Scalar sector highlights from the ATLAS experiment

Alan Barr
University of Oxford
On behalf of the ATLAS collaboration

\[ \mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda} \sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O} \left( \frac{1}{\Lambda^3} \right) \]
A much larger dataset

\( \sqrt{s} = 13 \text{ TeV} \)

Delivered: 156 fb\(^{-1}\)
Recorded: 147 fb\(^{-1}\)

Full Run-2 147 fb\(^{-1}\)

[Graph showing total integrated luminosity from January 2015 to July 2018 with green and yellow lines indicating LHC Delivered and ATLAS Recorded data respectively.]
A factory for many things

<table>
<thead>
<tr>
<th>Particle</th>
<th>Produced in 139 fb(^{-1}) at (\sqrt{s} = 13) TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs boson</td>
<td>7.7 million</td>
</tr>
<tr>
<td>Top quark</td>
<td>275 million</td>
</tr>
<tr>
<td>Z boson</td>
<td>2.8 billion ((\rightarrow \ell\ell), 290 million)</td>
</tr>
<tr>
<td>W boson</td>
<td>12 billion ((\rightarrow \ell\nu), 3.7 billion)</td>
</tr>
<tr>
<td>Bottom quark</td>
<td>(~40) trillion (significantly reduced by acceptance)</td>
</tr>
</tbody>
</table>

Andreas Hoecker, EPS-HEP-2019
The “discovery” plots... ...but with all that data
At the cost of lots of pileup

![Graph showing recorded luminosity vs mean number of interactions per crossing for different years: 2015: $\langle \mu \rangle = 13.4$, 2016: $\langle \mu \rangle = 25.1$, 2017: $\langle \mu \rangle = 37.8$, 2018: $\langle \mu \rangle = 36.1$, Total: $\langle \mu \rangle = 33.7$, with ATLAS Online, 13 TeV and $\int L dt = 146.9$ fb$^{-1}$]
Excellent reconstruction is still possible (with innovation)

Example: missing momentum
- Calculate resolution for each visible object
- Find likelihood that the vector sum differs from zero

\[
S^2 = 2 \ln \left( \frac{\mathcal{L}(E_T^{\text{miss}} | E_T^{\text{miss}})}{\mathcal{L}(E_T^{\text{miss}} | o)} \right)
\]

\[
= (E_T^{\text{miss}})^\top \left( \sum_i V^i \right)^{-1} (E_T^{\text{miss}})
\]
Making and breaking them

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} D \psi + \text{h.c.} + \bar{\psi} i D \psi \phi + \text{h.c.} + \partial^2 \phi^2 - V(\phi) \]
As of Scalars 2017

Production

3.5σ evidence

4.2σ
As of Scalars 2017

Decay

- $\mu\mu$: 0.02%
- $\tau\tau$: 6.3%
- $cc$: 2.9%
- $WW^*$: 21.4%
- $gg$: 8.2%
- $Z\gamma$: 0.15%
- $\gamma\gamma$: 0.23%
- $ZZ^*$: 2.6%

$bb$: 58.2%

- $<2.8\times SM$
- $<110\times SM$
- $<6.6\times SM$

$3.5\sigma$

1610.07922
Towards $H \rightarrow bb$

Previously:
b-layer added before Run-2

$1\%-8\%$ uncertainties

b-tagging measured using $tt$ events
VH production and $H \rightarrow bb$ decay both observed

**ATLAS**

$\sqrt{s} = 13$ TeV, 79.8 fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>0.94</td>
<td>+1.30</td>
<td>+0.85, -0.14</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>1.03</td>
<td>-0.54</td>
<td>-0.50, -0.22</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>1.17</td>
<td>+0.27</td>
<td>+0.16, +0.21</td>
</tr>
<tr>
<td>Comb.</td>
<td>5.3σ</td>
<td>+0.24</td>
<td>+0.15, +0.18</td>
</tr>
</tbody>
</table>

**ATLAS**

$\sqrt{s} = 7$ TeV, 8 TeV, and 13 TeV

4.7 fb$^{-1}$, 20.3 fb$^{-1}$, and 24.5-79.8 fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF+ggF</td>
<td>1.68</td>
<td>+1.16</td>
<td>+1.01, +0.57</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>1.00</td>
<td>+0.56</td>
<td>-0.27, -0.46</td>
</tr>
<tr>
<td>VH</td>
<td>0.98</td>
<td>+0.22</td>
<td>+0.14, +0.17</td>
</tr>
<tr>
<td>Comb.</td>
<td>5.4σ</td>
<td>+0.20</td>
<td>+0.12, +0.16</td>
</tr>
</tbody>
</table>

11/09/2019

Scalars 2019
Observation of \( \text{ttH} \) production

Photon identification and diphoton resolution were key

Four different decay modes contributed to \( \text{ttH} \) observation

\( \sigma_{\text{ttH}} / \sigma_{\text{ttH}}^{\text{SM}} \)

11/09/2019 Scalars 2019

6.3 \( \sigma \) observation

1806.00425
Observation of $ttH$ production

$H \rightarrow \gamma\gamma$

4.9$\sigma$ in a single decay channel
Display of a $tt(\rightarrow e+jets) + H(\rightarrow \mu \mu \mu \mu)$ candidate
Summary of some production and decay mode measurements
Probing the small couplings
$H \rightarrow \mu\mu$

$\text{BR}_{\text{SM}} = 2.2 \times 10^{-4}$

Upper limit on the signal strength: $1.7$
(expect 1.3 for the case of no signal)
\textbf{ATLAS Preliminary}

$\sqrt{s} = 13\text{ TeV}, 24.5 - 139\text{ fb}^{-1}$

$m_H = 125.09\text{ GeV}$

$\bar{m}_q(m_H)$ used for quarks

Particle mass [GeV]
Electron modes

$\text{BR}_{\text{SM}} \approx 5 \times 10^{-9}$

$\text{BR} < 3.6 \times 10^{-4}$

$\text{BR}_{\text{SM}} \approx 0$

$\text{BR} < 6.1 \times 10^{-5}$
More flavour-violating modes

Example signal region BDT scores

BR < 0.47%

BR < 0.28%
\[ V(H^\dagger H) = \mu^2 H^\dagger H + \eta (H^\dagger H)^2 \]
\[ \rightarrow \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta}{4} h^4, \]

\textbf{Loop effects}

\textbf{Direct HH searches}
**λHHH self-coupling**

**HH production**

**ATLAS**

\[ \bar{\gamma} = 13 \text{ TeV}, \ 27.5 - 36.1 \text{ fb}^{-1} \]

\[ \sigma_{ggF}^{\text{SM}} (pp \to HH) = 33.5 \text{ fb} \]

<table>
<thead>
<tr>
<th>Final state</th>
<th>Obs.</th>
<th>Exp.</th>
<th>Exp. stat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b\bar{b}+\tau^+\tau^-)</td>
<td>-7.4</td>
<td>-8.9</td>
<td>-7.8</td>
</tr>
<tr>
<td>(b\bar{b}\gamma\gamma)</td>
<td>-8.1</td>
<td>-8.1</td>
<td>-7.9</td>
</tr>
<tr>
<td>Combination</td>
<td>-5.0</td>
<td>-5.8</td>
<td>-5.3</td>
</tr>
</tbody>
</table>

\[ \mathcal{L} = \frac{1}{2} \kappa_\lambda (\hat{c}_\lambda)^2 \]

\[ -3.2 < \kappa_\lambda < 11.9 \]

See also:

- **HH\to bbWW** (139/fb)
  (1908.06765)
- **Φ\to HH \to bbbb (VBF)** 126/fb
  (ATLAS-CONF-2019-030)
Measure measure measure
Differential distributions

\[ p_T \]

\[ m_{jj} \]

\[ n_{jets} \]

\[ \Delta \phi_{jets} \]

11/09/2019

Scalars 2019
### EFT constraints

<table>
<thead>
<tr>
<th>$X^3$</th>
<th>$\varphi^6$ and $\varphi^4D^2$</th>
<th>$\psi^2\varphi^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_G$</td>
<td>$f^{ABC}G^{A\mu}_G G^{B\rho}_G G^{C\mu}_G$</td>
<td>$Q_\varphi$</td>
</tr>
<tr>
<td>$Q_{\bar{G}}$</td>
<td>$f^{ABC}G^{A\mu}_G G^{B\rho}_G G^{C\mu}_G$</td>
<td>$Q_{\bar{q}\varphi}$</td>
</tr>
<tr>
<td>$Q_W$</td>
<td>$\varepsilon^{IJK}W^{I\mu}<em>\mu W^{J\nu}</em>\nu W^{K\rho}_\rho$</td>
<td>$Q_{D\varphi}$</td>
</tr>
<tr>
<td>$Q_{\bar{W}}$</td>
<td>$\varepsilon^{IJK}\bar{W}^{I\mu}<em>\mu W^{J\nu}</em>\nu \bar{W}^{K\rho}_\rho$</td>
<td>$Q_{X^2\varphi^2}$</td>
</tr>
</tbody>
</table>

**Table 2:** Dimension-six operators other than the four-fermion ones.

$$L_{\text{SMEFT}} \supset \bar{C}_{HG} O'_g + \bar{C}_{HW} O'_{HW} + \bar{C}_{HB} O'_{HB} + \bar{C}_{HWB} O'_{HWB} + \tilde{C}_{HG} \tilde{O}'_g + \tilde{C}_{HW} \tilde{O}'_{HW} + \tilde{C}_{HB} \tilde{O}'_{HB} + \tilde{C}_{HWB} \tilde{O}'_{HWB},$$

$$\bar{C}_i \equiv C_i v^2 / \Lambda^2$$

“Warsaw basis”
Figure 10: The effect on the five differential distributions used in the analysis of (a) the CP-even coefficients $\overline{C}_{HG}$, $\overline{C}_{HB}$, $\overline{C}_{HW}$, $\overline{C}_{HWB}$ and (b) the CP-odd coefficients $\tilde{C}_{HG}$, $\tilde{C}_{HB}$, $\tilde{C}_{HW}$, $\tilde{C}_{HWB}$ of the SMEFT effective Lagrangian for values of the coefficients close to the observed limits.
EFT constraints

Table 6: The 95% CL observed limits on the $\tilde{C}_{HG}$, $\tilde{C}_{HW}$, $\tilde{C}_{HB}$, $\tilde{C}_{HWB}$ Wilson coefficients of the SMEFT basis and their CP-odd counterparts using interference-only terms and using both interference and quadratic terms. Limits are derived fitting one Wilson coefficient at a time while setting the other coefficients to zero.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>95% CL, interference-only terms</th>
<th>95% CL, interference and quadratic terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{C}_{HG}$</td>
<td>$[-4.2, 4.8] \times 10^{-4}$</td>
<td>$[-6.1, 4.7] \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tilde{C}_{HG}$</td>
<td>$[-2.1, 1.6] \times 10^{-2}$</td>
<td>$[-1.5, 1.4] \times 10^{-3}$</td>
</tr>
<tr>
<td>$\tilde{C}_{HW}$</td>
<td>$[-8, 2.7.4] \times 10^{-4}$</td>
<td>$[-8.3, 8.3] \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tilde{C}_{HW}$</td>
<td>$[-0.26, 0.33]$</td>
<td>$[-3.7, 3.7] \times 10^{-3}$</td>
</tr>
<tr>
<td>$\tilde{C}_{HB}$</td>
<td>$[-2.4, 2.3] \times 10^{-4}$</td>
<td>$[-2.4, 2.4] \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tilde{C}_{HB}$</td>
<td>$[-13.0, 14.0]$</td>
<td>$[-1.2, 1.1] \times 10^{-3}$</td>
</tr>
<tr>
<td>$\tilde{C}_{HWB}$</td>
<td>$[-4.0, 4.4] \times 10^{-4}$</td>
<td>$[-4.2, 4.2] \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tilde{C}_{HWB}$</td>
<td>$[-11.1, 6.5]$</td>
<td>$[-2.0, 2.0] \times 10^{-3}$</td>
</tr>
</tbody>
</table>
The other scalars?
Extended Higgs sector?

Other BSM Higgs searches (flipped 2HDM, scalar resonances, ...) at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HDBSPublicResults
Scalar leptons?

Difficult due to leptonic WW background, small cross section and low $p_T$ leptons

This region particularly interesting for
- DM relic density
- $g_\mu - 2$

First sensitivity beyond LEP

\[ \Delta m(\bar{\ell}, \bar{\chi}^0_1) \] [GeV]

\[ m(\bar{\ell}_{L,R}) \] [GeV]
First sensitivity to staus

Many more SUSY searches (stops, sbottoms, ...) at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
Long lived scalars

Many more exotic scalar searches (leptoquarks, dark scalars, ...) can be found at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

\[ \Phi \rightarrow s \bar{s} \rightarrow f \bar{f} f' \bar{f}' \]
59 $\gamma \gamma \rightarrow \gamma \gamma$ events observed for
12 $\pm$ 3 expected background (8.2$\sigma$)
Conclusion

• Run-2 data-taking was a great success
• VH and ttH production are now observed
• H → bb decay is now observed
• Second generation couplings getting closer
• Rare and flavour-violating decays being tested
• Differential distributions used to test EFTs
• Searches continue on a broad front

Lots more results at: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
Total width (off-shell measurement)

Constraints on off-shell Higgs boson production and the Higgs boson total width in $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell2\nu$ final states with the ATLAS detector

The ATLAS Collaboration

A measurement of off-shell Higgs boson production in the $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell2\nu$ decay channels, where $\ell$ stands for either an electron or a muon, is performed using data from proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 13\ \text{TeV}$. The data were collected by the ATLAS experiment in 2015 and 2016 at the Large Hadron Collider, and they correspond to an integrated luminosity of 36.1 $\text{fb}^{-1}$. An observed (expected) upper limit on the off-shell Higgs signal strength, defined as the event yield normalised to the Standard Model prediction, of 3.8 (3.4) is obtained at 95% confidence level (CL). Assuming the ratio of the Higgs boson couplings to the Standard Model predictions is independent of the momentum transfer of the Higgs production mechanism considered in the analysis, a combination with the on-shell signal-strength measurements yields an observed (expected) 95% CL upper limit on the Higgs boson total width of $14.4\ (15.2)\ \text{MeV}$.

$\Gamma_{\text{SM}} \approx 4.1\ \text{MeV}$
Higgs $\rightarrow$ invisible

- Interpretation in plane of direct detection cross-section vs WIMP mass

- $\text{BR} < 0.26$

**ATLAS**

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

- $\text{V(had)H}$
- $\text{Z(lep)H}$
- $\text{VBF}$
- $\text{Combined}$

**ATLAS**

$\sqrt{s} = 7 \text{ TeV, } 4.7 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV, } 20.3 \text{ fb}^{-1}$

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

- $B_{H \rightarrow \text{inv}}^{\text{observed}} < 0.24$
- All limits at 90% CL

Higgs portals
- Scalar WIMP
- Fermion WIMP

Other experiments
- Cresst-III
- DarkSide50
- LUX
- PandaX-II
- Xenon1T
The Standard Model Higgs boson decays $H \to J/\psi \gamma$ and $H \to \psi(2S) \gamma$ offer an opportunity to access the $c$-quark Yukawa coupling [15, 16] in a manner complementary to studies of the inclusive decay $H \to c\bar{c}$. The branching fraction for $H \to J/\psi \gamma$ has been calculated within the SM to be $\mathcal{B}(H \to J/\psi \gamma) = (2.99^{+0.12}_{-0.13}) \times 10^{-6}$ [17]. Other recent results on these calculations are given in Refs. [18–20]. For $H \to \psi(2S) \gamma$ the branching fraction was calculated by the authors of Ref. [17] to be $\mathcal{B}(H \to \psi(2S) \gamma) = (1.03 \pm 0.06) \times 10^{-6}$ using an estimate for the value of the order-$v^2$ NRQCD long-distance matrix element.

The corresponding decays in the bottomonium sector, $H \to \Upsilon(1S, 2S, 3S) \gamma$, can provide, in combination with $H \to b\bar{b}$ decays, information about the real and imaginary parts of the $b$-quark coupling to the Higgs boson [19], which could probe potential CP violation in the Higgs sector. However, the expected SM branching fractions, $\mathcal{B}(H \to \Upsilon(nS) \gamma) = (5.22^{+2.02}_{-1.26} 1.32^{+0.72}_{-0.57} 0.91^{+0.48}_{-0.30}) \times 10^{-9} \ (n = 1, 2, 3)$ [17, 18], are smaller due to a cancellation between the “direct” and “indirect” amplitudes. The direct amplitude proceeds through the $H \to q\bar{q}$ coupling with a subsequent photon emission before the $q\bar{q}$ hadronisation to $\Upsilon(nS)$. The indirect amplitude proceeds via the $H\gamma\gamma$ coupling followed by the fragmentation $\gamma \to \Upsilon(nS)$. 

### Branching fraction limit (95% CL)

<table>
<thead>
<tr>
<th>Branching Fraction</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(H \to J/\psi \gamma)$</td>
<td>$10^{-4}$</td>
<td>$3.0^{+1.4}_{-0.8}$</td>
</tr>
<tr>
<td>$\mathcal{B}(H \to \psi(2S) \gamma)$</td>
<td>$10^{-4}$</td>
<td>$15.6^{+7.7}_{-4.4}$</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \to J/\psi \gamma)$</td>
<td>$10^{-6}$</td>
<td>$1.1^{+0.5}_{-0.3}$</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \to \psi(2S) \gamma)$</td>
<td>$10^{-6}$</td>
<td>$6.0^{+2.7}_{-1.7}$</td>
</tr>
<tr>
<td>$\mathcal{B}(H \to \Upsilon(1S) \gamma)$</td>
<td>$10^{-4}$</td>
<td>$5.0^{+2.4}_{-1.4}$</td>
</tr>
<tr>
<td>$\mathcal{B}(H \to \Upsilon(2S) \gamma)$</td>
<td>$10^{-4}$</td>
<td>$6.2^{+3.0}_{-1.4}$</td>
</tr>
<tr>
<td>$\mathcal{B}(H \to \Upsilon(3S) \gamma)$</td>
<td>$10^{-4}$</td>
<td>$5.0^{+2.5}_{-1.4}$</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \to \Upsilon(1S) \gamma)$</td>
<td>$10^{-6}$</td>
<td>$2.8^{+1.2}_{-0.8}$</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \to \Upsilon(2S) \gamma)$</td>
<td>$10^{-6}$</td>
<td>$3.8^{+1.6}_{-1.1}$</td>
</tr>
<tr>
<td>$\mathcal{B}(Z \to \Upsilon(3S) \gamma)$</td>
<td>$10^{-6}$</td>
<td>$3.0^{+1.3}_{-0.8}$</td>
</tr>
</tbody>
</table>
Indirect constraint on charm Yukawa

\[ \text{cc} \rightarrow H \text{ affects } H \ p_T \text{ distribution} \]

\[
\frac{d\sigma_H(\kappa_c)}{d \rho_T^*} = \frac{d\sigma_H^{SM}}{d \rho_T^*}
\]

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Observed 95% CL limit</th>
<th>Expected 95% CL limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \kappa_c )</td>
<td>([-19, 24])</td>
<td>([-15, 19])</td>
</tr>
</tbody>
</table>
VH: $H \rightarrow e\bar{e}\mu\bar{\mu}$ candidate
ATLAS Simulation Preliminary

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

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

Expected Composition

Reconstructed Event Category

- $0j-p_T^{4l}$-Low
- $0j-p_T^{4l}$-Med
- $1j-p_T^{4l}$-Low
- $1j-p_T^{4l}$-Med
- $1j-p_T^{4l}$-High
- $1j-p_T^{4l}$BSM-Like
- $2j$
- $2j$BSM-Like
- $VH$-Lep-enriched
- $0j-p_T^{4l}$High
- $ttH$-Had-enriched
- $ttH$-Lep-enriched

Legend:
- $ggF-0j-p_T^{4l}$-Low
- $ggF-0j-p_T^{4l}$-High
- $VBF-p_T^{4l}$ Low
- $VBF-p_T^{4l}$ High
- $ggF-1j-p_T^{4l}$-Low
- $ggF-1j-p_T^{4l}$-Med
- $ggF-1j-p_T^{4l}$-High
- $ggF-2j$
- $VH$-Had
- $VH$-Lep
- $ttH+tH$
**ATLAS Preliminary**

\[ \sqrt{s} = 13 \text{ TeV}, \ 139 \text{ fb}^{-1} \]

\[ pp \rightarrow \tilde{\ell}_{L,R}^+ \tilde{\ell}_{L,R}^- , \ \tilde{\ell} \rightarrow \ell \chi_1^0 \]

All limits at 95% CL

- Observed limits
- Expected limits

8 TeV, 20.3 fb\(^{-1}\) $\ell \in [\tilde{e}, \tilde{\mu}]$ arXiv:1403.5294

2$\ell$ compressed $\ell \in [\tilde{e}, \tilde{\mu}]$ CONF-2019-014

2$\ell$ $\ell \in [\tilde{e}, \tilde{\mu}]$ CONF-2019-008

2$\tau$ hadronic $\ell = \tilde{\tau}$ CONF-2019-018

LEP $\tilde{\mu}_R$ excluded

July 2019
Figure 12: The observed 68% (green) and 95% (yellow) confidence level regions from the simultaneous fit to the $\bar{c}_{HW}$ and $\tilde{c}_{HW}$ Wilson coefficients of the SILH basis are shown in the left plot (a). The values of $\bar{c}_{HB}$ and $\tilde{c}_{HB}$ are set to be equal to $\bar{c}_{HW}$ and $\tilde{c}_{HW}$, respectively, and all other Wilson coefficients are set to zero. The SM expectation at $(0,0)$ is also shown. The corresponding limits from the simultaneous fit to $\bar{c}_g$ and $\tilde{c}_g$, setting all other Wilson coefficients to zero, are shown in the right plot (b).

Constraints on a different EFT basis (SILH) on two parameters
Search for diboson resonances in hadronic final states in 139 fb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

Narrow resonances decaying into $WW$, $WZ$ or $ZZ$ boson pairs are searched for in 139 fb$^{-1}$ of proton–proton collision data at a centre-of-mass energy of $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the Large Hadron Collider from 2015 to 2018. The diboson system is reconstructed using pairs of high transverse momentum, large-radius jets. These jets are built from a combination of calorimeter- and tracker-inputs compatible with the hadronic decay of a boosted $W$ or $Z$ boson, using jet mass and substructure properties. The search is performed for diboson resonances with masses greater than 1.3 TeV. No significant deviations from the background expectations are observed. Exclusion limits at the 95% confidence level are set on the production cross-section times branching ratio into dibosons for resonances in a range of theories beyond the Standard Model, with the highest excluded mass of a new gauge boson at 3.8 TeV in the context of mass-degenerate resonances that couple predominantly to gauge bosons.
Table 1: Tree-level fermion couplings of the 2HDM $h$, $H$, and $A$ bosons for model types I, II, X (or lepton-specific), and Y (or flipped). Here $U$, $D$, and $E$ refer to up-type quarks, down-type quarks, and charged leptons, respectively, $t_\beta \equiv \tan \beta$ is the ratio of the vacuum expectation values of the two scalar doublets, and $\epsilon = \cos (\beta - \alpha)$ where $\alpha$ is the mixing angle of the two CP-even scalar bosons [9]. The couplings are normalized to the SM Higgs boson couplings $h_{\text{SM}}UU$, $h_{\text{SM}}DD$, and $h_{\text{SM}}EE$ and are given in the alignment limit $\cos (\beta - \alpha) \approx 0$ where the couplings of the light scalar boson $h$ are close to SM expectations.

<table>
<thead>
<tr>
<th></th>
<th>$hUU$</th>
<th>$hDD$</th>
<th>$hEE$</th>
<th>$HUU$</th>
<th>$HDD$</th>
<th>$HEE$</th>
<th>$iA\bar{U}\gamma_5 U$</th>
<th>$iA\bar{D}\gamma_5 D$</th>
<th>$iA\bar{E}\gamma_5 E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$1 + \frac{\epsilon}{t_\beta}$</td>
<td>$1 + \frac{\epsilon}{t_\beta}$</td>
<td>$1 + \frac{\epsilon}{t_\beta}$</td>
<td>$-(\frac{1}{t_\beta} - \epsilon)$</td>
<td>$-(\frac{1}{t_\beta} - \epsilon)$</td>
<td>$-(\frac{1}{t_\beta} - \epsilon)$</td>
<td>$\frac{1}{t_\beta}$</td>
<td>$\frac{1}{t_\beta}$</td>
<td>$\frac{1}{t_\beta}$</td>
</tr>
<tr>
<td>II</td>
<td>$1 + \frac{\epsilon}{t_\beta}$</td>
<td>$1 - \epsilon t_\beta$</td>
<td>$1 - \epsilon t_\beta$</td>
<td>$-(\frac{1}{t_\beta} - \epsilon)$</td>
<td>$t_\beta + \epsilon$</td>
<td>$-\frac{1}{t_\beta}$</td>
<td>$-t_\beta$</td>
<td>$-t_\beta$</td>
<td>$-t_\beta$</td>
</tr>
<tr>
<td>X</td>
<td>$1 + \frac{\epsilon}{t_\beta}$</td>
<td>$1 + \frac{\epsilon}{t_\beta}$</td>
<td>$1 - \epsilon t_\beta$</td>
<td>$-(\frac{1}{t_\beta} - \epsilon)$</td>
<td>$t_\beta + \epsilon$</td>
<td>$-\frac{1}{t_\beta}$</td>
<td>$\frac{1}{t_\beta}$</td>
<td>$-t_\beta$</td>
<td>$-t_\beta$</td>
</tr>
<tr>
<td>Y</td>
<td>$1 + \frac{\epsilon}{t_\beta}$</td>
<td>$1 - \epsilon t_\beta$</td>
<td>$1 + \frac{\epsilon}{t_\beta}$</td>
<td>$-(\frac{1}{t_\beta} - \epsilon)$</td>
<td>$t_\beta + \epsilon$</td>
<td>$-\frac{1}{t_\beta}$</td>
<td>$-t_\beta$</td>
<td>$\frac{1}{t_\beta}$</td>
<td>$\frac{1}{t_\beta}$</td>
</tr>
</tbody>
</table>