Exploring the Higgs boson’s coupling to the charm quark with the ATLAS experiment

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The masses of the charged fermions appear randomly chosen and span several orders of magnitude...

What is the origin of this pattern?

Almost ten years since the discovery of the Higgs boson and verification of the Brout-Englert-Higgs mechanism, are we any closer to fundamentally understanding fermion mass generation?
“Yukawa” couplings between the Higgs ($\phi$) and fermion ($\psi$) fields are possible:

$$\mathcal{L}_{\text{fermion}} = -y_f \cdot [\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \phi \psi_L]$$

If $V(\phi)$ has a non-zero VEV, expansion leads to ($h$ is the physical Higgs field):

$$\mathcal{L}_{\text{fermion}} = -\frac{y_f V}{\sqrt{2}} \cdot \bar{\psi} \psi - \frac{y_f}{\sqrt{2}} \cdot h \bar{\psi} \psi$$

Leads to Higgs–fermion coupling proportional to the fermion mass ($y_f = \sqrt{2}m_f/v$)

- Gauge invariant fermion mass terms in SM ✓
- $y_f$ computed in SM given knowledge of $v$ and $m_f$ ($v = 2M_W/g \approx 246$ GeV from EW observables) ✓
- Offers no fundamental insight into the observed fermion mass hierarchy X

While Yukawa couplings provide concrete predictions for $Hf\bar{f}$ interactions, they fail to describe the fundamental origin of the fermion mass hierarchy...

Physics beyond the SM is clearly required to explain the fermion mass pattern!
Experimental verification of the Yukawa picture

ATLAS and CMS measurements of the Higgs boson confirm couplings to 3rd generation fermions and the muon are consistent with the SM Yukawa expectation.

Given the shortcomings of the Yukawa model, there’s no guarantee the couplings to other fermions will behave in the same way.

Any discrepancy could provide an important insight into the fundamental mechanism behind the fermion mass pattern.

We must endeavour to measure the couplings of the Higgs boson to all of the fermions.

The frontier now lies at the charm quark...

Figure from ATLAS-CONF-2021-053, annotations are my own
Why is the interaction of the Higgs boson with the charm quark interesting?

- The smallness of the SM charm quark Yukawa coupling ($\approx 4 \times 10^{-3}$) make possible modifications from potential new physics easier to spot.

- $H \rightarrow c\bar{c}$ decays constitute one of the largest expected contributions to $\Gamma_H$ for which we have no experimental evidence.

- Some BSM explanations of the fermion mass spectrum could naturally lead to an enhancement of Higgs boson couplings to the 1\textsuperscript{st} and 2\textsuperscript{nd} generation quarks to the level of the SM $b$-quark coupling\textsuperscript{†}.

Confronting the scenario $y_c = y_b^{\text{SM}}$ (around $4.6 \times y_c^{\text{SM}}$) is an important step on the path towards testing the SM prediction!

Several methods to study the $Hc\bar{c}$ coupling have been proposed in the literature, the ATLAS experiment has explored$^\dagger$ three of the most promising with Run 2 data:

**Idea 1 - Exclusive $H \to J/\psi \gamma$ decays**

- The rare radiative decay $H \to J/\psi \gamma$ (with $J/\psi \to \mu^+ \mu^-$) has been proposed as an experimentally clean probe of the $Hc\bar{c}$ coupling [Phys. Rev. D 88 (2013) 053003]

**Idea 2 - Inclusive $H \to c\bar{c}$ decays**

- Manifestly sensitive to the $Hc\bar{c}$ coupling, use $c$-jet tagging to identify decay

**Idea 3 - Charm quark initiated Higgs boson production**

- Contributions to $H +$ jet production such as $gg \to Hg$ (via $c$-quark loop), $gc \to Hc$ and $c\bar{c} \to Hg$ are directly sensitive to the $Hc\bar{c}$ coupling via cross-section and kinematic features (e.g. $p_T^H$) [Phys. Rev. Lett. 118 (2017) 121801]

Other possibilities, not yet investigated by ATLAS:

- $W^\pm H$ charge asymmetry [JHEP 02 (2017) 083]
- Constraints from global combination and limits on $\Gamma_H$ [CERN-2019-007]

The radiative decay $H \rightarrow J/\psi \gamma$ could provide a clean probe of the $Hc\bar{c}$ coupling at the LHC

- **Interference** between direct ($H \rightarrow c\bar{c}$) and indirect ($H \rightarrow \gamma\gamma^*$) contributions
- **Direct** (upper diagram) amplitude provides sensitivity to the magnitude and sign of the $Hc\bar{c}$ coupling
- **Indirect** (lower diagram) amplitude provides dominant contribution to the width, not sensitive to $Hc\bar{c}$ coupling
- Very rare decays in the SM, but rate dominated by indirect component, sensitivity to $Hc\bar{c}$ coupling rather diluted

\[
\Gamma \propto |A_I - A_D \cdot \frac{y_c}{y_{cSM}}|^2
\]
\[
|A_I| \approx 20 \times |A_D|
\]
\[
\mathcal{B}(H \rightarrow J/\psi \gamma) = (3.01 \pm 0.16) \times 10^{-6} \]

ATLAS has performed a search for $H \rightarrow J/\psi \gamma$ with 36 fb$^{-1}$ of 13 TeV pp collision data (analogous $Z$ decays and $\{\psi(2S), \Upsilon(nS)\}$ $\gamma$ channel also considered).

Observed 95% CL limit: $\mathcal{B}(H \rightarrow J/\psi \gamma) < 3.5 \times 10^{-4}$

When the sensitivity is far ($\approx 100 \times$) from the SM prediction, interpreting this branching fraction limit in terms of the $H c \bar{c}$ coupling is a delicate matter†

⚠️ Can be roughly interpreted as a bound of $|y_c/y_c^{\text{SM}}| < \mathcal{O}(100)$ ⚠

Prospects for the $H \rightarrow J/\psi \gamma$ channel in a HL-LHC scenario with $\sqrt{s} = 14$ TeV and $3000 \text{ fb}^{-1}$ were assessed based on a projection of the original ATLAS Run 1 $H \rightarrow J/\psi \gamma$ result [Phys. Rev. Lett. 114 (2015) 121801]

- In addition to the “cut-based” approach used in the Run 1 and 2 analyses, the sensitivity of an MVA-based event selection was considered.

- The MVA-based expected 95% CL branching fraction limit was found to be:
  \[ \mathcal{B}(H \rightarrow J/\psi \gamma) < (44^{+19}_{-12}) \times 10^{-6} \]

- Projected sensitivity remains far ($15 \times$) from SM expectation of $\mathcal{B}(H \rightarrow J/\psi \gamma) \approx 3 \times 10^{-6}$

New ideas likely required to approach SM sensitivity in a HL-LHC scenario with this channel!
Inclusive $H \rightarrow c\bar{c}$ decays are perhaps the most obvious probe of the $Hc\bar{c}$ coupling

- Compared to $H \rightarrow J/\psi \gamma$, a SM branching fraction of 2.9% is huge! Furthermore, the decay width scales directly with $y_c^2$ ✓
- Every 1 fb$^{-1}$ of $\sqrt{s} = 13$ TeV $pp$ collision data contains around 1600 $H \rightarrow c\bar{c}$ decays ✓
- This is still orders of magnitude below the huge multi-jet background at the LHC... X

How can we mitigate the background problem?

- Charm quark initiated jets ($c$-jet) will typically contain a $c$-hadron, while most of the jets produced in LHC $pp$ collisions will not
- Use $c$-jet tagging algorithms to exploit the presence of $c$-hadrons within the jets

What else can we do to help?
Focus on $VH$ production ($V = \{W, Z\}$)

- $V \rightarrow$ leptons offer convenient trigger strategy
- Enhanced $S/B$ w.r.t. inclusive production, particularly at high $p_T^V$

“Tried and Tested” - $VH$ successfully exploited by ATLAS and CMS to observe $H \rightarrow b\bar{b}$ decays!

Combine $c$-tagging and $VH$ production to search for $H \rightarrow c\bar{c}$ decays with ATLAS

- New result extends earlier Run 2 analysis\(^\dagger\) based on $36 \text{ fb}^{-1}$ dataset and $Z(\ell\ell)H(c\bar{c})$ channel alone
- Complete ATLAS Run 2 $\sqrt{s} = 13$ TeV $139 \text{ fb}^{-1} pp$ dataset used
- Both $Z(\ell\ell, \nu\nu)H$ and $W(\ell\nu)H$ production channels considered

\(^\dagger\) Phys. Rev. Lett. 120 (2018) 211802
Strategy closely linked to ATLAS $VH, H \rightarrow b\bar{b}$ analyses and based on 3 channels, each targeting a distinct sub-mode of $VH$ production:

**0 lepton channel**
- Target the $Z(\nu\nu)H(c\bar{c})$ signature with large $E_T^{\text{miss}}$

**1 lepton channel**
- Target the $W(\ell\nu)H(c\bar{c})$ signature with $E_T^{\text{miss}}$ and exactly one $e$ or $\mu$

**2 lepton channel**
- Target the $Z(\ell\ell)H(c\bar{c})$ signature with $e^+e^-$ or $\mu^+\mu^-$

Identify high $p_T^V$ $VH$, $V \rightarrow$ leptons signature in each of these channels, in addition to at least two jets, consistent with $H \rightarrow c\bar{c}$, by means of $c$-jet identification.
**VH, H → c̅c - Design of c-tagging algorithm**

A dedicated flavour tagging working point, optimised for the $VH, H → c̅c$ search, is built from two components:

1) - DL1 (Deep NN) algorithm implemented as a $c$-tagger

2) - MV2c10 (BDT) $b$-tagger implemented as a veto at the 70% $b$-jet efficiency working point

Jets are “c-tagged” if both conditions are passed.

Together with a $b$-tag veto on non-signal jets, this ensures orthogonality of the event selection with the $VH, H → b̅b$ analysis.

For more details on ATLAS flavour tagging algorithms, see:


**“Truth-flavour Tagging”** - To maximise the statistical power of the main background samples, events are weighted by their probability (parameterised by jet $p_T$, $|\eta|$ and $\Delta R_{jj}$) of being $c$-tagged, as opposed to accept/reject based on DL1 and MV2c10 discriminants.
Dedicated measurements of the $c$-tagging efficiency in data:

- Deploy baseline methods also used by ATLAS for $b$-tagging calibration
- Efficiency in data measured relative to simulation as a “scale factor” (SF) with a typical precision of 5 - 10%

**Light flavour jets** - Measured with a sample of $Z + \text{jet}$ events

$c$-jets (upper) and $b$-jets (lower) - Measured with a sample of semi-leptonic and di-leptonic $t\bar{t}$ events, respectively
Monte Carlo (MC) event generators are used to model both the $VH, H \rightarrow c\bar{c}/b\bar{b}$ signal processes and main background processes, normalised to the most accurate cross-section predictions available:

<table>
<thead>
<tr>
<th>Process</th>
<th>ME generator</th>
<th>ME PDF</th>
<th>PS and hadronisation</th>
<th>Tune</th>
<th>Cross-section order</th>
</tr>
</thead>
<tbody>
<tr>
<td>$qq \rightarrow VH$ ($H \rightarrow c\bar{c}/b\bar{b}$)</td>
<td>Powheg-Box v2 + GoSam + MiNLO</td>
<td>NNPDF3.0NLO</td>
<td>Pythia 8.212</td>
<td>AZNLO</td>
<td>NNLO(QCD) + NLO(EW)</td>
</tr>
<tr>
<td>$gg \rightarrow ZH$ ($H \rightarrow c\bar{c}/b\bar{b}$)</td>
<td>Powheg-Box v2</td>
<td>NNPDF3.0NLO</td>
<td>Pythia 8.212</td>
<td>AZNLO</td>
<td>NLO+NLL</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>Powheg-Box v2</td>
<td>NNPDF3.0NLO</td>
<td>Pythia 8.230</td>
<td>A14</td>
<td>NNLO + NNLL</td>
</tr>
<tr>
<td>$t/s$-channel single top</td>
<td>Powheg-Box v2</td>
<td>NNPDF3.0NLO</td>
<td>Pythia 8.230</td>
<td>A14</td>
<td>NLO</td>
</tr>
<tr>
<td>$Wt$-channel single top</td>
<td>Powheg-Box v2</td>
<td>NNPDF3.0NLO</td>
<td>Pythia 8.230</td>
<td>A14</td>
<td>Approx. NNLO</td>
</tr>
<tr>
<td>$V+$jets</td>
<td>Sherpa 2.2.1</td>
<td>NNPDF3.0NNLO</td>
<td>Sherpa 2.2.1</td>
<td>Default</td>
<td>NNLO</td>
</tr>
<tr>
<td>$qq \rightarrow VV$</td>
<td>Sherpa 2.2.1</td>
<td>NNPDF3.0NNLO</td>
<td>Sherpa 2.2.1</td>
<td>Default</td>
<td>NLO</td>
</tr>
<tr>
<td>$gg \rightarrow VV$</td>
<td>Sherpa 2.2.2</td>
<td>NNPDF3.0NNLO</td>
<td>Sherpa 2.2.2</td>
<td>Default</td>
<td>NLO</td>
</tr>
</tbody>
</table>

Generators used are typically NLO and normalised with at least NLO (or higher order) cross-section predictions.
$H \rightarrow c\bar{c}$ candidate selection

- Jets built with anti-$k_T$ ($R = 0.4$) applied to calorimeter clusters
- Any muons within $p_T$ dependent $\Delta R$ cone are used to correct the signal jet 4-vectors (recover energy in semi-leptonic $b/c$-hadron decays)
- At least two central jets required, one with $p_T > 45$ GeV
- Two highest $p_T$ central jets (denoted the signal jets) form the $H \rightarrow c\bar{c}$ candidate
- $p_T^V$-dependent $\Delta R$(jet 1, jet 2) requirement (see table $\rightarrow$)
- All non-signal jets must fail 70% $b$-jet efficiency $b$-tagging working point

Central jets: $|\eta| < 2.5, p_T > 20$ GeV
Forward jets: $2.5 < |\eta| < 4.5, p_T > 30$ GeV

Invariant mass of $H \rightarrow c\bar{c}$ candidate, $m_{cc}$, is primary $S/B$ discriminant

<table>
<thead>
<tr>
<th>$p_T^V$</th>
<th>$\Delta R$(jet 1, jet 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$75 &lt; p_T^V &lt; 150$ GeV</td>
<td>$\leq 2.3$</td>
</tr>
<tr>
<td>$150 &lt; p_T^V &lt; 250$ GeV</td>
<td>$\leq 1.6$</td>
</tr>
<tr>
<td>$p_T^V &gt; 250$ GeV</td>
<td>$\leq 1.2$</td>
</tr>
</tbody>
</table>
Candidate $Z(\nu\nu)H(c\bar{c})$ event with $E_T^{\text{miss}} = 155$ GeV and $m_{cc} = 125$ GeV
Event Selection and Categorisation

- Trigger events with $E_T^{\text{miss}}$ signature
- No leptons with $p_T > 7$ GeV
- $E_T^{\text{miss}} > 150$ GeV
- Requirements on angular variables built from hadronic signatures and $E_T^{\text{miss}}$ to negate multi-jet background

<table>
<thead>
<tr>
<th>Four Signal Regions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 c-tag, 2 jets</td>
<td>2 c-tags, 2 jets</td>
</tr>
<tr>
<td>1 c-tag, 3 jets</td>
<td>2 c-tags, 3 jets</td>
</tr>
</tbody>
</table>

Complicated background dominated by $W$+jets, $Z$+jets and top quark processes, with sub-leading contributions from $VVW$ and $VZ$ production.
Candidate $W(e\nu)H(c\bar{c})$ event with $m^W_T = 62$ GeV and $m_{cc} = 124$ GeV
Event Selection and Categorisation

- Trigger events with single electron or $E_T^{\text{miss}}$ signatures (muon sub-channel)
- Exactly one isolated electron or muon with $p_T > 27 (25)$ GeV
- No further leptons with $p_T > 7$ GeV
- $p_T^W > 150$ GeV
- $m_T^W < 120$ GeV and $E_T^{\text{miss}} > 30$ GeV (electron sub-channel only) to reduce multi-jet background

<table>
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<td>1 c-tag, 2 jets</td>
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</tr>
<tr>
<td>1 c-tag, 3 jets</td>
<td>2 c-tags, 3 jets</td>
</tr>
</tbody>
</table>

Background dominated by $W + \text{jets}$ and top quark processes (primarily $t\bar{t}$ and $Wt$), with sub-leading contributions from $VW$ and $VZ$ production

Small contribution from multijet events modelled with data-driven method
Candidate $Z(\mu^+\mu^-)H(c\bar{c})$ event with $m_{\mu^+\mu^-} = 92$ GeV and $m_{cc} = 123$ GeV
Event Selection and Categorisation

- Trigger events with single electron or single muon signatures
- Exactly two electrons or two muons, with $p_T > 27(7)$ GeV required for the (sub-)leading lepton
- Require consistency with $Z$ boson mass, $81 < m_{\ell\ell} < 101$ GeV
- $p_T^Z > 75$ GeV

<table>
<thead>
<tr>
<th>Eight Signal Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$75 &lt; p_T^Z &lt; 150$ GeV (&quot;low $p_T^Z$&quot;)</td>
</tr>
<tr>
<td>1 c-tag, 2 jets</td>
</tr>
<tr>
<td>1 c-tag, $\geq 3$ jets</td>
</tr>
<tr>
<td>$p_T^Z &gt; 150$ GeV (&quot;high $p_T^Z$&quot;)</td>
</tr>
<tr>
<td>1 c-tag, 2 jets</td>
</tr>
<tr>
<td>1 c-tag, $\geq 3$ jets</td>
</tr>
</tbody>
</table>

Background entirely dominated by $Z+\text{jets}$, with sub-leading contributions from $VW$ and $VZ$ production along with top quark processes in the low $p_T^Z$ categories
The complicated background composition calls for three classes of dedicated control regions (CR) to provide data-driven constraints on background modelling:

1) **Top CRs** to constrain modelling of top quark processes
   - 0/1 lepton - Invert $b$-tag veto in 1 c-tag, 3-jet events
   - 2 lepton - $e^\pm$ $\mu^\mp$ events with 1 c-tag

2) **$\Delta R_{jj}$ CRs** to constrain modelling of the $W/Z$+jets
   - Events with $\Delta R_{jj}$ above nominal selection criteria, up to $\Delta R_{jj} < 2.5$

3) **0 c-tag CRs** to constrain normalisation of $W/Z$+jets light flavour component
   - Events in 1 and 2 lepton channels where neither signal jet is c-tagged and any non-signal jets must fail the $b$-tagging requirement
Binned likelihood fit to the $m_{cc}$ distributions of 16 SRs and 28 CRs used to quantify the presence/absence of a statistically significant $VH, H \rightarrow c\bar{c}$ signal

- Di-boson processes $VW(cq)$ and $VZ(c\bar{c})$ provide in-situ validation channels
- 3 parameters of interest: signal strengths for $VH(c\bar{c})$, $VW(cq)$ and $VZ(c\bar{c})$
- Experimental, signal / background modelling and MC statistical uncertainties implemented as nuisance parameters in the likelihood fit

$\downarrow m_{cc}$ distributions for high purity 2 c-tag, 2 jet categories for 0, 1 and 2 lepton channels $\downarrow$

Categorisation and statistical model designed to maximise constraints from data and minimise reliance on MC simulation for background modelling
Floating background normalisation parameters determine the main background normalisations from the data itself:

- Three separate flavour component parameters each for $W + \text{jets}$ and $Z + \text{jets}$ (six in total)
- Three separate parameters for top quark processes, 0 and 1 lepton (with/without a $b$-quark), 2 lepton

$$hf = \{ bb, cc \}, mf = \{ bl, cl, bc \}, lf = \{ ll, \tau X \}$$

For each signal and background processes, four categories of uncertainty are considered:

- **Cross-section and acceptance uncertainties** (where a floating normalisation parameter is not used)
- **Flavour or process composition uncertainties**
- **Inter-category relative normalisation uncertainties**
- **$m_{cc}$ shape uncertainties**

Each uncertainty is estimated from theory uncertainties associated with cross-section / branching fraction predictions and / or alternative MC generator samples.
VH, H → c ¯c - “Philosophy” of fit model design

0 lepton ↓

1 lepton ↓

- VH, H → c ¯c - “Philosophy” of fit model design
- 2 lepton (low p_T)
- 2 lepton (high p_T)
Post-fit background subtracted $m_{cc}$ distributions for the sum of all SRs help to visualise the sensitivity of the analysis to the three processes of interest:

1 $c$-tag (left) categories drive sensitivity to $VW(cq)$, while the 2 $c$-tag categories (right) provide most sensitivity to $VZ(c\bar{c})$ and $VH(c\bar{c})$.
**VH, H → c\bar{c} - Results of likelihood fit**

- **VW(cq) and VZ(c\bar{c})** signal strength POIs found to be **consistent with SM predictions** → validation of the analysis methodology ✓

- **VH(c\bar{c})** signal strength similarly consistent with zero and unity  
  → **no evidence for signal at the SM rate**

- Probability of compatibility with SM (all 3 POI at unity) found to be **84%**

- Measurements in **individual lepton channels very consistent** with combination

For baseline 3 POI fit, correlations coefficients between the POIs are found to be:  
**VH(c\bar{c})** vs. **VW(cq): +17%**,  
**VH(c\bar{c})** vs. **VZ(c\bar{c}): +16%**,  
**VW(cq) vs. VZ(c\bar{c}): -17%**
The magnitude of statistical and systematic uncertainties are comparable for the \( \text{VH}(c\bar{c}) \) signal strength POI:

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>( \mu_{\text{VH}(c\bar{c})} )</th>
<th>( \mu_{\text{VW}(cq)} )</th>
<th>( \mu_{\text{VZ}(c\bar{c})} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>15.3</td>
<td>0.24</td>
<td>0.48</td>
</tr>
<tr>
<td>Statistical</td>
<td>10.0</td>
<td>0.11</td>
<td>0.32</td>
</tr>
<tr>
<td>Systematic</td>
<td>11.5</td>
<td>0.21</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Statistical uncertainties

- Signal normalisation: 7.8 0.05 0.23
- Other normalisations: 5.1 0.09 0.22

Theoretical and modelling uncertainties

- \( \text{VH}(\rightarrow c\bar{c}) \): 2.1 < 0.01 0.01
- \( \text{Z + jets} \): 7.0 0.05 0.17
- Top quark: 3.9 0.13 0.09
- \( \text{W + jets} \): 3.0 0.05 0.11
- Diboson: 1.0 0.09 0.12
- \( \text{VH}(\rightarrow b\bar{b}) \): 0.8 < 0.01 0.01
- Multi-jet: 1.0 0.03 0.02

Simulation samples size: 4.2 0.09 0.13

Experimental uncertainties

- Jets: 2.8 0.06 0.13
- Leptons: 0.5 0.01 0.01
- \( E_T^{\text{miss}} \): 0.2 0.01 0.01
- Pile-up and luminosity: 0.3 0.01 0.01

Flavour tagging

- \( c\)-jets: 1.6 0.05 0.16
- \( b\)-jets: 1.1 0.01 0.03
- light-jets: 0.4 0.01 0.06
- \( \tau\)-jets: 0.3 0.01 0.04

Flavour tagging

- \( \Delta R \) correction: 3.3 0.03 0.10
- Residual non-closure: 1.7 0.03 0.10

Largest contributions to the total systematic uncertainty for \( \mu_{\text{VH}(c\bar{c})} \) include:

- **Background modelling**, particularly for \( Z + \) jets
- Statistical uncertainty from limited size of MC samples available
- **Truth-flavour tagging** (though use of the method still provides a \( \approx 10\% \) sensitivity gain)

Sensitivity to \( \text{VZ}(c\bar{c}) \) and \( \text{VW}(cq) \) more clearly limited by systematic uncertainties, with hierarchy of contributions similar to that of \( \text{VH}(c\bar{c}) \)
**VH, H → c c̅ - Results**

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

**0+1+2 leptons**

1+2 c-tags, All SR

*Weighted by Higgs S/B*

**ATLAS**

\[\text{Events / 10 GeV (Weighted, B-subtracted)}\]

- Data
- VH→c c̅ (μ=9)
- VZ→c c̅ (μ=1.16)
- VW→c q (μ=0.83)
- B-only uncertainty
- SM VH→c c̅ × 26

**VW(cq) observed (expected) significance 3.8 (4.6)σ**

**VZ(c c̅) observed (expected) significance 2.6 (2.2)σ**

**Observed (expected) CLs limit on \(\mu_{\text{VH}(c\bar{c})}\) is 26 (31^{+12}_{-8}) at 95% CL**
The result is interpreted in terms of the $Hc\bar{c}$ coupling based on the $\kappa$-framework†, inspired by the leading-order contributions to production and decay processes.

- Simple scenario considered where only Higgs boson decay is parameterised in terms of $\kappa_c = y_c/y_c^{SM}$
- All other couplings remain fixed to their SM values, no BSM particle contributions to $\Gamma_H$ considered

✓ Easy to understand × Sensitive to assumptions on the Higgs total width $\Gamma_H$

\[\mu_{VH(\bar{c}c)}(\kappa_c) = 1/B_{H\to c\bar{c}}^{SM}(\kappa_c^2 - 1)\]

\[\lim_{\kappa_c \to 0} \mu_{VH(c\bar{c})}(\kappa_c) = 1/B_{H\to c\bar{c}}^{SM} = 34.6\]

ATLAS

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

$|\kappa_c| < 8.5$ at 95% CL

Observed (expected) constraint of $|\kappa_c| < 8.5$ (12.4) at 95% CL

† For more details, see LHC Higgs Cross Section Working Group Yellow Report 3 and Yellow Report 4
The careful design of the $VH, H \rightarrow c\bar{c}$ flavour tagging strategy allows for a straightforward combination with the ATLAS $VH, H \rightarrow b\bar{b}$ (resolved) analysis.

■ The signal regions of the two analyses are entirely orthogonal

■ A combined analysis allows correlations in the signal strength coupling parameterisations (via $\Gamma_H$ and $\sigma_{VH}$) between the two processes to be exploited

Such a combination has the power to derive more comprehensive and less model-dependent constraints on the $Hc\bar{c}$ and $Hb\bar{b}$ couplings.

For more details on the ATLAS $VH, H \rightarrow b\bar{b}$ (resolved channel) analysis see: Eur. Phys. J. C 81 (2021) 178
At the SM rates, $VH, H \rightarrow b\bar{b}$ contributions to the $VH, H \rightarrow c\bar{c}$ signal regions (left) are $2(8) \times$ the $VH, H \rightarrow c\bar{c}$ contributions in the $2(1)$ c-tag regions.

However, $VH, H \rightarrow c\bar{c}$ contributions to the $VH, H \rightarrow b\bar{b}$ signal regions (right) are very small (note the factor of 1000!)
Combination Procedure

- **Experimental systematic uncertainties** common to both analyses are treated as **correlated** (except $b/c$—tagging, due to differing calibration procedures)

- **Background modelling uncertainties and normalisation parameters** are treated as **uncorrelated** between the two analyses

- The alternative choice of correlating background normalisations was verified to have no impact on the results

**Combined Result**

\[
\mu_{VH(c\bar{c})} = -9 \pm 10 \text{ (stat.)} \pm 11 \text{ (syst.)}
\]

\[
\mu_{VH(b\bar{b})} = 1.06 \pm 0.12 \text{ (stat.)}^{+0.15}_{-0.13} \text{ (syst.)}
\]

- Consistent with results of the individual analyses

- Correlation coefficient between two parameters is -12%
The \( VH(b\bar{b}) \) and \( VH(c\bar{c}) \) signal strengths are parameterised in terms of \( \kappa_b \) and \( \kappa_c \), for both \( VH \) production and Higgs boson decay

- Fix other couplings to SM values, only SM production / decay channels considered

![Diagram](Image)

Expected and observed constraints in the \( \kappa_b \) vs. \( \kappa_c \) plane from combined profile-likelihood scan, best fit value is \( (\kappa_b, \kappa_c) = (-1.02, 0) \)

- Only \( b \)-quark (not \( c \)-quark) loop contributions to \( gg \rightarrow ZH \) parameterised, leading to small likelihood asymmetry in the \( \kappa_b \) direction which is absent for \( \kappa_c \)

- Log-likelihood difference between \( (\kappa_b, \kappa_c) = \{-1.02, +1.02\}, 0 \) is 0.02

For more details on the parameterisation, see ATLAS-CONF-2021-053
The $VH, H \rightarrow b\bar{b}/c\bar{c}$ signal strengths can also be parameterised in terms of the ratio of coupling modifiers $\kappa_{c}/\kappa_{b}$

- Ratio insensitive to $\Gamma_{H}$, no assumptions on decays to BSM particles required
- Profile likelihood scan of the ratio $\kappa_{c}/\kappa_{b}$ is performed, with $\kappa_{b}$ treated as a free parameter →

**Observed (expected) constraint of**

$|\kappa_c/\kappa_b| < 4.5 (5.1)$ at 95% CL

Observed constraint is smaller than the ratio of the $b$-quark and $c$-quark masses

$m_b/m_c = 4.578 \pm 0.008$ [Phys. Rev. D 98 (2018) 054517 (from lattice QCD)]

Experimental confirmation that the Higgs boson’s coupling to the charm quark is weaker than its coupling to the bottom quark!
Prospects for the $VH, H \rightarrow c\bar{c}/b\bar{b}$ analyses at the HL-LHC are assessed based on an extrapolation of the sensitivity of the existing Run 2 analyses:

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>0.5</td>
</tr>
<tr>
<td>Lepton</td>
<td>1</td>
</tr>
<tr>
<td>Jet</td>
<td>1</td>
</tr>
<tr>
<td>Flavour tagging $c$, $b$- and $\tau$-jets</td>
<td>0.5</td>
</tr>
<tr>
<td>Flavour tagging light-jets (MV2c10 in $VH(bb)$)</td>
<td>0.5</td>
</tr>
<tr>
<td>Flavour tagging light-jets (DL1 in $VH(cc)$)</td>
<td>1.0</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.58</td>
</tr>
<tr>
<td>Signal modelling</td>
<td>0.5</td>
</tr>
<tr>
<td>Background modelling</td>
<td>0.5</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0</td>
</tr>
<tr>
<td>Truth-tagging uncertainties ($VH,H \rightarrow c\bar{c}$ only)</td>
<td>0</td>
</tr>
</tbody>
</table>

↑ Extrapolation uncertainty scale factors ↑

- Signal and background event yield predictions scaled from 139 fb$^{-1}$ at $\sqrt{s} = 13$ TeV to 3000 fb$^{-1}$ at $\sqrt{s} = 14$ TeV
- Experimental and theory uncertainties are based on Run 2 values, but scaled to account for reductions in their statistical components and potential improvements in analysis techniques associated with the larger dataset

Event selection, signal/background modelling and statistical analysis remain unchanged with respect to the Run 2 $VH, H \rightarrow c\bar{c}/b\bar{b}$ analyses described earlier
Prospects for HL-LHC - VH, $H \rightarrow c\bar{c}$ analysis

**Expected limit on $VH(c\bar{c})$ signal strength of 6.4 at 95% CL**

Extrapolating to a HL-LHC scenario with 3000 fb$^{-1}$ of $\sqrt{s} = 14$ TeV pp collision data, the existing $VH, H \rightarrow c\bar{c}$ analysis is not expected to reach SM sensitivity

Further innovation required in order to overcome systematic uncertainty limitations and improve sensitivity towards testing the SM prediction for the $Hc\bar{c}$!
Expected signal strength precision:
\[ \mu_{VH(b\bar{b})} = 1.00 \pm 0.06 \]
\[ \mu_{VH(c\bar{c})} = 1.0 \pm 2.0 \text{ (stat.)}^{+2.6}_{-2.5} \text{ (syst.)} \]

ATLAS Preliminary
Projection from Run 2 data
\( \sqrt{s} = 14 \text{ TeV, } 3000 \text{ fb}^{-1} \)
\( VH(\rightarrow b\bar{b}, c\bar{c}) \)

\[ \text{Expected constraint of } |\kappa_c/\kappa_b| < 2.7 \text{ at 95% CL} \]

Extrapolating to a HL-LHC scenario with 3000 fb\(^{-1}\) of \( \sqrt{s} = 14 \text{ TeV pp collision data, the existing } VH, H \rightarrow c\bar{c}/b\bar{b} \text{ analyses fail to test SM prediction for } \kappa_c/\kappa_b \]

⚠️ Assumes no new innovation in analysis design or \( b/c \)-tagging performance ⚠️

Many yet to be exploited opportunities exist, including designing the \( VH, H \rightarrow c\bar{c}/b\bar{b} \text{ analyses in a more complementary manner!} \)
The rate and kinematic features of inclusive Higgs boson production are sensitive to the $HQ\bar{Q}$ ($Q = c, b$) couplings in two main ways (+ many sub-leading effects):

- Loop-induced $gg \rightarrow H(g)$ production
- Quark-initiated production processes, such as $gQ \rightarrow HQ$ and $Q\bar{Q} \rightarrow Hg$
- Modifications to the $HQ\bar{Q}$ couplings will alter the relative contributions of these processes to inclusive Higgs boson production
- Results in changes to cross-section and distortion of $p_T^H$ distribution

Examples of relevant Higgs boson production diagrams involving the $Hc\bar{c}$ coupling

Shape of $p_T^H$ is a relatively clean (exp. and th.) indirect probe of $y_c, b$, but modifications to rate are difficult to factorise from associated changes in $\Gamma_H$
Recently, the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ fiducial differential cross-section measurements based on the complete 139 fb$^{-1}$ ATLAS Run 2 dataset were statistically combined:

- Precision of the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ measurements is comparable.
- Combined measurement of $p_T^H$ remains dominated by statistical uncertainties.
- Compatibility of combined $p_T^H$ measurement with SM prediction is 20%.

**ATLAS-CONF-2022-002**


The individual and combined measurements are compared to a variety of theoretical predictions for $gg \rightarrow H$ production.
Only the measured shape of the $p_T^H$ distribution is interpreted

- This removes assumptions associated with variations in branching fractions caused by $\kappa_b, c$ dependence of $\Gamma_H$

↑ Expected fiducial $p_T^H$ differential cross-section for a variety of $\kappa_c$ and $\kappa_b$ scenarios, with measurements overlaid

- For example, large positive values of $\kappa_c$ would reduce the cross-section at high $p_T^H$, while increasing it at low $p_T^H$ (see $\kappa_c = 20$ scenario shown)
Measurements of $p_T^H$ - Constraint in $\kappa_b$ vs. $\kappa_c$ plane

68% and 95% CL contours from $H \rightarrow ZZ^* \rightarrow 4\ell$, $H \rightarrow \gamma\gamma$ and their combination

![Expected Contours](image)

![Observed Contours](image)

Combined expected constraint more stringent individual channels, though observed combined constraint is typically less stringent than that from $H \rightarrow ZZ^* \rightarrow 4\ell$

- Effect due to data fluctuations in some of the $p_T^H$ bins, differing best fit values and double log-likelihood minimum associated with quadratic dependence of differential cross-section on $\kappa_{b,c}$
Measurements of $p_T^H$ - Constraint on $\kappa_b$

Log-likelihood scans for $\kappa_b$, determined while profiling $\kappa_c$

\[ \downarrow \text{Expected} \downarrow \]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{log_likelihood_scans}
\end{figure}

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Channel & $\kappa_b$ & 95\% Confidence Interval & \\
& Best Fit & Expected & Observed \\
\hline
$H \rightarrow ZZ^*, H \rightarrow 4\ell$ & 1.8 & [-3.6,9.3] & [-1.9,6.3] \\
$H \rightarrow \gamma\gamma$ & 6.1 & [-2.8,8.1] & [-3.7,10.2] \\
Combination & 3.3 & [-2.2,7.4] & [-2.1,7.4] \\
\hline
\end{tabular}
\end{table}

While expected combined constraint is weaker than that from $VH, H \rightarrow b\bar{b}$, it offers complementary sensitivity to the sign of $\kappa_b$. 
Measurements of $p_T^H$ - Constraint on $\kappa_c$

Log-likelihood scans for $\kappa_c$, determined while profiling $\kappa_b$

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\kappa_c$ Best Fit</th>
<th>95% Confidence Interval</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ^*, H \rightarrow \gamma \gamma$</td>
<td>7.9</td>
<td>[-14.2,19.5]</td>
<td>[-9.0,18.5]</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>-0.7</td>
<td>[-12.0,-17.7]</td>
<td>[-14.5,19.1]</td>
<td></td>
</tr>
<tr>
<td>Combination</td>
<td>8.3</td>
<td>[-10.3,16.6]</td>
<td>[-10.1,18.3]</td>
<td></td>
</tr>
</tbody>
</table>

Expected combined constraint comparable to that of $VH, H \rightarrow c\bar{c}$ ($|\kappa_c| < 12.4$), yet subject to different assumptions and sources of uncertainty.
Summary of $\kappa_b$ vs. $\kappa_c$ constraints from ATLAS

Strong complementarity between the observed constraints in the $\kappa_b$ vs. $\kappa_c$ plane from interpretation of $VH, H \to b\bar{b}/c\bar{c}$ signal strengths and measurements of $p_T^H$ from $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$.
ATLAS is exploring the Higgs boson’s coupling to the charm quark in a variety of channels, providing several complementary constraints!

- The combination of the $VH, H \rightarrow b\bar{b}/c\bar{c}$ analyses provide experimental confirmation $Hc\bar{c}$ coupling is weaker than $Hb\bar{b}$ coupling

- Existing analyses, extrapolated to HL-LHC conditions, will probe important BSM scenarios, but likely fall short of testing the SM predictions

Plenty of scope for exciting new developments to meet the challenge of testing the SM prediction and shedding light on the mystery of the fermion masses!
Additional Slides
Summary of $\kappa_b$ vs. $\kappa_c$ constraints from ATLAS

Expected constraints in the $\kappa_b$ vs. $\kappa_c$ plane from interpretation of $VH, H \rightarrow b\bar{b}/c\bar{c}$ signal strengths and measurements of $p_T^H$ from $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$
The ATLAS Detector at the LHC in Run 2

General purpose detector, well suited to studying heavy flavour jets

- **Inner Detector (ID):** Silicon Pixels and Strips (SCT) with Transition Radiation Tracker (TRT) $|\eta| < 2.5$ and (new for Run 2) Insertable B-Layer (IBL)
- **LAr EM Calorimeter:** Highly granular + longitudinally segmented (3-4 layers)
- **Had. Calorimeter:** Plastic scintillator tiles with iron absorber (LAr in fwd. region)
- **Muon Spectrometer (MS):** Triggering $|\eta| < 2.4$ and Precision Tracking $|\eta| < 2.7$
- **Jet Energy Resolution:** Typically $\sigma_E/E \approx 50%/\sqrt{E(\text{GeV})} \oplus 3\%$
- **Track IP Resolution:** $\sigma_{d_0} \approx 60\ \mu\text{m}$ and $\sigma_{z_0} \approx 140\ \mu\text{m}$ for $p_T = 1\ \text{GeV}$ (with IBL)
ATLAS has performed a search for $H \rightarrow J/\psi \gamma$ and $H \rightarrow \psi(2S) \gamma$ decays with 36 fb$^{-1}$ of 13 TeV pp collision data

- Analysis exploits the experimentally clean $\psi(nS) \rightarrow \mu^+ \mu^-$ decay channels
- Dedicated photon + single muon triggers implemented to identify the distinctive event topology

**Photon Selection**

- “Tight” photon ID requirements
- Isolated in both tracker and calorimeter

\[ p_T^\gamma > 35 \text{ GeV} \]

\[ \Delta \phi(\psi, \gamma) > \pi/2 \]

**Di-muon Selection**

- Oppositely charged pair of muons
- Isolated in tracker (accounting for neighboring muon track)
- $L_{xy} / \sigma_{L_{xy}} < 3$ to reject $b \rightarrow \psi(nS)$

\[ p_T^{\mu_{\text{lead}}} > 18 \text{ GeV} \]

\[ p_T^{\mu_{\text{sub-lead}}} > 3 \text{ GeV} \]

(analogous rare $Z$ decays and $\Upsilon(nS) \gamma$ channel also considered)
VH, H → c\bar{c} - Understanding the sensitivity, continued...

\[ \Delta \mu \]

\[ Z^{+}\text{hf SR m}_{\text{W}} \text{ shape med } p_{T}^{\ell} \text{ 2 jet} \]

\[ \text{Top(bq) TopCR extrap. uncertainty} \]

\[ Z^{+}\text{hf m}_{\text{W}} \text{ shape med } p_{T}^{\ell} \text{ 2 jet} \]

\[ \text{Signal strength } \mu_{V_{20x}} \]

\[ \text{Signal strength } \mu_{V_{WQg7}} \]

\[ \text{Top nJet acceptance} \]

\[ W^{+}\text{cc 2 jet TT } dR \text{ uncertainty} \]

\[ Z^{+}\text{cc jet TT med } p_{T}^{\ell} \text{ 2 jet} \]

\[ Z^{+}\text{cc 2 jet TT } dR \text{ uncertainty} \]

\[ \text{stat. 0L SR, 1 tag, 2 jet, bin 7} \]

\[ Z^{+}\text{hf m}_{\text{W}} \text{ shape med } p_{T}^{\ell} \text{ 3 jet} \]

\[ Z^{+}\text{cc 2 jet TT } dR \text{ uncertainty} \]

\[ \text{W+cc 2 jet TT } dR \text{ uncertainty} \]

\[ \text{at } s = 13 \text{ TeV} \]

\[ 139 \text{ fb}^{-1} \]

\[ VH(c\rightarrow cc) \]

\[ \text{Pull}: (\theta - \theta_{0})/\Delta \theta \]

\[ \text{Normalisation} \]

\[ \text{Signal strength} \]

\[ +1\sigma \text{ Postfit Impact on } \mu \]

\[ -1\sigma \text{ Postfit Impact on } \mu \]
### VH, $H \rightarrow c\bar{c} - Floating Normalisation Parameters

<table>
<thead>
<tr>
<th>Background</th>
<th>$p_T^V$</th>
<th>Jets</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top$(b)$</td>
<td></td>
<td>0.91 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>Top(other)</td>
<td></td>
<td>0.94 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$ (2-lepton)</td>
<td>$p_T^V &gt; 150$ GeV</td>
<td>2</td>
<td>0.76 ± 0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.96 ± 0.13</td>
</tr>
<tr>
<td></td>
<td>$75 &lt; p_T^V &lt; 150$ GeV</td>
<td>2</td>
<td>1.08 ± 0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.06 ± 0.07</td>
</tr>
<tr>
<td>$W + hf$</td>
<td></td>
<td>1.16 ± 0.35</td>
<td></td>
</tr>
<tr>
<td>$W + mf$</td>
<td></td>
<td>1.28 ± 0.14</td>
<td></td>
</tr>
<tr>
<td>$W + lf$</td>
<td></td>
<td>2</td>
<td>1.02 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.97 ± 0.05</td>
</tr>
<tr>
<td>$Z + hf$</td>
<td></td>
<td>2</td>
<td>1.19 ± 0.22</td>
</tr>
<tr>
<td></td>
<td>$p_T^V &gt; 150$ GeV</td>
<td>3</td>
<td>1.25 ± 0.25</td>
</tr>
<tr>
<td>$Z + mf$</td>
<td></td>
<td>2</td>
<td>1.10 ± 0.15</td>
</tr>
<tr>
<td></td>
<td>$p_T^V &gt; 150$ GeV</td>
<td>3</td>
<td>1.11 ± 0.15</td>
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<tr>
<td>$Z + lf$</td>
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<td>2</td>
<td>1.07 ± 0.03</td>
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<tr>
<td></td>
<td>$p_T^V &gt; 150$ GeV</td>
<td>3</td>
<td>1.08 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>$75 &lt; p_T^V &lt; 150$ GeV</td>
<td>2</td>
<td>1.12 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.07 ± 0.06</td>
</tr>
</tbody>
</table>
### VH, H → c̅c - Post-fit event composition: 0 lepton

<table>
<thead>
<tr>
<th>Event Category</th>
<th>1 c-tag 2 jets SR</th>
<th>3 jets SR</th>
<th>2 c-tags 2 jets SR</th>
<th>3 jets SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z+lf</td>
<td>14 800 ± 2100</td>
<td>10 800 ± 1700</td>
<td>110 ± 30</td>
<td>81 ± 23</td>
</tr>
<tr>
<td>Z+mf</td>
<td>13 800 ± 1900</td>
<td>11 500 ± 1700</td>
<td>230 ± 40</td>
<td>195 ± 34</td>
</tr>
<tr>
<td>Z+hf</td>
<td>3500 ± 600</td>
<td>2900 ± 500</td>
<td>390 ± 60</td>
<td>370 ± 40</td>
</tr>
<tr>
<td>W+lf</td>
<td>13 700 ± 1700</td>
<td>8 800 ± 1300</td>
<td>125 ± 26</td>
<td>69 ± 18</td>
</tr>
<tr>
<td>W → τν</td>
<td>12 200 ± 1500</td>
<td>12 300 ± 1200</td>
<td>204 ± 31</td>
<td>205 ± 28</td>
</tr>
<tr>
<td>W+hf</td>
<td>1500 ± 400</td>
<td>1400 ± 400</td>
<td>170 ± 50</td>
<td>140 ± 40</td>
</tr>
<tr>
<td>Single top t-channel</td>
<td>163 ± 12</td>
<td>178 ± 18</td>
<td>1.8 ± 1.1</td>
<td>4.3 ± 1.1</td>
</tr>
<tr>
<td>Single top s-channel</td>
<td>22.2 ± 2.7</td>
<td>22 ± 1.9</td>
<td>0.88 ± 0.08</td>
<td>0.67 ± 0.07</td>
</tr>
<tr>
<td>top(b)</td>
<td>2570 ± 210</td>
<td>6 230 ± 3 50</td>
<td>110 ± 10</td>
<td>269 ± 17</td>
</tr>
<tr>
<td>top(other)</td>
<td>1010 ± 110</td>
<td>2300 ± 200</td>
<td>19.2 ± 2.5</td>
<td>44 ± 5</td>
</tr>
<tr>
<td>VZ(→ c̅c)</td>
<td>380 ± 150</td>
<td>200 ± 100</td>
<td>57 ± 22</td>
<td>38 ± 14</td>
</tr>
<tr>
<td>VW(→ cq)</td>
<td>1100 ± 300</td>
<td>1000 ± 270</td>
<td>20 ± 5</td>
<td>19 ± 6</td>
</tr>
<tr>
<td>VV Bkg</td>
<td>740 ± 60</td>
<td>720 ± 70</td>
<td>20.5 ± 2.6</td>
<td>18.9 ± 2.5</td>
</tr>
<tr>
<td>VH(→ b̅b)</td>
<td>57 ± 12</td>
<td>41 ± 8</td>
<td>2.4 ± 0.5</td>
<td>1.6 ± 0.33</td>
</tr>
<tr>
<td>Total background</td>
<td>65 500 ± 280</td>
<td>58 300 ± 250</td>
<td>1468 ± 35</td>
<td>1450 ± 30</td>
</tr>
</tbody>
</table>

### VH, H → c̅c - Post-fit event composition: 1 lepton

<table>
<thead>
<tr>
<th>Event Category</th>
<th>1 lepton, p_T^V &gt; 150</th>
</tr>
</thead>
<tbody>
<tr>
<td>VH(→ c̅c)</td>
<td>−60 ± 110</td>
</tr>
<tr>
<td>VH(→ c̅c) (expected)</td>
<td>8 ± 100</td>
</tr>
<tr>
<td>S/B (expected)</td>
<td>4.06 × 10^{-4}</td>
</tr>
<tr>
<td>Data</td>
<td>65490</td>
</tr>
</tbody>
</table>

\[ S/B (expected) = 4.06 \times 10^{-4} \]
\( \text{VH, } H \rightarrow c \bar{c} \) - Post-fit \( m_{cc} \) distributions: 0 lepton SRs

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, \) 139 fb\(^{-1}\)

0 lepton, 2 jets, 1 c-tag
\( \text{SR, } p_T^{V} \geq 150 \text{ GeV} \)

- **Data**
- **Signal + Background**
- **V2(\( \rightarrow \) c\( \ \bar{c} \)) (\( \mu = 1.16 \))**
- **VW(\( \rightarrow \) c\( \ \bar{c} \)) (\( \mu = 0.83 \))**
- **VV Bkg**
- **top(other)**
- **W+hf**
- **W+mf**
- **W+lf**
- **Z+hf**
- **Z+mf**
- **Z+lf**
- **VH(\( \rightarrow \) b\( \ \bar{b} \))**
- **Uncertainty**

**SM VH(\( \rightarrow \) c\( \ \bar{c} \)) \times 300**

**Events / 10 GeV**

Data/Pred.

**m_{cc} [GeV]**

\( 60 \) \( 80 \) \( 100 \) \( 120 \) \( 140 \) \( 160 \) \( 180 \) \( 200 \)

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, \) 139 fb\(^{-1}\)

0 lepton, 3 jets, 1 c-tag
\( \text{SR, } p_T^{V} \geq 150 \text{ GeV} \)

- **Data**
- **Signal + Background**
- **V2(\( \rightarrow \) c\( \ \bar{c} \)) (\( \mu = 1.16 \))**
- **VW(\( \rightarrow \) c\( \ \bar{c} \)) (\( \mu = 0.83 \))**
- **VV Bkg**
- **top(other)**
- **W+hf**
- **W+mf**
- **W+lf**
- **Z+hf**
- **Z+mf**
- **Z+lf**
- **VH(\( \rightarrow \) b\( \ \bar{b} \))**
- **Uncertainty**

**SM VH(\( \rightarrow \) c\( \ \bar{c} \)) \times 300**

**Events / 10 GeV**

Data/Pred.

**m_{cc} [GeV]**

\( 60 \) \( 80 \) \( 100 \) \( 120 \) \( 140 \) \( 160 \) \( 180 \) \( 200 \)

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, \) 139 fb\(^{-1}\)

0 lepton, 2 jets, 2 c-tags
\( \text{SR, } p_T^{V} \geq 150 \text{ GeV} \)

- **Data**
- **Signal + Background**
- **V2(\( \rightarrow \) c\( \ \bar{c} \)) (\( \mu = 1.16 \))**
- **VW(\( \rightarrow \) c\( \ \bar{c} \)) (\( \mu = 0.83 \))**
- **VV Bkg**
- **top(other)**
- **W+hf**
- **W+mf**
- **W+lf**
- **Z+hf**
- **Z+mf**
- **Z+lf**
- **VH(\( \rightarrow \) b\( \ \bar{b} \))**
- **Uncertainty**

**SM VH(\( \rightarrow \) c\( \ \bar{c} \)) \times 300**

**Events / 10 GeV**

Data/Pred.

**m_{cc} [GeV]**

\( 60 \) \( 80 \) \( 100 \) \( 120 \) \( 140 \) \( 160 \) \( 180 \) \( 200 \)

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, \) 139 fb\(^{-1}\)

0 lepton, 3 jets, 2 c-tags
\( \text{SR, } p_T^{V} \geq 150 \text{ GeV} \)

- **Data**
- **Signal + Background**
- **V2(\( \rightarrow \) c\( \ \bar{c} \)) (\( \mu = 1.16 \))**
- **VW(\( \rightarrow \) c\( \ \bar{c} \)) (\( \mu = 0.83 \))**
- **VV Bkg**
- **top(other)**
- **W+hf**
- **W+mf**
- **W+lf**
- **Z+hf**
- **Z+mf**
- **Z+lf**
- **VH(\( \rightarrow \) b\( \ \bar{b} \))**
- **Uncertainty**

**SM VH(\( \rightarrow \) c\( \ \bar{c} \)) \times 300**

**Events / 10 GeV**

Data/Pred.

**m_{cc} [GeV]**

\( 60 \) \( 80 \) \( 100 \) \( 120 \) \( 140 \) \( 160 \) \( 180 \) \( 200 \)
$VH, H \rightarrow c\bar{c}$ - Post-fit event composition: 1 lepton

<table>
<thead>
<tr>
<th></th>
<th>1 lepton, $p_T^V &gt; 150$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 c-tag</td>
</tr>
<tr>
<td></td>
<td>2 jets SR</td>
</tr>
<tr>
<td>$Z+lf$</td>
<td>1000 ± 100</td>
</tr>
<tr>
<td>$Z+mf$</td>
<td>570 ± 70</td>
</tr>
<tr>
<td>$Z+hf$</td>
<td>132 ± 13</td>
</tr>
<tr>
<td>$W+lf$</td>
<td>22000 ± 4000</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$</td>
<td>38000 ± 4000</td>
</tr>
<tr>
<td>$W+hf$</td>
<td>4300 ± 1200</td>
</tr>
<tr>
<td>Single top $t$-channel</td>
<td>365 ± 32</td>
</tr>
<tr>
<td>Single top $s$-channel</td>
<td>47 ± 4</td>
</tr>
<tr>
<td>top(b)</td>
<td>8400 ± 600</td>
</tr>
<tr>
<td>top(other)</td>
<td>3200 ± 330</td>
</tr>
<tr>
<td>Multi-jet ($\mu$)</td>
<td>1500 ± 800</td>
</tr>
<tr>
<td>Multi-jet ($e$)</td>
<td>900 ± 400</td>
</tr>
<tr>
<td>$VZ(\rightarrow c\bar{c})$</td>
<td>220 ± 90</td>
</tr>
<tr>
<td>$VW(\rightarrow cq)$</td>
<td>1600 ± 400</td>
</tr>
<tr>
<td>$VV$ Bkg</td>
<td>720 ± 70</td>
</tr>
<tr>
<td>$VH(\rightarrow b\bar{b})$</td>
<td>56 ± 14</td>
</tr>
<tr>
<td>Total background</td>
<td>84020 ± 320</td>
</tr>
</tbody>
</table>

$VH(\rightarrow c\bar{c})$ $-60 \pm 110$ $-50 \pm 80$ $-8 \pm 14$ $-10 \pm 10$

$VH(\rightarrow c\bar{c})$ (expected) $7 \pm 100$ $5 \pm 70$ $1 \pm 13$ $1 \pm 9$

$S/B$ (expected) $2.76 \times 10^{-4}$ $1.38 \times 10^{-4}$ $1.59 \times 10^{-3}$ $6.26 \times 10^{-4}$

Data 83947 86316 1897 2277
VH, $H \rightarrow c\bar{c}$ - Post-fit $m_{cc}$ distributions: 1 lepton SRs

![Graphs showing post-fit $m_{cc}$ distributions for different scenarios: 1 lepton, 2 jets, 1 c-tag, and 1 lepton, 3 jets, 2 c-tags.](image-url)

- **Scenario 1:** 1 lepton, 2 jets, 1 c-tag
  - $p_T > 150$ GeV
  - $m_{cc}$ distributions

- **Scenario 2:** 1 lepton, 3 jets, 1 c-tag
  - $p_T > 150$ GeV
  - $m_{cc}$ distributions

- **Scenario 3:** 1 lepton, 3 jets, 2 c-tags
  - $p_T > 150$ GeV
  - $m_{cc}$ distributions

Additional details:
- ATLAS dataset
- 13 TeV, 139 fb$^{-1}$
- Analysis includes top(multi-jet + other), VH(b) and VH(b) with uncertainty.

**Legend:**
- Data
- Signal + Background
- $Z\rightarrow c\bar{c}$ (μ=1.16)
- $W\rightarrow c\bar{c}$ (μ=0.83)
- top (other)
- top (b)
- multi-jet + other
- W+hf
- W+mf
- W+lf
- VH(b)
- Uncertainty
- SM VH(→ cē) > 300

**Significance:**
- Data/Pred. ratio
- Events / 10 GeV
- Values shown in the graphs correspond to the observed data and the predicted distributions under different hypotheses.
## VH, $H \rightarrow c\bar{c}$ - Post-fit event composition: 2 lepton “low $p_T^Z$”

<table>
<thead>
<tr>
<th></th>
<th>2 lepton, $75 &lt; p_T^V &lt; 150$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 c-tag</td>
</tr>
<tr>
<td></td>
<td>2 jets SR</td>
</tr>
<tr>
<td>Z+lf</td>
<td>16 000 ± 4000</td>
</tr>
<tr>
<td>Z+mf</td>
<td>19 000 ± 4000</td>
</tr>
<tr>
<td>Z+hf</td>
<td>5300 ± 800</td>
</tr>
<tr>
<td>W+lf</td>
<td>4.7 ± 1.3</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$</td>
<td>16 ± 11</td>
</tr>
<tr>
<td>W+hf</td>
<td>1.5 ± 0.4</td>
</tr>
<tr>
<td>Single top $Wt$-channel</td>
<td>72 ± 6</td>
</tr>
<tr>
<td>Single top $t$-channel</td>
<td>1.55 ± 0.34</td>
</tr>
<tr>
<td>Single top $s$-channel</td>
<td>0.07 ± 0.03</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>1080 ± 40</td>
</tr>
<tr>
<td>$VZ(\rightarrow c\bar{c})$</td>
<td>200 ± 80</td>
</tr>
<tr>
<td>$VW(\rightarrow cq)$</td>
<td>380 ± 110</td>
</tr>
<tr>
<td>$VV$ Bkg</td>
<td>390 ± 30</td>
</tr>
<tr>
<td>$VH(\rightarrow b\bar{b})$</td>
<td>24 ± 6</td>
</tr>
<tr>
<td>Total background</td>
<td>42 460 ± 220</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>VV Bkg</th>
<th>$VH(\rightarrow c\bar{c})$</th>
<th>$VH(\rightarrow c\bar{c})$ (expected)</th>
<th>$S/B$ (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>390 ± 30</td>
<td>-20 ± 40</td>
<td>-3 ± 5</td>
<td>2.04 × 10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>530 ± 60</td>
<td>-30 ± 50</td>
<td>-3 ± 5</td>
<td>1.58 × 10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>10 ± 1</td>
<td>0.4 ± 5.2</td>
<td>0.3 ± 4.4</td>
<td>1.13 × 10⁻³</td>
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<tr>
<td></td>
<td>13.9 ± 1.9</td>
<td>0.84 ± 0.26</td>
<td>7.73 × 10⁻³</td>
<td></td>
</tr>
</tbody>
</table>

Data

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td></td>
<td>42448</td>
<td>39808</td>
<td>1133</td>
<td>1009</td>
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</table>
$VH, \ H \rightarrow c\bar{c} -$ Post-fit $m_{cc}$ distributions: 2 lepton “low $p_T^Z$” SRs

**ATLAS**

<table>
<thead>
<tr>
<th>$p_T^Z$ Distribution</th>
<th>Events / 10 GeV</th>
<th>Data/Pred.</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.8 &lt; m_{cc} &lt; 1$</td>
<td>600</td>
<td>1.16</td>
<td></td>
</tr>
<tr>
<td>$1 &lt; m_{cc} &lt; 1.2$</td>
<td>800</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>$1.2 &lt; m_{cc} &lt; 1.5$</td>
<td>1000</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>$1.5 &lt; m_{cc} &lt; 2$</td>
<td>1200</td>
<td>0.8</td>
<td></td>
</tr>
</tbody>
</table>

**ATLAS**

<table>
<thead>
<tr>
<th>$p_T^Z$ Distribution</th>
<th>Events / 10 GeV</th>
<th>Data/Pred.</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.8 &lt; m_{cc} &lt; 1$</td>
<td>600</td>
<td>1.16</td>
<td></td>
</tr>
<tr>
<td>$1 &lt; m_{cc} &lt; 1.2$</td>
<td>800</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>$1.2 &lt; m_{cc} &lt; 1.5$</td>
<td>1000</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>$1.5 &lt; m_{cc} &lt; 2$</td>
<td>1200</td>
<td>0.8</td>
<td></td>
</tr>
</tbody>
</table>

**Uncertainty**

- SM $VH \rightarrow c\bar{c}$ × 300
## VH, $H \rightarrow c\bar{c}$ - Post-fit event composition: 2 lepton “high $p_T^Z$”

<table>
<thead>
<tr>
<th>2 lepton, $p_T^V &gt; 150$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 $c$-tag</td>
</tr>
<tr>
<td>2 jets SR</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td><strong>Z+lf</strong></td>
</tr>
<tr>
<td><strong>Z+mf</strong></td>
</tr>
<tr>
<td><strong>Z+hf</strong></td>
</tr>
<tr>
<td><strong>W+lf</strong></td>
</tr>
<tr>
<td><strong>W → τν</strong></td>
</tr>
<tr>
<td><strong>W+hf</strong></td>
</tr>
<tr>
<td>Single top $Wt$-channel</td>
</tr>
<tr>
<td>Single top $t$-channel</td>
</tr>
<tr>
<td>Single top $s$-channel</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
</tr>
<tr>
<td><strong>VZ(→ c\bar{c})</strong></td>
</tr>
<tr>
<td><strong>VW(→ cq)</strong></td>
</tr>
<tr>
<td><strong>VV Bkg</strong></td>
</tr>
<tr>
<td><strong>VH(→ b\bar{b})</strong></td>
</tr>
<tr>
<td>Total background</td>
</tr>
</tbody>
</table>

| VH(→ c\bar{c}) | $-13 ± 22$ | $-18 ± 32$ | $-1.7 ± 3.1$ | $-2 ± 4$ |
| VH(→ c\bar{c}) (expected) | $2 ± 20$ | $2 ± 28$ | $0.2 ± 2.9$ | $0.3 ± 3.4$ |
| S/B (expected)    | $7.11 \times 10^{-4}$ | $4.78 \times 10^{-4}$ | $5.51 \times 10^{-3}$ | $3.36 \times 10^{-3}$ |
| Data              | 7074      | 10812     | 189        | 302       |
**VH, H \rightarrow c\bar{c} - Post-fit m_{cc} distributions: 2 lepton “high \pT” SRs**

Data + Background

Signal + Background

VZ (c\bar{c}) (μ=1.16)

VV (c\bar{c}) (μ=0.83)

VV Bkg

Z+hf

Z+mf

Z+if

t + others

VH (b\bar{d})

Uncertainty

SM VH (c\bar{c}) > 300

Data/Pred.
“The improvements in this analysis relative to the previous ATLAS search for $ZH, H \rightarrow c\bar{c}$ are quantified by performing a fit in the 2-lepton channel to the 2015–2016 data, corresponding to 36 fb$^{-1}$. Using the same signal regions as the previous analysis a 36% improvement in the expected limit is found, with most of the improvement due to better flavour-tagging performance. After also including the new 2-lepton signal and control regions introduced in this analysis, a 43% improvement in the expected limit is found. Adding the full Run-2 dataset, along with the 0- and 1-lepton channels, the expected limit is improved by a factor of five in this analysis, relative to the previous ATLAS search.”

From arXiv:2201.11428
### Source of uncertainty

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\Delta \mu_{ZH}^{bb}$</th>
<th>$\Delta \mu_{WH}^{bb}$</th>
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<tbody>
<tr>
<td>Total</td>
<td>0.070</td>
<td>0.081</td>
</tr>
<tr>
<td>Statistical</td>
<td>0.034</td>
<td>0.039</td>
</tr>
<tr>
<td>Systematics</td>
<td>0.063</td>
<td>0.070</td>
</tr>
</tbody>
</table>

#### Statistical uncertainties

- Data statistics only: 0.031, 0.037
- $t\bar{t} e\mu$ control region: 0.006, 0.003
- Floating normalisations: 0.017, 0.028

#### Theoretical and modelling uncertainties

- Signal: 0.047, 0.031
- $Z$+jets: 0.017, 0.010
- $W$+jets: 0.004, 0.022
- single top: 0.005, 0.012
- $t\bar{t}$: 0.007, 0.017
- Diboson: 0.020, 0.027
- Multi-Jet: $<0.001$, 0.001

#### Experimental uncertainties

- Jets: 0.022, 0.032
- Leptons: 0.006, 0.011
- $E_T^{miss}$: 0.006, 0.005
- Pile-up and luminosity: 0.009, 0.009
  - $b$-jets: 0.018, 0.009
  - $c$-jets: 0.004, 0.035
  - light-jets: 0.006, 0.009

### Source of uncertainty

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\Delta \mu_{VH}^{c\bar{c}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>3.21</td>
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<tr>
<td>Statistical</td>
<td>1.97</td>
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<tr>
<td>Systematics</td>
<td>2.53</td>
</tr>
</tbody>
</table>

#### Statistical uncertainties

- Data statistics only: 1.59
- Floating normalisations: 0.95

#### Theoretical and modelling uncertainties

- $VH, H \rightarrow c\bar{c}$: 0.27
- $Z$+jets: 1.77
- Top-quark: 0.96
- $W$+jets: 0.84
- Diboson: 0.34
- $VH, H \rightarrow b\bar{b}$: 0.29
- Multi-Jet: 0.09

#### Experimental uncertainties

- Jets: 0.59
- Leptons: 0.20
- $E_T^{miss}$: 0.18
- Pile-up and luminosity: 0.19
  - $c$-jets: 0.61
  - $b$-jets: 0.16
  - light-jets: 0.51
  - $\tau$-jets: 0.19
**ATLAS** Preliminary

Projection from Run 2 data

$VH, H \rightarrow b\bar{b}$

$\sqrt{s}=14$ TeV, 3000 fb$^{-1}$

- Exp.
- Tot. unc.
- Stat. unc.

**Source of uncertainty**

<table>
<thead>
<tr>
<th></th>
<th>WH</th>
<th>WH</th>
<th>ZH</th>
<th>ZH</th>
<th>ZH</th>
<th>ZH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{W, t}$ &lt; 250 GeV</td>
<td>0.157</td>
<td>0.085</td>
<td>0.180</td>
<td>0.079</td>
<td>0.077</td>
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<tr>
<td>$p_T^{W, t}$ &gt; 250 GeV</td>
<td>0.068</td>
<td>0.029</td>
<td>0.003</td>
<td>0.005</td>
<td>0.003</td>
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<tr>
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<td>0.043</td>
<td>0.009</td>
<td>0.008</td>
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<td>0.005</td>
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<tr>
<td>Systematics</td>
<td>0.141</td>
<td>0.063</td>
<td>0.150</td>
<td>0.059</td>
<td>0.051</td>
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**Statistical uncertainties**

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<td>0.063</td>
<td>0.054</td>
<td>0.082</td>
<td>0.059</td>
<td>0.056</td>
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<tr>
<td>$tt, e\mu$ control region</td>
<td>0.018</td>
<td>0.004</td>
<td>0.050</td>
<td>0.012</td>
<td>0.004</td>
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<tr>
<td>Floating normalisations</td>
<td>0.063</td>
<td>0.023</td>
<td>0.090</td>
<td>0.030</td>
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**Theoretical and modelling uncertainties**

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<th>ZH</th>
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<tbody>
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<td>Signal</td>
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<td>0.023</td>
<td>0.028</td>
<td>0.036</td>
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<tr>
<td>$Z\nu$+jets</td>
<td>0.023</td>
<td>0.009</td>
<td>0.103</td>
<td>0.019</td>
<td>0.019</td>
<td></td>
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<tr>
<td>$W+\text{jets}$</td>
<td>0.049</td>
<td>0.018</td>
<td>0.021</td>
<td>0.008</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Single top</td>
<td>0.043</td>
<td>0.009</td>
<td>0.015</td>
<td>0.012</td>
<td>0.005</td>
<td></td>
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<tr>
<td>$t\bar{t}$</td>
<td>0.062</td>
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<td>0.024</td>
<td>0.008</td>
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<tr>
<td>Diboson</td>
<td>0.024</td>
<td>0.028</td>
<td>0.038</td>
<td>0.020</td>
<td>0.015</td>
<td></td>
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<tr>
<td>Multi-Jet</td>
<td>0.001 &lt; 0.001</td>
<td>0.001 &lt; 0.001</td>
<td>0.001 &lt; 0.001</td>
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**Experimental uncertainties**

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<td>Leptons</td>
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<td>0.013</td>
<td>0.022</td>
<td>0.005</td>
<td>0.009</td>
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<tr>
<td>$E_T^{miss}$</td>
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<td>0.012</td>
<td>0.058</td>
<td>0.008</td>
<td>0.007</td>
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<tr>
<td>Pile-up and luminosity</td>
<td>0.015</td>
<td>0.011</td>
<td>0.023</td>
<td>0.009</td>
<td>0.09</td>
<td></td>
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<tr>
<td>$b$-jets</td>
<td>0.020</td>
<td>0.008</td>
<td>0.071</td>
<td>0.026</td>
<td>0.010</td>
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<tr>
<td>$c$-jets</td>
<td>0.064</td>
<td>0.029</td>
<td>0.003</td>
<td>0.005</td>
<td>0.003</td>
<td></td>
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<tr>
<td>Light-jets</td>
<td>0.018</td>
<td>0.007</td>
<td>0.007</td>
<td>0.005</td>
<td>0.007</td>
<td></td>
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<td>Production cross section</td>
<td>Loops</td>
<td>Main interference</td>
<td>Effective modifier</td>
<td>Resolved modifier</td>
<td></td>
<td></td>
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<tr>
<td>--------------------------</td>
<td>-------</td>
<td>-------------------</td>
<td>-------------------</td>
<td>------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma(ggF)$</td>
<td>✓</td>
<td>$t-b$</td>
<td>$\kappa_g^2$</td>
<td>1.040 $\kappa_i^2 + 0.002 \kappa_b^2 - 0.038 \kappa_t \kappa_b - 0.005 \kappa_t \kappa_c$</td>
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</tr>
<tr>
<td>$\sigma(VBF)$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.733 $\kappa_W^2 + 0.267 \kappa_Z^2$</td>
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<tr>
<td>$\sigma(qq/gg \rightarrow ZH)$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$\kappa_Z^2$</td>
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<tr>
<td>$\sigma(gg \rightarrow ZH)$</td>
<td>✓</td>
<td>$t-Z$</td>
<td>$\kappa_{(ggZH)}$</td>
<td>$2.456 \kappa_Z^2 + 0.456 \kappa_i^2 - 1.903 \kappa_Z \kappa_t$</td>
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<tr>
<td>$\sigma(WH)$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$\kappa_W^2$</td>
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<tr>
<td>$\sigma(H)$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$\kappa_t^2$</td>
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<tr>
<td>$\sigma(tHW)$</td>
<td>-</td>
<td>$t-W$</td>
<td>-</td>
<td>2.909 $\kappa_t^2 + 2.310 \kappa_W^2 - 4.220 \kappa_t \kappa_W$</td>
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<tr>
<td>$\sigma(tHq)$</td>
<td>-</td>
<td>$t-W$</td>
<td>-</td>
<td>2.633 $\kappa_t^2 + 3.578 \kappa_W^2 - 5.211 \kappa_t \kappa_W$</td>
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<tr>
<td>$\sigma(H)$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$\kappa_b^2$</td>
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<th>Partial decay width</th>
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<tr>
<td>$\Gamma_{bb}^H$</td>
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<tr>
<td>$\Gamma_{WW}^H$</td>
</tr>
<tr>
<td>$\Gamma_{gg}^H$</td>
</tr>
<tr>
<td>$\Gamma_{\tau\tau}^H$</td>
</tr>
<tr>
<td>$\Gamma_{ZZ}^H$</td>
</tr>
<tr>
<td>$\Gamma_{cc}^H$</td>
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<tr>
<td>$\Gamma_{\gamma\gamma}^H$</td>
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<tr>
<td>$\Gamma_{\gamma\gamma}^H$</td>
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<tr>
<td>$\Gamma_{zz}^H$</td>
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<td>$\Gamma_{\mu\mu}^H$</td>
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<table>
<thead>
<tr>
<th>Total width ($B_l = B_u = 0$)</th>
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<tbody>
<tr>
<td>$\Gamma_H$</td>
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Figure from: ATLAS-CONF-2021-053
Measurements of $p_T^H$ - Bin-to-bin correlations

$\gamma\gamma \rightarrow H^*$, $ZZ \rightarrow H$ 
$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

Combination Systematic Uncertainty

Total Uncertainty

MG5 aMC@NLO $K=1.47$, $+XH$

ResBos2 $K=1.14$, $+XH$

SCETlib $K=1$, $+XH$

RadSH $K=1$, $+XH$

NNLOPS $K=1.1$, $+XH$

$XH=VBF+VH+Hb+bH+tH$

$\sigma_0$, $\sigma_1$, $\sigma_2$, $\sigma_3$, $\sigma_4$, $\sigma_5$, $\sigma_6$, $\sigma_7$, $\sigma_8$, $\sigma_9$, $\sigma_{10}$

$H \rightarrow ZZ^*$, $H \rightarrow \gamma\gamma$

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

$\sigma_0$, $\sigma_1$, $\sigma_2$, $\sigma_3$, $\sigma_4$, $\sigma_5$, $\sigma_6$, $\sigma_7$, $\sigma_8$, $\sigma_9$, $\sigma_{10}$

$H \rightarrow ZZ^*$, $H \rightarrow \gamma\gamma$

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
**Measurements of $p_T^H$ - Fiducial region definitions**

### $H \rightarrow \gamma\gamma$

#### Photon and jet definitions

**Photons:** All photons except for those originating from hadron decay
- $p_T > 15$ GeV, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$
- $E_T^{\text{iso}}(\Delta R < 0.2, p_T > 1$ GeV, charged) < 0.05 $E_T$

**Jets:**
- $p_T > 30$ GeV, $|y| < 4.4$

#### Event selection

**Diphoton fiducial:**
- $N_\gamma \geq 2$, $p_T^{\gamma_1} > 0.35m_{\gamma\gamma}$, $p_T^{\gamma_2} > 0.25m_{\gamma\gamma}$

**Mass window:**
- $105$ GeV < $m_{\gamma\gamma}$ < 160 GeV

---

### Lepton and jet definitions

**Leptons**
- Dressed leptons not originating from hadrons or $\tau$ decay
- $p_T > 5$ GeV, $|\eta| < 2.7$

**Jets**
- $p_T > 30$ GeV, $|y| < 4.4$

#### Lepton selection and pairing

**Lepton kinematics**
- $p_T$ threshold for three leading leptons: > 20, 15, 10 GeV

**Leading pair ($m_{12}$)**
- SFOC lepton pair with smallest $|m_Z - m_{\ell\ell}|$

**Subleading pair ($m_{34}$)**
- Remaining SFOC lepton pair with smallest $|m_Z - m_{\ell\ell}|$ as nominal.

#### Event selection (at most one quadruplet per event)

- **Mass requirements**
  - $50$ GeV < $m_{12}$ < 106 GeV and 12 GeV < $m_{34}$ < 115 GeV

- **Lepton separation**
  - $\Delta R(\ell_i, \ell_j) > 0.1$

- **Lepton/Jet separation**
  - $\Delta R(\ell_i, \text{jet}) > 0.1$

- **$J/\psi$ veto**
  - $m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs

- **Mass window**
  - $105$ GeV < $m_{4\ell}$ < 160 GeV

- **If extra lepton with $p_T$ > 12 GeV**
  - Quadruplet with largest ggF matrix element value

---

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