Higgs decays to bosons
ATLAS results

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On behalf of the ATLAS Collaboration
Introduction

- Bosonic channels analyses in ATLAS
  - $H \rightarrow ZZ^* \rightarrow l^+ l^- l^+ l^-$
  - $H \rightarrow \gamma\gamma$

- Mass measurement
- Fiducial and differential cross sections
- Couplings

- Results shown here are based on 36.1 fb$^{-1}$ of $\sqrt{s} = 13$ TeV p-p collision data collected by the ATLAS experiment in 2015 and 2016
- Focusing on the channels with new most recent updates
- All results from the recent ATLAS CONF-notes:
  - ATLAS-CONF-2017-046
  - ATLAS-CONF-2017-045
  - ATLAS-CONF-2017-043
  - ATLAS-CONF-2017-032
Higgs to four leptons event selection

- Four opposite sign, same flavour leptons ($\mu, e$), with $p_T > 20, 15, 10, 5(\mu)/7(e)$ GeV, isolated and from the primary vertex
- Cut on the two di-lepton mass pairs
- BDT discriminant to reduce ZZ background, based on $p_T^{4l}$, $\eta^{4l}$ and $D_{ZZ} = \ln(|M_{HZZ^*}|^2/|M_{ZZ^*}|^2)$
- Z-mass constraint on the leading lepton pair
- Jets: anti-$k_t$ algorithm with $R=0.4$, $p_T > 30$ GeV
Higgs to two photons event selection

- Two photons with $E_T/m_{\gamma\gamma} > 0.35, 0.25$ in $|\eta| < 2.37$, $(1.37 \leq |\eta| \leq 1.52$ excluded)
- Neural network combining photons directions and information from the Inner Detector for primary vertex identification
  - Rate of correct diphoton vertex selection in MC is 79% for gg-fusion events, 84-97% for other production mechanisms
- Keep events with $105 \text{ GeV} \leq m_{\gamma\gamma} \leq 160 \text{ GeV}$
- Jets: anti-$k_t$ algorithm with $R=0.4$, $p_T > 30$ GeV
- Selected events are categorized:
  - Use 31 categories sensitive to the production mode
  - Same categorization scheme for the mass measurement
MASS MEASUREMENT
Muon and e/\gamma calibrations

- Muon momentum scale and resolution calibration on \( J/\psi \rightarrow \mu^+\mu^- \) and \( Z \rightarrow \mu^+\mu^- \)
  - Scale systematics between \( \sim 0.05\% \) and \( \sim 0.2\% \)
  - Correction for sagitta measurement bias due to ID misalignments (affects resolution)

- Electron scale measured on \( Z \rightarrow e^+e^- \) and cross-checked on \( J/\psi \rightarrow e^+e^- \). Photon scale cross-checked on \( Z \rightarrow l^+l^-\gamma \)
  - \( \gamma \) scale uncertainty at \( \sim 60 \text{ GeV} \) is 0.4\% (barrel) and 0.8\% (endcap)
  - \( e \) uncertainty at 40 (10) GeV is 0.02\% (0.5\%) in the barrel and 0.1\% (0.8\%) in the endcap
Mass fit in the 4l channel

- Four exclusive categories in BDT bins (\(\sim 6\%\) resolution improvement)
- Z mass constraint applied to the leading lepton pair (\(\sim 15\%\) resolution improvement)
- Mass model as convolution of a BW with SM width, with a resolution function calculated per-event based on single-lepton resolutions
- Validation on \(Z \rightarrow 4l\) events

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

\(H \rightarrow ZZ^* \rightarrow 4l\) events

\(m_{4l} [\text{GeV}]\)

\(m_H [\text{GeV}]\)
Mass fit in the $\gamma\gamma$ channel

- Signal model is a double-sided Crystal Ball function
  - Parameters dependence on $m_H$ from samples weighted for production modes
  - Resolution ranging from 1.42 GeV to 2.14 GeV (1.87 GeV inclusive)

- Background parametrized with a continuous function for each category
  - Function chosen as the one that minimizes the fitted signal yield in a background-only sample (from CR or from MC)
  - Typically exponential for low-stat categories, power-law or exp of polynomial for the others
Mass fit results

- 4l mass fit:
  \[ m_{\gamma\gamma}^{ZZ^*} = 124.88 \pm 0.37 \text{(stat)} \pm 0.05 \text{(syst)} \text{ GeV} = 124.88 \pm 0.37 \text{ GeV} \]

- \( \gamma\gamma \) mass fit:
  \[ m_{\gamma\gamma}^{\gamma\gamma} = 125.11 \pm 0.21 \text{(stat)} \pm 0.36 \text{(syst)} \text{ GeV} = 125.11 \pm 0.42 \text{ GeV} \]

- The combined measurement will be presented by Bruno Mansoulié tomorrow

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Systematics for \( m_{4l} \)

<table>
<thead>
<tr>
<th>Source</th>
<th>Unc. [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon momentum scale</td>
<td>40</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>20</td>
</tr>
<tr>
<td>Background modelling</td>
<td>10</td>
</tr>
<tr>
<td>Simulation statistics</td>
<td>8</td>
</tr>
</tbody>
</table>

Systematics for \( m_{\gamma\gamma} \)

<table>
<thead>
<tr>
<th>Source</th>
<th>Unc. [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAr cell non-linearity</td>
<td>\pm 200</td>
</tr>
<tr>
<td>LAr layer calibration</td>
<td>\pm 190</td>
</tr>
<tr>
<td>Non-ID material</td>
<td>\pm 120</td>
</tr>
<tr>
<td>Lateral shower shape</td>
<td>\pm 110</td>
</tr>
<tr>
<td>ID material</td>
<td>\pm 110</td>
</tr>
<tr>
<td>Conversion reconstruction</td>
<td>\pm 50</td>
</tr>
<tr>
<td>( Z \rightarrow ee ) calibration</td>
<td>\pm 50</td>
</tr>
<tr>
<td>Background model</td>
<td>\pm 50</td>
</tr>
<tr>
<td>Primary vtx</td>
<td>\pm 40</td>
</tr>
<tr>
<td>Resolution</td>
<td>\pm 20</td>
</tr>
<tr>
<td>Signal model</td>
<td>\pm 20</td>
</tr>
</tbody>
</table>
CROSS SECTIONS AND COUPLINGS
Simplified template cross-sections

- Production cross section times BR is measured in mutually exclusive phase space regions (production bins), with $|y_H| < 2.5$
- Chosen to maximise the measurement precision and the sensitivity to BSM contributions

**Stage 0**

- Production bins
  - $ggF$
  - $VBF$
  - $VH$
  - $ttH$

**Reduced Stage 1**

- $ggF-0j$
- $ggF-1j-p_TH ^{<} 60 GeV$
- $ggF-1j-p_TH ^{>} 120 GeV$
- $ggF-2j$

**Reconstructed event categories**

- $0j$
- $1j p_TH ^{<} 60 GeV$
- $1j p_TH ^{>} 120 GeV$
- $m_{jj} ^{>} 120 GeV$
- $m_{jj} ^{<} 120 GeV$

†: VH-Had enriched is divided into $p_T > 150$ GeV and $p_T < 150$ GeV sub-categories for tensor structure measurement.
Categorization of reconstructed candidates

\[ H \rightarrow ZZ^* \rightarrow l^+l^-l^+l^- \] categorization

- Based on the presence of b-jets, jets and additional leptons in the event
- Further categorization based on kinematic cuts on \( p_T^{4l}, p_T^{j1}, m_{jj} \)
- End up with 9 categories each enriched in one or more production process
- Further separation using multi-variate discriminants in the categories with enough statistics, to select ggF, VBF, VH-hadronic

\[ H \rightarrow \gamma\gamma \] categorization

- 31 exclusive categories each enriched in one of the production mechanisms
- Dedicated BDT used for VBF- and ttH-enriched categories to increase the separation from ggF and background
Global signal strength:
\[ \mu = 1.28^{+0.18}_{-0.17} \text{(stat.)}^{+0.08}_{-0.06} \text{(exp.)}^{+0.08}_{-0.06} \text{(th.)} = 1.28^{+0.21}_{-0.19} \]
Cross sections by production mode: $\gamma\gamma$ channel

- Global signal strength:
  $$\mu = 0.99^{+0.12}_{-0.11} \text{(stat)}^{+0.06}_{-0.05} \text{(exp.)}^{+0.06}_{-0.05} \text{(th.)} = 0.99 \pm 0.14$$

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

- $H \rightarrow \gamma\gamma$, $m_H=125.09$ GeV

### Measurements

- $\sigma \times \text{BR Normalized to SM} \times \mu$
- Distributions for different production modes:
  - ggH
  - VBF
  - VH
  - Top

### ATLAS** Preliminary $\sqrt{s}=13$ TeV, 36.1 fb$^{-1}$

- $H \rightarrow \gamma\gamma$, $m_H=125.09$ GeV

- ggH (0 jet)
- ggH (1 jet, $p_T^\ell < 60$ GeV)
- ggH (1 jet, $60 < p_T^\ell < 120$ GeV)
- ggH (1 jet, $120 < p_T^\ell < 200$ GeV)
- ggH (2 jet)
- qq $\rightarrow$ Hqq ($p_T^\ell < 200$ GeV)
- ggH + qq $\rightarrow$ Hqq (BSM-like)
- VH (leptonic)
- VH (jets, $p_T < 200$ GeV)
- Top

- SM prediction
Tensor structure of couplings

- The tensor structure of couplings is studied in 4l within the framework of the effective Lagrangian of the Higgs characterization model [JHEP 1311 (2013) 043]
- Couplings fit based on the event yields in each of the 4l experimental categories
- Fits with $\kappa_{SM} = 1$ (SM coupling factor) fixed. Difference with respect to the SM expectation is mostly caused by the excess in the 2-jet category. Max deviation is $2.3\sigma$ for $k_{HVV}$.

Agreement with the SM hypothesis improves if $k_{SM}$ is left free in the fit
Fiducial and total cross sections

- Fiducial volume: cuts based on detector acceptance, to minimize model dependency in the extrapolation
- Corrections applied for detector effects: bin by bin unfolding as correction factors

$$\sigma_{i, \text{fid}} = \sigma_i \times A_i \times BR = \frac{N_{i, \text{fit}}}{L \times C_i}$$

- $\sigma_i \rightarrow$ total cross section
- $A_i \rightarrow$ acceptance
- $C_i \rightarrow$ correction factor

**ATLAS** Preliminary

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

$13 \text{ TeV, } 36.1 \text{ fb}^{-1}$

**Diphoton fiducial**

**VBF-enhanced**

$N_{\text{lepton}} \geq 1$

**ttH-enhanced**

$95\% \text{ C.L.}$

**High $E_T^{\text{miss}}$**

$m_H = 125.09 \text{ GeV}$

**Data**

- Syst. uncertainties
- LHCXSWG ggH @N$^3$LO + XH
- HRes 2.3, N$^3$LO+N$^2$LL + XH
- MG5 FxFx + XH
- Powheg NNLOPS + XH
Differential cross sections: $p_T$

- The differential $p_T$ distribution is sensitive to perturbative QCD calculations and presence of new additional particles in loops
- Agreement with the SM (NNLOPS): p-value 25% for 4l, 51% for $\gamma\gamma$
Differential cross sections: $N_{jets}$ and $|y_{\gamma\gamma}|$

- Sensitive to production mode composition and PDFs

**ATLAS** Preliminary

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

13 TeV, 36.1 fb$^{-1}$

Data

Syst. uncertainties

NNLOPS $k = 1.1$, +XH

$MG5$ FxFx $k = 1.47$, +XH

$XH = VBF+WH+ZH+ttH+bbH$

$p$-value NNLOPS = 33%

$p$-value MG5 FxFx = 55%

Syst. uncertainties

**ATLAS** Preliminary

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

- data, tot. unc.
- syst. unc.

$m_H = 125.09$ GeV

$H \rightarrow gg$

Scetlib+MCFM8 + $XH$

$XH = VBF+VH+ttH+bbH$

**Data/Theory**

<table>
<thead>
<tr>
<th>$N_{jets}$</th>
<th>Data/Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$\geq 3$</td>
<td>4</td>
</tr>
</tbody>
</table>

**do_{id} / dly_{\gamma\gamma} [fb]**

| $|y_{\gamma\gamma}|$ | do_{id} / dly_{\gamma\gamma} [fb] |
|---------------------|-----------------------------------|
| 0                   | 1                                 |
| 0.2                 | 2                                 |
| 0.4                 | 3                                 |
| 0.6                 | 4                                 |
| 0.8                 | 5                                 |
| 1.0                 | 6                                 |
| 1.2                 | 7                                 |
| 1.4                 | 8                                 |
| 1.6                 | 9                                 |
| 1.8                 | 10                                |
| 2.0                 | 11                                |
| 2.2                 | 12                                |
| 2.4                 | 13                                |

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24 July 2017
Limits on contact-interaction decay terms

- Terms modifying the contact-interaction between the Higgs and left- and right-handed leptons
  - Lepton universality assumed

- Double-differential cross section in the $m_{12}, m_{34}$ plane used to extract limits in the pseudo-observables framework [Eur. Phys. J. C (2015) 75: 128]
  - The differential information helps in constraining the couplings more than the total cross section alone
Conclusions

- The most recent results on $H \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$ and $H \rightarrow \gamma\gamma$ decay channels have been presented, based on the analysis of 36.1 fb$^{-1}$ of data collected at $\sqrt{s} = 13$ TeV in 2015 and 2016.

- Mass measurement
  - Based on the latest calibrations for muons, electrons and photons, and improved analysis techniques
  - Result in excellent agreement with the Run-1 ATLAS+CMS combination

- Updated cross section measurement per production mechanism

- Fiducial total and differential cross sections and extrapolations to the full phase-space

- First limits on contact interaction terms and updated limits on Higgs characterization effective couplings

- No deviation from the SM is observed

- Most of the measurements are limited by statistics

- See the talk tomorrow by B. Mansoulié on the combination of ATLAS measurements
BACKUP SLIDES
Electron and photon scale calibration

- Converted photons
- Unconverted photons

Calibration uncertainty

Measurement

$\gamma \rightarrow Z$ Preliminary

ATLAS-1

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

$\sqrt{s} = 13$ TeV, 0.7 fb$^{-1}$

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Muon scale calibration
Mass fit per channel

**ATLAS Preliminary**

- **$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$**
- $H \rightarrow ZZ^{*} \rightarrow 4\mu$

**ATLAS Preliminary**

- **$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$**
- $H \rightarrow ZZ^{*} \rightarrow 2e2\mu$

**ATLAS Preliminary**

- **$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$**
- $H \rightarrow ZZ^{*} \rightarrow 2\mu2e$

**ATLAS Preliminary**

- **$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$**
- $H \rightarrow ZZ^{*} \rightarrow 4e$
Z→4l mass fits

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Z4l_mass_fits.png}
\end{figure}
Sagitta bias correction

- Correct the effects of local ID misalignments, that are causing local charge-dependent biases on the muon sagitta measurement
- Improvement of Z mass resolution by 1% to 5%, depending on the $\eta$ and $\phi$ of the muons in the pair
Differential cross sections

- $m_{34}$ for the 4l channel and $\cos(\theta^*)$ for $\gamma\gamma$

![Graph showing differential cross sections for $m_{34}$ and $\cos(\theta^*)$ for $\gamma\gamma$.](image)

**ATLAS Preliminary**

- $H \rightarrow ZZ^* \rightarrow 4l$
- $13$ TeV, $36.1$ fb$^{-1}$
- $p$-value NNLOPS = 55%
- $p$-value MG5 FxFx = 60%

| $|\cos\theta^*|$ | Data/Theory |
|-----------------|-------------|
| 0.1             | 1.5         |
| 0.2             | 1.8         |
| 0.3             | 1.5         |
| 0.4             | 1.2         |
| 0.5             | 1.0         |
| 0.6             | 0.8         |
| 0.7             | 0.6         |
| 0.8             | 0.4         |
| 0.9             | 0.2         |

**Higgs Production**

- $H \rightarrow \gamma\gamma$, $\sqrt{s} = 13$ TeV, $36.1$ fb$^{-1}$
- $m_H = 125.09$ GeV
- $XH = VBF+WH+ZH+ttH+bbH$

**Data/Theory**

- $\gamma\gamma$/fId $\sigma_{d}$
- $0\quad 0.2\quad 0.4\quad 0.6\quad 0.8\quad 1\quad 1.2\quad 1.4\quad 1.6\quad 1.8\quad 2\quad 2.2\quad 2.4$
- $0\quad 20\quad 40\quad 60\quad 80$

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### Expected and observed events in the 4l channel

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Signal (full mass range)</th>
<th>Signal</th>
<th>$ZZ^*$</th>
<th>Other backgrounds</th>
<th>Total expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\mu$</td>
<td>$21.0 \pm 1.7$</td>
<td>$19.7 \pm 1.6$</td>
<td>$7.5 \pm 0.6$</td>
<td>$1.00 \pm 0.21$</td>
<td>$28.1 \pm 1.7$</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>$15.0 \pm 1.2$</td>
<td>$13.5 \pm 1.0$</td>
<td>$5.4 \pm 0.4$</td>
<td>$0.78 \pm 0.17$</td>
<td>$19.7 \pm 1.1$</td>
</tr>
<tr>
<td>$2\mu2e$</td>
<td>$11.4 \pm 1.1$</td>
<td>$10.4 \pm 1.0$</td>
<td>$3.57 \pm 0.35$</td>
<td>$1.09 \pm 0.19$</td>
<td>$15.1 \pm 1.0$</td>
</tr>
<tr>
<td>$4e$</td>
<td>$11.3 \pm 1.1$</td>
<td>$9.9 \pm 1.0$</td>
<td>$3.35 \pm 0.32$</td>
<td>$1.01 \pm 0.17$</td>
<td>$14.3 \pm 1.0$</td>
</tr>
<tr>
<td>Total</td>
<td>$59 \pm 5$</td>
<td>$54 \pm 4$</td>
<td>$19.7 \pm 1.5$</td>
<td>$3.9 \pm 0.5$</td>
<td>$77 \pm 4$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reconstructed category</th>
<th>Expected $N_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\text{Expected}$</td>
</tr>
<tr>
<td>$0j$, BDT-Bin 0-4</td>
<td>5 $^{+4}_{-3}$</td>
</tr>
<tr>
<td>$0j$, BDT-Bin 5-9</td>
<td>11 $^{+4}_{-3}$</td>
</tr>
<tr>
<td>$0j$, BDT-Bin 10-14</td>
<td>11 $^{+4}_{-3}$</td>
</tr>
<tr>
<td>$1j \ p_T^{4\ell}$-Low, BDT-Bin 0-4</td>
<td>5.8 $^{+3.2}_{-2.6}$</td>
</tr>
<tr>
<td>$1j \ p_T^{4\ell}$-Low, BDT-Bin 5-9</td>
<td>3.1 $^{+1.8}_{-1.8}$</td>
</tr>
<tr>
<td>$1j \ p_T^{4\ell}$-Med, BDT-Bin 0-4</td>
<td>3.5 $^{+2.5}_{-1.8}$</td>
</tr>
<tr>
<td>$1j \ p_T^{4\ell}$-Med, BDT-Bin 5-9</td>
<td>2.0 $^{+1.9}_{-1.2}$</td>
</tr>
<tr>
<td>$1j \ p_T^{4\ell}$-High</td>
<td>1.5 $^{+1.7}_{-1.0}$</td>
</tr>
<tr>
<td>VBF-enriched $p_T^{4\ell}$-Low, BDT-Bin 0-4</td>
<td>4.0 $^{+2.0}_{-1.5}$</td>
</tr>
<tr>
<td>VBF-enriched $p_T^{4\ell}$-Low, BDT-Bin 5-9</td>
<td>2.4 $^{+2.0}_{-1.3}$</td>
</tr>
<tr>
<td>VBF-enriched $p_T^{4\ell}$-High</td>
<td>0.6 $^{+1.5}_{-1.3}$</td>
</tr>
<tr>
<td>VH-Had enriched, BDT-Bin 0-4</td>
<td>2.4 $^{+2.1}_{-1.4}$</td>
</tr>
<tr>
<td>VH-Had enriched, BDT-Bin 5-9</td>
<td>1.3 $^{+0.9}_{-0.7}$</td>
</tr>
<tr>
<td>VH-Lep enriched</td>
<td>0.3 $^{+1.0}_{-1.0}$</td>
</tr>
<tr>
<td>$ttH$-enriched</td>
<td>0.4 $^{+1.1}_{-0.9}$</td>
</tr>
<tr>
<td>Combined acceptance</td>
<td>23.5 $^{+1.9}_{-1.8}$</td>
</tr>
</tbody>
</table>

**Acceptance [%]**

- $ggF$: $2.40 \pm 0.23$, $1.78 \pm 0.029$, $0.20 \pm 0.05$, $0.74 \pm 0.01$, $2.0 \pm 0.01$
- $VH$: $5.4 \pm 0.5$, $0.64 \pm 0.12$, $1.72 \pm 0.19$, $1.89 \pm 0.27$, $6.3 \pm 0.2$
- $ttH$: $3.1 \pm 0.16$, $1.9 \pm 0.05$, $2.9 \pm 0.14$, $2.8 \pm 0.4$, $1.0 \pm 0.05$
- $bbH$: $1.4 \pm 0.07$

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## $H \rightarrow \gamma\gamma$ reco categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>tH lep 0fwd</td>
<td>$N_{\text{lep}} = 1, N_{\text{cen}} \leq 3, N_{\text{b-tag}} \geq 1, N_{\text{fwd}} = 0$ ($p_T^{\text{jett}} &gt; 25$ GeV)</td>
</tr>
<tr>
<td>tH lep 1fwd</td>
<td>$N_{\text{lep}} = 1, N_{\text{cen}} \leq 3, N_{\text{b-tag}} \geq 1, N_{\text{fwd}} \geq 1$ ($p_T^{\text{jett}} &gt; 25$ GeV)</td>
</tr>
<tr>
<td>tH lep</td>
<td>$N_{\text{lep}} \geq 1, N_{\text{cen}} \geq 2, N_{\text{b-tag}} \geq 1, Z_{\ell\ell}$ veto ($p_T^{\text{jett}} &gt; 25$ GeV)</td>
</tr>
<tr>
<td>tH had BDT1</td>
<td>$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{\text{b-tag}} \geq 1$, BDT_{ttH} &gt; 0.92</td>
</tr>
<tr>
<td>tH had BDT2</td>
<td>$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{\text{b-tag}} \geq 1$, $0.83 &lt; $BDT_{ttH} &lt; 0.92</td>
</tr>
<tr>
<td>tH had BDT3</td>
<td>$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{\text{b-tag}} \geq 1$, $0.79 &lt; $BDT_{ttH} &lt; 0.83</td>
</tr>
<tr>
<td>tH had BDT4</td>
<td>$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{\text{b-tag}} \geq 1$, $0.52 &lt; $BDT_{ttH} &lt; 0.79</td>
</tr>
<tr>
<td>tH had 4j1b</td>
<td>$N_{\text{lep}} = 0, N_{\text{cen}} = 4, N_{\text{b-tag}} = 1$ ($p_T^{\text{jett}} &gt; 25$ GeV)</td>
</tr>
<tr>
<td>tH had 4j2b</td>
<td>$N_{\text{lep}} = 0, N_{\text{cen}} = 4, N_{\text{b-tag}} \geq 2$ ($p_T^{\text{jett}} &gt; 25$ GeV)</td>
</tr>
<tr>
<td>VH dilep</td>
<td>$N_{\text{lep}} \geq 2, 70$ GeV $\leq m_{\ell\ell} \leq 110$ GeV</td>
</tr>
<tr>
<td>VH lep HIGH</td>
<td>$N_{\text{lep}} = 1,</td>
</tr>
<tr>
<td>VH lep LOW</td>
<td>$N_{\text{lep}} = 1,</td>
</tr>
<tr>
<td>VH MET HIGH</td>
<td>$150$ GeV $&lt; E_{T\text{miss}} &lt; 250$ GeV, $E_{T\text{miss}}$ significance &gt; 9 or $E_{T\text{miss}} &gt; 250$ GeV</td>
</tr>
<tr>
<td>VH MET LOW</td>
<td>$80$ GeV $&lt; E_{T\text{miss}} &lt; 150$ GeV, $E_{T\text{miss}}$ significance &gt; 8</td>
</tr>
<tr>
<td>jet BSM</td>
<td>$p_{T,j1} &gt; 200$ GeV</td>
</tr>
<tr>
<td>VH had tight</td>
<td>$60$ GeV $&lt; m_{jj} &lt; 120$ GeV, BDT_{VH} &gt; 0.78</td>
</tr>
<tr>
<td>VH had loose</td>
<td>$60$ GeV $&lt; m_{jj} &lt; 120$ GeV, $0.35 &lt; $BDT_{VH} &lt; 0.78</td>
</tr>
<tr>
<td>VBF tight, high $p_T^{HJJ}$</td>
<td>$\Delta \eta_{jj} &gt; 2$, $</td>
</tr>
<tr>
<td>VBF loose, high $p_T^{HJJ}$</td>
<td>$\Delta \eta_{jj} &gt; 2$, $</td>
</tr>
<tr>
<td>VBF tight, low $p_T^{HJJ}$</td>
<td>$\Delta \eta_{jj} &gt; 2$, $</td>
</tr>
<tr>
<td>VBF loose, low $p_T^{HJJ}$</td>
<td>$\Delta \eta_{jj} &gt; 2$, $</td>
</tr>
<tr>
<td>ggH 2J BSM</td>
<td>$\geq 2$ jets, $p_T^{H} &gt; 200$ GeV</td>
</tr>
<tr>
<td>ggH 2J HIGH</td>
<td>$\geq 2$ jets, $p_T^{H} \in [120, 200]$ GeV</td>
</tr>
<tr>
<td>ggH 2J MED</td>
<td>$\geq 2$ jets, $p_T^{H} \in [60, 120]$ GeV</td>
</tr>
<tr>
<td>ggH 2J LOW</td>
<td>$\geq 2$ jets, $p_T^{H} \in [0, 60]$ GeV</td>
</tr>
<tr>
<td>ggH 1J BSM</td>
<td>$= 1$ jet, $p_T^{H} \geq 200$ GeV</td>
</tr>
<tr>
<td>ggH 1J HIGH</td>
<td>$= 1$ jet, $p_T^{H} \in [120, 200]$ GeV</td>
</tr>
<tr>
<td>ggH 1J MED</td>
<td>$= 1$ jet, $p_T^{H} \in [60, 120]$ GeV</td>
</tr>
<tr>
<td>ggH 1J LOW</td>
<td>$= 1$ jet, $p_T^{H} \in [0, 60]$ GeV</td>
</tr>
<tr>
<td>ggH 0J FWD</td>
<td>$= 0$ jets, one photon with $</td>
</tr>
<tr>
<td>ggH 0J CEN</td>
<td>$= 0$ jets, two photons with $</td>
</tr>
</tbody>
</table>
Couplings and $\sigma \times BR$ in the 4l channel

ATLAS Preliminary

H $\rightarrow$ ZZ* $\rightarrow$ 4l

13 TeV, 36.1 fb$^{-1}$

Best Fit

68% CL Obs.

95% CL Obs.

SM

ATLAS Preliminary

H $\rightarrow$ ZZ* $\rightarrow$ 4l

13 TeV, 36.1 fb$^{-1}$

Best Fit

68% CL Obs.

95% CL Obs.

SM

Stefano Rosati (INFN Roma)

Higgs Hunting 2017 - Paris

24 July 2017
### Cross Sections

<table>
<thead>
<tr>
<th>Cross section [fb]</th>
<th>Data (± (stat) ± (sys))</th>
<th>LHCXSWG prediction</th>
<th>$p$-value [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{4\mu}$</td>
<td>0.92 $^{+0.25}<em>{-0.23}$ $^{+0.07}</em>{-0.05}$</td>
<td>0.880 ± 0.039</td>
<td>88</td>
</tr>
<tr>
<td>$\sigma_{4e}$</td>
<td>0.67 $^{+0.28}<em>{-0.23}$ $^{+0.08}</em>{-0.06}$</td>
<td>0.688 ± 0.031</td>
<td>96</td>
</tr>
<tr>
<td>$\sigma_{2\mu2e}$</td>
<td>0.84 $^{+0.28}<em>{-0.24}$ $^{+0.09}</em>{-0.06}$</td>
<td>0.625 ± 0.028</td>
<td>39</td>
</tr>
<tr>
<td>$\sigma_{2e2\mu}$</td>
<td>1.18 $^{+0.30}<em>{-0.26}$ $^{+0.07}</em>{-0.05}$</td>
<td>0.717 ± 0.032</td>
<td>7</td>
</tr>
<tr>
<td>$\sigma_{comb}$</td>
<td>3.62 $^{+0.53}<em>{-0.50}$ $^{+0.29}</em>{-0.23}$</td>
<td>2.91 ± 0.13</td>
<td>18</td>
</tr>
<tr>
<td>$\sigma_{tot}$ [pb]</td>
<td>69 $^{+10}_{-9}$ ±5</td>
<td>55.6 ± 2.5</td>
<td>19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Measured cross section</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diphoton fiducial</td>
<td>54.7 ± 9.1 (stat.) ± 4.5 (syst.) fb</td>
<td>[N^3LO + XH]</td>
</tr>
<tr>
<td>VBF-enhanced</td>
<td>3.7 ± 0.8 (stat.) ± 0.5 (syst.) fb</td>
<td>[NNLOPS + XH]</td>
</tr>
<tr>
<td>$N_{\text{lepton}} \geq 1$</td>
<td>$\leq 1.39$ fb @ 95% CL</td>
<td>[NNLOPS + XH]</td>
</tr>
<tr>
<td>High $E_T^{miss}$</td>
<td>$\leq 1.00$ fb @ 95% CL</td>
<td>[NNLOPS + XH]</td>
</tr>
<tr>
<td>$t\bar{t}H$-enhanced</td>
<td>$\leq 1.27$ fb @ 95% CL</td>
<td>[NNLOPS + XH]</td>
</tr>
</tbody>
</table>

### Decay channel

<table>
<thead>
<tr>
<th>Total cross section ($pp \rightarrow H + X$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} = 7$ TeV</td>
</tr>
<tr>
<td>$\sqrt{s} = 8$ TeV</td>
</tr>
<tr>
<td>$\sqrt{s} = 13$ TeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
<th>$\sqrt{s} = 13$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>35$^{+13}_{-12}$ pb</td>
<td>30.5$^{+7.5}_{-7.4}$ pb</td>
<td>47.9$^{+9.1}_{-8.6}$ pb</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>33$^{+21}_{-16}$ pb</td>
<td>37$^{+9}_{-8}$ pb</td>
<td>68.0$^{+11.4}_{-10.4}$ pb</td>
</tr>
<tr>
<td>Combination</td>
<td>34 ± 10 (stat.) $^{+4}_{-2}$ (syst.) pb</td>
<td>33.3$^{+5.5}<em>{-5.3}$ (stat.) $^{+1.7}</em>{-1.3}$ (syst.) pb</td>
<td>57.0$^{+6.0}<em>{-5.9}$ (stat.) $^{+4.0}</em>{-3.3}$ (syst.) pb</td>
</tr>
<tr>
<td>SM prediction [8]</td>
<td>19.2 ± 0.9 pb</td>
<td>24.5 ± 1.1 pb</td>
<td>55.6$^{+2.4}_{-3.4}$ pb</td>
</tr>
</tbody>
</table>
Couplings and $\sigma \times \text{BR}$ in $\gamma\gamma$ channel

ATLAS Preliminary
$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
$H \rightarrow \gamma\gamma$, $m_H = 125.09$ GeV, $|\gamma_\mu| < 2.5$

Best fit
68% CL
95% CL
SM

$\kappa = \kappa_V = \kappa_W = \kappa_Z$
$\kappa_F = \kappa_\ell = \kappa_b = \kappa_\tau$

Stefano Rosati (INFN Roma)
Higgs Hunting 2017 - Paris
24 July 2017
Effective Lagrangian of the Higgs characterization model

$$\mathcal{L}_0^V = \left\{ \kappa_{SM} \left[ \frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^\mu_\mu W^{-\mu} \right] - \frac{1}{4} \left[ \kappa_{Hgg} g_{Hgg} G^{a,\mu\nu} G_{a,\mu\nu} + \tan \alpha \kappa_{Agg} g_{Agg} G^{a,\mu\nu} \tilde{G}_{a,\mu\nu} \right] - \frac{1}{4} \frac{1}{\Lambda} \left[ \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \tan \alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] - \frac{1}{2} \frac{1}{\Lambda} \left[ \kappa_{HWW} W^{\mu\nu}_\mu W^{-\mu\nu} + \tan \alpha \kappa_{AWW} W^{\mu\nu}_\mu W^{-\mu\nu} \right] \right\} x_0. \quad (1)$$
## Limits on EFT couplings

<table>
<thead>
<tr>
<th>BSM coupling</th>
<th>Fit configuration</th>
<th>Expected limit</th>
<th>Observed limit</th>
<th>Best-fit $\hat{\kappa}_{BSM}$</th>
<th>Best-fit $\hat{\kappa}_{SM}$</th>
<th>Deviation from SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_{Agg}$</td>
<td>$(\kappa_{Hgg} = 1, \kappa_{SM} = 1)$</td>
<td>[-0.47, 0.47]</td>
<td>[-0.68, 0.68]</td>
<td>$\pm 0.43$</td>
<td>-</td>
<td>$1.8\sigma$</td>
</tr>
<tr>
<td>$\kappa_{HVV}$</td>
<td>$(\kappa_{Hgg} = 1, \kappa_{SM} = 1)$</td>
<td>[-2.9, 3.2]</td>
<td>[0.8, 4.5]</td>
<td>2.9</td>
<td>-</td>
<td>$2.3\sigma$</td>
</tr>
<tr>
<td>$\kappa_{HVV}$</td>
<td>$(\kappa_{Hgg} = 1, \kappa_{SM} \text{ free})$</td>
<td>[-3.1, 4.0]</td>
<td>[-0.6, 4.2]</td>
<td>2.2</td>
<td>1.2</td>
<td>$1.7\sigma$</td>
</tr>
<tr>
<td>$\kappa_{AVV}$</td>
<td>$(\kappa_{Hgg} = 1, \kappa_{SM} = 1)$</td>
<td>[-3.5, 3.5]</td>
<td>[-5.2, 5.2]</td>
<td>$\pm 2.9$</td>
<td>-</td>
<td>$1.4\sigma$</td>
</tr>
<tr>
<td>$\kappa_{AVV}$</td>
<td>$(\kappa_{Hgg} = 1, \kappa_{SM} \text{ free})$</td>
<td>[-4.0, 4.0]</td>
<td>[-4.4, 4.4]</td>
<td>$\pm 1.5$</td>
<td>1.2</td>
<td>$0.5\sigma$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fit configuration</th>
<th>Best-fit $\hat{\kappa}_{HVV}$</th>
<th>Best-fit $\hat{\kappa}_{AVV}$</th>
<th>Best-fit $\hat{\kappa}_{SM}$</th>
<th>Deviation from SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_{Hgg} = 1, \kappa_{SM} = 1$</td>
<td>2.9</td>
<td>$\pm 0.5$</td>
<td>-</td>
<td>$1.9\sigma$</td>
</tr>
<tr>
<td>$\kappa_{Hgg} = 1, \kappa_{SM} \text{ free}$</td>
<td>2.1</td>
<td>$\pm 0.3$</td>
<td>1.7</td>
<td>$1.2\sigma$</td>
</tr>
</tbody>
</table>