Measurement of differential and production mode cross sections of the Higgs in decays to bosons using the ATLAS detector

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The Higgs Boson

- Existence of Higgs-like particle confirmed in 2012 with a mass of 125 GeV
- Bosonic decays of the Higgs key in discovery
Largely dominated by gluon-gluon fusion

Vector boson fusion is distinguished by the presence of widely separated jets in the event
Results presented in this talk:

- ggF and VBF production cross-section measurement using $H \rightarrow WW \rightarrow e\nu\mu\nu$ decays (36.1 $fb^{-1}$)
- $VH,H \rightarrow WW \rightarrow \ell\nu\ell\nu$ (36.1 $fb^{-1}$)
- $H \rightarrow \gamma\gamma$ differential cross-section and couplings measurement (79.8 $fb^{-1}$)
- $H \rightarrow ZZ$ differential cross-section and couplings measurement (79.8 $fb^{-1}$)
$H \rightarrow WW \rightarrow e\nu\mu\nu$: ggF and VBF production

- Measurement of the ggF and VBF production cross-section
- Separate between two production modes using jet multiplicity of the event
  - ggF: 0-1 jet
  - VBF: $\geq 2$ jets

$H \rightarrow WW \rightarrow e\nu\mu\nu$: Results

The observed (expected) ggF and VBF signals have significances of 6.0 (5.3) and 1.8 (2.6) $\sigma$

- Reasonable agreement with SM
Search for events with three ($WH$) or four ($ZH$) charged leptons (electrons and muons)

- Background processes dominated by $WZ$, $qq \rightarrow ZZ$, $t\bar{t}$ & $t\bar{t}V$
- Use b-tagging to suppress top-quark related processes
**WH analysis**

- Three leptons and missing transverse energy coming from the neutrinos

**Two Signal Regions:**

- Z-dominated: one same-flavour Opposite-sign pair
- Z-depleted: No Same-flavour Opposite-sign
- BDTs used to discriminate against diboson and Top background

**ZH analysis**

- Four leptons, with a pair close to the Z boson mass

**Two Signal Regions:**

- One Same-flavour Opposite-sign pair: very good S/B ($\sim2$)
- Two Same-flavour Opposite-sign pair: dominated by $ZZ \rightarrow 4\ell$ background, S/B ($\sim0.4$)

- ZZ Background shape estimated from MC and normalised in a control region
\( \text{VH,H} \rightarrow \text{WW} \rightarrow \ell \nu \ell \nu \): Background estimation

- Dedicated control regions used to normalise the prompt lepton background
- Orthogonal to Signal region by reversing selection criteria
**VH, H → WW → ℓνℓν: Results**

**ATLAS**
\( \sqrt{s}=13 \text{ TeV, 36.1 fb}^{-1} \)

- Data
- Uncertainty
- WH (μ=2.3)
- ZH (μ=2.9)
- Other Higgs
- WZ/WWγ*
- VVV
- ZZ*
- top-quark

- BDT score results used to classify events in various bins
- Consistent with SM within 1.5σ
Events categorised within a particular production mode
Aim to maximise the sensitivity of measurements by choosing regions of phase space which minimise theoretical uncertainties
All decay channels can be combined
Results obtained for each production mode

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https://arxiv.org/abs/1610.07922
Large background, but excellent sensitivity ensured by very good photon efficiency and resolution

Analysis categories designed to isolate out events from different production modes.
H → γγ: STXS Stage-0 and 1

● Find good agreement with SM expectation within 1σ
$H \rightarrow \gamma\gamma$: Differential cross-sections

- Cross-section measured differentially in dilepton $p_T$ and rapidity, leading jet $p_T$ and number of $b$-jets

<table>
<thead>
<tr>
<th>Distribution</th>
<th>$p(\chi^2)$ with Default MC Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{\gamma\gamma}$</td>
<td>31%</td>
</tr>
<tr>
<td>$</td>
<td>y_{\gamma\gamma}</td>
</tr>
<tr>
<td>$p_T^{J_1}$</td>
<td>88%</td>
</tr>
<tr>
<td>$N_{b\text{-jets}}$</td>
<td>84%</td>
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</tbody>
</table>

Dr. Marc Bret Cano

Latest Results on Higgs Boson analyses
The “golden channel”: Very clean channel with high S/B
Boosted decision tree used to suppress background and discriminate between production modes
$H \to ZZ^* \to 4\ell$: STXS Stage-0 and 1 and 2-D contour

All Stage-0 and reduced Stage-1 ggF measurements agree with the predictions for the SM Higgs boson within $2\sigma$.
$H \rightarrow ZZ^* \rightarrow 4\ell$: Differential fiducial cross-section

- xsec measured differentially in terms of the $p_{T,4\ell}$ and jet multiplicity for the ggF production mode
- Compared observed results to NNLOPS and MadGraph5 predictions
Conclusions

- Various measurements of the Higgs boson presented
- Still fairly limited by statistics... but still a good fraction of the Run-2 dataset left to investigate
- So far all compatible with SM expectation
- As usual, stay tuned!
BACKUP SLIDES
$H \rightarrow ZZ^* \rightarrow 4\ell$: the golden channel

Many useful features:
- Large signal to background ratio ($S/B \sim 2$) & excellent mass resolution ($\sim 1 – 2\%$)
- Main draw-back is the small branching ratio ($\sim 0.02\%$) $\rightarrow$ limited statistics

Analysis strategy:
- ATLAS uses invariant mass of the four-lepton system ($m_{4\ell}$) as your observable
- Leptons from the $Z^*$ are low $p_T$ $\rightarrow$ more prone to background contamination
- Non-resonant background coming from $ZZ$ (reduced via MVA)
- Fake background estimated in Control regions
The LHC & ATLAS has been working remarkably well, generally exceeded expectations.

Currently in shutdown until mid-end 2021
Higgs boson mass: Results

\[ m_{\text{ZZ}^*} = 124.79 \pm 0.37 \text{ GeV} \]
\[ m_{\gamma\gamma} = 124.93 \pm 0.40 \text{ GeV} \]

Combining with the 7 and 8 TeV dataset: \( m_H = 124.97 \pm 0.24 \text{ GeV} \)

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty in ( m_H ) [MeV]</th>
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</thead>
<tbody>
<tr>
<td>EM calorimeter response linearity</td>
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<tr>
<td>Non-ID material</td>
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<tr>
<td>EM calorimeter layer intercalibration</td>
<td>55</td>
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<tr>
<td>( Z \to ee ) calibration</td>
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</tr>
<tr>
<td>ID material</td>
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<tr>
<td>Lateral shower shape</td>
<td>40</td>
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<tr>
<td>Muon momentum scale</td>
<td>20</td>
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<tr>
<td>Conversion reconstruction</td>
<td>20</td>
</tr>
<tr>
<td>( H \to \gamma\gamma ) background modelling</td>
<td>20</td>
</tr>
<tr>
<td>( H \to \gamma\gamma ) vertex reconstruction</td>
<td>15</td>
</tr>
<tr>
<td>( e/\gamma ) energy resolution</td>
<td>15</td>
</tr>
<tr>
<td>All other systematic uncertainties</td>
<td>10</td>
</tr>
</tbody>
</table>
Higgs boson mass: Summary


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Latest Results on Higgs Boson analyses
May 6, 2019

ATLAS

Run 1: $\sqrt{s} = 7-8$ TeV, 25 fb$^{-1}$, Run 2: $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- Run 1 $H \rightarrow 4l$: $124.51 \pm 0.52$ (± 0.52) GeV
- Run 1 $H \rightarrow \gamma\gamma$: $126.02 \pm 0.51$ (± 0.43) GeV
- Run 2 $H \rightarrow 4l$: $124.79 \pm 0.37$ (± 0.36) GeV
- Run 2 $H \rightarrow \gamma\gamma$: $124.93 \pm 0.40$ (± 0.21) GeV
- Run 1+2 $H \rightarrow 4l$: $124.71 \pm 0.30$ (± 0.30) GeV
- Run 1+2 $H \rightarrow \gamma\gamma$: $125.32 \pm 0.35$ (± 0.19) GeV
- Run 1 Combined: $125.38 \pm 0.41$ (± 0.37) GeV
- Run 2 Combined: $124.86 \pm 0.27$ (± 0.18) GeV
- Run 1+2 Combined: $124.97 \pm 0.24$ (± 0.16) GeV
- ATLAS + CMS Run 1: $125.09 \pm 0.24$ (± 0.21) GeV

$m_H$ [GeV]
Obtained combining $\gamma\gamma$, $ZZ^*$, $WW^*$, $\tau\tau$, $b\bar{b}$ and $\mu\mu$ final states.

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 24.5 - 79.8 fb$^{-1}$

$m_H = 125.09$ GeV, $|y_H| < 2.5$

$p_{SM} = 76%$

**Total**  
**Stat.**  
**Syst.**

- **ggF**  
  1.04 ± 0.09 (± 0.07, +0.07, -0.06)

- **VBF**  
  1.21 +0.24 ± 0.18, -0.22, ± 0.16

- **WH**  
  1.30 +0.30 ± 0.28, -0.38, ± 0.29

- **ZH**  
  1.05 +0.31 ± 0.24, -0.29, ± 0.19

- **ttH+tH**  
  1.21 +0.26 ± 0.17, -0.24, ± 0.20

Cross-section normalized to SM value
Higgs Boson Production xsec and BR ratios

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 24.5 - 79.8 fb$^{-1}$

$m_H = 125.09$ GeV, $|y_H| < 2.5$

$p_{SM} = 93\%$

\[
\begin{align*}
\sigma_{ggF}^{ZZ} & = 1.13 \pm 0.13 (\pm 0.12, \pm 0.06) \\
\sigma_{VBF}/\sigma_{ggF} & = 1.24 \pm 0.59 (\pm 0.44, \pm 0.39) \\
\sigma_{WH}/\sigma_{ggF} & = 1.24 \pm 0.59 (\pm 0.44, \pm 0.39) \\
\sigma_{ZH}/\sigma_{ggF} & = 1.01 \pm 0.47 (\pm 0.37, \pm 0.30) \\
\sigma_{ttH+tH}/\sigma_{ggF} & = 1.20 \pm 0.31 (\pm 0.24, \pm 0.20) \\
B_{\gamma\gamma}/B_{ZZ} & = 0.87 \pm 0.14 (\pm 0.12, \pm 0.07) \\
B_{WW}/B_{ZZ} & = 0.84 \pm 0.18 (\pm 0.13, \pm 0.12) \\
B_{\tau\tau}/B_{ZZ} & = 0.86 \pm 0.26 (\pm 0.19, \pm 0.18) \\
B_{bb}/B_{ZZ} & = 0.93 \pm 0.38 (\pm 0.27, \pm 0.26)
\end{align*}
\]

Parameter normalized to SM value
Interpret the results in the $\kappa$ framework as a function of the particle mass assuming no BSM contributions to total width.

Probing universal coupling strength factors for fermions ($\kappa_f$) and bosons ($\kappa_V$).

Best fit shows values of $\kappa_f$ and $\kappa_V \neq 1.0$, but compatible with SM within uncertainties.
Higgs boson mass: per-event method \((ZZ \rightarrow 4\ell)\)

- \(m_{4\ell}\) signal distribution modelled as the convolution of the intrinsic Higgs boson lineshape and a four lepton invariant mass response function.

- The response function gives the probability of measuring a value \(m_{4\ell}^{\text{meas}}\) for a truth mass \(m_{4\ell}^{\text{true}}\).

- Validate the method by testing it with the \(Z\) boson.

<table>
<thead>
<tr>
<th>Category</th>
<th>(m_Z) in simulation [GeV]</th>
<th>(m_Z) in data [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4(\mu)</td>
<td>91.19^{+0.41}_{-0.41}</td>
<td>91.46^{+0.42}_{-0.41}</td>
</tr>
<tr>
<td>4e</td>
<td>91.19^{+1.02}_{-1.03}</td>
<td>91.75^{+1.08}_{-1.06}</td>
</tr>
<tr>
<td>2(\mu2e)</td>
<td>91.18^{+1.11}_{-1.11}</td>
<td>91.31^{+1.62}_{-1.33}</td>
</tr>
<tr>
<td>2e2(\mu)</td>
<td>91.19^{+0.90}_{-0.90}</td>
<td>92.49^{+0.91}_{-0.94}</td>
</tr>
<tr>
<td>Combined</td>
<td>91.19^{+0.34}_{-0.34}</td>
<td>91.62^{+0.35}_{-0.35}</td>
</tr>
</tbody>
</table>
Study off-shell production of Higgs boson at high mass $ZZ \rightarrow 4\ell$ and $2\ell\ell\nu\nu$ channels

Assume same couplings in on-shell/off-shell regions to indirectly constrain Higgs boson total width
Combination of $\gamma\gamma$ and $4\ell$ final states

Chosen for their excellent mass resolution