Searching for Higgs boson decays to charm quark pairs with charm jet tagging at ATLAS

Birmingham HEP Seminar

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Andy Chisholm (CERN)
“Yukawa” couplings between the Higgs ($\phi$) and fermion ($\psi$) fields are possible:

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

If $\phi$ has a non-zero VEV, expansion leads to:

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

where $h$ is the physical Higgs boson field...

The End Result:
- Gauge invariant fermion mass terms ✓
- Higgs–fermion coupling proportional to the fermion mass ($g_{Hf\bar{f}} = m_f / v$) ✓

While $y_f$ are still free parameters in the model, $v \approx 246$ GeV is known from electroweak measurements and we know the fermion masses...

We can predict the couplings in the SM!
Why is the charm quark Yukawa coupling important?

- The smallness of the charm ($c$) quark coupling ($y_c = \frac{\sqrt{2}m_c(m_H)}{v} \approx 4 \times 10^{-3}$) make it highly susceptible to modifications from potential new physics.

- $H \rightarrow c \bar{c}$ decays constitute the largest part of the SM prediction for $\Gamma_H$ for which we have no experimental evidence.

- To date, we only have experimental evidence for 3rd generation Yukawa couplings!

What are the existing indirect constraints?

- Constraints on unobserved Higgs decays impose around $\mathcal{B}(H \rightarrow c \bar{c}) < 20\%$, global fits to LHC data indirectly bound $\Gamma_H$ leading to $y_c/y_c^{SM} < 6$, assuming SM Higgs production and no BSM decays (arXiv:1310.7029, arXiv:1503.00290).

- Direct bound of around $\Gamma_H < 1$ GeV from $H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$ lineshapes impose around $y_c/y_c^{SM} < 120$, but this is model independent (arXiv:1503.00290).

How can we constrain these couplings in a more direct way?
Several methods to study the charm quark Yukawa couplings at the LHC have been proposed in the literature, the most promising (in my opinion) are:

**Idea 1 - Exclusive $H \rightarrow J/\psi \gamma$ decays**
- Rare exclusive radiative Higgs boson decays to vector mesons are sensitive to the $Hq\bar{q}$ couplings (arXiv:1503.00290)
- The $H \rightarrow J/\psi \gamma$ decay has been proposed as a clean probe of the charm quark to Yukawa coupling, though decay width “only” evolves as $(\text{const.} + y_c)^2$ (const. $\gg y_c$)
- Both ATLAS and CMS have already begun to search for such decays in LHC Run 1...

**Idea 2 - Associated production of a Higgs boson and charm quark**
- Use jet $c$-tagging to identify charm quark signature and a suitably “clean” Higgs decay (e.g. $H \rightarrow \gamma\gamma$)
- Alternatively, study $p_T^H$ distribution to look for potential shape modifications...

**Idea 3 - Inclusive $H \rightarrow c\bar{c}$ decays** *(The focus of this seminar...)*
- Inclusive $H \rightarrow c\bar{c}$ decays are directly sensitive to the charm quark to Yukawa coupling, with the decay width evolving as $\Gamma_{H\rightarrow c\bar{c}} \propto y_c^2$
- Use double jet $c$-tagging and focus on $VH$ ($V = W, Z$) production with leptonic $V$ decays to mitigate the large multi-jet background
Idea 1 - $H \rightarrow J/\psi \gamma$ Decays

The radiative decay $H \rightarrow J/\psi \gamma$ could provide a clean probe of charm quark Yukawa 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 Yukawa couplings

- Very rare decays in the SM, but rate dominated by “indirect” component, sensitivity to Yukawa coupling somewhat diluted

$$\Gamma = |C_I - C_D \cdot \frac{\gamma_c}{\gamma_{SM}}|^2 \times 10^{-7} \text{ MeV} \quad (C_I \approx 10, C_D \approx 1)$$

$$\mathcal{B}(H \rightarrow J/\psi \gamma) = (2.8 \pm 0.2) \times 10^{-6}$$

First search for such rare Higgs decays was performed by ATLAS with Run 1 dataset

- Studied $H \to J/\psi \gamma$ with $J/\psi \to \mu^+ \mu^-$
- **First direct information** on decay modes sensitive to the $Hc\bar{c}$ coupling
- Similar limit subsequently found by CMS$^\dagger$
- Interpreted as $Hc\bar{c}$ coupling limit of $y_c/y_c^{SM} < 220$ at 95% CL$^\ddagger$ (assuming dependence on $\sigma(pp \to H)/\Gamma_H$ is removed by considering ratio with $H \to 4\ell$ rate)


Run 1 $H \rightarrow J/\psi \gamma$ analysis projected to $\sqrt{s} = 14$ TeV scenario with 300(0) fb$^{-1}$

- Optimistic scenario with MVA analysis still only sensitive to $\mathcal{B}(H \rightarrow J/\psi \gamma)$ at 15×SM value with 3000 fb$^{-1}$

New ideas likely required to reach SM sensitivity in a HL-LHC scenario with this channel!
The production of Higgs boson in association with a charm quark is directly sensitive to the charm quark Yukawa coupling.

- **t-channel diagram (left)** is expected to dominate the cross-section and is sensitive to the Yukawa coupling, highly sensitive channel!
- No experimental measurements yet, though the sensitivity at the HL-LHC has been surveyed in the literature (arXiv:1507.02916)
- Assuming a data sample of $3 \text{ ab}^{-1}$ at $\sqrt{s} = 14$ TeV, $\mathcal{O}(1)$ constraints on $y_c/y_{c}^{SM}$ are expected to be obtained...
In the case of a modified heavy quark $Q = c, b$ Yukawa coupling, the shape of the inclusive $p_T^H$ spectrum would change due to the modified $g_Q \rightarrow HQ$ contribution.

- $p_T^H$ can be measured in the $H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$ channels, which imposes a 95% CL bound of $-16 < y_c / y_c^{SM} < 18$ (arXiv:1606.09253, based on ATLAS+CMS Run 1).

- Projecting to HL-LHC scenario with 3 ab$^{-1}$, bound evolves to $-0.6 < y_c / y_c^{SM} < 3.0$. 

↑ Left: Effect of modified $\kappa_c$ on $p_T^H$ from $cg \rightarrow Hc$ diagrams Right: bounds from Run 1 data (both from arXiv:1606.09253)
Idea 3 - Inclusive $H \rightarrow c\bar{c}$ decays

Motivation

- The branching fraction for $H \rightarrow c\bar{c}$ decays is around 2.9% for a SM Higgs boson with $m_H = 125$ GeV.
- In comparison to the $H \rightarrow J/\psi \gamma$ decay, this is a huge rate! Furthermore, it scales directly with $y_c^2$...
- In $\sqrt{s} = 13$ TeV $pp$ collisions, one expects around 1600 $H \rightarrow c\bar{c}$ decays in every 1 fb$^{-1}$ of data!
- But, how can we hope to separate $H \rightarrow c\bar{c}$ from the HUGE jet background at the LHC?

Strategy

- Charm quark initiated jets ($c$-jet) will typically contain a $c$-hadron, though most of the jets produced in LHC $pp$ collisions will not...
- If we can exploit the presence of a $c$-hadron within the jet, we can hope to separate $c$-jets from light flavour ($u, d, s, g$) and $b$-jets (which also have a unique signature)
- Focus on production channels involving leptons or large $E_T^{\text{miss}}$ (e.g. $Z(\ell\ell, \nu\nu)H$ and/or $W(\ell\nu)H$), to reduce the jet background
Part I - Charm jet tagging with ATLAS

Introduction

- Jets containing either $c$- or $b$-hadrons can be “tagged” by virtue of the unique properties of the heavy flavour hadrons.
- These techniques are collectively known as jet “flavour tagging” and only differ in the fine details if one is interested to “tag” $c$-jets or $b$-jets.
- I will describe how these techniques are implemented within the ATLAS experiment (“flavour tagging” can mean different things to different collider experiments).

Jet Labelling Conventions

- **$b$-jet**: Jets containing a $b$-hadron
- **$c$-jet**: Jets containing a $c$-hadron but no $b$-hadron
- **Light flavour jet**: Jets containing no $b$ or $c$-hadrons (originating from $u, d, s$ quark and gluon fragmentation)
The ATLAS Detector at the LHC

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 $\frac{\sigma_E}{E} \approx 50\% / \sqrt{E(\text{GeV})} \oplus 3\%$
- **Track IP Resolution:** $\sigma_{d_0} \approx 60 \mu m$ and $\sigma_{z_0} \approx 140 \mu m$ for $p_T = 1 \text{ GeV}$ (with IBL)
Properties of $b$-hadrons

- **Lifetime:** Long enough to lead to a measurable decay length (around 5mm for a 50 GeV boost)

- **Mass:** Weakly decaying $b$-hadrons have masses around 5 GeV, leading to high decay product multiplicities (average of 5 charged particles per decay)

- **Fragmentation:** Much harder than jets initiated by other species ($b$-hadrons carry around 75% of jet energy, on average)

**Left:** Mean charged multiplicity in $B^+$ mesons decays

**Right:** $b$-quark fragmentation function
Properties of $c$-hadrons

- **Lifetime:** Shorter than the $b$-hadrons by around a factor of 2-3, still enough for measurable decay length (around 1-3mm for a 50 GeV boost)

- **Mass:** Weakly decaying $c$-hadrons have masses around 2 GeV, around 2–3$\times$ lower than $b$-hadrons (mean of $\approx$ 2 charged particles per decay)

- **Fragmentation:** Softer than $b$-jets, but still harder than jets initiated by light species ($c$-hadrons carry around 55% of jet energy, on average)

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**Left:** Mean charged multiplicity in $D^+$ mesons decays

**Right:** $c$-quark fragmentation function
Anatomy of a light flavour ($u, d, s$) jet

Typical Experimental Signature

- Light-quarks hadronise into many light hadrons which share the jet energy
- Tracks from this vertex often have impact parameters consistent with zero
- Long-lived light hadrons (e.g. $K_S^0, \Lambda^0$) can be produced, though they are more likely to decay very far (many cm) from the primary $pp$ vertex
Anatomy of a $c$-jet

Typical Experimental Signature

- $c$-quark fragments into a $c$-hadron which carries around half of the jet energy
- $c$-hadron decay vertex often displaced from the primary $pp$ vertex by a few mm
- Tracks from this vertex can often have large impact parameters
Typical Experimental Signature

- $b$-quark fragments into a $b$-hadron which carries most of the jet energy
- Most $b$-hadrons ($\approx 90\%$) decay into $c$-hadrons
- $b$-hadron decay vertex often displaced from the primary $pp$ vertex by a few mm
- Subsequent $c$-hadron decay vertex often displaced by a further few mm
- Tracks from both of these vertices often have large impact parameters
Introduction to charm jet tagging

Charm tagging is not new, many experiments at high energy ($\sqrt{s} \gg m_{B\bar{B}}$) colliders (e.g. SpPpS, Tevatron, SLD, LEP, HERA) have built “charm taggers” which tend to fall within the following classes:

“Exclusive” charm jet tagging

- Focus on the full reconstruction of exclusive $c$-hadron decay chains (e.g. $D^{*\pm} \rightarrow D^0(K^-\pi^+)\pi^{\pm}$) or leptons from semi-leptonic $c$-hadron decays
- ✓ Can often provide a very pure sample of jets containing $c$-hadrons
- ✗ The efficiency is typically low $\mathcal{O}(1\%)$, limited by the $c$-hadron branching fractions of interest

“Inclusive” charm jet tagging

- An alternative approach is to exploit more “inclusive” observables, such as track impact parameters or secondary vertices
- ✓ The efficiency of this approach is typically very high $\mathcal{O}(10\%)$
- ✗ The $c$-jet purity is often lower than these “traditional” approaches
- More suited for use with machine learning (ML) techniques

**ATLAS** have developed an “inclusive” $c$-tagging algorithm based on several “low level” taggers combined into a “high level” tagger using ML techniques
The signed IPs of tracks associated to jets are powerful jet flavour discriminants:

- Exploit “sign” of impact parameter: positive if track point of closest approach to PV is downstream of plane defined by the PV and jet axis
- Tracks from $b$-hadrons tend to have highly significant ($IP/\sigma_{IP}$) positive IPs, while most tracks from the PV have a narrow, symmetric distribution
- ✓ Very inclusive and highly efficient
- X Relies upon accurate measurement of jet axis, sensitive to “mis-tag” high IP tracks from $V^0$ decays or material interactions, $IP/\sigma_{IP}$ difficult to model in detector simulation

![Graphs showing track signed d0 significance distribution and likelihood ratio discriminant based on 3D IPs of tracks](image-url)
Exploit expectation of a secondary vertex from either $b$ or $c$-hadron decays:

- Attempt to reconstruct a secondary vertex from high IP tracks associated with jet
- Use invariant mass of tracks at SV to discriminate $b$ or $c$-hadron decay vertices from $V^0$ decays or material interactions
- Exploit hard $c/b$-jet fragmentation, SV should carry a large fraction of jet energy
- ✓ SV found in up to $\approx 80\%$ of $b$-jets but only a few % of light flavour jets
- ✗ Degraded light jet rejection as jet $p_T$ increases, careful considerations to mitigate “tagging” of material interactions required

**Left:** Inv. mass of tracks at SV  
**Centre:** 3D SV decay length significance  
**Right:** Energy fraction of SV tracks
Exploit common occurrence of cascade decay chain; $b$-hadron $\rightarrow$ $c$-hadron:

- Use Kalman filter to search for common axis on which three vertices lie: primary ($pp$) $\rightarrow$ secondary ($b$-hadron) $\rightarrow$ tertiary ($c$-hadron)
- Can then look for “1 track vertices” with decay chain axis
- ✓ Addition of 1 track vertices improves efficiency, constraint to decay chain axis improves separation power of SV based discriminants
- ✗ Degraded performance for $c/b$-hadron vertices as jet $p_T$ increases, high fake rate for 1 track vertices (increases light jet “mis-tag” rate)
Combine approaches to exploit all features of $c/b$-jets and mitigate the shortcomings of the individual methods:

- ✓ Benefit from the advantages of all basic techniques/algorithms
- ✗ Complex sensitivity to convolution of all detector and physics modelling issues relies strongly on “calibration” in data (see next slide)
- Use the output of the three basic approaches as input to a boosted decision tree (BDT) to build two discriminants, one trained to separate $c$-jets from $b$-jets ($x$-axis), another to separate $c$-jets from light-jets ($y$-axis)

“$c$-tag” jets by making a cut in the 2D discriminant space, working point optimised for $H \rightarrow c\bar{c}$ is shown in the rectangular selection (shaded region rejected)
Performance of the ATLAS $c$-tagger

Efficiency of $c$-tagging algorithm for $b$-, $c$- and light flavour ($u$, $d$, $s$, $g$) jets measured in data ↑

- Working point for $H \rightarrow c \bar{c}$ exhibits a $c$-jet tagging efficiency of around 40%.
- Rejects $b$-jets by around a factor $4 \times$ and light jets by around a factor $10 \times$.
- Efficiency calibrated in data with samples of $b$-jets from $t \rightarrow Wb$ decays and $c$-jets from $W \rightarrow cs, cd$ decays (in $t \bar{t}$ events).
- Typical total relative uncertainties of around 25%, 5% and 20% for $c$-, $b$- and light jets, respectively.
How can we use the “charm tagger” to search for $H \rightarrow c\bar{c}$ decays?
Search for $H \rightarrow c\bar{c}$ with $pp \rightarrow ZH$ production

Given the success of the $W/Z$ associated production channel in providing evidence for $H \rightarrow b\bar{b}$ decays$^\dagger$, this channel is an obvious first candidate for a $H \rightarrow c\bar{c}$ search.

- Focus on $ZH$ production with $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ decays for first ATLAS analysis (ATLAS-CONF-2017-078)
- Low exposure to experimental uncertainties, main backgrounds from $Z + \text{jets}$, $Z(W/Z)$ and $t\bar{t}$
- Pioneer use of new $c$-tagging algorithm developed by ATLAS for Run 2 to identify the experimental signature of an inclusive $H \rightarrow c\bar{c}$ decay

In $\sqrt{s} = 13$ TeV $pp$ collisions, Higgs boson production in association with a $Z$ boson represents around 1.6% of the inclusive Higgs boson production rate

- The cross-section is dominated by the $q\bar{q} \rightarrow ZH$ process, with total cross-section $\sigma_{q\bar{q}} \approx 0.76$ pb
- Smaller contributions from $gg \rightarrow ZH$, with total cross-section $\sigma_{gg} \approx 0.12$ pb, though it exhibits a harder $p_T^H$ spectrum below $\approx 150$ GeV
Use a $\sqrt{s} = 13$ TeV $pp$ collision sample collected during 2015 and 2016 corresponding to an integrated luminosity of 36.1 fb$^{-1}$

**Z $\rightarrow \ell^+\ell^-$ Selection**
- Trigger with lowest available $p_T$ single electron or muon triggers
- Exactly two same flavour reconstructed leptons (e or $\mu$)
- Both leptons $p_T > 7$ GeV and at least one with $p_T > 27$ GeV
- Require opposite charges (dimuons only)
- $81 < m_{\ell\ell} < 101$ GeV
- $p_T^Z > 75$ GeV

**H $\rightarrow c\bar{c}$ Selection**
- Consider anti-$k_T$ $R = 0.4$ calorimeter jets with $|\eta| < 2.5$ and $p_T > 20$ GeV
- At least two jets with leading jet $p_T > 45$ GeV
- Form $H \rightarrow c\bar{c}$ candidate from the two highest $p_T$ jets in an event
- At least one $c$-tagged jet from $H \rightarrow c\bar{c}$ candidate
- Dijet angular separation $\Delta R_{jj}$ requirement which varies with $p_T^Z$

Split events into 4 categories (with varying S/B) based on $H \rightarrow c\bar{c}$ candidates with 1 or 2 $c$-tags and $p_T^Z$ above/below 150 GeV
Background Modelling

- Background dominated by $Z + \text{jets} \rightarrow (\text{enriched in heavy flavour jets})$
- Smaller contributions from $ZZ(q\bar{q})$, $ZW(q\bar{q'})$ and $t\bar{t}$
- Negligible ($< 0.5\%$) contributions from $W + \text{jets}$, $WW$, single-top and multi-jet

Simulation of $ZH(c\bar{c}/b\bar{b})$

- Normalised with LHC Higgs XS WG YR4 recommendations (arXiv:1610.07922)
- $ZH(b\bar{b})$ treated as background normalised to SM expectation (with $\sigma \times B$ uncertainty)

<table>
<thead>
<tr>
<th>Process</th>
<th>MC Generator</th>
<th>Normalisation Cross section</th>
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</thead>
<tbody>
<tr>
<td>$q\bar{q} \rightarrow ZH(c\bar{c}/b\bar{b})$</td>
<td>Powheg+GoSaM+MiNLO+Pythia8</td>
<td>NNLO (QCD) NLO (EW)</td>
</tr>
<tr>
<td>$gg \rightarrow ZH(c\bar{c}/b\bar{b})$</td>
<td>Powheg+Pythia8</td>
<td>NLO+NLL (QCD)</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>Sherpa 2.2.1</td>
<td>NNLO</td>
</tr>
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<td>$ZZ$ and $ZW$</td>
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<td>NLO</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>Powheg+Pythia8</td>
<td>NNLO+NNLL</td>
</tr>
</tbody>
</table>

The nominal MC generators used to model the signal and backgrounds
Background composition after $c$-tagging

**Left: 1 $c$-tag events**

**Right: 2 $c$-tag events**
Flavour composition of the $Z + $ jets sample enriched with $c$-jets

**Left:** 1 $c$-tag events

$ATLAS$ Preliminary

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

1 $c$-tag, $75 < p_T^c < 150 \text{ GeV}$

**Right:** 2 $c$-tag events

$ATLAS$ Preliminary

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

2 $c$-tags, $75 < p_T^c < 150 \text{ GeV}$

$ \rightarrow $
**ZZ and ZW flavour composition after c-tagging**

**c-tagged ZZ and ZW production enriched in Z → c"c and W → cs, cd decays**

Left: 1 c-tag events

Right: 2 c-tag events
Quantifying the presence/absence of $ZH(c\bar{c})$ production

**Statistical Model**

- Use the $H \rightarrow c\bar{c}$ candidate invariant mass $m_{c\bar{c}}$ as S/B discriminant
- Perform simultaneous binned likelihood fit to 4 categories within region $50 < m_{c\bar{c}} < 200$ GeV
- $ZH(c\bar{c})$ signal parameterised with free signal strength parameter, $\mu$, common to all categories
- $Z +$ jets background determined directly from data with separate free normalisation parameter for each of the four categories

**Systematic Uncertainties**

- Included in the fit model as constrained nuisance parameters which parametrize the constraints from auxiliary measurements (e.g. lepton/jet calibrations)
- Experimental uncertainties associated with luminosity, $c$-tagging, lepton and jet performance are all included in the model
- Normalisation, acceptance and $m_{c\bar{c}}$ shape uncertainties associated with signal and background simulation are also included
Sensitivity dominated by systematic uncertainties, clear that these uncertainties should be reduced in order to fully exploit a larger dataset in the future

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma/\sigma_{\text{tot}}$</th>
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<tbody>
<tr>
<td><strong>Statistical</strong></td>
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<tr>
<td>Floating $Z + \text{jets}$ Normalisation</td>
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<tr>
<td><strong>Systematic</strong></td>
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<tr>
<td>Flavour Tagging</td>
<td>73%</td>
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<tr>
<td>Background Modeling</td>
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<tr>
<td>Lepton, Jet and Luminosity</td>
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<tr>
<td>MC statistical</td>
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Note: correlations between nuisance parameters within groups leads to $\sum_i \sigma_i^2 \neq \sigma_{\text{Syst}}^2$.

- Background modelling (particularly $Z + \text{jets}$ shape uncertainties) followed by $c$-tagging uncertainties have the dominant impact.
- However, we can expect many of these uncertainties (particularly effect of the $Z + \text{jets}$ normalisation) to reduce with a larger dataset.
No significant evidence for $ZH(c\bar{c})$ production

Data consistent with background only hypothesis

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<td>1.2</td>
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<tr>
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Cross check with ZV production

■ To validate background modelling and uncertainty prescriptions, measure production rate of the sum of ZZ and ZW relative to the SM expectation
■ Observe (expect) ZV production with significance of 1.4σ (2.2σ)
■ Measure ZV signal strength of $0.6^{+0.5}_{-0.4}$, consistent with SM expectation

Limits on $ZH(c\bar{c})$ production

| 95% CL $CL_s$ upper limit on $\sigma(pp \to ZH) \times B(H \to c\bar{c})$ [pb] |
|-----------------|-----------------|-----------------|-----------------|
| Observed        | Median Expected | Expected $+1\sigma$ | Expected $-1\sigma$ |
| 2.7             | 3.9             | 6.0             | 2.8             |

■ No evidence for $ZH(c\bar{c})$ production with current dataset (as expected)
■ Upper limit of $\sigma(pp \to ZH) \times B(H \to c\bar{c}) < 2.7$ pb set at 95% CL, to be compared to an SM value of $2.55 \times 10^{-2}$ pb
■ Corresponds to $110 \times$ the SM expectation

World’s most stringent direct constraint on $H \to c\bar{c}$ decays!
Use the leading order motivated “kappa framework” to study how a potential modifications to the Higgs-charm coupling would affect $\sigma(pp \rightarrow ZH) \times B(H \rightarrow c\bar{c})$

\[ \sigma_i \cdot B_j = \frac{\sigma_i(\kappa) \cdot \Gamma_j(\kappa)}{\Gamma_H} \]

- As described in arXiv:1606.02266, assume the factorisation of production and decay shown above, afforded by the “narrow width approximation”
- Define set of “kappa” coupling modifiers $\kappa$ such that LO production or decay modes (e.g. $H \rightarrow c\bar{c}$) change as $\kappa_i^2 = \sigma_i/\sigma_i^{SM}$ or $\kappa_i^2 = \Gamma_i/\Gamma_i^{SM}$
- Production modes or decays involving loops (e.g. $H \rightarrow \gamma\gamma$, $gg \rightarrow H$) can also be studied by “resolving” the loop in terms of their tree level couplings (e.g. $t\bar{t}H$)

Can approximate modifications to $pp \rightarrow ZH$ cross section and $B(H \rightarrow c\bar{c})$ with:

\[ \sigma_{pp\rightarrow ZH}(\kappa_Z, \kappa_t) = \kappa_Z^2 \cdot \sigma_{q\bar{q}\rightarrow ZH} + (2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_t \kappa_Z) \cdot \sigma_{gg\rightarrow ZH} \]

\[ B(H \rightarrow c\bar{c})(\kappa_c) = \frac{\kappa_c^2 \cdot B(H \rightarrow c\bar{c})_{SM}}{1 + (\kappa_c^2 - 1) \cdot B(H \rightarrow c\bar{c})_{SM}} \]

(where the $gg \rightarrow c\bar{c}/b\bar{b} \rightarrow ZH$ loops have not been included (very small effect) and evolution of $\Gamma_H$ varies only with $\kappa_c$)

Warning: None of the following interpretation is sanctioned by ATLAS, responsibility lies solely with me!
Interpreting the limit in terms of a constraint on $y_c$ - II

For SM $pp \to ZH$ production, the rate vs. $\kappa_c$ saturates at around $33 \times$ the SM value when $\mathcal{B}(H \to c\bar{c}) \approx 1$ (far below the limit)... However, in a general BSM scenario, one could also expect the other Higgs couplings to be modified!

In a scenario where the $ZH$ coupling is modified (e.g. $\kappa_Z \approx 2$), strong bounds of around $\kappa_c < 10$ can be obtained (assuming the predicted $\Gamma_H$, i.e. no new particles)

Similarly, if one modifies the $t\bar{t}H$ coupling (e.g. $\kappa_t \approx 10$) bounds of around $\kappa_c < 40$ are also possible, **BUT** both scenarios are strongly disfavoured by LHC data...
For very large values of $\kappa_c$, the tree level $c\bar{c} \rightarrow ZH$ process (i.e. two $c$ quarks from the protons) becomes important! (see arXiv:1503.00290 for more details)

This additional production mechanism allows a bound of around $\kappa_c < 300$ to be obtained, without modifying any other Higgs boson couplings.

However, by the time this becomes relevent, $\Gamma_H$ would be saturated by $H \rightarrow c\bar{c}$ decays.
Summary

- Search for $ZH(c\bar{c})$ production exploiting new $c$-tagging techniques provides limit of $\sigma(pp \to ZH) \times B(H \to c\bar{c}) < 2.7\, \text{pb}$ excluding $110 \times \text{SM expectation}$

- Demonstrates that this inclusive channel is likely more sensitive to the charm quark Yukawa coupling than the exclusive $H \to J/\psi \gamma$ channel

- Not yet able to compete with constraints obtained from interpreting measurements of Higgs boson kinematic distributions in terms of modified $gc \to Hc$ production

- Clear that no single approach can yet claim it will manage to probe the charm quark Yukawa coupling down to the SM prediction by the end of the LHC era

- Likely that multiple approaches will be required, this channel will become ever more important as larger datasets are collected!

**What next for inclusive $H \to c\bar{c}$ decays?**

- Large gains in sensitivity possible with multivariate techniques and other $VH$ channels (e.g. $W(\ell\nu)/Z(\nu\nu)$) or a dedicated search/category in the high $p_T^H$ boosted regime

- If future $c$-tagging algorithms can reach the performance of today’s $b$-tagging, one could expect to observe $H \to c\bar{c}$ decays at the LHC!

- Performance of $c$-tagging is developing rapidly, next generation algorithms already exploit advanced ML techniques (ATL-PHYS-PUB-2017-013), huge scope for innovation!
Additional Slides
Examples of c-tagging input variables

More details in ATL-PHYS-PUB-2016-012
ATLAS Low Level Taggers: Using muons (Soft Muon Tagger)

Exploit the large branching fractions for the semi-leptonic $c/b$ hadron decays and the clean “muon-in-jet” experimental signature:

- Expect much higher rate of muons within $b/c$-jets, relative to light flavour jets, due to the decays $B \to \mu \nu X$ and $B \to DX \to \mu \nu X'$ ($B$ of around 10% each)

- ✓ Complementary to SV and IP based taggers, different $c/b$ hadron properties exploited and ATLAS detector components employed

- ✗ Light flavour jet backgrounds from muons produced in $\pi/K$ decays in flight difficult to model in simulation

Left: $\Delta R$ of muon w.r.t. jet axis  
Centre: $p_T$ of muon relative to the jet axis  
Right: BDT built from muon observables