Measurement of Higgs-boson properties in $H \rightarrow WW^*$ events

ICHEP 2018

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on behalf of the ATLAS collaboration
Present measurements in $H \rightarrow WW^*$ candidate events
  - Production cross section times branching ratio
  - Spin and parity in the decay vertex (Run I)

$ggF$ production is dominant, but other processes have cleaner signatures
  - VBF: two jets with large $m_{jj}$ and $\Delta \eta_{jj}$
  - VH: Additional lepton(s), high $E_{T}^{mis}$ or jets

$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ (for $\ell = e, \mu, \tau \rightarrow \ell\nu\nu$) is with 1.5% one of the most frequent decay modes
  - Cleaner signature wrt $H \rightarrow b\bar{b}$
  - Higher statistics than $H \rightarrow ZZ^*$ or $H \rightarrow \gamma\gamma$

Characteristics of $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay:
  - Two oppositely charged leptons with small opening angle and invariant mass $m_{ll}$
  - Presence of neutrinos prevents direct measurement of invariant mass $m_H$
Measurement of the ggF and VBF production cross sections

http://cds.cern.ch/record/2308392
ATLAS-CONF-2018-004
Analysis strategy (event selection)

- Select events with different-flavour leptons \((\ell = e, \mu)\) and opposite charge
  - \(p_T^{\text{lead}} > 22\text{GeV}\) and \(p_T^{\text{sublead}} > 15\text{GeV}\)
- Classify events according to multiplicity of jets with \(p_T > 30\text{GeV}\)
  - \(N_{\text{jets}} = 0\) and \(N_{\text{jets}} = 1\) categories target the ggF production mode
  - \(N_{\text{jets}} \geq 2\) category targets VBF production
- Reduce main backgrounds:
  - Veto events containing a heavy-flavour jet with \(p_T > 20\text{GeV}\)
  - Select events with low \(m_{\ell\ell}\) and \(\Delta\Phi_{\ell\ell}\) (ggF)
  - Central jet and outside lepton veto (VBF)
- Further enhance VBF signal using a MVA
  - Trained using eight input quantities: \(m_{jj}, \Delta Y_{jj}, m_{\ell\ell}, \Delta\Phi_{\ell\ell}, m_{H,T}, \ldots\)
Smaller backgrounds such as $WZ$, $ZZ$, $W\gamma$ or $Z\gamma$ are entirely taken from the simulation.

Constrain normalisation of most important backgrounds via control regions in data:
- $WW$, $t\bar{t} + Wt$ and $Z\gamma^* + \text{jets}$

Data-driven estimation of mis-identified lepton backgrounds ($W + \text{jets/multijet}$):
- Define control sample using events with
  - One well-defined lepton
  - One lepton failing nominal object definitions requirements but passing looser requirements (anti-identified)
- Contribution to signal region is estimated by scaling control sample via $p_T/\eta$ dependent extrapolation factors
- Extrapolation factor is ratio of well-defined leptons to anti-identified leptons

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Details on the likelihood procedure

- ggF and VBF cross sections are obtained by a simultaneous fit to control and signal regions (maximising a likelihood function)

- Input variables for the fit:
  - **ggF**: transverse mass $m_{H,T}$
    - Subdivide phase space using $m_{\ell\ell}$ as well as $p_T$ and flavour of subleading lepton
  - **VBF**: score of a boosted decision tree

- Systematic uncertainties enter as nuisance parameters in the likelihood function
  - Consider correlations
  - Dominant uncertainties are:
    - Modelling ($\pm 8\%$ ggF, $\pm 21\%$ VBF)
    - Data statistics ($\pm 8\%$ ggF, $\pm 46\%$ VBF)
    - MC statistics ($\pm 5\%$ ggF, $\pm 23\%$ VBF)
    - $b$-tagging ($\pm 5\%$ ggF, $\pm 6\%$ VBF)
Results

- Measured cross section times branching ratio:

  \[
  \sigma_{ggF} \times BR(H \rightarrow WW^*) = 12.6^{+1.3}_{-1.2}(\text{stat.})^{+1.9}_{-1.8}(\text{sys.}) \text{ pb}
  \]

  \[
  \sigma_{VBF} \times BR(H \rightarrow WW^*) = 0.5^{+0.24}_{-0.23}(\text{stat.}) \pm 0.18(\text{sys.}) \text{ pb}
  \]

- **Prediction:** 10.4 ± 0.6 pb (for ggf) and 0.81 ± 0.02 pb (for VBF)

- ggF measurement is dominated by systematics now (30% improved wrt Run-I)

- **Observed (expected) significances are:**
  - 6.3 (5.2) standard deviations for ggF
  - 1.9 (2.7) standard deviations for VBF

- Profile ggF production when determine significance of VBF production, and vice-versa
Measured cross section times branching ratio:

\[ \sigma_{ggF} \times \mathcal{B}(H \rightarrow WW^*) = 12.6^{+1.3}_{-1.2}(stat.)^{+1.9}_{-1.8}(sys.) \text{ pb} \]

\[ \sigma_{VBF} \times \mathcal{B}(H \rightarrow WW^*) = 0.5^{+0.24}_{-0.23}(stat.) \pm 0.18(sys.) \text{ pb} \]

Predictions: \(10.4 \pm 0.6\) pb (for ggF) and \(0.81 \pm 0.02\) pb (for VBF)

Signal strength parameter:

\[ \mu_{ggF} = 1.21^{+0.12}_{-0.11}(stat.)^{+0.18}_{-0.17}(syst.) \]

\[ \mu_{VBF} = 0.62^{+0.30}_{-0.28}(stat.) \pm 0.22(syst.) \]

Results are consistent with SM prediction within one standard deviation
Measurement of the $WH$ production cross section

http://cds.cern.ch/record/2231811/
ATLAS-CONF-2016-112

Based on partial 2015+2016 ATLAS dataset
Measurement will be updated in the next months
Analysis strategy

- Classify $N^\ell = 3$ events according to lepton pairing
  - $\geq 1$ Same-flavour opposite charge pair (Z-dominated): $S/B \approx 0.14$
  - No same-flavour opposite charge pair (Z-depleted): $S/B \approx 0.36$

- Normalisation of the dominant backgrounds is taken from control regions
  - $WZ/W\gamma^*, Z\gamma, Z+$jets and $t\bar{t}/Wt/t\bar{t} + V/...$

- Determine $\sigma_{WH}$ via simultaneous fits to all signal and control regions

- Systematic uncertainties enter as nuisance parameters in the likelihood function
  - Dominant uncertainties are:
    - Data ($\sim 120\%$) & MC statistics ($\sim 70\%$)
    - pile-up activity ($\sim 24\%$), Jet energy resolution ($\sim 23\%$)
    - Modelling of most dominant backgrounds ($\sim 20\%$ for $t\bar{t}$ gen.)
Results

- Measured cross section times branching ratio:

\[ \sigma_{WH} \times BR(H \to WW^*) = 0.9^{+1.1}_{-0.9}(\text{stat.})^{+0.7}_{-0.8}(\text{sys.}) \text{ pb} \]

- Predictions: \( 0.293 \pm 0.007 \text{ pb} \)

- Signal strength parameter:

\[ \mu_{WH} = 3.2^{+3.7}_{-3.2}(\text{stat.})^{+2.3}_{-2.7}(\text{sys.}) \]

- Measurements are consistent with the SM prediction

- Observed (expected) significance is \( 0.77\sigma \ (0.24\sigma) \)

- Upper limits at the 95% confidence level computed using the modified frequentist method \( CL_S: 3.3 \text{ pb} \)

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Determination of spin and parity of the Higgs-boson


Based on full Run-I ATLAS dataset
Similar event selection as for $\sigma_{ggF}$ measurement

Train boosted decision trees to distinguish between the SM and BSM Higgs-boson hypotheses as well as the SM backgrounds

- Exploit kinematical differences of Higgs-boson decay products

Perform hypothesis tests

- SM vs. Spin-2 ($J^P = 2^+$)
- SM vs. CP odd ($J^P = 0^-$)
- SM vs. BSM CP even ($J^P = 0^+$)

Scan CP mixing scenarios

- Angle $\alpha$ describes the mixing between CP-even and CP-odd states
- $\kappa_{HWW}$ and $\kappa_{AWW}$ are the BSM CP-even and CP-odd coupling parameters

Results are only based on shape information
Fit input: enrolled two-dimensional $BDT_0 \times BDT_{2/CP}$ distribution

Hypothesis tests:
- SM hypothesis is favoured in all tests
- Exclude:
  - Spin-2 hypothesis with non-universal couplings at 92.5% CL
  - Pure CP odd Higgs-boson at 96.5% CL
- Disfavour:
  - Spin-2 hypothesis for universal couplings at a 84.5% CL
  - A BSM CP even Higgs-boson at a 70.8% CL

CP-mixing scan:
- Exclude $(\tilde{\kappa}_{AWW}/\kappa_{SM}) \cdot \tan \alpha$ values below -6 and above 5 at a 95% CL
- Exclude $(\tilde{\kappa}_{HWW}/\kappa_{SM})$ values above 0.4 and below -2.2 at a 95% CL

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Summary and outlook

- Presented the latest measurements of the cross section times branching ratios for Higgs-bosons decaying via $H \to WW^*$:
  - In the ggF and VBF production modes for the data collected by ATLAS in 2015 & 2016
    - Cross sections are compatible to SM predictions within one standard deviation
  - In the $WH$ production mode for a partial 2015+2016 dataset
    - Upper cross section limit at a 95% CL was set to be $3.3 \text{ pb}$
    - Results corresponding to the combined 2015 and 2016 data periods will be published soon

- Also summarised the measurement of the Spin and parity of the Higgs-boson in $H \to WW^*$ events (Run I)
  - A pure CP odd Higgs-boson can be excluded at 96.5% CL
  - A BSM CP even Higgs-boson is disfavoured at 70.8% CL
  - Spin-2 hypothesis with universal couplings is disfavoured at 84.5% CL
  - Spin-2 hypothesis with non-universal couplings is excluded 92.5% CL

- Measurements of Higgs boson properties with Run II data ongoing in Higgs + 2 jets events (in both ggF and VBF production modes)
  - Exploit angle between jets $\Delta \Phi_{jj}$ to study parity and coupling strength to polarised vector bosons

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Back-up
Event selection (signal regions)

<table>
<thead>
<tr>
<th>Category</th>
<th>$N_{\text{jet}} = 0$</th>
<th>$N_{\text{jet}} = 1$</th>
<th>$N_{\text{jet}} \geq 2$, VBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>Two isolated, different-flavour, leptons ($\ell = e, \mu$) with opposite charge $p_{T}^{\text{lead}} &gt; 22 \text{ GeV}$, $p_{T}^{\text{sublead}} &gt; 15 \text{ GeV}$ $m_{\ell\ell} &gt; 10 \text{ GeV}$ $E_{T}^{\text{miss, track}} &gt; 20 \text{ GeV}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Background rejection</td>
<td>$\Delta \phi(\ell\ell, E_{T}^{\text{miss}}) &gt; \pi/2$ $p_{T}^{\ell\ell} &gt; 30 \text{ GeV}$</td>
<td>$\max (m_{T}^{\ell}) &gt; 50 \text{ GeV}$ $N_{b-\text{jet},(p_{T}&gt;20 \text{ GeV})} = 0$</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ topology</td>
<td>$m_{\ell\ell} &lt; 55 \text{ GeV}$ $\Delta \phi_{\ell\ell} &lt; 1.8$</td>
<td></td>
<td>Central Jet Veto Outside Lepton Veto</td>
</tr>
<tr>
<td>Discriminant Variable</td>
<td>$m_{T}$</td>
<td></td>
<td>BDT $m_{jj}, \Delta y_{jj}, m_{\ell\ell}, \Delta \phi_{\ell\ell}, m_{T}, \sum C_{\ell}, \sum_{\ell,j} m_{\ell j}, p_{T}^{\text{tot}}$</td>
</tr>
<tr>
<td>BDT input variables</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Event selection (control regions)

<table>
<thead>
<tr>
<th>CR</th>
<th>$N_{\text{jet}} = 0$</th>
<th>$N_{\text{jet}} = 1$</th>
<th>$N_{\text{jet}} \geq 2$, VBF</th>
</tr>
</thead>
</table>
| $WW$ | $55 < m_{\ell\ell} < 110 \text{ GeV}$  
$\Delta \phi_{\ell\ell} < 2.6$ | $m_{\ell\ell} > 80 \text{ GeV}$  
$|m_{\tau\tau} - m_Z| > 25 \text{ GeV}$ | $b$-jet veto  
$m_T^{\ell} > 50 \text{ GeV}$ |
| $\text{Top-quark}$ | $N_{b\text{-jet},(20 \text{ GeV} < p_T < 30 \text{ GeV})} > 0$  
$\Delta \phi(\ell\ell, E_T^{\text{miss}}) > \pi/2$  
$p_T^{\ell\ell} > 30 \text{ GeV}$  
$\Delta \phi_{\ell\ell} < 2.8$ | $N_{b\text{-jet},(p_T > 30 \text{ GeV})} = 1$  
$N_{b\text{-jet},(20 \text{ GeV} < p_T < 30 \text{ GeV})} = 0$  
$max(m_T^{\ell}) > 50 \text{ GeV}$ | Central Jet Veto  
$m_{\tau\tau} < m_Z - 25 \text{ GeV}$  
Outside Lepton Veto |
| $Z \to \tau\tau$ | no $E_T^{\text{miss}}$, track requirement  
$m_{\ell\ell} < 80 \text{ GeV}$ | Outside Lepton Veto  
Central Jet Veto  
$m_{\tau\tau} > m_Z - 25 \text{ GeV}$  
$N_{b\text{-jet},(p_T > 20 \text{ GeV})} = 0$ |
Distribution in signal region (VBF)

**ATLAS Preliminary**

$H \rightarrow WW^* \rightarrow e\nu\nu$, $N_{\text{jet}} \geq 2$ VBF

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- $H_{\text{ggF}}$
- $t\bar{t}/Wt$
- $WW$
- $Z/\gamma^*$
- Mis-Id
- VV

Uncertainty

$\times 30$

Events/200 GeV

**ATLAS Preliminary**

$H \rightarrow WW^* \rightarrow e\nu\nu$, $N_{\text{jet}} \geq 2$ VBF

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- $H_{\text{ggF}}$
- $t\bar{t}/Wt$
- $WW$
- $Z/\gamma^*$
- Mis-Id
- VV

Uncertainty

$\times 30$

Events

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# Event yields

<table>
<thead>
<tr>
<th>Process</th>
<th>$N_{\text{jet}} = 0$ SR</th>
<th>$N_{\text{jet}} = 1$ SR</th>
<th>$N_{\text{jet}} \geq 2$ VBF SR</th>
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</thead>
<tbody>
<tr>
<td>ggF</td>
<td>680 ± 110</td>
<td>303 ± 52</td>
<td>37 ± 13</td>
</tr>
<tr>
<td>VBF</td>
<td>6.8 ± 0.8</td>
<td>30.0 ± 1.9</td>
<td>30 ± 16</td>
</tr>
<tr>
<td>WW</td>
<td>2960 ± 670</td>
<td>1020 ± 390</td>
<td>386 ± 59</td>
</tr>
<tr>
<td>VV</td>
<td>323 ± 34</td>
<td>204 ± 30</td>
<td>71 ± 14</td>
</tr>
<tr>
<td>$t\bar{t}/Wt$</td>
<td>580 ± 128</td>
<td>1400 ± 180</td>
<td>1234 ± 89</td>
</tr>
<tr>
<td>Mis-Id</td>
<td>471 ± 80</td>
<td>246 ± 50</td>
<td>109 ± 38</td>
</tr>
<tr>
<td>$Z/\gamma^*$</td>
<td>27 ± 10</td>
<td>76 ± 22</td>
<td>298 ± 42</td>
</tr>
<tr>
<td>Total</td>
<td>5062 ± 67</td>
<td>3290 ± 51</td>
<td>2138 ± 47</td>
</tr>
<tr>
<td>Observed</td>
<td>5089</td>
<td>3264</td>
<td>2164</td>
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</table>
Breakdown of uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$\frac{\Delta \sigma_{ggF}}{\sigma_{ggF}}$ [%]</th>
<th>$\frac{\Delta \sigma_{VBF}}{\sigma_{VBF}}$ [%]</th>
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<tbody>
<tr>
<td>Data statistics</td>
<td>±8</td>
<td>±46</td>
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<tr>
<td>CR statistics</td>
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<td>±9</td>
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<td>MC statistics</td>
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<td>±23</td>
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<tr>
<td>Theoretical uncertainties</td>
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<td>±21</td>
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<tr>
<td>ggF signal</td>
<td>±5</td>
<td>±15</td>
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<tr>
<td>VBF signal</td>
<td>&lt;1</td>
<td>±15</td>
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<tr>
<td>WW</td>
<td>±5</td>
<td>±12</td>
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<tr>
<td>Top-quark</td>
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<td>±4</td>
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<tr>
<td>Experimental uncertainties</td>
<td>±9</td>
<td>±8</td>
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<tr>
<td>$b$-tagging</td>
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<td>Pile-up</td>
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<td>±2</td>
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<td>Jet</td>
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<tr>
<td>Electron</td>
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<td>Misidentified leptons</td>
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<tr>
<td>Luminosity</td>
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<td>±3</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td>±17</td>
<td>±59</td>
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### Details on Monte Carlo generators

<table>
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<tr>
<th>Process</th>
<th>Matrix Element</th>
<th>PDF</th>
<th>PS</th>
<th>Precision $\sigma$</th>
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<tbody>
<tr>
<td></td>
<td>(MG5_AMC@NLO)</td>
<td></td>
<td></td>
<td>(HERWIG 7 [24])</td>
</tr>
<tr>
<td>$VBF$</td>
<td>PMGHEG-BOX v2</td>
<td>PDF4LHC15 NLO</td>
<td>PYTHIA 8</td>
<td>NNLO QCD + NLO EW</td>
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<tr>
<td></td>
<td>(MG5_AMC@NLO)</td>
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<td>(HERWIG 7)</td>
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<td>$VH$</td>
<td>PMGHEG-BOX v2</td>
<td>PDF4LHC15 NLO</td>
<td>PYTHIA 8</td>
<td>NNLO QCD + NLO EW</td>
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<td>[25]</td>
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<td>$gg \rightarrow WW$</td>
<td>SHERPA 2.2.2 [29,29,30]</td>
<td>NNPDF3.0NNLO [31]</td>
<td>SHERPA 2.2.2 [32,33]</td>
<td>NLO [34]</td>
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<tr>
<td></td>
<td>(POWHEG-BOX v2, MG5_AMC@NLO)</td>
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<td>(HERWIG++ [24])</td>
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<td>$gg \rightarrow WW$</td>
<td>SHERPA 2.1.1 [34]</td>
<td>CT10 [35]</td>
<td>SHERPA 2.1</td>
<td>NLO [36]</td>
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<tr>
<td>$WZ/V\gamma^*/ZZ$</td>
<td>SHERPA 2.1</td>
<td>CT10</td>
<td>SHERPA 2.1</td>
<td>NLO [34]</td>
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<tr>
<td>$V\gamma$</td>
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<td>NNPDF3.0NNLO</td>
<td>SHERPA 2.2.2</td>
<td>NLO [34]</td>
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<td></td>
<td>(MG5_AMC@NLO)</td>
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<td>(CSS variation [32,37])</td>
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<tr>
<td>$t\bar{t}$</td>
<td>PMGHEG-BOX v2</td>
<td>NNPDF3.0NLO</td>
<td>PYTHIA 8 [39]</td>
<td>NNLO+NNLL [40]</td>
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<td>[38]</td>
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<td>(HERWIG 7)</td>
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<td>$Wt$</td>
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<td>(MG5_AMC@NLO)</td>
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<td>(HERWIG+++)</td>
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<tr>
<td>$Z+\text{jets}$</td>
<td>SHERPA 2.2.1</td>
<td>NNPDF3.0NNLO</td>
<td>SHERPA 2.2.1</td>
<td>NLO [43]</td>
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</tbody>
</table>
### Event selection \( WH \)

<table>
<thead>
<tr>
<th>Category</th>
<th>( Z )-dominated SR</th>
<th>( Z )-depleted SR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \geq 1 ) SFOS pair</td>
<td>no SFOS pair</td>
</tr>
</tbody>
</table>

**Preselection**

- Three isolated leptons (\( p_T >15 \) GeV)
- Total charge = \( \pm 1 \)
- \( \geq 1 \) lepton matches to the trigger

**Background Rejection**

- \( N_{\text{jet}} \leq 1, N_{\text{b-jet}} = 0 \)
- \( E_T^{\text{miss}} > 50 \) GeV
- \( |m_{\ell^+\ell^-} - m_Z| > 25 \) GeV
- \( m_{\ell^+\ell^-}^{\text{max}} < 200 \) GeV
- \( m_{\ell^+\ell^-}^{\text{min}} > 12 \) GeV
- \( m_{\ell^+\ell^-}^{\text{min}} > 6 \) GeV
- \( Z/\gamma^* \rightarrow ee \) veto
- \( m_{\ell^+\ell^-}^{\text{max}} < 200 \) GeV

\( \rightarrow H \rightarrow WW^{*} \rightarrow \ell^+\ell^-\nu\nu \) topology

- \( \Delta R_{\ell_0\ell_1} < 2.0 \)
**Analysis strategy**

- Effective field theory (Higgs characterisation model) approach used to describe (B)SM hypothesis
  - EFT lagrangian describing interaction between Spin-0 resonance and $W$-bosons:

$$
\mathcal{L}_0^W = \cos \alpha \kappa_{SM} (g_{HWW} W^+ W^{-\mu}) X_0
$$

$$
- \frac{1}{2\Lambda} \left( \cos \alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + \sin \alpha \kappa_{AWW} W_{\mu\nu}^+, \tilde{W}^{-\mu\nu} \right) X_0 + ...
$$

- Angle $\alpha$ describes the mixing between CP-even and CP-odd states
- $\kappa_{SM}$ describes the deviation of the Higgs-boson coupling to vector bosons wrt the SM predictions
- $\kappa_{HWW}$ and $\kappa_{AWW}$ are the BSM CP-even and CP-odd coupling parameters
- $\Lambda$ is the scale where new physics is expected (set to 1 TeV)

- Test four hypothesis vs. data
  - SM vs. BSM CP even ($\kappa_{SM} = \kappa_{AWW} = 0$ and $\kappa_{AWW} = \cos \alpha = 1$)
  - SM vs. CP odd ($\kappa_{SM} = \kappa_{HWW} = \cos \alpha = 0$ and $\kappa_{AWW} = 1$)
  - Scan over tan $\alpha$ ($\kappa_{SM} = \kappa_{AWW} = 1$ and $\kappa_{HWW} = 0$)
  - Scan over $\kappa_{HWW}$ ($\kappa_{SM} = \cos \alpha = 1$ and $\kappa_{AWW} = 0$)
Results on Spin measurement

- Perform hypothesis tests
  - Based on enrolled two-dimensional $BDT_0 \times BDT_2$ distribution

- Hypothesis tests:
  - SM hypothesis is favoured in all tests
  - Spin-2 hypothesis is disfavoured for universal couplings at a 84.5% CL
  - Spin-2 hypothesis with non-universal couplings is excluded 92.5% CL