COFUND. A project supported by the European Union

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

CMS Flavour Tagging Workshop, IIHE Brussels

11th April 2018

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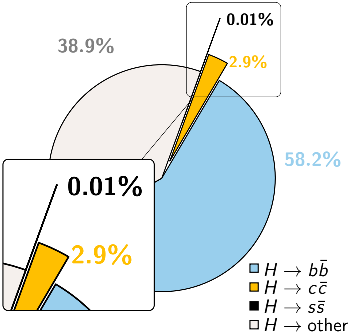
on behalf of the ATLAS collaboration

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?

How can we constrain the charm Yukawa couplings in a more direct way?

Exclusive $H \to J/\psi\,\gamma$ decays

- Exclusive radiative Higgs decays to J/ψ are sensitive to $Hc\bar{c}$ couplings, very rare in SM with $\mathcal{B}\,(H \to J/\psi\,\gamma) = (2.8 \pm 0.2) \times 10^{-6}$ (arXiv:1407.6695)
- Both ATLAS (arXiv:1501.03276) and CMS (arXiv:1507.03031) have searched for such decays, both leading to limits of $\mathcal{B}\,(H \to J/\psi\,\gamma) < 1.5 \times 10^{-3}$
- Implies bound on charm Yukawa coupling of $y_c/y_c^{SM} < 220$ at 95% CL (arXiv:1503.00290)
- **Side Note:** The analogous decays $H \to \phi\,\gamma$ and $H \to \rho\,\gamma$ are sensitive to the light quark Yukawa couplings (see arXiv:1712.02758)

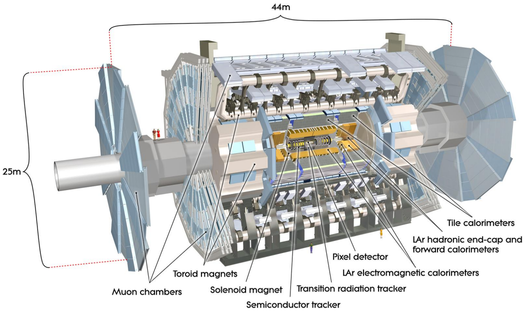
Kinematic distributions in inclusive production

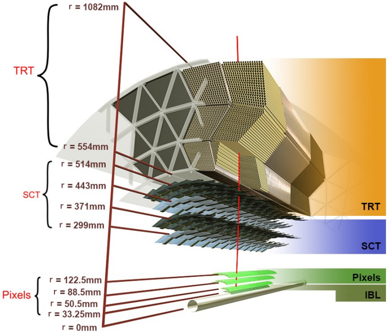
- Modifications to the heavy quark $\mathcal{Q} = c, b$ Yukawa couplings could change the shape of the inclusive p_T^H spectrum due to enhanced $g\mathcal{Q} \to H\mathcal{Q}$ contribution (arXiv:1606.09621)
- p_T^H well measured in the $H \to \gamma\gamma$ and $H \to 4\ell$ channels, which imposes a 95% CL bound of $-16 < y_c/y_c^{SM} < 18$, based on Run 1 ATLAS + CMS results (arXiv:1606.09253)

Inclusive $H \to c\bar{c}$ decays

- Study inclusive $H \to c\bar{c}$ decays with c-tagged jets, direct sensitivity to $Hc\bar{c}$ coupling
- First search from LHCb, though only sensitive to $\sim 5000\times$ SM rate (LHCb-CONF-2016-006)
- Recent ATLAS search for $Z(\ell\ell)H(c\bar{c})$ production (arXiv:1802.04329), **focus of this talk!**

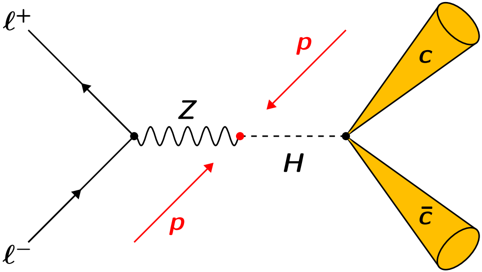
General purpose detector, well suited to studying heavy flavour jets

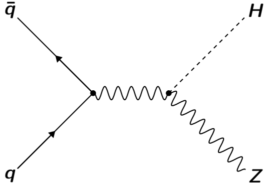




- **Inner Detector (ID):** Silicon Pixels and Strips (SCT) with Transition Radiation Tracker (TRT) $|\eta| < 2.5$ and (new for Run 2) Insertable B-Layer (IBL)
- **LAr EM Calorimeter:** Highly granular + longitudinally segmented (3-4 layers)
- **Had. Calorimeter:** Plastic scintillator tiles with iron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

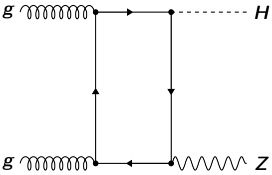
Given the success of the W/Z associated production channel in providing evidence for $H \to b\bar{b}$ decays†, this channel is an obvious first candidate for a $H \to c\bar{c}$ search





$pp \to ZH$ dominated $q\bar{q} \to ZH$ processes, $\sigma \approx 0.76$ pb at $\sqrt{s} = 13$ TeV

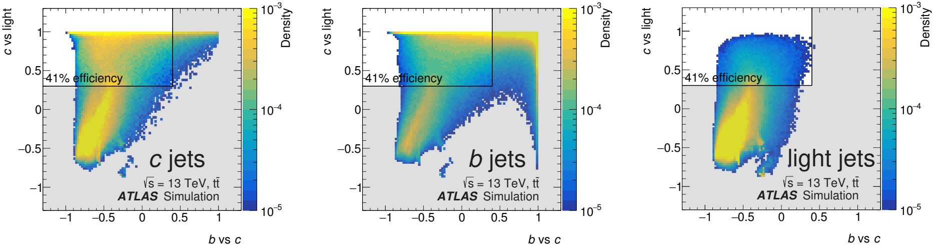
- **Focus on ZH production** with $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ decays for first ATLAS analysis
- Low exposure to experimental uncertainties, main backgrounds from $Z +$ jets, $Z(W/Z)$ and $t\bar{t}$
- Pioneer use of **new c-tagging algorithms** developed by ATLAS for Run 2 to identify the experimental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



Smaller contributions from $gg \to ZH$, but harder p_T^H, $\sigma \approx 0.12$ pb at $\sqrt{s} = 13$ TeV

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

New c-tagging algorithms developed by ATLAS for Run 2!

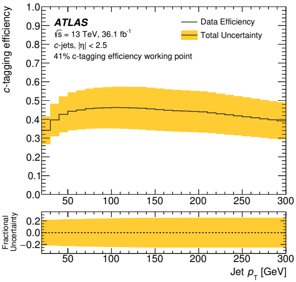


***c*-jets** **b-jets** **light flavour (u, d, s, g) jets**

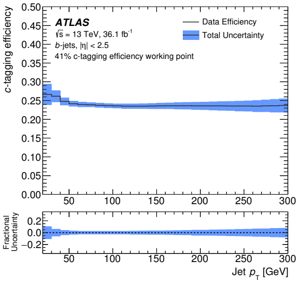
- Multivariate discriminant(s) built from input variables from low-level b-tagging algorithms (e.g. track impact parameter likelihood, secondary vertex finder)
- Trained with the same input variables used by the standard ATLAS Run 2 b-tagging algorithm (see ATL-PHYS-PUB-2015-022 for details)
- Implemented as two BDT 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 $ZH, H \rightarrow c\bar{c}$ is shown in the rectangular selection (shaded region rejected)

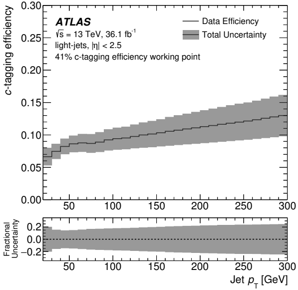
Introduction to *c*-jet tagging: Performance



_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 $ZH, H \to c\bar{c}$ 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 $t \to Wb$ (ATLAS-CONF-2014-004) and *c*-jets from $W \to cs, cd$ in $t\bar{t}$ events (ATLAS-CONF-2018-001)
- Typical total relative uncertainties of around **20%**, **5%** and **20%** for ***c*-**, ***b*-** and **light** jets, respectively

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 $p_{\mathrm{T}} > 7$ GeV and at least one with $p_{\mathrm{T}} > 27$ GeV
- Require opposite charges (dimuons only)
- $81 < m_{\ell\ell} < 101$ GeV
- $p_{\mathrm{T}}^{Z} > 75$ GeV

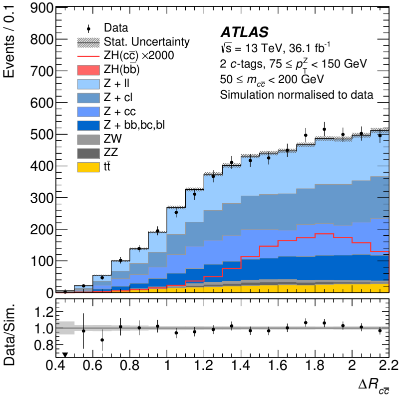
$H \to c\bar{c}$ Selection

- Consider anti-k_{T} $R = 0.4$ calorimeter jets with $|\eta| < 2.5$ and $p_{\mathrm{T}} > 20$ GeV
- At least two jets with leading jet $p_{\mathrm{T}} > 45$ 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 $ZH(c\bar{c}/b\bar{b})$

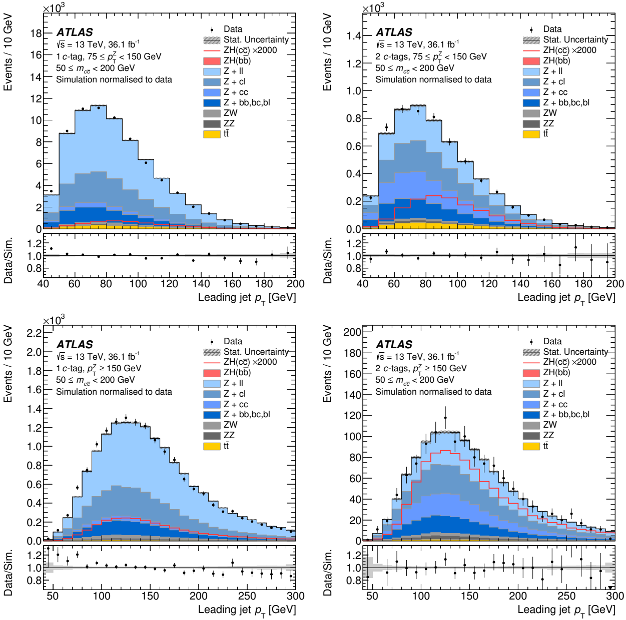
- Normalised with LHC Higgs XS WG YR4 recommendations (arXiv:1610.07922)
- $ZH(b\bar{b})$ treated as background normalised to SM expectation (with $\sigma \times \mathcal{B}$ uncertainty)

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

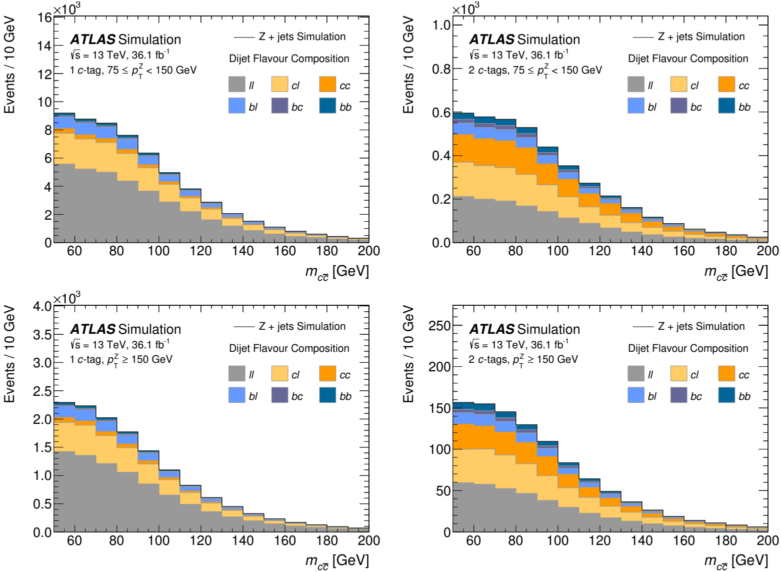


↑ Right: 2 c-tag events

$Z+$ jets flavour composition after c-tagging

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

↓ Left: 1 c-tag events

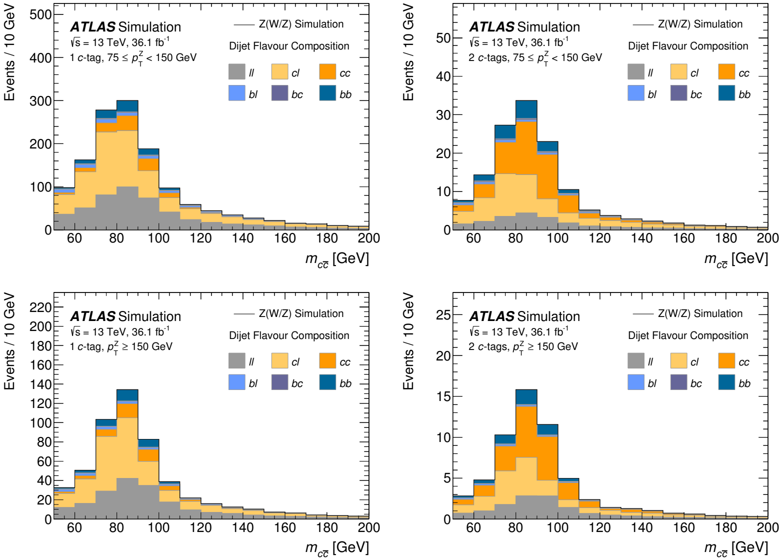


↑ Right: 2 c-tag events

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

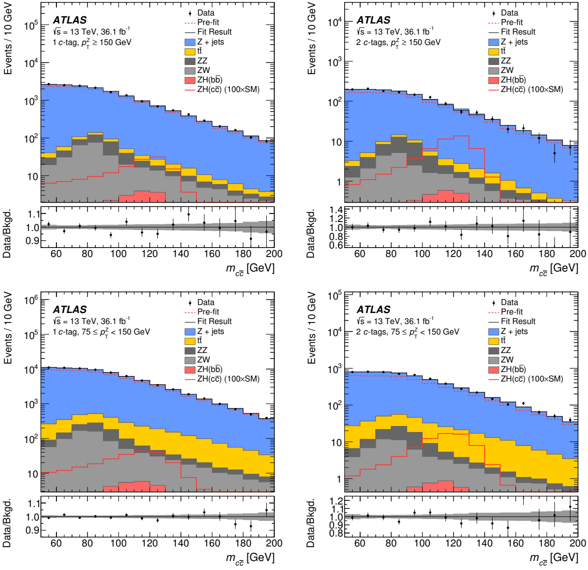
- Use the $H \to c\bar{c}$ candidate invariant mass $m_{c\bar{c}}$ as S/B discriminant
- Perform simultaneous binned likelihood fit to 4 categories within region $50 < m_{c\bar{c}} < 200$ GeV
- $ZH(c\bar{c})$ signal parameterised with free signal strength parameter, μ, common to all categories
- $Z +$ 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

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

$p_T^Z > 150$ GeV / **$75 < p_T^Z < 150$ GeV**



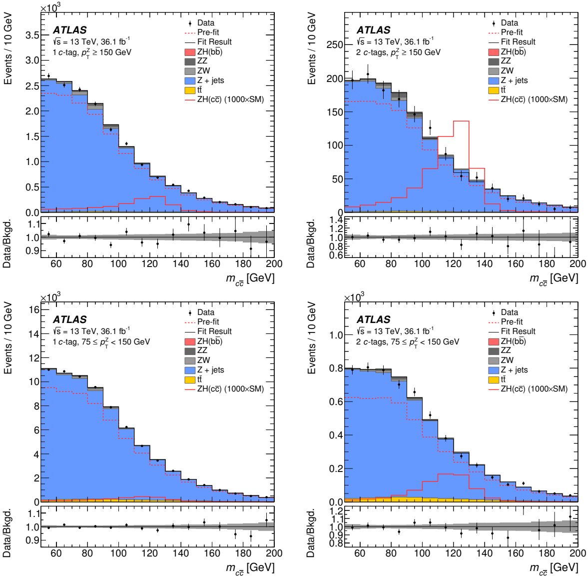
- No significant evidence for $ZH(c\bar{c})$ production
- Data consistent with background only hypothesis

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**

1 c-tag | 2 c-tags

$p_T^Z > 150$ GeV

$75 < p_T^Z < 150$ GeV



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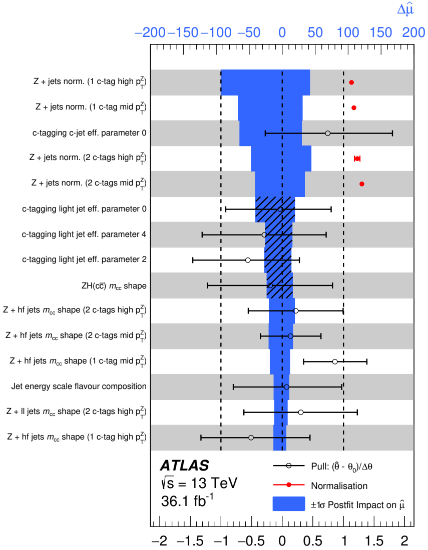
1 c-tag $75 < p_T^Z < 150$ GeV **2.1**
1 c-tag $p_T^Z > 150$ GeV **1.2**
2 c-tags $75 < p_T^Z < 150$ GeV **0.5**
2 c-tags $p_T^Z > 150$ GeV **0.3**

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 $\sum_i \sigma_i^2 \neq \sigma_{\text{syst.}}^2$

- *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 normalisation) to reduce with a larger dataset

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×** the SM expectation

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

Summary

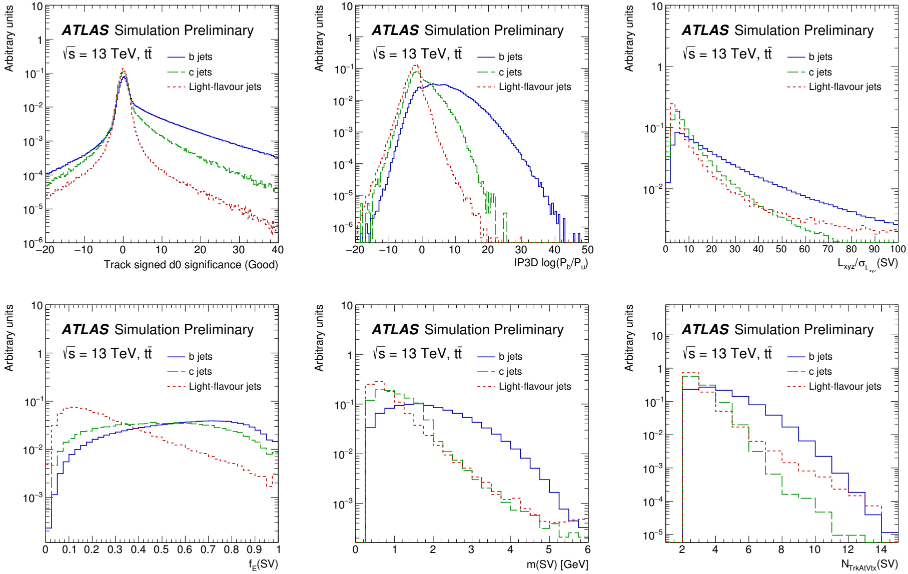
- Search for $\boldsymbol{ZH(c\bar{c})}$ production exploiting new c-tagging techniques provides limit of $\boldsymbol{\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c}) < 2.7\,\text{pb}}$ excluding **110× SM expectation**
- Demonstrates that this inclusive channel is likely more sensitive to the charm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

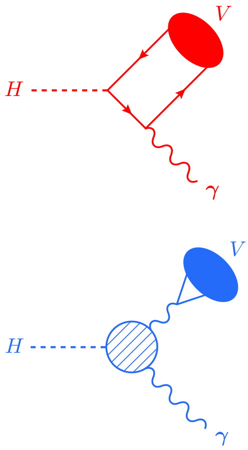
Examples of *c*-tagging input variables



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

$H \to \mathcal{Q}\,\gamma$ decays could provide a clean probe of the charm and light quark couplings

- $\mathcal{Q}$ is a vector ($J^{PC} = 1^{--}$) light meson or quarkonium state such as $V = J/\psi,\ \phi,\ \rho(770)$
- **Interference** between **direct** ($H \to q\bar{q}$) and **indirect** ($H \to \gamma\gamma^{*}$) contributions
- **Direct** (upper diagram) amplitude provides sensitivity to the **magnitude and sign** of the $Hq\bar{q}$ couplings (i.e. $\mathcal{Q} = J/\psi$ sensitive to $Hc\bar{c}$ coupling)
- **Indirect** (lower diagram) amplitude provides dominant contribution to the width, not sensitive to Yukawa couplings
- Very rare decays in the SM!



$$\mathcal{B}\,(H \to J/\psi\,\gamma) = (2.8 \pm 0.2) \times 10^{-6} \quad \ddagger$$
$$\mathcal{B}\,(H \to \phi\,\gamma) = (2.3 \pm 0.1) \times 10^{-6} \quad \dagger$$
$$\mathcal{B}\,(H \to \rho\,\gamma) = (1.7 \pm 0.1) \times 10^{-5} \quad \dagger$$

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

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

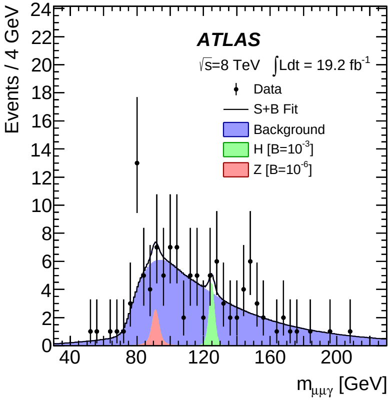
G. Aad *et al.**
(ATLAS Collaboration)

(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 quarkonium decays, in particular $H \to J/\psi\,\gamma$ (with $J/\psi \to \mu^+\mu^-$)
- Similar limit subsequently found by CMS†
- **First direct information** on decay modes sensitive to the $Hc\bar{c}$ coupling
- 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):

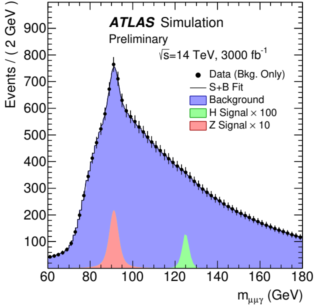
$$\mathcal{B}\,(H \to J/\psi\,\gamma) < 1.5 \times 10^{-3}$$

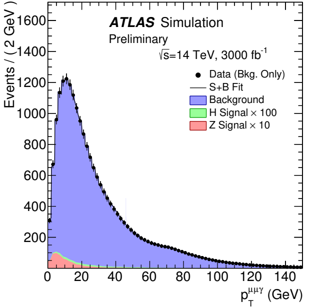
Around 500× the SM expectation

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

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

Prospects for $H \to J/\psi\,\gamma$ in a HL-LHC scenario





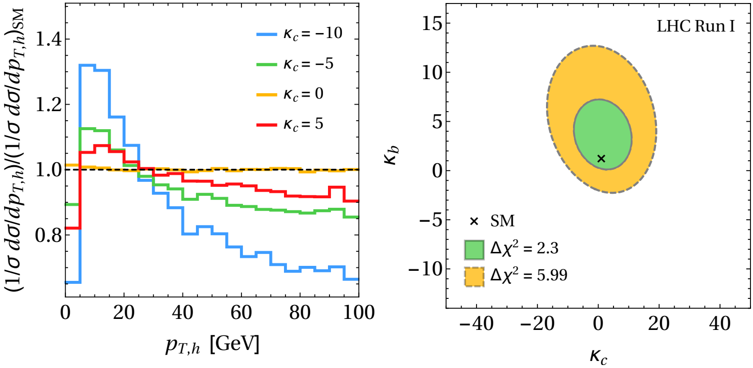
Run 1 $H \to J/\psi\,\gamma$ analysis projected to $\sqrt{s} = 14$ TeV scenario with 300(0) fb^{-1}

	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 $\mathcal{B}(H \to J/\psi\,\gamma)$ **15× SM value with 3000 fb^{-1}**
- New ideas likely required to reach SM sensitivity in a HL-LHC scenario!

More details in <u>ATL-PHYS-PUB-2015-043</u>



↑ **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 $-0.6 < y_c/y_c^{SM} < 3.0$