Measurements of the Higgs boson mass, width, CP and anomalous couplings with the ATLAS detector

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The Higgs boson plays a unique role in the SM of giving masses to other particles via the EW SSB.

The discovery of the Higgs boson was announced in July 4th, 2012 by ATLAS and CMS.

Precisely determining its properties is essential to test the SM.

Latest measurements of its mass, width and CP structure and search for anomalous couplings will be presented.
The Higgs boson mass is a free parameter in the SM but is crucial for determining other properties.

The combined measurement from ATLAS and CMS with Run-I dataset is

\[ m_H = 125.09 \pm 0.24 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.)} \text{ GeV} \]

\( \text{Phys. Rev. Lett. 114 (2015)} \)

√ Statistical uncertainty dominant

Run-II measurement in \( H \to ZZ^* \to 4\ell \) channel has been released.

3 dimensional fit exploring DNN, \( \sigma_i \), \( m_{4\ell} \) to extract \( m_H \)
Higgs boson mass measurement

\[ m_H = 124.99 \pm 0.19 \pm 0.18 \text{ (stat.)} \pm 0.04 \text{ (syst.)} \text{ GeV} \]

Still statistical uncertainty dominant

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>Contribution [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon momentum scale</td>
<td>±28</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>±19</td>
</tr>
<tr>
<td>Signal-process theory</td>
<td>±14</td>
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</tbody>
</table>
Higgs boson width measurement

- The width of the Higgs boson is very small (~4.1 MeV @ $m_H = 125$ GeV) as predicted by the SM
  ✓ Much smaller than experimental resolution (~1-2 GeV)
  → Unable to be directly measured from signal shape
- Could be extracted from the ratio of on-shell and off-shell signal strengths
  ✓ Assume equal couplings for on-shell and off-shell
  ✓ Interference with continuum $gg/VV \rightarrow VV$ production is important for off-shell → a negative impact for total yield

\[
\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma}{\Gamma_{\text{SM}}}
\]

\[
\sigma_{\text{on-shell}} \frac{1}{m_H^2 \Gamma_H} \sim \frac{g_{\text{gluon}}^2 g_V^2}{m_H^2 \Gamma_H}
\]

\[
\sigma_{\text{off-shell}} \frac{1}{m_V^2} \sim \frac{g_{\text{gluon}}^2 g_V^2}{m_V^2}
\]

- Several analyses performed since Run-I
  ✓ $H \rightarrow ZZ$ [139 fb$^{-1}$, arXiv:2304.01532]
Higgs boson width measurement

- Performed in $H \rightarrow ZZ \rightarrow 4\ell/2\ell 2\nu$ channels
  - $4\ell$ performs neural network to separate signal and backgrounds, $O_{NN}$ as the discriminator
  - $2\ell 2\nu$ uses $m_T^{\ell\ell}$ as the discriminator
- Three SR regions defined for each channel
  - $ggF$, Mixed, EW (VBF)
- $\mu_{on-shell} = 1.01 \pm 0.11$ from \textit{Eur. Phys. J. C} 80 (2020) 957

$\mu_{off-shell} = 1.1^{+0.7}_{-0.6}$

$3.3\sigma (2.2\sigma)$ obs (exp.) for off-shell Higgs boson

$\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

* Neyman construction to derive the confidence intervals*
• Results interpreted with SMEFT in terms of H-top and H-gluon couplings
  ✓ Test with $c_g - c_t$ framework ($c_g$, $c_t$)
  ✓ Test with Warsaw basis ($c_{\phi G}$, $c_{t\phi}$)

$$\frac{\sigma_{\text{SMEFT}}(c_t, c_g)}{\sigma_{\text{SM}}} \simeq (c_t + c_g)^2 \left(1 - \frac{7}{15} \frac{c_g}{c_t + c_g} \frac{m_h^2}{4m_i^2} \right)$$

Mass term can not be neglected for off-shell Higgs boson production

⇒ Separately probe $c_g$ and $c_t$

\[ c_{\phi G} = \frac{g_s^2 \Lambda^2}{48 \pi^2 v^2} c_g \]
\[ c_{t\phi} = -\frac{y_t \Lambda^2}{v^2} (c_t - 1) \]
The Higgs boson couplings are measured by ATLAS (see Luca’s talk)

✓ Generally agree with the SM predictions
✓ Still room for new physics (e.g. rare production/decay see Rocky’s talk)

• Measuring the anomalous coupling of the Higgs boson could also probe the new physics
✓ Test with the Effective Field Theory (EFT) approach
✓ Could include both CP-even and CP-odd contributions
  ➢ Test with differential results presented in Roberto’s talk

• In the SM, the Higgs boson is predicted as CP-even
• Explore CP-odd contribution in Higgs sector
✓ Mixture of CP-even and CP-odd still allows
✓ New source of CP violation
HVV anomalous coupling and CP structure

Based on the Effective Field Theory
Explore the **Optimal Observable (OO)**
- ✓ A CP-odd variable
- ✓ Fairly a model independent definition

- VBF $H \rightarrow \tau \tau$ [36 fb$^{-1}$] Phys. Lett. B 805 (2020) 135426
- VBF $H \rightarrow \gamma \gamma$ [139 fb$^{-1}$] arXiv:2208.02338
- $H \rightarrow ZZ$ arXiv:2304.09612
- ✓ $H \rightarrow ZZ$ also explore decay vertex

**$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$**

Dim-6 operators, 3 independent ones for CP-odd in SMEFT

$$OO = \frac{2Re(\mathcal{M}_{SM}^* \mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$$

- Two parametrization sets used: **Warsaw basis** and **Higgs basis**

- Also explored an even simpler parametrization as defined as

  $$\bar{d} : c_{H\bar{W}B} = 0, c_{H\bar{W}} = c_{H\bar{B}} = \frac{\Lambda^2}{v^2} \bar{d},$$

  $$\bar{c}_{zz} = 0, \quad \bar{c}_{\gamma\gamma} = \sin^2 \theta_W \cos^2 \theta_W \bar{c}_{zz} \propto \bar{d}$$
HVV anomalous coupling: VBF $H \rightarrow \gamma \gamma$

- Perform two BDTs to separate VBF/ggF and VBF/continuum background
- Define three SRs with two BDT scores
- Fit on $m_{\gamma\gamma}$ distributions on 6 $OO$ bins for each SR (in total 18 regions) to extract signal contribution
- Derived constraints for $\tilde{d}$ and $c_{H\tilde{W}}$

\[ \tilde{d} \in [-0.032, 0.059] \]
\[ \tilde{c}_{H\tilde{W}} \in [-0.55, 1.07] \]
HVV anomalous coupling: $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$

- Based on the Effective Field Theory approach, using **Optimal Observable (OO)** to probe CP-odd component
- Define two OOs: for **production** (VBF enriched) and for **decay** (inclusive)

**Production $OO_{jj}$**

**Decay $OO_{4\ell}$**

**ATLAS Simulation**

$H \rightarrow ZZ \rightarrow 4\ell$

$\sqrt{s} = 13$ TeV

$115$ GeV $< m_{4\ell} < 130$ GeV

$N_{jj} \geq 2$, $m_4 > 120$ GeV

**BSM/SM**

$0$, $1$ jet(s) or $m_{4\ell} < 120$ GeV

$\geq 2$ jets and $m_{4\ell} \geq 120$ GeV

Jet Selection

Total 7 coefficients (3 for **Warsaw basis**, 3 for **Higgs basis**, 1 for simple parametrization) are constrained

**arXiv:2304.09612**
HVV anomalous coupling: $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$

- A neural-network training performed to enhance the VBF purity
  - 4 VBF SRs defined with NN output
- Three types of fit perform
  - Production $\rightarrow$ CR($ZZ$, VBF-dep)+SR(VBF1-4)
  - Decay $\rightarrow$ CR($ZZ$)+SR(inclusive)
  - Combined $\rightarrow$ CR($ZZ$)+SR(VBF-dep, VBF1-4)
HVV anomalous coupling: $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$

ATLAS

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

$s = 13$ TeV, $139$ fb$^{-1}$

SMEFT CP-odd couplings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best Fit</th>
<th>68% CL</th>
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</thead>
<tbody>
<tr>
<td>$c_{H\tilde{B}}$</td>
<td>-0.08</td>
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<tr>
<td>$c_{H\tilde{W}B}$</td>
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<td>$c_{H\tilde{W}W}$</td>
<td>-0.06</td>
<td>[-0.22, 0.09]</td>
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<tr>
<td>$\tilde{d}$</td>
<td>-0.02</td>
<td>[-0.56, 0.53]</td>
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<tr>
<td>$\tilde{d}$</td>
<td>0.60</td>
<td>[-1.50, 1.50]</td>
</tr>
</tbody>
</table>

$\tilde{d}$

$\times 10$ -0.00 [-0.02, 0.01]

$\times 10$ 0.01 [-0.01, 0.03]

arXiv:2304.09612
The **CP-mixing** is parametrized to be sensitive to the angular of two tau planes from the Higgs boson in the Higgs boson center-of-mass frame.

\[
\frac{d\Gamma_{H\rightarrow\tau^+\tau^-}}{d\Omega} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16} \cos(\varphi^*_CP - 2\phi_\tau)
\]

Depending on tau decays: several methods developed to reconstruct \(\phi_{CP}\)

\[
\mathcal{L}_Y = -\frac{m_\tau}{\nu} H (\kappa_{\tau} \bar{\tau} \tau + \tilde{\kappa}_{\tau} \bar{\tau} i \gamma_5 \tau)
\]

\[
\tan(\phi_\tau) = \frac{\tilde{\kappa}_{\tau}}{\kappa_{\tau}}
\]
The **CP-mixing** is parametrized to be sensitive to the angular of two tau planes from the Higgs boson in the Higgs boson center-of-mass frame:

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d\Gamma_{\text{H-}\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16} \cos(\varphi^*_\text{CP} - 2\phi_\tau)
\]

Depending on tau decays: several methods developed to reconstruct \(\phi_{\text{CP}}\):

\[
\mathcal{L}_Y = -\frac{m_\tau}{v} H (k_\tau \tilde{\tau} \bar{\tau} + \kappa_\tau \tau i \gamma_5 \bar{\tau})
\]

\[
\tan(\phi_\tau) = \frac{\tilde{\kappa}_\tau}{k_\tau}
\]

\(\phi_\tau = 9 \pm 16\) deg. (\(\pm 28\) deg.)

Pure CP-odd excluded @ 3.4\(\sigma\)
CP structure in Higgs-Top interaction

- Measure the CP structure of H-top interaction in ttH production and search for anomalous coupling

\[ \mathcal{L} = - \frac{m_t}{v} \left\{ \bar{\psi}_t \kappa_t \left[ \cos(\alpha) + i \sin(\alpha) \gamma_5 \right] \psi_t \right\} H \]

- Studied in two decay channels
  - $H \to \gamma\gamma$ [Phys. Rev. Lett. 125 (2020) 061802]
  - $H \to b\overline{b}$ [arXiv:2303.05974]

BDT for Higgs/Bkg, CP-even/odd separation and categorization

Mixing angle $|\alpha| < 43^\circ$ @95% CL

Pure CP-odd excluded @3.9$\sigma$
CP structure in Higgs-Top interaction

- Explore $1\ell+\text{jets}$ (include boosted region) and $2\ell$ channels
- Train BDT to categorize events
- Two dedicated CP sensitive variables defined with top quark kinematic information
- Use BDT for boosted region CP-even/odd separation

\[
b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|}, \quad \text{and} \quad b_4 = \frac{p_1^Z p_2^Z}{|\vec{p}_1||\vec{p}_2|}
\]

\[\alpha = 11^{+52}_{-73}^\circ\]
• Measurements of the Higgs boson properties in terms of mass, width, CP and anomalous couplings with the ATLAS detector are presented

• The latest Higgs boson mass is determined as \( m_H = 124.99 \pm 0.19 \text{ GeV} \) from \( H \rightarrow ZZ^* \rightarrow 4\ell \) channel with full Run-II dataset

• Evidence of the off-shell Higgs boson is found with an observed significance of \( 3.3\sigma \) in \( H \rightarrow ZZ^* \rightarrow 4\ell/2\ell2\nu \) channel

  ✓ Higgs boson width is measured as \( \Gamma_H = 4.5^{+3.3}_{-2.5} \text{ MeV} \)

• The CP property of the Higgs boson is studied in various channels

  ✓ Pure CP-odd contribution is excluded for \( H\tau\tau \) and H-top interaction

  ✓ Still room for CP-mixture

• No significant derivation from the SM prediction observed in anomalous coupling measurements
Backup
The signal probability density function is modelled as

\[ P(m_{4\ell}, D_{NN}, \sigma_i | m_H) = P(m_{4\ell} | D_{NN}, \sigma_i, m_H) \cdot P(D_{NN} | \sigma_i, m_H) \cdot P(\sigma_i | m_H) \]

\[ \approx P(m_{4\ell} | D_{NN}, \sigma_i, m_H) \cdot P(D_{NN} | m_H), \]

where the following approximations are used:

- \( P(D_{NN} | \sigma_i, m_H) \approx P(D_{NN} | m_H) \) because the neural network discriminant does not directly depend on the per-event \( m_{4\ell} \) resolution,

- \( P(\sigma_i | m_H) \approx P(\sigma_i) \) since the averaged per-event resolution does not depend on \( m_H \) within the range of 105 to 160 GeV used in this measurement, and

- \( P(\sigma_i) \) is omitted from the probability density function because it was observed that it has approximately the same distribution for signal and background events in the Higgs boson peak region. Dedicated checks of the assumption that \( P(\sigma_i) \) can be omitted have shown that this has negligible impact on the measurement.

The probability density function \( P(m_{4\ell} | D_{NN}, \sigma_i, m_H) \) in each subchannel is described by a double-sided Crystal Ball [57] probability density function that consists of a Gaussian core and two power-law tails.
Higgs mass measurement

Signal parametrized with Double-sided Crystal ball function

Mean of Gaussian parametrized as

$$a^\lambda \cdot (m_H - 125 \text{ GeV}) + b^\lambda (D_{NN})$$
Off-shell Higgs boson to measure width

**Limit width through off-shell production**

- Higgs boson width could be constrained using off-shell production to 2 Z bosons away from the resonance peak. Gluon fusion is dominant.

\[
\frac{d\sigma_{gg\rightarrow H\rightarrow ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}\Gamma_{HZZ}}{m_{ZZ}^2 - m_H^2 + m_H^2 m_{Z}^2}.
\]

- Integrating around \(m_H\) or above \(2m_Z\) (where \(m_{ZZ} - m_H \gg \Gamma_H\));

\[
\sigma_{gg\rightarrow H\rightarrow ZZ}^{\text{on-shell}} \sim \frac{g_{ggH}\Gamma_{HZZ}}{m_{H}^2 \Gamma_{H}} \quad \text{and} \quad \sigma_{gg\rightarrow H\rightarrow ZZ}^{\text{off-shell}} \sim \frac{g_{ggH}\Gamma_{HZZ}}{(2m_Z)^2}.
\]

- Taking signal strengths in terms of coupling scale factors;

\[
\mu_{\text{on-shell}} \equiv \frac{\sigma_{gg\rightarrow H\rightarrow VV}^{\text{on-shell}}}{\sigma_{gg\rightarrow H\rightarrow VV}^{\text{on-shell}, \text{SM}}} = \frac{k_{V,\text{on-shell}}^2}{\Gamma_H/\Gamma_{H}^{\text{SM}}} \quad \mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma_{gg\rightarrow H\rightarrow VV}^{\text{off-shell}(\hat{s})}}{\sigma_{gg\rightarrow H\rightarrow VV}^{\text{off-shell}(\hat{s})}} = \frac{k_{V,\text{off-shell}}^2(\hat{s})}{\Gamma_H/\Gamma_{H}^{\text{SM}}}
\]

- On-shell (NWA) depends on total width Off-shell does not!

- Assumption of independence of scale factors from \(s\) (energy scale) in high mass region considered in the analysis.

- A measurement of the relative on-shell and off-shell production provides direct information on Higgs width, assuming coupling ratios unchanged (no new physics).

- NNLO K-factor for the \(gg\rightarrow VV\) process unknown. CMS assumes same NNLO K factor with the signal and adds 10% uncertainty. ATLAS provides the result as a function of the ratio of these two.
$\phi_\tau = 9 \pm 16$ deg. ($\pm 28$ deg.)

Pure CP-odd excluded @ 3.4$\sigma$
Constrain anomalous coupling with differential measurements

- Differential/STXS cross-section measurements could be interpreted to measure the anomalous coupling
- SMEFT approach used for $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, and $H \rightarrow WW$ results

$$L_{\text{SMEFT}}^\text{eff} \supset c_{HG}O'_g + c_{HW}O'_{HW} + c_{HB}O'_{HB} + c_{HWW}O'_{HWW}$$

**CP-even**

**CP-odd**

\(c_{HG}O'_g + c_{HW}\bar{O}'_{HW} + c_{HB}\bar{O}'_{HB} + c_{HWW}\bar{O}'_{HWW}\)

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**ATLAS**

- $H \rightarrow \gamma\gamma$ SWEFT (Interference only), $L = 1 \text{ TeV}$

- $H \rightarrow ZZ \rightarrow 4l$

H→WW  arXiv:2304.03053

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**H→γγ**  JHEP 08 (2022) 027

Higgs-Top CP structure: $H \rightarrow \gamma \gamma$
Higgs-Top CP structure: $H \rightarrow \gamma \gamma$
### ttH/tH Hbb CP measurement

<table>
<thead>
<tr>
<th>Region</th>
<th>Dilepton</th>
<th>( \ell^+ ) jets</th>
<th>( \ell^+ ) jets (TR^{boosted})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TR^{\geq 4j, \geq 4b}</td>
<td>CR^{\geq 4j, \geq 3b}</td>
<td>CR^{\geq 4j, \geq 3b}</td>
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<tr>
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<td>TR^{\geq 6j, \geq 4b}</td>
<td>CR^{\geq 3j, \geq 4b}</td>
<td>CR^{\geq 3j, \geq 4b}</td>
</tr>
<tr>
<td></td>
<td>TR^{boosted}</td>
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</table>

<table>
<thead>
<tr>
<th>( N_{\text{jets}} )</th>
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<tbody>
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</table>

| \( N_{\text{boosted cand.}} \) | \(-\) | \(-\) | \(-\) | \(-\) | \(-\) | \(-\) | \(-\) | \(-\) |

| Fit observable | \(-\) | \(-\) | \(-\) | \(-\) | \(-\) | \(-\) | \(-\) | \(-\) |

<table>
<thead>
<tr>
<th>Channel (TR)</th>
<th>Final SRs and CRs</th>
<th>Classification BDT selection</th>
<th>Fitted observable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton (TR^{\geq 4j, \geq 4b})</td>
<td>CR^{\geq 4j, \geq 4b}</td>
<td>BDT^{\geq 4j, \geq 4b} \in [(-1, -0.086)]</td>
<td>( \Delta \eta_{\ell\ell} ) ( b_4 )</td>
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<tr>
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<td>SR^{\geq 4j, \geq 4b} \text{2}_{\ell\ell}</td>
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<td>\text{b}_4</td>
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<td>( \ell^+ ) jets (TR^{\geq 6j, \geq 4b})</td>
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<td>SR^{\text{boosted}}</td>
<td>BDT^{\text{boosted}} \in [(-0.05, 1)]</td>
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</tr>
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ttH/tH Hbb CP measurement

**ATLAS**

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

Events

- $t\bar{t}$
- $t\bar{t} + 1b$
- $t\bar{t} + \geq 2b$
- $t\bar{t} + \geq 1c$
- Data
- Unc.
- Bkgd+$[t\bar{t}H + tH]$ ($\kappa_t' = 0.84$, $\alpha = 11^\circ$)
- $[t\bar{t}H + tH]$ ($\alpha = 0^\circ$)
- $[t\bar{t}H + tH]$ ($\alpha = 90^\circ$)

1 normalised to total data yield