Probing Higgs Sectors with Limits and Measurements

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6th LHC Reinterpretation Workshop, 16.2.21

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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

**HiggsBounds**

> 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
- machine readable format, ideally via HEPData
- rates in reference model (if normalized)
- details about model assumptions
## Input

### Model Predictions

- **production @ LHC and Tevatron**
  - $ggF, bbh, Wh, Zh, VBF, tth, th, tWh, h_ih_j$
  - $tbH^\pm, t \rightarrow H^\pm b, H^\pm h_i$

- **production @ LEP**
  - $hZ, bbh, \tau\tau h, h_ih_j$
  - $H^\pm H^\mp$

- **decay**
  - $h \rightarrow f\bar{f}, VV, \text{inv}, h_ih_j, h_iZ, H^\pm W$
  - $H^\pm \rightarrow tb, cs, cb, \tau\nu, h_jW, WZ$

**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.
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
  ⇒ 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
Interpreting Higgs searches — Exclusion Likelihoods

Simplified exclusion likelihood profiles are available for:

- LEP Higgs Combination [ALEPH, DELPHI, L3, OPAL hep-ex/0602042]
- ATLAS and CMS $H \rightarrow \tau\tau$ 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.

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

→ construct 95% C.L. $CL_s$ limits

→ as likelihood contribution in a fit

Contains full information for all sub-channel rates.
Interpreting Higgs Measurements

Fit model predictions to the latest measurements of $h_{125}$. $\rightarrow \chi^2$ or Likelihood

Two dedicated public codes:

**HiggsSignals** [Bechtle et al. 2012.09197] and **Lilith** [Kraml et al. 1908.03952]

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$^{-1}$ (HS)/ 36 fb$^{-1}$ (Lilith)
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]
Interpreting Higgs Measurements — 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 $\kappa$-fit.
Interpreting Higgs Measurements — Experimental Input

<table>
<thead>
<tr>
<th>Signal Strength Measurements — the old way</th>
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</thead>
<tbody>
<tr>
<td>Fully inclusive measurement assuming SM kinematics.</td>
</tr>
<tr>
<td>→ Need signal efficiencies for all sub-channels.</td>
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<table>
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<tr>
<th>STXS measurements — the modern way</th>
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<tbody>
<tr>
<td>Differential cxn measurements in predefined, theoretically pure bins.</td>
</tr>
<tr>
<td>→ still need signal efficiencies if different-process bins are merged</td>
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</tbody>
</table>

Inter-bin correlations are needed either way:

- experimental correlations between STXS bins/μ sub-channels
- theoretical correlations, especially for production modes with many STXS bins (e.g. ggF [2017 Scheme])

SM reference rates for all bins are essential as well.
If $m_H$ is a prediction of the theory, it usually has a theoretical mass uncertainty. All measurements and limits have an experimental mass resolution.

So what happens for a predicted Higgs mass of 124 ± 1 GeV?

- assignment of a particle to a measurement
- $\chi^2_{m_H}$ contribution from mass measurements
- pdf: treat $\Delta m_{H}^{\text{theo}}$ and $\Delta m_{H}^{\text{exp}}$ as a box or a gaussian error

Need mass resolution for rate measurements with fixed mass hypothesis.
What if $H_{1,2}$ with $\Delta m_{H_{1,2}}^{\text{theo}} = 0.5$ GeV and $\mu_{1,2} = 0.5$ are unresolved near 125 GeV?

Using gaussian pdf.

- $\Delta \chi^2_m$: mass $\chi^2$ for the rate-weighted average mass
- $\chi^2_{\text{sep}}$: separation $\chi^2$ to approximate a partially resolved signal
- $\Delta \chi^2_{\mu}$: $\sim 0$ for these $\mu$ if both scalars are assigned, large otherwise

STXS combinations of different decay modes assume a single contributing particle. [ATLAS 1909.02845]
What if e.g. $m_H \approx m_A$ in a search for additional scalars?

$M_{h_125}^{125}$ scenario [Bagnaschi et al. 2019]

1. cluster particles if $|m_H - m_A| \lesssim \Delta m^{\text{exp}}$
2. use the rate-weighted average mass as cluster mass
3. compare summed cluster rate to the limit at that mass

Caveat: ignores interference

Need an (approximate) value for $\Delta m^{\text{exp}}$. 
Summary — Presenting Limits from Higgs Searches

To publish search results for best reinterpretability, please:

- provide 95% C.L. observed and expected limits (or exclusion likelihoods) as a function of all relevant kinematical parameters,
  - i.e. for two unknown masses a 2D limit is much more useful than some 1D slices,
- put it on HEPData (or in an auxiliary table for few mass points),
- give reference model rates, especially if the limit is normalized,
- keep model assumptions minimal, for combinations of channels consider:
  1. exclusion likelihoods as a function of rates in pure sub-channels,
  2. provide signal efficiencies for a reference model (i.e. SM),
  3. assume SM-like signal composition, this will severly limit usability,
      - this includes small-seeming assumptions like \( \text{BR}(\rightarrow \mu\mu) / \text{BR}(\rightarrow \tau\tau) \),
- estimate a mass resolution.

See [Bechtle et al. 2006.06007] for details.
Summary — Presenting Higgs Measurements

To publish Higgs measurements for best reinterpretability, please provide:

• results in the signal strength or STXS framework, ideally both,
• SM signal efficiencies for all bins that are not pure channels,
  • this includes merged STXS bins!
• inter-bin experimental correlation matrices,
• theory uncertainty correlations, especially for STXS bins,
• SM reference rates for each bin,
• simplified model interpretation plots \((\kappa_V, \kappa_F)\) and \((\mu_V, \mu_F)\),
• an approximate mass resolution.

In your pheno studies, consider using HiggsBounds to handle limits from Higgs searches and HiggsSignals or Lilith to fit the Higgs measurements.

The codes

• contain large databases of experimental results.
• check specific model assumptions.
• make sure the statistical interpretation is sound,
  • see also Sec 3.3 in [Bechtle et al. 2012. 09197].
• help you with the required theory input,
  • e.g. by providing an effective coupling input.

Make sure to also cite the underlying experimental results.