COFUND. A project supported by the European Union

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

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Andy Chisholm
(CERN and University of Birmingham)

“Yukawa” couplings between the Higgs (ϕ) and fermion (ψ) fields are possible:

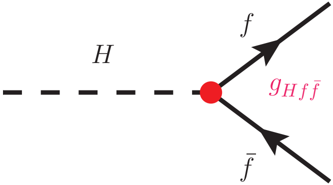
$$\mathcal{L}_{\text{fermion}} = -y_f \cdot \left[\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \bar{\phi} \psi_L\right]$$

If ϕ has a non-zero VEV, expansion leads to (where h is the physical Higgs field):

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

Results in Higgs–fermion coupling proportional to the fermion mass ($g_{Hf\bar{f}} = m_f/v$)

- Gauge invariant fermion mass terms in SM ✓
- y_f “predicted” in SM given knowledge of v and m_f ($v \approx 246$ GeV from EW observables) ✓
- Offers no fundamental insight into the observed fermion mass hierarchy ✗

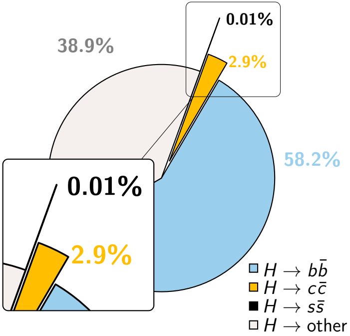


While Yukawa couplings provide concrete predictions for $Hf\bar{f}$ interactions, they fail to describe the origin of the fermion mass hierarchy i.e. why is $m_t/m_e \approx \mathcal{O}(10^5)$!?

Physics beyond the SM is clearly required to explain the fermion mass hierarchy!

Why is the charm quark Yukawa coupling important?

- The smallness of the SM charm (c) quark coupling ($y_c = \frac{\sqrt{2}m_c(m_H)}{v} \approx 4 \times 10^{-3}$) make possible **modifications from potential new physics easier to spot**
- $H \to c\bar{c}$ decays constitute the **largest part of the SM prediction for Γ_H for which we have no experimental evidence**
- **We only have experimental evidence for 3rd generation Yukawa couplings!**
- Many BSM models **predict modifications to 1st and 2nd generation fermion Higgs couplings alone**, with SM-like couplings to 3rd



Cartoon of SM 125 GeV $H \to q\bar{q}$ branching fractions, $H \to u\bar{u}/d\bar{d}$ too small to show!

What are the existing indirect constraints?

- Constraints on unobserved Higgs decays impose $\mathcal{B}(H \to c\bar{c}) < 20\%$, while global fits indirectly bound Γ_H leading to $y_c/y_c^{SM} < 6$, **assuming SM production and no BSM decays** (arXiv:1310.7029, arXiv:1503.00290)
- Direct bound of around $\Gamma_H < 1$ GeV from $H \to \gamma\gamma$ and $H \to 4\ell$ lineshapes impose around $y_c/y_c^{SM} < 120$, **but this is model independent** (arXiv:1503.00290)

Several methods to study the $Hc\bar{c}$ coupling at the LHC have been proposed in the literature, the most promising (in my opinion) are:

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

- Rare exclusive radiative Higgs boson decays to vector mesons are sensitive to the $Hq\bar{q}$ couplings (arXiv:1503.00290)
- The $H \to J/\psi\,\gamma$ decay has been proposed as a clean probe of the $Hc\bar{c}$ coupling, though decay width "only" evolves as $(\text{const.} + y_c)^2$ ($\text{const.} \gg y_c$)
- ATLAS pioneered searches in this channel during Run 1 (arXiv:1501.03276)

Idea 2 - Associated production of a Higgs boson and charm quark

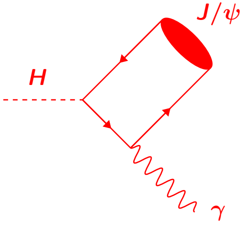
- Tree level sensitivity to $Hc\bar{c}$ coupling (arXiv:1507.02916, arXiv:1606.09253)
- Use jet c-tagging to identify charm quark signature and a suitably "clean" Higgs decay (e.g. $H \to \gamma\gamma$)
- Alternatively, study p_T^H distribution to look for potential shape modifications...

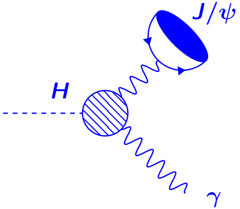
Idea 3 - Inclusive $H \to c\bar{c}$ decays (The focus of this seminar...)

- Inclusive $H \to c\bar{c}$ decays are directly sensitive to the $Hc\bar{c}$ coupling, with the decay width evolving as $\Gamma_{H\to c\bar{c}} \propto y_c^2$
- Use double jet c-tagging and focus on VH ($V = W, Z$) production with leptonic V decays to mitigate the large multi-jet backgrounds

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

- **Interference** between **direct** ($H \to c\bar{c}$) and **indirect** ($H \to \gamma\gamma^*$) 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 somewhat diluted

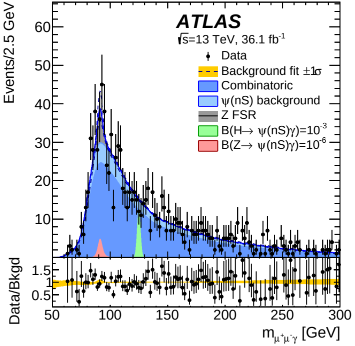


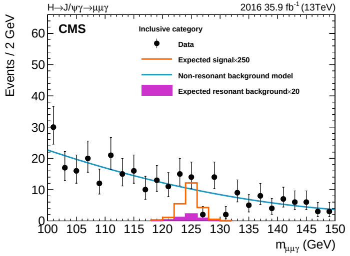


$$\Gamma = \left|C_{\mathrm{I}} - C_{\mathrm{D}} \cdot \frac{y_c}{y_c^{SM}}\right|^2 \times 10^{-7}\ \mathrm{MeV}\ (C_{\mathrm{I}} \approx 10, C_{\mathrm{D}} \approx 1)$$

$$\mathcal{B}(H \to J/\psi\,\gamma) = (2.99 \pm 0.16) \times 10^{-6}$$

More details: Phys. Rev. D 90, 113010 (2014) (arXiv:1407.6695) and JHEP 1508 (2015) 012 (arXiv:1505.03870)





Recently both ATLAS and CMS updated their searches for $H \to J/\psi\,\gamma$ decays with 36 fb^{-1} of $\sqrt{s} = 13$ TeV Run 2 data

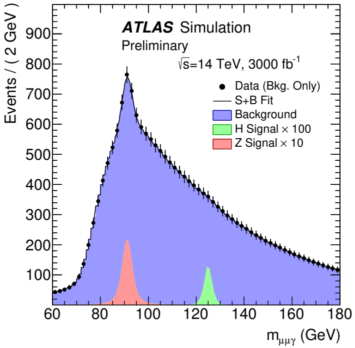
- Both search for $H \to J/\psi\,\gamma$ with $J/\psi \to \mu^+\mu^-$ using a "cut-based" analysis
- Sensitive to branching fractions around two orders of magnitude away from SM prediction
- Limits corresponds to $|y_c/y_c^{SM}| \approx 100$ (when considered relative to $H \to \gamma\gamma$ to remove Γ_H dependence)

Expt.	95% CL upper limit on $\mathcal{B}(H \to J/\psi\,\gamma)$		
	Expected	**Observed**	**Obs./$\mathcal{B}_{SM}$**
ATLAS†	$(3.0^{+1.4}_{-0.8}) \times 10^{-4}$	3.5×10^{-4}	**117×**
CMS‡	$(5.2^{+2.4}_{-1.6}) \times 10^{-4}$	7.6×10^{-4}	**253×**

† **Phys. Lett. B 786 (2018) 134 (arXiv:1807.00802)**

‡ **Submitted to EPJC (arXiv:1810.10056)**

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



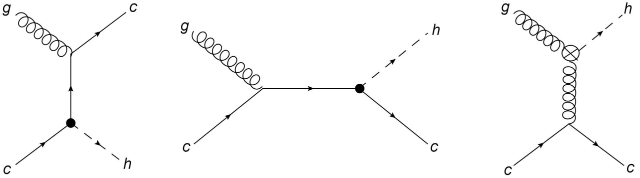
	Expected branching ratio limit at 95% CL		
	$\mathcal{B}(H \to J/\psi\gamma)$ [10^{-6}]		$\mathcal{B}(Z \to J/\psi\gamma)$ [10^{-7}]
	Cut Based	Multivariate Analysis	Cut Based
300 fb^{-1}	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
3000 fb^{-1}	55^{+24}_{-15}	44^{+19}_{-12}	$4.4^{+1.9}_{-1.1}$

	Standard Model expectation	
	$\mathcal{B}(H \to J/\psi\gamma)$ [10^{-6}]	$\mathcal{B}(Z \to J/\psi\gamma)$ [10^{-7}]
	2.9 ± 0.2	0.80 ± 0.05

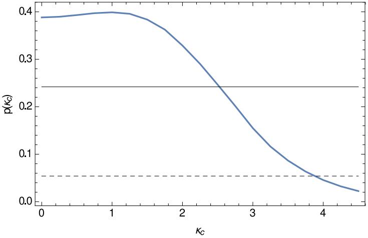
- Optimistic scenario with MVA analysis still only sensitive to $\mathcal{B}(H \to J/\psi\,\gamma)$ at **15× SM value with 3000 fb^{-1}**

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



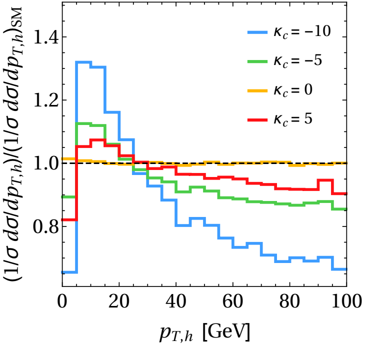
↑ **Examples of "direct" (left and centre) and "indirect" (right) $cg \to Hc$ diagrams (from arXiv:1507.02916)**



↑ **Expected p-value as a function of $\kappa_c = y_c/y_c^{SM}$ (from arXiv:1507.02916)**

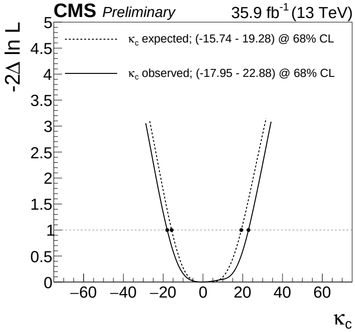
- t-channel diagram (left) is expected to dominate the cross-section and is sensitive to the $Hc\bar{c}$ coupling, highly sensitive channel!
- No experimental measurements yet, though the sensitivity at the HL-LHC has been surveyed in the literature (arXiv:1507.02916)
- Assuming a data sample of $3\,\text{ab}^{-1}$ at $\sqrt{s} = 14$ TeV, $\mathcal{O}(1)$ constraints on y_c/y_c^{SM} are expected to be obtained...

Idea 2 - Associated Higgs boson + charm quark production



Effect of modified y_c on p_T^H from $cg \to Hc$ diagrams

(Phys. Rev. Lett. 118, 121801 (2017), arXiv:1606.09253)



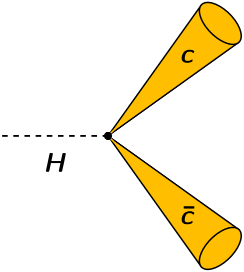
Bound on y_c/y_c^{SM} from Run 2 CMS data

(CMS-PAS-HIG-17-028)

- In the case of a modified Higgs coupling to heavy quarks $Q = c, b$, the shape of the inclusive p_T^H spectrum would change due to the modified $gQ \to HQ$ contribution
- Recently, CMS used their measured p_T^H distribution from $H \to \gamma\gamma$ and $H \to 4\ell$ accounting for dependence on y_c (and y_b)
- Considering only shape variation (no assumption on Γ_H, less model dependent) and profiling y_b/y_b^{SM}, obtain constrain of $-18 < y_c/y_c^{SM} < 23$ at 68% CL

Motivation

- The branching fraction for $H \to c\bar{c}$ decays is around 2.9% for a SM Higgs boson with $m_H = 125$ GeV
- In comparison to the $H \to J/\psi\,\gamma$ 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 $H \to c\bar{c}$ decays in every $1\,\text{fb}^{-1}$ of data!
- **But**, how can we hope to separate $H \to c\bar{c}$ 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ (e.g. $Z(\ell\ell, \nu\nu)H$ and/or $W(\ell\nu)H$), to reduce the jet backgrond

Part I - Charm jet tagging with ATLAS

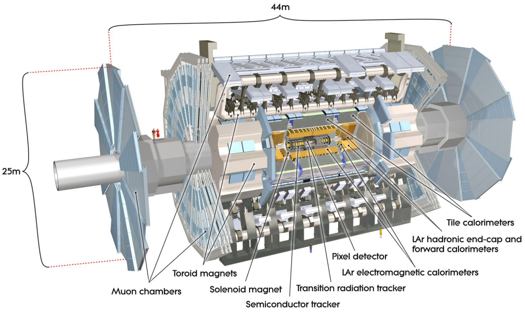
Introduction

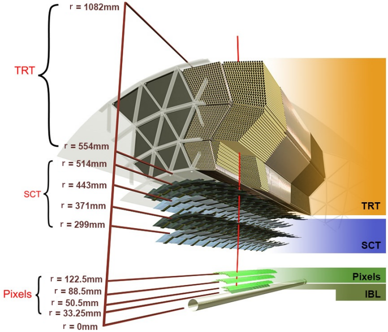
- Jets containing either c- or b-hadrons can be "tagged" by virtue of the unique properties of the heavy flavour hadrons
- These techniques are collectively known as jet "flavour tagging" and only differ in the fine details if one is interested to "tag" c-jets or b-jets
- **I will describe how these techniques are implemented within the ATLAS experiement** ("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)

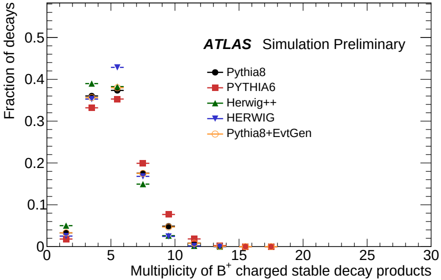
General purpose detector, well suited to studying heavy flavour jets

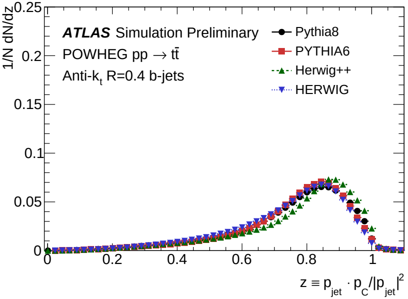




- **Inner Detector (ID):** Silicon Pixels and Strips (SCT) with Transition Radiation Tracker (TRT) $|\eta| < 2.5$ and (new for Run 2) Insertable B-Layer (IBL)
- **LAr EM Calorimeter:** Highly granular + longitudinally segmented (3-4 layers)
- **Had. Calorimeter:** Plastic scintillator tiles with iron 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 $p_T = 1$ GeV (with IBL)

- **Lifetime:** Long enough to lead to a measureable 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)

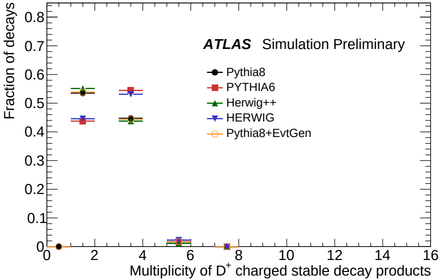


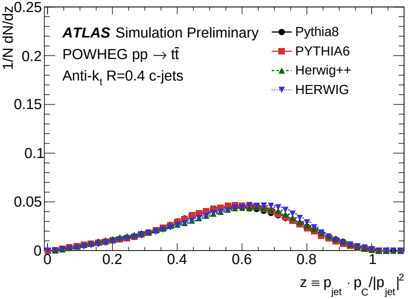


Left: Mean charged multiplicity in B^+ mesons decays

Right: *b*-quark fragmentation function

- **Lifetime:** Shorter than the *b*-hadrons by around a factor of 2-3, still enough for measureable 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)

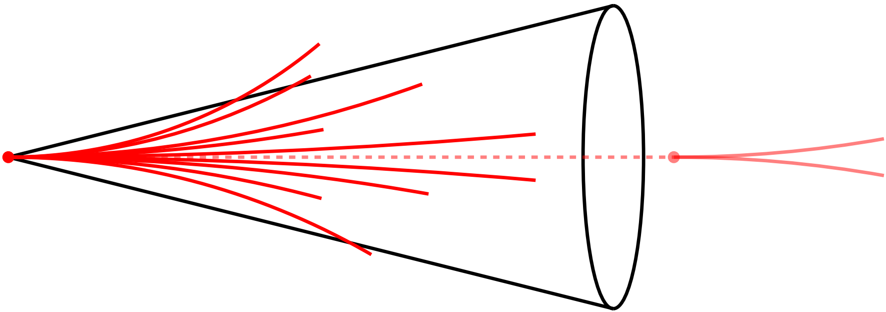




Left: Mean charged multiplicity in D^+ mesons decays

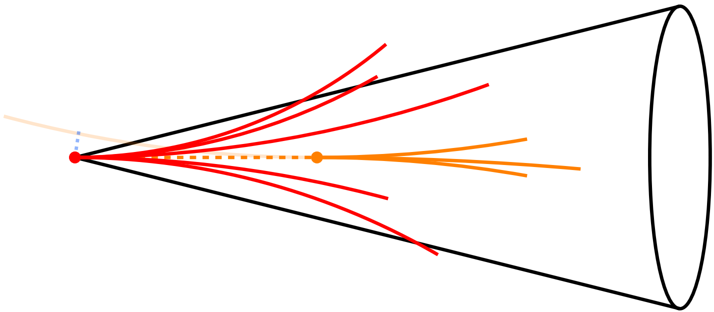
Right: *c*-quark fragmentation function

Anatomy of a light flavour (u, d, s) jet



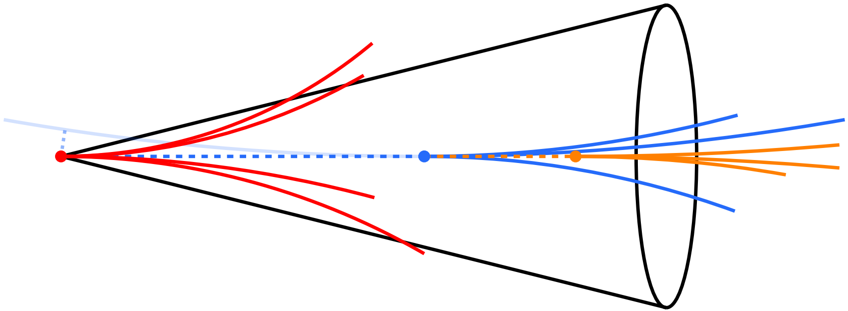
Typical Experimental Signature

- **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, Λ^0) can be produced, though they are more likely to decay very far (many cm) from the primary *pp* vertex**



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**

Charm tagging is not new, many experiments at high energy ($\sqrt{s} \gg m_{B\bar{B}}$) colliders (e.g. Sp$\bar{\text{p}}$S, 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. $D^{\star\pm} \to D^0(K^-\pi^+)\pi^\pm$) 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

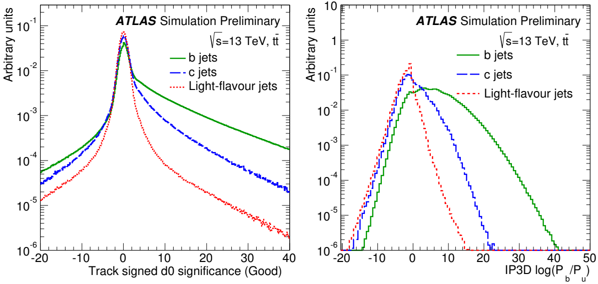
"Inclusive" charm jet tagging

- An alternative approach is to 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 distriminants:

- 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/σ_{IP}) positive IPs, while most tracks from the PV have a narrow, symmetric distribution
- ✓ Very inclusive and highly efficient
- ✗ Relies upon accurate measurement of jet axis, sensitive to "mis-tag" high IP tracks from V^0 decays or material interactions, IP/σ_{IP} difficult to model in detector simulation

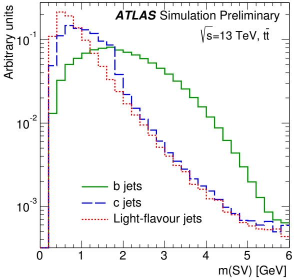


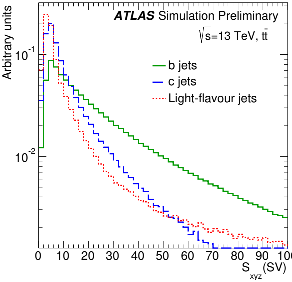
Left: Transverse IP significance distribution **Right: likelihood ratio discriminant based on 3D IPs of tracks**

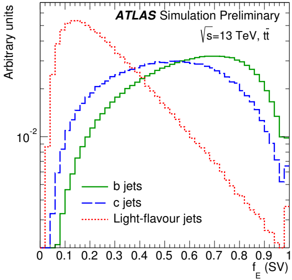
ATLAS Low Level Taggers: 2 - Secondary Vertices (SV)

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 interations
- Exploit hard c/b-jet fragmentation, SV should carry a large fraction of jet energy
- ✓ SV found in up to ≈ 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



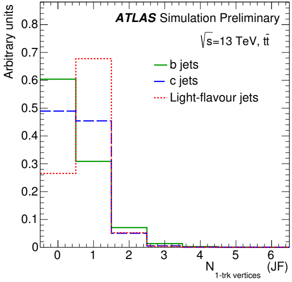


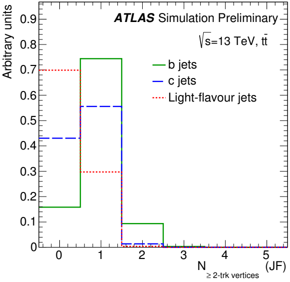


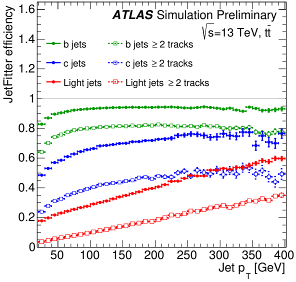
Left: Inv. mass of tracks at SV **Centre: 3D SV decay length significance** **Right: Energy fraction of SV tracks**

Exploit common occurance 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)





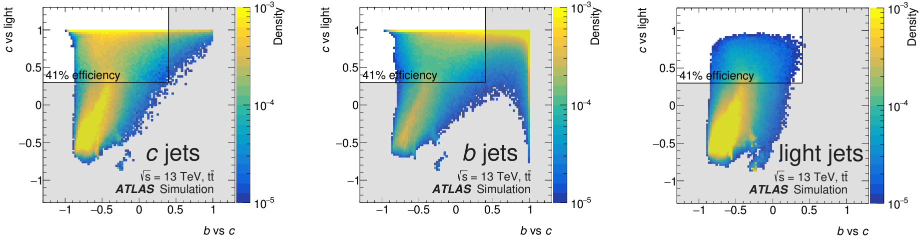


Left: Multiplicity of 1 track vertices **Centre: Multiplicity of 2+ track vertices** **Right: Reco. efficiency vs. jet p_T**

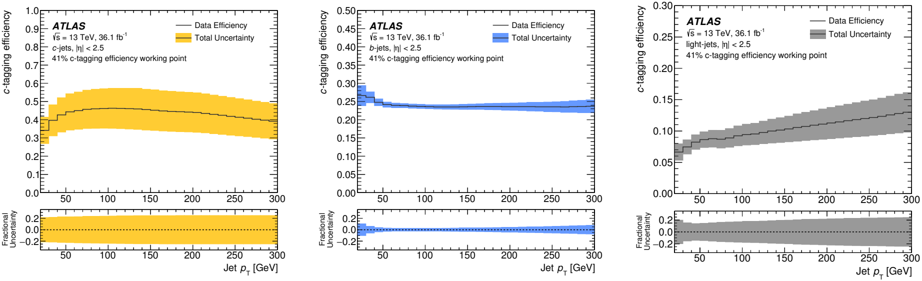
Combine approaches to exploit all features of *c*/*b*-jets and mitigate the shortcomings of the individual methods:

- ✓ 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-jets | **b-jets** | **light flavour (u, d, s, g) jets**



"*c*-tag" jets by making a cut in the 2D discriminant space, working point optimised for $H \to c\bar{c}$ limit is shown in the rectangular selection (shaded region rejected)



***c*-jets** **_b_-jets** **light flavour (u, d, s, g) jets**

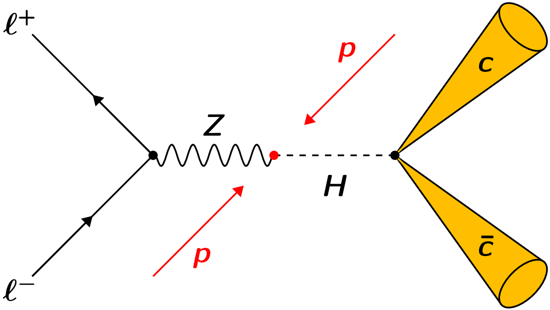
_c_-tagging efficiency for _b_-, _c_- and light flavour jets measured in data ↑

- Working point for $H \to c\bar{c}$ 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 $t \to Wb$ decays and c-jets from $W \to cs, cd$ decays (in $t\bar{t}$ events)
- Typical total relative uncertainties of around **25%**, **5%** and **20%** for ***c*-**, ***b*-** and **light** jets, respectively

Part II - Search for $H \rightarrow c\bar{c}$ decays with ATLAS

How can we use the "charm tagger" to search for $H \rightarrow c\bar{c}$ decays?

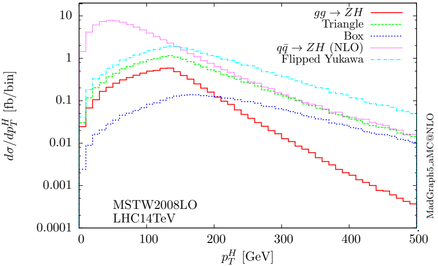
Given the success of the W/Z associated production channel in observing $H \to b\bar{b}$ decays[†], this channel is an obvious first candidate for a $H \to c\bar{c}$ search



- **Focus on ZH production** with $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ decays for first ATLAS analysis: **Phys. Rev. Lett. 120 (2018) 211802, arXiv:1802.04329**
- Low exposure to experimental uncertainties, main backgrounds from $Z+$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 $H \to c\bar{c}$ decay

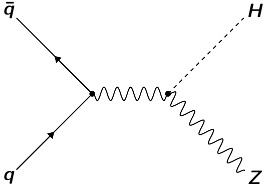
† ATLAS: Phys. Lett. B 786 (2018) 59 CMS: Phys. Rev. Lett. 121 (2018) 121801

- In $\sqrt{s} = 13$ TeV pp collisions, Higgs boson production in association with a Z boson represents around 1.6% of the inclusive production rate
- The cross-section is dominated by the $q\bar{q} \to ZH$ process, with total cross-section $\sigma_{q\bar{q}} \approx 0.76\,\text{pb}$
- Smaller contributions from $gg \to ZH$, with total cross-section $\sigma_{gg} \approx 0.12\,\text{pb}$, though it exhibits a harder p_T^H spectrum below ≈ 150 GeV

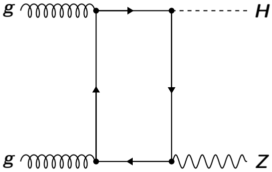


↑ **p_T^H distribution for $q\bar{q}$ and gg initiated ZH production (from arXiv:1503.01656)**

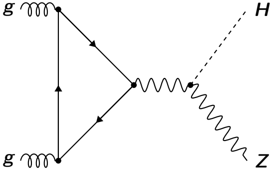
Representative Feynman diagrams for $q\bar{q}/gg \to ZH$ processes →



$q\bar{q} \to ZH$ diagram



$gg \to ZH$ "box" diagram



$gg \to ZH$ "triangle" diagram

Use a $\sqrt{s} = 13$ TeV pp collision sample collected during 2015 and 2016 corresponding to an integrated luminosity of $36.1\,\text{fb}^{-1}$

$Z \to \ell^+\ell^-$ Selection

- Trigger with lowest available p_T single electron or muon triggers
- Exactly two same flavour reconstructed leptons (e or μ)
- 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

$H \to c\bar{c}$ Selection

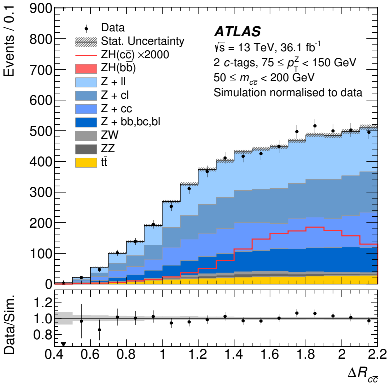
- Consider anti-k_T $R = 0.4$ calorimeter jets with $|\eta| < 2.5$ and $p_T > 20$ GeV
- At least two jets with leading jet $p_T > 45$ GeV
- Form $H \to c\bar{c}$ candidate from the two highest p_T jets in an event
- At least one c-tagged jet from $H \to c\bar{c}$ candidate
- Dijet angular separation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

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

Signal and Background Modelling

Background Modelling

- Background dominated by $Z+\text{jets} \rightarrow$ (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 $ZH(c\bar{c}/b\bar{b})$

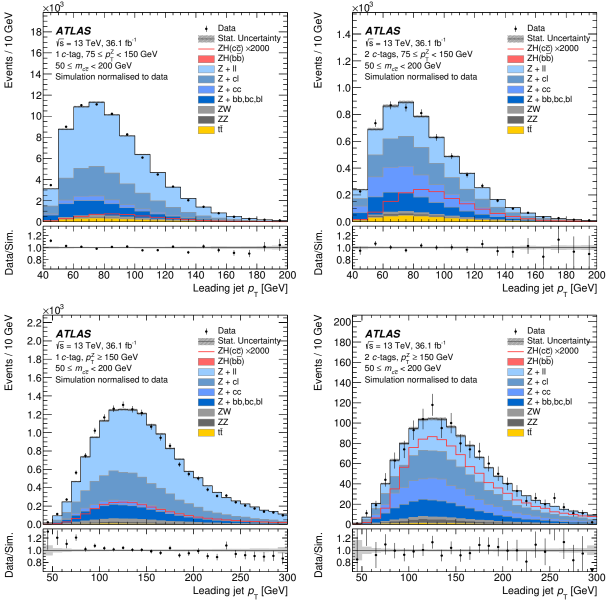
- Normalised with LHC Higgs XS WG YR4 recommendations (arXiv:1610.07922)
- $ZH(b\bar{b})$ treated as background normalised to SM expectation (with th. uncertainty)

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

The nominal MC generators used to model the signal and backgrounds

Background composition after c-tagging

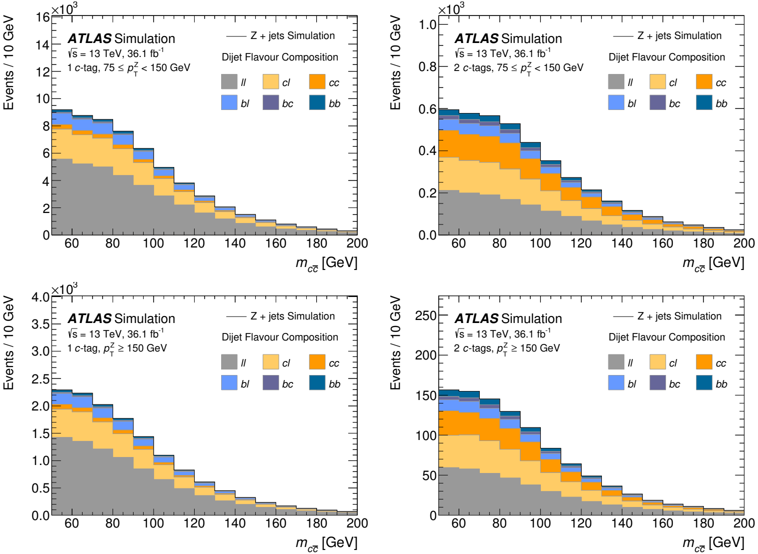
↓ Left: 1 c-tag events



↑ Right: 2 c-tag events

$Z+$ jets flavour composition after c-tagging

Flavour composition of the $Z+$ jets sample enriched with c-jets



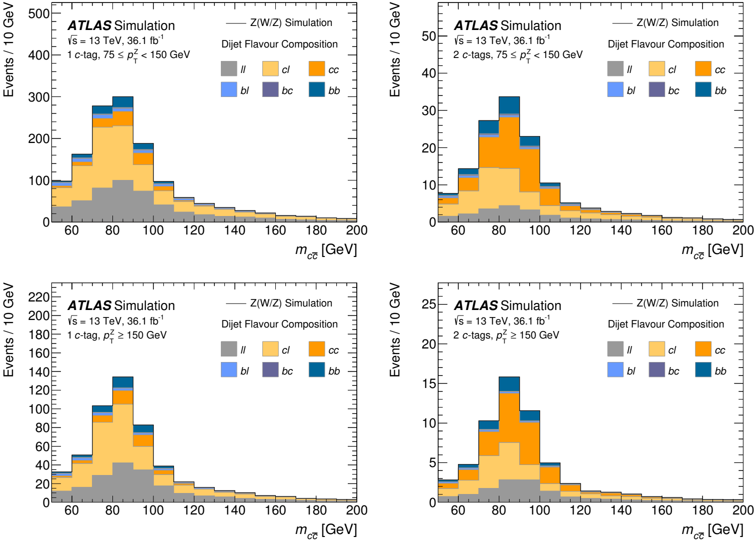
↓ Left: 1 c-tag events

Right: 2 c-tag events ↑

ZZ and ZW flavour composition after c-tagging

c-tagged ZZ and ZW production enriched in $Z \to c\bar{c}$ and $W \to cs, cd$ decays

↓ Left: 1 c-tag events



↑ Right: 2 c-tag events

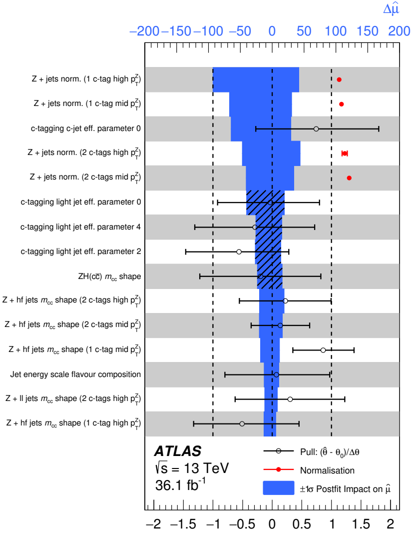
Statistical Model

- Use the $H \to c\bar{c}$ 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, μ, 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

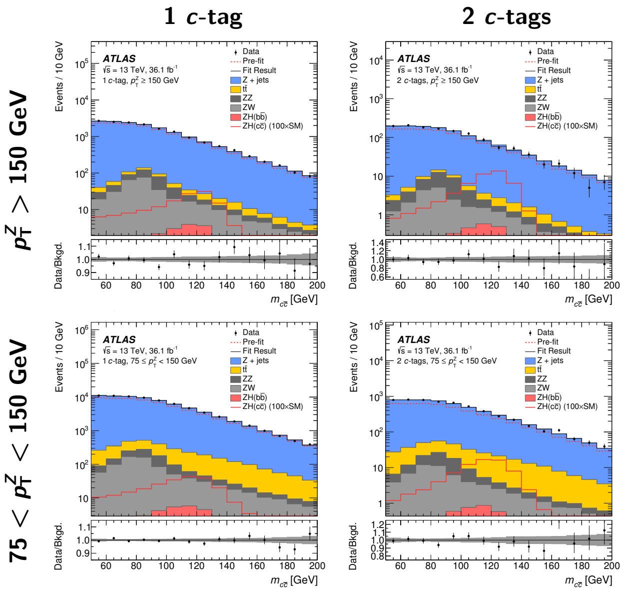
Sensitivity dominated by systematic uncertainties, clear that these uncertainties should be reduced in order to fully exploit a larger dataset in the future



Source	$\sigma/\sigma_{\text{tot}}$
Statistical	49%
Floating $Z+$jets Normalisation	31%
Systematic	87%
Flavour Tagging	73%
Background Modeling	47%
Lepton, Jet and Luminosity	28%
Signal Modeling	28%
MC statistical	6%

Note: correlations between nuisance parameters within groups leads to $\sum_i \sigma_i^2 \neq \sigma_{\text{syst.}}^2$

- c-tagging uncertainties and background modelling (particularly $Z+$jets $m_{c\bar{c}}$ shape) have the dominant impact
- However, we can expect many of these uncertainties (e.g. $Z+$jets norm.) to reduce with a larger dataset



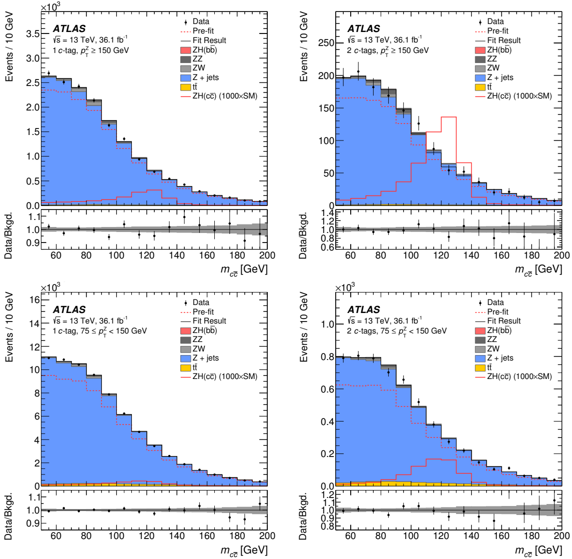
- No significant evidence for $ZH(c\bar{c})$ production
- Data consistent with background only hypothesis

SM expected number of $ZH(c\bar{c})$ events
1 c-tag $75 < p_T^Z < 150$ GeV
2.1
1 c-tag $p_T^Z > 150$ GeV
1.2
2 c-tags $75 < p_T^Z < 150$ GeV
0.5
2 c-tags $p_T^Z > 150$ GeV
0.3

1 c-tag | 2 c-tags

$p_T^Z > 150$ GeV

$75 < p_T^Z < 150$ GeV



- No significant evidence for $ZH(c\bar{c})$ production
- Data consistent with background only hypothesis

SM expected number of $ZH(c\bar{c})$ events
1 c-tag $75 < p_T^Z < 150$ GeV **2.1**
1 c-tag $p_T^Z > 150$ GeV **1.2**
2 c-tags $75 < p_T^Z < 150$ GeV **0.5**
2 c-tags $p_T^Z > 150$ GeV **0.3**

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 $\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c})$ [pb]			
Observed	Median Expected	Expected $+1\sigma$	Expected -1σ
2.7	3.9	6.0	2.8

- No evidence for $ZH(c\bar{c})$ production with current dataset (as expected)
- Upper limit of $\boldsymbol{\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c}) < 2.7}$ **pb** set at 95% CL, to be compared to an SM value of 2.55×10^{-2} pb
- Corresponds to **110**$\times$ $(150^{+80}_{-40}$ expected) the SM expectation

World's most stringent direct constraint on $H \to c\bar{c}$ decays!

⚠ **None of the following interpretation is sanctioned by ATLAS, responsibility lies solely with me!** However, everything is calculated using *published information alone*...

Ultimate goal is derive a model independent constraint on $Hc\bar{c}$ coupling, best way to do this is to exploit synergy with $ZH, H \to b\bar{b}$ channel

- Consider the ratio of $\mu_{ZH(c\bar{c})}/\mu_{ZH(b\bar{b})}$ for the $Z \to \ell^+\ell^-$ channel
- Sensitive to ratio κ_c/κ_b and <u>independent</u> of model dependent assumption on Γ_H
- Assume production is <u>identical</u> between $ZH(c\bar{c})$ and $ZH(b\bar{b})$ (i.e. selection phase space, categories etc.), leading to <u>perfect cancellation</u> of production cross-sections

$$\mu_{ZH(c\bar{c})} = \frac{\Gamma_{H\to c\bar{c}}}{\Gamma^{\text{SM}}_{H\to c\bar{c}}} \cdot \frac{\Gamma^{\text{SM}}_H}{\Gamma_H} \cdot \frac{\sigma(pp \to ZH)}{\sigma^{\text{SM}}(pp \to ZH)} = \kappa_c^2 \cdot \frac{\Gamma^{\text{SM}}_H}{\Gamma_H} \cdot \frac{\sigma(pp \to ZH)}{\sigma^{\text{SM}}(pp \to ZH)}$$

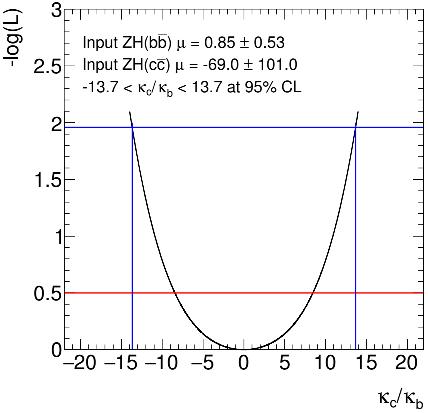
$$\mu_{ZH(b\bar{b})} = \frac{\Gamma_{H\to b\bar{b}}}{\Gamma^{\text{SM}}_{H\to b\bar{b}}} \cdot \frac{\Gamma^{\text{SM}}_H}{\Gamma_H} \cdot \frac{\sigma(pp \to ZH)}{\sigma^{\text{SM}}(pp \to ZH)} = \kappa_b^2 \cdot \frac{\Gamma^{\text{SM}}_H}{\Gamma_H} \cdot \frac{\sigma(pp \to ZH)}{\sigma^{\text{SM}}(pp \to ZH)}$$

$$\frac{\mu_{ZH(c\bar{c})}}{\mu_{ZH(b\bar{b})}} = \left(\frac{\kappa_c}{\kappa_b}\right)^2$$

- For now, consider systematic uncertainties for $ZH(c\bar{c})$ and $ZH(b\bar{b})$ as <u>uncorrelated</u>

What is the current sensitivity to κ_c/κ_b?

- Consider existing $ZH(c\bar{c})$ result and "combine" with recent ATLAS 80 fb^{-1} $Z(\ell\ell)H(b\bar{b})$ measurement†
- Small differences in selection and categories, but production cancellation hypothesis likely not too bad
- Treatment of systematics as un-correlated should give a more conservative constraint on κ_c/κ_b

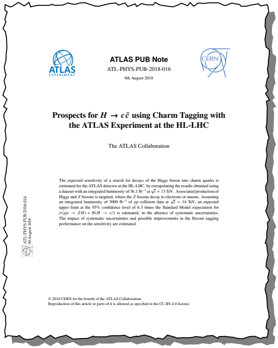


Existing results offer constraint at the level of $|\kappa_c/\kappa_b| < 14$ at 95% CL

- This is only possible when considering combination with $ZH(b\bar{b})$, not enough constraint (even with assumption for Γ_H) with $ZH(c\bar{c})$ analysis alone

† **Phys. Lett. B 786 (2018) 134 (arXiv:1807.00802)**

ATL-PHYS-PUB-2018-016


ATLAS PUB Note

ATL-PHYS-PUB-2018-016

8th August 2018

Prospects for $H \to c\bar{c}$ using Charm Tagging with the ATLAS Experiment at the HL-LHC

The ATLAS Collaboration

The expected sensitivity of a search for decays of the Higgs boson into charm quarks is estimated for the ATLAS detector at the HL-LHC, by extrapolating the results obtained using a dataset with an integrated luminosity of 36.1 fb^{-1} at $\sqrt{s}$ = 13 TeV. Associated production of Higgs and Z bosons is targeted, where the Z bosons decay to electrons or muons. Assuming an integrated luminosity of 3000 fb^{-1} of pp collision data at $\sqrt{s}$ = 14 TeV, an expected upper limit at the 95% confidence level of 6.3 times the Standard Model expectation for $\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c})$ is estimated, in the absence of systematic uncertainties. The impact of systematic uncertainties and possible improvements in the flavour tagging performance on the sensitivity are estimated.

ATL-PHYS-PUB-2018-016
08 August 2018

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What sensitivity can we expect for a HL-LHC scenario with a $\sqrt{s} = 14$ TeV 3000 fb^{-1} dataset?

- A projection of the existing $Z(\ell\ell)H, H \to c\bar{c}$ analysis was prepared for the upcoming HL-LHC physics yellow report
- Generally very simiar to the Run 2 analysis, with several minor changes (described below)

Similarities

- Consider $Z(\ell\ell)H$ channel only (no addition of $W(\ell\nu)H$ or $Z(\nu\nu)H$)
- Identical event selection, categorisation and fit procedure

Differences

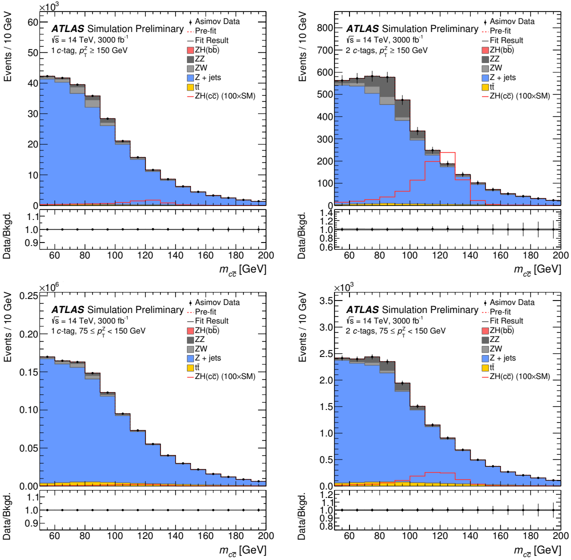
- Move to a tighter c-tagging working point (18% c-jet, 5% b-jets, 0.5% light jets)
- Don't consider systematic uncertainties (though their effect is estimated)

Prospects for $Z(\ell\ell)H, H \rightarrow c\bar{c}$ at the HL-LHC

1 c-tag | **2 c-tags**

$p_T^Z > 150$ GeV

$75 < p_T^Z < 150$ GeV



- Result of fit to expected ("Asimov") dataset for 3000 fb^{-1}
- Background composition (in terms of "process") very simiar
- Di-jet flavour composition now more c-jet enriched (you can't see that from these plots)

Projected Results

- Expected limit on $Z(\ell\ell)H, H \rightarrow c\bar{c}$ production at **$6.3\times$ SM prediction** at 95% CL (c.f. 150× expected for 36.1 fb^{-1} at 13 TeV)
- ⚠Corresponds to **around $|\kappa_c/\kappa_b| < 3$** (with naive scaling of ATLAS Run 2 $ZH(b\bar{b})$ result based on luminosity only)

Things to remember

- Limit deteriorates by up to +36% with the inclusion of systematic uncertainties (estimated from Run 2 analysis)
- Projection considers the **$Z(\ell\ell)H$ channel alone!** (sensitivity of $W(\ell\nu)H$ and $Z(\nu\nu)H$ channels at least as good)

⚠**As before, this is NOT an ATLAS result, but my estimate based on public information alone**

Summary

- Search for $pp \to ZH, H \to c\bar{c}$ production with c-tagging techniques provides limit of **$\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c}) < 2.7$ pb (110× SM expectation)** at 95% CL
- **Corresponds (roughly) to constraint of $|\kappa_c/\kappa_b| < 14$**, when considered within the context the latest ATLAS $ZH, H \to b\bar{b}$ measurement
- Limit expected to improve to **6× SM expectation for nominal HL-LHC scenario**
- This inclusive channel is more sensitive to the $Hc\bar{c}$ coupling than the $H \to J/\psi\,\gamma$ decay, but comparable to approaches based on modified $gc \to Hc$ production
- Clear that **no single approach can yet claim it will manage to probe the $Hc\bar{c}$ coupling down to the SM prediction** by the end of the LHC era

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

- Large gains in sensitivity possible with multivariate techniques and other VH channels ($W(\ell\nu)$ and $Z(\nu\nu)$)
- Performance of c-tagging is developing rapidly, next generation algorithms already exploit advanced ML techniques (ATL-PHYS-PUB-2017-013), huge scope for innovation!
- Much to gain (e.g. sensitivity to κ_c/κ_b) from synchronisation with $VH(b\bar{b})$ channel

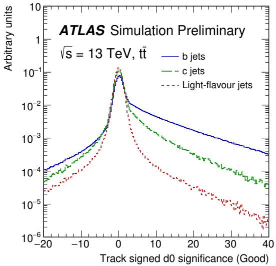
Thank you for your attention!

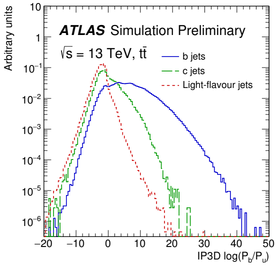
Additional Slides

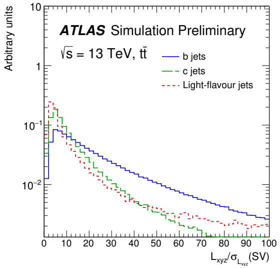
Background Composition

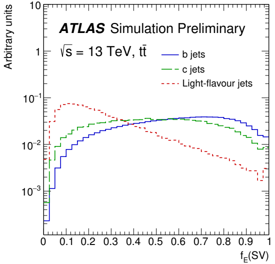
Sample	Yield, 50 $GeV < m_{c\bar{c}} <$ 200 GeV			
	1 c-tag		2 c-tags	
	$75 \leq p_{\mathrm{T}}^{Z} < 150\,GeV$	$p_{\mathrm{T}}^{Z} \geq 150\,GeV$	$75 \leq p_{\mathrm{T}}^{Z} < 150\,GeV$	$p_{\mathrm{T}}^{Z} \geq 150\,GeV$
$Z+$jets	69400 ± 500	15650 ± 180	5320 ± 100	1280 ± 40
ZW	750 ± 130	290 ± 50	53 ± 13	20 ± 5
ZZ	490 ± 70	180 ± 28	55 ± 18	26 ± 8
$t\bar{t}$	2020 ± 280	130 ± 50	240 ± 40	13 ± 6
$ZH(b\bar{b})$	32 ± 2	19.5 ± 1.5	4.1 ± 0.4	2.7 ± 0.2
$ZH(c\bar{c})$ (SM)	-143 ± 170 (2.4)	-84 ± 100 (1.4)	-30 ± 40 (0.7)	-20 ± 29 (0.5)
Total	72500 ± 320	16180 ± 140	5650 ± 80	1320 ± 40
Data	72504	16181	5648	1320

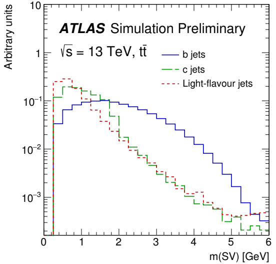
Examples of *c*-tagging input variables

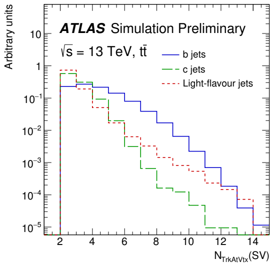








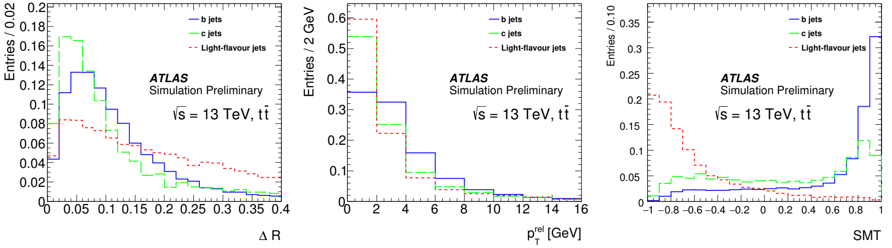




More details in ATL-PHYS-PUB-2016-012

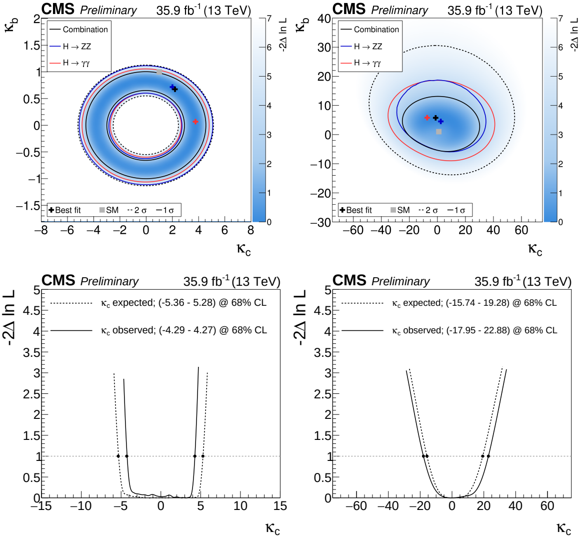
Exploit the large branching fractions for the semi-leptonic c/b hadron decays and the clean "muon-in-jet" experimental signature:

- 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 $B \to DX \to \mu\nu X'$ ($\mathcal{B}$ 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 π/K decays in flight difficult to model in simulation

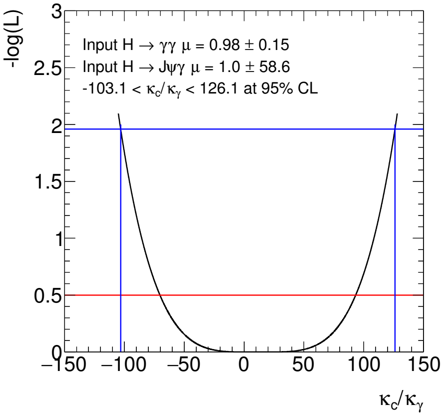


Left: ΔR of muon w.r.t. jet axis **Centre: p_T of muon relative to the jet axis** **Right: BDT built from muon observables**

Top: κ_c vs. κ_b **Bottom: κ_c, profiling κ_b**



Left: Normalisation + shape information **Right: Only shape information**



- Consider the ratio of signal strength measurements for $H \to J/\psi\,\gamma$ w.r.t. $H \to \gamma\gamma$
- Dependence on Γ_H and $\sigma(pp \to H)$ (approximately) cancels in this ratio, sensitive to κ_c/κ_γ
- Figure above based on ATLAS Run 2 $H \to J/\psi\,\gamma$ search and latest $H \to \gamma\gamma$ measurement (arXiv:1802.04146)

⚠ **This is NOT an ATLAS result, but my estimate based on public information alone**

Focus on the experimentally clean $J/\psi \to \mu^+\mu^-$ decays and target high rate inclusive H production

Trigger and Data Sample

- Dedicated photon + single muon triggers implemented to identify distinctive event topology
- Collected **$36.1\,\mathrm{fb}^{-1}$ $\sqrt{s} = 13\,\mathrm{TeV}$ pp dataset** during the 2015 and 2016 LHC runs

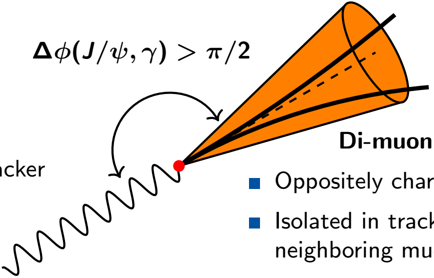
J/ψ Selection

- Require $m_{\mu^+\mu^-}$ loosely consistent with J/ψ mass
- **Minimum $p_{\mathrm{T}}^{J/\psi}$ requirement** varying with $m_{J/\psi\,\gamma}$ from 34 – 54.4 GeV, depending on channel (to optimise both H and Z searches)

$\Delta\phi(J/\psi, \gamma) > \pi/2$

$p_{\mathrm{T}}^{\mu\,\mathrm{lead}} > 18$ GeV

$p_{\mathrm{T}}^{\mu\,\mathrm{sub\text{-}lead}} > 3$ GeV



Photon Selection

- "Tight" photon ID requirements
- Isolated in both tracker and calorimeter

$p_{\mathrm{T}}^{\gamma} > 35$ GeV

Di-muon Selection

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