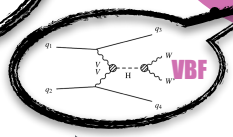
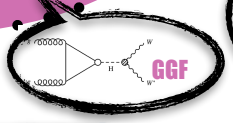
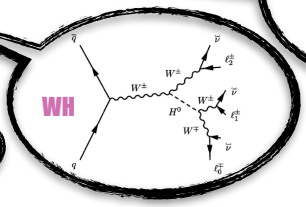
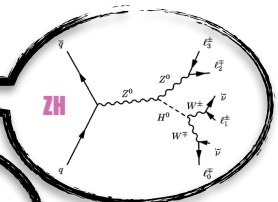
# Higgs boson measurements in the H→WW→lνlν decay channel

**Why H→WW?**
- Large Branching ratio
- Distinguishable signal in leptonic decay mode
- Highest sensitivity to total signal strength




**ggF+VBF 36.1 fb$^{-1}$**

* Results derived with simultaneous maximum likelihood fit.
* Observables used in the fit:
  - ☞ for ggF $m_T$

$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{miss}\right)^2 - \left|\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{miss}\right|^2}$$

  - ☞ for VBF BDT with input variables $m_{jj}$, $\Delta y_{jj}$, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $m_T$, $\sum_\ell C_\ell$, $\sum_{\ell,j} m_{\ell j}$, $p_T^{tot}$

$\Delta\phi_{ll}$: difference between the azimuthal angles of the two leptons

$C_l = |2\eta_l - \sum\eta_j| / \eta_{jj}$, where η: pseudorapidity

$m_{ll}$ ($m_{lj}$) {$m_{lj}$}: invariant mass of 2 leading leptons (2 leading jets) {lepton-jet pair}

$p_T^{tot}$: total transverse momentum

$\Delta y_{jj}$: difference between the two jet rapidities

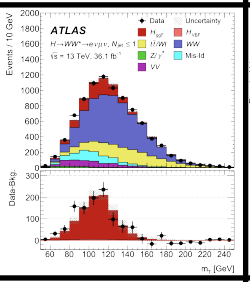
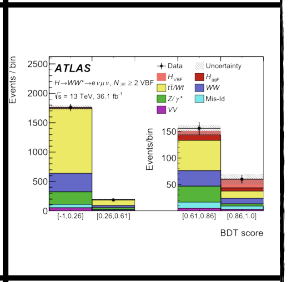
**Signal Region** — Event selection criteria to get signal dominated region

| Category | $N_{jet,(p_T>30\ GeV)} = 0$ ggF | $N_{jet,(p_T>30\ GeV)} = 1$ ggF | $N_{jet,(p_T>30\ GeV)} \geq 2$ VBF |
|---|---|---|---|
| Preselection | Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge<br>$p_T^{lead} > 22$ GeV, $p_T^{subl} > 15$ GeV<br>$m_{\ell\ell} > 10$ GeV<br>$p_T^{miss} > 20$ GeV | | |
| Background rejection | $\Delta\phi(\ell\ell, E_T^{miss}) > \pi/2$<br>$p_T^{\ell\ell} > 30$ GeV | $N_{b\text{-jet},(p_T>20\ GeV)} = 0$<br>$\max(m_T^\ell) > 50$ GeV | $m_{\tau\tau} < m_Z - 25$ GeV |
| $H \to WW^* \to e\nu\mu\nu$ topology | $m_{\ell\ell} < 55$ GeV<br>$\Delta\phi_{\ell\ell} < 1.8$ | | central jet veto<br>outside lepton veto |
| Discriminant variable<br>BDT input variables | $m_T$ | | BDT<br>$m_{jj}$, $\Delta y_{jj}$, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $m_T$, $\sum_\ell C_\ell$, $\sum_{\ell,j} m_{\ell j}$, $p_T^{tot}$ |

**Control Regions**
- Used to normalise the predictions of some of the background processes.
- Defined for the main background processes:
  - WW ☞ high $M_{ll}$ region.
  - $t\bar{t}$/Wt ☞ events with b-tag jets.
  - Z/γ* ☞ $M_{ll}$ within $m_Z$ window.

**Uncertainty**
- Sources of systematic uncertainty:
  - Experimental (8% ggF, 9% VBF)
  - Theoretical (10% ggF, 19% VBF)
- Dominant experimental uncertainties:
  - Misidentified leptons (6% ggF, 9% VBF)
  - b-tagging efficiency (4% ggF, 6% VBF)
  - Pile-up (5% ggF, 2% VBF)
- Dominant theoretical uncertainties:
  - ggF: WW background (6%)
  - VBF: ggF background (13%)

**Results** — https://doi.org/10.1016/j.physletb.2018.11.064

| Signal | ggF | VBF |
|---|---|---|
| Post-fit distributions |  |  |
| Signal Strength | $\mu_{ggF} = 1.10^{+0.10}_{-0.09}(stat.)^{+0.13}_{-0.11}(theo\ syst.)^{+0.14}_{-0.13}(exp\ syst.)$<br>$= 1.10^{+0.21}_{-0.20}$ | $\mu_{VBF} = 0.62^{+0.29}_{-0.27}(stat.)^{+0.12}_{-0.13}(theo\ syst.) \pm 0.15(exp\ syst.)$<br>$= 0.62^{+0.36}_{-0.35}$ |
| Cross section * branching ratio | $\sigma_{ggF} \cdot \mathcal{B}_{H\to WW^*}$<br>$= 11.4^{+1.7}_{-1.1}(stat.)^{+1.7}_{-1.3}(theo\ syst.)^{+1.4}_{-1.3}(exp\ syst.)$ pb<br>$= 11.4^{+2.2}_{-2.1}$ pb | $\sigma_{VBF} \cdot \mathcal{B}_{H\to WW^*}$<br>$= 0.50^{+0.24}_{-0.23}(stat.) \pm 0.10(theo\ syst.)^{+0.12}_{-0.13}(exp\ syst.)$ pb<br>$= 0.50^{+0.29}_{-0.28}$ pb. |
| Observed (Expected) significance | $Z_0^{ggF} = 6.0(5.3)$ | $Z_0^{VBF} = 1.8(2.6)$ |

**NEW RESULTS** **VBF 139 fb$^{-1}$**

* Results derived with simultaneous maximum likelihood fit.
* Most notable improvements with respect to previous Run2 analysis:
  - ☞ refinements in object selection together with an increased number of Monte Carlo (MC) simulated events.
  - ☞ A new multi-variate discriminant using a Deep Neural Network (DNN).

**Signal Region** — Event selection criterion to get signal dominated region

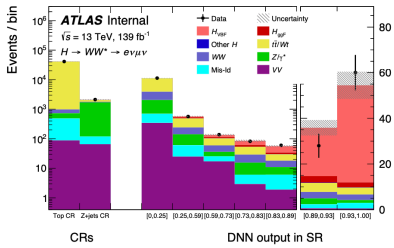
| | |
|---|---|
| Pre-selection | Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge<br>$p_T^{lead} > 22$GeV , $p_T^{subl} > 15$ GeV<br>$m_{\ell\ell} > 10$ GeV, $N_{jet} \geq 2$<br>$N_{b\text{-jet},(p_T>20\ GeV)} = 0$ |
| Selection | $m_{\tau\tau} < 66.2$ GeV<br>$m_{jj} > 120$ GeV<br>central jet veto<br>outside lepton veto |
| | A DNN is applied in the SR that uses 15 discriminant variables:<br>$\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, $m_T$, $\Delta y_{jj}$, $m_{jj}$, $p_T^{tot}$, $\sum_\ell C_\ell$, $m_{\ell 1 j 1}$, $m_{\ell 1 j 2}$, $m_{\ell 2 j 1}$, $m_{\ell 2 j 2}$,<br>$p_T^{jet_1}$, $p_T^{jet_2}$, $p_T^{jet_3}$, and MET significance |

**Control Regions**
- Two Control regions.
- CR yields normalise top-quark and Z+jets backgrounds in the SR.

| $Z \to \tau\tau$ CR | Top-quark CR |
|---|---|
| Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge<br>$p_T^{lead} > 22$GeV , $p_T^{subl} > 15$ GeV<br>$m_{\ell\ell} > 10$ GeV, $N_{jet} \geq 2$ | |
| $N_{b\text{-jet},(p_T>20\ GeV)} = 0$ | $N_{b\text{-jet},(p_T>20\ GeV)} = 1$ |
| $\lvert m_{\tau\tau} - m_Z \rvert < 25$ GeV | $m_{\tau\tau} < 66.2$ GeV |
| – | – |
| $m_{\ell\ell} < 70$ GeV<br>central jet veto<br>outside lepton veto | – |

**Uncertainty**
- Sources of systematic uncertainty:
  - Experimental (8.8%)
  - Theoretical (signal 14.4%, background 7.7%)
- Dominant experimental uncertainty:
  - missing transverse momentum measurement (4.7%)
- Dominant background theoretical uncertainty:
  - ggF background (5.2%)

**Results** — ATLAS-CONF-2020-045

| | |
|---|---|
| Post-fit distributions |  |
| Signal Strength | $\mu_{VBF} = 1.04^{+0.24}_{-0.20}$<br>$= 1.04^{+0.13}_{-0.12}(stat.)^{+0.09}_{-0.08}(exp\ syst.)^{+0.17}_{-0.12}(sig.\ theo.)^{+0.08}_{-0.07}(bkg.\ theo.)$ |
| Cross section * branching ratio | $\sigma_{VBF} \cdot \mathcal{B}_{H\to WW^*} = 0.85^{+0.20}_{-0.17}$ pb<br>$= 0.85 \pm 0.10(stat.)^{+0.08}_{-0.07}(exp\ syst.)^{+0.13}_{-0.10}(sig.\ theo.)^{+0.07}_{-0.06}(bkg.\ theo.)$ pb |
| Observed (Expected) significance | $Z_0^{VBF} = 7.0(6.2)$ — FIRST OBSERVATION FOR VBF HWW |

**WH+ZH 36.1 fb$^{-1}$**

* In the WH, H→WW* production, the Higgs boson couples only to W bosons, at both the production and decay vertices.
* This measurement is the most precise measurement of this channel to date.

SFOS: same-flavour opposite-sign charge (lepton pair)

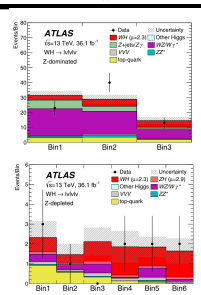
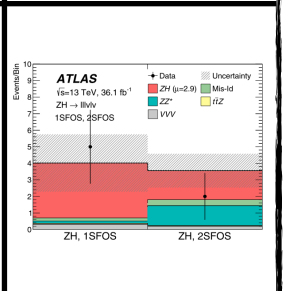
**Signal Region** — Event selection criterion to get signal dominated region

| | $WH$ | | $ZH$ | |
|---|---|---|---|---|
| Preselection | 3 isolated leptons ($p_T > 15$ GeV)<br>total lepton charge ±1 | | 4 isolated leptons ($p_T > 10$ GeV)<br>total lepton charge 0 | |
| Category | $Z$-dominated | $Z$-depleted | 2-SFOS | 1-SFOS |
| Number of SFOS | 2 or 1 | 0 | 2 | 1 |
| Number of jets | ≤ 1 | – | ≤ 1 | ≤ 2 |
| Number of $b$-jets | 0 | 0 | 0 | 0 |
| $E_T^{miss}$ [GeV] | > 30 | – | > 45 | – |
| $p_T^{4\ell}$ [GeV] | – | – | > 45 | – |
| $m_{\ell\ell}$ [GeV] | > 12 (min. SFOS) | – | > 10 | > 10 |
| $\lvert m_{\ell\ell} - m_Z \rvert$ [GeV] | > 25 (SFOS) | – | < 10 ($m_{\ell_2\ell_3}$) | < 10 ($m_{\ell_2\ell_3}$) |
| $m_{\ell_2\ell_3}$ [GeV] | – | – | < 55 | < 60 |
| $\Delta\phi_{\ell_0\ell_1}^{boost}$ | – | – | < 2.3 | < 1.9 |
| $m_{\tau\tau}$ [GeV] | – | – | – | < 50 |
| $\Delta\phi_{\ell_0\ell_1, \vec{p}_T^{miss}}$ [rad] | – | – | – | > 0.4 |
| $m_{4\ell}$ [GeV] | – | – | > 140 | – |
| BDT | $BDT_{Zdom} > 0.3$ | $BDT_{ri} > 0.2 \& BDT_{WZ} > 0.15$ | – | – |

**Control Regions**
- CRs normalise the main background processes.
- WZ/Wγ* and top-quark processes for the WH channel.
- ZZ* for the ZH channel in the 2-SFOS SR.
- In the 1-SFOS SR, ZZ*is estimated purely from simulation.

**Uncertainty**
- Sources of systematic uncertainty:
  - Experimental (12% WH, 7% ZH)
  - Theoretical (16% WH, 15% ZH)
- Dominant experimental uncertainties:
  - Misidentified leptons (8% WH, 3% ZH)
- Dominant theoretical uncertainty:
  - WH: WZ/Wγ*background (12%)
  - ZH: ZH signal (14%)

**Results** — https://www.sciencedirect.com/science/article/pii/S0370269319306719

| Signal | WH | ZH |
|---|---|---|
| Post-fit distributions |  |  |
| Signal Strength | $\mu_{WH} = 2.3^{+1.1}_{-0.9}(stat.)^{+0.49}_{-0.36}(exp\ syst.)^{+0.41}_{-0.33}(theo\ syst.) = 2.3^{+1.2}_{-1.0}$ | $\mu_{ZH} = 2.9^{+1.7}_{-1.3}(stat.)^{+0.54}_{-0.28}(exp\ syst.)^{+0.66}_{-0.27}(theo\ syst.) = 2.9^{+1.9}_{-1.3}$ |
| Cross section * branching ratio | $\sigma_{WH} \cdot \mathcal{B}_{H\to WW^*}$<br>$= 0.67^{+0.31}_{-0.27}(stat.)^{+0.14}_{-0.11}(exp\ syst.)^{+0.11}_{-0.09}(theo\ syst.)$ pb | $\sigma_{ZH} \cdot \mathcal{B}_{H\to WW^*}$<br>$= 0.54^{+0.31}_{-0.24}(stat.)^{+0.10}_{-0.05}(exp\ syst.)^{+0.11}_{-0.05}(theo\ syst.)$ pb |
| Observed (Expected) significance | $Z_0^{WH} = 2.6\ (1.3)$ | $Z_0^{ZH} = 2.8(1.2)$ |

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