Higgs boson couplings to bosons with the ATLAS detector: run 1 legacy.

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DESY

on behalf of the ATLAS collaboration

XXIX Rencontres de Physique de la Vallée d'Aoste
La Thuile
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Introduction

♦ **Final** measurements of the Higgs boson decaying into bosons with LHC run 1 data
  - $H \rightarrow WW^* \rightarrow l\nu l\nu$: submitted in December 2014
  - $H \rightarrow ZZ^* \rightarrow 4l$: published in January 2015
  - $H \rightarrow \gamma\gamma$: published in December 2014

♦ Benefits from **final performance** of objects calibration, identification, ...

♦ **Improved** analyses, to be sensitive to production modes

♦ Here, only discussion of couplings, mass discussed in the talk by A. Armbruster
  - $m_H = 125.36$ GeV considered here

Higgs boson production and decays modes

♦ Production modes:

- $ggF$: 86.4%
- $q_1q_2\rightarrow q_3q_4$: VBF 7.1%
- $q_1\bar{q}_1\rightarrow H$: ZH, WH 5.0%
- $q_1g\rightarrow t\bar{t}H$: $t\bar{t}H$ 1.5%

♦ Decay modes:

- $H\rightarrow b\bar{b}$
- $H\rightarrow \tau\bar{\tau}$
- $H\rightarrow W^+W^-$
- $H\rightarrow Z\gamma$

♦ Measuring cross-sections and partial widths $\Rightarrow$ go back to couplings

♦ Parameter of interest: signal strength $\mu = \frac{N_{\text{obs}}}{N_{\text{SM}}}$
Final performance for run 1

Some examples:

- Muon calibration
  - 0.04-0.2% uncertainty on energy scale (ES)

- e/γ calibration
  - e: 0.04% uncertainty on ES at 45 GeV
  - γ from Higgs boson: 0.3% uncertainty on ES
  - γγ mass resolution improved by 10%

- electron ID
  - >40% more rejection for same efficiency
Two same-flavour, opposite-sign lepton pairs
- well identified and isolated
- $p_T > 20/15/10/6-7$ GeV
- FSR photon correction
- Z-mass constraint (15% improvement on resolution)

$50 < m_{12} < 106$ GeV
$12-50 < m_{34} < 115$ GeV

Number of events in $120 < m_{4l} < 130$ GeV
- $ZZ^*$ from simulation
- $Z+\text{jets}$ and $t\bar{t}$ from data-driven estimates

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>ZZ</th>
<th>Z+jets, tt</th>
<th>S/B</th>
<th>Total expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>7+8 TeV</td>
<td>16.2</td>
<td>7.4</td>
<td>3.0</td>
<td>1.6</td>
<td>26.6</td>
<td>37</td>
</tr>
</tbody>
</table>

Two well identified and isolated photons
- \( E_{T\gamma_1} > 0.35 m_{\gamma\gamma}, E_{T\gamma_2} > 0.25 m_{\gamma\gamma} \)
- \( \gamma\gamma \) purity: 77-84%

Divide events in exclusive categories
- with different resolution
- with different S/B

Signal+background fit of \( m_{\gamma\gamma} \)

Number of expected signal events and measured background
- window with 90% of signal

<table>
<thead>
<tr>
<th>signal</th>
<th>background</th>
<th>( S/(S+B) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7+8 TeV</td>
<td>421.8</td>
<td>13196.4</td>
</tr>
</tbody>
</table>

Two isolated well identified leptons
- $p_T > 22/10$ GeV

$E_T^{\text{miss}}$ cuts, Z veto, $m_{ll}$, $\Delta \phi_{ll}$, etc

Events divided in exclusive categories
- $e\mu + e\mu$, $ee + \mu\mu$
- 0, 1, 2 jets

Background estimation
- normalisation: data (CR)
- extrapolation to SR: typically from MC
- shape of discriminating variable: typically from MC

Number of expected/observed events (7+8 TeV):

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>Background</th>
<th>S/B</th>
<th>total expected</th>
<th>observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 jet</td>
<td>358</td>
<td>4005</td>
<td>0.09</td>
<td>4363</td>
<td>4344</td>
</tr>
<tr>
<td>1 jet</td>
<td>138</td>
<td>1746</td>
<td>0.08</td>
<td>1884</td>
<td>1900</td>
</tr>
<tr>
<td>2 jets, ggF</td>
<td>50</td>
<td>1017</td>
<td>0.05</td>
<td>1067</td>
<td>1017</td>
</tr>
</tbody>
</table>
Datasets divided in exclusive categories enriched in production modes

4l selection
- VBF enriched
  - VH hadronic
    - VH 1-lepton
      - 1 untagged category

di-photon selection
- ttH leptonic
  - ttH hadronic
    - VH dilepton
      - VH 1-lepton
        - VH \( E_T^{miss} \)
          - VH hadronic
            - VBF tight
              - VBF loose
                - 4 untagged categories

WW selection
- 0 jet
- 1 jet
- 2 jets ggF
- 2 jets VBF

* in talk by F. Filthaut
VBF production mode (1)

- Cross-section at 125 GeV: 1.578 pb
- Higgs boson produced with 2 forward jets:
  - Usual cuts:
    - $\Delta\eta_{jj}$
    - $m_{jj}$
    - veto 3rd central jet

![Diagram of VBF production mode](image)

**ATLAS Simulation**

- $H \rightarrow ZZ^* \rightarrow 4\ell$
- $s = 7$ TeV \( \int L dt = 4.5 \, fb^{-1} \)
- $s = 8$ TeV \( \int L dt = 20.3 \, fb^{-1} \)

VBF enriched category
**VBF production mode (2)**

- **BDT analyses for 4ℓ, γγ, WW**

**H → ZZ → 4ℓ**

- **ATLAS Simulation**
  - H → ZZ → 4ℓ
  - m_H = 125 GeV
  - 1s = 7 TeV, |Δt| = 4.5 fb⁻¹
  - 1s = 8 TeV, |Δt| = 20.3 fb⁻¹
  - VBF enriched category

**H → γγ**

- **ATLAS**
  - m_H = 125 GeV
  - VBF, ggF, γγ + γγ + jj

**Number of expected/observed events:**

<table>
<thead>
<tr>
<th></th>
<th>signal</th>
<th>VBF/Higgs</th>
<th>background</th>
<th>observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>7+8 TeV 4ℓ</td>
<td>1.13</td>
<td>55%</td>
<td>0.16</td>
<td>1</td>
</tr>
<tr>
<td>7+8 TeV γγ</td>
<td>11.0</td>
<td>60%</td>
<td>44.0</td>
<td></td>
</tr>
<tr>
<td>8 TeV WW</td>
<td>12.5</td>
<td>60%</td>
<td>82.0</td>
<td>90</td>
</tr>
</tbody>
</table>

**E. Petit - XXIX Rencontres de physique de la vallée d'Aoste**
Cross-section at 125 GeV: 1.1 pb

Divide into categories depending on the W/Z decay

1 lepton + $E_T^{\text{miss}}$

2 leptons

0 lepton + $E_T^{\text{miss}}$

2 jets with $m_{jj}$ close to 80-90 GeV
H → ZZ → 4l
- BDT analysis for VH hadronic
- 1 additional lepton

H → γγ
- 2 leptons
- 1 lepton + E_T^{miss}
- 0 lepton + E_T^{miss}
- VH hadronic

Number of expected/observed events (7+8 TeV):

<table>
<thead>
<tr>
<th></th>
<th>signal</th>
<th>VH/Higgs</th>
<th>background</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4l</td>
<td>hadronic</td>
<td>0.64</td>
<td>33%</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>1 lepton</td>
<td>0.08</td>
<td>84%</td>
<td>0.03</td>
</tr>
<tr>
<td>2 leptons</td>
<td>0.4</td>
<td>99%</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>1 lepton</td>
<td>2.0</td>
<td>96%</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>γγ</td>
<td>ETmiss</td>
<td>1.4</td>
<td>88%</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>hadronic</td>
<td>3.8</td>
<td>49%</td>
<td>18</td>
</tr>
</tbody>
</table>
H→ZZ*→4l: global results

- 2D fit to $m_{4l}$ and a BDT output designed to distinguish signal from ZZ* background
  - mass
  - inclusive $\mu$

- Local significance at $m_H = 125.36$ GeV
  - observed: 8.1 $\sigma$
  - expected: 6.2 $\sigma$

- Inclusive signal strength:
  $\mu = 1.50^{+0.35}_{-0.31}$ (stat)$^{+0.19}_{-0.13}$ (syst)
H → γγ: global results

♦ Local significance at m_H = 125.36 GeV
  - observed: 5.2 σ
  - expected: 4.6 σ

♦ Signal strength:
  - \( \mu = 1.17^{+0.23}_{-0.23} \) \( (\text{stat})^{+0.10}_{-0.08} \) \( (\text{syst})^{+0.12}_{-0.08} \) \( (\text{theo}) \)
  - main systematic uncertainties:
    • theory (yield): 0.09
    • resolution: 0.07
  - 0.7σ compatibility with SM prediction
  - only slight dependence on m_H

\[ \mu = \frac{N_{\text{obs}}}{N_{\text{SM}}} \]
H→WW*→lνlν: global results

♦ Fit procedure:
  - binned likelihood function
  - ggF: m_T, p_T^{sublead}, m_ll
  - VBF: BDT discriminant
  - simultaneous fit to all the categories (SR, CR, 7/8TeV)

♦ Local significance at m_H = 125.36 GeV
  - observed: 6.1 σ
  - expected: 5.8 σ

♦ Inclusive signal strength:
  \[ \mu = 1.09^{+0.16}_{-0.15} \text{(stat)}^{+0.17}_{-0.14} \text{(syst)} \]

\[ \mu = \frac{N_{\text{obs}}}{N_{\text{SM}}} \]
## Results for couplings (1)

### Signal strength \( \mu \) /production mode:

<table>
<thead>
<tr>
<th></th>
<th>4l</th>
<th>YY</th>
<th>WW</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>( 1.7^{+0.5}_{-0.4} )</td>
<td>( 1.32 \pm 0.38 )</td>
<td>( 1.02^{+0.29}_{-0.26} )</td>
</tr>
<tr>
<td>VBF</td>
<td>( 0.3^{+1.6}_{-0.9} )</td>
<td>( 0.8 \pm 0.7 )</td>
<td>( 1.27^{+0.53}_{-0.45} )</td>
</tr>
<tr>
<td>WH</td>
<td>( 1.0 \pm 1.6 )</td>
<td>( 0.1^{+3.7}_{-0.1} )</td>
<td>( 1.32 \pm 0.38 )</td>
</tr>
<tr>
<td>ZH</td>
<td>( 0.3 \pm 1.6 )</td>
<td>( 0.8 \pm 0.9 )</td>
<td>( 1.27^{+0.53}_{-0.45} )</td>
</tr>
<tr>
<td>ttH</td>
<td>( 1.6^{+2.7}_{-1.8} )</td>
<td>( 0.3 \pm 1.6 )</td>
<td>( 0.8 \pm 0.9 )</td>
</tr>
</tbody>
</table>

- all compatible with SM expectation

### Diagrams

- **H → ZZ → 4l**
  - SM
  - 68% CL
  - 95% CL
  - \( m_H = 125.36 \text{ GeV} \)

- **H → YY**
  - Best fit
  - 68% CL
  - 95% CL
  - SM
  - \( m_H = 125.4 \text{ GeV} \)

- **H → WW → llνν**
  - ATLAS
  - \( \sqrt{s} = 7 \text{ TeV}, 4.5 \text{ fb}^{-1} \)
  - \( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)
  - \( H \rightarrow \gamma\gamma, m_H = 125.4 \text{ GeV} \)

### Expressions

\[
\mu = \frac{N_{\text{obs}}}{N_{\text{SM}}}
\]
Results for couplings (2)

♦ Evidence of VBF production in WW channel!
  - 3.2σ observed
  - 2.7σ expected

♦ Couplings scale factors κ to compare to SM prediction
  - κ_F for fermionic couplings
  - κ_V for bosonic couplings

♦ Inputs to global coupling fits

\[ \frac{\mu}{\mu_{SM}} = \frac{N_{obs}}{N_{SM}} \]
One step further: cross-sections

- Computed from number of observed signal events: $\sigma_{\text{fid(tot)}} \cdot BR = \frac{N_{\text{sig, obs}}}{(A) \cdot C.L}$
  - $A =$ acceptance correction factor
  - $C =$ detector correction factor
  - $L =$ integrated luminosity

- Allows easier comparison to theory predictions

- **Total** cross-sections in $ZZ, \gamma\gamma, WW$

- **Fiducial** cross-sections in $ZZ, \gamma\gamma$

- All measurements compatible with expectation within $\sim 2\sigma$

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One step further: differential cross-sections

♦ Variables sensitive to
  - Higgs production
  - spin/CP
  - QCD effect

♦ New! Combination of γγ and 4l channels (reduces uncertainty by ~30%)
Conclusions

♦ **Final** ATLAS results on study of the Higgs boson decaying into bosons with run 1 data

♦ Separate *production modes* to go back to couplings
  - data divided in categories enriched in production modes

♦ Signal strengths /production modes compatible with expectations

♦ Total, fiducial and differential cross-sections

♦ More on the combinations of the different channels in the talk by A. Armbruster
Back-up slides
H → 4l: selection

- Two same-flavour, opposite sign lepton pairs
- \( p_T^1 > 20 \text{ GeV}, \ p_T^2 > 15 \text{ GeV}, \ p_T^3 > 10 \text{ GeV}, \ p_T^4 > 7/6 (e/\mu) \text{ GeV} \)
- \( 50 < m_{12} < 106 \text{ GeV} \)
- \( m_{\text{min}} < m_{34} < 115 \text{ GeV} \) with \( m_{\text{min}} \) from 12 to 50 GeV for \( m_{4\ell} < 190 \text{ GeV}, 50 \text{ GeV above} \)
- \( \Delta R > 0.1 \) between same flavour leptons, \( \Delta R > 0.2 \) otherwise
- \( |d_0|/\sigma_{d_0} < 6.5/3.5 (e/\mu) \)
- \( p_T^{\text{iso, track}, \Delta R=0.2}/p_T < 0.15 \)
- \( E_T^{\text{iso, calo}, \Delta R=0.2}/E_T \)
  - \( < 0.3/0.2 (7/8 \text{ TeV}) \) for electrons
  - \( < 0.3 \) for muons, \( < 0.15 \) for standalone muons

Selection efficiency:
Some FSR photons can be identified in the calorimeter and incorporated to the 4-lepton measurements.

- Efficiency of recovery:
  - 70% for collinear photons (85% purity)
  - 60% for non-collinear photons (95% purity)

- Expected fraction of corrected events:
  - 4% of collinear photons
  - 1% of non-collinear photons
H → 4l: background

- ZZ, WZ: from simulation
- Z+jets, tt: data-driven
  - llll+μμ: simultaneous unbinned fit of four orthogonal control regions
  - llll+ee: simultaneous unbinned fit of nblayer and rTRT in 3ll+X control region
  - extrapolated to signal region with transfer factors

Number of expected and observed events in 120 < m4l < 130 GeV:

<table>
<thead>
<tr>
<th>Final state</th>
<th>Signal full mass range</th>
<th>Signal</th>
<th>ZZ*</th>
<th>Z + jets, tt</th>
<th>S/B</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4μ</td>
<td>1.00 ± 0.10</td>
<td>0.91 ± 0.09</td>
<td>0.46 ± 0.02</td>
<td>0.10 ± 0.04</td>
<td>1.7</td>
<td>1.47 ± 0.10</td>
<td>2</td>
</tr>
<tr>
<td>2e2μ</td>
<td>0.66 ± 0.06</td>
<td>0.58 ± 0.06</td>
<td>0.32 ± 0.02</td>
<td>0.09 ± 0.03</td>
<td>1.5</td>
<td>0.99 ± 0.07</td>
<td>2</td>
</tr>
<tr>
<td>2μ2e</td>
<td>0.50 ± 0.05</td>
<td>0.44 ± 0.04</td>
<td>0.21 ± 0.01</td>
<td>0.36 ± 0.08</td>
<td>0.8</td>
<td>1.01 ± 0.09</td>
<td>1</td>
</tr>
<tr>
<td>4e</td>
<td>0.46 ± 0.05</td>
<td>0.39 ± 0.04</td>
<td>0.19 ± 0.01</td>
<td>0.40 ± 0.09</td>
<td>0.7</td>
<td>0.98 ± 0.10</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>2.62 ± 0.26</td>
<td>2.32 ± 0.23</td>
<td>1.17 ± 0.06</td>
<td>0.96 ± 0.18</td>
<td>1.1</td>
<td>4.45 ± 0.30</td>
<td>6</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 7$ TeV

<table>
<thead>
<tr>
<th>Final state</th>
<th>Signal full mass range</th>
<th>Signal</th>
<th>ZZ*</th>
<th>Z + jets, tt</th>
<th>S/B</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4μ</td>
<td>5.80 ± 0.57</td>
<td>5.28 ± 0.52</td>
<td>2.36 ± 0.12</td>
<td>0.69 ± 0.13</td>
<td>1.7</td>
<td>8.33 ± 0.6</td>
<td>12</td>
</tr>
<tr>
<td>2e2μ</td>
<td>3.92 ± 0.39</td>
<td>3.45 ± 0.34</td>
<td>1.67 ± 0.08</td>
<td>0.60 ± 0.10</td>
<td>1.5</td>
<td>5.72 ± 0.37</td>
<td>7</td>
</tr>
<tr>
<td>2μ2e</td>
<td>3.06 ± 0.31</td>
<td>2.71 ± 0.28</td>
<td>1.17 ± 0.07</td>
<td>0.36 ± 0.08</td>
<td>1.8</td>
<td>4.23 ± 0.30</td>
<td>5</td>
</tr>
<tr>
<td>4e</td>
<td>2.79 ± 0.29</td>
<td>2.38 ± 0.25</td>
<td>1.03 ± 0.07</td>
<td>0.35 ± 0.07</td>
<td>1.7</td>
<td>3.77 ± 0.27</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>15.6 ± 1.6</td>
<td>13.8 ± 1.4</td>
<td>6.24 ± 0.34</td>
<td>2.00 ± 0.28</td>
<td>1.7</td>
<td>22.1 ± 1.5</td>
<td>31</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 8$ TeV

<table>
<thead>
<tr>
<th>Final state</th>
<th>Signal full mass range</th>
<th>Signal</th>
<th>ZZ*</th>
<th>Z + jets, tt</th>
<th>S/B</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4μ</td>
<td>6.80 ± 0.67</td>
<td>6.29 ± 0.61</td>
<td>2.82 ± 0.14</td>
<td>0.79 ± 0.13</td>
<td>1.7</td>
<td>9.81 ± 0.64</td>
<td>14</td>
</tr>
<tr>
<td>2e2μ</td>
<td>4.58 ± 0.45</td>
<td>4.04 ± 0.40</td>
<td>1.99 ± 0.10</td>
<td>0.69 ± 0.11</td>
<td>1.5</td>
<td>6.72 ± 0.42</td>
<td>9</td>
</tr>
<tr>
<td>2μ2e</td>
<td>3.56 ± 0.36</td>
<td>3.15 ± 0.32</td>
<td>1.38 ± 0.08</td>
<td>0.72 ± 0.12</td>
<td>1.5</td>
<td>5.24 ± 0.35</td>
<td>6</td>
</tr>
<tr>
<td>4e</td>
<td>3.25 ± 0.34</td>
<td>2.77 ± 0.29</td>
<td>1.22 ± 0.08</td>
<td>0.76 ± 0.11</td>
<td>1.4</td>
<td>4.75 ± 0.32</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>18.2 ± 1.8</td>
<td>16.2 ± 1.6</td>
<td>7.41 ± 0.40</td>
<td>2.95 ± 0.33</td>
<td>1.6</td>
<td>26.5 ± 1.7</td>
<td>37</td>
</tr>
</tbody>
</table>
## H → 4l: multivariate discriminants

<table>
<thead>
<tr>
<th>input variables</th>
<th>sample</th>
<th>usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDT(_{ZZ^*})</td>
<td>KD(<em>{ZZ^*}), pT(4l), (\eta</em>{4l})</td>
<td>115 &lt; (m_{4l}) &lt; 130 GeV</td>
</tr>
<tr>
<td>BDT(_{VBF})</td>
<td>(m_{jj}), (\Delta\eta_{jj}), pT(j_1), pT(j_2), (\eta_{j1})</td>
<td>(m_{jj}) &gt; 130 GeV</td>
</tr>
<tr>
<td>BDT(_{VH})</td>
<td>(m_{jj}), (\Delta\eta_{jj}), pT(j_1), pT(j_2), (\eta_{j1})</td>
<td>40 &lt; (m_{jj}) &lt; 130 GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
H → 4l: ggF enriched category

◊ Signal:

◊ Background ZZ*:  

◊ Background Z+jets:

**ATLAS Simulation**  
\( H \rightarrow ZZ^* \rightarrow 4l \)

\( \sqrt{s} = 7 \text{ TeV} \int \text{L}_\text{int} = 4.5 \text{ fb}^{-1} \)
\( \sqrt{s} = 8 \text{ TeV} \int \text{L}_\text{int} = 20.3 \text{ fb}^{-1} \)

\( m_{4l} = 125 \text{ GeV} \mu = 1.51 \)
H → 4l: VBF enriched category

♦ VBF:

♦ ggF:

♦ Background ZZ*:
For the combined analysis:

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>4μ</th>
<th>2e2μ</th>
<th>2μ2e</th>
<th>4e</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron reconstruction and identification efficiencies</td>
<td>–</td>
<td>1.7%</td>
<td>3.3%</td>
<td>4.4%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Electron isolation and impact parameter selection</td>
<td>–</td>
<td>0.07%</td>
<td>1.1%</td>
<td>1.2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Electron trigger efficiency</td>
<td>–</td>
<td>0.21%</td>
<td>0.05%</td>
<td>0.21%</td>
<td>&lt;0.2%</td>
</tr>
<tr>
<td>ℓℓ + ee backgrounds</td>
<td>–</td>
<td>–</td>
<td>3.4%</td>
<td>3.4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Muon reconstruction and identification efficiencies</td>
<td>1.9%</td>
<td>1.1%</td>
<td>0.8%</td>
<td>–</td>
<td>1.5%</td>
</tr>
<tr>
<td>Muon trigger efficiency</td>
<td>0.6%</td>
<td>0.03%</td>
<td>0.6%</td>
<td>–</td>
<td>0.2%</td>
</tr>
<tr>
<td>ℓℓ + μμ backgrounds</td>
<td>1.6%</td>
<td>1.6%</td>
<td>–</td>
<td>–</td>
<td>1.2%</td>
</tr>
<tr>
<td>QCD scale uncertainty</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>6.5%</td>
</tr>
<tr>
<td>PDF, αs uncertainty</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>6.0%</td>
</tr>
<tr>
<td>H → ZZ* branching ratio uncertainty</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>4.0%</td>
</tr>
</tbody>
</table>
In the different production mode categories:

<table>
<thead>
<tr>
<th>Process</th>
<th>$gg \rightarrow H, q\bar{q}/gg \rightarrow b\bar{b}H/\mathbf{t}\bar{t}H$</th>
<th>$qq' \rightarrow Hqq'$</th>
<th>$q\bar{q} \rightarrow W/ZH$</th>
<th>$ZZ^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VBF enriched category</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical cross section</td>
<td>20.4%</td>
<td>4%</td>
<td>4%</td>
<td>8%</td>
</tr>
<tr>
<td>Underlying event</td>
<td>6.6%</td>
<td>1.4%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>9.6%</td>
<td>4.8%</td>
<td>7.8%</td>
<td>9.6%</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.9%</td>
<td>0.2%</td>
<td>1.0%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Total</td>
<td>23.5%</td>
<td>6.4%</td>
<td>8.8%</td>
<td>12.6%</td>
</tr>
<tr>
<td><strong>VH-hadronic enriched category</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical cross section</td>
<td>20.4%</td>
<td>4%</td>
<td>4%</td>
<td>2%</td>
</tr>
<tr>
<td>Underlying event</td>
<td>7.5%</td>
<td>3.1%</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>9.4%</td>
<td>9.3%</td>
<td>3.7%</td>
<td>12.6%</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>1.0%</td>
<td>1.7%</td>
<td>0.6%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Total</td>
<td>23.7%</td>
<td>10.7%</td>
<td>5.5%</td>
<td>12.9%</td>
</tr>
<tr>
<td><strong>VH-leptonic enriched category</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical cross section</td>
<td>12%</td>
<td>4%</td>
<td>4%</td>
<td>5%</td>
</tr>
<tr>
<td>Leptonic VII-specific cuts</td>
<td>1%</td>
<td>1%</td>
<td>5%</td>
<td>–</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>8.8%</td>
<td>9.9%</td>
<td>1.7%</td>
<td>3.2%</td>
</tr>
<tr>
<td>Total</td>
<td>14.9%</td>
<td>10.7%</td>
<td>6.6%</td>
<td>5.9%</td>
</tr>
<tr>
<td><strong>ggF enriched category</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical cross section</td>
<td>12%</td>
<td>4%</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>2.2%</td>
<td>6.6%</td>
<td>4.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Total</td>
<td>12.2%</td>
<td>7.7%</td>
<td>5.7%</td>
<td>4.1%</td>
</tr>
</tbody>
</table>
H → 4l: changes wrt last public paper


♦ electron identification: likelihood method: improve bkg rejection for same efficiency

♦ electron transverse energy measurement improved: refined cluster energy reconstruction + combination of cluster energy and track momentum

♦ energy scale of electrons and momentum scale of muons improved

♦ correction of FSR for non-collinear photons

♦ BDT against ZZ* background

♦ better estimate of ll+jets and tt bkg

♦ VH category with two jets + BDT for VBF
H→WW: analysis strategy

exclusive categories based on jet multiplicity and lepton flavour

Most sensitive categories:

- Njet = 0 and eμ for ggF
- Njet ≥ 2 and eμ for VBF
### H→WW: selection

<table>
<thead>
<tr>
<th>Objective</th>
<th>ggF-enriched</th>
<th>VBF-enriched</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_{j} = 0 )</td>
<td>( n_{j} = 1 )</td>
<td>( n_{j} \geq 2 ) ggF</td>
</tr>
</tbody>
</table>

**Preselection**

\[
\begin{align*}
& \quad p_{T}^{\ell_1} > 22 \text{ for the leading lepton } \ell_1 \\
& \quad p_{T}^{\ell_2} > 10 \text{ for the subleading lepton } \ell_2 \\
& \text{Opposite-charge leptons} \\
& \quad m_{\ell\ell} > 10 \text{ for the } e\mu \text{ sample} \\
& \quad m_{\ell\ell} > 12 \text{ for the } ee/\mu\mu \text{ sample} \\
& \quad |m_{\ell\ell} - m_{Z}| > 15 \text{ for the } ee/\mu\mu \text{ sample} \\
& \quad p_{T}^{\text{miss}} > 20 \text{ for } e\mu \\
& \quad E_{T,\text{rel}}^{\text{miss}} > 40 \text{ for } ee/\mu\mu
\end{align*}
\]

**Reject backgrounds**

\[
\begin{align*}
& \quad p_{T,\text{rel}}^{\text{miss (trk)}} > 40 \text{ for } ee/\mu\mu \\
& \quad f_{\text{recoil}} < 0.1 \text{ for } ee/\mu\mu \\
& \quad p_{T}^{\ell} > 30 \\
& \quad \Delta \phi_{\ell,\text{MET}} > \pi/2 \\
& \quad m_{T} > 35 \text{ for } e\mu \\
& \quad m_{T} > 50 \text{ for } e\mu \\
& \quad n_{b} = 0 \\
& \text{DY} \\
& \text{Misid.} \\
& \text{Top}
\end{align*}
\]

**VBF topology**

\[
\begin{align*}
& \text{See Sec. IV D for rejection of VBF & VH (W, Z → jj),} \\
& \text{where } H → WW^* \\
& \quad m_{\ell\ell} < 55 \\
& \quad \Delta \phi_{\ell\ell} < 1.8 \\
& \quad \Delta \phi_{\ell\ell} < 1.8 \\
& \quad \Delta \phi_{\ell\ell} < 1.8 \\
& \text{decay topology} \\
& \quad \text{No } m_{T} \text{ requirement} \\
& \text{inputs to BDT} \\
& \text{inputs to BDT} \\
& \text{inputs to BDT} \\
& \text{inputs to BDT} \\
& \text{inputs to BDT} \\
& \text{inputs to BDT} \\
& \text{inputs to BDT} \\
& \text{inputs to BDT} \\
& \text{inputs to BDT} \\
\end{align*}
\]

\( H → WW^* → \ell\nu\ell\nu \)
H→WW: background

<table>
<thead>
<tr>
<th>Name</th>
<th>Process</th>
<th>Feature(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>WW</td>
<td>Irreducible</td>
</tr>
</tbody>
</table>

**Top quarks**

\[ t\bar{t} \rightarrow WbW\bar{b} \quad \text{Unidentified } b\text{-quarks} \]

\[ t \quad \begin{cases} tW \quad \text{Unidentified } b\text{-quark} \\ \bar{t}b, t\bar{q}b \quad q \text{ or } b \text{ misidentified as } \ell; \text{ unidentified } b\text{-quarks} \end{cases} \]

**Misidentified leptons (Misid.)**

\[ Wj \quad W + \text{jet(s)} \quad j \text{ misidentified as } \ell \]

\[ jj \quad \text{Multijet production} \quad jj \text{ misidentified as } \ell\ell; \text{ misidentified neutrinos} \]

**Other dibosons**

\[ VV \quad \begin{cases} W\gamma \quad \gamma \text{ misidentified as } e \\ W\gamma^*, WZ, ZZ \rightarrow \ell\ell \ell\ell \quad \text{Unidentified lepton(s)} \\ ZZ \rightarrow \ell\ell \nu\nu \quad \text{Irreducible} \\ Z\gamma \quad \gamma \text{ misidentified as } e; \text{ unidentified lepton} \end{cases} \]

**Drell-Yan (DY)**

\[ ee/\mu\mu \quad Z/\gamma^* \rightarrow ee, \mu\mu \quad \text{Misidentified neutrinos} \]

\[ \tau\tau \quad Z/\gamma^* \rightarrow \tau\tau \rightarrow \ell\nu\ell\nu \quad \text{Irreducible} \]
H$\rightarrow$WW: systematic uncertainties

♦ Three major categories of uncertainties:

- stat: for backgrounds which use data for normalization (sample statistics)
- experimental: leptons, jets, ETmiss, pTmiss, charge mis-identification, ...
- theo.: x-sec scale, acceptance, modelling . . .

♦ Leading sources of uncertainties on $\mu$:

- WW generator modelling (on the mT shape and extrapolation)
- ggF, QCD scale on the total x-sec
- top generator modeling (on the extrapolation),
- corrections to the mis-identification factor, ...
Fit procedure:

- binned likelihood function constructed as a product of Poisson probabilities and systematic constraints,
- profile likelihood ratio test statistic is used
- simultaneous fit to all the categories (SR, CR, 7/8TeV)

Free parameters:

- $\mu$ - signal strength parameter
- $\beta$ – background normalization
- $\theta$ - uncertainty constraint parameter

<table>
<thead>
<tr>
<th>$n_j$, flavor</th>
<th>$m_\ell\ell$</th>
<th>$p_T^{\ell_2}$</th>
<th>$\ell_2$</th>
<th>SR category $i$</th>
<th>Fit var.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_j = 0$</td>
<td></td>
<td></td>
<td></td>
<td>$e\mu$</td>
<td>$[10, 30, 55]$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$ee/\mu\mu$</td>
<td>$[12, 55]$</td>
</tr>
<tr>
<td>$n_j = 1$</td>
<td></td>
<td></td>
<td></td>
<td>$e\mu$</td>
<td>$[10, 30, 55]$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$ee/\mu\mu$</td>
<td>$[12, 55]$</td>
</tr>
<tr>
<td>$n_j \geq 2$</td>
<td>$ggF$</td>
<td>$[10, 55]$</td>
<td>$[10, \infty]$</td>
<td>$e\mu$</td>
<td>$[10, 55]$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$ee/\mu\mu$</td>
<td>$[12, 50]$</td>
</tr>
</tbody>
</table>
## H→WW: cross-sections

### Total cross-sections (pb):

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Process</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>σ_{ggF}, BR(H → WW*)</td>
<td>2.0 ± 1.7 (stat) +1.2-1.1 (syst)</td>
<td>3.3 ± 0.4</td>
</tr>
<tr>
<td>8</td>
<td>σ_{ggF}, BR(H → WW*)</td>
<td>4.6 ± 0.9 (stat) +0.8-0.7 (syst)</td>
<td>4.6 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>σ_{VBF}, BR(H → WW*)</td>
<td>0.51 ±0.17-0.15 (stat) +0.13-0.08 (syst)</td>
<td>0.35 ± 0.02</td>
</tr>
</tbody>
</table>

### Fiducial cross-sections

- **Fiducial volume definition:**

### Cross-sections in fb:

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Process</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>σ_{ggF}, 0 jet</td>
<td>27.6 ±5.4-5.3 (stat) +4.1-3.9 (syst)</td>
<td>19.9 ± 3.3</td>
</tr>
<tr>
<td></td>
<td>σ_{ggF}, 1 jet</td>
<td>8.3 ±3.1-3.0 (stat) +3.1-3.0 (syst)</td>
<td>7.3 ± 1.8</td>
</tr>
</tbody>
</table>
H→WW: changes wrt last public paper


♦ optimized object and event selection: pT, mT resolution, ...

♦ increased signal acceptance: lower lepton pT thresholds, electron likelihood

♦ background estimation techniques: b-tagging efficiency from data, jj estimate, Z + jets sample for Wj estimate, ...

♦ optimized VBF signal category

♦ new analysis category (Njet ≥ 2 ggF-enriched),

♦ more powerful statistical treatment (binned in mT and pT_{l2})

♦ 50% increase in the expected sensitivity
H → γγ: selection

- $E_T^{\gamma_1}/m_{\gamma\gamma} > 0.35$, $E_T^{\gamma_2}/m_{\gamma\gamma} > 0.25$
- tight identification
- $E_{T\text{iso,calo}} < 6 \text{ GeV}$, $E_{T\text{iso,track}} < 2.6 \text{ GeV}$

- γγ purity: 77±3% at 8 TeV
H→γγ: systematic uncertainties

♦ Main systematics and impact on μ:

<table>
<thead>
<tr>
<th>Uncertainty group</th>
<th>σ_{μ}^{syst.}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory (yield)</td>
<td>0.09</td>
</tr>
<tr>
<td>Experimental (yield)</td>
<td>0.02</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.03</td>
</tr>
<tr>
<td>MC statistics</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Theory (migrations)</td>
<td>0.03</td>
</tr>
<tr>
<td>Experimental (migrations)</td>
<td>0.02</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.07</td>
</tr>
<tr>
<td>Mass scale</td>
<td>0.02</td>
</tr>
<tr>
<td>Background shape</td>
<td>0.02</td>
</tr>
</tbody>
</table>
H → γγ: results

♦ Signal strength /production mode:

\[ \mu_{t\bar{t}H} \]
\[ \mu_{ZH} \]
\[ \mu_{WH} \]
\[ \mu_{VBF} \]
\[ \mu_{ggF} \]

**ATLAS**

\[ H \rightarrow \gamma\gamma, \; m_H = 125.4 \text{ GeV} \]

Total uncertainty

\[ \pm 1\sigma \]
\[ \pm 2\sigma \]

\[ \mu_{VBF} / \mu_{ggF} = 0.6^{+0.8}_{-0.5} \]
\[ \mu_{VH} / \mu_{ggF} = 0.6^{+1.1}_{-0.6} \]
\[ \mu_{t\bar{t}H} / \mu_{ggF} = 1.2^{+2.2}_{-1.4} \]

\[ \int L dt = 4.5 \text{ fb}^{-1}, \; \sqrt{s} = 7 \text{ TeV} \]
\[ \int L dt = 20.3 \text{ fb}^{-1}, \; \sqrt{s} = 8 \text{ TeV} \]
H→γγ: compatibility of results

♦ checked with jackknife resampling technique

♦ Phys. Lett. B 726 (2013) : \( \mu = 1.55^{+0.33}_{-0.28} \)
  - 142681 events selected there
  - 111791 events selected in current analysis
  - 104407 events selected in both
  - significance of the 0.4 difference between the \( \mu \) (with effect of the 74% correlation between the two measurements): 2.3 \( \sigma \).

♦ Mass measurement : \( \mu = 1.29 \pm 0.30 \)
  - compatible within 1\( \sigma \)

♦ Fiducial cross-sections: \( \mu \approx 1.4 \) (8 TeV only)
  - compatible within 1.2\( \sigma \)
H→γγ: changes wrt last public paper


♦ Relative $E_T/m_{\gamma\gamma}$ cuts

♦ Improved material description

♦ Improved calibrations
  - mass resolution improved by 10%
  - resolution uncertainty reduced by factor 2

♦ Reduced uncertainties on photon ID and isolation

♦ Categories changed
  - added ttH leptonic, hadronic
  - split VH into 1-lepton (WH) and 2-lepton (ZH)
  - reduce number of untagged categories (without loss of sensitivity)

♦ 10% gain on combined signal strength
H → γγ: Total and fiducial cross-sections

♦ Fiducial volume:

- photons with $E_T^{\gamma 1}/m_{\gamma\gamma} > 0.35$, $E_T^{\gamma 2}/m_{\gamma\gamma} > 0.25$, |η| < 2.37
- particle isolation (in ΔR = 0.4) <14 GeV

♦ Results:

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Measured cross section (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>$43.2 \pm 9.4$ (stat.) $^{+3.2}_{-2.9}$ (syst.) ± 1.2 (lumi)</td>
</tr>
<tr>
<td>$N_{jets} \geq 1$</td>
<td>$21.5 \pm 5.3$ (stat.) $^{+1.2}_{-1.1}$ (syst.) ± 0.6 (lumi)</td>
</tr>
<tr>
<td>$N_{jets} \geq 2$</td>
<td>$9.2 \pm 2.8$ (stat.) $^{+1.3}_{-1.2}$ (syst.) ± 0.3 (lumi)</td>
</tr>
<tr>
<td>$N_{jets} \geq 3$</td>
<td>$4.0 \pm 1.3$ (stat.) ± 0.7 (syst.) ± 0.1 (lumi)</td>
</tr>
<tr>
<td>VBF-enhanced</td>
<td>$1.68 \pm 0.58$ (stat.) $^{+0.24}_{-0.25}$ (syst.) ± 0.05 (lumi)</td>
</tr>
<tr>
<td>$N_{leptons} \geq 1$</td>
<td>&lt; 0.80</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; 80$ GeV</td>
<td>&lt; 0.74</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Theoretical prediction (fb)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>$30.5 \pm 3.3$</td>
<td>LHC-XS [57] + XH</td>
</tr>
<tr>
<td></td>
<td>$34.1 \pm 3.6$</td>
<td>STWZ [99] + XH</td>
</tr>
<tr>
<td></td>
<td>$27.2 \pm 3.6$</td>
<td>HRES [103] + XH</td>
</tr>
<tr>
<td>$N_{jets} \geq 1$</td>
<td>$13.8 \pm 1.7$</td>
<td>BLPTW [106] + XH</td>
</tr>
<tr>
<td></td>
<td>$11.7 \pm 2.0$</td>
<td>JetVHeto [107] + XH</td>
</tr>
<tr>
<td></td>
<td>$9.3 \pm 1.8$</td>
<td>MINLO HJ + XH</td>
</tr>
<tr>
<td>$N_{jets} \geq 2$</td>
<td>$5.65 \pm 0.87$</td>
<td>BLPTW + XH</td>
</tr>
<tr>
<td></td>
<td>$3.99 \pm 0.56$</td>
<td>MINLO HJJ + XH</td>
</tr>
<tr>
<td>$N_{jets} \geq 3$</td>
<td>$0.94 \pm 0.15$</td>
<td>MINLO HJJ + XH</td>
</tr>
<tr>
<td>VBF-enhanced</td>
<td>$0.87 \pm 0.08$</td>
<td>MINLO HJJ + XH</td>
</tr>
<tr>
<td>$N_{leptons} \geq 1$</td>
<td>$0.27 \pm 0.02$</td>
<td>XH</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; 80$ GeV</td>
<td>$0.14 \pm 0.01$</td>
<td>XH</td>
</tr>
</tbody>
</table>

♦ Total cross-section: $31.4 \pm 7.2$ (stat) ± 1.6 (sys) pb
Fiducial volume:

Results:
- \( \sigma_{\text{fid}} = 2.11 \pm 0.53 \text{ (stat)} \pm 0.08 \text{(syst)} \text{ fb} \)

Total cross-section:
- \( 5.1 \pm 8.4 \text{ (stat)} \pm 1.8 \text{(syst) pb} \)