Search for a high mass neutral Higgs boson using the ATLAS detector

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on behalf of the ATLAS Collaboration

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After the 125GeV Higgs boson discovery, an important question remains:

**Is this the only Higgs boson?**

- Extensions to the SM predict additional heavy Higgs boson(s) we could observe in proton-proton collisions at the LHC

In this presentation: The latest search limits from ATLAS of heavy neutral Higgs decaying in the diboson channels, using $20.3/fb$ at $\sqrt{s} = 8 TeV$

- $H \rightarrow \gamma\gamma$ (July 2014: Phys. Rev. Lett. 113, 171801)
- $H \rightarrow ZZ$ (July 2015: arXiv:1507.05930)
- $H \rightarrow WW$ (August 2015: Preliminary results to be submitted)
As one discovery channel for the 125GeV Higgs, \( H \rightarrow \gamma\gamma \) has additional importance in high mass searches (Phys. Rev. Lett. 113, 171801)

- resonant signal on smooth background: clean search!

Signal Model:

- double-sided Crystal Ball with parameters fit on different simulated mass points
- All production modes use same PDF
Backgrounds:

Composition in data:
\[ \gamma\gamma (83.7\%), \gamma \text{ jet}(15.1\%), \text{ jet jet}(1.2\%) \]

Where $\gamma\gamma$ includes doubly-converted DY $Z \rightarrow ee$

Composition derived using a 2Dx2D sideband method in isolation vs identification for both photons [arXiv:1107.0581]

- Parameterized by pol-2 in sliding window
- Shape/window choice:
  - Fit S+B on background only spectrum
  - signal yield bias < 20% stat. error
**Statistical Interpretation**

- Limits are $95\%CL_s$ using the $q_\mu$ test statistic

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**Narrow-width approximation**

For different mass hypotheses find limits on:

$$\sigma_{fid} \cdot BR(X \rightarrow \gamma\gamma) = \frac{N_{data}}{C_X \mathcal{L}}$$

Efficiency factor derived from MC ggF samples

$$C_X = \frac{N_{reco}^{MC}}{N_{fid}^{MC}}$$

MC samples have $\Gamma_H = 4\, MeV$

**Narrow-width limit: bias < 10% signal yield**

---

**ATLAS Simulation**

\[ \Gamma_X < 0.09\, GeV + 0.01\, m_X \]

Narrow-width Region
Largest excess corresponds to $z_0 = 2.2$ at $m_X = 530 \ GeV$
The other discovery channel for the 125 GeV Higgs, $H \rightarrow ZZ$, is a powerful probe to search for additional heavy Higgs.

Four decay channels enter ATLAS’ search (arXiv:1507.05930):

$$H \rightarrow ZZ \rightarrow llll, llqq, llnn, \nu\nuqq$$

Some background processes modelled using MC simulation:

- $ggF H (200 \text{ GeV})$
- $Zjj$
- $Z+\text{jets}$
- $Z+\text{tt}$
- Uncertainty

Others use data-driven estimates, often fit simultaneously between channels:

- $qq \rightarrow ZZ$
  - in $llll, ll\nu\nu, \nu\nuqq$

eg. $Z + Jets$ here in a sub-channel of $llqq$

(important in all channels).

Control region built by requiring $m_{jj}$ far from $m_{Z}$. 

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SUSY2015
Analysis outline:

- Each channel (ℓℓℓℓ, ℓℓqq, ℓℓνν, ννqq) has a discriminating variable sensitive to $m_H$.

- Distributions are made for signal & background in each channel.
- Channels separate categories for ggF and VBF production based on additional jets in the event (except: $ννqq$ does not model VBF).
- Additional sub-channels designed to improve sensitivity based on lepton flavour, jet categorization.

eg:

fully reconstructed channels: invariant mass  
channels with neutrinos: transverse mass
**Statistical Interpretation**

- The four channels enter a simultaneous fit
- Limits are 95%\(CL_s\) using the \(\tilde{q}_\mu\) test statistic
- Both interpretations derived using MC samples with \(\Gamma_H = 4\) MeV

---

**Model-independent (narrow width) interpretation**

No assumption is made on relative contribution of ggF and VBF to production

For different mass hypotheses find limits on parameters of interest:

\[
\begin{align*}
\sigma_{ggF} & \ast BR(H \rightarrow ZZ) \\
\sigma_{VBF} & \ast BR(H \rightarrow ZZ)
\end{align*}
\]

---

**2HDM interpretation**

*Type-I and Type-II* considered

Relative contribution of ggF and VBF, and branching ratios are fixed by 2HDM

Limits set in parameter space of \(m_H, \tan\beta, \cos(\beta - \alpha)\)

Parameter ranges are set such that \(\Gamma_H < 0.5\% m_H\) and the light Higgs couplings are not enhanced by more than 3 times the Standard Model
**ggF limits**

- 530 fb @ 195 GeV
- 8 fb @ 950 GeV

**VBF limits**

- 310 fb @ 195 GeV
- 9 fb @ 950 GeV
Outline

- 2HDM Type-I
- 2HDM Type-II

Summary

**ATLAS**

$H \rightarrow ZZ$, $m_H = 200$ GeV

2HDM Type I

\[ \tan \beta \]

\[ \cos (\beta - \alpha) \]

\(\text{Obs 95\% CL limit}\)

\(\pm 1\sigma\) band

\(\pm 2\sigma\) band

Excluded

\(\sqrt{s} = 8\) TeV

20.3 fb$^{-1}$

**ATLAS**

$H \rightarrow ZZ$, $m_H = 200$ GeV

2HDM Type II

\[ \tan \beta \]

\[ \cos (\beta - \alpha) \]

\(\text{Obs 95\% CL limit}\)

\(\pm 1\sigma\) band

\(\pm 2\sigma\) band

Excluded

\(\sqrt{s} = 8\) TeV

20.3 fb$^{-1}$

2HDM Type-I

2HDM Type-II
2HDM Type-I

2HDM Type-II
**H → WW** also very powerful due to high branching ratio (~60% for masses probed)

Two decay channels enter ATLAS’ search:

\[
H \rightarrow WW \rightarrow ℓνℓν, ℓνqq
\]

Different backgrounds dominate different channels: **WW, Top, W + jets, multijet**

Where possible, estimations are **data-driven**. General approach:
- build control regions to enrich each background
- extrapolation factors bring the fit result from the CR to the yield in the SR

![Control region enriched in WW](image1)

![Control region enriched in Top](image2)
• Analyses split into categories designed to increase sensitivity
• Signal production modes and background sources vary by category

\[ \ell \nu \nu \nu \] is split by
- same/different flavour leptons
- \( N_{jets} = 0, 1, \geq 2 \)

\[ \ell \nu q q \] is split by
- flavour/charge of lepton

Each channel calculates a mass discriminant on which the final fit is done:

\[ \ell \nu \nu \nu \rightarrow m_T \]
transverse mass of \( \ell, \ell, E_T^{miss} \)

\[ \ell \nu q q \rightarrow m_{\ell \nu jj} \]
invariant mass where \( m_W, E_T^{miss} \) are used to constrain \( \vec{p}_T \)
Statistical Interpretation

- Both channels $\ell\nu\ell\nu$, $\ell\nu qq$ enter combined limit setting

Narrow-Width Approximation

Width of resonance is fixed for all mass at $\Gamma_H = 4.07\text{MeV}$

No assumption is made on relative contribution of ggF and VBF to production

Standard Model Width Scenario

Width of resonance is the SM Higgs boson width for that mass $\Gamma_H = \Gamma_{H,SM}^{SM}$

No assumption is made on relative contribution of ggF and VBF to production

Intermediate-Width Scenario

Width of resonance intermediate to above - parameterized as $\Gamma_H = \kappa r^2 \cdot \Gamma_{H,SM}$
Limits in Narrow Width Approximation \( \Gamma_H = 4.07 \text{MeV} \)

**ggF limits**
- \(~900 \text{ fb} @ 300 \text{ GeV}\)
- \(~20 \text{ fb} @ 1500 \text{ GeV}\)

**VBF limits**
- \(~230 \text{ fb} @ 300 \text{ GeV}\)
- \(~6 \text{ fb} @ 1500 \text{ GeV}\)
Limits in Standard Model-like scenario with $\Gamma_H = \Gamma_H^{SM}$

**ggF limits**
- $\sim 1100$ fb @ 300 GeV
- $\sim 40$ fb @ 1000 GeV

**VBF limits**
- $\sim 250$ fb @ 300 GeV
- $\sim 20$ fb @ 1000 GeV
Limits in Intermediate-Width Scenario with $\Gamma_H = (20\%, 40\%, 80\%) \cdot \Gamma_H^{SM}$

**ATLAS** Preliminary

$H \rightarrow WW$

$\sqrt{s} = 8$ TeV $\int L dt = 20.3$ fb$^{-1}$

95% CL Limit on $\frac{\sigma}{\kappa^{1/2}} \times \text{BR}(H \rightarrow WW)$ [pb]

- Obs. $\kappa^{1/2} = 0.8$
- Exp. $\kappa^{1/2} = 0.8$
- Obs. $\kappa^{1/2} = 0.4$
- Exp. $\kappa^{1/2} = 0.4$
- Obs. $\kappa^{1/2} = 0.2$
- Exp. $\kappa^{1/2} = 0.2$

n.b. limit on $\frac{\sigma}{\kappa^{1/2}}$ to separate otherwise overlapping results
Summary

Shown here were searches for high-mass neutral Higgs bosons decaying in the diboson channels using the full 20.3/fb of ATLAS data at $\sqrt{s} = 8\,\text{TeV}$

- $H \to \gamma\gamma$ : limits set on $\sigma_{fid} \cdot BR(X \to \gamma\gamma)$ for narrow resonances up to 600GeV.

- $H \to ZZ$ : limits set on $\sigma_{ggF(VBF)} \cdot BR(X \to ZZ)$ for narrow resonances up to 1 TeV. Limits are also set in the 2HDM context providing the strongest ever exclusions in some of the parameter space probed. [See backup for MSSM interpretations]

- $H \to WW$ : limits set on $\sigma_{ggF(VBF)} \cdot BR(X \to WW)$ for narrow resonances up to 1.5 TeV, and SM-width resonances up to 1 TeV. Limits are also set for intermediate widths for masses up to 1 TeV.
The following slides all come from Phys. Rev. Lett. 113, 171801 + auxiliary figures unless otherwise noted

Systematics

**TABLE II. Summary of the systematic uncertainties**

<table>
<thead>
<tr>
<th>Source and Higgs boson yield</th>
<th>$Z$ component of Drell–Yan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>Normalization\textsuperscript{b} 9–25%</td>
</tr>
<tr>
<td>Trigger</td>
<td>Peak position\textsuperscript{b} 1.5–3.5%</td>
</tr>
<tr>
<td>$\gamma$ identification\textsuperscript{a}</td>
<td>Template shape\textsuperscript{b} 1.5–3%</td>
</tr>
<tr>
<td>$\gamma$ isolation\textsuperscript{a}</td>
<td>Higgs boson background</td>
</tr>
<tr>
<td>Energy resolution\textsuperscript{a,b}</td>
<td>Cross-section\textsuperscript{c} 9.6%</td>
</tr>
<tr>
<td>$\gamma\gamma$, $\gamma j$, $jj$, $DY$</td>
<td>Branching ratio 4.8%</td>
</tr>
<tr>
<td>Signal bias\textsuperscript{a}</td>
<td>$C_X$ factor</td>
</tr>
<tr>
<td></td>
<td>Topology\textsuperscript{a} 3–15%</td>
</tr>
<tr>
<td></td>
<td>Pile-up &amp; U. E.\textsuperscript{a} 1.4–3.2%</td>
</tr>
</tbody>
</table>

\textsuperscript{a} mass-dependent.
\textsuperscript{b} category-dependent.
\textsuperscript{c} factorization scale + PDF uncertainties [1307.1347]
\( H \rightarrow \gamma \gamma \) Event Selection

- Primary Vertex with at least 2 tracks with \( p_T > 0.4 \text{GeV} \)
- Two photons with \( E_T > 22 \text{GeV}, |\eta| < 2.37 \) excluding barrel/endcap transition region with poor efficiency \( 1.37 < |\eta| < 1.56 \)
- ID: Shower shape criteria used to achieve efficiencies ranging from 70 - 99%
- Calorimeter isolation: \( E_T^{iso} < 6 \text{GeV} \) using a cone of \( \Delta R = 0.4 \)
- Track Isolation: \( p_T^{iso} < 2.6 \text{GeV} \) using a cone of \( \Delta R = 0.2 \)
- Invariant mass: \( E_T^{\gamma 1(2)}/m_\gamma \gamma > 0.4(0.3) \)

The Fiducial Cuts (used to calculate \( C_X \)) are identical except the following:

- Transition region \( 1.37 < |\eta| < 1.56 \) is included
- Both isolation requirements replaced by requiring \( p_T^{iso (no \nu)} < 12 \text{GeV} \) in a cone of \( \Delta R = 0.4 \)
\[ C_X = \frac{N_{reco}^{MC}}{N_{fid}^{MC}} \]

- \( C_X \) from ggF is used in final fit
- Systematic uncertainty covers largest spread per bin in this plot
The following slides all come from arXiv:1507.05930 + auxiliary figures unless otherwise noted

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>Effect [%]</th>
<th>Systematic source</th>
<th>Effect [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow ZZ$ K-factor uncertainty</td>
<td>27</td>
<td>$gg \rightarrow ZZ$ acceptance</td>
<td>13</td>
</tr>
<tr>
<td>$Z$+hf $\Delta\phi$ reweighting</td>
<td>5.3</td>
<td>Jet vertex fraction ($\ell\ell qq/\nu\nu qq$)</td>
<td>13</td>
</tr>
<tr>
<td>Luminosity</td>
<td>5.2</td>
<td>$gg \rightarrow ZZ$ K-factor uncertainty</td>
<td>13</td>
</tr>
<tr>
<td>Jet energy resolution ($\ell\ell qq/\nu\nu qq$)</td>
<td>3.9</td>
<td>$Z$ + jets $\Delta\phi$ reweighting</td>
<td>7.9</td>
</tr>
<tr>
<td>QCD scale $gg \rightarrow ZZ$</td>
<td>3.7</td>
<td>Jet energy scale $\eta$ modelling ($\ell\ell qq/\nu\nu qq$)</td>
<td>5.3</td>
</tr>
</tbody>
</table>

$m_H = 200$ GeV

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>Effect [%]</th>
<th>Systematic source</th>
<th>Effect [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$qq \rightarrow ZZ$ PDF</td>
<td>21</td>
<td>$Z$ + jets estimate ($\ell\ell \nu\nu$)</td>
<td>34</td>
</tr>
<tr>
<td>QCD scale $qq \rightarrow ZZ$</td>
<td>13</td>
<td>Jet energy resolution ($\ell\ell\ell\ell/\ell\ell \nu\nu$)</td>
<td>6.5</td>
</tr>
<tr>
<td>$Z$ + jets estimate ($\ell\ell \nu\nu$)</td>
<td>13</td>
<td>VBF $Z$ + jets $m_{\ell\ell jj}$</td>
<td>5.5</td>
</tr>
<tr>
<td>Signal acceptance ISR/FSR ($\ell\ell\ell\ell/\ell\ell \nu\nu$)</td>
<td>7.8</td>
<td>Jet flavour composition ($\ell\ell\ell\ell/\ell\ell \nu\nu$)</td>
<td>5.3</td>
</tr>
<tr>
<td>$Z + bb$, $Z + c\bar{c}$, $p_T^{\ell\ell}$</td>
<td>5.6</td>
<td>Jet vertex fraction ($\ell\ell qq/\nu\nu qq$)</td>
<td>4.8</td>
</tr>
</tbody>
</table>

$m_H = 400$ GeV

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>Effect [%]</th>
<th>Systematic source</th>
<th>Effect [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$qq \rightarrow ZZ$ PDF</td>
<td>7</td>
<td>$Z$ + jets estimate ($\ell\ell \nu\nu$)</td>
<td>19</td>
</tr>
<tr>
<td>Jet mass scale ($\ell\ell qq$)</td>
<td>7</td>
<td>$Z$ + jets estimate ($\ell\ell \nu\nu$)</td>
<td>19</td>
</tr>
<tr>
<td>$Z + jj$ $p_T^{\ell\ell}$ shape ($\nu\nu qq$)</td>
<td>5.6</td>
<td>Jet mass scale ($\ell\ell qq$)</td>
<td>8.7</td>
</tr>
<tr>
<td>$qq \rightarrow ZZ$ PDF</td>
<td>4.3</td>
<td>$Z + jj$ $p_T^{\ell\ell}$ shape</td>
<td>7.3</td>
</tr>
<tr>
<td>QCD scale $qq \rightarrow ZZ$</td>
<td>3.5</td>
<td>Jet energy resolution ($\ell\ell\ell\ell/\ell\ell \nu\nu$)</td>
<td>4.4</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.6</td>
<td>Jet flavour composition (V/V/Signal)</td>
<td>2.6</td>
</tr>
</tbody>
</table>

$m_H = 900$ GeV

Systematics
## Monte Carlos used in analysis

<table>
<thead>
<tr>
<th>Physics process</th>
<th>$H \rightarrow ZZ$ search final state</th>
<th>Generator</th>
<th>Cross-section normalization</th>
<th>PDF set</th>
<th>Tune</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z/\gamma^* \rightarrow \ell^+\ell^-/\nu\bar{\nu}$</td>
<td>$\ell\ell/\ell\ell\nu\nu$</td>
<td>Alpgen 2.14</td>
<td>NNLO</td>
<td>CTEQ6L1</td>
<td>AUET2</td>
</tr>
<tr>
<td></td>
<td>$\ell\ell\ell/\nu\nu\bar{\nu}$</td>
<td>Sherpa 1.4.1</td>
<td>NNLO</td>
<td>NLO CT10</td>
<td>SHERPA default</td>
</tr>
<tr>
<td>$W \rightarrow \ell\nu$</td>
<td>$\ell\ell\ell\nu\bar{\nu}$</td>
<td>Alpgen 2.14</td>
<td>NNLO</td>
<td>CTEQ6L1</td>
<td>AUET2</td>
</tr>
<tr>
<td></td>
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<td>Sherpa 1.4.1</td>
<td>NNLO</td>
<td>NLO CT10</td>
<td>SHERPA default</td>
</tr>
</tbody>
</table>

### Summary

- **Monte Carlos**
  - Used in analysis
$H \rightarrow ZZ \rightarrow llll$

- Only channel which includes search for VH production: included for $m_H < 200 \text{ GeV}$
- Due to high resolution, only channel using unbinned likelihood fit

- Split in 3 production categories based on jets in event
- $ggF$ split further into 4 channels to improve resolution ($4e, 4\mu, 2e2\mu, 2\mu2e$)
- Dominant background $qq \rightarrow ZZ$ estimated using MC corrected to NNLO
- Other backgrounds:
  - $gg \rightarrow ZZ$ estimated using MC corrected to NNLO
  - $Z + Jets, t\bar{t}$ estimated using fits to $m_{\ell\ell}$ distributions in control regions with inverted cuts for $\ell\ell\mu\mu$ or fits on inner detector variables in relaxed control regions for $\ell\ell ee$
    which are then extrapolated to the signal region

observable: invariant mass $m_{llll}$
**H → ZZ → ℓℓνν**

- Events contain exactly 2 very high quality leptons with $76 < m_{ℓℓ}/GeV < 106$, and no additional high $p_T$ leptons
- Events categorized as ggF or VBF based on additional jets
  - VBF: $m_{jj} > 550\, GeV$
  - ggF: maximum 1 jet $p_T > 30\, GeV$, $\eta_j < 2.5$
- Drell-Yan Z production suppressed by cut on $\Delta\phi(p_ℓ^ℓ, \vec{E}_T^{miss})$
- Boosed Z's enriched by requiring $\Delta\phi_\ell\ell < 1.4$

**Observables**

Transverse mass $m_T^{ZZ}$

\[
(m_T^{ZZ})^2 = \left( \sqrt{m_Z^2 + |p_{T\ell}|^2} + \sqrt{m_Z^2 + |\vec{E}_T^{miss}|^2} \right)^2 - |p_T^\ell + \vec{E}_T^{miss}|^2
\]

**Backgrounds**

- $gg/qq \rightarrow ZZ$ estimated as in $ℓllll$
- $WZ$ estimated using MC (Powheg), validated on data containing additional leptons
- $WW, t\bar{t}, Wt, Z \rightarrow ττ$ estimated from data using $e^±\mu^±$ pairs
- $Z + Jets$ is estimated from data using an ABCD method on $Δϕ(p_ℓ^ℓ, \vec{E}_T^{miss})$ and $Δϕ_\ell\ell$
**H → ZZ → ℓℓqq**

- Events contain exactly 2 very high quality leptons with $83 < m_{ℓℓ}/GeV < 99$, and no additional high $p_T$ leptons
- ggF events are sub-categorized as *resolved* or *merged* to account that at high $m_H$, the jets from $Z \rightarrow q\bar{q}$ decay will overlap and not be resolved
- In the resolved channel, events are sub-categorized based on number of b-tagged jets
- Backgrounds:

  - $Z + Jets$ shape from MC, normalizations (in each category above) are nuisance params in final fit. Control regions are built by inverting cuts on $m_{jj}$ and building pdfs in the b-tagging category.
  - $ZZ/WZ$ taken from MC simulation; differences between generators treated as systematic uncertainty.
  - $Top$ estimated using $e^±\mu±$ pairs; top scaling fit simultaneously during final combination.

**observable: transverse mass** $m_{ℓℓj(j)}$ in the merged (resolved) channel
\( H \rightarrow ZZ \rightarrow \nu\nu qq \)

- Events contain no leptons (as defined in \( \ell\ell qq \) search)
- Require \( E_T^{\text{miss}} > 160 \text{ GeV}, \quad 70 < m_{jj}/\text{GeV} < 105 \)
- To suppress multijet backgrounds, require
  \[
  \Delta \phi(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\text{miss}}) < \pi/2, \quad \Delta \phi(\vec{E}_T^{\text{miss}}, j_{\text{nearest}}) > 0.6
  \]
- Search divided into categories from number of b-tagged jets
- Sensitivity improved by a floating cut on \( p_T^{j} \) increasing linearly with the test mass \( m_H \)
- Jet momenta are scaled to bring \( m_{jj} \rightarrow m_Z \)

observable: transverse mass \( m_{ZZ}^{T} \)

\[
(m_{ZZ}^{T})^2 = \left( \sqrt{m_Z^2 + |p_T^{jj}|^2} + \sqrt{m_Z^2 + |E_T^{\text{miss}}|^2} \right)^2 - |p_T^{jj} + E_T^{\text{miss}}|^2
\]

the range of \( m_{ZZ}^{T} \) used in fit depends on \( m_H \)

Backgrounds:

- \( W + \text{Jets} \) estimated from data using CR with exactly 1 loose muon, in each of several b-tagging categories of the jets
- \( Z + \text{Jets} \) same as with \( \ell\ell qq \) with an additional CR containing exactly 2 loose muons
- A further \( E_T^{\text{miss}} \) - dependant function corrects the MC shape

\( WW/WZ, Top \) same as other channels
2HDM Overview  

[arXiv:1106.0034]

Two doublets $\Phi_1, \Phi_2$ couple to fermions as:

<table>
<thead>
<tr>
<th>Type I</th>
<th>$u, d, \ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type II</td>
<td>$d, \ell, u$</td>
</tr>
</tbody>
</table>

5 physical Higgs bosons: CP-even $h$, $H$, one CP-odd $A$, two charged $H^\pm$

- assumed to be the 125GeV Higgs
- high-mass Higgs under search

Additional parameters:
- $\tan \beta$ ratio between vacuum expectation value of two doublets
- $\alpha$ mixing angle of doublets

- $HZZ$ coupling proportional to $\cos(\beta - \alpha)$
- Alignment Limit $\cos(\beta - \alpha) \rightarrow 0$ leaves the $h$ indistinguishable from a SM Higgs

2HDM considered in presented limits:

$$m_h = 125 \text{ GeV}, \ m_A = m_H = m_{H^\pm}, \ m_{12}^2 = m_A^2 \tan \beta / (1 + \tan \beta^2)$$
MSSM Interpretations

as defined in 1307.1347, 1302.7033, 1101.0593

The value of $m_A$ fully determines the value of $m_H$. For the lightstau model the trilinear coupling was set to $A_T = A_b$. The vertical dashed grey lines indicate contours of constant $m_H$, while the horizontal dashed purple lines indicate contours of constant $m_h$ (for the hMSSM model $m_h = 125$ GeV for the entire phase space shown, so the constant $m_h$ contours are not shown).
\[ H \rightarrow WW \]

The following slides all represent ATLAS Preliminary results: to be submitted
\[ H \rightarrow WW \rightarrow \ell\nu\ell\nu \]

### Signal Regions

**0 jets**

**1 jet**

**2+ jets**

**same flavour**

**different flavour**
$H \rightarrow WW \rightarrow \ell \nu \ell \nu$

Control Regions

**WW Control Regions**

- only different flavour final state is used

**Top Control Regions**

- in 1-jet category, only different-flavour final state is used
- in 2+jet category, both different/same-flavour finals states are used
**H → WW → ℓνqq**

Signal Regions

Signal regions have a mass hypothesis-specific selection to enhance sensitivity

 applying 500 GeV selection

**ggF category**

**VBF category**
Control Regions

$H \rightarrow WW \rightarrow \ell \nuqq$

**ATLAS Preliminary**

**Summary**

**ggF category**

**VBF category**

**WW-enriched CRs**

**Top-enriched CRs**
Statistics used


\[ C L_s \]

\[
\frac{\int_{q_{obs}}^{\infty} f(q|\mu, \hat{\theta}(\mu, obs)) dq}{\int_{q_{obs}}^{\infty} f(0|\mu, \hat{\theta}(0, obs)) dq} = 5\%
\]

\( q_\mu \)

\[
\begin{cases} 
-2 \ln \lambda(\mu) & \hat{\mu} \leq \mu \\
0 & \hat{\mu} > \mu 
\end{cases}
\]

\( \tilde{q}_\mu \)

\[
\begin{cases} 
-2 \ln \tilde{\lambda}(\mu) & \hat{\mu} \leq \mu \\
0 & \hat{\mu} > \mu 
\end{cases}
\]

\( \lambda(\mu) = \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})} \)

\( \tilde{\lambda}(\mu) \)

\[
\begin{cases} 
\lambda(\mu) & \hat{\mu} \geq 0 \\
\frac{L(\mu, \hat{\theta})}{L(0, \hat{\theta})} & \hat{\mu} < 0
\end{cases}
\]

- modified confidence interval (not actually a confidence interval) which protects against downwards fluctuations excluding arbitrarily small signal strengths

- test statistics for upper limit setting. Defined around physical limitation \( \mu > 0 \), and common sense limitations - observing \( \hat{\mu} > \mu \) should be treated as signal-like