Search for heavy resonances decaying into a pair of $Z$ bosons with the ATLAS detector

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Motivation: Multiple Higgs bosons?

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  - Production cross sections, branching ratios, couplings to vector bosons and fermions.
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  - The Minimal Supersymmetric Standard Model (MSSM) is one such 2HDM model.
The ATLAS Higgs-like search program

The ATLAS Experiment at the LHC

- General-purpose detector at the Large Hadron Collider.
- Recorded 139 fb\(^{-1}\) of \(pp\) collision data at \(\sqrt{s} = 13\) TeV during Run 2 of the LHC.
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Focus of this talk

Searches for \(X \rightarrow ZZ\)
Searches for heavy $ZZ$ resonances

Search for heavy spin-0 (heavy Higgs) and spin-2 (graviton) resonances with full Run 2 dataset

- Combination of $4\ell$ and $\ell\ell\nu\nu$ channels:
  - Benefit from mass resolution of $4\ell$ and larger branching ratio of $\ell\ell\nu\nu$.
- Improves upon previous ATLAS search at $\sqrt{s} = 13$ TeV using $36.1 \, \text{fb}^{-1}$ (from 2015+16)
  - Observed two excesses of $\sim 2.5\sigma$ global significance in $4\ell$ channel at $\sim 240$ and $700$ GeV, none in $\ell\ell\nu\nu$.
- General analysis improvements:
  - Increased luminosity $\rightarrow$ larger dataset
  - Improved lepton reconstruction/isolation and use of particle-flow jets
  - Improved background modelling $\rightarrow$ extend search range up to 2 TeV
  - Improved event selection in $\ell\ell\nu\nu$ channel
  - Use of Neural Network (NN) for event classification in $4\ell$ channel
$ZZ \rightarrow 4\ell$ Analysis
Selections, Event Categorization and Signal Modelling

- Select **two** same-flavour, opposite-sign lepton pairs ($\ell = e, \mu$).
  - Three final states: $4\mu$, $4e$, and $2\mu2e$.
  - Select only isolated leptons sharing a common vertex.
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- Event categorization by two separate neural networks: one classifier for ggF and one for VBF:
  - 5 event categories depending on jet multiplicity and NN score (with $ggF-MVA$-high subdivided by lepton flavour).

Narrow-width approximation ($NWA$): signal $m_{4\ell}$ shape parameterized in each $4\ell$ final state from fit to MC simulation.

Large-width assumption ($LWA$): parton-level lineshape $\otimes$ detector resolution (interference effects accounted for).
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Backgrounds

Irreducible Backgrounds

- **Main background** from non-resonant $ZZ$ ($\sim 97\%$ of total background events):
  - $q\bar{q} \rightarrow ZZ$
  - $gg \rightarrow ZZ$
  - EW vector-boson scattering ($ZZjj$, mostly in VBF category)

- Shape modelled by empirical function, normalization allowed to vary freely in fit to data.
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Reducible Backgrounds

- $Z$+jets and $t\bar{t}$ ($\sim$1% of expected backgrounds):
  - Estimated using data-driven methods in dedicated $ll+\mu\mu$ and $ll+ee$ control regions.
- $t\bar{t}V$ and $VVV$ ($<1$% of expected backgrounds):
  - Shape and normalization directly from MC.
Neural network outputs show good performance of categorization system.

Good agreement between data and background-only predictions over full mass range in all categories.

→ No significant excesses observed.
ZZ → llνν Analysis
Select one same-flavour, opposite-sign lepton pair + $E_T^{\text{miss}}$.

- Require $E_T^{\text{miss}} > 120$ GeV and **high** $E_T^{\text{miss}}$ significance.
- Also require $E_T^{\text{miss}}$ to be back-to-back with lepton pair: $\Delta \phi(\vec{p}_T^\ell, \vec{E}_T^{\text{miss}}) > 2.5$ rad

Full invariant mass cannot be reconstructed → use transverse mass as discriminating variable:

$$m_T \equiv \sqrt{\left[\sqrt{m_Z^2 + (p_T^\ell)^2} + \sqrt{m_Z^2 + (E_T^{\text{miss}})^2}\right]^2 - \left|\vec{p}_T^\ell + \vec{E}_T^{\text{miss}}\right|^2}$$

Use cut-based approach to categorize ggF-like and VBF-like events:
- VBF-like if $m_{jj} > 550$ GeV, $\Delta \eta_{jj} > 4.4$. 
Selections, Event Categorization and Backgrounds

- Select **one** same-flavour, opposite-sign lepton pair + $E_T^{\text{miss}}$.
  
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Background Modelling and Results

- **Dominant backgrounds** from $ZZ$ and $WZ$:
  - $ZZ$ from simulation with floating normalization.
  - $WZ$ estimated using data-driven method with 3-lepton control region.

Results:

Good agreement between data and background-only predictions in all categories.

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- **Small background contributions** from $Z(\rightarrow ee, \mu\mu)+jets$ and $WW/top/Z \rightarrow \tau\tau$
  - Estimated using data-driven methods in dedicated control regions.
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- **Results**: Good agreement between data and background-only predictions in all categories.
  - **No significant excess observed.**
Combined Results
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- Combine 4\ell and \ell\ell\nu channels: **no significant excess observed**.
  - Set upper limits on $\sigma \times BR(X \rightarrow ZZ)$.
- Narrow-width signals: fits for ggF and VBF processes done separately (while profiling the other process) to remain model independent, *i.e.* assume no relative production rate between the two.
- Large-width signals: consider ggF only for widths of 1\%, 5\%, 10\% and 15\% of $m_H$ [see Backup].
- Interpretations also in 2HDM models and for a Randall-Sundrum graviton [see Backup].

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**Upper Limits (95\% CL)**

- **ggF:**
  - 200 fb at 240 GeV
  - 2.6 fb at 2000 GeV
- **VBF:**
  - 87 fb at 250 GeV
  - 1.9 fb at 1800 GeV
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[Graphs showing observed and expected CL limits for ggF and VBF production processes]
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### Upper Limits (95\% CL)

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ATLAS has an active BSM-Higgs and diboson-resonance search program, with many new results using the full Run 2 dataset, e.g.:

- $H \rightarrow \gamma\gamma$: arXiv 2102.13405
- $H^{\pm} \rightarrow tb$: arXiv 2102.10076
- $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$: arXiv 2101.11961

No new physics observed, but substantial update of constraints on 2HDM and other BSM models.

Only small subset of results shown today: still many exciting new regions of phase space to probe using the full Run 2 dataset and beyond in LHC Run 3 (2022–2024) and at the high-luminosity LHC.

Latest ATLAS results at https://twiki.cern.ch/twiki/bin/view/AtlasPublic
DNN inputs for the $4\ell$ classifier

Input features used in the VBF (left) and the ggF (right) classifiers. ‘rNN’ stands for the recurrent neural network and ‘MLP’ for the multilayer perceptron.

### VBF classifier

<table>
<thead>
<tr>
<th>Model</th>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>rNN</td>
<td>$p_T^{j0}, p_T^{j1}$</td>
<td>transverse momenta of the two leading jets</td>
</tr>
<tr>
<td></td>
<td>$\eta^{j0}, \eta^{j1}$</td>
<td>pseudorapidity of the two leading jets</td>
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<td>$p_T^{\ell0}, p_T^{\ell1}, p_T^{\ell2}, p_T^{\ell3}$</td>
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<td>MLP</td>
<td>$m_{4\ell}$</td>
<td>invariant mass of the four-lepton system</td>
</tr>
<tr>
<td></td>
<td>$m_H$</td>
<td>invariant mass of the two-leading-jet system</td>
</tr>
<tr>
<td></td>
<td>$p_T^H$</td>
<td>transverse momentum of the two-leading-jet system</td>
</tr>
<tr>
<td></td>
<td>$\Delta\eta_{H,j}$</td>
<td>difference in pseudorapidity between the four-lepton system and the leading jet</td>
</tr>
<tr>
<td></td>
<td>$\text{min}\Delta R_{jZ}$</td>
<td>minimum distance between one of the two lepton pairs and a jet</td>
</tr>
</tbody>
</table>

### ggF classifier

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<td>$\eta^{4\ell}$</td>
<td>pseudorapidity of the four-lepton system</td>
</tr>
<tr>
<td></td>
<td>$\cos \theta^*$</td>
<td>production angle of the leading Z defined in the four-lepton rest frame</td>
</tr>
<tr>
<td></td>
<td>$\cos \theta_1$</td>
<td>angle between the negative final state lepton and the direction of flight of leading Z in the Z rest frame</td>
</tr>
<tr>
<td></td>
<td>$\cos \theta_2$</td>
<td>angle between the negative final state lepton and the direction of flight of sub-leading Z in the Z rest frame</td>
</tr>
<tr>
<td></td>
<td>$\Phi$</td>
<td>angle between the decay planes of the four final state leptons expressed in the four-lepton rest frame</td>
</tr>
<tr>
<td></td>
<td>$p_T^{j0}$</td>
<td>transverse momentum of the leading jet</td>
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Additional $4\ell$ results

$\ell^+\ell^-\ell^+\ell^-$ Distributions

- Distributions of the four-lepton invariant mass $m_{4\ell}$ in each of the five event categories in the $\ell^+\ell^-\ell^+\ell^-$ channel.
The ZZ normalisation factors together with their total uncertainties in each category of the two final states, which scale the number of ZZ events estimated from the simulations, obtained from a simultaneous likelihood fit of the two final states under the background-only hypothesis.

<table>
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<tr>
<th>Final state</th>
<th>Normalisation factor</th>
<th>Fitted value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ℓ⁺ℓ⁻ℓ⁺'ℓ'⁻</td>
<td>( \mu_{\text{VBF-MVA}}^{ZZ} )</td>
<td>0.9 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>( \mu_{\text{ggF-MVA-high}}^{ZZ} )</td>
<td>1.07 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>( \mu_{\text{ggF-MVA-low}}^{ZZ} )</td>
<td>1.12 ± 0.03</td>
</tr>
<tr>
<td>ℓ⁺ℓ⁻ν¯ν</td>
<td>( \mu_{\text{ZZ}} )</td>
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Additional combined results

Large-width spin-0 Interpretations

- 95% CL upper limits on $\sigma_{ggF} \times \text{BR}(H \to ZZ)$ as a function of $m_H$ assuming a width of 1, 5, 10 and 15% of $m_H$. 

![Diagram showing 95% CL limits on $\sigma_{ggF} \times \text{BR}(H \to ZZ)$ as a function of $m_H$ assuming a width of 1, 5, 10, and 15% of $m_H$.]
Additional combined results

2HDM Interpretations

- Exclusion contour in the Type-I and Type-II 2HDM models:
  - As a function of the parameters $\cos(\beta - \alpha)$ and $\tan \beta$, with $m_H = 220$ GeV
  - As a function of $m_H$ and $\tan \beta$, with $\cos(\beta - \alpha) = -0.1$
Additional combined results

RS Graviton Interpretations

- 95% CL upper limits on $\sigma \times \text{BR}(G_{KK} \rightarrow ZZ)$ for a KK graviton produced with $k/\tilde{M}_{Pl} = 1$. 

![Graph showing limits on $\sigma \times B(G_{KK} \rightarrow ZZ)$ vs. $m(G_{KK})$ [GeV].](image)
Impact of the leading systematic uncertainties, the data statistical uncertainties and the total uncertainties on the predicted signal event yield with the cross section times branching ratio being set to the expected upper limit, expressed as a percentage of the signal yield:

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>ggF production Impact [%]</th>
<th>VBF production Impact [%]</th>
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<tbody>
<tr>
<td>$m_H = 300$ GeV</td>
<td></td>
<td></td>
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<tr>
<td>ZZ parameterisation ($\ell^+\ell^-\ell'^+\ell'^-$)</td>
<td>4.5</td>
<td>4.0</td>
</tr>
<tr>
<td>$Z +$ jets modelling ($\ell^+\ell^-\nu\bar{\nu}$)</td>
<td>2.3</td>
<td>2.5</td>
</tr>
<tr>
<td>Parton showering of ggF ($\ell^+\ell^-\ell'^+\ell'^-$)</td>
<td>2.2</td>
<td>2.5</td>
</tr>
<tr>
<td>$e\mu$ statistical uncertainty $\ell^+\ell^-\nu\bar{\nu}$</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Data stat. uncertainty</td>
<td>53</td>
<td>54</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>55</td>
<td>56</td>
</tr>
<tr>
<td>$m_H = 600$ GeV</td>
<td></td>
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<tr>
<td>Electroweak corrections for $q\bar{q} \rightarrow ZZ (\ell^+\ell^-\nu\bar{\nu})$</td>
<td>4.9</td>
<td>5.0</td>
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<td>QCD scale of $q\bar{q} \rightarrow ZZ (\ell^+\ell^-\nu\bar{\nu})$</td>
<td>2.5</td>
<td>2.4</td>
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<td>$Z +$ jets modelling ($\ell^+\ell^-\nu\bar{\nu}$)</td>
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<td>Data stat. uncertainty</td>
<td>54</td>
<td>55</td>
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<tr>
<td>Total uncertainty</td>
<td>57</td>
<td>58</td>
</tr>
<tr>
<td>$m_H = 1000$ GeV</td>
<td></td>
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<td>Electroweak corrections for $q\bar{q} \rightarrow ZZ (\ell^+\ell^-\nu\bar{\nu})$</td>
<td>9.3</td>
<td>6.9</td>
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<td>Parton showering ($\ell^+\ell^-\nu\bar{\nu}$)</td>
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<td>4.7</td>
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<td>2.4</td>
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<td>$m_H = 1500$ GeV</td>
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<td>Parton showering ($\ell^+\ell^-\nu\bar{\nu}$)</td>
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</tr>
<tr>
<td>PDF of $q\bar{q} \rightarrow ZZ (\ell^+\ell^-\nu\bar{\nu})$</td>
<td>5.4</td>
<td>3.4</td>
</tr>
<tr>
<td>QCD scale of $q\bar{q} \rightarrow ZZ (\ell^+\ell^-\nu\bar{\nu})$</td>
<td>4.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Data stat. uncertainty</td>
<td>57</td>
<td>55</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>59</td>
<td>57</td>
</tr>
</tbody>
</table>
Expected and observed event yields

<table>
<thead>
<tr>
<th>Process</th>
<th>4ℓ</th>
<th>ggF-MVA-high</th>
<th>gbF-MVA-low</th>
</tr>
</thead>
<tbody>
<tr>
<td>q̅q → ZZ</td>
<td>11 ± 4</td>
<td>232 ± 10</td>
<td>389 ± 17</td>
</tr>
<tr>
<td>gg → ZZ</td>
<td>3 ± 2</td>
<td>37 ± 6</td>
<td>64 ± 10</td>
</tr>
<tr>
<td>ZZ (EW)</td>
<td>4.1 ± 0.4</td>
<td>4.5 ± 0.2</td>
<td>7.5 ± 0.4</td>
</tr>
<tr>
<td>Z + jets, t̅t</td>
<td>0.08 ± 0.02</td>
<td>0.6 ± 0.1</td>
<td>1.7 ± 0.4</td>
</tr>
<tr>
<td>t̅V, VVV</td>
<td>0.97 ± 0.1</td>
<td>9.8 ± 0.2</td>
<td>17.5 ± 0.4</td>
</tr>
<tr>
<td>Total background</td>
<td>19 ± 5</td>
<td>284 ± 12</td>
<td>480 ± 20</td>
</tr>
<tr>
<td>Observed</td>
<td>19</td>
<td>271</td>
<td>493</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>ℓℓνν</th>
<th>ggF-MVA-high</th>
<th>gbF-MVA-low</th>
</tr>
</thead>
<tbody>
<tr>
<td>q̅q → ZZ</td>
<td>714 ± 38</td>
<td>817 ± 44</td>
<td>2.9 ± 0.2</td>
</tr>
<tr>
<td>gg → ZZ</td>
<td>94 ± 29</td>
<td>105 ± 32</td>
<td>1 ± 0.5</td>
</tr>
<tr>
<td>ZZ (EW)</td>
<td>6.6 ± 0.5</td>
<td>7 ± 0.5</td>
<td>0.8 ± 0.1</td>
</tr>
<tr>
<td>WZ</td>
<td>412 ± 14</td>
<td>455 ± 12</td>
<td>2.5 ± 0.5</td>
</tr>
<tr>
<td>Z + jets</td>
<td>43 ± 13</td>
<td>60 ± 22</td>
<td>0.3 ± 0.2</td>
</tr>
<tr>
<td>Non-resonant-ℓℓ</td>
<td>66 ± 6</td>
<td>77 ± 7</td>
<td>0.2 ± 0.2</td>
</tr>
<tr>
<td>t̅V, VVV</td>
<td>5.9 ± 0.4</td>
<td>5.9 ± 0.4</td>
<td>0.09 ± 0.02</td>
</tr>
<tr>
<td>Total backgrounds</td>
<td>1342 ± 52</td>
<td>1527 ± 60</td>
<td>7.8 ± 0.8</td>
</tr>
<tr>
<td>Observed</td>
<td>1323</td>
<td>1542</td>
<td>8</td>
</tr>
</tbody>
</table>
Analysis improvements

- Improvements on the expected 95% CL upper limits w.r.t. previous and cut-based analyses for the \textit{ggF} production mode (left) and the \textit{VBF} production mode (right).

\textit{ggF}

\begin{align*}
\text{Expected 95\% CL limits on } & \sigma_{\text{ggF}} \times B(H \rightarrow ZZ) \,[\text{pb}] \\
\text{ATLAS} & \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \\
H \rightarrow ZZ & \rightarrow l^+ l^- l'^+ l'^- + l^+ l^- \nu \bar{\nu} \\
\text{NWA, ggF production} & 
\end{align*}

\textit{VBF}

\begin{align*}
\text{Expected 95\% CL limits on } & \sigma_{\text{VBF}} \times B(H \rightarrow ZZ) \,[\text{pb}] \\
\text{ATLAS} & \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \\
H \rightarrow ZZ & \rightarrow l^+ l^- l'^+ l'^- + l^+ l^- \nu \bar{\nu} \\
\text{NWA, VBF production} & 
\end{align*}