COFUND. A project supported by
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Constraining the charm and light quark Yukawa couplings with ATLAS

Higgs Couplings 2017, Heidelberg

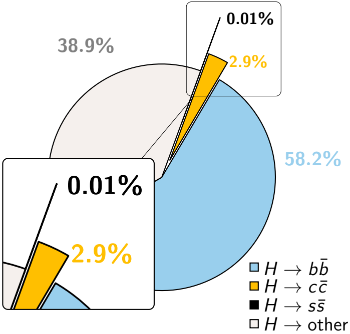
9th November 2017

Andy Chisholm (CERN)
on behalf of the ATLAS collaboration

Introduction

Why are the charm and light quark Yukawa couplings important?

- The smallness of the light (u, d, s) and charm (c) quark couplings ($y_q = \frac{\sqrt{2}m_q}{v} \approx \frac{m_q}{174\text{ GeV}}$) make them **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)
- Analogous but much looser bounds on the light (u, d, s) quark couplings...

Direct probes of the charm and light Yukawa couplings at the LHC

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

Exclusive $H \to \mathcal{Q}\,\gamma$ decays

- Rare exclusive radiative Higgs decays to vector mesons are sensitive to $Hq\bar{q}$ couplings
- **ATLAS Results:** Searches for the rare decays $H \to J/\psi\,\gamma$ (arXiv:1501.03276) and $H \to \phi/\rho\,\gamma$ (ATLAS-CONF-2017-057)

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

- Study inclusive $H \to c\bar{c}$ decays with c-tagged jets
- **ATLAS Results:** Search for $Z(\ell\ell)H(c\bar{c})$ production (ATLAS-CONF-2017-078)
- **New result for Higgs Couplings 2017!**

Kinematic distributions in inclusive production

- Shape of p_T^H or y^H distributions sensitive to modified Yukawa couplings (arXiv:1606.09621)
- **ATLAS Results:** Differential cross section measurements in $H \to \gamma\gamma$ (ATLAS-CONF-2017-045) and $H \to 4\ell$ channels (arXiv:1708.02810)

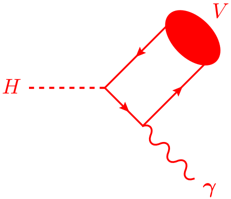
Will focus on the first two approaches, results pertinent to the third approach already covered by Monday's speakers

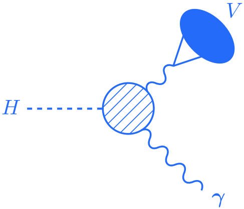
$H \to \mathcal{Q}\,\gamma$ - Introduction

$H \to \mathcal{Q}\,\gamma$ 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!

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

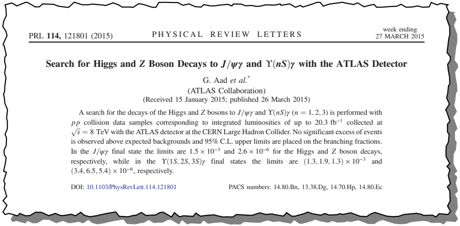




More details: † JHEP 1508 (2015) 012 (arXiv:1505.03870) and ‡ Phys. Rev. D 90, 113010 (2014) (arXiv:1407.6695)

$H \to J/\psi\,\gamma$ - 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

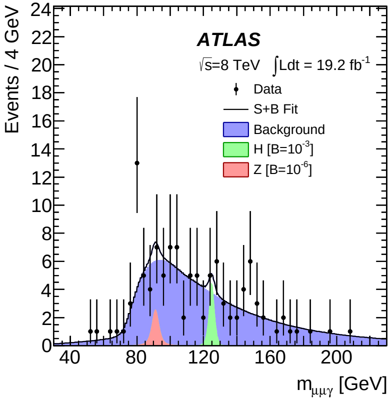
Search for Higgs and Z Boson Decays to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ with the ATLAS Detector

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 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

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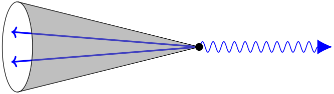
† Phys. Lett. B753 (2016) 341 (arXiv:1507.03031)

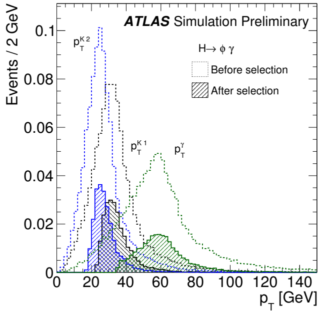
‡ Phys. Rev. D92, 033016 (2015) (arXiv:1503.00290)

$H \rightarrow \phi\gamma$ and $H \rightarrow \rho\gamma$ - Introduction (ATLAS-CONF-2017-057)

Recent search for $H/Z \rightarrow \phi/\rho\gamma$ using up to 35.5fb^{-1} of $\sqrt{s} = 13$ TeV *pp* collisions

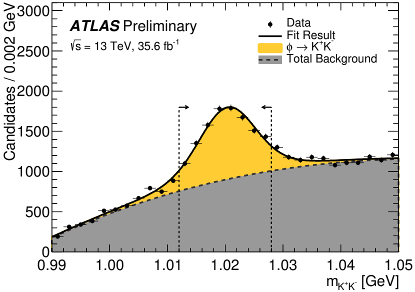


Decays characterised by high p_T isolated photon recoiling against high p_T pair of oppositely charged tracks



↑ **p_T distributions for $H \rightarrow \phi(K^+K^-)\gamma$ decay products, before and after selection**

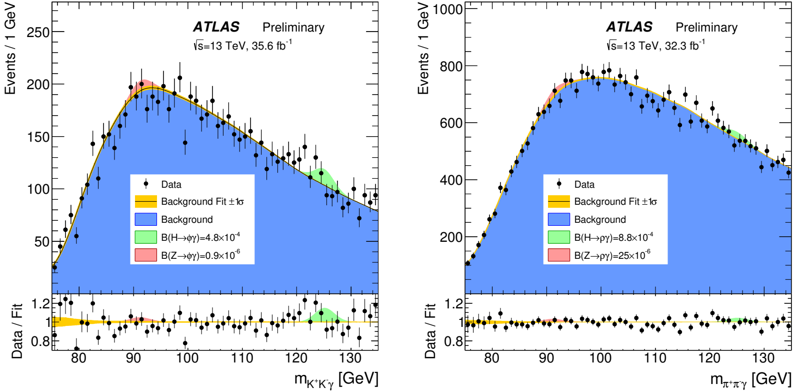
- Focus on high rate channels $\phi \rightarrow K^+K^-$ ($\mathcal{B} \approx 49\%$) and $\rho \rightarrow \pi^+\pi^-$ ($\mathcal{B} \approx 99\%$)
- Dedicated γ + di-track triggers (based on existing τ lepton triggers) developed
- Background dominated by γ + jet and multi-jet production, modelled with data-driven method



↑ **Clear ϕ meson peak observed for selected $K^+K^-\gamma$ candidates**

$H \to \phi\gamma$ and $H \to \rho\gamma$ - Run 2 Results

First constraint on the light quark Yukawa couplings from search for $H \to \rho\gamma$ decays!



↑ **Distribution of $K^+K^-\gamma$ (left) and $\pi^+\pi^-\gamma$ (right) candidate invariant mass**

- Limit on $H \to \phi\gamma$ improved by almost 2× w.r.t. earlier ATLAS search†

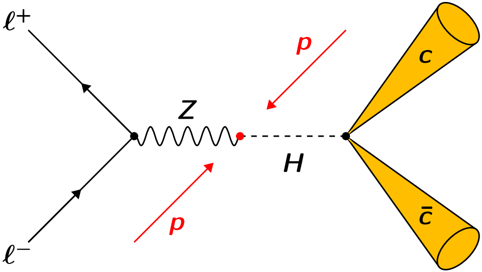
† Phys. Rev. Lett. 117 (2016), 111802 (arXiv:1607.03400)

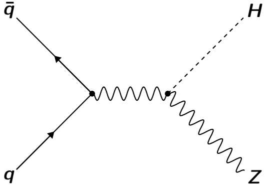
Decay	**Expected**	**Observed**	**Obs./$\mathcal{B}_{SM}$**
$\mathcal{B}(H \to \phi\gamma)$	$(4.2^{+1.8}_{-1.2}) \times 10^{-4}$	4.8×10^{-4}	**208×**
$\mathcal{B}(H \to \rho\gamma)$	$(8.4^{+4.1}_{-2.4}) \times 10^{-4}$	8.8×10^{-4}	**52×**

95% CL upper limits on $\mathcal{B}(H \to \mathcal{Q}\gamma)$, absolute and relative to SM prediction ↑

Introduction $ZH, H \to c\bar{c}$ (ATLAS-CONF-2017-078)

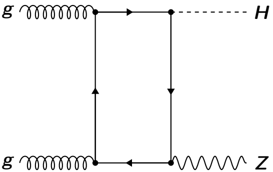
Given the success of the W/Z associated production channel in providing evidence for $H \to b\bar{b}$ decays†, this channel is an obvious first candidate for a $H \to c\bar{c}$ search





$pp \to ZH$ 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

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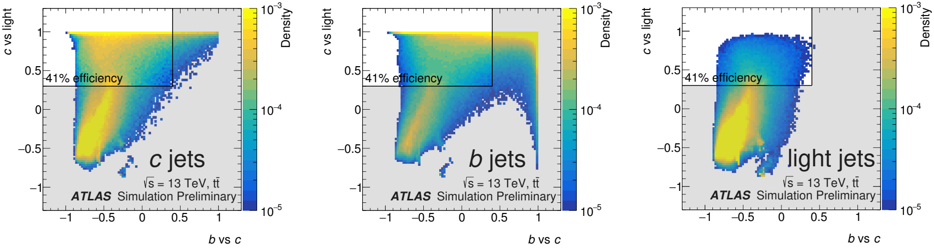
† ATLAS: arXiv:1708.03299 CMS: arXiv:1708.04188

Introduction to jet *c*-tagging: Algorithm

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

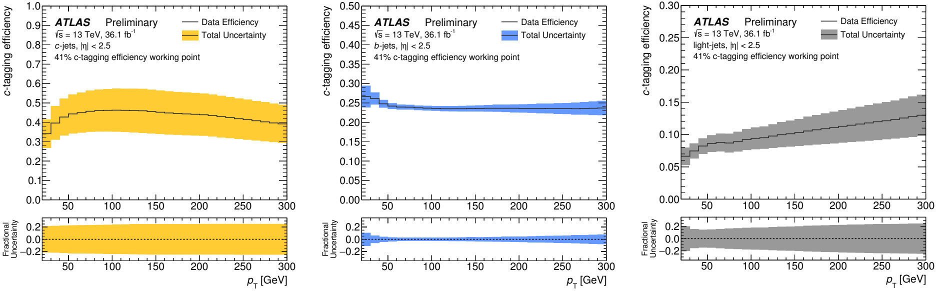


c-jets **b-jets** **light flavour (u, d, s, g) jets**

- 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 jet *c*-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 $4\times$ 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 **20%**, **5%** and **20%** for ***c*-**, ***b*-** and **light** jets, respectively

Data Sample and Event Selection

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

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

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

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

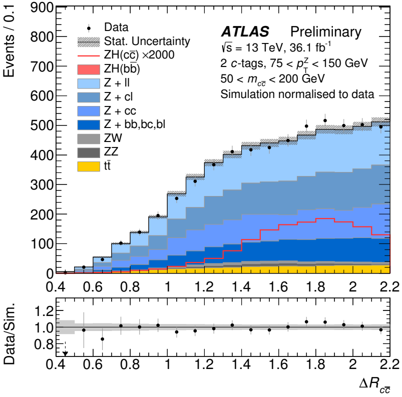
- Consider anti-k_T $R = 0.4$ calorimeter jets with $|\eta| < 2.5$ and $p_\text{T} > 20$ GeV
- At least two jets with leading jet $p_\text{T} > 45$ GeV
- Form $H \rightarrow c\bar{c}$ candidate from the two highest p_T jets in an event
- At least one c-tagged jet from $H \rightarrow c\bar{c}$ candidate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

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

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

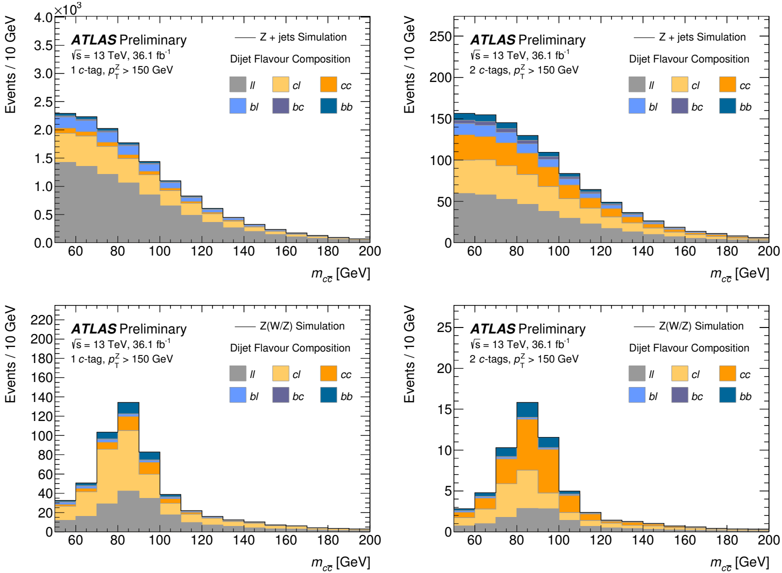
- Normalised with LHC Higgs XS WG YR4 recommendations (arXiv:1610.07922)
- $ZH(b\bar{b})$ treated as background normalised to SM expectation (with $\sigma \times \mathcal{B}$ uncertainty)

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)
$Z + \text{jets}$	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

Upper: Flavour composition of the $Z + \text{jets}$ sample enriched with c-jets



Lower: c-tagged $Z(Z/W)$ production enriched in $Z \to c\bar{c}$ and $W \to cs, cd$ decays

↓ Left: 1 c-tag events

↑ Right: 2 c-tag events

Quantifying the presence/absence of $ZH(c\bar{c})$ production

Statistical Model

- Use the $H \to c\bar{c}$ 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

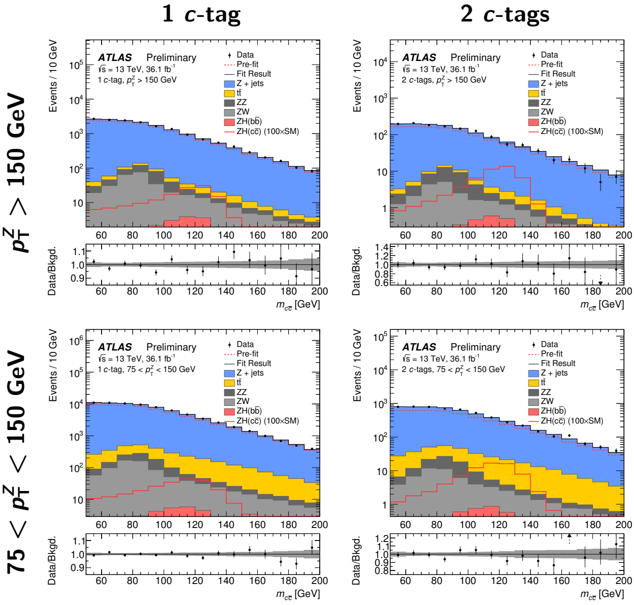
Sensitivity dominated by systematic uncertainties, clear that these uncertainties should be reduced in order to fully exploit a larger dataset in the future

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

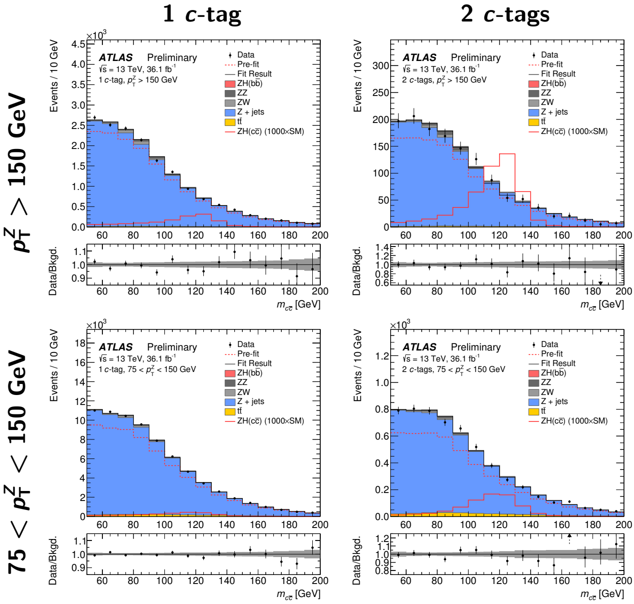
Fit Result



- 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**

Fit Result



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SM expected number of $ZH(c\bar{c})$ events
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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**

Results

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

Summary and Prospects

ATLAS is pioneering the study of several novel channels sensitive to the charm and light quark Yukawa couplings

- Limit on $\mathcal{B}\,(H \to J/\psi\,\gamma)$ corresponds to an upper bound on the **$Hc\bar{c}$ coupling of 220× SM expectation**
- New search for $ZH(c\bar{c})$ production exploiting new c-tagging techniques provides limit of $\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c}) < 2.7\,\text{pb}$ excluding **110× SM expectation**
- Limits on $\mathcal{B}\,(H \to \phi(\rho)\,\gamma)$ exclude values above **208(52)× SM expectations**

These channels will become ever more important as larger datasets are collected!

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

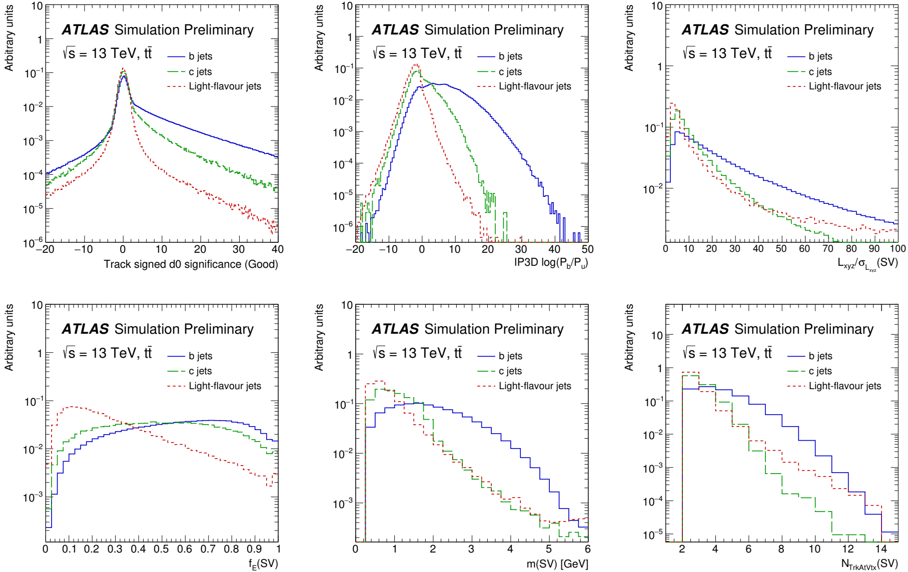
- Large gains in sensitivity possible with multivariate techniques and other VH channels (e.g. $W(\ell\nu)/Z(\nu\nu)$) or a dedicated search/category in the high p_T^H boosted regime
- Performance of c-tagging is developing rapidly, next generation of algorithms exploiting advanced ML techniques (ATL-PHYS-PUB-2017-013)

What next for exclusive $H \to \mathcal{Q}\,\gamma$ decays?

- Limit on $H \to \rho\,\gamma$ "only" 52× from SM expectation with $32\,\text{fb}^{-1}$, very promising for HL-LHC scenario
- First "proof of principle" analyses employ cut-based selection, scope for improvement with advanced MVA techniquies, distinct signatures with several handles to exploit

Additional Slides

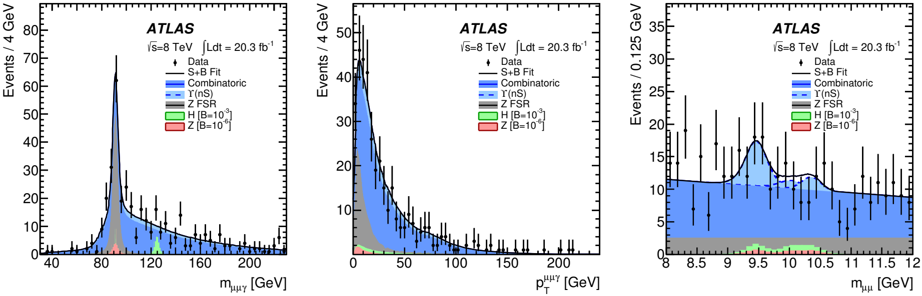
Examples of *c*-tagging input variables



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

Search for of $H/Z \to \Upsilon(nS)\gamma$

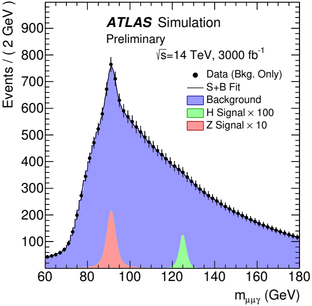
$H \to \Upsilon(nS)\gamma$ decays sensitive to magnitude and sign of $Hb\bar{b}$ coupling

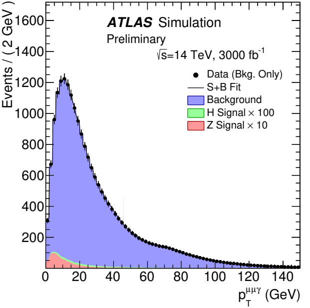


- Within same analysis, seach for $H \to \Upsilon(nS)\gamma$ also performed
- Much rarer decay than J/ψ case due to near cancelation in interference between direct/indirect aplitudes
- $\mathcal{B}(H \to \Upsilon(1S)\gamma) \approx 6 \times 10^{-10}$ predicted within SM (arXiv:1407.6695)

	95% CL_s Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum^n \Upsilon(nS)$
$\mathcal{B}(Z \to \mathcal{Q}\gamma)$ [10^{-6}]					
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
$\mathcal{B}(H \to \mathcal{Q}\gamma)$ [10^{-3}]					
Expected	$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed	1.5	1.3	1.9	1.3	2.0
$\sigma(pp \to H) \times \mathcal{B}(H \to \mathcal{Q}\gamma)$ [fb]					
Expected	26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed	33	29	41	28	44

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!

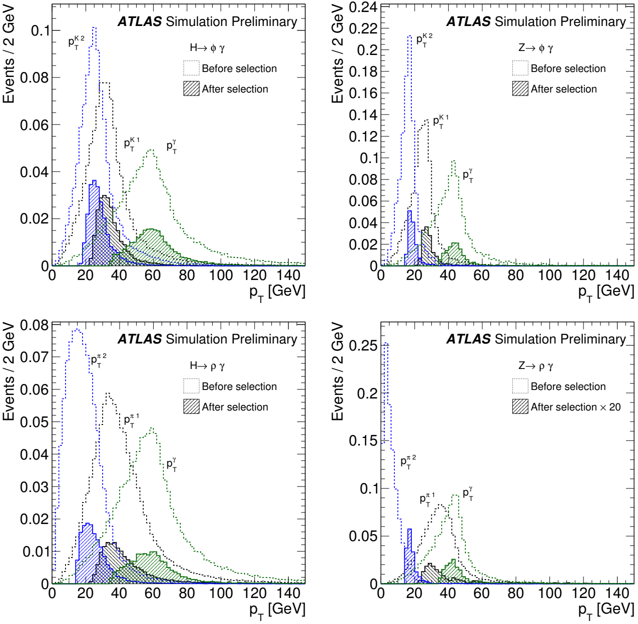
More details in ATL-PHYS-PUB-2015-043

$H \to \phi\gamma$ and $H \to \rho\gamma$ - Run 2 Results

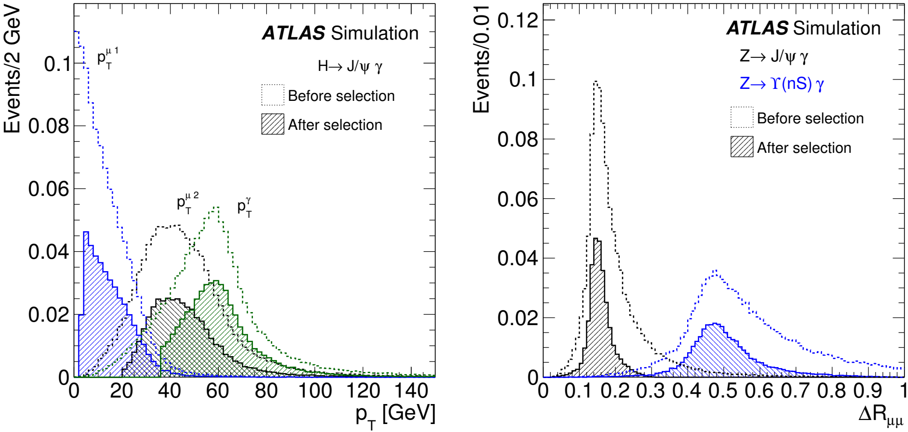
Decay	Expected	Observed	Obs./$\mathcal{B}_{SM}$
$\mathcal{B}(H \to \phi\gamma)$	$(4.2^{+1.8}_{-1.2}) \times 10^{-4}$	4.8×10^{-4}	**208×**
$\mathcal{B}(Z \to \phi\gamma)$	$(1.3^{+0.6}_{-0.4}) \times 10^{-6}$	0.9×10^{-6}	**87×**
$\mathcal{B}(H \to \rho\gamma)$	$(8.4^{+4.1}_{-2.4}) \times 10^{-4}$	8.8×10^{-4}	**52×**
$\mathcal{B}(Z \to \rho\gamma)$	$(33^{+13}_{-9}) \times 10^{-6}$	25×10^{-6}	**595×**

95% CL upper limits on $\mathcal{B}(H, Z \to \mathcal{Q}\gamma)$, absolute and relative to SM prediction ↑

Kinematics of $H/Z \to \phi/\rho\,\gamma$ events



Kinematics of $H/Z \to J/\psi\,\gamma$ events



More details in HIGG-2014-03