Measurement of the Higgs boson properties with the ATLAS experiment

Manuela Venturi (University of Victoria)

CAP 2015 Congress, Edmonton, 15.06.2015
In 2012, the ATLAS collaboration reported the discovery of a resonance compatible with the Higgs boson, as predicted by the Standard Model, at a mass around 125 GeV.

Results with the full Run1 dataset (25 fb$^{-1}$ at $\sqrt{s} = 7$ and 8 TeV) on the properties of the new resonance will be presented here, for the individual decay channels and their combination.
Latest/final ATLAS results for Run1

- **Mass:**
  - Measurement of the Higgs boson mass from the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels with the ATLAS detector at the LHC [Phys.Rev. D90, 052004 (2014)]

- **Spin and Parity:**
  - Combination of the Higgs boson spin and parity analyses of the Higgs boson in the $H \to ZZ^* \to 4\ell$, $H \to WW^* \to \ell\ell\nu\nu$ and $H \to \gamma\gamma$ final states [ATLAS-CONF-2015-008]

- **Couplings:**
  - Measurements of the Higgs boson production and decay rates and couplings using $pp$ collisions data at $\sqrt{s} = 7$ and 8 TeV in the ATLAS experiment [ATLAS-CONF-2015-007]

- **Off-Shell Width:**
  - Determination of the off-shell Higgs boson signal strength in the high-mass $ZZ$ and $WW$ final states with the ATLAS detector [arXiv:1503.01060]

- **Total and differential cross section:**
  - Measurements of the Total and Differential Higgs Boson Production Cross Sections Combining the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ Decay Channels at $\sqrt{s} = 8$ TeV with the ATLAS Detector [arXiv:1504.05833]
Mass Results
Mass measurement approach

- **Model-independent measurement**
  - fit the spectra of the reconstructed invariant masses, without assumptions on signal production and decay yields
- **Narrow peak** expected in both channels (1.6 - 2 GeV resolution), over a smoothly falling background
- **Final Run1 results** (25 fb\(^{-1}\) \(\sqrt{s} = 7+8\) TeV) improve with respect to previous publications on electron and photon calibration, muon momentum scale uncertainty, event categorisation

Two unconverted photons, \(m = 126.9\) GeV

Four electrons, \(m = 124.6\) GeV
Higgs boson properties with the ATLAS experiment

- Excellent identification and measurement (energy, direction) of photons thanks to the design of the EM calorimeter

- Selection:
  - Two photons in \(|\eta| < 2.37\)
    - \(p_T > 20\) GeV (7 TeV data)
    - \(p_T > 25, 35\) GeV (8 TeV)
  - Tight identification criteria (shower shape), isolation, association with primary vertex
  - Further cuts on the diphoton \(E_T\)
  - Mass window \((105,160)\) GeV

- 95k (17k) candidates in 8(7) TeV data, split into ten categories:
  - converted/unconverted \(\times p_T\) criteria \(\times \eta\) range
  - maximising S/B ratio and mass resolution

- Signal model: Crystal Ball for the bulk + wide Gaussian for the tails
- Background (mostly irreducible SM \(\gamma\gamma\)) model: fit to data

- Combined fit to the ten categories, in the S+B hypothesis
- Mass and signal strength (assuming gluon fusion only) are treated as parameters of interest
H → ZZ* → 4ℓ

- High S/B ratio in this channel (~2 in the mass window 120 - 130 GeV), despite the low statistics, and excellent mass resolution
- 4µ (1.6 GeV mass resolution), 4e (2.2 GeV), 2µ2e, 2e2µ
  - Selection:
    - Four leptons, quality criteria applied
    - Muons in |η| < 2.7, electrons is |η| < 2.47
    - p_T > 20, 15, 10, 6 (7 if electron) GeV
    - Invariant masses of same-sign pairs must be close to Z mass
- Data-driven estimations for the backgrounds
- BDT discriminant trained against the irreducible ZZ* background, input variables:
  - p_T and eta of 4ℓ system
  - Matrix Element discriminant
    \[ D_{ZZ*} = \ln \left( \frac{|M_{\text{sig}}|^2}{|M_{ZZ*}|^2} \right) \]
- Combined fit to (BDT, m(4ℓ)) in the mass window (110,140) GeV
## Individual and combined results

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mass measurement [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>$125.98 \pm 0.42 \text{ (stat)} \pm 0.28 \text{ (syst)} = 125.98 \pm 0.50$</td>
</tr>
<tr>
<td>$H \to ZZllll$</td>
<td>$124.51 \pm 0.52 \text{ (stat)} \pm 0.06 \text{ (syst)} = 124.51 \pm 0.52$</td>
</tr>
<tr>
<td>Combined</td>
<td>$125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst)} = 125.36 \pm 0.41$</td>
</tr>
</tbody>
</table>

$\Delta m_H = 1.47 \pm 0.67 \text{ (stat)} \pm 0.28 \text{ (syst)} \text{ GeV}$

$\approx 1.47 \pm 0.72 \text{ GeV}$

compatible with 0 in 1.97$\sigma$

Profile likelihood ratio, treating $\mu(4\ell')$ and $\mu(\gamma\gamma)$ as independent nuisance parameters:

$$\Lambda(m_H) = \frac{L(m_H, \hat{\mu}_{\gamma\gamma}(m_H), \hat{\mu}_{4\ell}(m_H), \hat{\theta}(m_H))}{L(m_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{\theta})}$$

Mass measurement uncorrelated to the signal yield:

<table>
<thead>
<tr>
<th>Signal strength (in terms of $\sigma$)</th>
<th>Width (GeV) at 95% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.29 ± 0.30</td>
<td>$\Gamma$ (expected 4.2)</td>
</tr>
<tr>
<td>1.66</td>
<td>$\Gamma$ (expected 3.5)</td>
</tr>
</tbody>
</table>
Combination of signal strengths and couplings
The Kappa Framework

Assumptions

- All observed signals originate from a single, narrow resonance
  - due to the narrow-width approximation, production and decay factorise
- The tensor structure is the one predicted by the SM, $J^{PC}=0^{++}$
- Also assuming SM production and decay kinematics

- The production/rate decay can vary, according to the signal strength

- The couplings can also vary, according to $\mathcal{G}_{Hii} \rightarrow \kappa_i \cdot \mathcal{G}_{Hii}$

Thus in general:

$$\sigma \cdot \text{BR}(i \rightarrow H \rightarrow f) = \frac{\sigma_i^{\text{SM}} \cdot \Gamma_f^{\text{SM}}}{\Gamma_H^{\text{SM}}} \cdot \frac{k_i^2 k_f^2}{k_H^2}$$

- Combine all available channels using a simultaneous maximum likelihood fit with the following test statistic (in the asymptotic approximation):

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\alpha})}{L(\hat{\alpha}, \hat{\theta})}$$

Parameters of interest can be $\mu$, $m_H$, $k$ and their ratios $\lambda$ 

Nuisance parameters are the systematic uncertainties, correlated among all analyses
Combined result at $m_H = 125.36$ GeV:

- compatibility with SM ($\mu=1$): p-value = 18%
- compatibility with a single narrow resonance: p-value = 76%

main theoretical uncertainties are on SM production cross section and decay branching ratios - at the level of our experimental precision
Many interesting results in several different scenarios, just a few examples here.

Production mechanism:
Higgs coupling to fermions (ggf, ttH) or vector bosons (VBF, VH)

$\mu_{ggH,ttH} = \mu_{ggH} = \mu_{ttH}$

$\mu_{VBF,VH} = \mu_{VBF} = \mu_{VH}$

Branching fractions cancel in the ratio

Couplings to fermions and bosons
Spin and Parity Quantum Numbers
Spin/parity measurement approach

The spin/parity SM assignment, $J^p=0^+$, can be tested against alternative models:
- **fixed-hypothesis test:** $2^+, 0^-, 0^+$ with higher-order operators,
- **CP mixing:** mixture of spin-0 states, implying CP violation in the Higgs sector

- **Higgs characterization Model** from Madgraph5 (effective field theory, cut-off scale $\Lambda = 1$ TeV)
- All bosonic channels used (only $ZZ$ and $WW$ for spin-0 studies)
  - in all cases, only the most sensitive categories are used

- Spin=2: Higgs-like graviton-inspired resonance, with universal [gravity-like] and non-universal couplings to quarks and gluons (in various $k_g, k_q$ fractions)

- NLO effects lead to a tail in $p_T^H$
  for a spin-2 Higgs-like boson when jets are present > cut on $p_T^H$
  to preserve unitarity

<table>
<thead>
<tr>
<th>Choice of QCD couplings</th>
<th>$p_T^h$ cut-off (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_q = \kappa_g$</td>
<td>Universal couplings</td>
</tr>
<tr>
<td>$\kappa_q = 0$</td>
<td>Low light-quark fraction 300 125</td>
</tr>
<tr>
<td>$\kappa_q = 2\kappa_g$</td>
<td>Low gluon fraction 300 125</td>
</tr>
</tbody>
</table>

\[ \text{ATLAS} \]
Simulation $\sqrt{s} = 8$ TeV
$H \rightarrow WW^*, \eta_1 = 1, e\mu$
Spin: sensitive variables

**ATLAS Simulation Preliminary**

- $\sqrt{s} = 8$ TeV
- $p_T^{\gamma\gamma} < 125$ GeV

**H → $\gamma\gamma$ observed**

**ATLAS**

- $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
- $H \rightarrow WW^*$, $n_j = 0$, $e\mu$

**H → $WW$ observed**

**ATLAS Preliminary**

- $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
- $H \rightarrow \gamma\gamma$, $n_j = 0$, $e\mu$

**H → $\gamma\gamma$ expected**

**H → $WW$ expected**
Parity: sensitive variables

In the $ZZ^* \rightarrow 4\ell$ case, the entire decay topology can be reconstructed: decay angles + invariant masses = 8 degrees of freedom

$\cos(\theta_1), \cos(\theta_2), \Phi, m_{12}, m_{34}$

CP Sensitive

$m_{4l}, \cos(\theta^*), \Phi_1$

Background rejecting

$WW \rightarrow e\nu\mu\nu$ is harder due to the presence of the two neutrinos, but the angular difference between $e$ and $\mu$ is sensitive to spin/parity.
Final discriminants

Most sensitive bins of the BDT discriminant after subtracting post-fit background from the data:

**Boosted Decision trees**

- **BDT0**: SM vs background
- **BDT2**: ALT vs background

Both trained with \(M_T\), \(M_{ll}\), \(P_{Tll}\), \(\Delta \phi_{ll}\)

- **BDT0**: SM vs background
- **BDT2**: SM vs CP-odd

**Checking if performance improves doing (SM+CP-odd) vs background**

**ZZ uses the Matrix Element**

- Method in a tight mass window, fed with optimal observables

Manuela Venturi

Manuela Venturi (Uni Victoria)

Higgs boson properties with the ATLAS experiment
Fixed-hypothesis results

Combined results for SM 0$^+$ vs a fixed alternative hypothesis:
all non-SM models excluded at > 99\% CL

<table>
<thead>
<tr>
<th>Tested Hypothesis</th>
<th>$p_{\text{exp, } \mu = 1}^{\text{ALT}}$</th>
<th>$p_{\text{exp, } \mu = \hat{\mu}}^{\text{ALT}}$</th>
<th>$p_{\text{obs}}^{\text{SM}}$</th>
<th>$p_{\text{obs}}^{\text{ALT}}$</th>
<th>Obs. CLS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^+$</td>
<td>$2.5 \cdot 10^{-2}$</td>
<td>$4.7 \cdot 10^{-3}$</td>
<td>0.85</td>
<td>$7.1 \cdot 10^{-5}$</td>
<td>$4.7 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>0$^-$</td>
<td>$1.8 \cdot 10^{-3}$</td>
<td>$1.3 \cdot 10^{-4}$</td>
<td>0.88</td>
<td>$&lt; 3.1 \cdot 10^{-5}$</td>
<td>$&lt; 2.6 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>2$^+$</td>
<td>$4.3 \cdot 10^{-3}$</td>
<td>$2.9 \cdot 10^{-4}$</td>
<td>0.61</td>
<td>$4.3 \cdot 10^{-5}$</td>
<td>$1.1 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>2$^+$ ($\kappa_q = 0; \ p_T &lt; 300$)</td>
<td>$&lt; 3.1 \cdot 10^{-5}$</td>
<td>$&lt; 3.1 \cdot 10^{-5}$</td>
<td>0.52</td>
<td>$&lt; 3.1 \cdot 10^{-5}$</td>
<td>$&lt; 6.5 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>2$^+$ ($\kappa_q = 0; \ p_T &lt; 125$)</td>
<td>$3.4 \cdot 10^{-3}$</td>
<td>$3.9 \cdot 10^{-4}$</td>
<td>0.71</td>
<td>$4.3 \cdot 10^{-5}$</td>
<td>$1.5 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>2$^+$ ($\kappa_q = 2\kappa_g; \ p_T &lt; 300$)</td>
<td>$&lt; 3.1 \cdot 10^{-5}$</td>
<td>$&lt; 3.1 \cdot 10^{-5}$</td>
<td>0.28</td>
<td>$&lt; 3.1 \cdot 10^{-5}$</td>
<td>$&lt; 4.3 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>2$^+$ ($\kappa_q = 2\kappa_g; \ p_T &lt; 125$)</td>
<td>$7.8 \cdot 10^{-3}$</td>
<td>$1.2 \cdot 10^{-3}$</td>
<td>0.80</td>
<td>$7.3 \cdot 10^{-5}$</td>
<td>$3.7 \cdot 10^{-2}$</td>
</tr>
</tbody>
</table>
Scanning on possible components of CP-odd or CP-even higher-orders mix with SM (only one at a time).

Same BSM couplings assumed for $ZZ$ and $WW$.

No significant deviation from pure SM composition found.
Off-Shell width results
Off-shell width approach

For high masses ($m_{VV} > 2m_V$), sensitivity to Physics beyond the SM can be achieved via off-shell Higgs boson production and interference effects, negligible around 125 GeV.

\[ \sigma_{gg \rightarrow H^* \rightarrow VV} \text{ off-shell} \]

independent from the total width $\Gamma_H$:

\[ \mu_{\text{off-shell}}(\delta) \equiv \frac{\sigma_{gg \rightarrow H^* \rightarrow VV}^{\text{off-shell}}(\delta)}{\sigma_{gg \rightarrow H^* \rightarrow VV}^{\text{off-shell, SM}}(\delta)} = k_{g,\text{off-shell}}(\delta) \cdot k_{V,\text{off-shell}}(\delta) \]

while the on-shell term depends on $\Gamma_H$:

\[ \mu_{\text{on-shell}} \equiv \frac{\sigma_{gg \rightarrow H \rightarrow VV}^{\text{on-shell}}}{\sigma_{gg \rightarrow H \rightarrow VV}^{\text{on-shell, SM}}} = \frac{k_{g,\text{on-shell}}^2 \cdot k_{V,\text{on-shell}}^2}{\Gamma_H / \Gamma_{H,\text{SM}}} \]

- Therefore, assuming identical on/off-shell couplings $k$, the total width $\Gamma_H$ can be indirectly constrained.
- Alternatively, assuming this only for VBF but not ggF, and fixing $\Gamma_H = \Gamma_{H,\text{SM}}$, the gluon ratio can be constrained:

\[ R_{gg} = k_{g,\text{off-shell}}^2 / k_{g,\text{on-shell}}^2 \]

Interference is negative over the whole mass range

\[ \text{SM } \Gamma_H = 4.12 \text{ MeV at } m_H=125.4 \text{ GeV} \]
High-mass spectra of $H \rightarrow ZZ, WW$

$H \rightarrow ZZ^* \rightarrow 4\ell$

$H \rightarrow ZZ^* \rightarrow 2\ell 2\nu$

$H \rightarrow WW^* \rightarrow e\nu\mu\nu + \text{jets}$

Matrix element discriminant built with the topological observables

Transverse mass to account for the presence of neutrinos

New variable $R_8 > 450$ GeV:

$R_8 = \sqrt{m_{4\ell}^2 + (a \cdot m_{WW}^T)^2}$

to reject on-shell Higgs boson decays
Combination of on- and off-shell results

Measurement of $\Gamma_H/\Gamma_H^{SM}$ assuming $\kappa_g = \kappa_g,\text{on-shell} = \kappa_g,\text{off-shell}$ and $\kappa_V = \kappa_V,\text{on-shell} = \kappa V,\text{off-shell}$ for both ggF and VBF, as in the SM.

There is no prediction for NLO corrections to the $gg \rightarrowVV$ background at high mass, thus results are given as a function of $R^B$, in the range (0.5, 2).

<table>
<thead>
<tr>
<th>$R^B_H$</th>
<th>Observed</th>
<th>Median expected</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>$\Gamma_H/\Gamma_H^{SM}$</td>
<td>4.5</td>
<td>5.5</td>
<td>11.2</td>
</tr>
</tbody>
</table>

For $R^B = 1$

$\Gamma_H < 22.7$ (exp 33.0) MeV
Combination of on- and off-shell results

Measurement of $\frac{R_{gg} = \kappa_{g, off-shell}^2}{\kappa_{g, on-shell}^2}$ assuming $\kappa_V = \kappa_{V, on-shell} = \kappa_{V, off-shell}$ for VBF only, while ggF can deviate (different $k_g$ on/off shell). Also assuming $\Gamma_H = \Gamma_H^{(SM)}$.

Like before, results as a function of RB.

<table>
<thead>
<tr>
<th>$R^B_H$</th>
<th>Observed</th>
<th>Median expected</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>4.7</td>
<td>7.1</td>
<td>$\kappa_{V, on-shell} = \kappa_{V, off-shell}$, $\Gamma_H/\Gamma_H^{(SM)} = 1$</td>
</tr>
<tr>
<td>1.0</td>
<td>6.0</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>8.6</td>
<td>13.4</td>
<td></td>
</tr>
</tbody>
</table>
Production Cross Section at $\sqrt{s} = 8$ TeV
Combination of $ZZ$ and $\gamma\gamma$ measurements at 8 TeV, ~30% improvement on individual results. Common mass of 125.36 GeV assumed.

**THEO-EXP compatibility:**
- p-value = 5.5% for LHC-XS
- 9% for ADDFGHLM

Same trend as a function of $N_{\text{jets}} > 1$: exp > theo:
Differential cross sections

• Measured as a function of the Higgs $p_T$ and $|y|$, and of leading jet $p_T$.
• Comparison to NNLO computations.
• Need more data to study the shapes and verify the observed deviations.
Conclusions

The final results for the measurement of the Higgs boson properties, with the full Run1 dataset (25 fb⁻¹ at sqrt(s)=7 and 8 TeV) collected and analysed by the ATLAS collaboration, have been presented.

All the aspects of the Higgs boson physics have been explored, finding no significant deviation from the Standard Model expectations. Looking forward to Run2 results at 13 TeV, coming up later this year!

<table>
<thead>
<tr>
<th>Combination of channels</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>γγ, ZZ</td>
</tr>
</tbody>
</table>
| Spin                    | γγ, WW   | • 2⁺ universal  
                          |          | • 2⁺ non-universal |
| Parity                  | WW, ZZ   | • 0⁻ excluded 
                          |          | • 0⁺h |
| CP-mixing               | WW, ZZ   | • $\tilde{K}_{AV}/K_{SM}$ $\tan(\alpha)$ in (-2.2, 0.8) at 95% CL 
                          |          | • $\tilde{K}_{HW}/K_{SM}$ in (-0.7, 0.6) at 95% CL |
| Cross section (8 TeV)   | γγ, ZZ   | $\sigma_{pp}$ |
| Off-shell width         | WW, ZZ   | $\Gamma_H$ |
Outlook to Run2

Run2 Higgs analyses will be dominated by **systematic uncertainties**

\[ \sigma_{pp \rightarrow H} = 33.0 \pm 5.3 \text{(stat)} \pm 1.6 \text{(sys)} \text{ pb} \]

- **Run1**: ± 5.5 pb total
- **Run2**: ± 2.3 pb total

(from LHC Higgs XS WG)

<table>
<thead>
<tr>
<th></th>
<th>( \sigma(8 \text{ TeV}) )</th>
<th>( \sigma(13 \text{ TeV}) )</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>( gg \rightarrow H )</td>
<td>19.3</td>
<td>43.9</td>
<td>2.3</td>
</tr>
<tr>
<td>VBF</td>
<td>1.58</td>
<td>3.75</td>
<td>2.4</td>
</tr>
<tr>
<td>WH</td>
<td>0.70</td>
<td>1.38</td>
<td>2.0</td>
</tr>
<tr>
<td>ZH</td>
<td>0.42</td>
<td>0.87</td>
<td>2.1</td>
</tr>
<tr>
<td>( ttH )</td>
<td>0.13</td>
<td>0.51</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Much more on Run2 prospects in Pierre Savard's plenary talk on Thursday.
Back up
**HWW analysis strategy**

**Boosted Decision trees** used as discriminants:

- **BDT0**: train SM signal vs background
- **BDT2**: train ALT signal vs background
- Both BDT0 and BDT2 use as input: \( m(\ell\ell) , \Delta\phi^{\ell\ell} , p_{T}^{\ell\ell} , m_{T}^{\text{track}} \)
- Combine (BDT0, BDT2) and fit the 1d projection

- **BDT0**: train SM signal vs background (as for spin)
- **BDT_{CP}**: train SM signal vs ALT signal:
  - BSM CP-odd: \( m_{\ell\ell} , \Delta\phi^{\ell\ell} , E_{\ell\ell\nu\nu} \) and \( \Delta p_{T} \)
  - BSM CP-even: \( m_{\ell\ell} , \Delta\phi^{\ell\ell} , p_{T}^{\ell\ell} \) and \( E_{T}^{\text{miss}} \)

\[
E_{\ell\ell\nu\nu} = p_{T}^{\ell_{1}} - 0.5p_{T}^{\ell_{2}} + 0.5E_{T}^{\text{miss}} \\
\Delta p_{T} = \left| p_{T}^{\ell_{1}} - p_{T}^{\ell_{2}} \right|
\]

Training performed for the pure CP hypothesis only, no retraining for the various CP fractions.
CP violation in the Higgs sector

\[ L_0^V = \left\{ c_\alpha \kappa_{SM} \left[ \frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^\mu_\mu W^{-\mu} \right] \right\} \]

- \frac{1}{4} \left[ c_\alpha k_{HYY} g_{HYY} A_{\mu\nu} A^{\mu\nu} + s_\alpha k_{AYY} g_{AYY} A_{\mu\nu} A^{\mu\nu} \right]
- \frac{1}{2} \left[ c_\alpha k_{HZY} g_{HZY} Z_{\mu\nu} A^{\mu\nu} + s_\alpha k_{AZY} g_{AZY} Z_{\mu\nu} A^{\mu\nu} \right]
- \frac{1}{4} \left[ c_\alpha k_{Hgg} g_{Hgg} G_{\mu\nu}^a G_{\mu\nu}^a + s_\alpha k_{agg} g_{agg} G_{\mu\nu}^a G_{\mu\nu}^a \right]
- \frac{1}{4} \left[ c_\alpha k_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha k_{AZZ} Z_{\mu\nu} Z^{\mu\nu} \right]
- \frac{1}{2} \left[ c_\alpha k_{HWW} W^\mu_\mu W^{-\mu} + s_\alpha k_{AWW} W^\mu_\mu W^{-\mu} \right]

\text{kHWW: Higher order CP-even}

\text{kAWW} \times \tan \alpha: \text{CP violation in the Higgs sector}
$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

$H \rightarrow WW^*, n_j = 0, e\mu$

$-2\Delta LL$

**ATLAS**

- **Observed**
- **Expected, $\mu = \hat{\mu}$**
- **Expected, $\mu = 1$**
- **68% CL**
- **95% CL**

$\frac{\kappa_{HWW}}{\kappa_{SM}}$