HL-LHC $Z(\ell^+\ell^-)H(c\bar{c})$ Search Prospects

Elliot Reynolds for the ATLAS Collaboration
CERN HE/HL-LHC Workshop, 19/6/18
Run 2 $ZH(c\bar{c})$ Analysis

Phys. Rev. Lett. 120, 211802
Motivation

- $H \rightarrow c\bar{c}$ is SM process with largest Yukawa coupling to lack experimental evidence
- Smallness of $y_c^{SM}$ makes potential new physics more pronounced over small SM rate

Aims

- Use 2015+16 data ($36.1 \text{ fb}^{-1}$) to set direct limit on $Z(\ell\ell)H(c\bar{c})$
- Focus on associated production with $Z(\ell\ell)$
- Analysis strategy very similar to cut-based 2-lepton $VH(b\bar{b})$ analysis
- Pioneer use of new Run 2 c-tagging algorithm

Present Constraints

- Global fits impose $BR(H \rightarrow c\bar{c}) < 20\%$
- $H \rightarrow J/\psi\gamma$ sets limit of $220 \times y_c^{SM}$

†Phys. Rev. D 89, 033014
‡Phys. Rev. Lett. 114, 121801
### Data and Trigger

36.1 fb\(^{-1}\) of 13 TeV data, collected in 2015 and 2016 using single electron/muon triggers

### Z → ℓ⁺ℓ⁻ Selection

- Exactly 2 same flavour leptons (e or μ), passing loose identification, impact parameter and isolation requirements
- Require opposite charges (μ only)
- Both leptons \(p_T > 7\) GeV, with at least one \(p_T > 27\) GeV and \(|\eta| < 2.5\)
- \(81\) GeV < \(m_{\ell\ell}\) < 101 GeV
- \(p_T^{Z} > 75\) GeV

### H → c\(\bar{c}\) Selection

- At least 2 jets with \(|\eta| < 2.5\) and \(p_T > 20\) GeV
- Leading jet \(p_T > 45\) GeV
- \(H \rightarrow c\bar{c}\) candidate formed from two highest \(p_T\) jets
- Dijet \(\Delta R_{c\bar{c}}\) requirement on \(H \rightarrow c\bar{c}\) jets which varies with \(p_T^H\)
- At least one \(H \rightarrow c\bar{c}\) jet c-tagged

### Event Categorisation

Events divided into 4 categories, each with \(H \rightarrow c\bar{c}\) candidates from 1 or 2 c-tagged jets, and \(p_T^{Z}\) above or below 150 GeV
BDT-based discriminant built using low-level $b$-tagging variables
BDTs trained to separate $c$-jets from $b$-jets (x-axes), and from light-jets (y-axes)
Rectangular cuts in 2D discriminant space optimised for analysis
$c$-jet efficiency of 41% for a $b$-jet rejection of 4 and a light-jet rejection of 10
Efficiency calibrated in data
Uncertainties of 5% for $b$-jets, 20% for light-jets, and 25% for $c$-jets
'Truth-tagging', parameterised in $p_T$ and $|\eta|$, applied to simulated events to preserve statistics
**Backgrounds**

- Background dominated by $Z + \text{jets}$ (esp. HF)
- Smaller contributions from $ZZ$, $ZW$ and $t\bar{t}$
- $W + \text{jets}$, $WW$, single-top and multi-jet shown to be negligible ($< 0.5\%$)
- $ZH(b\bar{b})$ treated as a background, and constrained to SM expectation: $1 \pm 0.04$

**Simulation**

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>Parton Shower</th>
<th>Cross-section (QCD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q} \rightarrow ZH$</td>
<td>POWHEG-BOX v2</td>
<td>PYTHIA 8</td>
<td>NNLO</td>
</tr>
<tr>
<td>$gg \rightarrow ZH$</td>
<td>POWHEG-BOX v2</td>
<td>PYTHIA 8</td>
<td>NLO+NLL</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>SHERPA 2.2.1</td>
<td>SHERPA</td>
<td>NNLO</td>
</tr>
<tr>
<td>$ZW, ZZ$</td>
<td>SHERPA 2.2.1</td>
<td>SHERPA</td>
<td>NLO</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>POWHEG-BOX v2</td>
<td>PYTHIA 8</td>
<td>NNLO+NNLL</td>
</tr>
</tbody>
</table>

**Figure:** Phys. Rev. Lett. 120, 211802
Statistical Model Overview

- Simultaneous likelihood fit performed in all 4 event categories
- $m_{c\bar{c}}$ used as observable
- **Signal yield** used as parameter of interest
- $Z +$ jets background normalisation free in fit
- All other background yields constrained to theory expectations
- The $ZV$ production rate was measured to cross-check the analysis methods

Implementation of Systematic Uncertainties

- Uncertainties modelled as nuisance parameters in fit, constrained using auxiliary measurements
- Impact of categories of uncertainty evaluated

**Figure:** Phys. Rev. Lett. 120, 211802
Signal and Background Modelling

- $ZH(c\bar{c}/b\bar{b})$ cross-section uncertainties from YR4†
- Signal $m_{c\bar{c}}$ shape and acceptance uncertainties from alternative parton shower model
- Background cross-section, acceptance and $m_{c\bar{c}}$ shape uncertainties from MC generator comparisons

Experimental Uncertainties

- **Leptons**: Trigger, reconstruction, identification, track to vertex association ($\mu$-only) and isolation scale factor uncertainties; with energy/momentum scale and resolution uncertainties
- **Jets**: Energy scale, resolution, and jet vertex tagging scale factor uncertainties
- **Flavour-Tagging**: Eigen-vector reduction, resulting in 11 NPs for fit
- **Miscellaneous**: Luminosity and pileup reweighting uncertainties

### Table: Phys. Rev. Lett. 120, 211802

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma/\sigma_{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Statistical</strong></td>
<td></td>
</tr>
<tr>
<td>$Z + \text{jets Normalisation}$</td>
<td>49%</td>
</tr>
<tr>
<td><strong>Systematic</strong></td>
<td></td>
</tr>
<tr>
<td>Flavour Tagging</td>
<td>73%</td>
</tr>
<tr>
<td>Background Modelling</td>
<td>47%</td>
</tr>
<tr>
<td>Lepton, Jet and Lumi.</td>
<td>28%</td>
</tr>
<tr>
<td>Signal Modelling</td>
<td>28%</td>
</tr>
<tr>
<td>MC statistical</td>
<td>6%</td>
</tr>
</tbody>
</table>

†arXiv:1610.07922
Results of Run 2 Analysis

- $\hat{\mu}_{ZV}(c\bar{c}) = 0.6^{+0.5}_{-0.4}$
- $\hat{\mu}_{ZH}(c\bar{c}) = -69 \pm 101$
- 95% $CL_s$ upper limit on $\mu_{ZH}(c\bar{c})$ of 110 (Expected: 150), or 2.7 pb (Expected: 3.9 pb)
- Worlds tightest direct constraint on $H \rightarrow c\bar{c}$!

Figure: Phys. Rev. Lett. 120, 211802
HL-LHC Extrapolation

ATL-PHYS-PUB-2018-XYZ (in preparation)
General Strategy

- Expected limit calculated using pre-fit Asimov dataset and stat-only fit from Run 2 analysis
- Expected limit recalculated after scaling all histograms up to expected $3000 \text{ fb}^{-1}$
- Energy increase to 14 TeV accounted for

14 TeV Energy Increase

- Effect of 13 TeV $\rightarrow$ 14 TeV energy increase estimated by scaling inputs
- Higgs process cross sections scaled up by 11%†
- Acceptance corrections applied separately for each $p_T^Z$ category
- $Z + \text{jets}$ background cross sections scaled by $\Sigma q\bar{q}$ parton luminosity ratio of 9%†

†arXiv:1610.07922
Tight Flavour Tagging

- Loose FT WP used for Run-2 analysis due to low signal expectation
- Tight FT WP reconsidered due to:
  - Greater signal statistics
  - Increased sensitivity to kinematically irreducible $ZH(b\bar{b})$ background
- Tight FT WP evaluated by scaling Loose WP processes and categories by relative normalisation SF:
  \[ \frac{n_{Tight}(Sample, Category)}{n_{Loose}(Sample, Category)} \]
- Method assumes any shape effects due to different FT WPs negligible
- Tight FT WP has $c$-jet efficiency of 24\% for $b$-jet and light-jet rejections of 17 and 100, respectively
- Tight FT WP has 46\% signal event efficiency wrt Loose WP for a factor 5.3 better light-jet rejection
- Tight FT WP improved expected limit by 6\%

Figure: Phys. Rev. Lett. 120, 211802
Background Yields

- Z+jets normalisation free in fit (as per Run 2)
- ZHbb allowed to vary within expected HL-LHC ATLAS measurement uncertainty of 14%†
- Diboson and $t\bar{t}$ backgrounds fixed to SM expectation

Table: ATL-PHYS-PUB-2018-XYZ (in preparation)

<table>
<thead>
<tr>
<th>Sample</th>
<th>1 c-tag 75 ≤ $p_T^Z$ &lt; 150 GeV</th>
<th>2 c-tag $p_T^Z$ &gt; 150 GeV</th>
<th>1 c-tag 75 ≤ $p_T^Z$ &lt; 150 GeV</th>
<th>2 c-tag $p_T^Z$ &gt; 150 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z + \text{jets}$</td>
<td>271 000 ± 3200</td>
<td>59 300 ± 690</td>
<td>4350 ± 51</td>
<td>892 ± 10</td>
</tr>
<tr>
<td>$WZ$</td>
<td>3750 ± 190</td>
<td>1570 ± 78</td>
<td>44.5 ± 2.2</td>
<td>27.2 ± 1.4</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>2360 ± 120</td>
<td>934 ± 47</td>
<td>87.9 ± 4.4</td>
<td>86.4 ± 4.3</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>14 200 ± 92</td>
<td>766 ± 5.0</td>
<td>214 ± 1.4</td>
<td>23.3 ± 0.15</td>
</tr>
<tr>
<td>$ZH(b\bar{b})$</td>
<td>441 ± 17</td>
<td>327 ± 12</td>
<td>10.7 ± 0.41</td>
<td>9.38 ± 0.36</td>
</tr>
<tr>
<td>$ZH(c\bar{c})$</td>
<td>74.4 ± 2.8</td>
<td>52.6 ± 2.0</td>
<td>8.54 ± 0.32</td>
<td>6.89 ± 0.26</td>
</tr>
<tr>
<td>Total</td>
<td>291 000 ± 3200</td>
<td>63 000 ± 700</td>
<td>4710 ± 51</td>
<td>1040 ± 11</td>
</tr>
</tbody>
</table>

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$Z(\ell^+\ell^-)H(c\bar{c})$ Prospects

16/4/18
Expected stat-only upper limit of:
\[ \mu_{ZH(c\bar{c})} < 6.3^{+2.5}_{-1.8} \]

Run 2 stat+sys expected upper limit of: \[ \mu_{ZH(c\bar{c})} < 150 \]

Expected best fit value of: \[ \hat{\mu}_{ZH(c\bar{c})} = 1 \pm 3.2 \]

Figure: ATL-PHYS-PUB-2018-XYZ (in preparation)
- All uncertainties based on Run 2 performance

**Table: ATL-PHYS-PUB-2018-XYZ (in preparation)**

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Change in limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background shape</td>
<td>+37%</td>
</tr>
<tr>
<td>$c$-tagging efficiency</td>
<td>+34%</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>+18%</td>
</tr>
<tr>
<td>Lepton reconstruction and identification</td>
<td>+12%</td>
</tr>
</tbody>
</table>

- HL-LHC analysis may use a data-driven background model, removing dominant background modelling uncertainty
- $c$-tagging is dominant component of flavour tagging uncertainty
- ITk is expected to offer improved flavour tagging performance, despite higher pileup
- Jet energy scale and smaller resolution uncertainties will be changed by reduced material in the ITk and increased pileup
Studies into the $b$-tagging performance of the ITk show better light-jet rejection capabilities, despite the higher pileup. These suggest an improvement of a factor of $\sim 2.5$ light-jet rejection. Scaling light-jet rejection by a factor of 2.5 improves expected limit by 10%. The extended coverage will also enable $c$-tagging in the forward region. Room for improvement in $c$-tagging algorithms.

**Figure:** ATLAS Flavour-Tagging Public Plots
Largest Yukawa coupling of any SM decay yet to be measured makes $H \rightarrow c \bar{c}$ a promising Higgs decay channel

Using 36.1 fb$^{-1}$ of data, ATLAS has already set world’s tightest limit at $\mu_{ZH(c \bar{c})} < 110$

300 fb$^{-1}$ expected limit (with systematics): $\mu_{ZH(c \bar{c})} < 31^{+16}_{-9}$

3000 fb$^{-1}$ stat-only expected limit: $\mu_{ZH(c \bar{c})} < 6.3$

Potential 10% improvement in expected limit due to improved flavour tagging performance due to ITk

Potential for further gains through use of:

- Other associated production channels ($Z(\nu \nu)H$ and $W(\ell \nu)H$)
- MVA-based analysis strategy
- Search expected to gain substantially from advances in $c$-tagging algorithms
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Thank you for listening!
Backup Slides

- $c$-tagging efficiencies (Run 2)
- Linear post-fit $m_{c\bar{c}}$ distributions (Run 2)
- Background flavour compositions (Run 2):
  1. $Z + \text{jets}$
  2. Diboson
- Post-fit control distributions (Run 2):
  1. $p_T^Z$
  2. $p_T^{\text{lead jet}}$
  3. $p_T^{\text{sublead jet}}$
**c-Tagging Efficiencies (Run 2)**

Figure: Phys. Rev. Lett. 120, 211802
Data consistent with background-only hypothesis

Best fit signal strength value: $\hat{\mu} = -69^{+73}_{-129}$

Data used to set 95% CL $C_{L_S}$ upper limit on signal strength

Post-fit $Z + \text{jets}$ normalisation parameters between 1.1 and 1.3

**Figure:** Phys. Rev. Lett. 120, 211802
$Z + \text{jets}$ Flavour Composition (Run 2)

1 $c$-tag

2 $c$-tags

Figure: Phys. Rev. Lett. 120, 211802

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Diboson Flavour Composition (Run 2)

1 $c$-tag

\[ \frac{p_T^Z}{\text{GeV}} > 150 \]

\[ \frac{p_T^T}{\text{GeV}} < 150 \]

$75 < \frac{p_T^Z}{\text{GeV}} < 150$

$1 \text{ c-tag}, \ p_T^Z \geq 150 \text{ GeV}$

$1 \text{ c-tag}, \ p_T^Z < 150 \text{ GeV}$

$2 \text{ c-tags}$

\[ \frac{p_T^Z}{\text{GeV}} > 150 \]

\[ \frac{p_T^T}{\text{GeV}} < 150 \]

$75 < \frac{p_T^Z}{\text{GeV}} < 150$

$2 \text{ c-tags}, \ p_T^Z \geq 150 \text{ GeV}$

$2 \text{ c-tags}, \ p_T^Z < 150 \text{ GeV}$

Figure: Phys. Rev. Lett. 120, 211802

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$Z(\ell^+\ell^-)H(c\bar{c})$ Prospects

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**$p_T^Z$ Distributions (Run 2)**

**1 c-tag**

!![](image1)

**2 c-tags**

!![](image2)

Figure: Phys. Rev. Lett. 120, 211802

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$Z(\ell^+\ell^-)H(c\bar{c})$ Prospects  

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**Figure:** Phys. Rev. Lett. 120, 211802
$p_T^{\text{sublead jet}}$ Distributions (Run 2)

$\frac{p_T^Z}{\text{GeV}} > 150$

$\frac{p_T^Z}{\text{GeV}} < 150$

$75 < \frac{p_T^Z}{\text{GeV}} < 150$

Figure: Phys. Rev. Lett. 120, 211802

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