Measurement of the Higgs properties in bosonic decay channels at 13 TeV in ATLAS

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Blois 2017 - May 31, 2017
The Higgs Boson and the LHC

- In Run 2, higher energy and more statistics.
- By the end of 2016, total of 36.1 fb\(^{-1}\) of pp data.
- New \(N^3\)LO QCD corrections in ggF.
- Latest and greatest measurements!
- Results used in EFT frameworks and to calculate pseudo observables.

More Data!

![](image1)

More Cross Section!

![](image2)

ATLAS Online Luminosity

- 2011 pp \(\sqrt{s} = 7\) TeV
- 2012 pp \(\sqrt{s} = 8\) TeV
- 2015 pp \(\sqrt{s} = 13\) TeV
- 2016 pp \(\sqrt{s} = 13\) TeV

\[\text{total XS} \sim \times 2!\]

\[\text{ttH} \times 3.8!\]
Bosonic Decay Modes of the Higgs

- **WW**:  
  - Second highest BR of all Higgs decays.  
  - Most precise measurement in Run 1.

- **ZZ and γγ**:  
  - Fully reconstruct mass and kinematics of the Higgs.  
  - Quark couplings measured indirectly through ggF prod mode, and γγ decay.

\[
H \rightarrow WW \rightarrow l\nu l\nu \quad \text{and} \quad H \rightarrow ZZ \rightarrow 4l
\]
Branching ratios of the Higgs

for 36.1/fb of integrated luminosity...

<table>
<thead>
<tr>
<th>Branching Ratio</th>
<th>Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma \times L$ (all Higgs produced)</td>
<td>$\sim 1,987,555$</td>
<td></td>
</tr>
<tr>
<td>$\sigma \times L \times BR(H \rightarrow WW \rightarrow l\nu l\nu)$</td>
<td>21108 (1.06%)</td>
<td></td>
</tr>
<tr>
<td>$\sigma \times L \times BR(H \rightarrow \gamma\gamma)$</td>
<td>4512 (0.23%)</td>
<td></td>
</tr>
<tr>
<td>$\sigma \times L \times BR(H \rightarrow ZZ \rightarrow 4l)$</td>
<td>249 (0.01%)</td>
<td></td>
</tr>
<tr>
<td>$\sigma \times L \times BR(H \rightarrow \text{sum}(WW+ZZ+\gamma\gamma))$</td>
<td>25869 (1.30%)</td>
<td></td>
</tr>
</tbody>
</table>

Only considering $l = e, \mu$. Numbers are before detector reconstruction and event selection.

- Of $\sim 2$ million Higgs, $\sim 25,000$ will decay to $WW^* \rightarrow l\nu l\nu$, $ZZ^* \rightarrow 4l$, or $\gamma\gamma$.
- Numbers from Yellow Report 4: arXiv:1610.07922
- Event selection and reconstruction further reduce this by $\sim 75-90%$. 
H → WW* → ℓνℓν Selection

ATLAS-CONF-2016-112 - 5.8 fb⁻¹

- 5.8 fb⁻¹ of data.
- VBF:
  - Opposite sign e and μ.
  - ≥ 2 jets.
  - Veto on 3 leptons.
- Main bkg: Top, WW/WZ, Z → ττ/jets
- VBF SR: uses BDT
  - H properties e.g. spin 0 = small Δφ∥
  - VBF e.g. large mjj and Δyjj
  - others: mjj, mT, pT_Tot, ηcentrality
- Simultaneous likelihood fit in SR and CR.
- 1.9σ significance assuming H=125 GeV.

$$\mu_{VBF} = 1.7^{+1.0}_{-0.8} (\text{stat})^{+0.6}_{-0.4} (\text{sys})$$

$$\sigma_{VBF} \cdot B_{H \rightarrow WW} = 1.4^{+1.0}_{-0.8} (\text{stat})^{+0.5}_{-0.4} (\text{sys}) \text{ pb}$$
H → γγ Selection

ATLAS-CONF-2016-067 - 13.3 fb⁻¹

<table>
<thead>
<tr>
<th></th>
<th>diphoton baseline</th>
<th>VBF enhanced</th>
<th>single lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>η</td>
<td>&lt; 1.37 or 1.52 &lt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>p_T</td>
<td>&gt; 0.35 m_γγ</td>
</tr>
<tr>
<td></td>
<td>and</td>
<td>p_T</td>
<td>&gt; 0.25 m_γγ</td>
</tr>
<tr>
<td>Jets</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>p_T</td>
<td>&gt; 30 GeV,</td>
</tr>
<tr>
<td></td>
<td>m_\gamma_\gamma &gt; 400 GeV,</td>
<td>Δy_\gamma_\gamma &gt; 2.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Δφ_\gamma_\gamma,\gamma &gt; 2.6</td>
<td></td>
</tr>
<tr>
<td>Leptons</td>
<td>-</td>
<td></td>
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</tbody>
</table>

- σ x L x BR(H → γγ) = ~1662.
- Neural network selects a diphoton vertex (uses track/calo info).
- bkg: γγ (79%), γj (18.5%) and jj (2.5%).
- Exponential exp(pol2) fit to data used for bkg extraction.
- At 13.3 fb⁻¹, 124,137 events pass selection, 439 H extracted → 0.3% purity.
ATLAS-CONF-2016-067

H → γγ Differential Cross Section

- Baseline prediction Powheg NNLOPS (at QCD NNLO + EW NLO) in blue.
- Normalized to N^3LO with k-factor.
- JVE+N3LO includes NNLL resummation of the pT of the leading jet.
- STWZ-BLPTW is a NNLL+NNLO resummation for the pT of the leading jet, combined with a NLL+NLO resummation for the subleading jet.
- GoSam has NLO QCD accuracy in the inclusive 1, 2, and 3-jet region.

\[ \sigma / \text{prediction} \]

**\( p_T \)**

**\( N_{\text{jets}} \)**

**\( \frac{\text{data}}{\text{prediction}} \)**

**\( \frac{\text{d} \sigma_{\text{id}}}{\text{d} p_T} \)**

**\( m_h = 125.09 \text{ GeV} \)**

**\( k_{gg-H} = 1.10 \)**

**\( m_t = 125.09 \text{ GeV} \)**

**\( \frac{\text{data}}{\text{prediction}} \)**

**\( N_{\text{jets}} \)**

**\( \frac{\text{d} \sigma_{\text{id}}}{\text{d} p_T} \)**

**\( m_t = 125.09 \text{ GeV} \)**

**\( \frac{\text{data}}{\text{prediction}} \)**

**\( N_{\text{jets}} \)**
• $|y_{\gamma\gamma}|$ probes PDF.
• $|\cos\theta^*|$ and $\Delta\phi_{jj}$ test spin and parity.
• $p_{T,j1}$ is sensitive to models of parton radiation in ggF.
H → ZZ* → 4l Selection

- $\sigma \times L \times \text{BR}(H \rightarrow ZZ \rightarrow 4l) = 249$.
- Major bkg is ZZ* (84%).
- 4l channel has high signal to noise.
- H extraction done by fitting signal and bkg shapes to $m_{4l}$ distribution.
- At $36.1 \text{ fb}^{-1}$ looking at $115 < m_{4l} < 130$, 102 events pass selection, and we expect 31 bkg events. Purity $\rightarrow$ 70%.
$H \rightarrow ZZ^* \rightarrow 4l$ Diff. Cross Section

- Baseline is NNLOPS again (this time in red.)
- Normalized to the $N^3LO$ cross section with the listed $k$-factors.
- Compared with NNLO FxFx and HRes.
- Consistent with SM predictions.

\begin{itemize}
\item $\frac{\sigma}{fb}$
\item $N_{\text{jets}}$
\item $p_T$ (GeV)
\end{itemize}

\textbf{Data/Theory}

\textbf{H $p_T$}
$H \rightarrow ZZ^* \rightarrow 4l$ Diff. Cross Section

- $|y_{4l}|$ probes PDF.
- $|\cos \theta^*|$ and $\Delta \phi_{jj}$ test spin and parity.
- $m_{jj}$ is sensitive to different production modes.
H $\rightarrow$ ZZ$^*$ $\rightarrow$ 4l Double Diff. XS

- $p_T$ distribution as a function of N jets.
- 2D cross section $p_T$ vs. $N_{jets}$ can be used to measured QCD perturbations by production mode.
- Non-linear on x-axis!

$N_{jets} = 0$  $N_{jets} = 1$  $N_{jets} \geq 2$
H → ZZ* → 4l Pseudo Observ.

- $m_{12}$ vs. $m_{34}$ can be used to set limits on modified Higgs boson interactions, in the context of pseudo observables.
- PO independent variables in the absence of specific symmetry assumptions- Testing if such relations are verified by data.
- These limits are on contact terms to L-/R-handed leptons.
ATLAS has analyzed 36.1 fb\(^{-1}\) of pp collisions at 13 TeV, and so far, things are looking consistent with the Standard Model in the bosonic decay channels.

- Differential cross section measurements demonstrate a high resolution way to measure many Higgs properties.
- Other Higgs boson properties like mass and spin/CP will be calculated with 13 TeV data.
- A future combination of \(H \rightarrow ZZ^*\), \(H \rightarrow \gamma\gamma\) and possibly \(H \rightarrow WW^*\), as well as a combination with CMS will constrain the statistical uncertainty even further.
- More than 100 fb\(^{-1}\) expected at the end of Run 2!
Thank You!
Fiducial Cross Section

- ‘Fiducial’ means cross sections within a phase space that ATLAS can directly measure.
- Theory predictions compared to the constrained fiducial phase space.

\[
\frac{d\sigma_i}{dx} = \frac{\nu_i^{\text{sig}}}{c_i \Delta x_i \int L \, dt} 
\]

\[
c_i = \frac{n_i,\text{reco}}{n_i,\text{fid}} \quad \text{(numerator is reconstructed truth MC)}
\]

- \(\nu^{\text{sig}}\) is extracted signal events from data.
- \(\Delta x\) is the bin width.
- \(c\) is correction factor, derived from MC.
  - models detector effects
    - trigger, resolution, identification and reconstruction.
  - in H\(\gamma\gamma\), \(c = 78.5\%\) inclusively.
  - in HZZ, \(c = 53\%\) inclusively.

can’t measure as well at high \(\eta\)