Recent ATLAS Higgs Results

Nicolas Berger (LAPP), for the ATLAS collaboration

Charting the Unknown: interpreting LHC data from the energy frontier, Aug 8th, 2016
The Higgs Boson in Run 2

ATLAS ICHEP Dataset (2015+2016): 13.2 fb\(^{-1}\) to 14.8 fb\(^{-1}\) of data at 13 TeV

2016 Peak LHC Luminosity: 1.16 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)

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1.16 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}

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<td>ttH</td>
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<td>H→γγ</td>
<td>H→4l</td>
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H(125) Covered Topics

H \rightarrow bb \quad H \rightarrow WW/\tau \tau \quad H \rightarrow \gamma \gamma \quad H \rightarrow 4l

- ggF
- VBF
- VH
- ttH

H \rightarrow bb: Searches in VH, ttH, VBF+\gamma
H(125) Covered Topics

H → bb: Searches in VH, ttH, VBF+γ

H → ZZ* → 4l

ggF/VBF/VH cross-section measurements

High mass:
4l, vvll, lvlv, llqq, lvqq, vvqq
Covered in K. Terashi’s presentation
# H(125) Covered Topics

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<tr>
<td>VH</td>
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<td></td>
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</tr>
<tr>
<td>ttH</td>
<td></td>
<td></td>
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<td></td>
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</table>

- **H→bb**: Searches in VH, ttH, VBF+γ
- **H→WW/ττ**: ggF/VBF/VH cross-section measurements
- **High mass H→ZZ*→4l**: ggF/VBF/VH cross-section measurements
- **γγ covered in L. Carminati’s presentation**
- **High mass H→Zγ**: γγ covered in K. Terashi’s presentation
H(125) Covered Topics

**H → bb**
- Searches in VH, ttH, VBF + γ

**H → WW/ττ**
- In Preparation

**H → γγ**
- ggF/VBF/VH/ttH cross-section measurements
- Differential distributions
- **High mass** H → Zγ
  - γγ covered in L. Carminati’s presentation

**H → 4l**
- ttH → multileptons: WW, ττ, ZZ
- ggF/VBF/VH cross-section measurements
- **High mass** 4l, vvlv, llqq, lvqq, vvqq
- Covered in K. Terashi’s presentation
H(125) Covered Topics

- **H → bb**: Searches in VH, ttH, VBF + γ
- **H → WW/ττ**: In Preparation
- **H → γγ**:
  - ggF/VBF/VH/ttH cross-section measurements
  - Differential distributions
- **H → ZZ* → 4l**: High mass
  - 4l, vvll, lvlv, llqq, lvqq, vvvq
  - Covered in K. Terashi’s presentation
- **H → γγ**:
  - ggF/VBF/VH/ttH cross-section measurements
  - Differential distributions
- **H → ZZ**
  - γγ covered in L. Carminati’s presentation
- **ttH → multileptons**: WW, ττ, ZZ

**ttH Combination**

**H → γγ + H → ZZ** Combination
H → bb

See P. Conde Muino’s ICHEP presentation
VH searches: 3 channels

- **0-lepton:**
  \[ E_{T}^{\text{miss}} > 150 \text{ GeV} \]

- **1-lepton:**
  \[ e/\mu, p_{T} > 25 \text{ GeV} \]
  
  Tight isolation
  
  Missing \( E_{T} \)
  
  \[ p_{T}^{V} > 150 \text{ GeV} \]

- **2-leptons:**
  
  Isolated ee, \( \mu \mu \)
  
  \[ p_{T}^{1} > 25 \text{ GeV}, p_{T}^{2} > 7 \text{ GeV} \]
  
  No missing \( E_{T} \),
  
  \[ m_{\tau} \text{ compatible with } m_{Z} \]

- **Two jets**
  
  anti-kT with \( R=0.4 \)
  
  \[ p_{T}^{j1} > 45 \text{ GeV} \]
  
  \[ p_{T}^{j2} > 20 \text{ GeV} \]

- **Improved b-tagging with respect to Run 1:**
  
  Eff: 70% , light jet rejection: 380, charm rejection: 12

- **Analysis categories:**
  
  2/3 jets (0/1lepton)
  
  2\geq3 jets (2lept.)
  
  \[ p_{T}^{V} \leftrightarrow 150 \text{ GeV} \text{ (2lept)} \]
Multi-variate analysis

- Boosted decision tree (BDT)
  
  Combine many different variables
  
  Trained in 8 categories: 3 lepton, 2/3 jets, low/high $p_T$ bin (2 lepton channel)
  
- Most discrimination from $m_{bb}$ and $\Delta R(b_1, b_2)$

![Graph showing $m_{bb}$ vs $\Delta R(b_1, b_2)$]

- New in run 2: $m_{Top}$, $|\Delta Y(V,H)| \rightarrow +7\%$ in sensitivity
- Profiled likelihood fit to measure the signal strength
- Take into account all event categories
- Use BDT discriminant as input
- Post-fit distributions:
  - $E_T^{miss}$
  - 0 lep, 2 jets, 2 btags
  - $W$ transverse mass
  - 1 lep, 3 jets, 2 btags

![Graphs showing event distributions for different categories.](image)
Results $H \rightarrow bb$ in association with a W or Z

- Combined signal strength with 13.2 fb$^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV

$$\mu_{VH, H \rightarrow bb} = 0.21^{+0.51}_{-0.50}$$

Systematic and statistical uncertainties of the same size

Dominant systematics from b-tagging and background normalization & modelling (W+jets, Z+jets, top)

- Fit cross checked with di-boson signal (WZ+ZZ with Z→bb)

Observed significance: 3.2$\sigma$

$$\mu_{VZ} = 0.91 \pm 0.17 \, (stat)^{+0.32}_{-0.23} \, (sys)$$
Combined signal strength with 13.2 fb$^{-1}$ of pp collisions at $\sqrt{s}=13$ TeV

$\mu_{VH, H\rightarrow bb} = 0.21^{+0.51}_{-0.50}$
**ttH(bb) analysis: event selection and background**

- **Event selection** (event triggered by single lepton triggers)
  - Single lepton channel (one leptonic W decay)
    - one electron or muon
    - at least 4 jets
    - at least 2 b-tagged jets
  - Dilepton channel (two leptonic W decays)
    - 2 opposite charge light (e,μ) leptons
    - at least 3 jets
    - at least 2 b-tagged jets
  - Events are categorised according to no. of jets and no. of b-tagged jets.

![Diagram showing event selection and background](image-url)
**tH(bb) analysis: event selection and background**

- **Event selection** (event triggered by single lepton triggers)
  - **Single lepton channel** (one leptonic W decay)
    - one electron or muon
    - at least 4 jets
    - at least 2 b-tagged jets
  - $t\bar{t} + \geq 1$ b-jet, $t\bar{t} + \geq 1$ c-jet, and $t\bar{t} +$ light-jets are the dominant backgrounds.

- **Dilepton channel** (two leptonic W decays)
  - 2 opposite charge light ($e,\mu$) leptons
  - at least 3 jets
  - at least 2 b-tagged jets

Exploit different background compositions in simultaneous fit of all regions to reduce uncertainties.
\( \bar{t}tH(bb) \) analysis: result

- Data vs. prediction in all analysis bins, ranked by S/B \( \rightarrow \) left plot.
- Summary of signal strength measurements \( \rightarrow \) right plot.
- 95% C.L. upper limit on the \( \bar{t}tH \) signal strength \( \rightarrow \) bottom table.

\begin{table}
\begin{tabular}{|c|c|c|c|c|}
\hline
 & Observed & Expected (\( \mu = 0 \)) & Expected (\( \mu = 1 \)) \\
\hline
Dilepton & 10.1 & 5.3 & [3.8, 7.9] & [2.8, 12.6] & 6.0 \\
Single lepton & 3.6 & 2.2 & [1.6, 3.2] & [1.2, 4.7] & 2.9 \\
Combined & 4.0 & 1.9 & [1.4, 2.8] & [1.0, 4.2] & 2.7 \\
\hline
\end{tabular}
\end{table}

Run 1: \( \mu = 1.4 \pm 1.0 \)

Uncertainty of the measurement is dominated by normalization and modelling of \( \bar{t}t + b/c \)-jet backgrounds.

J. Keller (DESY)
Use a profile likelihood fit
Non resonant background estimated with 2nd order polynomial fit in $m_{bb}$ sideband
Fit tested searching for $Z \rightarrow bb + \gamma$ production:

Expected 95% CL limit: $1.8^{+0.7}_{-0.5}$
Observed: 2.0

Observed signal strength in the Higgs search:
$\mu_{H,VBF+\gamma} = -3.9^{+2.8}_{-2.7}$
Expected 95% CL limit:
$6.0^{+2.3}_{-1.7}$
Observed 95% CL limit:
$4 \times (\sigma \times BR)_SM$

<table>
<thead>
<tr>
<th>Result</th>
<th>$H(\rightarrow b\bar{b}) + \gamma jj$</th>
<th>$Z(\rightarrow b\bar{b}) + \gamma jj$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected significance</td>
<td>0.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Expected $p$-value</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Observed $p$-value</td>
<td>0.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Expected limit</td>
<td>6.0 $^{+2.3}_{-1.7}$</td>
<td>1.8 $^{+0.7}_{-0.5}$</td>
</tr>
<tr>
<td>Observed limit</td>
<td>4.0 $^{-1.7}$</td>
<td>2.0</td>
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<tr>
<td>Observed signal strength $\mu$</td>
<td>$-3.9^{+2.8}_{-2.7}$</td>
<td>0.3 $^{+0.8}_{-0.8}$</td>
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Low BDT score region:

High BDT score region:
See L. Aperio-Bella’ ICHEP presentation
Golden channel: Two pairs of same flavour, opposite sign leptons: 4e, 2e2μ, 2μ2e, 4μ
- S/B better than 2 for all the channel
  - el ch: Improved suppression of conversion/heavy flavour background contributions with the new inner most pixel layer.
- Narrow peak (1.6-2.3 GeV @125 GeV) on top of smooth background
- \( m_{Z_1} \) (+ FSR photons) kinematically constrained to \( m_Z \rightarrow 15\% \) improvement in the resolution
- Signal acceptance x efficiency range 15-37% @mH 125 GeV

Selection Challenge: high lepton reconstruction/identification efficiency \( \rightarrow \) to catch lowest p\(_T\) leptons
- e and \( \mu \) selection down to low PT (7, 5 GeV)
  - lowering muon p\(_T\) cut from 6 to 5 GeV \( \rightarrow \) ~8% increase on the signal acceptance
  - Vertex compatibility cut added for the 4l candidates
Cross section by production mode

In $118 < m_{4l} < 129$ GeV **Dedicated exclusive event categories** used to measure:
- cross section per production mode
- but also sensitive to BSM interactions between the Higgs boson and the SM vector bosons.

**Cross section measurement per production mode:**

- **ATLAS Preliminary**
  - $H \rightarrow ZZ^* \rightarrow 4l$
  - 13 TeV, 14.8 fb$^{-1}$
  - $N_{Jet} = 2$ VBF-enriched

- **ATLAS Preliminary**
  - $H \rightarrow ZZ^* \rightarrow 4l$
  - 13 TeV, 14.8 fb$^{-1}$
  - $N_{Jet} = 0$

- Multivariate discriminants (BDT) are used in each category to improve the sensitivity to each production mode.
- Signal extraction through a LH fit to the BDT in different category.
- The cross sections for different production modes are evaluated assuming $m_H = 125.09$ GeV.
Cross section measurement per production mode

**H4l Couplings Results**

**ATLAS** Preliminary

**H → ZZ* → 4l**

13 TeV, 14.8 fb⁻¹

<table>
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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>(σ_{ggF+bbH+\bar{t}H} \cdot \mathcal{B}(H \rightarrow ZZ^*))</td>
<td>1.80^{+0.49}_{-0.44} \text{ pb}</td>
</tr>
<tr>
<td>(σ_{VBF} \cdot \mathcal{B}(H \rightarrow ZZ^*))</td>
<td>0.37^{+0.28}_{-0.21} \text{ pb}</td>
</tr>
<tr>
<td>(σ_{VH} \cdot \mathcal{B}(H \rightarrow ZZ^*))</td>
<td>0^{+0.15}_{-0.21} \text{ pb}</td>
</tr>
<tr>
<td>(σ_{SM,ggF+bbH+\bar{t}H} \cdot \mathcal{B}(H \rightarrow ZZ^*))</td>
<td>1.31 ± 0.07 pb</td>
</tr>
<tr>
<td>(σ_{SM,VBF} \cdot \mathcal{B}(H \rightarrow ZZ^*))</td>
<td>0.100 ± 0.003 pb</td>
</tr>
<tr>
<td>(σ_{SM,VH} \cdot \mathcal{B}(H \rightarrow ZZ^*))</td>
<td>0.059 ± 0.002 pb</td>
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**Compatibility to the SM prediction**

\(σ_{ggF+bbH+ttH} \cdot \mathcal{B}(H \rightarrow ZZ^*)\) is 1.1\(σ\) and \(σ_{VBF} \cdot \mathcal{B}(H \rightarrow ZZ^*)\) is 1.4\(σ\).
ttH → multileptons

See J. Keller’s ICHEP presentation
$\bar{t}tH$ (multileptons) analysis: event selection and background

- Events are separated into **4 orthogonal channels**:
  - two same-charge light leptons + no $\tau_{\text{had}}$ $\rightarrow$ $2\ell 0\tau_{\text{had}}$
    - (at least 5 jets and at least 1 b-jet)
  - two same-charge light leptons + one $\tau_{\text{had}}$ $\rightarrow$ $2\ell 1\tau_{\text{had}}$
    - (at least 4 jets and at least 1 b-jet)
  - three light leptons $\rightarrow$ $3\ell$ ($\geq 4\text{jets,} \geq 1\text{bjet, or} 3\text{jets,} \geq 2\text{bjets}$)
  - four light leptons $\rightarrow$ $4\ell$ ($\geq 2\text{jets,} \geq 1\text{bjet}$)

- **Dominant backgrounds**:
  - $\bar{t}tW$, $\bar{t}tZ$ $\rightarrow$ estimated from simulation
  - di-boson (VV) $\rightarrow$ estimated from simulation
  - non-prompt light leptons $\rightarrow$ estimated from data control region
  - electron charge mis-identification $\rightarrow$ estimated from data of $Z+$jets events
  - hadronic tau mis-reconstruction $\rightarrow$ estimated from simulation and normalised to data control region.
ttH (multileptons) analysis: result

- Cut-and-count analysis in 6 categories: $2\ell 0\tau_{\text{had}}$ ($ee, e\mu, \mu\mu$), $2\ell 1\tau_{\text{had}}$, $3\ell$ and $4\ell$.

- Pre-fit predictions and observed data events.

- Best fit values of the ttH signal strength.

Systematic uncertainty is dominated by non-prompt background estimates in the $2\ell 0\tau_{\text{had}}$, $2\ell 1\tau_{\text{had}}$, and $3\ell$ channels.

Run 1:

$2.1 \pm 1.4$ ($\pm 1.1$)
See A. Pilkington’s ICHEP presentation
Extraction of Higgs boson signal

- Signal extracted by fitting the diphoton invariant mass ($m_{\gamma\gamma}$) spectrum
  - **Selection**: two isolated photons with $p_{T,1} > 0.35 \, m_{\gamma\gamma}$, $p_{T,2} > 0.25 \, m_{\gamma\gamma}$ and $|\eta| < 2.37$ (excluding $1.37 < |\eta| < 1.52$)

- **Signal model**: double-sided Crystal Ball (parameters from simulation)
- **Background model**: exponential of polynomial, or Bernstein polynomial
- **Dominant systematic**: photon energy resolution and background choice bias.
Production cross section and signal strength methodology (I)

- Events are split into 13 orthogonal categories that exploit topological differences between production mechanisms

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**ATLAS Simulation Preliminary**

$H \rightarrow \gamma \gamma$  $\sqrt{s}=13$ TeV

<table>
<thead>
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<td>19</td>
</tr>
<tr>
<td>72</td>
</tr>
<tr>
<td>3</td>
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<tr>
<td>8</td>
</tr>
<tr>
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<td>66</td>
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<td>937</td>
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<td>604</td>
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<td>3977</td>
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<tr>
<td>85129</td>
</tr>
<tr>
<td>1319</td>
</tr>
<tr>
<td>31907</td>
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</tbody>
</table>
Production cross section and signal strength measurements

**Total Higgs production cross section**

\[
\begin{align*}
\sigma_{ggH} \times \mathcal{B}(H \rightarrow \gamma\gamma) &= 65^{+32}_{-31} \text{ fb} \\
\sigma_{VBF} \times \mathcal{B}(H \rightarrow \gamma\gamma) &= 19.2^{+6.8}_{-6.1} \text{ fb} \\
\sigma_{VH} \times \mathcal{B}(H \rightarrow \gamma\gamma) &= 1.2^{+6.5}_{-5.4} \text{ fb} \\
\sigma_{t\bar{t}H} \times \mathcal{B}(H \rightarrow \gamma\gamma) &= -0.28^{+1.44}_{-1.12} \text{ fb}
\end{align*}
\]

**Higgs production cross section (|\gamma| < 2.5)**

\[
\begin{align*}
\sigma_{ggH} \times \mathcal{B}(H \rightarrow \gamma\gamma) &= 63^{+30}_{-29} \text{ fb} \\
\sigma_{VBF} \times \mathcal{B}(H \rightarrow \gamma\gamma) &= 17.8^{+6.3}_{-5.7} \text{ fb} \\
\sigma_{VHlep} \times \mathcal{B}(H \rightarrow \gamma\gamma) &= 0.96^{+2.52}_{-1.90} \text{ fb} \\
\sigma_{VHhad} \times \mathcal{B}(H \rightarrow \gamma\gamma) &= -2.3^{+6.8}_{-5.8} \text{ fb} \\
\sigma_{t\bar{t}H} \times \mathcal{B}(H \rightarrow \gamma\gamma) &= -0.28^{+1.43}_{-1.12} \text{ fb}
\end{align*}
\]
• Good agreement between data and theory
  – very slightly harder Higgs $p_T$ spectrum in data as in Run-I (left)
  – data in agreement with theory expectation for scalar CP-even particle (right)
Jet activity

- Good agreement between data and theory
  - Data in agreement with state-of-art theory predictions
Event selection

- Selection criteria similar to 2015 analysis
  - single and di-lepton triggers
  - two isolated, opposite-sign leptons \((p_T^e>19 \text{ GeV}, p_T^\mu>24,10 \text{ GeV})\) with \(m_{ll} \sim m_Z\)
    - isolation computed in small \(\Delta R\) cones, subtracting contribution from other lepton to avoid inefficiencies at high \(m_X\)
  - one isolated photon, \(p_T^\gamma/m_{ll}^\gamma>0.3\) (exploit spin-0 isotropic decay in \(X\) center-of-mass reference frame)
  - quality requirements on leptons and photon (tracks, hits in muon detector, shower shape in calorimeter, track-cluster match..)
  - \(m_{ll}^\gamma>200 \text{ GeV}\)

<table>
<thead>
<tr>
<th></th>
<th>ee</th>
<th>(\mu\mu)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events</td>
<td>306</td>
<td>485</td>
<td>791</td>
</tr>
<tr>
<td>Highest mass</td>
<td>1.5 TeV</td>
<td>1.3 TeV</td>
<td>1.5 TeV</td>
</tr>
</tbody>
</table>
Results

- No significant excess
- Good fit quality
- Largest deviation from bkg-only hypothesis in $250 < m_X < 2400$ GeV: local significance of $\sim 2.2\sigma$ at $m_X \sim 270$ GeV
Limits on $\sigma(pp\to X)\times\text{BR}(X\to Z\gamma)$

- 95% CL upper limits set with CL$_s$ method (w/ asymptotic approximation of test statistic)

- Expected: 5–105 fb, observed: 5–215 fb
Combinations

See ICHEP presentations by B. Laforge and J. Keller
**Summary of the $t\bar{t}H$ signal strength measurements (left) and upper limits (right).**

**Expected and observed significance with respect to background-only hypothesis.**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}H, H \rightarrow \gamma \gamma$</td>
<td>-0.2</td>
</tr>
<tr>
<td>$t\bar{t}H, H \rightarrow (WW, \tau\tau, ZZ)$</td>
<td>2.2</td>
</tr>
<tr>
<td>$t\bar{t}H, H \rightarrow b\bar{b}$</td>
<td>2.4</td>
</tr>
<tr>
<td>$t\bar{t}H$ combination</td>
<td>2.8</td>
</tr>
</tbody>
</table>

**Run 1:**

$1.9 \pm 0.8 \pm 0.7$
Higgs boson combination at Run 2 using ZZ(4\ell) and γγ final states

Which data?
Inclusive samples H→γγ and H→Z→4l
No categorisation

Which fit is performed?
Fit total cross-section using SM BR, acceptance from SM MC samples

\[ N_{γγ} = \sigma_{pp→H} \times BR_{SM(γγ)} \times \text{Eff.} \times \text{Acc.} \times \text{Lumi}_{γγ} \]

\[ N_{4\ell} = \sigma_{pp→H} \times BR_{SM(4\ell)} \times \text{Eff.} \times \text{Acc.} \times \text{Lumi}_{4\ell} \]

Use profiled likelihood ratio fit with ~200 nuisance parameters θ and get vector α (params of interest: here \( \sigma_{pp→H} \))

\[ \Lambda(\alpha) = \frac{L(\alpha, \hat{θ}(α))}{L(\hat{α}, \hat{θ})} \]

04/08/16

B. LAFOREST - Higgs Studies with ATLAS

ATLAS-CONF-2016-081
Higgs boson combination at Run 2 using $ZZ(4\ell)$ and $\gamma\gamma$ final states

ATLAS-CONF-2016-081

Which data?

Inclusive samples $H\rightarrow\gamma\gamma$ and $H\rightarrow Z\rightarrow 4\ell$

No categorisation

Which fit is performed?

Global signal strength after fit is:

$$\mu = 1.13^{+0.18}_{-0.17}$$

Higgs production is observed with 10 $\sigma$ significance (8.6 expected) with 13 TeV data in agreement with SM expectations

Use profiled likelihood ratio fit with $\sim 200$ nuisance parameters $\theta$ and get vector $\alpha$ (params of interest: here $\sigma_{pp\rightarrow H}$)

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\theta}(\alpha))}{L(\hat{\alpha}, \hat{\theta})}$$

Table 8: Total $pp \rightarrow H + X$ cross sections measured using $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ decays, and their combination, for centre-of-mass energies of 7, 8 and 13 TeV. The SM predictions [7] are computed for a Higgs boson mass of 125.09 GeV [9].

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Total cross section ($pp \rightarrow H + X$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sqrt{s} = 7$ TeV</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$35^{+13}_{-12}$ pb</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>$33^{+21}_{-16}$ pb</td>
</tr>
<tr>
<td>Combination</td>
<td>$34 \pm 10$ (stat.) $^{+1}_{-2}$ (syst.) pb</td>
</tr>
<tr>
<td>SM predictions [7]</td>
<td>$19.2 \pm 0.9$ pb</td>
</tr>
</tbody>
</table>
Higgs boson combination at Run 2 using ZZ and $\gamma\gamma$ final states

Which fit performed?

Use categorised data and allow different production cross-section (restricted to fiducial region) and different BR (7 parameters)

$\sigma_1$: cross-section fiducial definition is $|y_H|<2.5$

$bbH$ is coupled with $gg \to H$ by assuming SM predictions for the ratios of the two processes, $tH$ is coupled with $ttH$, by assuming SM predictions for the ratios of the $pp \to tH$ and the $pp \to ttH$ cross sections, together reported as “top”.

$WH$ and $ZH$ are merged, separately for the leptonic and the hadronic $V$ decays\(^1\), into $V(\to q\bar{q})H$ and $V(\to$ leptons)$H$, reported as “$VH$had” and “$VH$lep”, respectively. The merging assumes the SM prediction for the ratio of the production cross sections and includes the contributions from both $q\bar{q} \to VH$ and $gg \to ZH$.

**ATLAS**

Preliminary

$m_H = 125.09$ GeV

$s_0 = 13$ TeV, $13.3$ fb$^{-1}(\gamma\gamma)$, $14.5$ fb$^{-1}$(ZZ)

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$ggF$</th>
<th>VBF</th>
<th>VH had</th>
<th>VH lep</th>
<th>top</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>$(\sigma \cdot B)_{ggF}^{\gamma\gamma}$</td>
<td>$(\sigma \cdot B)_{VBF}^{\gamma\gamma}$</td>
<td>$(\sigma \cdot B)_{VH had}^{\gamma\gamma}$</td>
<td>$(\sigma \cdot B)_{VH lep}^{\gamma\gamma}$</td>
<td>$(\sigma \cdot B)_top^{\gamma\gamma}$</td>
</tr>
<tr>
<td>$H \to ZZ^*$</td>
<td>$(\sigma \cdot B)_{ggF}^{ZZ}$</td>
<td>$(\sigma \cdot B)_{VBF}^{ZZ}$</td>
<td>fixed to SM</td>
<td>fixed to SM</td>
<td>fixed to SM</td>
</tr>
</tbody>
</table>

**ATLAS**

Preliminary

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<td>$(\sigma \cdot B)_{VBF}^{ZZ}$</td>
<td>fixed to SM</td>
<td>fixed to SM</td>
<td>fixed to SM</td>
</tr>
</tbody>
</table>

Parameter value norm. to SM value

Good agreement with SM
Higgs boson combination at Run 2 using ZZ and gg final states

ATLAS-CONF-2016-081

Which fit performed?
Use categorised data and allow different production cross-section (restricted to fiducial region) and assume SM BR (5 parameters)

<table>
<thead>
<tr>
<th>Best fit value (pb)</th>
<th>SM prediction (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{ggF}$</td>
<td>47.8 $^{+9.8}_{-9.4}$</td>
</tr>
<tr>
<td>$\sigma_{VBF}$</td>
<td>7.9 $^{+2.8}_{-2.4}$</td>
</tr>
<tr>
<td>$\sigma_{VH\text{had}}$</td>
<td>$-2.5$ $^{+2.9}_{-2.6}$</td>
</tr>
<tr>
<td>$\sigma_{VH\text{lep}}$</td>
<td>0.32 $^{+1.07}_{-0.79}$</td>
</tr>
<tr>
<td>$\sigma_{\text{top}}$</td>
<td>$-0.11$ $^{+0.67}_{-0.54}$</td>
</tr>
</tbody>
</table>

No sensitivity yet to VH and ttH
Which fit is performed?

Use categorised data and allow different production cross-section (restricted to fiducial region) and different BR.

Use as a reference (from SM):
- ggF cross-section
- $H \rightarrow ZZ$ Branching ratio

Then fit 3 parameters only:

$$(\sigma \cdot B)^f_i = (\sigma \cdot B)^{ZZ}_{ggF} \cdot \left( \frac{\sigma_i}{\sigma_{ggF}} \right) \cdot \left( \frac{B_f}{B_{ZZ}} \right)$$

$\sigma_i$: cross-section fiducial definition is $|y_H|<2.5$

No sensitivity yet to VH and ttH, fit VBF, ggF and $B_{\gamma\gamma}/B_{ZZ}$ and profile the other ratios in the fit.
Search for $H \rightarrow \mu\mu$

- $H \rightarrow \mu\mu$ is rare decay in the SM: BR = 0.0218% @ 125 GeV
- Probe Yukawa-coupling to 2nd-generation fermions and mass dependence
- Clean signature in huge $Z \rightarrow \mu\mu$ and continuum background
Search for $H \rightarrow \mu\mu$

- Separate by Higgs production mode:
  - **VBF-enriched** category selected by multivariate classifier (**new in run-2**)
  - 6 **ggF-enriched** categories depending on $p_T^H$ and $|\eta_\mu|$ to maximize significance
- Signal shape parametrized for regions: Crystal-Ball + Gaussian

- $H \rightarrow \mu\mu$ is rare decay in the SM: BR = 0.0218% @ 125 GeV
- Probe Yukawa-coupling to 2nd-generation fermions and mass dependence
- Clean signature in huge $Z \rightarrow \mu\mu$ and continuum background

See C. Grefe’s talk at ICHEP
Search for $H \rightarrow \mu\mu$

13.2 fb$^{-1}$ @ 13 TeV

- Background shape free in the fit:
  
  Breit-Wigner $\otimes$ Gaussian (Z-peak) + $e^{Ax}/x^3$ (continuum)
Search for $H \rightarrow \mu\mu$

13.2 fb$^{-1}$ @ 13 TeV

95% CL BR upper limit for $M_H = 125.09$ GeV

**Run-1:** $\mu < 7.1$ (obs.), 7.2 (exp.)
**Run-2:** $\mu < 4.4$ (obs.), 5.5 (exp.)

**Combined:** $\mu < 3.5$ (obs.), 4.3 (exp.)

- Background shape free in the fit:
  Breit-Wigner $\otimes$ Gaussian (Z-peak) $+$ $e^{Ax}/x^3$ (continuum)
Conclusion

- The Higgs is still here!
- Properties still compatible with the SM
- Sensitivity already equal to Run 1 or higher for many measurements
- Much more data to come in Run 2
  - Already ~20 fb\(^{-1}\) in 2016
  - 30 fb\(^{-1}\) planned, more possible
Results not Covered in this Presentation

• **High-mass searches**: see K. Terashi’s presentation in the previous session
  – **WW**: $ll\nu\nu$ (ATLAS-CONF-2016-074), $lvqq$ (ATLAS-CONF-2016-062), see K. Koeneke’s ICHEP presentation
  – **ZZ**: $4\ell$ (ATLAS-CONF-2016-079), $ll\nu\nu$ (ATLAS-CONF-2016-056), $llqq$, $vvqq$ (ATLAS-CONF-2016-082), see again K. Koeneke’s ICHEP presentation
  – **$\gamma\gamma$** (ATLAS-CONF-2016-059), covered by L. Carminati’s presentation on Friday, see also B. Lenzi’s ICHEP presentation.
  – **Fermionic modes**: $\tau\tau$ (ATLAS-CONF-2016-085), $tt$ (ATLAS-CONF-2016-073) see T. Vickey’s ICHEP presentation

• **Di-Higgs**: see K. Terashi’s presentation in the previous session and T. Varol’s ICHEP presentation
  – **HH → WW$\gamma\gamma$** (ATLAS-CONF-2016-071)
  – **HH → 4b** (ATLAS-CONF-2016-049)

• **ZH→invisible**: ATLAS-CONF-2016-056, see M. Trovatelli’s ICHEP presentation

• **Charged Higgs searches**: C. Gwilliam’s ICHEP presentation
  – **$H → \tau\nu$** (ATLAS-CONF-2016-088)
  – **$H → tb$** (ATLAS-CONF-2016-089)

• **Rare and exotic decays**
  – **$H → aa → \gamma\gamma$** see L. Zivkovic’s ICHEP presentation
  – **$H → \phi\gamma$, LFV** see D. Gerbaudo’s ICHEP presentation

• **$H → \gamma\gamma +\text{MET}$**: ATLAS-CONF-2016-087
Results Shown here

- $H \rightarrow bb$: See P. Conde Muino’s ICHEP presentation
  - VH (ATLAS-CONF-2016-09), VBF+g (ATLAS-CONF-2016-063)
- $H \rightarrow 4l$: See L. Aperio-Bella’ ICHEP presentation
  - ATLAS-CONF-2016-079
- $H \rightarrow \gamma\gamma$: See A. Pilkington’s ICHEP presentation
  - ATLAS-CONF-2016-067
- $4l+\gamma\gamma$ Combination: See B. Laforge’s ICHEP presentation
  - ATLAS-CONF-2016-081
- **Fermionic Decays**: See C. Grefe’s talk at ICHEP
  - $H \rightarrow \mu\mu$ (ATLAS-CONF-2016-041)
- $H \rightarrow Z\gamma$: See G. Marchiori’s ICHEP presentation, ATL-CONF-2016-044
- $ttH$: See J. Keller’s ICHEP presentation
  - $H \rightarrow bb$ (ATLAS-CONF-2016-080)
  - Mutileptons (ATLAS-CONF-2016-058)
  - Combination (ATLAS-CONF-2016-068)
Backup
The Higgs Boson and Decay

High Yields/Higher Bkg

- ggF
- VBF
- VH
- ttH

Clean Signature/
Lower Yields

Production

Decay

H→bb  H→WW/ττ  H→γγ  H→4l
VBF+$\gamma$ search

- **Trigger:**
  - L1 trigger: single photon ($p_T > 25$ GeV)
  - High level trigger: 4 jets $p_T > 35$ GeV, $m_{jj} > 700$ GeV

- **Selection:**
  - Tight ID photon, $p_T > 30$ GeV
  - 4 jets with $p_T > 40$ GeV
  - 2 central ($|\eta|<2.5$) b-tagged jets
  - $p_T$(bb system) > 80 GeV
  - Non b-tagged jets: $m_{jj} > 800$ GeV

- **BDT discriminant**
  - Built with variables uncorrelated to $m_{bb}$
  - $\Delta R(jet, \gamma), m_{jj}, \Delta \eta_{jj}, H_T^{soft}, jet width, \gamma$ centrality, $p_T^{balance}$

- Define 3 regions with different S/B
- Fit $m_{bb}$ in these 3 regions
**SM ZZ**: dominant bkg is estimated from MC

- **qq→ZZ** simulated with Powheg and Sherpa 2.1.1
- NNLO QCD and NLO EW corrections are considered for the quark-initiated ZZ* as function of mZZ*

- **gg→ZZ**
  - For high mZZ*, is modelled by Sherpa 2.1.1 which includes also the off-shell Higgs boson signal and their interference.
  - For low mZZ* gg2VV generator is used.
  - for both generator higher order QCD k-factor for massless quark loops in the heavy top-quark approximation including $H^*\rightarrow ZZ$ processes

<table>
<thead>
<tr>
<th>Final State</th>
<th>Signal full mass range</th>
<th>$ZZ^*$</th>
<th>$Z +$ jets, $t\bar{t}$</th>
<th>$S/B$</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\mu$</td>
<td>$8.8 \pm 0.6$</td>
<td>$8.2 \pm 0.6$</td>
<td>$3.11 \pm 0.30$</td>
<td>$0.31 \pm 0.04$</td>
<td>2.4</td>
<td>11.6 ± 0.7</td>
</tr>
<tr>
<td>$2e2\mu$</td>
<td>$6.1 \pm 0.4$</td>
<td>$5.5 \pm 0.4$</td>
<td>$2.19 \pm 0.21$</td>
<td>$0.30 \pm 0.04$</td>
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</tr>
<tr>
<td>$2\mu2e$</td>
<td>$4.8 \pm 0.4$</td>
<td>$4.4 \pm 0.4$</td>
<td>$1.39 \pm 0.16$</td>
<td>$0.47 \pm 0.05$</td>
<td>2.3</td>
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</tr>
<tr>
<td>$4e$</td>
<td>$4.8 \pm 0.5$</td>
<td>$4.2 \pm 0.4$</td>
<td>$1.46 \pm 0.18$</td>
<td>$0.46 \pm 0.05$</td>
<td>2.2</td>
<td>6.1 ± 0.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$24.5 \pm 1.8$</td>
<td>$22.3 \pm 1.6$</td>
<td>$8.2 \pm 0.8$</td>
<td>$1.54 \pm 0.18$</td>
<td>2.3</td>
<td>32.0 ± 1.8</td>
</tr>
</tbody>
</table>

L. Aperio Bella
**SM ZZ**: dominant bkg is estimated from MC
- $\bar{q}q\rightarrow ZZ$ simulated with Powheg and Sherpa 2.1.1
- $gg\rightarrow ZZ$ as
- Massless quark loop in the heavy top-quark approximation including $H^*\rightarrow ZZ$ processes

### Higgs boson

- **ATLAS** Preliminary

<table>
<thead>
<tr>
<th>Final State</th>
<th>Signal full mass range</th>
<th>$\mu V, VV, WZ$</th>
<th>$\bar{t}t$</th>
<th>$S/B$</th>
<th>Expected</th>
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</table>

$$118 < m_{4\ell} < 129 \text{ GeV}$$
Fiducial cross section

Fiducial selection: designed to closely replicate the analysis selection at particle level

\[ \sigma^{\text{tot}} = \frac{N_s}{\mathcal{A} \cdot \mathcal{C} \cdot \mathcal{B} \cdot \mathcal{L}_{\text{int}}} \]

\[ \sigma^{\text{fid channel}}_{\text{fid}} = \frac{N_s}{\mathcal{C} \cdot \mathcal{L}_{\text{int}}} \]

\( N_s \): # of observed signal events

\( \mathcal{A} \): kinematic and geometric acceptance in the fiducial region

\( \mathcal{C} \): detector correction factor (reco, trigger and id efficiencies, reco resolution)

- **Fiducial cross sections** extracted with a likelihood fit on m4l distribution in a range 115 < \( |m_4| \) < 130 GeV

  - Detector level bin-by-bin correction factor for unfolding from simulation

  - Fid. cross section extracted by final state and separately for the same and opposite flavour

- **Total cross-section** calculated assuming SM BR.

- Measurement still dominated by statistic

  - Main sys uncertainty Luminosity and lepton SF \( \sim 3\% \).

\[ \sigma^{\text{tot,SM}}_{\text{fid}} = 55.5^{+3.8}_{-4.4} \text{ pb} \]

\[ \sigma^{\text{tot}} = 81^{+18}_{-16} \text{ pb} \]

<table>
<thead>
<tr>
<th>Final state</th>
<th>measured ( \sigma^{\text{fid}} ) [fb]</th>
<th>( \sigma^{\text{fid,SM}} ) [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4( \mu )</td>
<td>1.28^{+0.48}_{-0.40}</td>
<td>0.93^{+0.06}_{-0.08}</td>
</tr>
<tr>
<td>4e</td>
<td>0.81^{+0.51}_{-0.38}</td>
<td>0.73^{+0.05}_{-0.06}</td>
</tr>
<tr>
<td>2( \mu )2e</td>
<td>1.29^{+0.58}_{-0.46}</td>
<td>0.67^{+0.04}_{-0.04}</td>
</tr>
<tr>
<td>2( e )2( \mu )</td>
<td>1.10^{+0.49}_{-0.40}</td>
<td>0.76^{+0.05}_{-0.06}</td>
</tr>
</tbody>
</table>

Compatibility \( \sigma^{\text{tot}}_{\text{SM}} \) and \( \sigma^{\text{tot,SM}}_{\text{fid}} \) 1.6\( \sigma \)
BSM sensitivity

Yields in the exclusive event category are also sensitive to BSM interactions in the HZZ vertex.

- BSM interactions, parametrised via additional effective Lagrangian terms.

\[ \mathcal{L}_0^V = \left\{ c_0^{\text{BSM}} \left[ \frac{1}{2} g_{\text{HZZ}} Z_\mu Z_\nu + g_{\text{HW}} W^+_\mu W^-_\nu \right] \right\} \]

\[ - \frac{1}{4} \left[ c_0^{\text{BSM}} g_{\gamma\gamma} A_\mu A_\nu + s_0^{\text{BSM}} g_{A\gamma} A_\mu A_\nu \right] \]

\[ - \frac{1}{2} \left[ c_0^{\text{BSM}} h_{\gamma Z} A_\mu A_\nu + s_0^{\text{BSM}} h_{A Z} Z_\mu Z_\nu \right] \]

\[ - \frac{1}{4} \left[ c_0^{\text{BSM}} h_{\gamma\gamma} Z_\mu Z_\nu \right] \]

\[ - \frac{1}{2} \left[ c_0^{\text{BSM}} h_{Z Z} W_\mu W_\nu + s_0^{\text{BSM}} h_{A W} W_\mu W_\nu \right] \]

The scalar (kHVV) and pseudo-scalar (kAVV) BSM couplings are investigated:

- The main sensitivity come from the VBF and VH production yields → expected to scale \( k_{\text{BSM}}^4 \)
- Possible changes in the BR(H\( \rightarrow \)ZZ*) proportional to \( k_{\text{BSM}}^2 \) in ggF production

\[ \text{MadGraph5_aMC@NLO} \] used to generate BSM template

**Morphing techniques** employed to predict observables shape for any value of the BSM couplings

30% uncertainty on the BSM signal acceptance in each category assign to take into account possible higher order correction on the kinematic distribution
BSM interpretation

- Limits on the BSM parameters $\kappa_{HVV}$ and $\kappa_{AVV} \cdot \sin \alpha$ are derived with a fit of the yields in each categories
  - **SM part of the Lagrangian is fixed to the SM.**
  - exploit the yield in each category to extract information on the BSM couplings.
  - Additional information from kinematic observables in the decay is not used.
  - Only one of the two BSM couplings at a time is considered.

\[
\begin{align*}
-2\Delta\ln(L) & \quad -2\Delta\ln(L) \\
\kappa_{HVV} & \quad \kappa_{AVV} \cdot \sin(\alpha)
\end{align*}
\]

ATLAS Preliminary

\[
H \rightarrow ZZ^* \rightarrow 4l
13\text{ TeV}, 14.8\text{ fb}^{-1}
\]

ATLAS Preliminary

\[
H \rightarrow ZZ^* \rightarrow 4l
13\text{ TeV}, 14.8\text{ fb}^{-1}
\]

Observed exclusion limits are weaker than the expected limits.

- Small excess of events wrt the prediction in the 2-jet VBF enriched category
- The agreement between $\kappa_{HVV} = 0$ and the observed value is $2.1\sigma$ and for $\kappa_{AVV} \cdot \sin \alpha = 0$ is $1.8\sigma$

<table>
<thead>
<tr>
<th>Not excluded range at 95% CL</th>
<th>$\kappa_{HVV}$</th>
<th>$\kappa_{AVV} \cdot \sin \alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected</td>
<td>observed</td>
<td>expected</td>
</tr>
<tr>
<td>$[-6.3, 5.1]$</td>
<td>$[0.9, 7.5]$</td>
<td>$[-6.3, 6.5]$</td>
</tr>
</tbody>
</table>
Analysis strategy:

- Same selection as SM $H_{125} \rightarrow ZZ \rightarrow 4l$ measurement
  - require both $Z$ on-shell
- Narrow (VBF and $ggF$) and large-width (inclusive) signals studied
  - Breit-Wigner signal shape with width: 4.07 MeV, 1%, 5%, 10%
H → ZZ → llvv

Analysis strategy:

- 2 isolated leptons (e⁺e⁻, μ⁺μ⁻) consistent with originating from Z
- Large missing $E_T$
- Backgrounds:
  - $ZZ → llvv$: irreducible, taken from prediction
  - $WZ → llvv$: 3l control region
  - $Z+\text{jets}$: data ABCD
  - non-resonant-II: $e\mu$ control region
  - $W+\text{jets}$: fake-factor from data
- Likelihood fit in

$$m_T^{ZZ} = \left( \sqrt{m_Z^2 + p_T^{\ell\ell}} + \sqrt{m_Z^2 + |E_T^{\text{miss}}|^2} \right)^2 - |p_T^{\ell\ell} + E_T^{\text{miss}}|^2.$$
Analysis strategy:

- Fully-leptonic, different-flavor
  \( H \rightarrow WW \rightarrow l\ell\bar{l}\ell \ (l = e, \mu) \)

- Vector-boson fusion
  - \( \geq 2 \) jets with \( m_{jj} > 500 \) GeV and \( |\Delta y_{jj}| > 4 \)
  - 1 jet with \( |\eta_j| > 2.4 \) and \( \min(|\Delta \eta_{jl}|) > 1.75 \)

- Gluon-fusion:
  - Everything that remains

- Likelihood fit with Top and WW data control regions
\[ H \rightarrow ZZ \rightarrow \text{llll} \]

**Results** for narrow-width-approximation:

- Largest deviation near 705 GeV: 2.9\( \sigma \) (1.9\( \sigma \)) local (global)

---

**ATLAS** Preliminary
13 TeV, 14.8 fb\(^{-1}\)
NWA

- Observed \( CL_s \) limit
- Expected \( CL_s \) limit
- Expected \( \pm 1 \sigma \)
- Expected \( \pm 2 \sigma \)

95\% CL limits on \( \sigma_{ggF} \times BR(S \rightarrow ZZ \rightarrow 4l) \) (fb)

3-4 times better limit w.r.t. Dec. 2015 results

**New at 13 TeV**

**ATLAS** Preliminary
13 TeV, 14.8 fb\(^{-1}\)
NWA

- Observed \( CL_s \) limit
- Expected \( CL_s \) limit
- Expected \( \pm 1 \sigma \)
- Expected \( \pm 2 \sigma \)

95\% CL limits on \( \sigma_{VBF} \times BR(S \rightarrow ZZ \rightarrow 4l) \) (fb)
Results for ggF large-width-approximation:

- Interference with SM background small, thus neglected
- New interpretation w.r.t. December 2015 results
Results:

- **Narrow-width-approximation**
  - ggF and VBF
  - 300 — 3000 GeV

- **Large-width-approximation**
  - ggF with 5%, 10%, and 15% widths
  - 400 — 3000 GeV

- At low-mass: better than previous combined limit
$H \rightarrow WW \rightarrow l\nu l\nu$

Signal regions:

- No significant excess observed

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 13.2 fb$^{-1}$

- $H \rightarrow WW \rightarrow e\nu\nu$ ggF SR
- $H \rightarrow WW \rightarrow e\nu\nu + 1$ jet VBF SR
- $H \rightarrow WW \rightarrow e\nu\nu + 2$ jets VBF SR

**VBF 1-jet SR**

**VBF 2-jet SR**
## Fiducial cross sections

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Measured cross section (fb)</th>
<th>SM prediction (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>$43.2 \pm 14.9$ (stat.) $\pm 4.9$ (syst.)</td>
<td>$62.8 \pm 3.4$</td>
</tr>
<tr>
<td>VBF-enhanced single lepton</td>
<td>$4.0 \pm 1.4$ (stat.) $\pm 0.7$ (syst.)</td>
<td>$2.04 \pm 0.13$ $[N^3LO + XH]$</td>
</tr>
<tr>
<td></td>
<td>$1.5 \pm 0.8$ (stat.) $\pm 0.2$ (syst.)</td>
<td>$0.56 \pm 0.03$ $[NNLOPS + XH]$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>diphophot baseline</th>
<th>VBF enhanced</th>
<th>Single lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.37$ or $1.52 &lt;</td>
</tr>
<tr>
<td>Jets</td>
<td>-</td>
<td>$p_T &gt; 30$ GeV, $</td>
<td>y</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$m_{jj} &gt; 400$ GeV, $</td>
<td>\Delta y_{jj}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$</td>
<td>\Delta \phi_{\gamma\gamma, jj}</td>
</tr>
<tr>
<td>Leptons</td>
<td>-</td>
<td>-</td>
<td>$p_T &gt; 15$ GeV $</td>
</tr>
</tbody>
</table>
Sample composition

- Fractions of $Z+\gamma$ and $Z+\text{jet}$ events studied with 2 data-driven methods based on identification and isolation of photon candidate.

- $Z+\gamma$ fraction $\sim 90\%$

- Good agreement between different methods

- Fractions not used in final fit to data, but only for bias studies (“spurious signal”) related to the choice of the functional form that models the background.
Signal invariant mass distribution

- **Double-sided Crystal-Ball** function (Gaussian with power-law tails)
- **Parameters** described by **polynomial functions of mass**, extracted from simultaneous fit to all generated samples

![Graph 1]

*ATLAS Simulation Preliminary*

$gg \rightarrow X \rightarrow Z\gamma$

$m_X = 300$ GeV

$\sqrt{s} = 13$ TeV

![Graph 2]

*ATLAS Simulation Preliminary*

$gg \rightarrow X \rightarrow Z\gamma$

$m_X = 1500$ GeV

$\sqrt{s} = 13$ TeV

- **Resolution** $1–0.6\%$ (ee$\gamma$), $1–1.4\%$ ($\mu\mu\gamma$) for $m_X=250–2400$ GeV [Z-mass constraint: $\sim20\%$ improvement except in $Z\rightarrow ee$ at high mass]
- **Uncertainties:** $l,\gamma$ energy scales ($<\%$ on $<m>$) and resolution ($10–35\%$ on $\sigma_m$)
Background invariant mass distribution

- background modelled with functional form:

\[ f_{\text{bkg}}(x) = N (1 - x^k)^{p_1} x^{p_2} \quad x = m_{\ell\ell\gamma}/\sqrt{s}, \quad k=1/3 \]

- \( N, p_1, p_2 \) are free parameters in fit to data

- \( f \) with minimum number of free parameters chosen among those that

  - fit well a bkg-only control sample: small bias on signal, quantified as “spurious signal” in signal+bkg fit to high-statistics \((Z+\gamma) + (Z+\text{jet})\) bkg control sample: <20% of bkg uncertainty

  - fit well the data (no significant improvement of fit quality when adding more degrees of freedom)

- uncertainty related to bkg model = spurious signal
Search for $H \rightarrow \mu\mu$

**Run-1**

$\sqrt{s} = 7$ TeV, 4.5 fb$^{-1}$

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

95% CL BR upper limit for $M_H = 125.09$ GeV

Run-1: $\mu < 7.1$ (obs.), 7.2 (exp.)

Run-2: $\mu < 4.4$ (obs.), 5.5 (exp.)

**Run-2**

$\sqrt{s} = 13$ TeV, 13.2 fb$^{-1}$

$H \rightarrow \mu\mu$

95% CL Limit on $\sigma \times BR(H \rightarrow \mu\mu)$ [pb]

Combined: $\mu < 3.5$ (obs.), 4.3 (exp.)
H/Z → ϕγ

- Sensitivity to s-quark Yukawa couplings
- Reconstruct ϕ → K⁺K⁻, Br(ϕ → K⁺K⁻) = 49%
- Two high-p_T (20, 15 GeV) isolated collinear tracks (ΔR < 0.05, m_{KK} ∼ m_ϕ) recoiling against γ (p_T > 35 GeV)
- Dedicated trigger (~78% efficiency wrt. offline selection)
- Data-driven template modeling of bkg

<table>
<thead>
<tr>
<th>Branching Fraction Limit (95% CL)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>B(H → ϕγ) [ 10^{-3} ]</td>
<td>1.5^{+0.7}_{-0.4}</td>
<td>1.4</td>
</tr>
<tr>
<td>B(Z → ϕγ) [ 10^{-6} ]</td>
<td>4.4^{+2.0}_{-1.2}</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Expected SM values:
- B(H → ϕγ) = (2.3 ± 0.1) × 10^{-6} - JHEP 1508 (2015) 012 (arXiv:1505.03870)
- B(Z → ϕγ) = (1.2 ± 0.1) × 10^{-8} - PRD 92, 014007 (2015) (arXiv:1411.5924)
### STXS Acceptance $|y_H| < 2.5$

| Process                      | Contributing to | $\sigma_i(|y_H| < 2.5)/\sigma_i$ |
|------------------------------|-----------------|-----------------------------------|
| $gg \rightarrow H$          | ggF             | 0.907                             |
| $qq' \rightarrow qq'H$      | VBF             | 0.932                             |
| $q\bar{q}' \rightarrow WH(W \rightarrow \text{had})$ | VHhad           | 0.870                             |
| $q\bar{q}/gg \rightarrow ZH(Z \rightarrow \text{had})$ | VHhad           | 0.900                             |
| $q\bar{q}' \rightarrow WH(W \rightarrow \text{lep})$ | VHlep           | 0.869                             |
| $q\bar{q} \rightarrow ZH(Z \rightarrow \text{lep})$ | VHlep           | 0.900                             |
| $gg \rightarrow ZH(Z \rightarrow \text{lep})$     | VHlep           | 0.965                             |
| $q\bar{q}/gg \rightarrow t\bar{t}H$ | top             | 0.985                             |
Hbb Distributions of mbb

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV $\int Ldt = 13.2$ fb$^{-1}$

0 lep., 2 jets, 2 tags

$p_T^V \geq 150$ GeV