Associated production of $H(b\bar{b},c\bar{c})$ with a $W$ or a $Z$ in ATLAS

Jason Nielsen
Santa Cruz Institute for Particle Physics
University of California, Santa Cruz
On behalf of the ATLAS Collaboration

53$^{rd}$ Rencontres de Moriond — EWK 2018
La Thuile, Valle d’Aosta, Italy
12 March 2018
Introduction and Outline

- Measurement of Hbb (& Hcc) couplings is a long-standing challenge
- Associated Higgs boson production with W or Z vector boson
  - Calculated at NNLO (QCD) + NLO (EW)
  - Clean signature to reject background
  - But 20x smaller cross sect. than gluon fusion

Overview of VH(\(b\bar{b}\)) measurement strategy
- Multivariate event selection and background rejection
- Results for VH(\(b\bar{b}\)) production, and combination with Run-1 data
- Results for benchmark VZ(\(b\bar{b}\)) production
- Search for related ZH(\(c\bar{c}\)) production in 13 TeV data
Measurement Strategy for VH(b\bar{b})

- Capture WH and ZH through 0-, 1-, and 2- charged lepton channels
  - Each channel divided into 2- and 3-jet categories to improve sensitivity
  - Focus on boosted V production: $p_T > 150$ GeV (75 GeV for 2-lepton)
- Tag b-jets to reconstruct Higgs boson candidate
  - Multivariate method based on impact parameter, vertexing, decay length
  - Dedicated b-jet energy corrections for energy losses from muons and neutrinos (plus kinematic fit in 2-lepton)
- Fits to data to determine Higgs vs. non-resonant background
  - Discriminating variable is output of kinematic Boosted Decision Tree
  - Floating normalizations in signal/control region channels and categories
Event Selection & Background Rejection

- **Basic event requirements:**
  - 2 b-tagged jets with $p_T > 20$ GeV (lead jet $p_T > 45$ GeV)
  - Split into 2- and 3-jet samples
  - $E_T^{miss} > 150$ (0-lep), 30 GeV (1-ele)
  - $p_T^V$ ranges vary by channel
    - $p_T^V > 150$ GeV for 0,1-lep
    - $75 > p_T^V > 150$ GeV or $> 150$ GeV for 2-lep
- **Boosted Decision Tree trained in each signal region**
  - Use event-level BDT variables, including $m_{bb}$, in TMVA

### Event kinematic variables used in BDT training

<table>
<thead>
<tr>
<th>Variable</th>
<th>0-lepton</th>
<th>1-lepton</th>
<th>2-lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^V$</td>
<td>$E_T^{miss}$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$E_T^{miss}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$p_{b_1}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$p_{b_2}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$m_{bb}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$\Delta R(\vec{b}_1, \vec{b}_2)$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta(\vec{b}_1, \vec{b}_2)</td>
<td>$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$\Delta \phi(\vec{V}, \vec{bb})$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta(\vec{V}, \vec{bb})</td>
<td>$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$m_{eff}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$\min[\Delta \phi(\vec{\ell}, \vec{b})]$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$m_W$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$m_{top}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta Y(\vec{V}, \vec{bb})</td>
<td>$</td>
<td>$\times$</td>
</tr>
</tbody>
</table>

Only in 3-jet events:

<table>
<thead>
<tr>
<th>Variable</th>
<th>0-lepton</th>
<th>1-lepton</th>
<th>2-lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{jet_3}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$m_{bbj}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
</tbody>
</table>
2-b-tag 2-jet 0-lepton Candidate Event

ATLAS EXPERIMENT

Run: 284213
Event: 1927020336
2015-10-31 04:17:36 CEST
**Strategies for Estimating Background**

- **Background fractions differ between signal regions**
  - Fit templates from simulation to find floating normalization factors, especially for $W/Z+$heavy flavor and $t\bar{t}$ backgrounds

```
<table>
<thead>
<tr>
<th>2-jet</th>
<th>3-jet</th>
<th>Control regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z+HF, \bar{t}t$</td>
<td>$\bar{t}t, Z+HF$</td>
<td>$W+HF$</td>
</tr>
<tr>
<td>$\bar{t}t, W+HF$</td>
<td>$\bar{t}t$</td>
<td>$m_{bb} &lt; 75$</td>
</tr>
<tr>
<td>$Z+HF, \bar{t}t$</td>
<td>$Z+HF, \bar{t}t$</td>
<td>$m_{top} &gt; 225$</td>
</tr>
</tbody>
</table>
```

Combine for $Z+HF$ norm.

Separate to fit all normalization factors.
Example: Z+Heavy Flavor Backgrounds

- Enough data to constrain Z+HF & W+HF separately in 2- & 3-jet events

- Top is constrained in 0- & 1-lep combined, plus separate 2-lep 2- and 3-jet categories

Post-fit results with all normalization factors applied

<table>
<thead>
<tr>
<th>Process</th>
<th>Normalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>W + HF 2-jet</td>
<td>1.22 ± 0.14</td>
</tr>
<tr>
<td>W + HF 3-jet</td>
<td>1.27 ± 0.14</td>
</tr>
<tr>
<td>Z + HF 2-jet</td>
<td>1.30 ± 0.10</td>
</tr>
<tr>
<td>Z + HF 3-jet</td>
<td>1.22 ± 0.09</td>
</tr>
</tbody>
</table>
**VH Measurement Results @ 13 TeV**

- **Overall fitted signal strength** \( \mu = 1.20^{+0.24}_{-0.23} \) (stat.) \( ^{+0.34}_{-0.28} \) (syst.)
  - Observed excess 3.5\( \sigma \) significance (3.0\( \sigma \) expected)

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>VH, H(bb) ( \sqrt{s}=13 \text{ TeV, } 36.1 \text{ fb}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td>Stat.</td>
</tr>
<tr>
<td>0L</td>
<td>( 0.45 \pm 0.53 ) (Total) ( ^{+0.39}<em>{-0.37} ), ( ^{+0.36}</em>{-0.34} ) (Stat., Syst.)</td>
</tr>
<tr>
<td>1L</td>
<td>( 1.43 \pm 0.59 ) (Total) ( ^{+0.40}<em>{-0.38} ), ( ^{+0.56}</em>{-0.45} ) (Stat., Syst.)</td>
</tr>
<tr>
<td>2L</td>
<td>( 1.90 \pm 0.78 ) (Total) ( ^{+0.51}<em>{-0.49} ), ( ^{+0.59}</em>{-0.42} ) (Stat., Syst.)</td>
</tr>
<tr>
<td>Comb.</td>
<td>( 1.20 \pm 0.42 ) (Total) ( ^{+0.24}<em>{-0.23} ), ( ^{+0.34}</em>{-0.28} ) (Stat., Syst.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>VH, H(bb) ( \sqrt{s}=13 \text{ TeV, } 36.1 \text{ fb}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td>Stat.</td>
</tr>
<tr>
<td>WH</td>
<td>( 1.35 \pm 0.68 ) (Total) ( ^{+0.40}<em>{-0.38} ), ( ^{+0.55}</em>{-0.45} ) (Stat., Syst.)</td>
</tr>
<tr>
<td>ZH</td>
<td>( 1.12 \pm 0.50 ) (Total) ( ^{+0.34}<em>{-0.33} ), ( ^{+0.37}</em>{-0.30} ) (Stat., Syst.)</td>
</tr>
<tr>
<td>Comb.</td>
<td>( 1.20 \pm 0.42 ) (Total) ( ^{+0.24}<em>{-0.23} ), ( ^{+0.34}</em>{-0.28} ) (Stat., Syst.)</td>
</tr>
</tbody>
</table>

- **Measurements of WH and ZH rates consistent with SM**
  - \( \sigma(WH) \times B(H \rightarrow b\bar{b}) = 1.08^{+0.54}_{-0.47} \) pb
  - \( \sigma(ZH) \times B(H \rightarrow b\bar{b}) = 0.57^{+0.26}_{-0.23} \) pb

J. Nielsen (Santa Cruz)
Cross-Check Measurement with mbb

- Alternative fit to $m_{bb}$ with tighter selection, more regions
- Irreducible VZ($b\bar{b}$) background kinematically similar to VH

J. Nielsen (Santa Cruz)
VZ Result from Diboson Analysis

- Train a separate BDT$_{VZ}$ adapted for softer $m_{bb}$, $p_T$ spectra
  - In this fit, Higgs VH production is treated as a background!
  - Result is a VZ(bb) measurement with 5.8$\sigma$ significance
  - This is a very good validation of the Higgs boson analysis

In this fit, Higgs VH production is treated as a background!

- Result is a VZ(bb) measurement with 5.8$\sigma$ significance
- This is a very good validation of the Higgs boson analysis
Combined ATLAS VH(b̅b) Results

- **Comparison with 7 & 8 TeV results from LHC Run 1**
  - Use the signal strength $\mu_{VH}$ for different values of $\sqrt{s}$
  - Combined observed significance $3.6\sigma$ ($4.0\sigma$ expected)

- **Consistent with Standard Model, so far...**

J. Nielsen (Santa Cruz)
Focus on Dominant Uncertainties

- **WH and ZH signal acceptance:**
  - Uncertainties in $V p_T$ and $m_{bb}$ due to missing higher orders, PS tune

- **Monte Carlo statistics:**
  - Few events with high-$p_T$, 2-b-tags, and high BDT values

- **Background normalizations**
  - Control of backgrounds will improve with more data in CRs

- **B-tagging efficiency:**
  - MC-to-data correction factors, parameterized in $p_T$, $|\eta|$

Prospects for improvements!

---

From 13 TeV results only

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\sigma_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>0.39</td>
</tr>
<tr>
<td><strong>Statistical</strong></td>
<td>0.24</td>
</tr>
<tr>
<td><strong>Systematic</strong></td>
<td>0.31</td>
</tr>
</tbody>
</table>

**Experimental uncertainties**

- Jets 0.03
- $E_{miss}$ 0.03
- Leptons 0.01

**b-tagging**

- $b$-jets 0.09
- $c$-jets 0.04
- Light jets 0.04
- Extrapolation 0.01

- Pile-up 0.01
- Luminosity 0.04

**Theoretical and modelling uncertainties**

- Signal 0.17

- Floating normalisations 0.07
- $Z +$ jets 0.07
- $W +$ jets 0.07
- $t\bar{t}$ 0.07
- Single top quark 0.08
- Diboson 0.02
- Multijet 0.02

- MC statistical 0.13
Search for $Z\cbar H(c\cbar)$ Production

- **New inclusive approach to constrain $H_{cc}$ coupling**
  - Focus on 2-lepton channel for simpler background composition

- **Dedicated multivariate discriminants similar to b-tagger:**
  - Separate $c$-jets from light-jets and $c$-jets from $b$-jets
  - Challenges of short $\tau_c$, low track multiplicity in $c$-hadron decays
  - Both 1 $c$-tag and 2 $c$-tag events are used to keep efficiency high

ATLAS Simulation
\[ \sqrt{s} = 13 \text{ TeV}, \, \mathbf{t} \mathbf{t} \]

ATLAS Simulation
\[ \sqrt{s} = 13 \text{ TeV}, \, 36.1 \text{ fb}^{-1} \]

$Z + \text{jets}$ Simulation
\[ \sqrt{s} = 13 \text{ TeV}, \geq 50 \text{ GeV} \]

**Dijet Flavour Composition**

\[
\begin{array}{cc}
\text{ll} & \text{cl} \\
\text{cc} & \text{bl} \\
\text{bb} &
\end{array}
\]

J. Nielsen (Santa Cruz)
Results for ZH(c⁻c⁺) and ZZ/ZW

Cut-based event selection with fit to m_{cc}

- **Target c⁻c⁺ resonances**
  - Requirement on ΔR_{cc} varies from 2.2 at low p_T^Z to 1.3 at high p_T^Z (>200 GeV)
  - p_T^Z ranges 75-150, >150 GeV

- **Simultaneous fit of signal and Z+jets background**
  - Flavor tagging uncertainty is dominant limitation on uncert.

Validation: $\mu_{Z\nu} = 0.6^{+0.5}_{-0.4}$
(1.4σ observed, 2.2σ expected)

Observed upper limit of 2.7 pb on $\sigma(ZH) \times B(H \rightarrow c\bar{c})$
(SM predicts 26 fb at 13 TeV)
Summary and Conclusions

- **Updated Run-2 ATLAS evidence for H(bb) in VH production**
  - $3.5\sigma$ observed significance in 13 TeV result: $\sigma(VH) \times BR(bb) = 1.58^{+0.55}_{-0.47}$ pb
  - Combination with Run-1 results: $\mu = 0.90 \pm 0.18$ (stat.$)^{+0.21}_{-0.19}$ (syst.)

- **New ATLAS limit on Higgs ZH production and decay to c\bar{c}**
  - $\sigma \times BR$ limit of 2.7 pb is most stringent yet in direct searches for H(c\bar{c})

- **For further details on the published results:**
  - ZH(c\bar{c}) result with 36.1 fb$^{-1}$ at 13 TeV: [arXiv:1802.04329](https://arxiv.org/abs/1802.04329) (submitted to PRL)

Looking forward to more 13 TeV data and improved measurements