Combination of Higgs measurements:

Couplings and $\kappa$-framework

Jonathon Langford

On behalf of the ATLAS and CMS Collaborations

LHCP 2020
The Higgs sector

- Higgs boson is the only fundamental scalar particle (spin 0) in the SM

- Run 2: focus shifted towards **precision measurements** of H couplings
  - unique tool to scrutinize predictions of SM
The Higgs sector

- Higgs boson is the only fundamental scalar particle (spin 0) in the SM

- Gauge boson interactions: $H - V$ couplings

- Run 2: focus shifted towards **precision measurements** of $H$ couplings
  - unique tool to scrutinize predictions of SM
The Higgs sector

- Higgs boson is the only fundamental scalar particle (spin 0) in the SM

- Gauge boson interactions: H-\(V\) couplings

- Yukawa interactions: H-\(f\) couplings

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  - unique tool to scrutinize predictions of SM
The Higgs sector

- Higgs boson is the only fundamental scalar particle (spin 0) in the SM

- Gauge boson interactions: $H - V$ couplings

- Yukawa interactions: $H - f$ couplings

- Higgs potential: self couplings

- Run 2: focus shifted towards **precision measurements** of $H$ couplings
  - unique tool to scrutinize predictions of SM
Run 2 combinations

- Wealth of data allows for unprecedented levels of precision!
  - tighter constraints on BSM models which distort H couplings
- Combinations across decay channels provides ultimate sensitivity
  - both collaborations completing full Run II analyses in individual channels
- This talk: focus on latest **intermediate combinations** from CMS & ATLAS:
  - 35.9–137 fb$^{-1}$ (Jan 2020): CMS-PAS-HIG-19-005
## Input analyses

|------------|----|----------------------|----|------------------------|

(*) Not included in all results

(*) Some inputs have now been superseded with full Run 2 analyses

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Signal strengths: $\mu = \text{rate of H boson production} / \text{SM prediction}$

- Inclusive: all signal rates scale according to single $\mu$
  
  - $\mu = 1.02 \pm 0.04(\text{th.}) \pm 0.04(\text{exp.}) \pm 0.04(\text{stat.})$
  
  - $\mu = 1.11^{+0.05}_{-0.04}(\text{sig th.}) \pm 0.03(\text{bkg th.})^{+0.05}_{-0.04}(\text{exp.}) \pm 0.05(\text{stat.})$

- Systematic uncertainties are becoming increasingly important!
  
  - adapt measurement framework to reduce theory dependencies...

![Diagram with CMS and ATLAS logos](image_url)
Cross sections

- Measure cross sections (and their ratios) as opposed to signal strengths
  - dominant theory uncertainties cancel in ratios

- Both CMS & ATLAS report significances $\geq 5\sigma$ for major production modes

- All results consistent with SM predictions
  - more granular fits ($\mu_i^f$) in [Back-up]

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**ATLAS**

- $\sqrt{s} = 13$ TeV, 24.5 - 79.8 fb$^1$
- $m_H = 125.09$ GeV, $|y_H| < 2.5$
- $p_{SM} = 76$

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_{ggF}$</th>
<th>$\sigma_{VBF}/\sigma_{ggF}$</th>
<th>$\sigma_{WH}/\sigma_{ggF}$</th>
<th>$\sigma_{ZH}/\sigma_{ggF}$</th>
<th>$\sigma_{tH+tH}/\sigma_{ggF}$</th>
<th>$B_{WW}/B_{ZZ}$</th>
<th>$B_{s}/B_{ZZ}$</th>
<th>$B_{bb}/B_{ZZ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggF$</td>
<td>1.04 $\pm 0.09 (\pm 0.07, + 0.07)$</td>
<td>1.21 $+0.24, +0.18, +0.16$ $-0.22, -0.17, -0.13$</td>
<td>1.30 $+0.40, +0.28, +0.29$ $-0.38, -0.27, -0.27$</td>
<td>1.05 $+0.31 (\pm 0.24, +0.19)$ $-0.29$</td>
<td>1.21 $+0.26 (\pm 0.17, +0.20)$ $-0.24$</td>
<td>1.04 $\pm 0.09 (\pm 0.07, + 0.07)$</td>
<td>1.21 $+0.24, +0.18, +0.16$ $-0.22, -0.17, -0.13$</td>
<td>1.30 $+0.40, +0.28, +0.29$ $-0.38, -0.27, -0.27$</td>
</tr>
</tbody>
</table>

**Parameter normalized to SM value**

- $0$ $0.5$ $1$ $1.5$ $2$ $2.5$ $3$
- Total Stat. Syst. SM

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**Back-up**
Simplified template cross sections: more detail in ▶ Back-up

- Measure cross sections in increasingly granular “bins”
  - split by production mode + kinematics ($|y_H| < 2.5$)

- Leave no stone/region of space space unturned!
  - full Run 2 measurements will adhere to stage 1.2 binning ▶ Back-up
Simplified template cross sections

- Insufficient scope to measure all bins of STXS given current datasets
  - merge bins with low sensitivity ($\gtrsim 100\%$) or high (anti)-correlations
  - increases model dependence
  - e.g. 19 parameter fit
  => also finer granularity fit:

- At this level of splitting
  => stat unc. dominate

- Differential information
  - motivates (re)-interpretation
  - + provide full correlation matrix between fitted params:

- Very much in agreement with SM!
**κ-framework:** $\mu \rightarrow \mu(\kappa)$

- Multiplicative coupling modifiers $\Rightarrow$ SM: positive + equal to unity
- Two possible treatments for loop diagrams:
  - resolved into SM components
  - effective vertices

### Limitations
1. LO framework
2. Ignores shape effects
3. Specific to H physics
**κ-framework**

- Under assumption of no additional H boson decays beyond SM particles
- Universal modifiers for H couplings to V bosons ($\kappa_V$) and fermions ($\kappa_F$)
  - resolve loops into SM components
  - $\kappa_V = \kappa_Z = \kappa_W$
  - $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$

![Diagram showing Higgs couplings](image)

- Probe new particles in loops:
  - $\Rightarrow$ ggH, $H \rightarrow \gamma\gamma$:
    - effective coupling strengths: $\kappa_g$, $\kappa_\gamma$
    - assume all other $\kappa_j = 1$
\(\kappa\)-framework

- Extend to include Higgs boson self coupling \((\kappa_\lambda)\), see talk by Stefano

- Under assumption of no additional H boson decays beyond SM particles

\[
\begin{array}{l}
\text{Parameter} \quad \text{Result} \\
\kappa_Z & 1.10 \pm 0.08 \\
\kappa_W & 1.05 \pm 0.08 \\
\kappa_b & 1.06 \pm 0.19 \\
\kappa_t & 1.02 \pm 0.11 \\
\kappa_\tau & 1.07 \pm 0.15 \\
\kappa_\mu & < 1.53 \text{ at 95\% CL} \\
\end{array}
\]

\(~5\text{–}20\%\) precision on H couplings to gauge bosons & 3rd gen fermions. Agrees with SM!

- correlation matrix in Back-up

- Sensitive to relative sign of \(\kappa_W, Z - \kappa_t\)

- effective model: via interference in \(tH + ggZH\) processes
κ-framework: beyond SM

- additional benchmarks to account for BSM effects in H decay
  - on-shell production...
    \[ \sigma_i \cdot B^f = \frac{\sigma_i(\vec{\kappa}) \Gamma^f(\vec{\kappa})}{\Gamma_H(\vec{\kappa}, B_{\text{inv}}, B_{\text{undet}})} \]
  - \( B_{\text{inv}} \): H\rightarrow\text{invisible decays (MET)}
  - \( B_{\text{undet}} \): final states not measured

1. \( B_{\text{undet}} > 0, \kappa_V < 1 \):
   - includes results from H\rightarrow inv. searches
   - \( B_{\text{undet}} < 21\% \) & \( B_{\text{inv}} < 30\% \) @ 95\% C.L.

2. \( B_{\text{BSM}} = B_{\text{undet}} + B_{\text{inv}} \)
   - includes off-shell H\rightarrow ZZ^* meas.
   - assumes \( \kappa_{\text{on}} = \kappa_{\text{off}} \)
     \[ (\sigma_i \cdot B^f)_{\text{off-shell}} \sim \sigma_i(\kappa_{\text{off}}) \Gamma^f(\kappa_{\text{off}}) \]
   - \( B_{\text{BSM}} < 49\% \) @ 95\% C.L.

- also fit ratios of coupling modifiers
- + 2HDM/hMSSM interpretations

Back-up + 2HDM/hMSSM interpretations
EFT interpretation of STXS measurements

- Extend $\mathcal{L}_{SM}$ with higher-dim operators:
  $$\mathcal{L} = \mathcal{L}_{SM} + \sum_j f_j \mathcal{O}_j / \Lambda^2$$

- Parametrize $\sigma + BR$ as function of EFT parameters: $c_j \propto f_j / \Lambda^2$
  - for each bin of STXS
  - beyond $\kappa$’s: shape effects

- Using Higgs Effective Lagrangian
  - SILH basis
  - combination of STXS stage 0, 1 and 1.1

- Neglected acceptance corrections
  - sizeable in some channels:
    - e.g. $H \rightarrow 4\ell$: submitted to EPJC
  - future EFT interpretations will account for such effects!

- $\Rightarrow$ SMEFT (Warsaw)

More info in talk by Nikita
Differential combinations: more detail in talk by Andrea

- Also combination of $d\sigma/dX$ measurements across major channels
- Fiducial $\leftrightarrow$ model independence
- Shape is sensitive to Yukawa couplings + new physics in loop diagrams!

- $4\ell + \gamma\gamma$ using full Run 2 data (140 fb$^{-1}$): ATLAS-CONF-2019-032
- Several full Run 2 inputs ready e.g. $H \rightarrow WW$...
Looking to the future

- Presented results of Higgs combinations using partial Run 2 data
  - signal strengths, cross sections, STXS, $\kappa$-framework, EFT
  - all in agreement with SM predictions

- Full Run 2 combinations will provide never-before-reached levels of precision
  - both collaborations completing full Run 2 analyses in individual channels

- STXS + differential measurements offer finer granularity

- Interpretation: emphasis shifting $\kappa$-framework $\Rightarrow$ EFT

- Ultimate precision: inter-collaboration combination (as in Run 1)
Back-Up Slides
Statistical procedure for combination

- **Methodology** used by ATLAS and CMS collaborations

- Profile likelihood ratio: \( q(\vec{\alpha}) \)
  
  ▶ estimate POIs (\( \vec{\alpha} \)) and corresponding confidence intervals e.g. \( \mu, \kappa \) etc.
  
  ▶ \( \vec{\theta} \): nuisance param (NP) describing experimental + theoretical unc.

\[
q(\vec{\alpha}) = -2 \ln \left( \frac{L(\vec{\alpha}, \hat{\vec{\theta}}_{\vec{\alpha}})}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})} \right)
\]

- Confidence intervals: regions where \( q(\vec{\alpha}) \) below threshold in \( F_{\chi^2_n}^{-1}(1 - p) \)
  
  ▶ \( F_{\chi^2_n}^{-1} \): quantile function of \( \chi^2 \) dist. with \( n \) d.o.f
  
  ▶ compatibility with SM measured with \( p \)-value: \( p_{\text{SM}} = 1 - F_{\chi^2_n}(q(\vec{\alpha}_{\text{SM}})) \)

- e.g. 1D measurements: \( 1\sigma \) (\( 2\sigma \)) intervals \( \rightarrow q(\vec{\alpha}) < 1 \) (\( q(\vec{\alpha}) < 4 \))
  
  ▶ models with more than one POI: treat other POIs as NP (profiling)

- For expected results: construct likelihood functions w.r.t. Asimov data set
  
  ▶ using expected (SM) values of the POIs
## Global signal strength: uncertainty breakdown

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta \mu/\mu$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainty</td>
<td>4.4</td>
</tr>
<tr>
<td>Systematic uncertainties</td>
<td>6.2</td>
</tr>
<tr>
<td>Theory uncertainties</td>
<td>4.8</td>
</tr>
<tr>
<td>Signal</td>
<td>4.2</td>
</tr>
<tr>
<td>Background</td>
<td>2.6</td>
</tr>
<tr>
<td>Experimental uncertainties (excl. MC stat.)</td>
<td>4.1</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.0</td>
</tr>
<tr>
<td>Background modeling</td>
<td>1.6</td>
</tr>
<tr>
<td>Jets, $E_T^{\text{miss}}$</td>
<td>1.4</td>
</tr>
<tr>
<td>Flavor tagging</td>
<td>1.1</td>
</tr>
<tr>
<td>Electrons, photons</td>
<td>2.2</td>
</tr>
<tr>
<td>Muons</td>
<td>0.2</td>
</tr>
<tr>
<td>$\tau$-lepton</td>
<td>0.4</td>
</tr>
<tr>
<td>Other</td>
<td>1.6</td>
</tr>
<tr>
<td>MC statistical uncertainty</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>Total uncertainty</strong></td>
<td><strong>7.6</strong></td>
</tr>
</tbody>
</table>
CMS: $\mu^f_i$

- Separate signal strengths for all possible production mode ($i \rightarrow H$) $\times$ decay channel ($H \rightarrow f$) combinations

<table>
<thead>
<tr>
<th>CMS Preliminary</th>
<th>Observed ±1σ</th>
<th>$\mu^f_i$ combined ±1σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ZZ$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WW$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$bb$</td>
<td>2.45 $^{+2.53}_{-2.35}$</td>
<td></td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>0.31 $^{+1.82}_{-1.81}$</td>
<td>3.18 $^{+8.22}_{-7.93}$</td>
</tr>
</tbody>
</table>

$\sigma_1 \pm \text{Observed}$

$p_{SM} = 90\%$

35.9-137 fb$^{-1}$ (13 TeV)
CMS: $\mu_i^f$ correlations

- Separate signal strengths for all possible production mode ($i \rightarrow H$) $\times$ decay channel ($H \rightarrow f$) combinations

<table>
<thead>
<tr>
<th>CMS Preliminary</th>
<th>35.9-137 fb$^{-1}$ (13 TeV)</th>
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</thead>
<tbody>
<tr>
<td>$\mu_i^f$</td>
<td></td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td></td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td></td>
</tr>
<tr>
<td>$Z^+Z^-$</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td></td>
</tr>
<tr>
<td>$W^+H$</td>
<td></td>
</tr>
<tr>
<td>$Z^0H$</td>
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<td>$ggH$</td>
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<td>$VBF$</td>
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<tr>
<td>$WH$</td>
<td></td>
</tr>
<tr>
<td>$ZH$</td>
<td></td>
</tr>
<tr>
<td>$ttH$</td>
<td></td>
</tr>
</tbody>
</table>

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Higgs combination

LHCP 29.05.20
**ATLAS: \( \sigma_i \times BR(H \rightarrow f) \)**

- Separate parameters for all possible production mode \((i \rightarrow H) \times \) decay channel \((H \rightarrow f)\) combinations

### ATLAS

- \( \sqrt{s} = 13 \text{ TeV}, 24.5 - 79.8 \text{ fb}^{-1} \)
- \( m_H = 125.09 \text{ GeV}, |y_H| < 2.5 \)
- \( p_{SM} = 71\% \)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Total</th>
<th>Stat.</th>
<th>Syst.</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( gg )</td>
<td>0.96</td>
<td>±0.14</td>
<td>±0.09</td>
<td>1</td>
</tr>
<tr>
<td>( ZZ^* )</td>
<td>1.04</td>
<td>±0.16</td>
<td>±0.08</td>
<td>1</td>
</tr>
<tr>
<td>( WW^* )</td>
<td>0.96</td>
<td>±0.59</td>
<td>±0.37</td>
<td>1</td>
</tr>
<tr>
<td>( b\bar{b} )</td>
<td>1.04</td>
<td>±0.09</td>
<td>±0.07</td>
<td>1</td>
</tr>
<tr>
<td>( \gamma\gamma )</td>
<td>1.39</td>
<td>±0.40</td>
<td>±0.21</td>
<td>2</td>
</tr>
<tr>
<td>( ZZ^* )</td>
<td>2.68</td>
<td>±0.98</td>
<td>±0.27</td>
<td>1</td>
</tr>
<tr>
<td>( WW^* )</td>
<td>0.59</td>
<td>±0.36</td>
<td>±0.24</td>
<td>2</td>
</tr>
<tr>
<td>( \tau\tau )</td>
<td>1.16</td>
<td>±0.50</td>
<td>±0.23</td>
<td>2</td>
</tr>
<tr>
<td>( b\bar{b} )</td>
<td>3.01</td>
<td>±1.67</td>
<td>±1.17</td>
<td>1</td>
</tr>
<tr>
<td>( \gamma\gamma )</td>
<td>1.21</td>
<td>±0.26</td>
<td>±0.12</td>
<td>2</td>
</tr>
<tr>
<td>( ZZ^* )</td>
<td>1.09</td>
<td>±0.54</td>
<td>±0.22</td>
<td>2</td>
</tr>
<tr>
<td>( bb )</td>
<td>0.68</td>
<td>±0.78</td>
<td>±0.27</td>
<td>2</td>
</tr>
<tr>
<td>( \gamma\gamma )</td>
<td>1.19</td>
<td>±0.24</td>
<td>±0.14</td>
<td>2</td>
</tr>
<tr>
<td>( ZZ^* )</td>
<td>1.15</td>
<td>±0.52</td>
<td>±0.26</td>
<td>2</td>
</tr>
<tr>
<td>( b\bar{b} )</td>
<td>1.09</td>
<td>±0.59</td>
<td>±0.26</td>
<td>1</td>
</tr>
<tr>
<td>( \gamma\gamma )</td>
<td>1.38</td>
<td>±0.60</td>
<td>±0.28</td>
<td>2</td>
</tr>
<tr>
<td>( ZZ^* )</td>
<td>0.79</td>
<td>±0.09</td>
<td>±0.02</td>
<td>2</td>
</tr>
<tr>
<td>( b\bar{b} )</td>
<td>1.21</td>
<td>±0.24</td>
<td>±0.12</td>
<td>1</td>
</tr>
</tbody>
</table>

\( \sigma \times BR \) normalized to SM

\( -2 - 0 - 2 - 4 - 6 - 8 \)

\( \sigma \times BR \) normalized to SM

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Higgs combination

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ATLAS: $\sigma_i \times \text{BR}(H \rightarrow f)$ correlations

- Separate parameters for all possible production mode ($i \rightarrow H$) $\times$ decay channel ($H \rightarrow f$) combinations

\[ \sqrt{s} = 13 \text{ TeV}, 24.5 - 79.8 \text{ fb}^{-1} \]
\[ m_H = 125.09 \text{ GeV}, |y_H| < 2.5 \]
Simplified template cross sections

- Coherent framework for increasingly granular Higgs measurements
  - isolate mutually exclusive regions of Higgs phase space (bins)
  - split by production mode + kinematics ($|y_H| < 2.5$)

- Aims: maximise experimental sensitivity whilst systematically reducing theory dependence folded into measurements
  - design bins to have constant theory unc.
  - + isolate possible BSM physics
  - decouple interpretation from measurement: long-term useful
  - coherence permits combinations across decay channels
- Build up more granular picture of the Higgs Boson
STXS stage 1.0

- Measure cross sections in increasingly granular “bins”
  - split by production mode + kinematics ($|y_H| < 2.5$)
STXS stage 1.2

- Evolves in stages: increased granularity to match increase in statistics
- Updates w.r.t stage 1.1: split ttH and ggH $p_T^H > 200$ GeV...

![Diagram showing the STXS stage 1.2](image-url)
STXS: ATLAS merging scheme + sensitivity breakdown

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 36.1 - 79.8 \text{ fb}^{-1} \)
\( m_H = 125.09 \text{ GeV}, |y_\mu| < 2.5 \)

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>( gg \to H, \geq 1 \text{ jet} ), ( p_T^H \geq 200 \text{ GeV} )</td>
<td>( \gamma\gamma )</td>
</tr>
<tr>
<td>( gg \to H, 0 \text{-jet} )</td>
<td>( WW^* )</td>
</tr>
<tr>
<td>( gg \to H, 1 \text{-jet}, 120 \leq p_T^H &lt; 200 \text{ GeV} )</td>
<td>( \tau\tau )</td>
</tr>
<tr>
<td>( gg \to H, 1 \text{-jet}, 60 \leq p_T^H &lt; 120 \text{ GeV} )</td>
<td>( b\bar{b} )</td>
</tr>
<tr>
<td>( gg \to H, \geq 2 \text{ jet} ), ( p_T^H \geq 200 \text{ GeV} )</td>
<td>( WW^* + \tau\tau )</td>
</tr>
</tbody>
</table>

Decay channel contribution

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Higgs combination

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STXS: correlations

- Correlation matrix between fitted parameters: crucial for re-interpretation

\[ \sqrt{s} = 13 \text{ TeV}, 36.1 - 79.8 \text{ fb}^{-1} \]

\[ m_H = 125.09 \text{ GeV}, |y_H| < 2.5 \]

### ATLAS

<table>
<thead>
<tr>
<th></th>
<th>0-jet</th>
<th>1-jet, ( p_T^H &lt; 60 \text{ GeV} )</th>
<th>1-jet, ( 60 \leq p_T^H &lt; 120 \text{ GeV} )</th>
<th>1-jet, ( 120 \leq p_T^H &lt; 200 \text{ GeV} )</th>
<th>( \geq 2 \text{-jet}, p_T^H \geq 200 \text{ GeV} )</th>
<th>( \geq 1 \text{-jet}, p_T^H \geq 200 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-jet</td>
<td>1</td>
<td>0.27 -0.21 0.18 0.10 0.00 0.22 0.32 0.03 -0.01</td>
<td>0.15 0.12 0.03 0.08 0.12 0.33 -0.52 -0.17 -0.50 -0.25</td>
<td>0.00 0.01 0.01 0.00 0.02 0.04 0.00 -0.02 -0.05 -0.01</td>
<td>0.18 0.09 0.17 0.01 0.01 0.05 0.03 -0.02 -0.02 -0.01</td>
<td>0.01 0.02 0.00 0.01 0.00 0.00 0.00 0.00 0.00 0.00</td>
</tr>
<tr>
<td>1-jet, ( p_T^H &lt; 60 \text{ GeV} )</td>
<td>0.27</td>
<td>1 -0.17 0.07 -0.01</td>
<td>0.02 -0.01 0.04 0.04 0.01 0.02 0.02 0.06</td>
<td>0.10 -0.13 -0.13 -0.11</td>
<td>0.02 0.00 0.01 0.00 0.01 0.02 0.01 0.04 0.06</td>
<td>0.11 -0.13 -0.11 -0.18</td>
</tr>
<tr>
<td>1-jet, ( 60 \leq p_T^H &lt; 120 \text{ GeV} )</td>
<td>0.18</td>
<td>0.09 0.22 0.05</td>
<td>0.03 0.04 0.01 0.00 0.00 0.00 0.00</td>
<td>0.01 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00</td>
<td>0.01 0.00 0.00 0.00</td>
<td>0.01 0.00 0.00 0.00</td>
</tr>
<tr>
<td>1-jet, ( 120 \leq p_T^H &lt; 200 \text{ GeV} )</td>
<td>0.18</td>
<td>0.17 0.01</td>
<td>0.00 0.00 0.00 0.00 0.00 0.00 0.00</td>
<td>0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00</td>
<td>0.00 0.00 0.00 0.00</td>
<td>0.00 0.00 0.00 0.00</td>
</tr>
<tr>
<td>( \geq 2 \text{-jet}, p_T^H \geq 200 \text{ GeV} )</td>
<td>0.22</td>
<td>-0.01 0.01</td>
<td>-0.01 -0.01 -0.01 -0.01 -0.01 -0.01</td>
<td>-0.01 -0.01 -0.01 -0.01 -0.01 -0.01 -0.01</td>
<td>-0.01 -0.01 -0.01 -0.01</td>
<td>-0.01 -0.01 -0.01 -0.01</td>
</tr>
<tr>
<td>( \geq 1 \text{-jet}, p_T^H \geq 200 \text{ GeV} )</td>
<td>0.22</td>
<td>-0.01 0.01</td>
<td>-0.01 -0.01 -0.01 -0.01 -0.01 -0.01</td>
<td>-0.01 -0.01 -0.01 -0.01 -0.01 -0.01 -0.01</td>
<td>-0.01 -0.01 -0.01 -0.01</td>
<td>-0.01 -0.01 -0.01 -0.01</td>
</tr>
</tbody>
</table>

**Legend:**
- \( \rho(X, Y) \) represents the correlation coefficient between two variables.
- Colors indicate the strength and direction of the correlation:
  - **Red** indicates a positive correlation.
  - **Blue** indicates a negative correlation.
  - **White** indicates no correlation.

- **VBF top + Rest** represents a cross-section relation between different processes.
- **VH top** represents another cross-section relation.
- **Higgs** represents another process.
- **Higgs + Higgs** represents the summation of similar processes.

- **qq, qZ** represents another cross-section relation.
- **gg, gZ** represents another cross-section relation.
- **B_{VH}, B_{tt}** represents another cross-section relation.

**Note:**
- The correlation matrix is crucial for re-interpretation of experimental data in high-energy physics, particularly in the context of the Higgs boson and its decay products.
STXS: finer granularity

- Higher granularity fit
- Closer to nominal STXS stage 1.0 definition
- Reduced model dependence!

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV}, \, 36.1 - 79.8 \text{ fb}^{-1} \]
\[ m_H = 125.09 \text{ GeV}, \, |y_H| < 2.5 \]

**Higgs combination**

- Parameter normalized to SM value

<table>
<thead>
<tr>
<th>( B_{T}/B_{Z^{*}} )</th>
<th>( B_{T}/B_{Z^{*}} )</th>
<th>( B_{T}/B_{Z^{*}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.81</td>
<td>0.61</td>
<td>0.93</td>
</tr>
<tr>
<td>0.14 ± 0.12</td>
<td>0.29 ± 0.18</td>
<td>0.59 ± 0.42</td>
</tr>
<tr>
<td>0.07 ± 0.06</td>
<td>0.10 ± 0.09</td>
<td>0.12 ± 0.07</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( p_{\gamma}^{0} ) &gt; 60 GeV</th>
<th>( p_{\gamma}^{0} ) &gt; 50 GeV</th>
<th>( p_{\gamma}^{0} ) &gt; 40 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10 ± 0.10</td>
<td>0.11 ± 0.07</td>
<td>0.12 ± 0.05</td>
</tr>
<tr>
<td>0.10 ± 0.09</td>
<td>0.11 ± 0.08</td>
<td>0.12 ± 0.06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( p_{T}^{h} ) &gt; 150 GeV</th>
<th>( p_{T}^{h} ) &gt; 150 GeV</th>
<th>( p_{T}^{h} ) &gt; 150 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.81 ± 1.67</td>
<td>1.60 ± 1.49</td>
<td>1.19 ± 0.93</td>
</tr>
<tr>
<td>1.57 ± 1.56</td>
<td>1.51 ± 1.49</td>
<td>1.61 ± 1.64</td>
</tr>
</tbody>
</table>

- Parameter normalized to SM value
Correlations matrices indicate how parameters influence each other.

Positive correlations due to total width: $\Gamma_H$

**ATLAS**

$\sqrt{s} = 13$ TeV, 24.5 - 79.8 fb$^{-1}$

$m_H = 125.09$ GeV, $|y_H| < 2.5$

Parameter Y

| $\kappa_W$ | 1 | 0.59 | 0.47 | 0.81 | 0.49 | 0.01 |
| $\kappa_Z$ | 0.59 | 1 | 0.13 | 0.54 | 0.40 | 0.00 |
| $\kappa_t$ | 0.47 | 0.13 | 1 | 0.74 | 0.26 | 0.04 |
| $\kappa_b$ | 0.81 | 0.54 | 0.74 | 1 | 0.45 | 0.03 |
| $\kappa_\tau$ | 0.49 | 0.40 | 0.26 | 0.45 | 1 | 0.01 |
| $\kappa_\mu$ | 0.01 | 0.00 | 0.04 | 0.03 | 0.01 | 1 |

Parameter X
Higgs boson self coupling

- Indirect probe of H self coupling ($\lambda_3$) using single H measurements
  - via NLO EWK corrections to $\sigma$ & BR
- Anomolous coupling parametrization: $\kappa_\lambda = \lambda_3/\lambda_3^{\text{SM}}$
- Three parameter model: $\kappa_V$, $\kappa_F$, $\kappa_\lambda$

- Lose sensitivity to $\kappa_\lambda$ if float both $\kappa_V$ and $\kappa_F$ in fit
- Kinematic effects are neglected
  - only inclusive shifts in production mode and decay channel rates

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Best fit $\kappa_\lambda$</th>
<th>95% CL interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_F = \kappa_V = 1$</td>
<td>6.7 $^{+4.6}_{-6.6}$</td>
<td>[−3.5, 14.5]</td>
</tr>
<tr>
<td></td>
<td>$^{+8.3}_{-3.8}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{+8.2}_{-4.0}$</td>
<td></td>
</tr>
<tr>
<td>$\kappa_F = 1$</td>
<td>10.3 $^{+6.1}_{-10.0}$</td>
<td>[−5.5, 21.7]</td>
</tr>
<tr>
<td></td>
<td>$^{+8.8}_{-5.0}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{+8.2}_{-4.0}$</td>
<td></td>
</tr>
<tr>
<td>$\kappa_V = 1$</td>
<td>6.6 $^{+4.5}_{-6.1}$</td>
<td>[−3.3, 14.4]</td>
</tr>
<tr>
<td></td>
<td>$^{+8.2}_{-4.0}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{+8.2}_{-4.0}$</td>
<td></td>
</tr>
</tbody>
</table>
**H + HH combination**

- True scope realised in combining with HH measurements
- **H** (79.8 fb$^{-1}$) + HH combination (36.1 fb$^{-1}$): ATLAS-CONF-2019-049
  - H inputs: $\gamma\gamma$, ZZ*, WW, $\tau\tau$ and bb
  - HH inputs: bbbb, bb$\tau\tau$, bb$\gamma\gamma$
  - Extra caution to remove overlap between input analyses
- Remain sensitive to $\kappa\lambda$ including other coupling modifiers to SM particles
**Ratios of coupling modifiers**

- Most model-independent coupling strength measurement in $\kappa$ framework
  - independent of assumptions on total width, $\Gamma_H$
- Of particular interest...
  - $\lambda_{WZ}$: identical coupling strength for $W/Z$ required by tight bounds on SU(2) custodial symmetry + $\rho$ parameter measured @ LEP & Tevatron
  - $\lambda_{\gamma Z}$: sensitive to NP in $H \rightarrow \gamma\gamma$ loop, unlike $H \rightarrow ZZ^*$
  - $\lambda_{tg}$: new coloured particle in $ggH$ loop, unlike $ttH$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition in terms of $\kappa$ modifiers</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_{gZ}$</td>
<td>$\kappa_g \kappa_Z / \kappa_H$</td>
<td>$1.06 \pm 0.07$</td>
</tr>
<tr>
<td>$\lambda_{tg}$</td>
<td>$\kappa_t / \kappa_g$</td>
<td>$1.10 \pm 0.15$</td>
</tr>
<tr>
<td>$\lambda_{Zg}$</td>
<td>$\kappa_Z / \kappa_g$</td>
<td>$1.12 \pm 0.15$</td>
</tr>
<tr>
<td>$\lambda_{WZ}$</td>
<td>$\kappa_W / \kappa_Z$</td>
<td>$0.95 \pm 0.08$</td>
</tr>
<tr>
<td>$\lambda_{\gamma Z}$</td>
<td>$\kappa_\gamma / \kappa_Z$</td>
<td>$0.94 \pm 0.07$</td>
</tr>
<tr>
<td>$\lambda_{\tau Z}$</td>
<td>$\kappa_\tau / \kappa_Z$</td>
<td>$0.95 \pm 0.13$</td>
</tr>
<tr>
<td>$\lambda_{bZ}$</td>
<td>$\kappa_b / \kappa_Z$</td>
<td>$0.93 \pm 0.15$</td>
</tr>
</tbody>
</table>

- All in agreement with SM!
Ratios of coupling modifiers: correlations

- Correlations matrices indicate how parameters influence each other.
- Independent of total width: observe negative correlations.

\[
\begin{bmatrix}
1 & -0.18 & -0.12 & -0.46 & -0.55 & -0.26 & -0.27 \\
-0.18 & 1 & 0.44 & -0.21 & -0.16 & -0.21 & -0.32 \\
-0.12 & 0.44 & 1 & -0.56 & -0.33 & -0.32 & -0.66 \\
-0.46 & -0.21 & -0.56 & 1 & 0.47 & 0.27 & 0.50 \\
-0.55 & -0.16 & -0.33 & 0.47 & 1 & 0.38 & 0.44 \\
-0.26 & -0.21 & -0.32 & 0.27 & 0.38 & 1 & 0.34 \\
-0.27 & -0.32 & -0.66 & 0.50 & 0.44 & 0.34 & 1
\end{bmatrix}
\]

\[\sqrt{s} = 13 \text{ TeV}, 24.5 - 79.8 \text{ fb}^{-1}, m_H = 125.09 \text{ GeV}, |y_H| < 2.5\]
2HDM/hMSSM interpretations

- Cast coupling modifiers into parameters of benchmark SUSY models

\[\begin{align*}
\kappa_v &= \sin(\beta - \alpha) \quad \sin(\beta - \alpha) \quad \sin(\beta - \alpha) \\
\kappa_u &= \frac{\cos(\alpha)}{\sin(\beta)} \quad \frac{\cos(\alpha)}{\sin(\beta)} \quad \frac{\cos(\alpha)}{\sin(\beta)} \\
\kappa_d &= \frac{\cos(\alpha)}{\sin(\beta)} \quad -\frac{\sin(\alpha)}{\cos(\beta)} \quad -\frac{\sin(\alpha)}{\cos(\beta)} \\
\kappa_l &= \frac{\cos(\alpha)}{\sin(\beta)} \quad -\frac{\sin(\alpha)}{\cos(\beta)} \quad -\frac{\sin(\alpha)}{\cos(\beta)}
\end{align*}\]

ATLAS
\[\begin{align*}
\sqrt{s} &= 13 \text{ TeV}, 24.5 - 79.8 \text{ fb}^{-1} \\
m_H &= 125.09 \text{ GeV}, |y_H| < 2.5
\end{align*}\]
Additional 2HDM interpretations

- **Type I**: One Higgs doublet couples to vector bosons, while the other one couples to fermions. The first doublet is fermiophobic in the limit where the two Higgs doublets do not mix.

- **Type II**: One Higgs doublet couples to up-type quarks and the other one to down-type quarks and charged leptons.

- **Lepton-specific**: The Higgs bosons have the same couplings to quarks as in the Type I model and to charged leptons as in Type II.

- **Flipped**: The Higgs bosons have the same couplings to quarks as in the Type II model and to charged leptons as in Type I.
Effective field theory couplings: STXS re-interpretation

- EFT: in light of no new physics @ TeV scale, assume exists at $\Lambda \gg q^2$
  - couplings in Lagrangian modified by higher dimensional operators

- Parametrize STXS bin in terms of EFT params: \textbf{Higgs Effective Lagrangian (HEL)}

\[
\mathcal{L}_{\text{HEL}} = \mathcal{L}_{\text{SM}} + \sum_j \mathcal{O}_j^{(6)} f_j / \Lambda^2
\]

  - introduces 39 flavor independent dim-6 operators
  - new physics: deviations from 0 in $f_j$
  - consider eight of these

- Scaling functions: $\mu_i(c_j) = \sigma_i^{\text{EFT}} / \sigma_i^{\text{SM}}$
  - for each STXS bin, $i$, where $c_j \propto f_j$
  
  \[
  \sigma_i^{\text{EFT}} = \sigma_i^{\text{SM}} + \sigma_i^{\text{int}} + \sigma_i^{\text{BSM}}
  \]

  \[
  \Rightarrow \mu_i(c_j) = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k
  \]

- Derive $A_j$ and $B_{jk}$ coefficients for each STXS bin

\begin{align*}
\mathcal{O}_g &= |H|^2 G_{\mu\nu}^A G^{A\mu\nu} \\
\hat{O}_g &= |H|^2 G_{\mu\nu}^A \tilde{G}^{A\mu\nu} \\
\mathcal{O}_\gamma &= |H|^2 B_{\mu\nu} B^{\mu\nu} \\
\hat{O}_\gamma &= |H|^2 B_{\mu\nu} \tilde{B}^{\mu\nu} \\
\mathcal{O}_u &= y_u |H|^2 \tilde{Q}_L H^\dagger u_R + \text{h.c.} \\
\mathcal{O}_d &= y_d |H|^2 \tilde{Q}_L H d_R + \text{h.c.} \\
\mathcal{O}_\ell &= y_\ell |H|^2 \tilde{L}_L H \ell_R + \text{h.c.}
\end{align*}

\begin{align*}
\mathcal{O}_H &= (\partial^\mu |H|^2)^2 \\
\mathcal{O}_6 &= (H^\dagger H)^3
\end{align*}

\begin{align*}
\mathcal{O}_{HW} &= i (D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu} \\
\hat{O}_{HW} &= i (D^\mu H)^\dagger \sigma^a (D^\nu H) \tilde{W}^a_{\mu\nu} \\
\mathcal{O}_{HB} &= i (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
\hat{O}_{HB} &= i (D^\mu H)^\dagger (D^\nu H) \tilde{B}_{\mu\nu}
\end{align*}

\begin{align*}
\mathcal{O}_W &= i \left( H^\dagger \sigma^a \tilde{D}^\mu H \right) D^\nu W^a_{\mu\nu} \\
\mathcal{O}_B &= i \left( H^\dagger \tilde{D}^\mu H \right) \partial^\nu B_{\mu\nu}
\end{align*}
EFT parametrization: derivation

\[ \mu_i(c_j) = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k \]

- Using **EFT20bs tool**: not specific to Higgs
  1. Generate events per Higgs prod. mode (LO): **Madgraph** w/ **Pythia** showering
  2. Import HEL (UFO): reweight events for different points in HEL param space
     \( \Rightarrow \) SM: all \( c_j = 0 \)
     \( \Rightarrow \) vary \( c_j \) individually: \( (c_j = w,0,...,0), (0,w,0,...,0), ... \)
     \( \Rightarrow \) pairwise to calc. \( B_{jk} \) cross terms \( (j \neq k): (w,w,0,...,0), (w,0,w,0,...,0), ... \)
  3. Propagate events through **Rivet tool**: STXS classification (0, 1 and 1.1)
  4. Extract dependence of STXS bin, \( i \), on \( c_j \) (or \( c_j c_k \)): \( A_j \) & \( B_{jk} \)
     \( \Rightarrow \) comparing reweighted cross section to SM

WH Leptonic

\[ p_T^V [0, 150] = 1 + 33 c_{WW} + 12 c_{HW} + 320 c_{WW}^2 + ... \]

- Complete HEL parametrization of STXS stage 0, 1 and 1.1 bins provided
EFT interpretation: correlations

- Correlations matrices indicate how parameters influence each other.