Combined measurements of the Higgs boson production and decay rates using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS experiment

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Introduction

- Higgs boson has a unique role in the SM. Need to understand how Higgs boson couples with other particles through measuring production and decay rates.
- This talk: latest combined Higgs coupling measurement results using $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ channels based on 36.1 fb$^{-1}$ of 13 TeV data.
Significant boost in production cross sections from increased center-of-mass energy

<table>
<thead>
<tr>
<th>XS in pb</th>
<th>13 TeV</th>
<th>8 TeV</th>
<th>(\sigma_{13 \text{ TeV}}/\sigma_{8 \text{ TeV}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>48.52</td>
<td>21.39</td>
<td>2.3</td>
</tr>
<tr>
<td>VBF</td>
<td>3.78</td>
<td>1.60</td>
<td>2.4</td>
</tr>
<tr>
<td>WH</td>
<td>1.37</td>
<td>0.70</td>
<td>2.0</td>
</tr>
<tr>
<td>ZH</td>
<td>0.88</td>
<td>0.42</td>
<td>2.1</td>
</tr>
<tr>
<td>bbH</td>
<td>0.49</td>
<td>0.20</td>
<td>2.4</td>
</tr>
<tr>
<td>ttH</td>
<td>0.51</td>
<td>0.13</td>
<td>3.8</td>
</tr>
<tr>
<td>tH</td>
<td>0.092</td>
<td>0.023</td>
<td>3.9</td>
</tr>
</tbody>
</table>
SM Higgs boson decays

- Both diphoton and four-lepton channels have small BR
  - Nonetheless, they are very important for Higgs property measurements due to excellent sensitivity and mass resolution
## Dataset used for analysis

<table>
<thead>
<tr>
<th>√s</th>
<th>Integrated luminosity (fb⁻¹)</th>
<th>Number of H produced</th>
<th>Decayed to diphoton</th>
<th>Decayed to four-lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>4.5</td>
<td>~90,000</td>
<td>~200</td>
<td>~10</td>
</tr>
<tr>
<td>8 TeV</td>
<td>20.3</td>
<td>~500,000</td>
<td>~1,100</td>
<td>~60</td>
</tr>
<tr>
<td>13 TeV</td>
<td>36.1</td>
<td>~2,000,000</td>
<td>~4,600</td>
<td>~250</td>
</tr>
</tbody>
</table>

Assuming SM prediction @m_H=125.09 GeV (from LHC Run 1 Higgs mass measurement)

- Statistics from 13 TeV data has increased by ~4 compared with Run 1 (7 TeV / 8 TeV)
- Signal selection efficiency: ~40% in diphoton channel, ~20% in four-lepton channel
Total cross section measurement

- Cross section extracted from inclusive spectra: agnostic about production modes
- Extrapolate to full phase-space
- Good compatibility with SM (p-value = 84%)
- Compatibility between two channels: 1σ

<table>
<thead>
<tr>
<th>XS in pb</th>
<th>7 TeV</th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>$35^{+13}_{-12}$</td>
<td>$30.5^{+7.5}_{-7.4}$</td>
<td>$47.9^{+9.1}_{-8.6}$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^{*} \rightarrow 4l$</td>
<td>$33^{+21}_{-16}$</td>
<td>$37^{+9}_{-8}$</td>
<td>$68.0^{+11.4}_{-10.4}$</td>
</tr>
<tr>
<td>Combination</td>
<td>$34 \pm 10$(stat.)$^{+4}_{-2}$(syst.)</td>
<td>$33.3^{+5.5}<em>{-5.3}$(stat.)$^{+1.7}</em>{-1.3}$(syst.)</td>
<td>$57.0^{+6.0}<em>{-5.9}$(stat.)$^{+4.0}</em>{-3.3}$(syst.)</td>
</tr>
<tr>
<td>SM prediction</td>
<td>$19.2 \pm 0.9$</td>
<td>$24.5 \pm 1.1$</td>
<td>$55.6^{+2.4}_{-3.4}$</td>
</tr>
</tbody>
</table>
• Introduce categories to distinguish different production modes and a variety of kinematic regions

Results presented from this point on are all based on categorized analyses!
**Signal strength measurement**

\[-2\ln(\Lambda)\]

- **ATLAS Preliminary**
  - $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
  - $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$
  - $m_H = 125.09$ GeV

\[\mu = 1.09 \pm 0.12\]

\[= 1.09 \pm 0.09\text{(stat.)}^{+0.06}_{-0.05}\text{(exp.)}^{+0.06}_{-0.05}\text{(th.)}\]

- Very good compatibility with SM (p-value=45%)
- Stat. uncertainty dominates. Experimental and theory uncertainty are comparable

**Source**

<table>
<thead>
<tr>
<th>Source</th>
<th>Up</th>
<th>Down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{ggF}^{\text{SM}}$ (perturbative)</td>
<td>$-0.045$</td>
<td>$+0.044$</td>
</tr>
<tr>
<td>PDFs</td>
<td>$\pm 0.018$</td>
<td></td>
</tr>
<tr>
<td>Branching fractions</td>
<td>$\pm 0.014$</td>
<td></td>
</tr>
<tr>
<td>$\alpha_S$</td>
<td>$-0.011$</td>
<td>$+0.012$</td>
</tr>
<tr>
<td>Experimental</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>$-0.037$</td>
<td>$+0.038$</td>
</tr>
<tr>
<td>Electron and photon resolution</td>
<td>$+0.021$</td>
<td>$-0.019$</td>
</tr>
<tr>
<td>Pileup</td>
<td>$+0.014$</td>
<td>$-0.015$</td>
</tr>
</tbody>
</table>

**Signal strength**

$sig.\text{obs.}/n_{\text{sig.}\text{exp.}}$
Measurement of production mode cross sections

- Cross sections measured for ggF(±bbH), VBF, VH and ttH(+tH), assuming SM BRs
  - Measurement performed for \(|y_H| < 2.5\): no sensitivity beyond
- All measurements dominated by statistical uncertainties
- 4D compatibility with SM: 5%

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>y_H</td>
<td>&lt; 2.5)</td>
<td>Total</td>
</tr>
<tr>
<td>ggF</td>
<td>43.9</td>
<td>+6.2</td>
<td>-5.5</td>
</tr>
<tr>
<td>VBF</td>
<td>7.9</td>
<td>+2.1</td>
<td>+1.7</td>
</tr>
<tr>
<td>VH</td>
<td>0.3</td>
<td>+1.6</td>
<td>+1.5</td>
</tr>
<tr>
<td>ttH</td>
<td>0.27</td>
<td>+0.37</td>
<td>+0.36</td>
</tr>
</tbody>
</table>

ATLAS-CONF-2017-047
ggF vs. VBF contour & correlation matrix

• Correlation between production modes comes from crosstalk
  • E.g. ggF contamination in VBF categories
**Ratio of production cross-sections and BRs**

- No assumptions on BR: $B_{\gamma\gamma}/B_{4\ell}$ floating in the fit
- Ratios allow cancellation of common systematic uncertainties
- 5D compatibility with SM 3%

### ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$

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

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### Measurement

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Result</th>
<th>Uncertainty</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{ggF} \cdot B_{4\ell}$ [fb]</td>
<td>6.6</td>
<td>$+1.2$ $-1.0$ $(+1.1$ $-1.0$ $\pm 0.4$ $\pm 0.2)$</td>
<td>$5.6^{+0.3}_{-0.4}$</td>
</tr>
<tr>
<td>$B_{\gamma\gamma}/B_{4\ell}$</td>
<td>12.5</td>
<td>$+2.8$ $-2.3$ $(+2.6$ $-2.2$ $+0.9$ $-0.7$ $\pm 0.2)$</td>
<td>$18.1 \pm 0.2$</td>
</tr>
<tr>
<td>$\sigma_{VBF}/\sigma_{ggF}$ $[10^{-2}]$</td>
<td>21.5</td>
<td>$+8.5$ $-6.3$ $(+7.3$ $-5.6$ $+2.8$ $-1.7$ $+3.6$ $-2.2)$</td>
<td>$7.9^{+0.4}_{-0.6}$</td>
</tr>
<tr>
<td>$\sigma_{VH}/\sigma_{ggF}$ $[10^{-2}]$</td>
<td>0.2</td>
<td>$+4.5$ $-3.4$ $(+4.2$ $-3.2$ $+1.2$ $-0.9$ $+0.9$ $-0.4)$</td>
<td>$4.5^{+0.2}_{-0.3}$</td>
</tr>
<tr>
<td>$\sigma_{ttH}/\sigma_{ggF}$ $[10^{-2}]$</td>
<td>0.7</td>
<td>$+1.0$ $-0.9$ $(+1.0$ $-0.9$ $+0.2$ $-0.1$ $\pm 0.1)$</td>
<td>$1.3 \pm 0.1$</td>
</tr>
</tbody>
</table>
Simplified Template Cross Section (STXS) framework

- In Run 1 LHC Higgs boson coupling measurements, the production processes are accessed inclusively assuming SM predicted kinematic distributions
- In Run 2, we have started exploring different kinematic regions using the **STXS framework**
  - Regroup production processes according to final states
  - Divide cross sections into kinematic regions ("bins") and thus **reduces dependence on theory predictions**
    - Division granularity will increase in “stages” as data statistics grow
      - **Stage 0**: essentially Run-1 style inclusive measurements
      - **Stage 1**: start introducing splitting in kinematic regions
    - Rely on SM predictions in each production bin ("template")
Diagram slightly modified from *Les Houches 2015 proceeding*

- Develop merging scheme which
  - Keeps interesting BSM bins
  - <100% expected uncertainty in the rest of the bins
  - Minimizes correlations between bins

**gg → H:** ggF+ggZ(qq)H+bbH

- 0-jet
- 1-jet
- ≥ 2-jet

**VHlep:** W(lv)H+qq/ggZ(ll/vv)H

- q̅q → VH
- W → ℓν
- Z → ℓℓ + ν̅ν

**qq → Hqq:** VBF+W(qq)H+qqZ(qq)H

- VBF cuts
- ≥ 2-jet
- Rest

**ttH:** ttH+tH

- ≥ 2-jet VBF cuts
- ≥ 2-jet VH cuts

**gg → ZH**

- ≥ 0-jet
- ≥ 1-jet
STXS results

- Besides cross section of production bins, $B_{γγ}/B_{4l}$ is also a free parameter measured from data
  - Therefore, the reported cross sections are actually corresponding to $σ_1 × B_{4l}$.
    $B_{4l}^{SM}$ is divided out in above plot
- 10D compatibility with SM: 9%
- $σ(gg→H+≥2j, p_T^H>200$ GeV – $qq2Hqq, p_T^j>200$ GeV) is floating in the fit.
  The best fit result is $1.7^{+1.7}_{-1.5}$ pb
$D_{γγ}/B_{4l}$

$gg\rightarrow H$ (0-jet)

$gg\rightarrow H$ (1-jet, $p^H_T < 60$ GeV)

$gg\rightarrow H$ (1-jet, $60 \leq p^H_T < 120$ GeV)

$gg\rightarrow H$ (1-jet, $120 \leq p^H_T < 200$ GeV)

$gg\rightarrow H$ (2-jet, $p^H_T < 200$ GeV)

or VBF-like

$gg\rightarrow H$ ($\geq$ 1-jet, $p^H_T \geq 200$ GeV)

$+ qq\rightarrow Hqq \ (p^q_T \geq 200$ GeV)

$qq\rightarrow Hqq \ (p^q_T < 200$ GeV)

$gg/qq\rightarrow Hll/Hl

$gg/qq\rightarrow ttH

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, $36.1$ fb$^{-1}$

$H\rightarrow γγ$ and $H\rightarrow ZZ^*\rightarrow 4l$

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

Correlation matrix for STXS results

ATLASCONF-2017-047
Kappa framework for deriving coupling info

Leading-order tree-level motivated framework: kappa framework

\[
(\sigma \times \text{BR})(gg \rightarrow H \rightarrow \gamma\gamma) \sim \frac{\kappa_g^2(\kappa_t, \kappa_b, \ldots)\kappa_\gamma^2(\kappa_W, \kappa_t, \ldots)}{\kappa_H^2(\kappa_b, \kappa_W, \kappa_Z, \kappa_\tau, \kappa_t, \ldots)}
\]

- Can handle other production and decay vertices in a similar way (much simpler in most cases)
**Kappa model: \( \kappa_V \) vs. \( \kappa_f \)**

- Assume uniform coupling modifiers for all weak vector bosons (\( \kappa_V \)) and all fermions (\( \kappa_f \)), including those in the loops. In addition, no BSM contribution to loop vertices or total width.
- 2D compatibility with SM: 52%

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**Diagram:**

- SM prediction
- Best fit
- Combined 68% CL
- Combined 95% CL
- \( H \rightarrow \gamma \gamma \) 68% CL
- \( H \rightarrow ZZ^* \rightarrow 4l \) 68% CL

**Legend:**

- **ATLAS Preliminary**
  - \( \sqrt{s} = 13 \text{ TeV, } 36.1 \text{ fb}^{-1} \)
  - \( H \rightarrow \gamma \gamma \) and \( H \rightarrow ZZ^* \rightarrow 4l \)
  - \( m_h = 125.09 \text{ GeV} \)

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**Graph:**

- \( \kappa_V = 1.03 \pm 0.06 \)
- \( \kappa_f = 0.89^{+0.20}_{-0.15} \)

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**Observed**

- ATLAS-CONF-2017-047
Kappa model: $\kappa_g$ vs. $\kappa_\gamma$

- Assign coupling modifier to $gg \rightarrow H/H \rightarrow gg$ ($\kappa_g$) and $H \rightarrow \gamma\gamma$ ($\kappa_\gamma$). All the other couplings fixed to SM. In addition, no BSM decays contributing to total width.

- 2D compatibility with SM: 68%

**ATLAS** Preliminary

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

\( H \rightarrow \gamma\gamma \) and \( H \rightarrow ZZ^* \rightarrow 4l \)

\( m_H = 125.09 \text{ GeV} \)

\( \kappa_\gamma = 0.93^{+0.09}_{-0.08} \)

\( \kappa_g = 1.08^{+0.11}_{-0.10} \)
Kappa model: generic model

- No assumptions on loop vertices or total width: define $K_{gV} = K_g K_V / K_H$, $\lambda_{Vg} = K_V / K_g$, $\lambda_{fV} = K_f / K_V$, $\lambda_{fg} = K_f / K_g$

- Allow $\lambda_{fg}$ to be negative. Other parameters assume to be positive without losing generality.

- 4D compatibility with SM: 15%
Conclusion

• Measurement of Higgs boson production and decay performed based on 36.1 fb$^{-1}$ of 13 TeV data, combining info from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$

• Total XS @13 TeV: $57.0^{+6.0}_{-5.9}\text{(stat.)}^{+4.0}_{-3.3}\text{(syst.)} \text{ pb}$

• Signal strength: $1.09 \pm 0.09\text{(stat.)}^{+0.06}_{-0.05}\text{(exp.)}^{+0.06}_{-0.05}\text{(th.)}$

• Production mode cross sections, ratios of production mode cross sections and BRs, and merged Stage 1 STXS are measured. Data also interpreted using kappa framework

• Measurements are still dominated by statistical uncertainty!

• In all cases, compatibility between data and SM is at 2$\sigma$ level or better

• More channels and more interpretations to be added later this year. Stay tuned!
References

- LHC Higgs XS WG twiki: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG
- ATLAS-CONF-2017-045: Measurements of Higgs boson properties in the diphoton decay channel with 36.1 fb\(^{-1}\) pp collision data at the center-of-mass energy of 13 TeV with the ATLAS detector
- ATLAS-CONF-2017-032: Measurement of inclusive and differential fiducial cross sections in the H\(\rightarrow\) ZZ\(\rightarrow\) 4\(\ell\) decay channel at 13 TeV with the ATLAS detector
- ATLAS-CONF-2017-043: Measurement of the Higgs boson coupling properties in the H\(\rightarrow\) ZZ\(\rightarrow\) 4\(\ell\) decay channel at \(\sqrt{s} = 13\) TeV with the ATLAS detector
- ATLAS-CONF-2017-047: Combined measurements of Higgs boson production and decay in the H\(\rightarrow\)ZZ\(*\rightarrow\)4\(\ell\) and H\(\rightarrow\)γγ channels using \(\sqrt{s} = 13\) TeV proton-proton collision data collected with the ATLAS experiment
Backup
Large Hadron Collider at CERN

- Four collision points with detectors: ATLAS, CMS, ALICE, LHCb
- 27 km
- p-p collision up to $\sqrt{s}=14$ TeV
Understanding uncertainty components

- “Theory” uncertainty only include those on signal
  - When measuring cross sections, only theory uncertainties on signal acceptance are considered. The uncertainties on the inclusive xs are indicated on SM predictions.
  - When measuring signal strength and coupling modifiers, full theory uncertainties are considered.
  - BR uncertainty will be considered when the SM BR is assumed (otherwise not).

- All the other systematics, including theory uncertainties on background (in four-lepton channel), are classified as “Experimental”.

- “Systematic” = “Experimental” $\oplus$ ”Theory”
### Summary of analysis categorizations

<table>
<thead>
<tr>
<th>( H \rightarrow \gamma\gamma )</th>
<th>( H \rightarrow ZZ^* \rightarrow 4\ell )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ttH+tH ) leptonic (two ( tHX ) and one ( ttH ) categories)</td>
<td>( ttH )</td>
</tr>
<tr>
<td>( ttH+tH ) hadronic (two ( tHX ) and four BDT ( ttH ) categories)</td>
<td>( VH ) leptonic</td>
</tr>
<tr>
<td>( VH ) dilepton</td>
<td>2-jet ( VH )</td>
</tr>
<tr>
<td>( VH ) one-lepton, ( p_T^{\ell+\text{MET}} \geq 150 \text{ GeV} )</td>
<td>2-jet ( VH ), ( p_T^{\ell_1} \geq 200 \text{ GeV} )</td>
</tr>
<tr>
<td>( VH ) one-lepton, ( p_T^{\ell+\text{MET}} &lt; 150 \text{ GeV} )</td>
<td>2-jet ( VH ), ( p_T^{\ell_1} &lt; 200 \text{ GeV} )</td>
</tr>
<tr>
<td>( VH ) ( E_T^{\text{miss}}, E_T^{\text{miss}} \geq 150 \text{ GeV} )</td>
<td>1-jet ggF, ( p_T^{A_\ell} \geq 120 \text{ GeV} )</td>
</tr>
<tr>
<td>( VH ) ( E_T^{\text{miss}}, E_T^{\text{miss}} &lt; 150 \text{ GeV} )</td>
<td>1-jet ggF, 60 GeV &lt; ( p_T^{A_\ell} &lt; 120 \text{ GeV} )</td>
</tr>
<tr>
<td>( VH ) hadronic (BDT tight and loose categories)</td>
<td>1-jet ggF, ( p_T^{A_\ell} &lt; 60 \text{ GeV} )</td>
</tr>
<tr>
<td>VBF, ( p_T^{\gamma\gamma jj} \geq 25 \text{ GeV} ) (BDT tight and loose categories)</td>
<td>0-jet ggF</td>
</tr>
<tr>
<td>VBF, ( p_T^{\gamma\gamma jj} &lt; 25 \text{ GeV} ) (BDT tight and loose categories)</td>
<td>ggF 2-jet, ( p_T^{\gamma\gamma} \geq 200 \text{ GeV} )</td>
</tr>
<tr>
<td>ggF 2-jet, ( p_T^{\gamma\gamma} \geq 200 \text{ GeV} )</td>
<td>ggF 2-jet, 120 GeV &lt; ( p_T^{\gamma\gamma} &lt; 200 \text{ GeV} )</td>
</tr>
<tr>
<td>ggF 2-jet, 60 GeV ( p_T^{\gamma\gamma} &lt; 120 \text{ GeV} )</td>
<td>ggF 2-jet, 60 GeV &lt; ( p_T^{\gamma\gamma} &lt; 120 \text{ GeV} )</td>
</tr>
<tr>
<td>ggF 2-jet, ( p_T^{\gamma\gamma} &lt; 60 \text{ GeV} )</td>
<td>ggF 1-jet, ( p_T^{\gamma\gamma} \geq 200 \text{ GeV} )</td>
</tr>
<tr>
<td>ggF 1-jet, ( p_T^{\gamma\gamma} \geq 200 \text{ GeV} )</td>
<td>ggF 1-jet, 120 GeV &lt; ( p_T^{\gamma\gamma} &lt; 200 \text{ GeV} )</td>
</tr>
<tr>
<td>ggF 1-jet, 60 GeV &lt; ( p_T^{\gamma\gamma} &lt; 120 \text{ GeV} )</td>
<td>ggF 1-jet, 60 GeV &lt; ( p_T^{\gamma\gamma} &lt; 120 \text{ GeV} )</td>
</tr>
<tr>
<td>ggF 1-jet, ( p_T^{\gamma\gamma} &lt; 60 \text{ GeV} )</td>
<td>ggF 0-jet (central and forward categories)</td>
</tr>
</tbody>
</table>
Signal composition in $H \rightarrow \gamma \gamma$ categories expressed in STXS bins

**ATLAS Preliminary** \( H \rightarrow \gamma \gamma, m_H = 125.09 \text{ GeV} \)

**STXS Regions**
- ggH (0-jet)
- ggH (1-jet, \( p_T < 150 \text{ GeV} \))
- ggH (1-jet, \( 150 \leq p_T < 200 \text{ GeV} \))
- ggH (1-jet, \( p_T \geq 200 \text{ GeV} \))
- ggH (2-jet, \( p_T \geq 150 \text{ GeV} \))
- ggH (2-jet, \( 60 \leq p_T < 120 \text{ GeV} \))
- ggH (2-jet, \( p_T < 60 \text{ GeV} \))
- ggH (1-jet, \( p_T \geq 200 \text{ GeV} \))
- ggH (1-jet, \( 120 \leq p_T < 200 \text{ GeV} \))
- ggH (1-jet, \( 60 \leq p_T < 120 \text{ GeV} \))
- ggH (1-jet, \( p_T < 60 \text{ GeV} \))
- ggH (0-jet)

**Region Purity / Category**
- 0
- 0.1
- 0.2
- 0.3
- 0.4
- 0.5
- 0.6
- 0.7
- 0.8
- 0.9

**ATLAS-CONF-2017-045**
Likelihood scans for production mode cross sections

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

- ggF
  - Observed
  - SM expected

- VH
  - Observed
  - SM expected

- VBF
  - Observed
  - SM expected

- ttH
  - Observed
  - SM expected

\( m_H = 125.09 \text{ GeV}, |y_H| < 2.5 \)

Preliminary ATLAS -1
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

-4l \(\rightarrow\) ZZ\(^*\) \(\rightarrow\) H and \(\gamma\gamma \rightarrow\) H

Observed

SM expected

normalized to SM

\(-2 \ln(\Lambda) = \frac{1}{2} \ln(\frac{\text{Observed}}{\text{SM expected}})\)

\(\sigma_{ggF}^{\text{normalized to SM}}\)

\(\sigma_{VBF}^{\text{normalized to SM}}\)

\(\sigma_{VH}^{\text{normalized to SM}}\)

\(\sigma_{ttH}^{\text{normalized to SM}}\)
Likelihood scans for ratios of production x-sections and BRs

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 36.1 fb$^1$

$H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$

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

$\sigma_{ggF} \cdot B_{4l}$

Normalized to SM

**B_{\gamma\gamma}/B_{4l}**

ATLAS-CONF-2017-047

$H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$

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

Normalized to SM

**$\sigma_{VBF}/\sigma_{ggF}$**

$\sigma_{VBF}/\sigma_{ggF}$ normalized to SM

**$\sigma_{VH}/\sigma_{ggF}$**

$\sigma_{VH}/\sigma_{ggF}$ normalized to SM

**$\sigma_{ttH}/\sigma_{ggF}$**

$\sigma_{ttH}/\sigma_{ggF}$ normalized to SM

Hongtao Yang (LBNL)
**Correlation matrices for the ratio model**

- **Strong correlation between parameters**
  - $\sigma_{ggF}$ or $B_{4l}$ shared among parameters
  - $\sigma_{ggF} \cdot B_{4l}$ and $B_{\gamma\gamma}/B_{4l}$ anti-correlate in $H \rightarrow \gamma\gamma$ channel
Likelihood scans for kappa generic model

-2ln(Λ)

**λ<sub>Vg</sub> = K<sub>V</sub> / K<sub>g</sub>**

**λ<sub>γV</sub> = K<sub>γ</sub> / K<sub>V</sub>**

**λ<sub>fg</sub> = K<sub>f</sub> / K<sub>g</sub>**

**K<sub>gV</sub> = K<sub>g</sub> K<sub>V</sub> / K<sub>H</sub>**

ATLAS Preliminary

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

**H → γγ** and **H → ZZ* → 4l**

**m<sub>h</sub> = 125.09 GeV**
Correlation matrices and numerical results for kappa generic model

**ATLAS Preliminary**
\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]
\[ H \rightarrow \gamma\gamma \text{ and } H \rightarrow ZZ^{*} \rightarrow 4l \]
\[ m_H = 125.09 \text{ GeV} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Result</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \kappa_{gV} )</td>
<td>1.07 ± 0.09</td>
<td>( \pm 0.08 ) ± 0.03 + 0.04 − 0.03</td>
</tr>
<tr>
<td>( \lambda_{Vg} )</td>
<td>1.41 +0.26 −0.23</td>
<td>+0.23 −0.20 +0.08 −0.06 +0.09 −0.08</td>
</tr>
<tr>
<td>( \lambda_{\gamma V} )</td>
<td>0.84 +0.09 −0.08</td>
<td>±0.08 +0.03 ±0.01</td>
</tr>
<tr>
<td>( \lambda_{fg} )</td>
<td>0.74 +0.41 −0.63</td>
<td>+0.40 +0.06 +0.07 −0.14 −0.05</td>
</tr>
</tbody>
</table>

**ATLAS-CONF-2017-047**
SM correlation matrices for production mode x-section and STXS measurements

- Good agreement between data and SM prediction

**ATLAS-CONF-2017-047**
Normalized STXS summary plot

\[ gg \rightarrow H (0\text{-}jet) \]

\[ gg \rightarrow H (1\text{-}jet, \ p_T^H < 60 \text{ GeV}) \]

\[ gg \rightarrow H \]
\[ (1\text{-}jet, \ 60 \leq p_T^H < 120 \text{ GeV}) \]

\[ gg \rightarrow H \]
\[ (1\text{-}jet, \ 120 \leq p_T^H < 200 \text{ GeV}) \]

\[ gg \rightarrow H (\geq 2\text{-}jet, \ p_T^H < 200 \text{ GeV} \]
\[ \text{or VBF-like}) \]

\[ gg \rightarrow H (\geq 1\text{-}jet, \ p_T^H \geq 200 \text{ GeV}) \]
\[ + \ qq \rightarrow Hqq \ (p_T^j \geq 200 \text{ GeV}) \]

\[ qq \rightarrow Hqq \ (p_T^j < 200 \text{ GeV}) \]

\[ gg/qq \rightarrow Hll/Hl\nu \]

\[ gg/qq \rightarrow ttH \]

**ATLAS** Preliminary
\[ \sqrt{s} = 13 \text{ TeV, 36.1 fb}^{-1} \]
\[ H \rightarrow \gamma \gamma \text{ and } H \rightarrow ZZ^* \rightarrow 4l \]
\[ m_H = 125.09 \text{ GeV, } |y_H| < 2.5 \]

\[ B_{\gamma \gamma} / B_{4l} \]

Ratio normalized to SM

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Stat. uncertainty</th>
<th>Syst. uncertainty</th>
<th>SM prediction</th>
</tr>
</thead>
</table>

ATLAS-CONF-2017-047
### Stage 1 STXS production bin definitions

<table>
<thead>
<tr>
<th>STXS process</th>
<th>Production modes</th>
<th>Stage 1 STXS measurement region</th>
</tr>
</thead>
<tbody>
<tr>
<td>gg → H</td>
<td>ggF+ ggZ(qq)H+ bbH</td>
<td>0-jet</td>
</tr>
<tr>
<td></td>
<td>1-jet, pTH&lt;60 GeV</td>
<td>≥2-jet, pTH&lt;60 GeV</td>
</tr>
<tr>
<td></td>
<td>1-jet 60 GeV&lt;pTH&lt;120 GeV</td>
<td>≥2-jet 60 GeV&lt;pTH&lt;120 GeV</td>
</tr>
<tr>
<td></td>
<td>1-jet 120 GeV&lt;pTH&lt;200 GeV</td>
<td>≥2-jet 120 GeV&lt;pTH&lt;200 GeV</td>
</tr>
<tr>
<td></td>
<td>VBF-like, pTHjj&lt;25 GeV</td>
<td>VBF-like, pTHjj&gt;25 GeV</td>
</tr>
<tr>
<td></td>
<td>1-jet pTH&gt;200 GeV</td>
<td>≥2-jet pTH&gt;200 GeV</td>
</tr>
<tr>
<td>qq → Hqq</td>
<td>VBF+ W(qq)H+ qqZ(qq)H</td>
<td>pTj1&gt;200 GeV</td>
</tr>
<tr>
<td></td>
<td>VBF-like, pTHjj&lt;25 GeV</td>
<td>VBF-like, pTHjj&gt;25 Gev</td>
</tr>
<tr>
<td></td>
<td>pTj1&lt;200 GeV, VH-like</td>
<td>pTj1&lt;200 GeV, Rest</td>
</tr>
<tr>
<td>VHlep</td>
<td>W(lν)H+ qq/ggZ(lν/vv)H</td>
<td>pTV&lt;150 GeV</td>
</tr>
<tr>
<td></td>
<td>150 GeV&lt;pTV&lt;250 GeV, ≥1-jet</td>
<td>150 GeV&lt;pTV&lt;250 GeV, 0-jet</td>
</tr>
<tr>
<td></td>
<td>pTV&gt;250 GeV</td>
<td></td>
</tr>
<tr>
<td>ttH</td>
<td>ttH+tH</td>
<td>—</td>
</tr>
</tbody>
</table>

- Stage 1 STXS framework has too fine granularity given current data statistics, and introduces large anti-correlation between bins.
- Red background means merging the bins under same process into 1 bin. Blue background means reporting the sum and difference between two processes.
## Summary of kappa parameterizations

<table>
<thead>
<tr>
<th>Production</th>
<th>Loops</th>
<th>Interference</th>
<th>Effective scaling factor</th>
<th>Resolved scaling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma(ggF))</td>
<td>(\checkmark)</td>
<td>(t-b)</td>
<td>(\kappa_s^2)</td>
<td>(1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b)</td>
</tr>
<tr>
<td>(\sigma(VBF))</td>
<td></td>
<td></td>
<td></td>
<td>(0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2)</td>
</tr>
<tr>
<td>(\sigma(WH))</td>
<td></td>
<td></td>
<td>(\kappa_W^2)</td>
<td></td>
</tr>
<tr>
<td>(\sigma(qq/qg \to ZH))</td>
<td></td>
<td></td>
<td>(\kappa_Z^2)</td>
<td></td>
</tr>
<tr>
<td>(\sigma(gg \to ZH))</td>
<td>(\checkmark)</td>
<td>(t-Z)</td>
<td>(2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t)</td>
<td></td>
</tr>
<tr>
<td>(\sigma(ttH))</td>
<td></td>
<td></td>
<td>(\kappa_t^2)</td>
<td></td>
</tr>
<tr>
<td>(\sigma(gb \to tHW))</td>
<td></td>
<td>(t-W)</td>
<td></td>
<td>(1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W)</td>
</tr>
<tr>
<td>(\sigma(qq/qb \to tHq))</td>
<td></td>
<td>(t-W)</td>
<td>(3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W)</td>
<td></td>
</tr>
<tr>
<td>(\sigma(bbH))</td>
<td></td>
<td></td>
<td>(\kappa_b^2)</td>
<td></td>
</tr>
</tbody>
</table>

### Partial decay width

| \(\Gamma^{ZZ}\)        |        |              | \(\kappa_Z^2\)          |                         |
| \(\Gamma^{WW}\)        |        |              | \(\kappa_W^2\)          |                         |
| \(\Gamma^{\gamma\gamma}\) | \(\checkmark\) | \(t-W\)     | \(\kappa_{\gamma}^2\)  | \(1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t\) |
| \(\Gamma^{\tau\tau}\)  |        |              | \(\kappa_{\tau}^2\)    |                         |
| \(\Gamma^{bb}\)        |        |              | \(\kappa_b^2\)          |                         |
| \(\Gamma^{\mu\mu}\)    |        |              | \(\kappa_{\mu}^2\)     |                         |

### Total width (\(B_{BSM} = 0\))

| \(\Gamma_H\)            | \(\checkmark\) |              | \(\kappa_{H}^2\)       | \(0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_s^2 + 0.06 \cdot \kappa_t^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_{\gamma}^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_{\mu}^2\) |