Measurement of cross sections and couplings of the Higgs boson in the WW decay channel using the ATLAS detector

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On behalf of the ATLAS collaboration

ICHEDP
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Higgs boson production

- Higgs boson couplings measurement essential SM consistency test
  → Search for rare production modes
- Continue search for additional states at high mass in parallel

![Graphical representation of Higgs boson production modes](image)

- **Gluon-gluon fusion (“ggF”)**
- **Vector boson fusion (“VBF”)**
- **Associated production (“VH”)**

![Graphical representation of Higgs boson production modes](image)
**H → WW → ℓνℓν**

**WW channel well-suited to exploring rare production modes and searching at high-mass**

Large branching ratio and good S/B from clean dilepton signature

<table>
<thead>
<tr>
<th>channel</th>
<th>σ(pp→H) @ 8 TeV</th>
<th>BR (H→VV)</th>
<th>BR(VV→4l)</th>
<th>evt. yield in 20 fb⁻¹</th>
<th>S/B (approx.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → γγ</td>
<td>22.3 pb</td>
<td>0.0023</td>
<td>-</td>
<td>1000</td>
<td>0.03 – 0.5</td>
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<tr>
<td>H → ZZ → 4l</td>
<td>22.3 pb</td>
<td>0.026</td>
<td>0.0011</td>
<td>130</td>
<td>2</td>
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<tr>
<td>H → WW → ℓνℓν</td>
<td>0.22</td>
<td>0.047</td>
<td>4700</td>
<td>0.1 – 0.4</td>
<td></td>
</tr>
</tbody>
</table>

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The WW signature

Final state
2 charged leptons + 2 neutrinos
(lvjj important as well for high $m_H$ searches)

Jets depend on production mode
Spin zero resonance

Can’t go bump hunting like $\gamma\gamma$ or $ZZ \to 4l$ channels

Transverse mass $M_T$: invariant mass without $p_z$ of vs $\rightarrow$ signal discriminant with edge at $m_H$

$$M_T^2 = \left( E_T^{\ell\ell} + E_T^{\text{miss}} \right)^2 - \left( \vec{p}_T^{\ell\ell} + \vec{E}_T^{\text{miss}} \right)^2$$

$$\left( E_T^{\ell\ell} \right)^2 = \left( \vec{p}_T^{\ell\ell} \right)^2 + \left( m_{\ell\ell} \right)^2$$
Backgrounds

WW: quasi-irreducible

W+jets: fake leptons

Z/γ*: no νs

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Analysis strategy

Starting point: dilepton data after missing transverse energy cut

1. Categorize events by number of jets, number of leptons, lepton flavors
   → Separate by production mode and background composition

2. Cut away backgrounds and normalize to control regions enriched in a particular background but orthogonal to the signal region
**WW – quasi-irreducible**

**WW is dominant ggF background**

7.4% **total uncertainty in 0-jet**

→ 1.6% from theory

![Graph](image)

1) Normalize to data

2) subtract other contributions

\[ N_{SR} = \left( \frac{N_{SR}^{MC}}{N_{CR}^{MC}} \right) (N_{data}^{CR} - N_{other}^{CR}) \]

3) extrapolate using simulation

**Dilepton invariant mass** \( m_{ll} \) **is a good signal discriminant** because the spin-0 of the Higgs boson, combined with V-A structure of W decay correlates lepton directions.
W+X backgrounds

• "Same-sign validation region"
• WZ, Wγ*, Wγ estimated from theory + MC simulation
  → 14% total uncertainty in 0-jet category
  → Z, γ, and γ* produce lepton with same or opposite charge as W with equal probability

W+jets: isolation / ID on 2nd lepton separates SR and CR
• Transfer factor for extrapolation to SR from dijet data
• Stringent lepton ID / isolation → "fake" leptons, particularly muons, are often true leptons from heavy-flavor hadron decays
  → 40-45% uncertainty on fake factor from sample composition

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μ± νs + → "ℓ"
The raw data

0 jet

1 jet

2 jet (VBF)

VBF signal

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**lvlv signal strength**

Combined $WW \rightarrow lvlv$ signal strength $\mu = \sigma / \sigma_{SM}$ (2011+2012, all Njet):

$\mu = 0.99 \pm 0.21 \text{ (stat.)} \pm 0.21 \text{ (sys)}$

VBF vs. ggF: virtual contributions for ggF only
Sensitive to BSM particles in the loops

$\mu_{ggF} = 0.8 \pm 0.2 \text{ (stat.)} \pm 0.3 \text{ (syst.)}$

$\mu_{VBF} = 1.7 \pm 0.7 \text{ (stat.)} \pm 0.4 \text{ (syst.)}$
Cross section measurement

\[ \mu = \sigma / \sigma_{SM} \]

<table>
<thead>
<tr>
<th>Category</th>
<th>Source</th>
<th>Uncertainty, up (%)</th>
<th>Uncertainty, down (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>Observed data</td>
<td>+21</td>
<td>-21</td>
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<tr>
<td>Theoretical</td>
<td>Signal yield (( \sigma \cdot B ))</td>
<td>+12</td>
<td>-9</td>
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<tr>
<td>Theoretical</td>
<td>WW normalisation</td>
<td>+12</td>
<td>-12</td>
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<tr>
<td>Experimental</td>
<td>Objects and DY estimation</td>
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<td>Theoretical</td>
<td>Signal acceptance</td>
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<tr>
<td>Experimental</td>
<td>MC statistics</td>
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<td>-7</td>
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<tr>
<td>Experimental</td>
<td>W+ jets fake factor</td>
<td>+5</td>
<td>-5</td>
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<tr>
<td>Theoretical</td>
<td>Backgrounds, excluding WW</td>
<td>+5</td>
<td>-4</td>
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<tr>
<td>Luminosity</td>
<td>Integrated luminosity</td>
<td>+4</td>
<td>-4</td>
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<tr>
<td><strong>Total</strong></td>
<td></td>
<td>+32</td>
<td>-29</td>
</tr>
</tbody>
</table>

- \( \mu = \sigma / \sigma_{SM} \); measured cross section \( \sigma = \mu \times \sigma_{SM} \)
- Remove uncertainties on signal cross section but not acceptance

\[ (\sigma \cdot \text{Br}(H \rightarrow WW))_{\text{obs}, 8 \text{TeV}} = 6.0 \pm 1.1 \text{ (stat.)} \pm 0.8 \text{ (theo.)} \pm 0.7 \text{ (expt.)} \pm 0.3 \text{ (lumi.)} \text{ pb} \]

\[ = 6.0 \pm 1.6 \text{ pb} \]

\[ (\sigma \cdot \text{Br}(H \rightarrow WW))_{\text{exp}, 8 \text{TeV}} = 4.8 \pm 0.7 \text{ pb} \]
Clean 3-lepton (WH) and 4-lepton (ZH) signatures, additional info on HWW vertex (complement to VBF mode)

**WH: Z-enriched category**
(OS same-flavor pair)

- Minimum $\Delta R$ between any two leptons: same physics as $\Delta \phi(ll)$ and $m_{ll}$

**WH: Z-depleted category**
(no OS same-flavor pair)

- 4-lepton: 2 OS pairs, one with $|m_{ll} - m_Z| < 10$ GeV
- 1 event expected, $S/B \sim 1/5$
- $\rightarrow$ zero observed

!!ATLAS Preliminary!!

**信号区域**

$\sqrt{s} = 8$ TeV, $\mathcal{L} = 20.7$ fb$^{-1}$

3-lepton (Z-enriched)

SR: $S/B \sim 1/18$

4-lepton:

- 2 OS pairs, one with $|m_{ll} - m_Z| < 10$ GeV
- 1 event expected, $S/B \sim 1/5$
- $\rightarrow$ zero observed
VH, H $\rightarrow$ WW Results

cross section limits (@95% confidence) and significance of excess over BG for $m_H=125$ GeV

<table>
<thead>
<tr>
<th></th>
<th>expected</th>
<th>observed</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH (8 TeV)</td>
<td>$5.2 \times \sigma_{SM}$</td>
<td>$10 \times \sigma_{SM}$</td>
<td>2.3 $\sigma$ ($p_0 = 1.2%$)</td>
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<tr>
<td>ZH (8 TeV)</td>
<td>$9.6 \times \sigma_{SM}$</td>
<td>$14 \times \sigma_{SM}$</td>
<td>1.5 $\sigma$ ($p_0 = 7.2%$)</td>
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<tr>
<td>Combined (7+8 TeV)</td>
<td>$3.6 \times \sigma_{SM}$</td>
<td>$7.2 \times \sigma_{SM}$</td>
<td>2.0 $\sigma$ ($p_0 = 2.1%$)</td>
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</tbody>
</table>

- No SM sensitivity yet but observed limit higher than expected one
The Road Ahead

- WW was essential to discovery, combined rate measurement, and connecting the new particle to electroweak symmetry breaking
- Now: Is this the **SM Higgs boson or something more interesting?**
  - **WW channel can address this from multiple angles**
    - + Good S/B and large branching ratio
    - - Challenging backgrounds in ggF and VBF
  - **ggF and VBF modes key inputs to coupling measurement combinations**
  - **Search for rarer production modes (WH, VH, ttH...)**
  - **Properties measurements (starting from spin)**
  - **Search at high mass for additional states**
- 13 TeV run (2015-2017) will bring much-needed data and stronger statements in response to all of these questions
backup
Spin measurement

- Test spin hypothesis with kinematic variables through a BDT
  → No direct measurement of angles (cannot reconstruct rest frame)
- Use ggF eμ zero-jet category → highest sensitivity
  → Then loosen requirements on spin-sensitive variables: \( m_\parallel < 80 \text{ GeV}, \ p_T^\parallel > 20, \ \Delta\phi(\parallel) < 2.8 \)
Spin measurement

- Train two BDTs
  - One for SM signal (0\textsuperscript{+}) against background
  - Second for alternate spin/parity hypothesis (2\textsuperscript{+}, 1\textsuperscript{+}, 1\textsuperscript{-}) against background
- Fit data to discriminate hypotheses
- 2\textsuperscript{+} excluded at \geq 95\% CL by WW
Drell Yan ($Z/\gamma^*$)

Measure missing transverse energy only with tracks: more robust against extra interactions (pileup)

\[ \vec{E}_{T}^{\text{miss}} = - \sum_{\text{objects } i} \vec{p}_{T}^{\text{object}} \]

- Left: additional rejection after initial $E_{T}^{\text{miss}}$ requirement
  → First inclusion of $ee+\mu\mu$ channels in 2012 WW analysis
The ATLAS Detector

Inner Detector (tracking):
- Pixels (silicon)
- SCT (silicon strips)
- TRT (straw tubes/ionization)

Electromagnetic calorimeter:
- Liquid Argon (LAr) with lead absorber

Hadronic calorimeter (jets, hadrons):
- Steel absorber + scintillator
- LAr with copper/tungsten absorber

Muon Detectors: large radii for precise momentum measurement
- Precision: Drift tubes (MDT) and Cathode Strip Chambers (CSC)
- Trigger: Resistive Plate Chamber (RPC) and Thin Gap Chamber (TGC)
Top background to VBF

≥ 2-jet data after a b-veto: still top-dominated

Reject further background with unique VBF signature: energetic well-separated jets

These cuts reject additional 95% of total background but cost 70% of VBF signal
Estimating top in VBF phase space

<table>
<thead>
<tr>
<th>Uncertainties on top normalization</th>
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<tbody>
<tr>
<td>stat.</td>
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<tr>
<td>10%</td>
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</table>

- Normalize to control region (like WW)
  → Apply all VBF jet cuts, extrapolate from \(b\)-tagged \(\rightarrow\) \(b\)-vetoed

\[ N_{SR} = \left( \frac{N_{SR}^{MC}}{N_{CR}^{MC}} \right) \left( N_{CR}^{data} - N_{CR}^{other} \right) \]
Full systematic uncertainties

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<th>Source</th>
<th>Signal processes (%)</th>
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<td>Theoretical uncertainties</td>
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<td>QCD scale for ggF signal for $N_{\text{jet}} \geq 2$</td>
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<td>Parton shower and UE model (signal only)</td>
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<td>$H \rightarrow WW$ branching ratio</td>
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<td>Jet energy scale and resolution</td>
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<td>$b$-tagging efficiency</td>
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<td>$f_{\text{recoil}}$ efficiency</td>
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</tbody>
</table>
\( \frac{Z/\gamma^* \to \tau\tau \to l\nu l\nu}{\text{Reduce uncertainties by normalizing dominant background to data in signal-depleted “control regions” (CR)}} \)

**ATLAS Preliminary**

\( \ell s = 8 \text{ TeV}, \int \mathcal{L}t = 20.7 \text{ fb}^{-1} \)

\( H \to \text{WW}^{(*)} \to \ell^+\ell^-\nu\bar{\nu} + 0 \text{ jets} \)

- Data
- SM (sys @ stat)
- WW
- WZ/ZZ/W\gamma
- t\bar{t}
- Single Top
- Z+jets
- W+jets
- H [125 GeV]

\[ N_{SR} = \left( \frac{N_{SR}^{MC}}{N_{CR}^{MC}} \right) \left( N_{CR}^{\text{data}} - N_{CR}^{\text{other}} \right) \]

**Azimuthal lepton opening angle**

\( \Delta \phi(ll) \) works well for the same reasons
1-jet analysis: top and the b-veto

control region: b-jet tag

signal region: b-jet veto

Extrapolate from tag to veto

Experimental systematics dominate (b-tag efficiency calibration)
High-mass / BSM WW searches

- High-mass searches now explicitly BSM
- Include SM-like, narrow-width, 2HDM signal models

**Combine ggF and VBF channels** for SM-like hypothesis (assume production cross section ratio unchanged from SM)

**2HDM:** general BSM Higgs model, neural-net based search

**heavy H masses up to ~200 GeV** excluded (model + mixing angle dependent)

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**ATLAS** Preliminary

$H \rightarrow WW \rightarrow e\nu\mu\nu$, SM width

$\sqrt{s} = 8$ TeV, $L_{\text{int}} = 20.7$ fb$^{-1}$

95% CL Limit on $\sigma \times \text{BR}$

$\sigma_{\text{th}} \times \text{BR}$

$\pm 1 \sigma$

$\pm 2 \sigma$

Events / 0.07

**ATLAS** Preliminary

$\int L \, dt = 13.0$ fb$^{-1}$, $\sqrt{s}=8$ TeV

$H \rightarrow WW \rightarrow e\nu\mu\nu + 0$ jets

NN $@240$ GeV

Data

- SM Higgs $m_h=125$ GeV
- W+jets
- Z/$\gamma^*$+jets
- $t\bar{t}$/Wt/tq/t\bar{t}5
- WW/WZ/ZZ/WW/$\gamma$/WW$^*$

SM (sys $\oplus$ stat)

$\chi^2$-prob.: 76%