Measurement of fiducial and differential cross sections of the SM Higgs boson in the di-photon and 4l decay channels using the ATLAS detector

Andrea Gabrielli
on behalf of ATLAS experiment
channels: 4l and $\gamma\gamma$

Higgs to four leptons

- fully reconstructible final state
- clear signal: $S/B \sim 2.3$ @13 TeV
- excellent mass resolution: 1-2% $m_H$
- small rate: $BR \sim 1.3 \times 10^{-4}$
- virtual Z boson decays to low $p_T$ leptons

Higgs to two photons

- rate: $BR \sim 10^{-3}$
- excellent mass resolution: 1-2% $m_H$
- $S/B \sim 0.02-0.2$ @13 TeV
- background evaluated from sidebands
- 5 fiducial regions: inclusive, $N_{lep}$, VBF, MET, ttH
Fiducial cross section:
- cross section with kinematic and other selection cuts consistent with the sensitive detector acceptance
- **minimise extrapolation** into experimentally invisible phase space -> reduce the model dependency
- correction for detector effects (resolution and efficiencies)
- easy interpretation for theorist

**event selection @particle level:**
“replica” of the selection criteria applied at detector level

minimise extrapolation: e.g.
we cannot measure muons with $|\eta| > 2.7$
**selection at particle level and unfolding**

### Higgs to four leptons

| μ   | p_T > 5 GeV, |η|< 2.7 |
|-----|--------------|-------|
| e   | E_T > 7 GeV, |η|< 2.47 |
| jet | anti-k_T, p_T >30 GeV |y|< 4.4 |
| p_T 3 lead lep | 20, 15, 10 GeV |
| quadruplet | 2 pairs same flavour |
| m_{12} | 50 < m_{12} < 106 GeV |
| m_{34} | 12 < m_{34} < 115 GeV |
| veto m_{ll} | m_{ll} > 5 GeV |
| ΔR_{ll} > 0.1 (0.2) | for all same (diff) lep flavour |
| ΔR_{jet-l} > 0.1 (0.2) | for muons (electrons) |

### Higgs to γγ

<table>
<thead>
<tr>
<th>γ</th>
<th>p_T &gt; 0.35(0.25) x m_{γγ}</th>
</tr>
</thead>
<tbody>
<tr>
<td>jet</td>
<td></td>
</tr>
<tr>
<td>VBF</td>
<td>m_{jj} &gt; 400 GeV,</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>ttH</td>
<td>n_{jets} ≥ 3 (1 lep) or n_{jets} ≥ 4 (0 lep)</td>
</tr>
<tr>
<td></td>
<td>at least 1 b-jet</td>
</tr>
<tr>
<td>leptons (VH)</td>
<td>p_T &gt; 15 GeV,</td>
</tr>
<tr>
<td>MET (VH)</td>
<td>E_T^{miss} &gt; 80 GeV, p_T^{γγ} &gt; 80 GeV</td>
</tr>
</tbody>
</table>

### the unfolding technique used is bin-by-bin correction factor:
- \( A_i \) = acceptance at particle level
- \( C_i \) = correction for detector eff. and res.
- \( N_{i,\text{fit}} \) = number of signal events observed

### method has been cross checked with alternative techniques
fiducial and total cross section @ 13 TeV

**ATLAS Preliminary**

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

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

<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 ±0.07</td>
<td>0.880 ±0.039</td>
<td>88</td>
</tr>
<tr>
<td>$\sigma_{4e}$</td>
<td>0.67 ±0.28 ±0.08</td>
<td>0.688 ±0.031</td>
<td>96</td>
</tr>
<tr>
<td>$\sigma_{2e2\mu}$</td>
<td>0.84 ±0.28 ±0.09</td>
<td>0.625 ±0.028</td>
<td>39</td>
</tr>
<tr>
<td>$\sigma_{2\mu2\mu}$</td>
<td>1.18 ±0.30 ±0.07</td>
<td>0.717 ±0.032</td>
<td>7</td>
</tr>
<tr>
<td>$\sigma_{comb}$</td>
<td>3.62 ±0.53 ±0.25</td>
<td>2.91 ±0.13</td>
<td>18</td>
</tr>
<tr>
<td>$\sigma_{tot}$ [pb]</td>
<td>69.69 ±5 ±5</td>
<td>55.6 ±2.5</td>
<td>19</td>
</tr>
</tbody>
</table>

**NEW!**

- Diphoton fiducial
- VBF-enhanced
- ttH-enhanced
- High $E_T^{miss}$

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

$95\%$ C.L.

$m_H = 125.09$ GeV

$N^3\text{LO + }XH$

$\gamma\gamma \rightarrow H^0$

Data, tot. unc.  syst. unc.

Preliminary

ATLAS

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

$\text{LO + }XH$

$\text{MG5 FxFx + }XH$

$\text{Powheg NNLOPS + }XH$

$\text{New!}$

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

$95\%$ C.L.

$ttH$-enhanced

$XH = \text{VBF+VH+ttH+bbH}$
fiducial and total cross section @ 13 TeV

- agreement with the SM (ggF @N3LO): 84%
- compatibility between the channels: 29%
differential cross section: $p_T$

Higgs-boson transverse momentum $p_T$ is sensitive to:
- perturbative QCD calculations
- heavy additional particle in the loop would change the high Higgs $p_T$ region
- low Higgs $p_T$ region is sensitive to the Yukawa coupling of the b and charm quark

agreement with the Standard Model prediction (NNLOPS):
- $4l$: p-value 25%  $\gamma\gamma$: p-value 51%
differential cross sections: $y$, $n_{\text{jet}}$

- number of jets $n_{\text{jets}}$ is sensitive to: production mode composition and gluon emission
- the Higgs-boson rapidity distribution $|y|$ is sensitive to the parton distribution functions (PDFs) of the colliding protons

**agreement with the Standard Model prediction (NNLOPS):**
- $4\ell$ ($n_{\text{jets}}$): $p$-value $33\%$  \ 
$\gamma\gamma$ ($y$): $p$-value $57\%$
double differential cross section: \( p_T \) vs \( n_{jets} \)

Higgs-boson transverse momentum \( p_T \) when separated into exclusive jet multiplicities is sensitive to:
- perturbative QCD, production modes composition and BSM couplings
- low \( p_T \) 0-jets sensitive to ggF
- high \( p_T \) 0-jets sensitive to VH
- 2 jets sensitive to VBF

agreement with the Standard Model prediction (NNLOPS):
- 4l: p-value 17% (2-dim)
Double differential cross section $m_{12} \text{ vs } m_{34}$ is used to put limits on anomalous couplings within the pseudo-observables framework [Eur. Phys. J. C (2015) 75: 128]

Limits on contact terms interaction between Higgs and leptons left(right)-handed $\varepsilon_L(\varepsilon_R)$ assuming lepton flavour universality.
conclusions

- presented fiducial and differential measurements in the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels
- differential cross section measurements demonstrate a high resolution way to measure many Higgs properties and to put limits on BSM couplings
- no significant deviations from SM predictions observed... **but many results are limited by statistical uncertainties**
- with the LHC Run 2 dataset we enter the precision measurement era!
  waiting for more data to improve the measurements

**other Higgs results from ATLAS**
- couplings : Ruchi Gupta
- $ttH$: Judith Katzy
- mass measurement : Karolos Potamianos
- combination results : Tamara Vazquez Schroeder
backup
differential XS

\[ \frac{d\sigma}{dp_{T,\gamma}} [\text{fb/GeV}] \]

\[ m_H = 125.09 \text{ GeV} \]

\[ gg\to H \text{ default MC + } XH \]

\[ XH = VBF+VH+ttH+bbH \]

\[ \text{data, tot. unc.} \quad \text{syst. unc.} \]

\[ \gamma \gamma \to H \text{ data, tot. unc.} \quad \text{syst. unc.} = 125.09 \text{ GeV} \]

\[ H \to gg \quad \text{default MC + } XH \]

\[ H \to gg \text{ SCETlib+MCFM8 + } XH \]

\[ XH = VBF+VH+ttH+bbH \]

\[ \text{Ratio w/ default MC + } XH \]

\[ \text{Ratio w/ default MC + } XH \]

\[ \theta^* \quad \cos(\theta^*) \]
**ATLAS** Preliminary

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

- **Data, tot. unc.**
- **Syst. unc.**

$m_H = 125.09$ GeV

$gg \rightarrow H$ default MC + $XH$

$gg \rightarrow H$ SCETlib+MCFM8 + $XH$

$XH = VBF+VH+ttH+bbH$

<table>
<thead>
<tr>
<th>Variable</th>
<th><strong>POWHEG NNLOPS + XH</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{\gamma\gamma}$</td>
<td>57%</td>
</tr>
<tr>
<td>$p_T^{\gamma\gamma}$</td>
<td>38%</td>
</tr>
<tr>
<td>$</td>
<td>y_{\gamma\gamma}</td>
</tr>
<tr>
<td>$</td>
<td>\cos \theta^*</td>
</tr>
<tr>
<td>$</td>
<td>\Delta y_{\gamma\gamma}</td>
</tr>
</tbody>
</table>
differential XS

**ATLAS Preliminary**

H → ZZ* → 4l
13 TeV, 36.1 fb⁻¹

Data: black line
Syst. uncertainties: shaded area
HRes k = 1.1, +XH: red line
NNLOPS k = 1.1, +XH: green line
MG5 FxFx k = 1.47, +XH: blue line
XH = VBF+WH+ZH+ttH+bbH

*p*-value NNLOPS = 65%
*p*-value MG5 FxFx = 66%
*p*-value HRes = 64%

**ATLAS Preliminary**

H → ZZ* → 4l
13 TeV, 36.1 fb⁻¹

Data: black line
Syst. uncertainties: shaded area
NNLOPS k = 1.1, +XH: red line
MG5 FxFx k = 1.47, +XH: blue line
XH = VBF+WH+ZH+ttH+bbH

*p*-value NNLOPS = 42%
*p*-value MG5 FxFx = 44%

Upper limit @95% CL

Data/Theory
differential XS

**ATLAS Preliminary**

H → ZZ⁺ → 4l
13 TeV, 36.1 fb⁻¹

$p$-value NNLOPS = 55%
$p$-value MG5 FxFx = 60%

Data
Syst. uncertainties

NNLOPS $k = 1.1$, +XH
MG5 FxFx $k = 1.47$, +XH
XH = VBF+WH+ZH+ttH+bbH

Data/Theory

$\sigma$ [fb]

$\theta$ |

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

$\sigma$ [fb/GeV]

$T_{p_{\text{lead. jet}}}$ [GeV]

30 40 55 75 120 350

ATLAS Preliminary
H → ZZ⁺ → 4l
13 TeV, 36.1 fb⁻¹

$p$-value NNLOPS = 18%
$p$-value MG5 FxFx = 37%

Data/Syst. uncertainties = 1.1, +XH
NNLOPS $k = 1.1$, +XH
MG5 FxFx $k = 1.47$, +XH
XH = VBF+WH+ZH+ttH+bbH
differential XS

\[ \frac{d\sigma}{d(\Delta \phi_{jj})} \text{ [fb/\text{rad}]} \]

**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 = 11%
- \( p \)-value MG5 FxFx = 20%

---

\[ \sigma \text{ [fb]} \]

**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 = 41%
- \( p \)-value MG5 FxFx = 54%

---

**Data/Theory**

\[ m_{12} \text{ vs } m_{34} \]

<table>
<thead>
<tr>
<th>bin 0</th>
<th>bin 1</th>
<th>bin 2</th>
<th>bin 3</th>
<th>bin 4</th>
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<tbody>
<tr>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
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<tr>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Systematic uncertainties for di-photon

<table>
<thead>
<tr>
<th>Source</th>
<th>Diphoton</th>
<th>VBF-enhanced</th>
<th>$N_{\text{lepton}} \geq 1$</th>
<th>$t\bar{t}H$-enhanced</th>
<th>High $E_T^{\text{miss}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit (stat.)</td>
<td>17%</td>
<td>22%</td>
<td>72%</td>
<td>150%</td>
<td>53%</td>
</tr>
<tr>
<td>Fit (syst.)</td>
<td>6%</td>
<td>8%</td>
<td>28%</td>
<td>170%</td>
<td>13%</td>
</tr>
<tr>
<td>Photon efficiency</td>
<td>1.8%</td>
<td>1.8%</td>
<td>1.8%</td>
<td>1.8%</td>
<td>1.9%</td>
</tr>
<tr>
<td>Jet energy scale/resolution</td>
<td>-</td>
<td>8.9%</td>
<td>-</td>
<td>4.5%</td>
<td>6.9%</td>
</tr>
<tr>
<td>$b$-jet flavour tagging</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3%</td>
<td>-</td>
</tr>
<tr>
<td>Lepton selection</td>
<td>-</td>
<td>-</td>
<td>0.8%</td>
<td>0.2%</td>
<td>-</td>
</tr>
<tr>
<td>Pileup</td>
<td>1.1%</td>
<td>2.9%</td>
<td>1.3%</td>
<td>4.4%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Theoretical modeling</td>
<td>4.2%</td>
<td>8.2%</td>
<td>8.7%</td>
<td>12.7%</td>
<td>30%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.2%</td>
<td>3.2%</td>
<td>3.2%</td>
<td>3.2%</td>
<td>3.2%</td>
</tr>
</tbody>
</table>
systematic uncertainties for 4l

<table>
<thead>
<tr>
<th>Observable</th>
<th>Stat unc. [%]</th>
<th>Systematic unc. [%]</th>
<th>Dominant systematic components [%]</th>
<th>Model</th>
<th>$Z + \text{jets} + t\bar{t}$</th>
<th>Lumi</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{comb}$</td>
<td>14</td>
<td>7</td>
<td>$e$ $&lt; 0.5$ $\mu$ $2$ $ZZ^*$ theo $0.8$</td>
<td>0.8</td>
<td>1.1 4</td>
<td></td>
</tr>
<tr>
<td>$d\sigma/dp_{T,4\ell}$</td>
<td>30 - 150</td>
<td>3 - 11</td>
<td>$1 - 4$ $&lt; 0.5$ $1 - 3$ $0 - 7$ $0 - 6$</td>
<td>1 - 6</td>
<td>3 - 5</td>
<td></td>
</tr>
<tr>
<td>$\partial \sigma/\partial p_{T,4\ell}$ (0j)</td>
<td>31 - 52</td>
<td>10 - 18</td>
<td>$2 - 5$ $3 - 16$ $1 - 4$ $3 - 8$ $1$</td>
<td>2 - 3</td>
<td>3 - 5</td>
<td></td>
</tr>
<tr>
<td>$\partial \sigma/\partial p_{T,4\ell}$ (1j)</td>
<td>35 - 15</td>
<td>6 - 30</td>
<td>$1 - 4$ $2 - 29$ $1 - 3$ $1 - 4$ $1 - 11$</td>
<td>1 - 2</td>
<td>3 - 5</td>
<td></td>
</tr>
<tr>
<td>$\partial \sigma/\partial p_{T,4\ell}$ (2j)</td>
<td>30 - 41</td>
<td>5 - 21</td>
<td>$1 - 3$ $2 - 19$ $1 - 3$ $1 - 5$ $1 - 7$</td>
<td>1 - 2</td>
<td>3 - 5</td>
<td></td>
</tr>
<tr>
<td>$d\sigma/d</td>
<td>y_{4\ell}</td>
<td>$</td>
<td>29 - 120</td>
<td>5 - 8</td>
<td>$2 - 4$ $&lt; 0.5$ $2 - 3$ $1 - 2$ $0 - 1$</td>
<td>1 - 1</td>
</tr>
<tr>
<td>$d\sigma/d</td>
<td>\cos \theta^*</td>
<td>$</td>
<td>31 - 100</td>
<td>5 - 8</td>
<td>$2 - 4$ $&lt; 0.5$ $2 - 3$ $1 - 2$ $0 - 2$</td>
<td>1 - 4</td>
</tr>
<tr>
<td>$d\sigma/dm_{34}$</td>
<td>26 - 53</td>
<td>4 - 13</td>
<td>$2 - 5$ $&lt; 0.5$ $1 - 5$ $1 - 6$ $0 - 1$</td>
<td>1 - 3</td>
<td>3 - 5</td>
<td></td>
</tr>
<tr>
<td>$\partial^2 \sigma/\partial m_{12} \partial m_{34}$</td>
<td>21 - 40</td>
<td>4 - 12</td>
<td>$2 - 4$ $&lt; 0.5$ $1 - 4$ $1 - 6$ $0 - 1$</td>
<td>1 - 4</td>
<td>3 - 5</td>
<td></td>
</tr>
<tr>
<td>$d\sigma/dN_{jets}$</td>
<td>22 - 44</td>
<td>6 - 31</td>
<td>$1 - 4$ $4 - 22$ $1 - 3$ $2 - 4$ $1 - 22$</td>
<td>1 - 2</td>
<td>3 - 5</td>
<td></td>
</tr>
<tr>
<td>$d\sigma/dp_{T}^{lead.jett}$</td>
<td>30 - 53</td>
<td>5 - 18</td>
<td>$1 - 4$ $3 - 16$ $1 - 3$ $2 - 3$ $1 - 8$</td>
<td>1 - 2</td>
<td>3 - 5</td>
<td></td>
</tr>
<tr>
<td>$d\sigma/d\Delta \phi_{jj}$</td>
<td>29 - 43</td>
<td>9 - 17</td>
<td>$1 - 3$ $8 - 14$ $1 - 3$ $3 - 4$</td>
<td>1 - 7</td>
<td>1 - 1</td>
<td></td>
</tr>
<tr>
<td>$d\sigma/dm_{jj}$</td>
<td>23 - 100</td>
<td>9 - 27</td>
<td>$1 - 4$ $8 - 24$ $1 - 4$ $3 - 8$</td>
<td>1 - 7</td>
<td>0 - 3</td>
<td></td>
</tr>
</tbody>
</table>

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Higgs pseudo-observables

\[ \varepsilon_R = 0.48 \times \varepsilon_L \]
from TGC measurements

\[ H \rightarrow ZZ^* \rightarrow 4l \]
13 TeV, 36.1 fb\(^{-1} \)

\[ \varepsilon_L \]

\[ \kappa \]

\[ \Lambda \]

-2ln\( \Lambda \)

ATLAS Preliminary

95% CL Obs

SM

95% CL Exp

4l → ZZ* → 4l

13 TeV, 36.1 fb\(^{-1} \)

ATLAS

Preliminary