `HiggsBounds` and `HiggsSignals` (public beta in a few weeks).

- much more flexible input framework
- complete code modernization/cleanup (`Fortran` → `C++`)
- searches (and measurements) fully implemented through json files
- native python interface

```python
import Higgs
from Higgs import predictions as HP
pred = Higgs.Predictions()
h = pred.addParticle(HP.NeutralScalar("h")) # add a particle called `h`
h.setMass(200.0)
h.setCxn("LHC13", "ggH", 20.) # set 13 TeV LHC gluon fusion cxn to 20pb
h.setDecayWidth("tautau", 1e-2) # set one partial decay width -> BR(h>tautau)=1
bounds = Higgs.Bounds() # loads all limits from data files
print(bounds(pred)) # run HiggsBounds and print the results
```

Summary

`HiggsBounds` and `HiggsSignals` compare models with (extended) scalar sectors to the available limits and measurements. They

- contain large databases of experimental results,
  - that should be cited when using the codes.
- check specific model assumptions.
- make sure the statistical interpretation is sound,
  - see also Sec 3.3 in [Bechtle et al. 2012.09197].
- help with the required theory input,
  - *e.g.* by providing an effective coupling input.

We encourage the experimental collaborations to make minimal and clear model assumptions, provide signal efficiencies, correlations, and reference values whenever possible (see also [LHC Reinterpretation Forum 2003.07868; Bechtle et al. 2006.06007, 2012.09197]).