Searches for rare and non-Standard-Model decays of the Higgs boson

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on behalf of the ATLAS collaboration
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Introduction

• Current experimental constraint on the branching ratio (BR) of the SM Higgs rare and non-SM decays is less than 34% at 95% CL. (JHEP08(2016)045)

• There is still large room to explore for these interesting decays that can help

  • Examine the SM Higgs properties
  • Probe enhancement coming beyond the SM (BSM)

  • Rare decays
    • $H \to \text{meson} + \text{photon}$
    • $H \to Z\gamma$ (for heavy resonant searches, see Flavia’s talk)
    • $H \to \text{fermions}$ (see already Carlo’s and Yiwen’s talks)
    • “$H^* \to HH$”, self-coupling (see Yaquan’s and Giacomo’s talks)

  • Non-SM decays
    • $H \to \text{aa, light bosons}$
    • $H \to \text{invisible, dark matter}$ (see William’s talk)
Higgs decaying to a meson + a photon

- The Higgs rare decays to a meson and a photon, such as \( \text{BR}(H \rightarrow \rho \gamma) \) at \( 10^{-5} \), \( \text{BR}(H \rightarrow \phi \gamma) \) at \( 10^{-6} \) exist in the SM
  - They can be used to probe Higgs couplings to the first and second quark generations and enhancement from BSM (Higgs compositeness etc.)
  - The small decay amplitude is a result of
    - The smallness of Higgs-light-quark couplings
    - The destructive interference between the diagrams
  - The \textit{indirect} process predominantly contribute to the BR
- The latest ATLAS results of Higgs and Z bosons to \( \phi \gamma \) and \( \rho \gamma \) were published in arXiv:1712.02758 Dec 2017
  - Replacing last \( \phi \gamma \) results in \textit{Phys. Rev. Lett. 117, 111802}
  - For earlier results on 8 TeV J/ψ and Y see \textit{Phys. Rev. Lett. 114 (2015) 121801}
$H \rightarrow \phi \gamma$ and $\rho \gamma$: event selection

- The dominant decays of $\varphi \rightarrow K^+K^-$ and $\rho \rightarrow \pi^+\pi^-$ are chosen for the analysis.

- The final states include a pair of tracks and a photon.

- Given soft kinematics, special triggers on ditracks originating from mesons are developed to increase the acceptance.

<table>
<thead>
<tr>
<th>$p_T &gt; 15$ GeV, at least one with $p_T &gt; 20$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
</tr>
<tr>
<td>Opposite charge</td>
</tr>
<tr>
<td>Ditrack $p_T^{K+K^-}$ cut</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>$\phi$ isolation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$p_T &gt; 35$ GeV</th>
</tr>
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<tbody>
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</tr>
</tbody>
</table>

| $\Delta \phi(K^+K^-, \gamma) > \pi/2$ |

Table shows $\phi \gamma$ selections while $\rho \gamma$'s are similar.

Overall selection efficiency:
- $\varepsilon(\phi \gamma) \sim 17\%$
- $\varepsilon(\rho \gamma) \sim 10\%$

arXiv:1712.02758
$H \rightarrow \phi \gamma$ and $\rho \gamma$: mass resolution

- The $m(K^+K^-)$ resolution is 4 MeV compared to 4.3 MeV of $\phi$ natural width, while $m(\pi^+\pi^-)$ has much broader distribution given larger $\rho$ width.

- The mass resolutions of $m(K^+K^-\gamma)$ and $m(\pi^+\pi^-\gamma)$ that are used as the final fit template are both 1.8%.
H→φγ and ργ: background estimation

- Dominant background comes from multijet and γ+jets
- The background shape is modelled from pseudo-data and the normalisation is free in the final fit
- Pseudo-data is made from a background-dominated generation region (GR) by relaxing cuts on $p_T^{KK}$, meson and photon isolation

- Random sampling the distributions of relevant variables: $\eta_{K+K^-}$, $\varphi_{K+K^-}$, $m_{K+K^-}$, $p_T^{K+K^-}$ for the meson, and, $\Delta\varphi(K^+K^-, \gamma)$, $\Delta\eta(K^+K^-, \gamma)$, $p_T^{\gamma}$ for the photon, with their correlations considered

- The model is examined in validation regions (VR) in which some of the relaxed cuts are recovered ργ has similar procedure as above
H→φγ and ργ: results

- The final fits is performed on m(K+K−γ) and m(π+π−γ) with an unbinned likelihood.

- The observed data are consistent with the expected background-only prediction.

- Upper limits are set on BRs with the SM Higgs cross section assumed:
  - Corresponding to 208 and 52 times of SM predictions for H→φγ and H→ργ

<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^{-4} ]</td>
<td>4.2^{+1.8}_{-1.2}</td>
<td>4.8</td>
</tr>
<tr>
<td>B(Z → φγ) [ 10^{-6} ]</td>
<td>1.3^{+0.6}_{-0.4}</td>
<td>0.9</td>
</tr>
<tr>
<td>B(H → ργ) [ 10^{-4} ]</td>
<td>8.4^{+4.1}_{-2.4}</td>
<td>8.8</td>
</tr>
<tr>
<td>B(Z → ργ) [ 10^{-6} ]</td>
<td>33^{+13}_{-9}</td>
<td>25</td>
</tr>
</tbody>
</table>

Reduce the limits by a factor of 3 from last ATLAS results:
BR(H→φγ) < 1.4×10^{-3}
(1.5×10^{-3})
Higgs decaying to Zγ

- $H \rightarrow Z\gamma$ is one of the SM Higgs rare decays and has a BR at $10^{-3}$ level in the SM, comparable to $H \rightarrow \gamma\gamma$, but very challenging due to Z decays.

- It can be enhanced by various BSM sources, such as Higgs compositeness, additional colourless particles in the $H \rightarrow Z\gamma$ loop, etc.

- The latest ATLAS result is JHEP 10 (2017) 112.

- Only $Z \rightarrow e^+e^-$, $e^\mu\mu$, $ggF + VBF + VH$ are considered, and major selections include:
  - Two same-flavour opposite-charge $e^\pm\mu^\mp$
  - At least one photon
  - $m_Z$ window
  - Categorisation (boosted decision tree, photon $p_T$ etc.)
**Zγ event categories**

<table>
<thead>
<tr>
<th>Category</th>
<th>Events</th>
<th>$S_{90}$</th>
<th>$S_{90}/\sqrt{S_{90} + B_{90}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF-enriched</td>
<td>88</td>
<td>1.2</td>
<td>0.32</td>
</tr>
<tr>
<td>High relative $p_T$</td>
<td>443</td>
<td>2.3</td>
<td>0.26</td>
</tr>
<tr>
<td>$ee$ high $p_{Tt}$</td>
<td>1053</td>
<td>3.3</td>
<td>0.19</td>
</tr>
<tr>
<td>$ee$ low $p_{Tt}$</td>
<td>11707</td>
<td>11.2</td>
<td>0.18</td>
</tr>
<tr>
<td>$\mu\mu$ high $p_{Tt}$</td>
<td>1413</td>
<td>4.0</td>
<td>0.22</td>
</tr>
<tr>
<td>$\mu\mu$ low $p_{Tt}$</td>
<td>16529</td>
<td>14.5</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Category I is a VBF-enriched region with a fraction 67.5% from VBF events. The overall signal efficiency is about 20% for each production modes.
Zγ fits and results

• Signals are modelled with double-sided Crystal Ball functions, while backgrounds by Bernstein polynomials (Z+γ taking up 80%)

• No significant excess is found in data. The observed 95% CL limit on $\sigma(pp\rightarrow H)BR(H\rightarrow Z\gamma)$ is found to be 6.6 times the SM prediction

• Assuming SM production, upper limit on $BR(H\rightarrow Z\gamma)$ is 1%
Higgs decaying to light bosons

- Many BSM scenarios (2HDM+S, NMSSM, dark matter related etc.) predict non-SM Higgs decays
  - Higgs decaying to a pair of new spin-0 light bosons is one of the most simplest and interesting possibilities
- The light bosons have a rich decay variety into SM particles
- ATLAS latest result includes $H \to aa \to \gamma\gamma jj$, arXiv:1803.11145 March 2018, $H \to ZZ_d/Z_dZ_d/aa \to llll$ arXiv:1802.03388 January 2018
- Previous ATLAS results not in this talk include $b\bar{b}b\bar{b}$ (Eur. Phys. J. C 76 (2016) 605), $\mu\mu\tau\tau$ (Phys. Rev. D92 (2015) 052002), $\gamma\gamma\gamma\gamma$ (Eur. Phys. J. C 76 (2016) 210),

http://exotichiggs.physics.sunysb.edu/
**ΥΥjj: event selection**

- Optimise event selection for the VBF production:
  - At least 2 isolated photons, $E_T > 27$ to 40 depending on the trigger
  - At least 4 jets, leading $p_T > 60$ GeV, $m_{jj}^{VBF} > 500$ GeV
  - $100 < m_{ΥΥjj} < 150$ GeV
- Define 5 overlapping "$m_{ΥΥ}$ regimes" for different signal mass ranges
**$\gamma\gamma jj$: background estimation**

- Dominant background comes from $\gamma\gamma$+multi-jet events, estimated with data-driven method by defining 4 orthogonal regions
  - AB (CD) with photon isolation tight and loose for each (tight for both)
  - AC (BD) are $> (<) x_R$
- Small correlation between photon isolation and $|m_{jj} - m_{\gamma\gamma}|$ makes the formula hold
- Closure check is performed in $m_{\gamma\gamma jj}$ sideband and the bias is treated as uncertainty

<table>
<thead>
<tr>
<th>Photon requirements</th>
<th>TightLoose</th>
<th>TightTight</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>m_\gamma - m_{\gamma\gamma}</td>
<td>$ $&gt; x_R$</td>
</tr>
<tr>
<td>$</td>
<td>m_{jj} - m_{\gamma\gamma}</td>
<td>$ $\leq x_R$</td>
</tr>
</tbody>
</table>

Signal region

$$N_D^{\text{bkg}} = \frac{N_B^{\text{bkg}} N_C^{\text{bkg}}}{N_A^{\text{bkg}}}$$

<table>
<thead>
<tr>
<th>$m_{\gamma\gamma}$ regime</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Relative closure uncert.</th>
<th>Predicted background yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>4</td>
<td>28</td>
<td>4</td>
<td>0.50</td>
<td>$6^{+7}_{-4}$</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>6</td>
<td>34</td>
<td>15</td>
<td>0.32</td>
<td>$8^{+7}_{-4}$</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>16</td>
<td>29</td>
<td>26</td>
<td>0.20</td>
<td>$37^{+23}_{-14}$</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>12</td>
<td>19</td>
<td>38</td>
<td>0.21</td>
<td>$27^{+22}_{-12}$</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>20</td>
<td>20</td>
<td>36</td>
<td>0.20</td>
<td>$66^{+56}_{-28}$</td>
</tr>
</tbody>
</table>
\[\gamma\gamma jj: \text{results}\]

- The final statistical treatment takes both numbers of signal \(\mu_S\) and background \(\mu_{bkg}\) as free parameters, as well as \(\tau_B\) (B/D ratio of events) and \(\tau_C\) (C/D).

- A simultaneous fit in all ABCD regions is performed.

- No large excess is observed. Upper limits are set on the BRs as a function of the light boson mass.
4l analysis

- Search for (X stands for Zd from a SM extension of a dark-sector and a from 2HDM+S)
  - $H \rightarrow ZX \rightarrow 4l$ in $15 \text{ GeV} < m_X < 55 \text{ GeV}$
  - $H \rightarrow XX \rightarrow 4l$ in $15 \text{ GeV} < m_X < 60 \text{ GeV}$
  - $H \rightarrow XX \rightarrow 4\mu$ in $1 \text{ GeV} < m_X < 15 \text{ GeV}$

- Major selections include $m_{ll}$ windows, $m_{4l}$ windows, quarkonia resonance rejection, $m_{34}/m_{12}>0.85$ (the latter two only for XX)

- Background estimation rely on MC
  - The dominant background is irreducible $H \rightarrow ZZ^* \rightarrow 4l$
  - For low mass searches, quarkonia heavy flavour, VVV/VBS and ZZ* also contribute largely
4l: results

- No significant data excess is found
- Set limits fiducial cross section (backup) and branching ratio
Summary

• Various rare and non-SM Higgs decays are probed

  • With no significant data excess, upper limits are set on the BRs

  • Many existing channels are updated with big improvement

  • Many new channels are explored for the first time

• Statistical uncertainty is often the constraining factor

  • The statistics to the end of Run 2 of the LHC can bring free improvements

• Extensive programs are undergoing to cover more final states
Backup
H→φγ and ργ

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>Yield uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total $H$ cross section</td>
<td>6.3%</td>
</tr>
<tr>
<td>Total $Z$ cross section</td>
<td>2.9%</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>3.4%</td>
</tr>
<tr>
<td>Photon ID efficiency</td>
<td>2.5%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>2.0%</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>6.0%</td>
</tr>
</tbody>
</table>

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-13/
$H \rightarrow \phi\gamma$ and $\rho\gamma$
The component of the transverse momentum of the $Z\gamma$ system that is perpendicular to the difference of the 3-momenta of the $Z$ boson and the photon candidate ($p_{Tt} = 2|p_x^Z p_y^\gamma - p_x^\gamma p_y^Z|/p_T^{Z\gamma}$),

<table>
<thead>
<tr>
<th>Process</th>
<th>Technique</th>
<th>QCD (gen.)</th>
<th>QCD (norm.)</th>
<th>EW (norm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>MiNLO &amp; NNLOPS</td>
<td>NNLO (incl.), NLO ($H + 1$-jet)</td>
<td>NNNLO</td>
<td>NLO</td>
</tr>
<tr>
<td>VBF</td>
<td>POWHEG</td>
<td>NLO</td>
<td>approx. NNLO</td>
<td>NLO</td>
</tr>
<tr>
<td>$VH$</td>
<td>MiNLO</td>
<td>NLO (incl. and $H + 1$-jet)</td>
<td>NNLO</td>
<td>NLO</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>$\epsilon$ [%]</th>
<th>$f$ [%]</th>
<th>$\epsilon$ [%]</th>
<th>$f$ [%]</th>
<th>$\epsilon$ [%]</th>
<th>$f$ [%]</th>
<th>$\epsilon$ [%]</th>
<th>$f$ [%]</th>
<th>$\epsilon$ [%]</th>
<th>$f$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF-enriched</td>
<td>0.25</td>
<td>30.5</td>
<td>6.5</td>
<td>67.5</td>
<td>0.34</td>
<td>1.3</td>
<td>0.24</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High relative $p_T$</td>
<td>1.1</td>
<td>71.5</td>
<td>2.6</td>
<td>14.3</td>
<td>4.0</td>
<td>8.3</td>
<td>4.1</td>
<td>5.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ee high $p_{Tt}$</td>
<td>1.7</td>
<td>80.8</td>
<td>2.8</td>
<td>11.0</td>
<td>3.2</td>
<td>4.7</td>
<td>3.6</td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ee low $p_{Tt}$</td>
<td>7.1</td>
<td>93.2</td>
<td>3.6</td>
<td>4.1</td>
<td>3.7</td>
<td>1.5</td>
<td>4.2</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu\mu$ high $p_{Tt}$</td>
<td>2.2</td>
<td>80.4</td>
<td>3.6</td>
<td>11.3</td>
<td>4.1</td>
<td>4.8</td>
<td>4.2</td>
<td>3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu\mu$ low $p_{Tt}$</td>
<td>9.2</td>
<td>93.4</td>
<td>4.7</td>
<td>4.1</td>
<td>4.6</td>
<td>1.5</td>
<td>4.8</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total efficiency (%)</td>
<td>21.5</td>
<td>23.8</td>
<td>20.2</td>
<td>21.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected events</td>
<td>35</td>
<td>3.3</td>
<td>1.0</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

$\epsilon$: efficiency  
$f$: fraction
# Zy systematic uncertainties

<table>
<thead>
<tr>
<th>Sources</th>
<th>$H \rightarrow Z\gamma$</th>
<th>$X \rightarrow Z\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Luminosity [%]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td><strong>Signal efficiency [%]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modelling of pile-up interactions</td>
<td>0.02–0.03</td>
<td>&lt; 0.01–0.2</td>
</tr>
<tr>
<td>Photon identification efficiency</td>
<td>0.7–1.7</td>
<td>2.0–2.6</td>
</tr>
<tr>
<td>Photon isolation efficiency</td>
<td>0.07–0.4</td>
<td>0.6–0.6</td>
</tr>
<tr>
<td>Electron identification efficiency</td>
<td>0.0–1.6</td>
<td>0.0–2.6</td>
</tr>
<tr>
<td>Electron isolation efficiency</td>
<td>0.0–0.2</td>
<td>0.0–3.5</td>
</tr>
<tr>
<td>Electron reconstruction efficiency</td>
<td>0.0–0.4</td>
<td>0.0–1.0</td>
</tr>
<tr>
<td>Electron trigger efficiency</td>
<td>0.0–0.1</td>
<td>0.0–0.2</td>
</tr>
<tr>
<td>Muon selection efficiency</td>
<td>0.0–1.6</td>
<td>0.0–0.7</td>
</tr>
<tr>
<td>Muon trigger efficiency</td>
<td>0.0–3.5</td>
<td>0.0–4.2</td>
</tr>
<tr>
<td>MC statistical uncertainty</td>
<td>–</td>
<td>1.2–2.0</td>
</tr>
<tr>
<td>Jet energy scale, resolution, and pile-up</td>
<td>0.2–10</td>
<td>–</td>
</tr>
<tr>
<td>Total (signal efficiency)</td>
<td>2.1–10</td>
<td>4.0–6.3</td>
</tr>
</tbody>
</table>

**Signal modelling on $\sigma_{CB}$ [%]**

<table>
<thead>
<tr>
<th>Sources</th>
<th>$H \rightarrow Z\gamma$</th>
<th>$X \rightarrow Z\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron and photon energy scale</td>
<td>0.6–3.5</td>
<td>1.0–4.0</td>
</tr>
<tr>
<td>Electron and photon energy resolution</td>
<td>1.1–4.0</td>
<td>4.0–30</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>0.0–0.5</td>
<td>0.0–3.0</td>
</tr>
<tr>
<td>Muon ID resolution</td>
<td>0.0–3.7</td>
<td>0.0–2.0</td>
</tr>
<tr>
<td>Muon MS resolution</td>
<td>0.0–1.7</td>
<td>0.0–4.0</td>
</tr>
</tbody>
</table>

**Signal modelling on $\mu_{CB}$ [%]**

<table>
<thead>
<tr>
<th>Sources</th>
<th>$H \rightarrow Z\gamma$</th>
<th>$X \rightarrow Z\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron and photon energy scale</td>
<td>0.1–0.2</td>
<td>0.2–0.6</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>0.0–0.03</td>
<td>0.0–0.03</td>
</tr>
<tr>
<td>Higgs mass</td>
<td>0.2</td>
<td>–</td>
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</tbody>
</table>

**Background modelling [Events]**

<table>
<thead>
<tr>
<th>Sources</th>
<th>$H \rightarrow Z\gamma$</th>
<th>$X \rightarrow Z\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spurious signal</td>
<td>1.7–25</td>
<td>0.005–6.1</td>
</tr>
</tbody>
</table>

**Total cross section and efficiency [%]**

<table>
<thead>
<tr>
<th>Sources</th>
<th>$H \rightarrow Z\gamma$</th>
<th>$X \rightarrow Z\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underlying event</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>ggF perturbative order</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>ggF PDF and $\alpha_s$</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>VBF perturbative order</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>VBF PDF and $\alpha_s$</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>$WH (ZH)$ perturbative order</td>
<td>0.5 (3.8)</td>
<td></td>
</tr>
<tr>
<td>$WH (ZH)$ PDF and $\alpha_s$</td>
<td>1.9 (1.6)</td>
<td></td>
</tr>
<tr>
<td>Interference</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>$B(H \rightarrow Z\gamma)$</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td>Total (total cross section and efficiency)</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

**Category acceptance [%]**

<table>
<thead>
<tr>
<th>Sources</th>
<th>$H \rightarrow Z\gamma$</th>
<th>$X \rightarrow Z\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF $H + 2$-jets in VBF-enriched category</td>
<td>0.5–45</td>
<td></td>
</tr>
<tr>
<td>ggF BDT variables</td>
<td>0.2–15</td>
<td></td>
</tr>
<tr>
<td>ggF Higgs $p_T$</td>
<td>8.4–22</td>
<td></td>
</tr>
<tr>
<td>PDF and $\alpha_s$</td>
<td>0.2–2.0</td>
<td></td>
</tr>
<tr>
<td>Underlying event</td>
<td>2.9–25</td>
<td></td>
</tr>
<tr>
<td>Total (category acceptance)</td>
<td>9.5–49</td>
<td></td>
</tr>
</tbody>
</table>
Overall signal efficiency

<table>
<thead>
<tr>
<th>$m_a$ [GeV]</th>
<th>$m_{\gamma\gamma}$ regime</th>
<th>Efficiency ($\times 10^{-5}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>0.50$^{+0.16}_{-0.14}$</td>
</tr>
<tr>
<td>25</td>
<td>1</td>
<td>0.67$^{+0.27}_{-0.33}$</td>
</tr>
<tr>
<td>25</td>
<td>2</td>
<td>0.67$^{+0.27}_{-0.33}$</td>
</tr>
<tr>
<td>30</td>
<td>2</td>
<td>1.22$\pm$0.34</td>
</tr>
<tr>
<td>35</td>
<td>2</td>
<td>1.8$\pm$1.1</td>
</tr>
<tr>
<td>35</td>
<td>3</td>
<td>0.53$^{+1.20}_{-0.24}$</td>
</tr>
<tr>
<td>40</td>
<td>3</td>
<td>1.2$\pm$0.4</td>
</tr>
<tr>
<td>45</td>
<td>3</td>
<td>2.5$\pm$1.0</td>
</tr>
<tr>
<td>45</td>
<td>4</td>
<td>2.2$\pm$0.9</td>
</tr>
<tr>
<td>50</td>
<td>4</td>
<td>0.93$\pm$0.30</td>
</tr>
<tr>
<td>55</td>
<td>4</td>
<td>0.37$\pm$0.11</td>
</tr>
<tr>
<td>55</td>
<td>5</td>
<td>0.23$\pm$0.16</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
<td>0.77$^{+0.32}_{-0.30}$</td>
</tr>
</tbody>
</table>

$m_{\gamma\gamma}$ regime

<table>
<thead>
<tr>
<th>Definition</th>
<th>Range of $m_a$ values</th>
<th>$x_R$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.5 GeV &lt; $m_{\gamma\gamma}$ &lt; 27.5 GeV</td>
<td>20 GeV ≤ $m_a$ ≤ 25 GeV</td>
</tr>
<tr>
<td>2</td>
<td>22.5 GeV &lt; $m_{\gamma\gamma}$ &lt; 37.5 GeV</td>
<td>25 GeV ≤ $m_a$ ≤ 35 GeV</td>
</tr>
<tr>
<td>3</td>
<td>32.5 GeV &lt; $m_{\gamma\gamma}$ &lt; 47.5 GeV</td>
<td>35 GeV ≤ $m_a$ ≤ 45 GeV</td>
</tr>
<tr>
<td>4</td>
<td>42.5 GeV &lt; $m_{\gamma\gamma}$ &lt; 57.5 GeV</td>
<td>45 GeV ≤ $m_a$ ≤ 55 GeV</td>
</tr>
<tr>
<td>5</td>
<td>52.5 GeV &lt; $m_{\gamma\gamma}$ &lt; 65.0 GeV</td>
<td>55 GeV ≤ $m_a$ ≤ 60 GeV</td>
</tr>
<tr>
<td>$M_{\gamma\gamma}$ regime</td>
<td>$m_\gamma$ [GeV]</td>
<td>ggF signal efficiency</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------------</td>
<td>----------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>0.25±^{0.17}_{-0.12}</td>
</tr>
<tr>
<td>1</td>
<td>25</td>
<td>0.20±0.22</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>0.20±0.22</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>0.86±0.24</td>
</tr>
<tr>
<td>2</td>
<td>35</td>
<td>1.4±1.1</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>0.31±^{1.40}_{-0.16}</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>0.67±0.25</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>2.1±0.9</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>2.0±0.9</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>0.28±0.14</td>
</tr>
<tr>
<td>4</td>
<td>55</td>
<td>0.17±0.06</td>
</tr>
<tr>
<td>5</td>
<td>55</td>
<td>0.00±0.23</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>0.16±^{0.19}_{-0.11}</td>
</tr>
</tbody>
</table>
**YYjj**

Maximum fractional impact on the fitted number of signal events $\mu_S$

<table>
<thead>
<tr>
<th>Source of Uncert.</th>
<th>$m_\gamma\gamma$ regime</th>
<th>$m_\gamma = 20$ GeV</th>
<th>$m_\gamma = 30$ GeV</th>
<th>$m_\gamma = 40$ GeV</th>
<th>$m_\gamma = 50$ GeV</th>
<th>$m_\gamma = 60$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>1</td>
<td>0.73</td>
<td>0.51</td>
<td>0.89</td>
<td>1.13</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.44</td>
<td>0.27</td>
<td>0.39</td>
<td>0.64</td>
<td>0.89</td>
</tr>
<tr>
<td>Modelling</td>
<td>3</td>
<td>0.35</td>
<td>0.34</td>
<td>0.46</td>
<td>0.42</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.58</td>
<td>0.38</td>
<td>0.25</td>
<td>0.90</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.06</td>
<td>0.05</td>
<td>0.10</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>Lumi and Pile-up</td>
<td>6</td>
<td>0.06</td>
<td>0.04</td>
<td>0.27</td>
<td>0.14</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Maximum-likelihood fit values for each of the free parameters

<table>
<thead>
<tr>
<th>$m_\gamma\gamma$ regime</th>
<th>$m_\gamma$ [GeV]</th>
<th>$\mu_S$</th>
<th>$\mu_{bkg}$</th>
<th>$\tau_B$</th>
<th>$\tau_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>-7±18</td>
<td>11±17</td>
<td>0.5±0.4</td>
<td>2.9±3.1</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>8±8</td>
<td>7±6</td>
<td>0.68±0.32</td>
<td>4.3±3.1</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>-30±80</td>
<td>60±70</td>
<td>0.35±0.19</td>
<td>0.67±0.33</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>22±28</td>
<td>16±23</td>
<td>0.5±0.4</td>
<td>0.9±1.0</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>-290±260</td>
<td>340±340</td>
<td>0.21±0.05</td>
<td>0.24±0.05</td>
</tr>
</tbody>
</table>
# 4ℓ: event yields

<table>
<thead>
<tr>
<th>Process</th>
<th>$2\ell 2\mu$</th>
<th>$2\ell 2e$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to ZZ^* \to 4\ell$</td>
<td>$34.3 \pm 3.6$</td>
<td>$21.4 \pm 3.0$</td>
<td>$55.7 \pm 6.3$</td>
</tr>
<tr>
<td>$ZZ^* \to 4\ell$</td>
<td>$16.9 \pm 1.2$</td>
<td>$9.0 \pm 1.1$</td>
<td>$25.9 \pm 2.0$</td>
</tr>
<tr>
<td>Reducible background</td>
<td>$2.1 \pm 0.6$</td>
<td>$2.7 \pm 0.7$</td>
<td>$4.8 \pm 1.1$</td>
</tr>
<tr>
<td>VVV, $t\bar{t} + V$</td>
<td>$0.20 \pm 0.05$</td>
<td>$0.20 \pm 0.04$</td>
<td>$0.40 \pm 0.06$</td>
</tr>
<tr>
<td>Total expected</td>
<td>$53.5 \pm 4.3$</td>
<td>$33.3 \pm 3.4$</td>
<td>$86.8 \pm 7.5$</td>
</tr>
<tr>
<td>Observed</td>
<td>65</td>
<td>37</td>
<td>102</td>
</tr>
</tbody>
</table>

### H→ZX→4ℓ

### H→XX→4ℓ

<table>
<thead>
<tr>
<th>Process</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZZ^* \to 4\ell$</td>
<td>$0.8 \pm 0.1$</td>
</tr>
<tr>
<td>$H \to ZZ^* \to 4\ell$</td>
<td>$2.6 \pm 0.3$</td>
</tr>
<tr>
<td>VVV/VBS</td>
<td>$0.51 \pm 0.18$</td>
</tr>
<tr>
<td>$Z + (t\bar{t}/J/Ψ) \to 4\ell$</td>
<td>$0.004 \pm 0.004$</td>
</tr>
<tr>
<td>Reducible Background</td>
<td>Negligible</td>
</tr>
<tr>
<td>Total</td>
<td>$3.9 \pm 0.3$</td>
</tr>
<tr>
<td>Data</td>
<td>6</td>
</tr>
</tbody>
</table>

### H→XX→4μ

<table>
<thead>
<tr>
<th>Process</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZZ^* \to 4\ell$</td>
<td>$0.10 \pm 0.01$</td>
</tr>
<tr>
<td>$H \to ZZ^* \to 4\ell$</td>
<td>$0.1 \pm 0.1$</td>
</tr>
<tr>
<td>VVV/VBS</td>
<td>$0.06 \pm 0.03$</td>
</tr>
<tr>
<td>Heavy flavour</td>
<td>$0.07 \pm 0.04$</td>
</tr>
<tr>
<td>Total</td>
<td>$0.4 \pm 0.1$</td>
</tr>
<tr>
<td>Data</td>
<td>0</td>
</tr>
</tbody>
</table>
**4l: distribution**

**Diagram: 4l: distribution**

- **Data**
- **Reducible bkg**
- **VVV/VBS**
- **ZZ*→4l**
- **m_{Zd}=15 GeV**
- **m_{Zd}=35 GeV**
- **m_{Zd}=55 GeV**

**ATLAS**
- 13 TeV, 36.1 fb^{-1}
- H → XX → 4l

**Graphs: m_{34} vs. m_{12}**

- **ATLAS**
  - 13 TeV, 36.1 fb^{-1}
  - H → XX → 4l

**Legend:**
- **ATLAS**
- **4e channel [2 evts]**
- **2e2μ channel [7 evts]**
- **4μ channel [8 evts]**
- **Failed Z veto [25 evts]**
- **Signal region**

**Legend:**
- **4μ low mass channel [0 evts]**
- **Outside 120 < m_{4l} < 130 window [16 evts]**
- **Signal region**
- **Quarkonia veto**
**4l: fiducial cross section**

<table>
<thead>
<tr>
<th></th>
<th>$H \rightarrow ZX \rightarrow 4\ell$</th>
<th>$H \rightarrow XX \rightarrow 4\ell$</th>
<th>$H \rightarrow XX \rightarrow 4\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(15 GeV $&lt; m_X &lt; 55$ GeV)</td>
<td>(15 GeV $&lt; m_X &lt; 60$ GeV)</td>
<td>(1 GeV $&lt; m_X &lt; 15$ GeV)</td>
</tr>
<tr>
<td>Electrons</td>
<td>Dressed with prompt photons within $\Delta R = 0.1$</td>
<td>$p_T &gt; 7$ GeV $</td>
<td>\eta</td>
</tr>
<tr>
<td>Muons</td>
<td></td>
<td>$p_T &gt; 5$ GeV $</td>
<td>\eta</td>
</tr>
<tr>
<td>Quadruplet</td>
<td>Three leading-$p_T$ leptons satisfy $p_T &gt; 20$ GeV, 15 GeV, 10 GeV</td>
<td>$\Delta R &gt; 0.1$ between SF (OF) leptons</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$50$ GeV $&lt; m_{12} &lt; 106$ GeV</td>
<td>$m_{34}/m_{12} &gt; 0.85$</td>
<td></td>
</tr>
<tr>
<td>12 GeV $&lt; m_{34} &lt; 115$ GeV</td>
<td>10 GeV $&lt; m_{12,34} &lt; 64$ GeV</td>
<td>$0.88$ GeV $&lt; m_{12,34} &lt; 20$ GeV</td>
<td></td>
</tr>
<tr>
<td>115 GeV $&lt; m_{4\ell} &lt; 130$ GeV</td>
<td>5 GeV $&lt; m_{14,32} &lt; 75$ GeV if $4e$</td>
<td>$m_{\gamma(1S)} - 0.70$ GeV $&lt; m_{12,34,14,32} &lt; (m_{\gamma(3S)} + 0.75$ GeV)</td>
<td>Reject event if either of:</td>
</tr>
<tr>
<td>$m_{12,34,14,32} &gt; 5$ GeV</td>
<td>or $4\mu$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**ATLAS**

$H \rightarrow ZX \rightarrow 4\ell$

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

- **Observed**
- **Expected**

---

$H \rightarrow XX \rightarrow 4\mu$

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

- **Observed**
- **Expected ± 2σ**
$4\ell$ 8TeV

Final State: $4e + 2e2\mu + 4\mu$

95% CL

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

Upper Bound on BR ($H \rightarrow Z_d Z_d$)

- Observed
- Expected

$\pm 1\sigma$

$\pm 2\sigma$