COFUND. A project supported by the European Union

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

Birmingham HEP Seminar

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Introduction - Yukawa Couplings

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

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

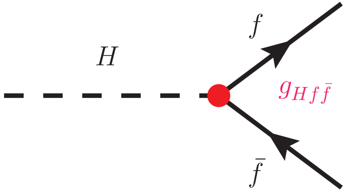
If ϕ has a non-zero VEV, expansion leads to:

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

where h is the physical Higgs boson field...

The End Result:

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

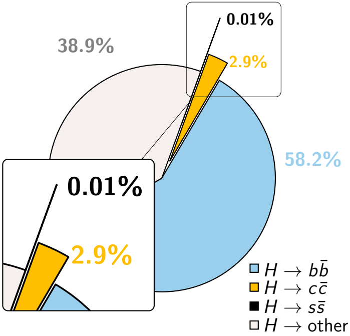


While y_f are still free parameters in the model, $v \approx 246$ GeV is known from electroweak measurements and we know the fermion masses...

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**
- $H \to c\bar{c}$ decays constitute the **largest part of the SM prediction for Γ_H for which we have no experimental evidence**
- To date, we **only have experimental evidence for 3rd generation Yukawa couplings!**



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 around $\mathcal{B}(H \to c\bar{c}) < 20\%$, global fits to LHC data indirectly bound Γ_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 $H \to \gamma\gamma$ and $H \to 4\ell$ lineshapes impose around $y_c/y_c^{SM} < 120$, **but this is model independent** (arXiv:1503.00290)

How can we constrain these couplings in a more direct way?

Direct probes of the charm quark Yukawa coupling at the LHC

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 $H \to J/\psi\,\gamma$ 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 charm quark to Yukawa coupling, though decay width "only" evolves as $(\text{const.} + y_c)^2$ $(\text{const.} \gg y_c)$
- 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**

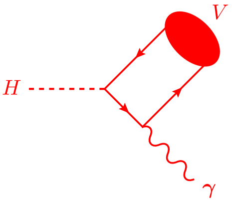
- Tree level sensitivity to charm quark to Yukawa coupling (arXiv:1507.02916, arXiv:1606.09253)
- Use jet c-tagging to identify charm quark signature and a suitably "clean" Higgs decay (e.g. $H \to \gamma\gamma$)
- Alternatively, study p_T^H distribution to look for potential shape modifications...

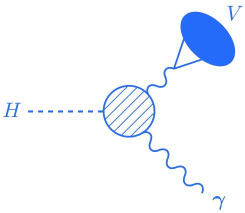
Idea 3 - **Inclusive $H \to c\bar{c}$ decays** **(The focus of this seminar...)**

- Inclusive $H \to c\bar{c}$ decays are directly sensitive to the charm quark to Yukawa 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 background

The radiative decay $H \to J/\psi\,\gamma$ could provide a clean probe of charm quark Yukawa 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 Yukawa couplings
- Very rare decays in the SM, but **rate dominated by "indirect" component**, sensitivity to Yukawa coupling somewhat diluted





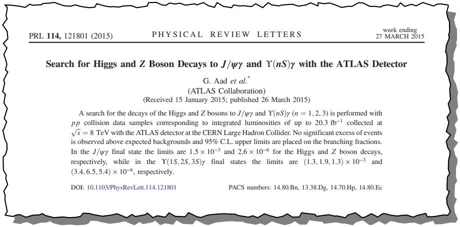
$$\Gamma = \left| C_I - C_D \cdot \frac{y_c}{y_c^{SM}} \right|^2 \times 10^{-7}\,\text{MeV}\;(C_I \approx 10, C_D \approx 1)$$

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

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

$H \to J/\psi\,\gamma$ - Run 1 Results (Phys. Rev.Lett. 114 (2015), 121801 (arXiv:1501.03276))

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



PRL **114,** 121801 (2015) PHYSICAL REVIEW LETTERS week ending 27 MARCH 2015

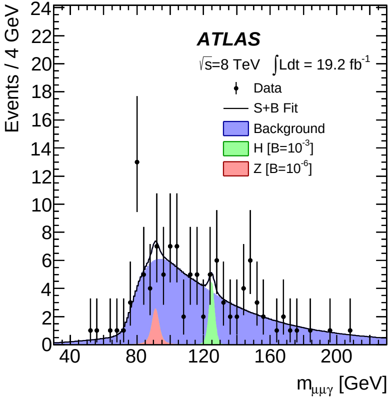
Search for Higgs and Z Boson Decays to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ with the ATLAS Detector

G. Aad *et al.*[*]
(ATLAS Collaboration)
(Received 15 January 2015; published 26 March 2015)

A search for the decays of the Higgs and Z bosons to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ ($n = 1, 2, 3$) is performed with pp collision data samples corresponding to integrated luminosities of up to 20.3 fb^{-1} collected at $\sqrt{s} = 8$ TeV with the ATLAS detector at the CERN Large Hadron Collider. No significant excess of events is observed above expected backgrounds and 95% C.L. upper limits are placed on the branching fractions. In the $J/\psi\gamma$ final state the limits are 1.5×10^{-3} and 2.6×10^{-6} for the Higgs and Z boson decays, respectively, while in the $\Upsilon(1S, 2S, 3S)\gamma$ final states the limits are $(1.3, 1.9, 1.3) \times 10^{-3}$ and $(3.4, 6.5, 5.4) \times 10^{-6}$, respectively.

DOI: 10.1103/PhysRevLett.114.121801 PACS numbers: 14.80.Bn, 13.38.Dg, 14.70.Hp, 14.80.Ec

- 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†
- Interpreted as $Hc\bar{c}$ coupling limit of $y_c/y_c^{SM} < 220$ at 95% CL‡ (assuming dependence on $\sigma(pp \to H)/\Gamma_H$ is removed by considering ratio with $H \to 4\ell$ rate)



Branching fraction limit (95% CL):

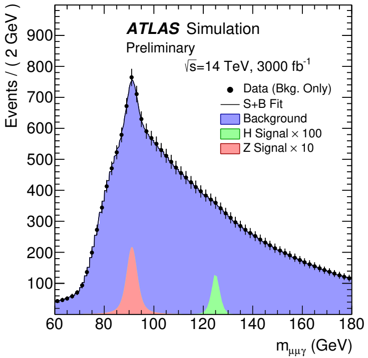
$$\mathcal{B}\,(H \to J/\psi\,\gamma) < 1.5 \times 10^{-3}$$

Around 500× the SM expectation

† Phys. Lett. B753 (2016) 341 (arXiv:1507.03031)

‡ Phys. Rev. D92, 033016 (2015) (arXiv:1503.00290)

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

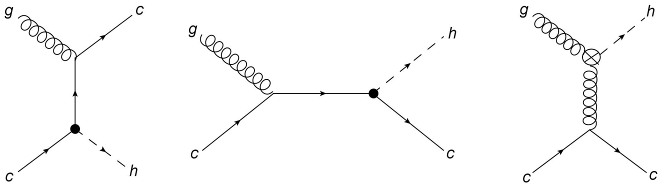


	Expected branching ratio limit at 95% CL		
	$\mathcal{B}(H \to J/\psi\gamma)$ [10^{-6}]		$\mathcal{B}(Z \to J/\psi\gamma)$ [10^{-7}]
	Cut Based	Multivariate Analysis	Cut Based
300 fb^{-1}	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
3000 fb^{-1}	55^{+24}_{-15}	44^{+19}_{-12}	$4.4^{+1.9}_{-1.1}$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

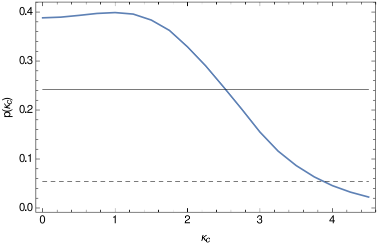
- Optimistic scenario with MVA analysis still only sensitive to $\mathcal{B}(H \to J/\psi\,\gamma)$ at **15×SM value with 3000 fb^{-1}**

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



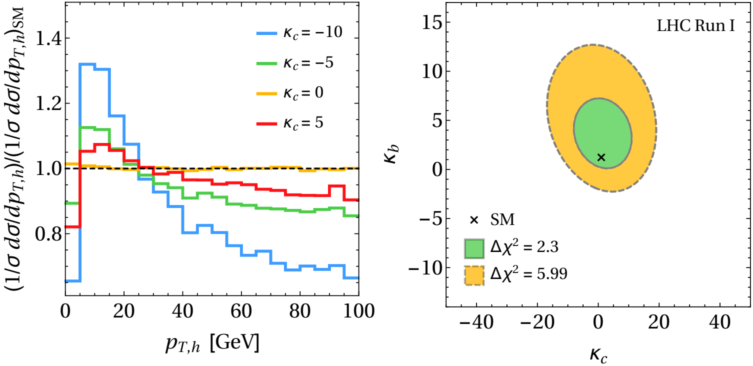
↑ **Examples of "direct" (left and centre) and "indirect" (right) $cg \to Hc$ diagrams (from arXiv:1507.02916)**



↑ **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 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...

Alternatively, don't c-tag at all...

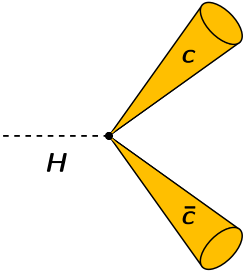


↑ **Left: Effect of modified κ_c on p_T^H from $cg \to Hc$ diagrams Right: bounds from Run 1 data (both from arXiv:1606.09253)**

- In the case of a modified heavy quark $\mathcal{Q} = c, b$ Yukawa coupling, the shape of the inclusive p_T^H spectrum would change due to the modified $g\mathcal{Q} \to H\mathcal{Q}$ contribution
- p_T^H can be measured in the $H \to \gamma\gamma$ and $H \to 4\ell$ 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 $3\,\text{ab}^{-1}$, bound evolves to $-0.6 < y_c/y_c^{SM} < 3.0$

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

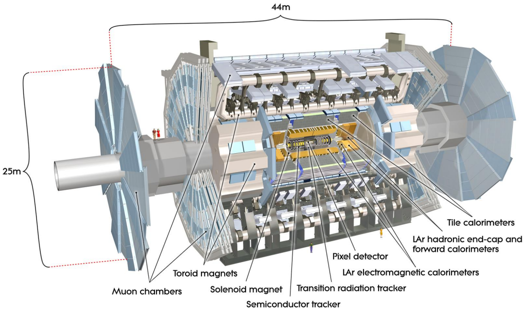
- Jets containing either *c*- or *b*-hadrons can be "tagged" by virtue of the unique properties of the heavy flavour hadrons
- These techniques are collectively known as jet "flavour tagging" and only differ in the fine details if one is interested to "tag" *c*-jets or *b*-jets
- **I will describe how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

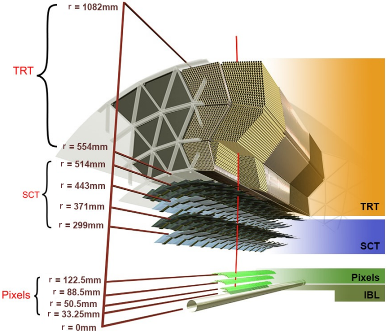
Jet Labelling Conventions

- ***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)

The ATLAS Detector at the LHC

General purpose detector, well suited to studying heavy flavour jets

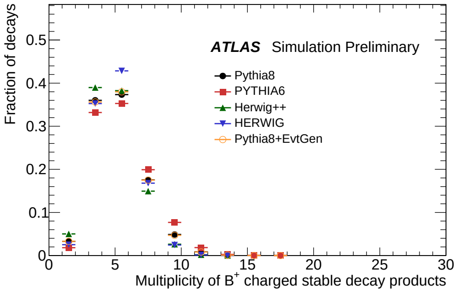


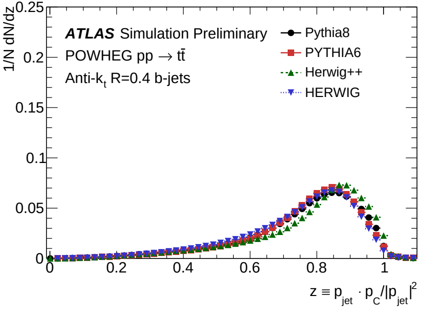


- **Inner Detector (ID):** Silicon Pixels and Strips (SCT) with Transition Radiation Tracker (TRT) $|\eta| < 2.5$ and (new for Run 2) Insertable B-Layer (IBL)
- **LAr EM Calorimeter:** Highly granular + longitudinally segmented (3-4 layers)
- **Had. Calorimeter:** Plastic scintillator tiles with iron absorber (LAr in fwd. region)
- **Muon Spectrometer (MS):** Triggering $|\eta| < 2.4$ and Precision Tracking $|\eta| < 2.7$
- **Jet Energy Resolution:** Typically $\sigma_E/E \approx 50\%/\sqrt{E(\text{ GeV})} \oplus 3\%$
- **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)

Properties of *b*-hadrons

- **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)



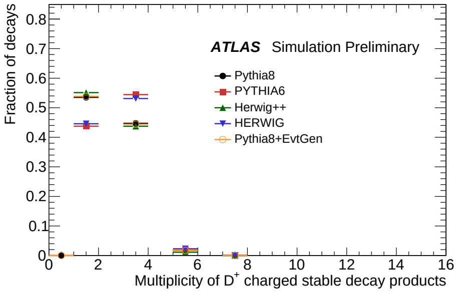


Left: Mean charged multiplicity in B^+ mesons decays

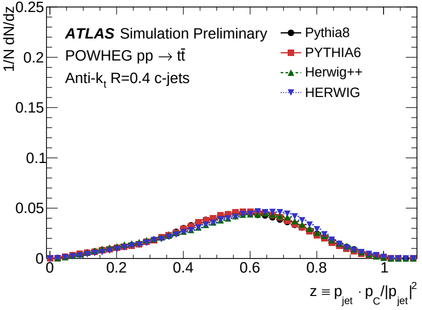
Right: *b*-quark fragmentation function

Properties of c-hadrons

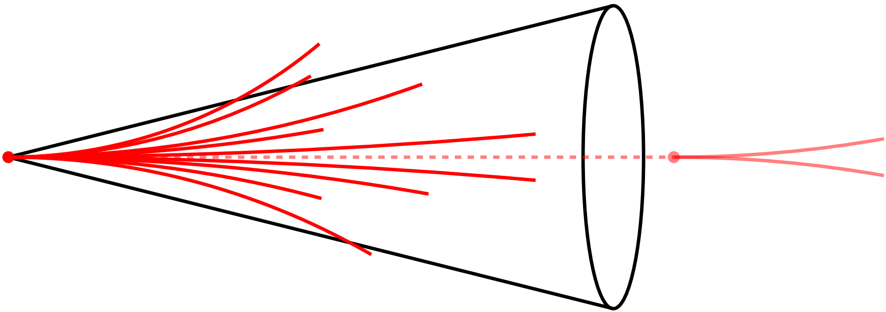
- **Lifetime:** Shorter than the b-hadrons by around a factor of 2-3, still enough for measureable decay length (around 1-3mm for a 50 GeV boost)
- **Mass:** Weakly decaying c-hadrons have masses around 2 GeV, around 2–3$\times$ lower than b-hadrons (mean of $\approx$ 2 charged particles per decay)
- **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



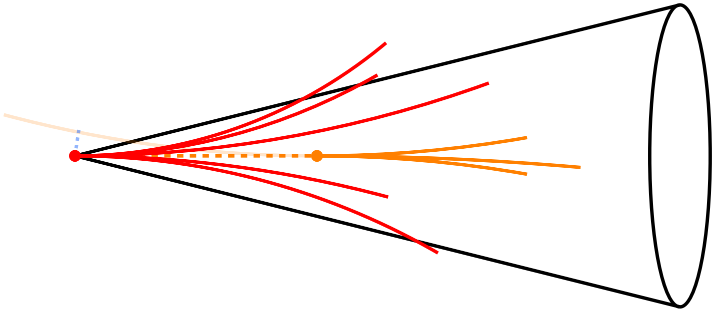
Right: c-quark fragmentation function



Typical Experimental Signature

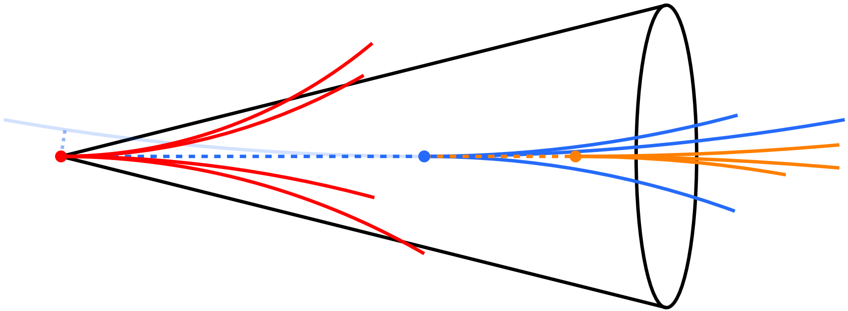
- Light-quarks hadronise into many light hadrons which share the jet energy
- Tracks from this vertex often have impact parameters consistent with zero
- Long-lived light hadrons (e.g. K_S^0, Λ^0) can be produced, though they are more likely to decay very far (many cm) from the primary pp vertex

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

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

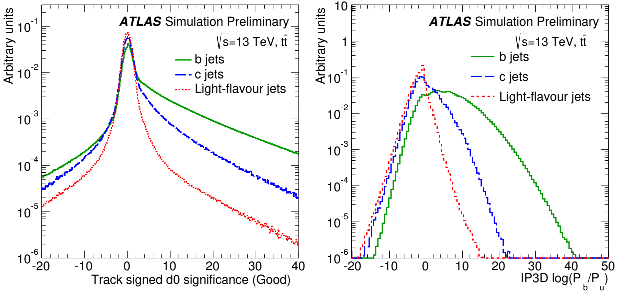
"Inclusive" charm jet tagging

- 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:

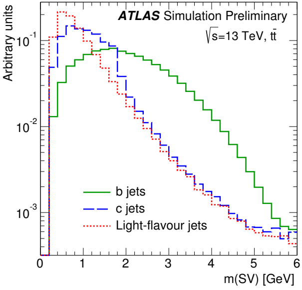
- Exploit "sign" of impact parameter: positive if track point of closest approach to PV is downstream of plane defined by the PV and jet axis
- Tracks from *b*-hadrons tend to have highly significant (IP/σ_{IP}) positive IPs, while most tracks from the PV have a narrow, symmetric distribution
- ✓ Very 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



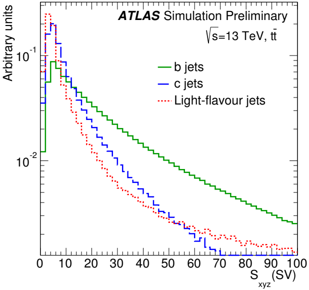
Left: Transverse IP significance distribution **Right: likelihood ratio discriminant based on 3D IPs of tracks**

Exploit expectation of a secondary vertex from either *b* or *c*-hadron decays:

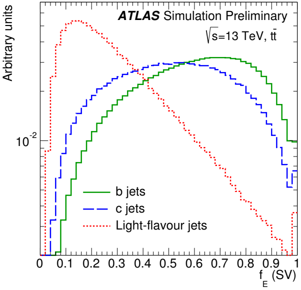
- Attempt to reconstruct a secondary vertex from high IP tracks associated with jet
- Use invariant mass of tracks at SV to discriminate *b* or *c*-hadron decay vertices from V^0 decays or material interations
- Exploit hard *c*/*b*-jet fragmentation, SV should carry a large fraction of jet energy
- ✓ 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



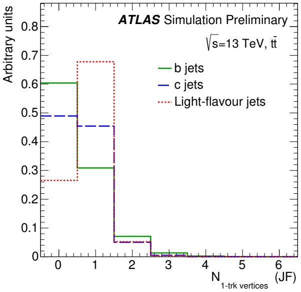
Centre: 3D SV decay length significance

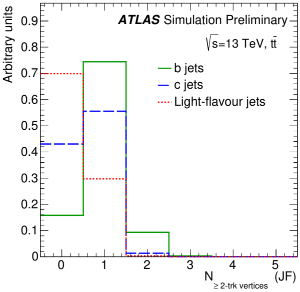


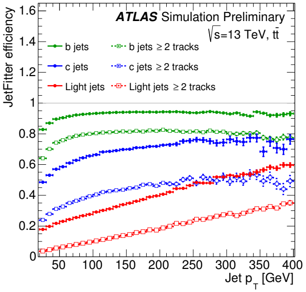
Right: Energy fraction of SV tracks

Exploit common occurance of cascade decay chain; *b*-hadron → *c*-hadron:

- Use Kalman filter to search for common axis on which three vertices lie: primary (*pp*) → secondary (*b*-hadron) → 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)





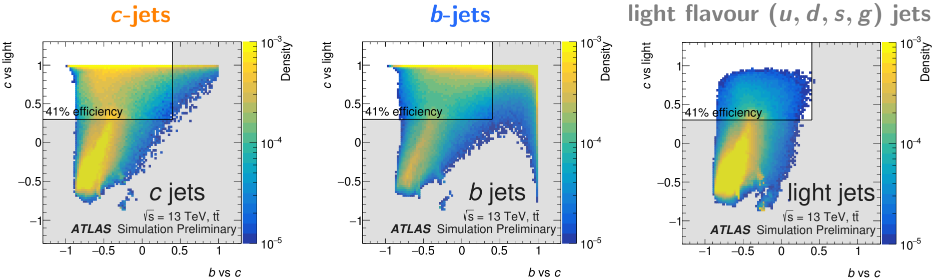


Left: Multiplicity of 1 track vertices **Centre: Multiplicity of 2+ track vertices** **Right: Chain reco. efficiency vs. jet p_T**

ATLAS High Level *c*-tagger - Bringing Everything Together

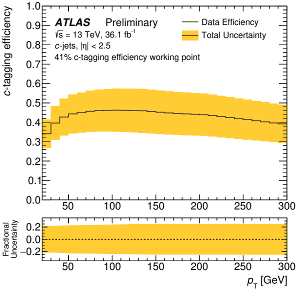
Combine approaches to exploit all features of c/b-jets and mitigate the shortcomings of the individual methods:

- ✓ 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)

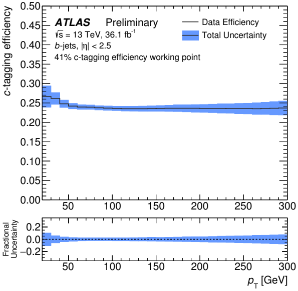


"c-tag" jets by making a cut in the 2D discriminant space, working point optimised for $H \to c\bar{c}$ is shown in the rectangular selection (shaded region rejected)

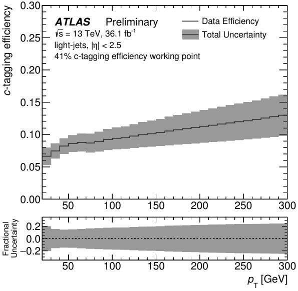
Performance of the ATLAS *c*-tagger



***c*-jets**



***b*-jets**



light flavour (u, d, s, g) jets

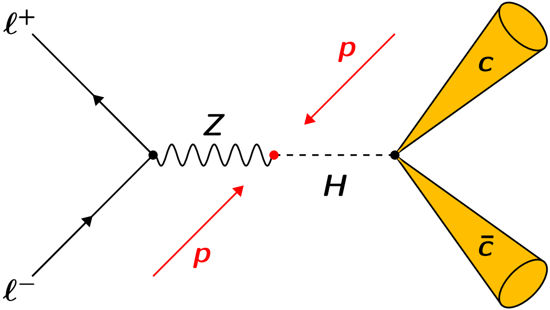
Efficiency of *c*-tagging algorithm for *b*-, *c*- and light flavour jets measured in data ↑

- 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× and light jets by around a factor 10×
- 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 $H \to c\bar{c}$ decays with ATLAS

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

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



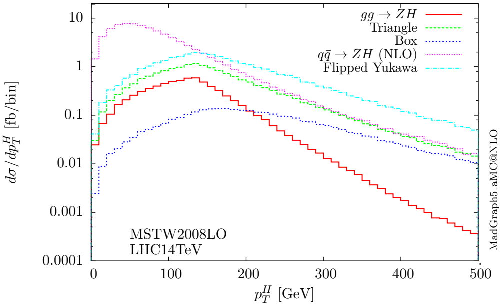
- **Focus on ZH production** with $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ decays for first ATLAS analysis (ATLAS-CONF-2017-078)
- Low exposure to experimental uncertainties, main backgrounds from $Z +$ jets, $Z(W/Z)$ and $t\bar{t}$
- Pioneer use of **new c-tagging algorithm** developed by ATLAS for Run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

† **ATLAS: arXiv:1708.03299 CMS: arXiv:1708.04188**

Introduction to $pp \to ZH$ production at the LHC

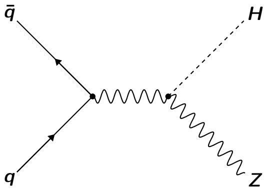
In $\sqrt{s} = 13$ TeV pp collisions, Higgs boson production in association with a Z boson represents around 1.6% of the inclusive Higgs boson production rate

- The cross-section is dominated by the $q\bar{q} \to ZH$ process, with total cross-section $\sigma_{q\bar{q}} \approx 0.76$ pb
- Smaller contributions from $gg \to ZH$, with total cross-section $\sigma_{gg} \approx 0.12$ pb, though it exhibits a harder p_T^H spectrum below ≈ 150 GeV

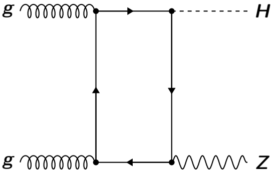


↑ **p_T^H distribution for $q\bar{q}$ and gg initiated ZH production (from arXiv:1503.01656)**

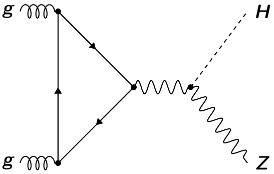
Representative Feynman diagrams for $q\bar{q}/gg \to ZH$ processes →



$q\bar{q} \to ZH$ 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 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

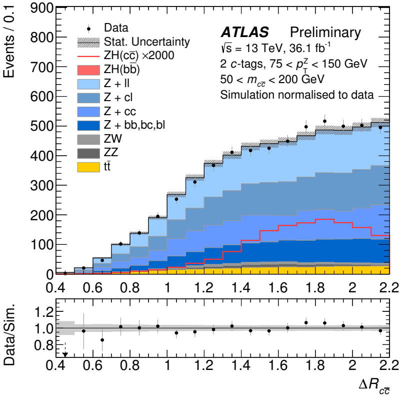
$H \to c\bar{c}$ Selection

- 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

Background Modelling

- Background dominated by $Z +$ 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 $W +$ jets, WW, single-top and multi-jet



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

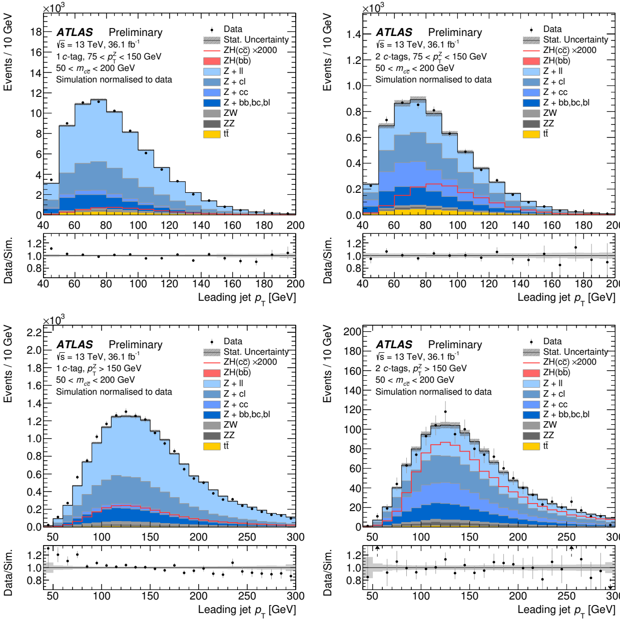
- Normalised with LHC Higgs XS WG YR4 recommendations (arXiv:1610.07922)
- $ZH(b\bar{b})$ treated as background normalised to SM expectation (with $\sigma \times \mathcal{B}$ uncertainty)

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)
$Z +$ 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

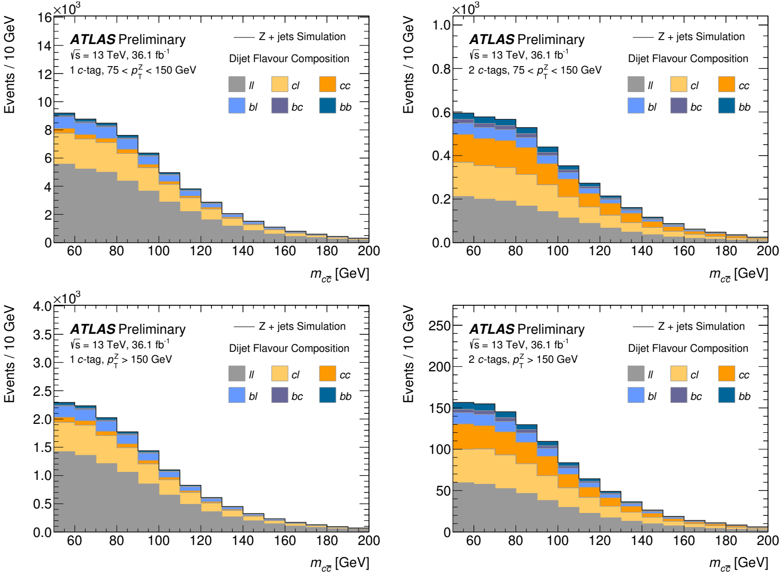
↓ Left: 1 c-tag events



↑ Right: 2 c-tag events

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

↓ Left: 1 c-tag events



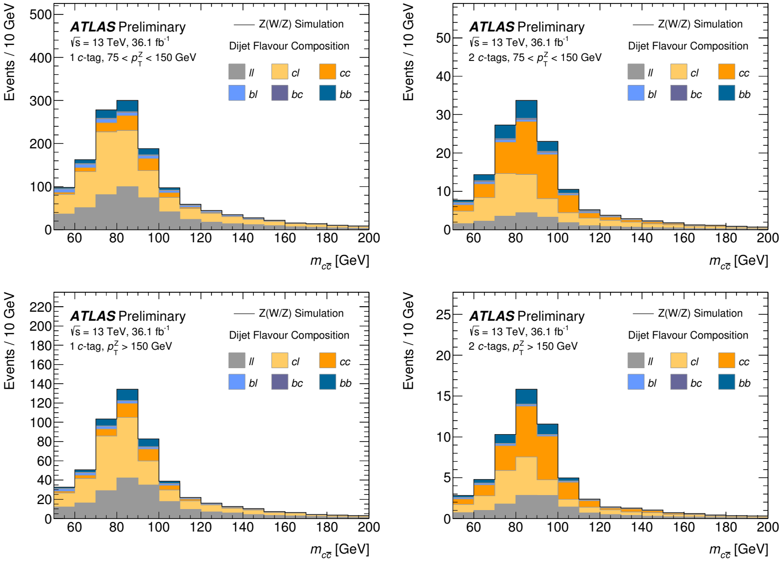
↑ Right: 2 c-tag events

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

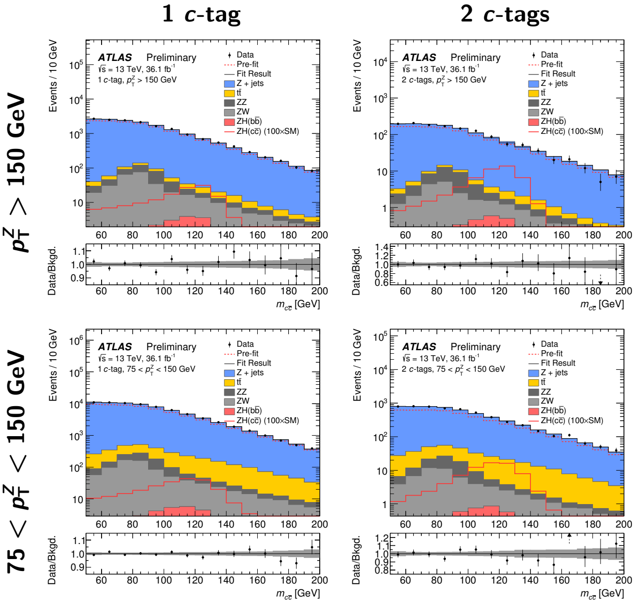
Understanding the Sensitivity

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 $\sum_i \sigma_i^2 \neq \sigma^2_{\text{Syst.}}$

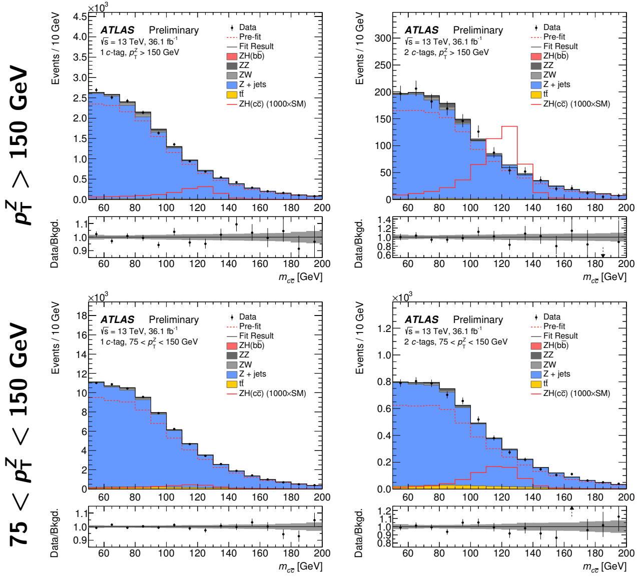
- Background modelling (particularly $Z+$jets shape uncertainties) followed by c-tagging uncertainties have the dominant impact
- However, we can expect many of these uncertainties (particularly effect of the $Z+$jets normalisation) to reduce with a larger dataset



- 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**



- 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**$\times$ the SM expectation

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

Warning: None of the following interpretation is sanctioned by ATLAS, responsibility lies solely with me!

Use the leading order motivated "kappa framework" to study how a potential modifications to the Higgs-charm coupling would affect $\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c})$

$$\sigma_i \cdot \mathcal{B}_j = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma_j(\vec{\kappa})}{\Gamma_H}$$

- 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 $\vec{\kappa}$ such that LO production or decay modes (e.g. $H \to c\bar{c}$) 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. $H \to \gamma\gamma$, $gg \to H$) can also be studied by "resolving" the loop in terms of their tree level couplings (e.g. $t\bar{t}H$)

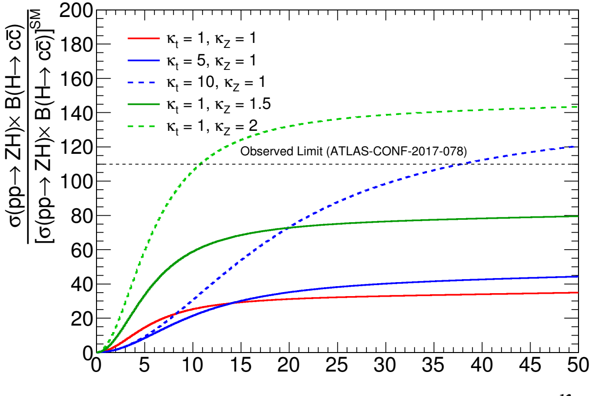
Can approximate modifications to $pp \to ZH$ cross section and $\mathcal{B}(H \to c\bar{c})$ with:

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

$$\mathcal{B}(H \to c\bar{c})(\kappa_c) = \frac{\kappa_c^2 \cdot \mathcal{B}(H \to c\bar{c})_{SM}}{1 + (\kappa_c^2 - 1) \cdot \mathcal{B}(H \to c\bar{c})_{SM}}$$

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

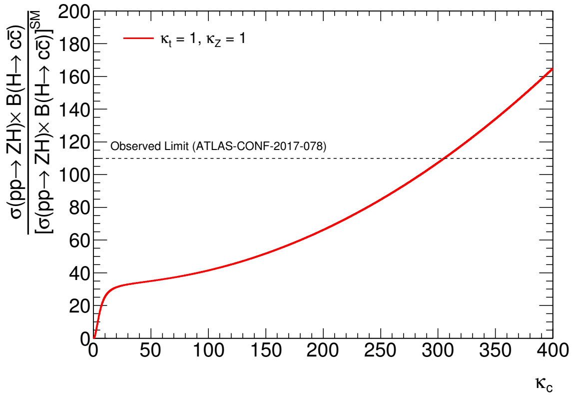
For SM $pp \to ZH$ production, the rate vs. κ_c saturates at around 33$\times$ the SM value when $\mathcal{B}(H \to c\bar{c}) \approx 1$ (far below the limit)... However, in a general BSM scenario, one could also expect the other Higgs couplings to be modified!

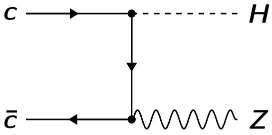


- In a scenario where the ZH coupling is modified (e.g. $\kappa_Z \approx 2$), strong bounds of **around $\kappa_c < 10$** can be obtained (assuming the predicted Γ_H, i.e. no new particles)
- Similarly, if one modifies the $t\bar{t}H$ coupling (e.g. $\kappa_t \approx 10$) bounds of **around $\kappa_c < 40$** are also possible, **BUT** both scenarios are strongly disfavoured by LHC data...

Interpreting the limit in terms of a constraint on y_c - III

For very large values of κ_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 additonal 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, Γ_H would be saturated by $H \rightarrow c\bar{c}$ decays

Summary

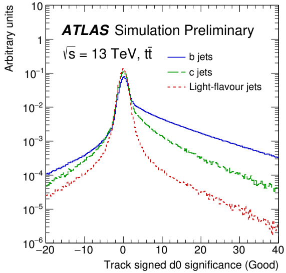
- Search for $\boldsymbol{ZH(c\bar{c})}$ production exploiting new c-tagging techniques provides limit of $\boldsymbol{\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c}) < 2.7\,\text{pb}}$ excluding **110× SM expectation**
- Demonstrates that this inclusive channel is likely more sensitive to the charm 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!

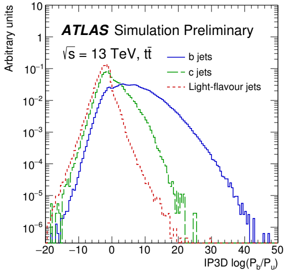
What next for inclusive $H \to c\bar{c}$ decays?

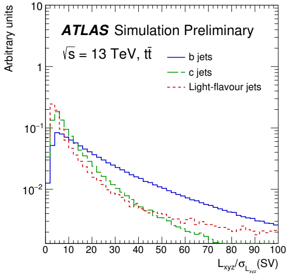
- Large gains in sensitivity possible with multivariate techniques and other VH channels (e.g. $W(\ell\nu)/Z(\nu\nu)$) or a dedicated search/category in the high p_T^H boosted regime
- If future c-tagging algorithms can reach the performance of today's b-tagging, one could expect to observe $H \to c\bar{c}$ 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!

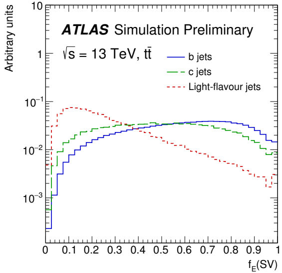
Additional Slides

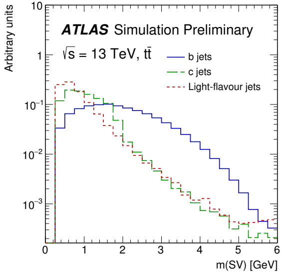
Examples of *c*-tagging input variables

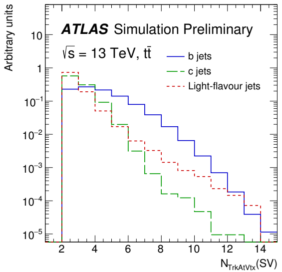










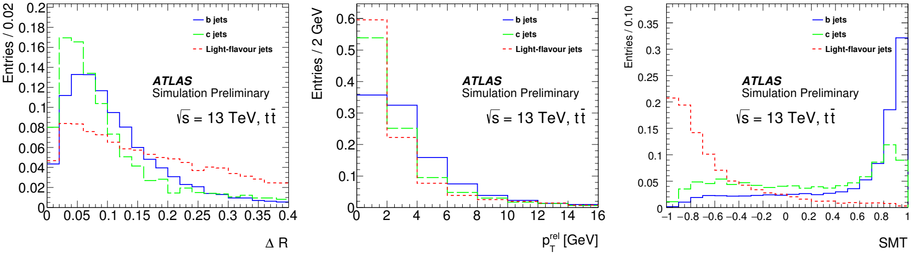


More details in ATL-PHYS-PUB-2016-012

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 $B \to DX \to \mu\nu X'$ ($\mathcal{B}$ 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**