Higgs fiducial cross sections

a nearly model independent path to constrain new physics in the Higgs sector
Fiducial cross sections \textit{versus} coupling strength measurements

How did we find the Higgs? — \textit{Illustrated for Higgs to di-photon or Higgs to di-tau}

- In a \textit{signal strength fit}, category II gets more statistical weight than category I due to the higher expected S/B.
- Events from a \textit{very specific region of phase space} can get very high weight in a combined fit.

\begin{itemize}
  \item All of phase space
  \begin{itemize}
    \item \textbf{Problem:}
    \begin{itemize}
      \item if efficiencies are wrong, get a \textit{biased result}
      \item Pretend to measure all of phase space, but effective sensitivity from a small, very specific region.
    \end{itemize}
  \end{itemize}
\end{itemize}
Fiducial cross sections versus coupling strength measurements

Fiducial cross sections avoid such extrapolations

In particle physics:

a fiducial cross-section is a cross-section measured only for the fiducial region, a clearly defined region in phase-space in which the detector operates with high efficiency, without extrapolating to regions where the experiment has no sensitivity.

To obtain a cross section, one needs to account for migrations in & outside the fiducial region, i.e. unfold

\[
\sigma_i = \frac{n_i}{\mathcal{L} c_i}
\]
Object isolation

- Isolation important in reconstructing leptons and photons in measurements.
  - Typically require cone-type isolation and use tracks or clusters
- Need to be mapped to particle-level to avoid extrapolations
  - i.e. if a reco event is rejected due to high activity, so should a truth event.

\[ c_i = \frac{n_i^{det}}{n_i^{ptcl}} \]
Run 1 results

- Measurement of fiducial differential cross sections of gluon-fusion production of Higgs bosons decaying to $WW^* \rightarrow e\nu\mu\nu$ with the ATLAS detector at $\sqrt{s}=8$ TeV, ATLAS Collaboration, arXiv:1604.02997

- Measurement of the transverse momentum spectrum of the Higgs boson produced in pp collisions at $\sqrt{s}=8$ TeV using the $H \rightarrow WW$ decays, CMS Collaboration, CMS-PAS-HIG-15-010

- Measurement of differential and integrated fiducial cross sections for Higgs boson production in the four-lepton decay channel in pp collisions at $\sqrt{s}=7$ and 8 TeV, CMS Collaboration, arXiv:1512.08377

- Measurement of differential cross sections for Higgs boson production in the diphoton decay channel in pp collisions at $\sqrt{s}=8$ TeV, CMS Collaboration, arXiv:1508.07819

- Constraints on non-Standard Model Higgs boson interactions in an effective field theory using differential cross sections measured in the $H \rightarrow \gamma\gamma$ decay channel at $\sqrt{s}=8$ TeV with the ATLAS detector, ATLAS Collaboration, arXiv:1508.02507

- Measurements of the Total and Differential Higgs Boson Production Cross Sections Combining the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ Decay Channels at $\sqrt{s}=8$ TeV with the ATLAS detector, ATLAS Collaboration, Phys. Rev. Lett. 115, 091801 (2015)

- Fiducial and differential cross sections of Higgs boson production measured in the four-lepton decay channel in pp collisions at $\sqrt{s}=8$ TeV with the ATLAS detector, ATLAS Collaboration, Physics Letters B 738 (2014) 234-253

- Measurements of fiducial and differential cross sections for Higgs boson production in the diphoton decay channel at $\sqrt{s}=8$ TeV with ATLAS, ATLAS Collaboration, JHEP09(2014)112
Run 1 Gallery

From left to right: H → γγ, H → ZZ* → 4ℓ, H → WW → 2ℓ2ν

CERN, 2016, June 16

(Re)interpreting the results of new physics searches at the LHC
Interpretations

Fiducial measurements are a great starting point, to constrain new physics.

Benefits:
- There are no cut-flows and reco selections you need to replicate; all detector effects are accounted for
- Everything is unfolded to particle-level
- Measurement nearly independent of underlying theory, ie. fully consistent tests are possible

Disclaimer: Not an official ATLAS result, no one reviewed this and hacked together in one day

(Re)interpreting the results of new physics searches at the LHC
A lame example

Time to play! — Let’s do a kappa fit

- Use ATLAS $H \rightarrow \gamma\gamma$ & $H \rightarrow ZZ^* \rightarrow 4l$ Higgs pT spectra
- Modify SM cross sections according to the formula on RHS
- Just build a simple $\chi^2$ between data points and predictions
- Do a scan for $k_V$ (scaling coupling of Higgs to vector bosons) and $k_F$ (scaling coupling of Higgs to fermions)

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![Graph showing $\kappa_V$ vs $\kappa_F$ and contours for 68% CL and 95% CL](image)

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CERN, 2016, June 16
Time to play! — Let’s do a Spin hypothesis test

- Use ATLAS H → γγ measurement of |cos Θ_{CSL}|
- aMC@NLO templates for Spin 2
- Just build a simple \(\chi^2\) between data points and predictions
- Do a scan for \(\kappa_g/\kappa_q\) (coupling strength of Spin 2 particle and gluons or quarks)

![Spin0 Pseudo-experiments](Spin2_KR100 Pseudo-experiments)

\(\kappa_f = \kappa_g/\kappa_q = 100\)

![Spin2 test statistic](Hypothesis Median)

68% / 95% / 99.5%

\(\kappa_f = \kappa_g/\kappa_q\)
That’s nice, and I can see that with that I can do combined fits with one distribution per channel and experiment. But what if you want to fit several distributions at once?

- All distributions use the same data; bins are statistically (not so trivial) and systematically (trivial) correlated

\[ \rho = ? \]
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For high-statistics channels there is an elegant way to derive such correlations from the data:

**Bootstrapping** — analyzing a weighted subset of the data to extract the correlation information
Time to play! — Let’s constrain new physics with an effective Lagrangian

- Uses 5 ATLAS H → γγ differential distributions
- Takes into account their statistical correlations
- Build a χ² between data points and predictions
- Do a scan for various Wilson coefficients of the SILH Lagrangian, e.g. $c_g$ (eff. coupling to gluons), $c_γ$ (eff. coupling to photons), etc. + CP Conjugate counterparts

**SM**

**NP**

\[
\frac{dσ}{dX} = \sum_j \left( \frac{dσ_j}{dX} \right)_{c_i} \left( \frac{dσ_j}{dX} \right)_{MG5} \left/ \left( \frac{dσ_j}{dX} \right)_{c_i=0} \right.
\]

\[
\mathcal{L} = \bar{c}_γ O_γ + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \bar{c}_γ \bar{O}_γ + \bar{c}_g \bar{O}_g + \bar{c}_{HW} \bar{O}_{HW} + \bar{c}_{HB} \bar{O}_{HB},
\]
A non-lame example
But fiducial cross sections are not for everyone (yet)

Similar methods might work for $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW \rightarrow 2l2\nu$

- Many kinematic distributions that characterize **Higgs production and decay**
- Many sensitive to **new physics**
- Combination of various distributions can be pretty powerful

But: fiducial cross sections are not for everyone (yet)

- Channels with low sensitivity or channels that rely on MVAs won’t be able to quote fiducial cross sections for a while
- Is there a path in the middle?

Illustration from Frank Tackmann, Kerstin Tackmann

**Measurement**  
**theory-independent**

**Interpretation**  
**theory-dependent**
But fiducial cross sections are not for everyone (yet)

Similar methods might work for $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW \rightarrow 2l2v$

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Summary (1/2)

Fiducial cross sections can be a powerful tool to constrain new physics

• Nearly independent of underlying theory
• Detector effects are reverted, distributions unfolded to particle level
• Quoted inside a well defined fiducial volume, many analyses provide Rivet routines that can be used

Do you have a new physics model and it impacts kinematics in the Higgs sector? Why not test it! Do you want to know how well certain dim-6 operator hold up against the measurements? Want to do your own Spin test?

Hype – (Hyp)othesis (e)valuator for unfolded distributions

Features:

i. Easily perform hypothesis tests between two or more hypotheses
ii. Plug-ins: µ and -type scans
iii. Direct import of Hep-Data measurements
iv. Easy to interface custom code
v. For hypothesis tests: automatically determines number of pseudo-experiments needed

Project home: https://hype.hepforge.org/
The YR4 has chapters about fiducial and simplified template cross sections

- If you are interested, check it out!

https://cds.cern.ch/record/2157092 (fiducial cross sections)

https://cds.cern.ch/record/2138079 (simplified template cross sections)

Thank you for your attention!