Direct Search for the Higgs Boson to Charm Quarks Coupling at ATLAS

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on behalf of the ATLAS Collaboration

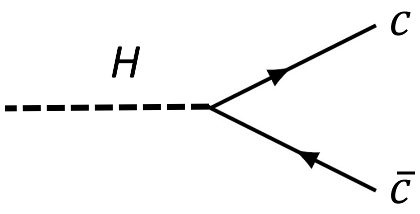
La Thuile 2022

10th March 2022

Motivation

- Couplings of Higgs field to quarks and leptons – Yukawa couplings - are a potential source of the fermion masses
- **Interaction so far only observed for 3rd generation of fermions** (top, bottom and tau) and evidence found for coupling with muons
- **Yukawa couplings don't explain the large disparities between the fermion masses**
- **There is no guarantee all Higgs fermion couplings behave in a similar way**
- **Of utmost importance to measure all Higgs couplings to fermions!**

- Probability of Higgs boson decays to charm quarks of 3.9% in Standard Model
- **Standard Model Higgs** Yukawa **coupling** to charm quarks is rather **small** ($y_c = \sqrt{2}\, m_c(\mu{=}m_H)/v \simeq 0.2 \times y_b$)
- Susceptible to **significant modifications** in some **new physics** scenarios[+] (e.g. two Higgs doublet models)
- **One of largest contributions to Γ_H** (by SM expectations) **yet to be established experimentally**

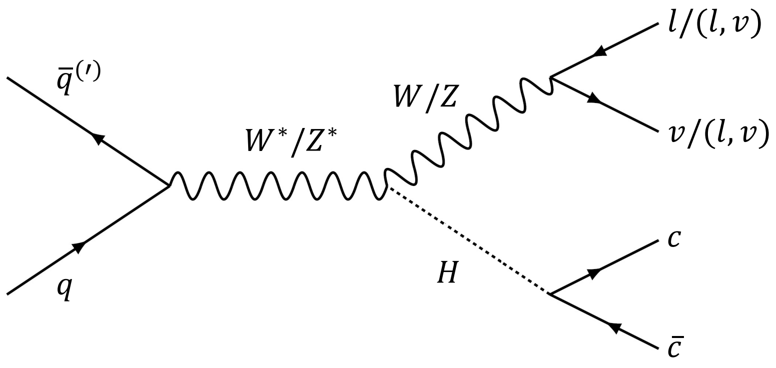


[+] PRD 94 (2016) 115031, PLB 755 (2016) 504, PRD 98 (2018) 055001

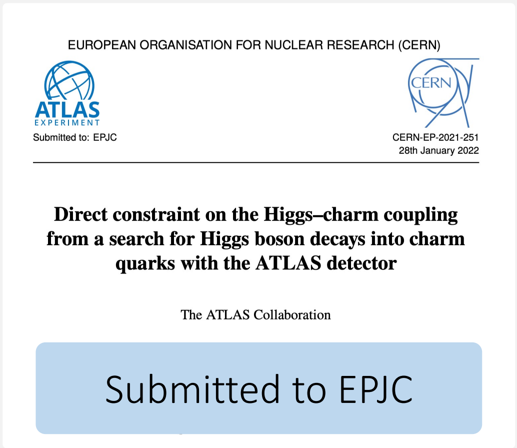
VH (H → $c\bar{c}$) Searches

Note: $\mu_{\mathrm{VH\ (H \to c\bar{c})}} = \frac{\sigma(\mathrm{VH})\times \mathrm{BR}(\mathrm{H} \to c\bar{c})_{\mathrm{observed}}}{\sigma(\mathrm{VH})\times \mathrm{BR}(\mathrm{H} \to c\bar{c})_{\mathrm{SM}}}$

- Built around the use of **c-jet tagging algorithms**
- Targeting **VH production (V = W, Z)**
  - W/Z boson decays into leptons allow for a **convenient trigger strategy**
  - **Suppression of multi-jet backgrounds**
  - **Enhanced Signal over Background ratio** w.r.t to inclusive Higgs production



- ATLAS Early Run 2 with integrated luminosity of L = 36.1 fb^{-1} (PRL 120 (2018) 211802)
  - Z(→*ll*)H(→$c\bar{c}$) production targeted
  - Observed (expected) upper limit $\mu_{\mathrm{ZH\ (H \to c\bar{c})}}$ at 95% C.L. of 110 (150^{+80}_{-40}) × SM
- ATLAS Full Run 2 analysis (arXiv:2201.11428v1) →
  - **Integrated luminosity of L = 139 fb^{-1}**
  - **Z(→ *νν*)H(→ $c\bar{c}$), W(→ *lν*)H(→ $c\bar{c}$), Z(→ *ll*)H(→ $c\bar{c}$)** productions targeted
  - **Combination of VH (H → $c\bar{c}$) and VH (H → $b\bar{b}$) analyses** for improved constraints on coupling modifiers


EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: EPJC

CERN-EP-2021-251
28th January 2022

Direct constraint on the Higgs–charm coupling from a search for Higgs boson decays into charm quarks with the ATLAS detector

The ATLAS Collaboration

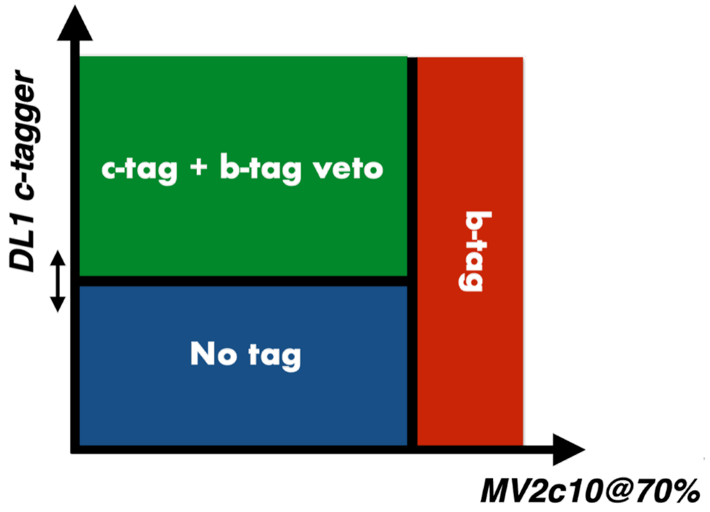
Submitted to EPJC

Equivalent CMS studies: CMS Run 2 with L = 35.9 fb^{-1} (JHEP 2003 (2020) 131), CMS Full Run 2 with L = 138 fb^{-1} (CMS-PAS-HIG-21-008)

Flavour Tagging Design

Dedicated working point and optimised for the analysis built from two components

- **DL1** (deep neural network) algorithm: **c-tagger**
- **MV2c10** (boosted decision tree): b-tagger, for b-jets vetoes, using the 70% b-jet efficiency working point
- **'c-tagged' jet** must pass both conditions, i.e, have a c-tag with a b-veto
- **Additional jets** to the two forming the Higgs candidate have a b-tag veto
- **Signal regions orthogonal to VH ($H \to b\bar{b}$) analysis** (allowing for combination)

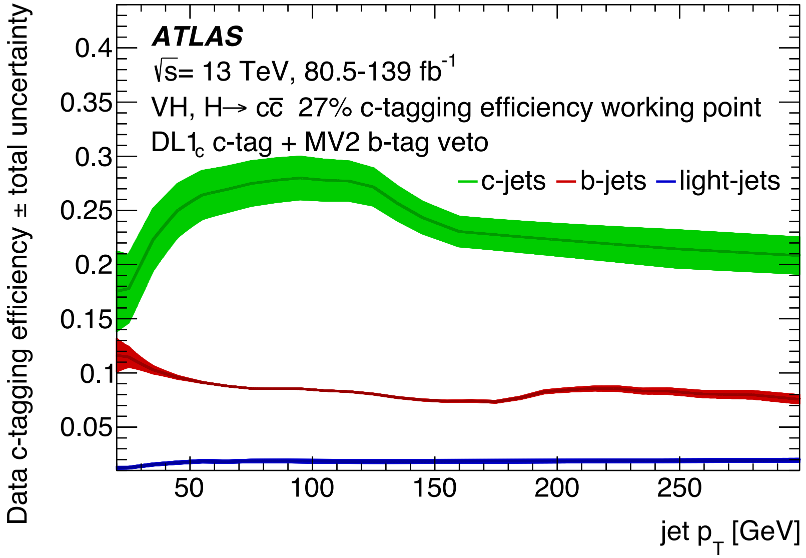


Efficiencies

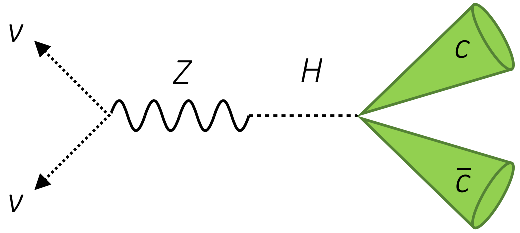
- Signal more sensitive to rejection of light jets than b-jets

Jet Flavour	Efficiency (Rejection)
c-jets	27% (-)
b-jets	8% (13)
Light flavour jets	1.6% (63)

- Efficiency in data measured relative to simulation as a "scale factor" with a **typical precision of 5 - 10% and generally consistent with unity**

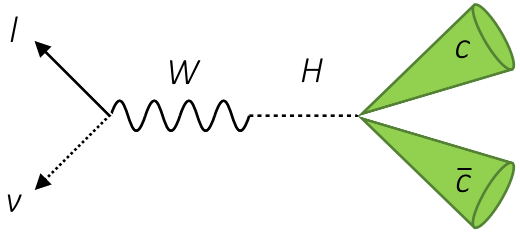


Analysis Strategy



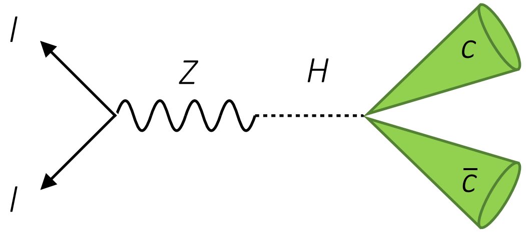
0 lepton (0L) channel

- Large missing transverse energy



1 lepton (1L) channel

- Large missing transverse energy
- One electron or muon



2 lepton (2L) channel

- e^+e^- or $\mu^+\mu^-$ pairs

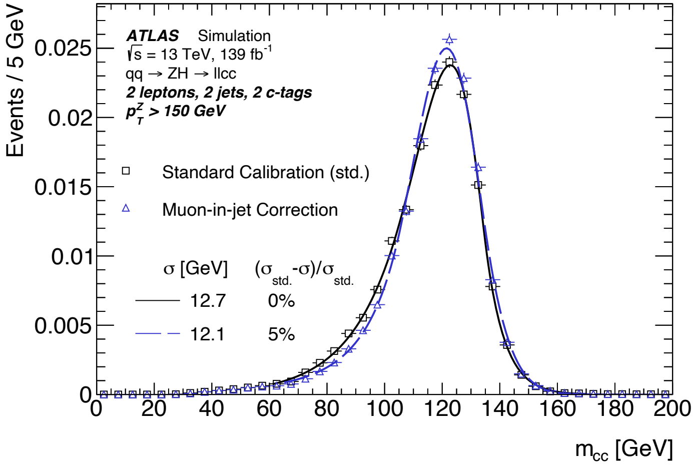
Event Categorisation

- p_T^V is p_T of associated vector boson produced

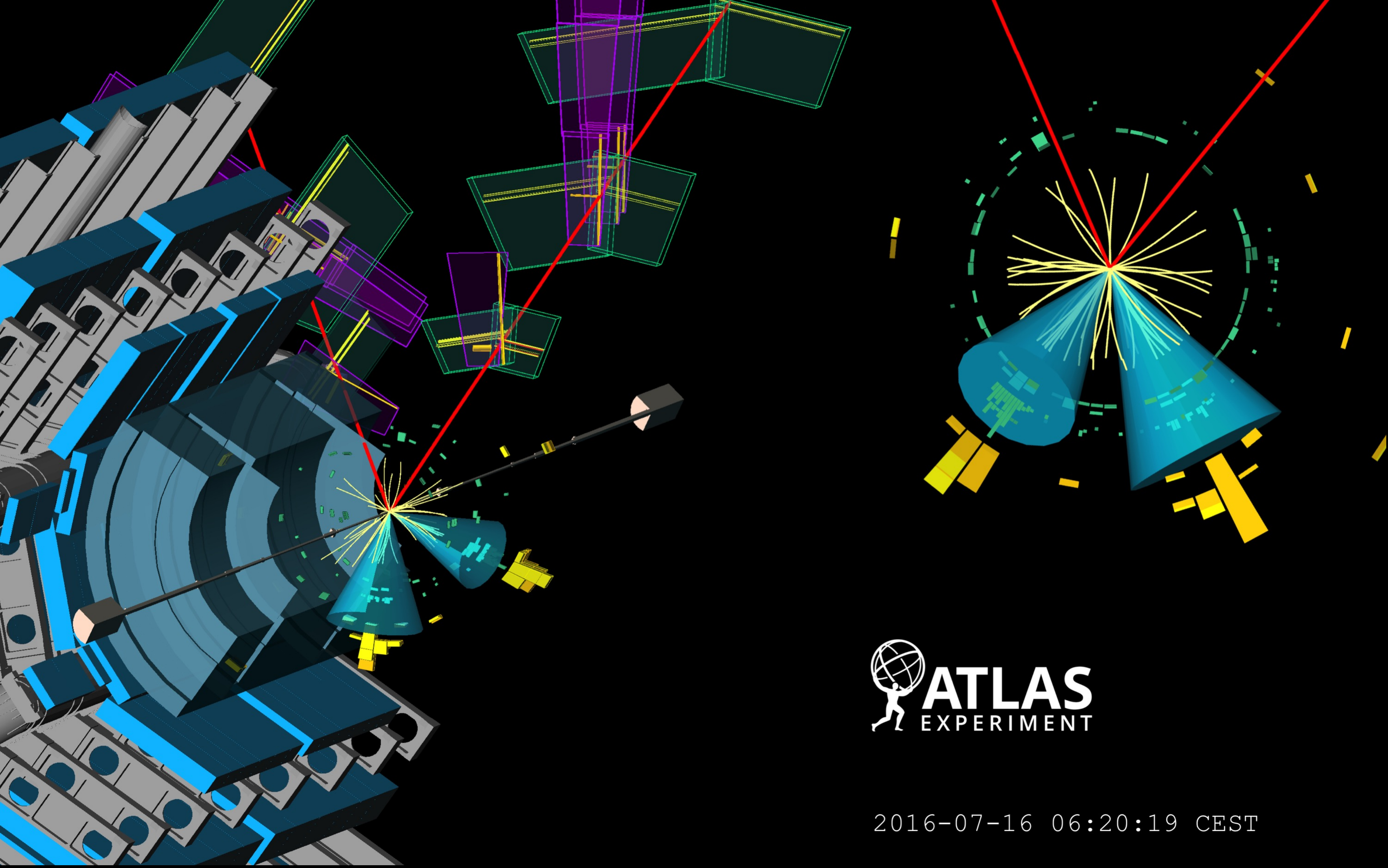
Channel	Tag categories	nJets	p_T^V
0 lepton	1 and 2 c-tags	2 and 3 jets	p_T^V > 150 GeV
1 lepton			
2 lepton		2 and 3+ jets	75 < p_T^V < 150 GeV
			p_T^V > 150 GeV

Higgs candidate selection

- **Higgs candidate:** two highest p_T jets
- **c-tag** with **b-veto** on two **Higgs candidate jets**
- **b-veto** on **additional jets**
- **ΔR(cc) selection optimised** for VH($c\bar{c}$) sensitivity



2 lepton event



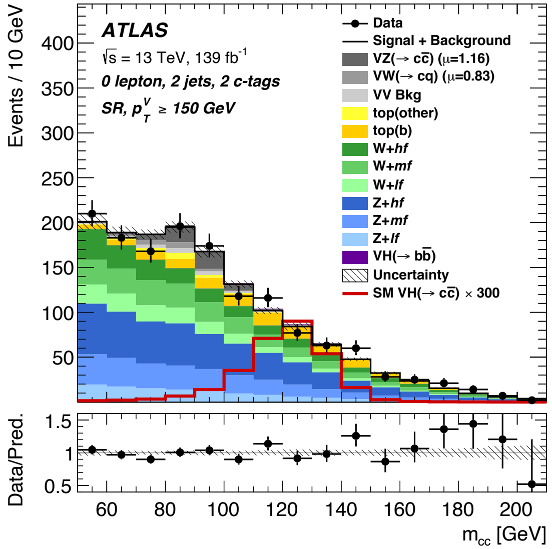
Z(μμ)H(c$\bar{c}$) candidate event

- Muon
- Jet
- EM Calorimeter cluster
- Hadronic Calorimeter cluster

Two muons with a di-lepton invariant mass of 92 GeV. The reconstructed Z boson has a transverse momentum of 150 GeV. The Higgs boson candidate is reconstructed from two charm-tagged R=0.4 jets. The leading and sub-leading jets have transverse momenta of 123 GeV and 71 GeV respectively. The Higgs boson candidate has a reconstructed invariant mass of 123 GeV.

Signal and Control Regions (SR & CR)

0 lepton SR



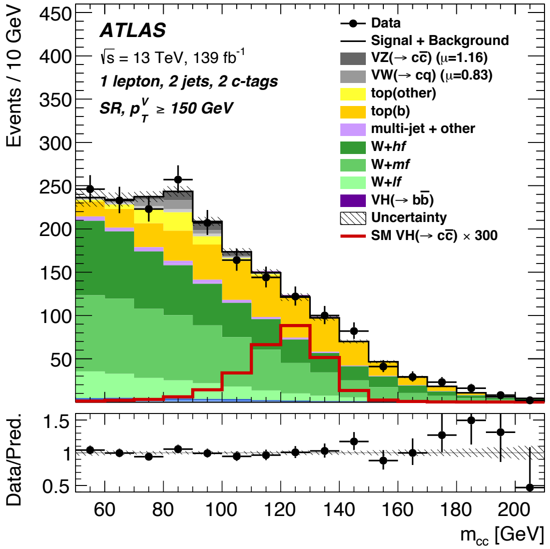
Main backgrounds

Z+jets | W+jets | Top

Subdominant backgrounds

VW and VZ production

1 lepton SR



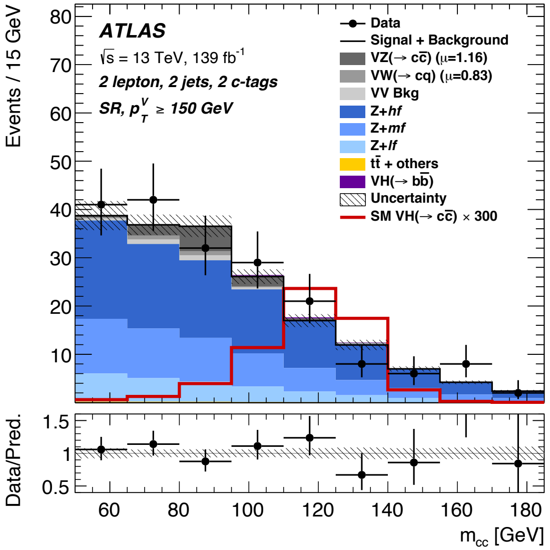
Main backgrounds

W+jets | Top

Subdominant backgrounds

VW and VZ production; Multi-jet

2 lepton SR



Main backgrounds

Z+jets

Subdominant backgrounds

VW/VZ production; Top processes

Control Regions

- High ΔR CR – **Constrain modelling of W/Z+jets:** Events with ΔR_{jj} > SR cuts and ΔR_{jj}< 2.5
- Top CRs - **Constrain modelling of top processes: inverted b-tag veto** in 1 c-tag, 3 jets events in 0L/1L; **$e^{\pm}\mu^{\mp}$ events** w/ 1 c-tag in 2L
- 0-tag CR – **Constrain normalisations of W/Z+jets light flavour component**: in 1/2L events

Fit Strategy

$$\mathcal{L}(\boxed{\mu},\vec{\theta},\vec{\gamma}) = \prod_{i\,\epsilon\,\text{bins}} \boxed{Poiss(N_i\,|\,\mu\, s_i(\vec{\theta}) + \gamma_i\, b_i(\vec{\theta}))} \times \prod_{\theta\epsilon\vec{\theta}} \boxed{\frac{1}{\sqrt{2\pi}}\, e^{-\theta^2/2}} \times \prod_{i\,\epsilon\,\text{bins}} \boxed{Gauss(\beta_i\,|\,\gamma_i\,\beta_i, \sqrt{\gamma_i\,\beta_i})}$$

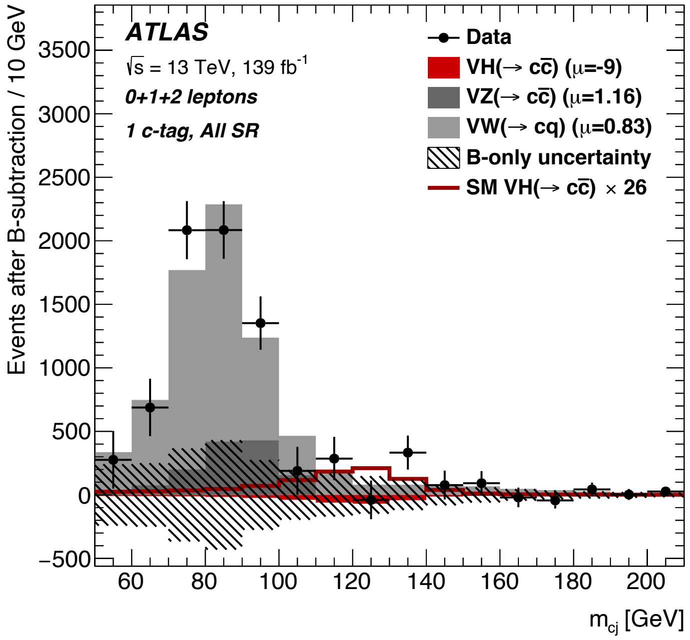
POI | Poissonian likelihood | Constraints on NPs | Constraints on MC statistics

- Simultaneous binned likelihood fit to m_{cc} distributions of the analysis categories (16 SRs and 28 CRs)
- **Measuring simultaneously following signal strengths:**
  - $\mu_{VH\ (H\rightarrow c\bar{c})}$
  - $\mu_{VW\ (W\rightarrow cq)}$ → validation of 1 c-tag category
  - $\mu_{VZ\ (Z\rightarrow c\bar{c})}$ → validation of 2 c-tag category

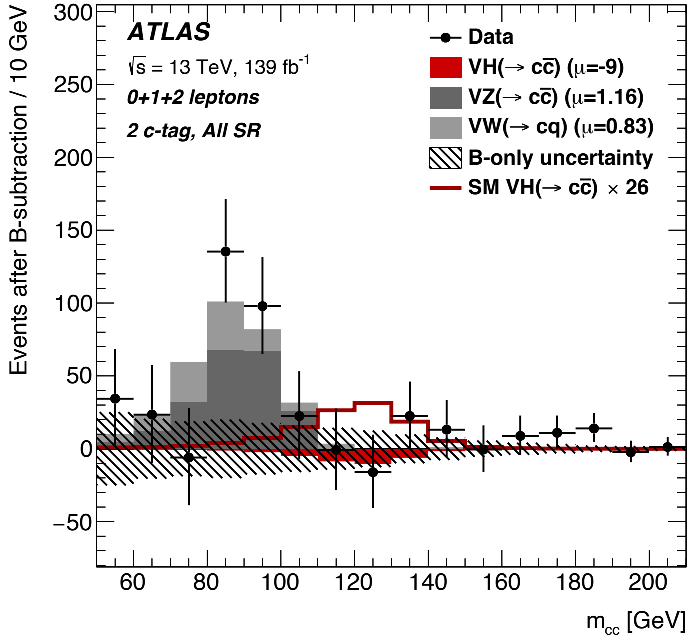
  → 3 Parameters of Interest (POIs)
- **Nuisance Parameters (NPs)**
  - Full set of detector systematics: flavour tagging, jets, leptons, MET, luminosity, pile-up
  - Full set of modelling uncertainties: Uncertainties on cross-section and acceptance, flavour or process composition, inter-category relative normalisation and m_{cc} shape
  - Statistical uncertainties from simulation samples size
- **Normalisations of main backgrounds obtained from data:** Z+jets, W+jets, top processes (with/without b-quark in 0 and 1 lepton channels and separate parameter in 2 lepton)

Fit Results

Post-fit Background Subtracted Mass Distributions for sum of all SRs



1 c-tag categories most sensitive to VW (W → cq)



2 c-tag categories most sensitive to VZ (Z → cc̄) and VH (H → cc̄)

Observed signal strengths

- VH (H → $c\bar{c}$): $\mu = -9 \pm 15$
- VZ (Z → $c\bar{c}$): $\mu = 1.16 + 0.50 - 0.46$
- VW (W → cq): $\mu = 0.83 + 0.25 - 0.23$

Significance	Expected	Observed
VZ (Z → $c\bar{c}$)	2.2σ	2.6σ
VW (W → cq)	4.6σ	3.8σ

Breakdown of uncertainties

VH (H → $c\bar{c}$)

- Statistical and systematic uncertainties of the same magnitude
- Main systematic uncertainties
  - Background modelling: V+jets and top processes
  - Statistical uncertainty from limited size of MC samples
  - Truth-flavour tagging (TT): Tagging (in-)efficiency of the Higgs candidate jets as event weights
    - Corrections of TT yields to match Direct Tagging (DT)
    - ΔR dependent correction applied for V+jets
    - Small remaining DT/TT non-closure:
      - Additional norm-only systematic uncertainty
    - Use of **truth-tagging** represents nevertheless **10% improvement on limit w.r.t direct tagging**

VW (W → cq) and VZ (Z → $c\bar{c}$)

- Sensitivity limited by systematic uncertainties
- Similar hierarchy of contributions to VH (H → $c\bar{c}$)

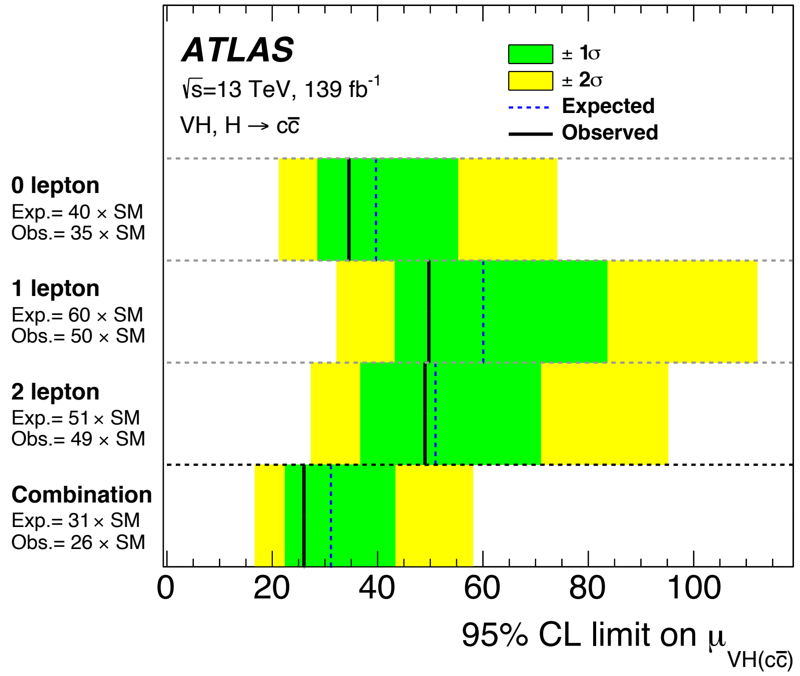
Source of uncertainty		$\mu_{VH(c\bar{c})}$	$\mu_{VW(cq)}$	$\mu_{VZ(c\bar{c})}$
Total		15.3	0.24	0.48
Statistical		10.0	0.11	0.32
Systematic		11.5	0.21	0.36
Statistical uncertainties				
Signal normalisation		7.8	0.05	0.23
Other normalisations		5.1	0.09	0.22
Theoretical and modelling uncertainties				
$VH(\rightarrow c\bar{c})$		2.1	< 0.01	0.01
Z + jets		7.0	0.05	0.17
Top quark		3.9	0.13	0.09
W+ jets		3.0	0.05	0.11
Diboson		1.0	0.09	0.12
$VH(\rightarrow b\bar{b})$		0.8	< 0.01	0.01
Multi-jet		1.0	0.03	0.02
Simulation samples size		4.2	0.09	0.13
Experimental uncertainties				
Jets		2.8	0.06	0.13
Leptons		0.5	0.01	0.01
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.2	0.01	0.01
Pile-up and luminosity		0.3	0.01	0.01
Flavour tagging	c-jets	1.6	0.05	0.16
	b-jets	1.1	0.01	0.03
	light-jets	0.4	0.01	0.06
	τ-jets	0.3	0.01	0.04
Truth-flavour tagging	ΔR correction	3.3	0.03	0.10
	Residual non-closure	1.7	0.03	0.10

Run 2 Limit and κ_c Interpretation

Note: Limits for individual channels result from fit decorrelated in respective way

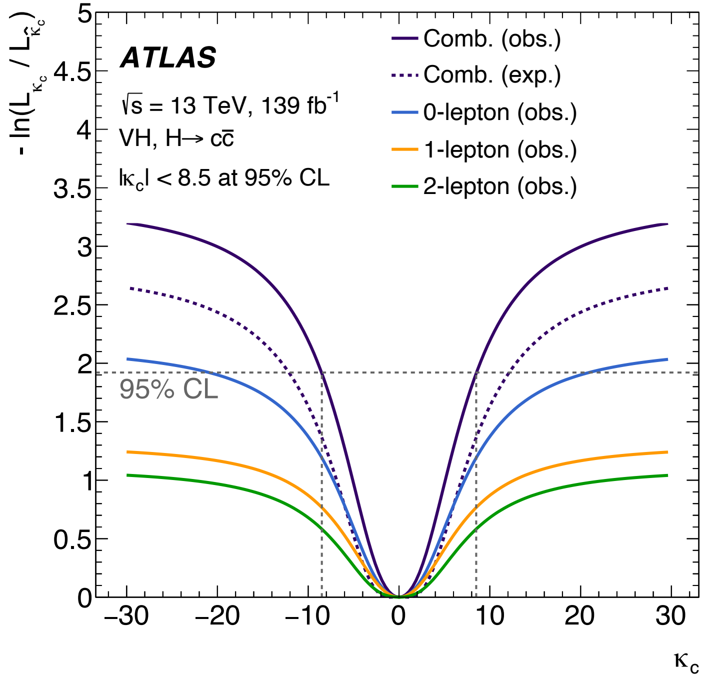
- Parametrisation of $\mu(\kappa_c)$: $\mu = \frac{\kappa_c^2}{(1-BR_{Hcc})+BR_{Hcc}*\kappa_c^2}$
- Other coupling modifiers set to 1, no BSM contributions to Higgs width, only modifications to decay considered

95% CL limit on $\mu_{VH\ (H\to c\bar{c})}$



Observed μ_{VHcc} limit of 26.0 × SM @ 95 CL

Profile likelihood scans on κ_c

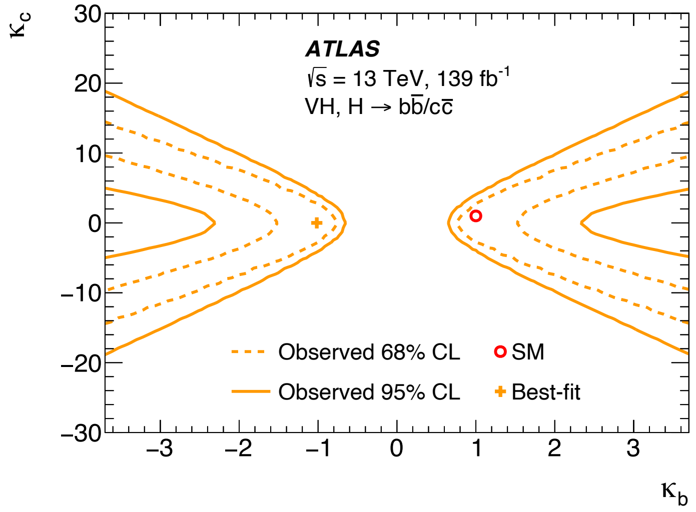


Observed constraint of $|\kappa_c| \leq 8.5$ at 95% CL

Combination with VH ($H \to b\bar{b}$)

- VH ($H \to b\bar{b}$) and VH ($H \to c\bar{c}$) searches with **similar analysis features**
- **Orthogonal signal regions between the two make combination possible**
- Possibility to measure the **ratio of coupling modifiers** κ_c/κ_b, with no assumptions on the Higgs width
- **Common experimental systematic uncertainties correlated** between the two analyses
- Exceptions for flavour tagging and background modelling uncertainties (different implementations or parametrisations)

Profile likelihood scans on κ_c and κ_b



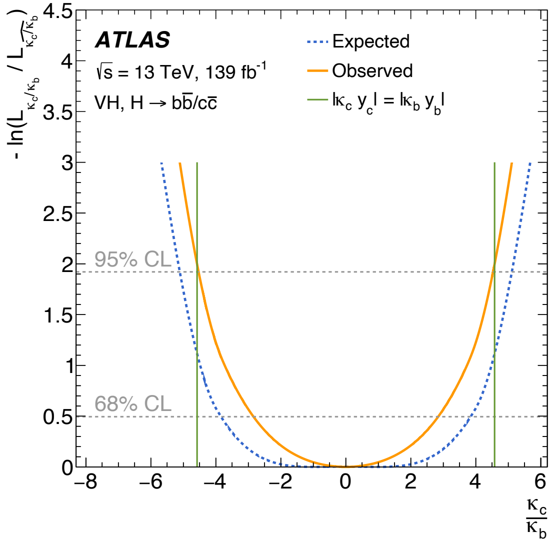
Observed best fit value (κ_b, κ_c) = (−1.02, 0)

Small likelihood asymmetry from b-quark loop contributions to gg → ZH production

Profile likelihood scans on κ_c/κ_b, with κ_b free to float

Observed constraint of $|\kappa_c/\kappa_b| \leq 4.5$ at 95% CL

- If one assumes the same Higgs coupling strength to bottom and charm quarks
- $\kappa_b y_b = \kappa_c y_c$
  $\to \kappa_c/\kappa_b$
  $= m_b(m_H)/m_c(m_H)$
  $= 4.578 \pm 0.008$ ◊



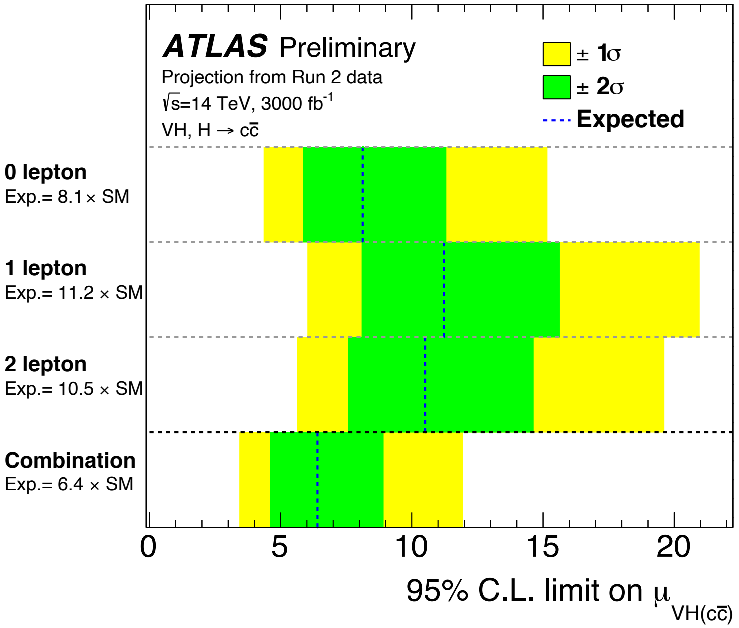
$|\kappa_c/\kappa_b|$ ratio constraints Higgs boson's coupling to charm quarks to be weaker than its coupling to bottom quarks

◊ Phys. Rev. D 98 (2018) 054517 (from lattice QCD)

Prospects for the HL-LHC

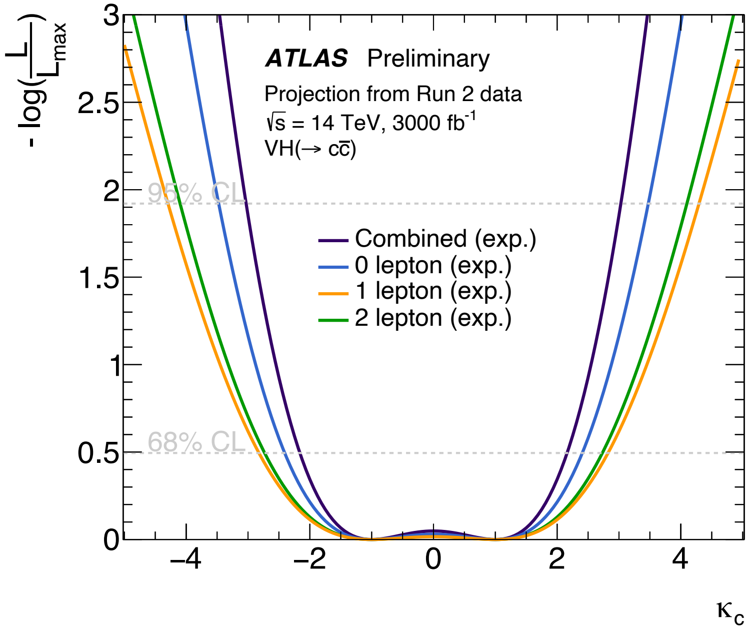
- Extrapolation of Run 2 analyses to HL-LHC scenario: $\sqrt{s} = 14$ TeV, 3000 fb^{-1}
- qq → VH (gg → ZH) signal scaled by 1.10 (1.18), $t\bar{t}$ and gg → ZZ scaled by 1.16, qq → VV and V+jets by 1.10
- Flavour tagging (except light-jets in VH (H → $c\bar{c}$)), theory and background uncertainties scaled by 1/2

95% CL Limit on μ_{VHcc}



Expected μ_{VHcc} limit of 6 × SM @ 95% CL

Profile likelihood scans on κ_c

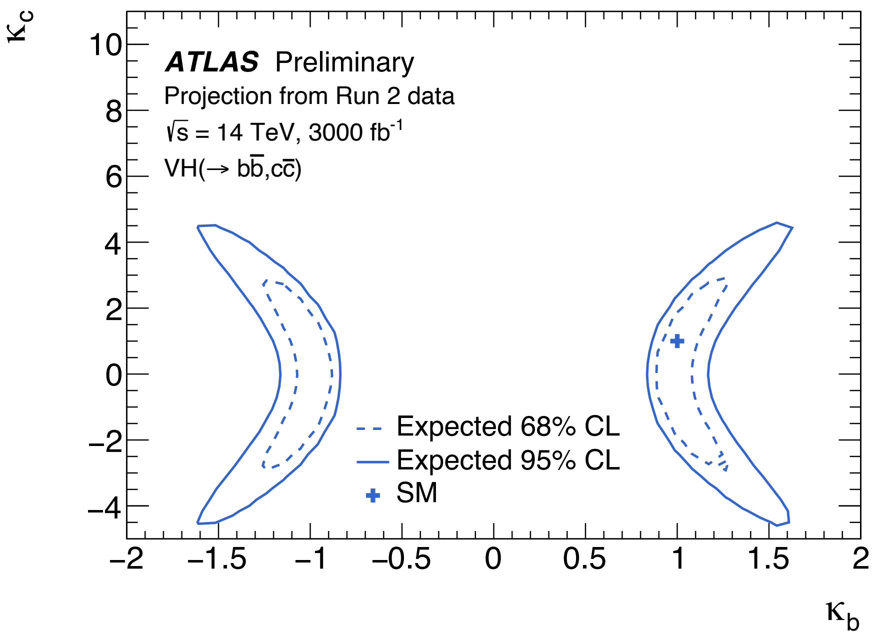


Expected constraint of $|\kappa_c| \leq 3.0$ at 95% CL

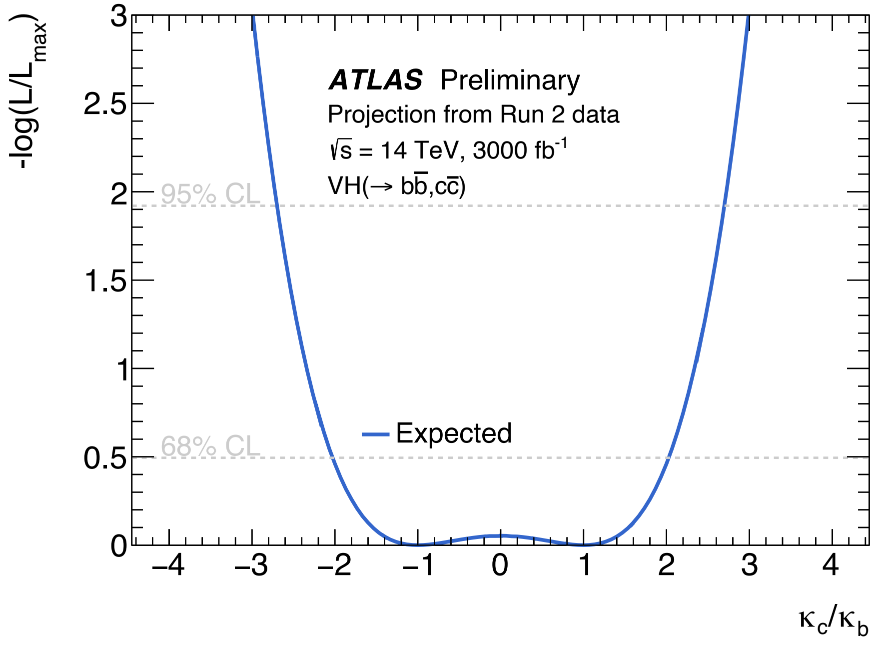
- **Leading uncertainties** on results from **Z+jets modelling** and **flavour tagging**

Prospects for the HL-LHC: VH, H → $c\bar{c}$/$b\bar{b}$ combination

Profile likelihood scans on κ_c and κ_b



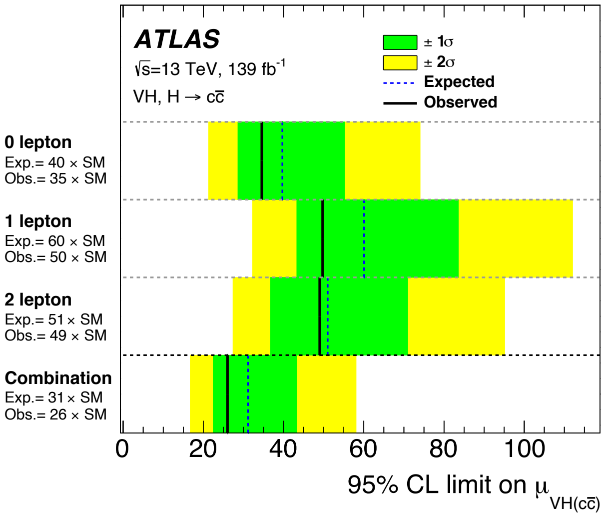
Profile likelihood scans on κ_c/κ_b, κ_b free to float



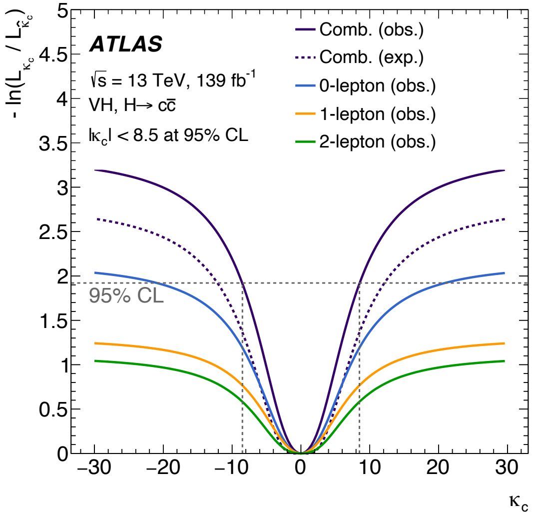
- Expected constraint of $|\kappa_c/\kappa_b| \leq 2.7$ at 95% CL
- Run 2 analyses extrapolated to HL-LHC are not sensitive enough to test SM predictions
- Improvements such as changes on the analysis design (e.g to a MVA-based VH, H → $c\bar{c}$ analysis) and better flavour tagging performance not considered in extrapolation → Plenty of room to improve!

Summary

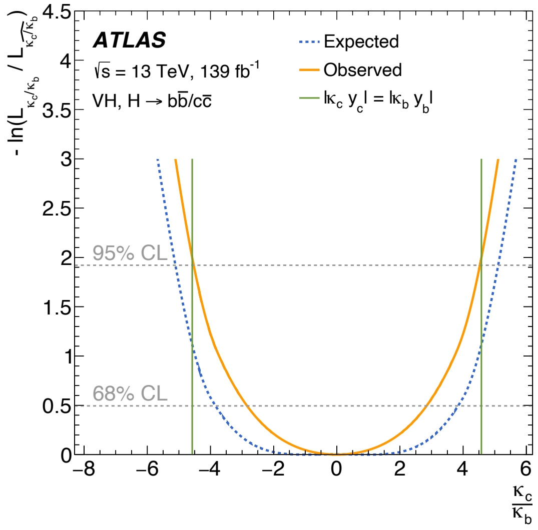
95% CL limit+ on μ_{VHcc}



Likelihood scan on κ_c



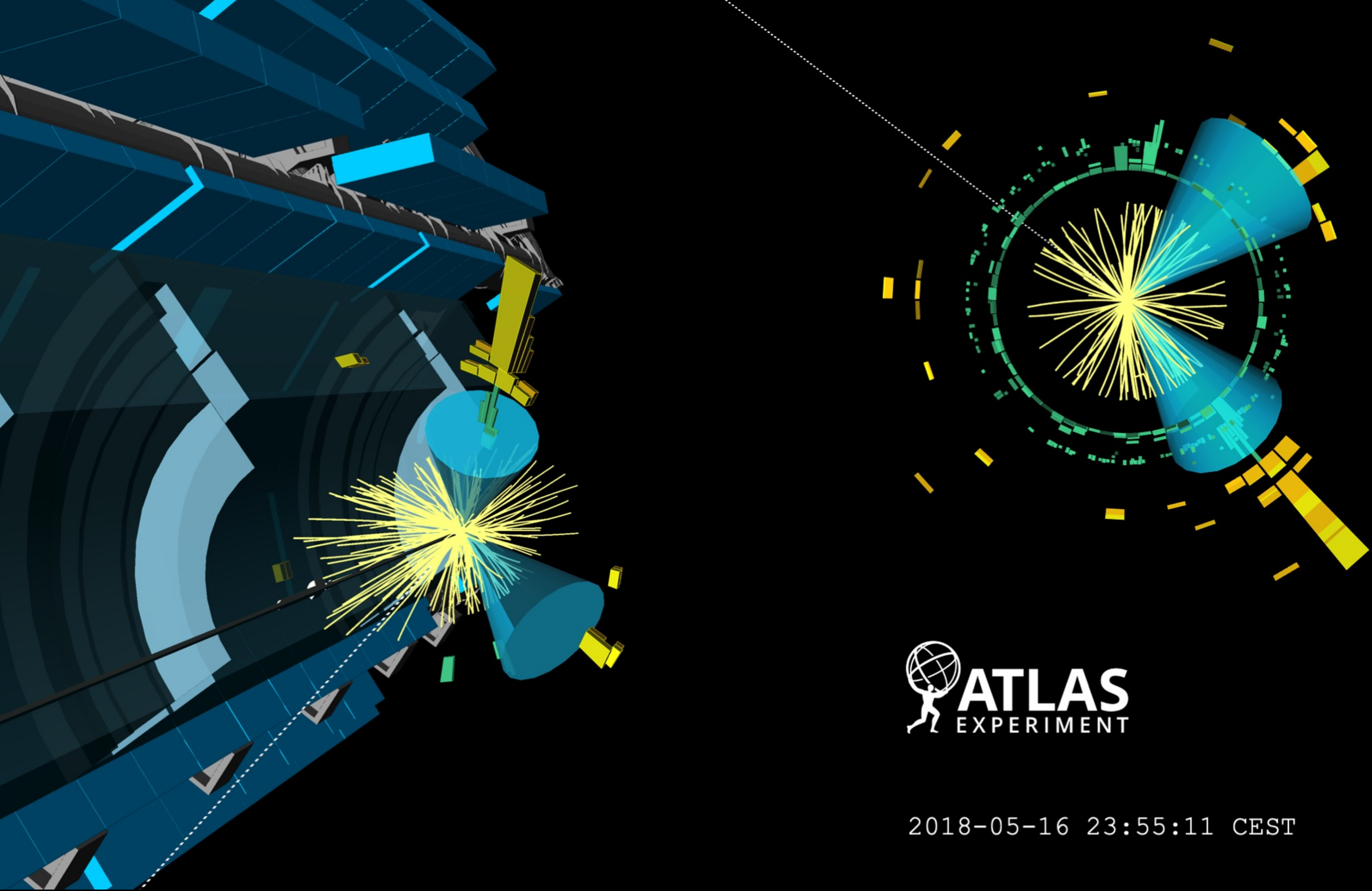
Likelihood scan on κ_c/κ_b



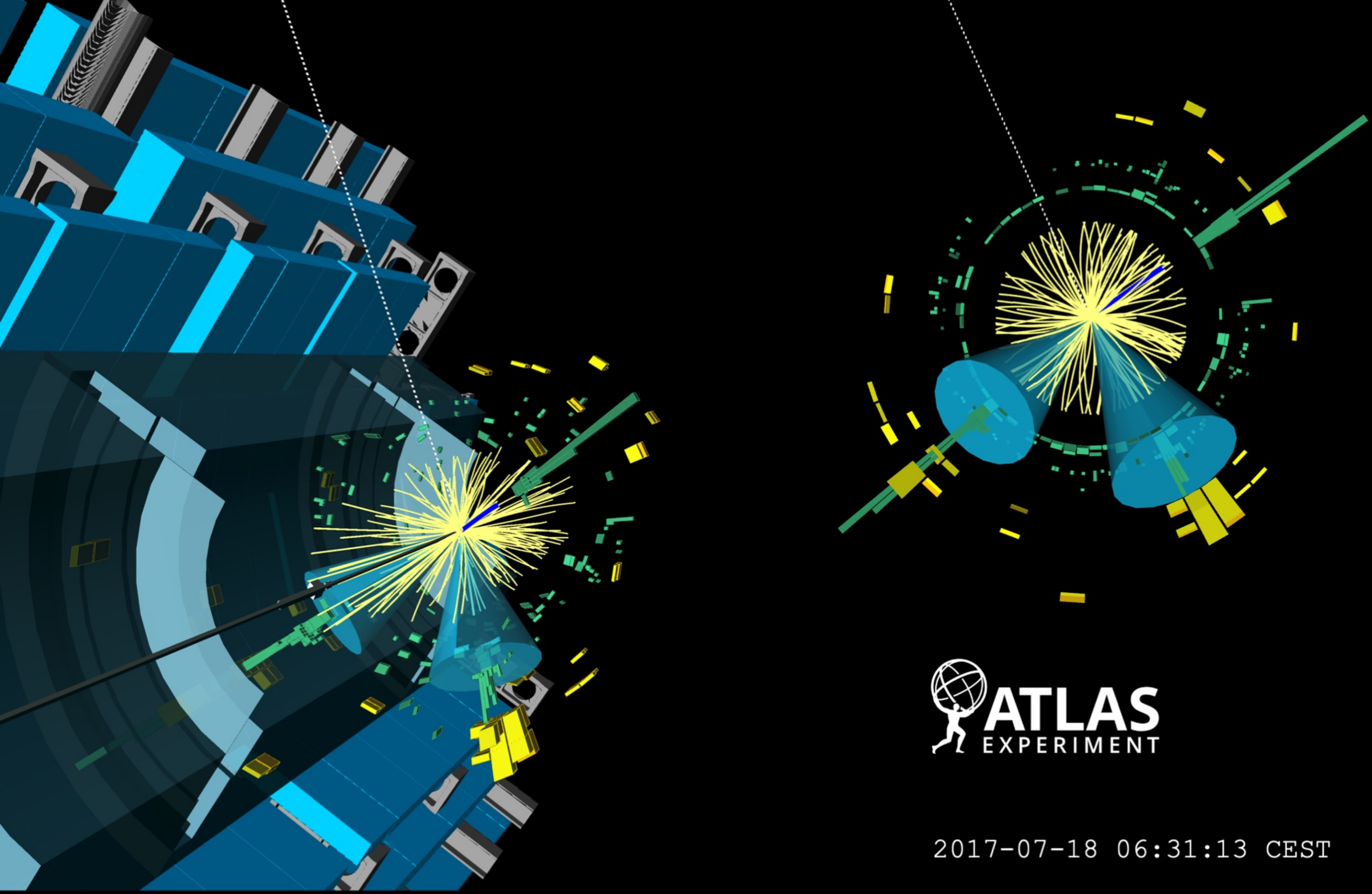
- Observed μ_{VHcc} limit of 26 × SM
- Observed constraint of $|\kappa_c| \leq 8.5$ at 95% CL
- Observed constraint of $|\kappa_c/\kappa_b| \leq 4.5$ at 95% CL ← Higgs boson coupling to charm quarks weaker than coupling to bottom quarks
- Observed significances of **3.8σ** and **2.6σ** for **VW (W → cs/cd) and VZ (Z → cc̄)** production, respectively
- SM sensitivity out of reach with HL-LHC extrapolation of current VH (H → cc̄) and VH (H → bb̄) analyses → **innovation needed!**

+ Limits for individual channels from fit with VH(cc) POI decorrelated in channels

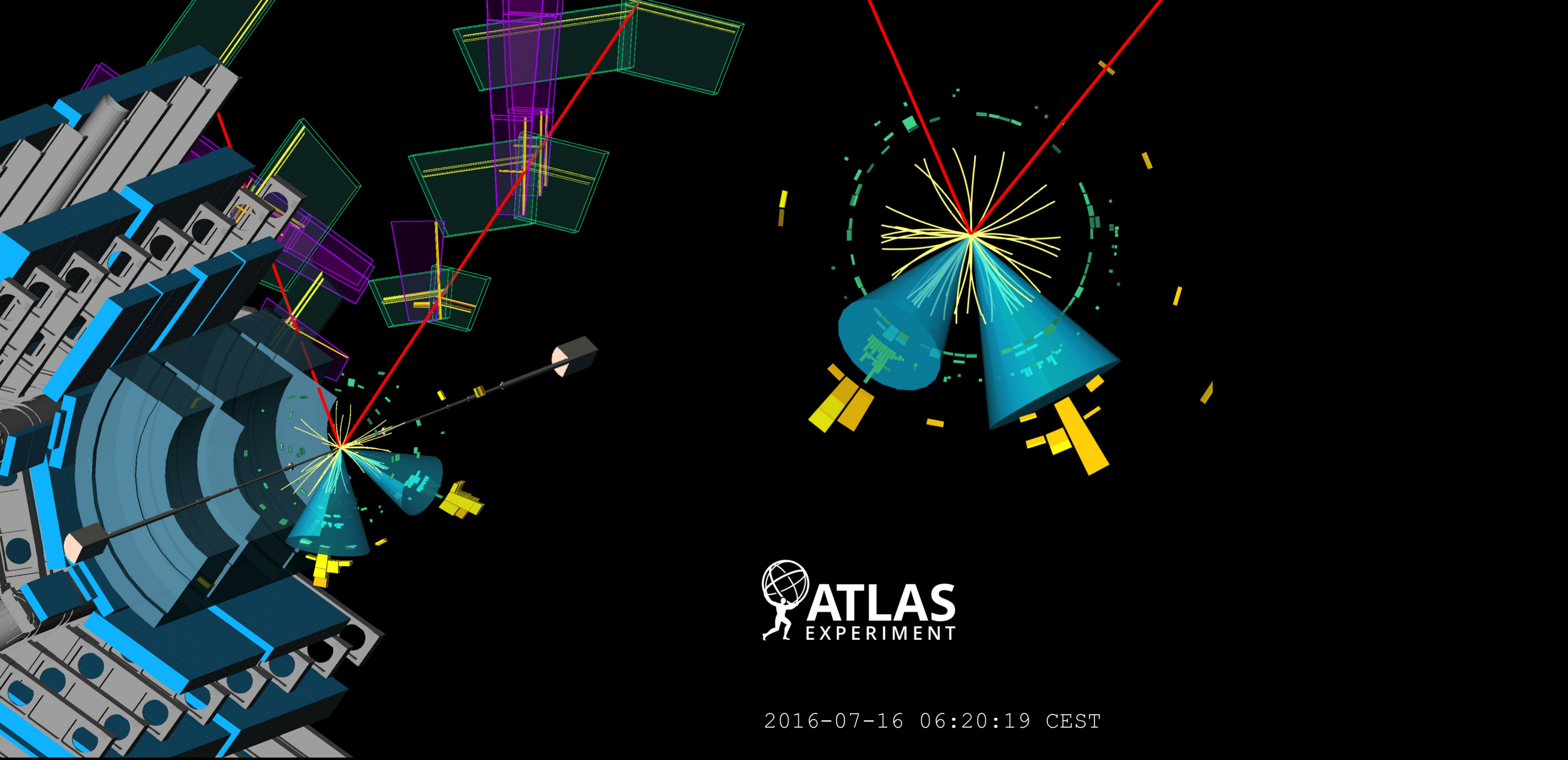
Backup



Candidate event for the process ZH → νν$c\bar{c}$ (Run 350440, Event 1105654304). The missing transverse energy is identified by a white dashed line and it has a magnitude of 155 GeV. The Higgs boson candidate is reconstructed from two charm-tagged R=0.4 jets (blue cones), which have associated energy deposits in both the electromagnetic (green) and hadronic (yellow) calorimeters. The leading and sub-leading jets have transverse momenta of 176 GeV and 22 GeV respectively. The Higgs boson candidate has a reconstructed invariant mass of 125 GeV.



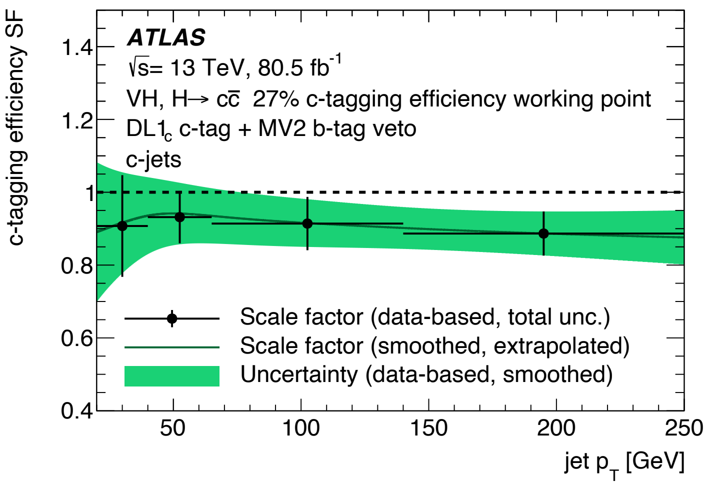
Candidate event for the process WH → eνcc̄ (Run 329964, Event 500775771). An electron can be seen as a blue track with large associated energy deposits in the electromagnetic calorimeter (green). The missing transverse energy is identified by a white dashed line and it has a magnitude of 116 GeV; the transverse momentum of the electron-ETmiss system is 151 GeV. The reconstructed transverse mass of the W boson is 72 GeV. The Higgs boson candidate is reconstructed from two charm-tagged R=0.4 jets (blue cones), which have associated energy deposits in both the electromagnetic (green) and hadronic (yellow) calorimeters. The leading and sub-leading jets have transverse momenta of 111 GeV and 81 GeV respectively. The Higgs boson candidate has a reconstructed invariant mass of 124 GeV.



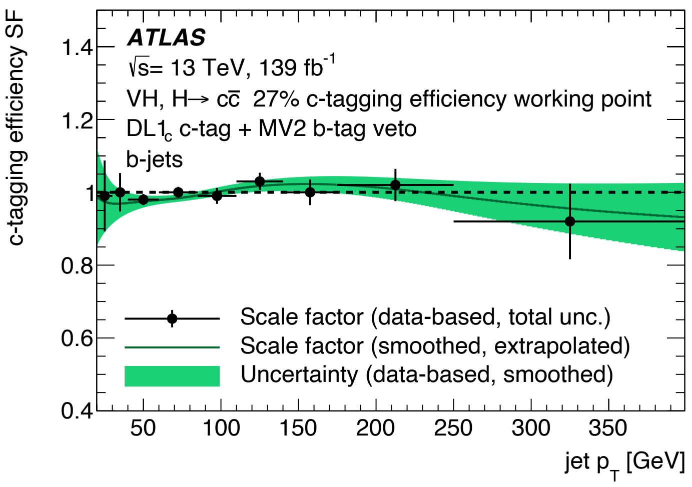
Candidate event for the process ZH → μμcc̄ (Run 309892, Event 4866214607). Two muons, which have a di-lepton invariant mass of 92 GeV, are shown as red tracks producing hits (green) in the endcap muon chambers. The reconstructed Z boson has a transverse momentum of 150 GeV. The Higgs boson candidate is reconstructed from two charm-tagged R=0.4 jets (blue cones), which have associated energy deposits in both the electromagnetic (green) and hadronic (yellow) calorimeters. The leading and sub-leading jets have transverse momenta of 123 GeV and 71 GeV respectively. The Higgs boson candidate has a reconstructed invariant mass of 123 GeV.

Calibration of c-tagging algorithm

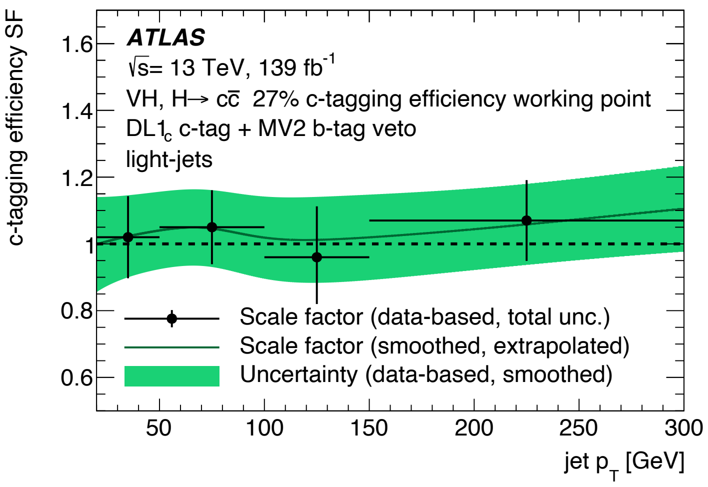
- c-tagging efficiencies in simulation are corrected to reflect the c-tagging efficiency in data
- **Scale factors (SF)** derived from dedicated data-driven study for each flavour, with **typical precision of 5-10%**



Measured with sample of semi-leptonic $t\bar{t}$ events



Measured with sample of di-leptonic $t\bar{t}$ events



Measured with sample of Z+jets events

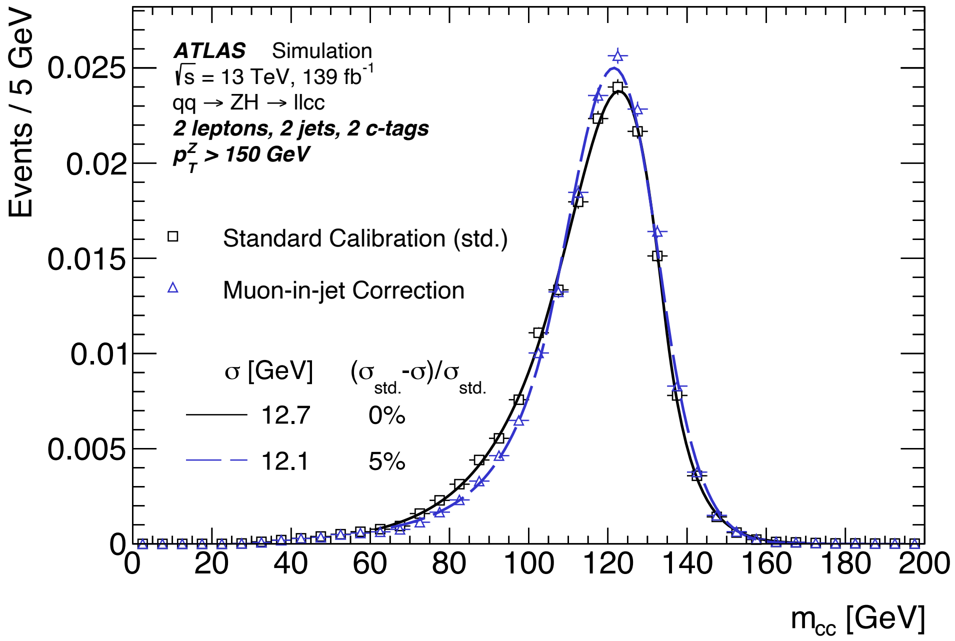
Event Selection

Common Selections	
Central jets	≥ 2
Signal jet p_T	≥ 1 signal jet with $p_T > 45$ GeV
c-jets	1 or 2 c-tagged signal jets
b-jets	No b-tagged non-signal jets
Jets	2, 3 (0- and 1-lepton), 2, ≥ 3 (2-lepton)
p_T^V regions	75–150 GeV (2-lepton) > 150 GeV
$\Delta R(\textbf{jet 1}, \textbf{jet 2})$	$75 < p_T^V < 150$ GeV: $\Delta R \leq 2.3$ $150 < p_T^V < 250$ GeV: $\Delta R \leq 1.6$ $p_T^V > 250$ GeV: $\Delta R \leq 1.2$
0 Lepton	
Trigger	E_T^{miss}
Leptons	0 *loose* leptons
E_T^{miss}	> 150 GeV
p_T^{miss}	> 30 GeV
H_T	> 120 GeV (2 jets), > 150 GeV (3 jets)
$\min \lvert\Delta\phi(\boldsymbol{E}_T^{miss}, \textbf{jet})\rvert$	$> 20°$ (2 jets) , $> 30°$ (3 jets)
$\lvert\Delta\phi(\boldsymbol{E}_T^{miss}, \boldsymbol{H})\rvert$	$> 120°$
$\lvert\Delta\phi(\textbf{jet1}, \textbf{jet2})\rvert$	$< 140°$
$\lvert\Delta\phi(\boldsymbol{E}_T^{miss}, \boldsymbol{p}_T^{miss})\rvert$	$< 90°$
1 Lepton	
Trigger	e sub-channel: single electron μ sub-channel: E_T^{miss}
Leptons	1 *tight* lepton and no additional *loose* leptons
E_T^{miss}	> 30 GeV (e sub-channel)
m_T^W	< 120 GeV
2 Lepton	
Trigger	single lepton
Leptons	2 *loose* leptons Same flavour, opposite-charge for $\mu\mu$
m_{ll}	$81 < m_{ll} < 101$ GeV

- **ΔR(cc) selection re-optimised** for VH(cc) sensitivity
- 0-lepton: **multi-jet** and **non-collisional background rejection**
- 1 lepton: **reduction of multi-jet contamination**
  - tighter lepton selection
  - m_T^W cut

Jet energy corrections

- **Muon-in-jet correction** applied in all channels (for jets w/ muons found within a p_T-dependent cone around the jet axis)
- **Improved m(cc) resolution: ~5%**
- Smaller improvement w.r.t VH (H → bb̄) due to less semi-leptonic decays



0 Lepton Channel Signal Regions

Event Selection

- Missing transverse energy $E_T^{miss} > 150$ GeV
- No leptons with $p_T > 7$ GeV and satisfying loose criteria
- Angular cuts built with E_T^{miss} and hadronic related variables for **multi-jet suppression**
- Additional cuts for **non-collisional background rejection**

Four Signal Regions

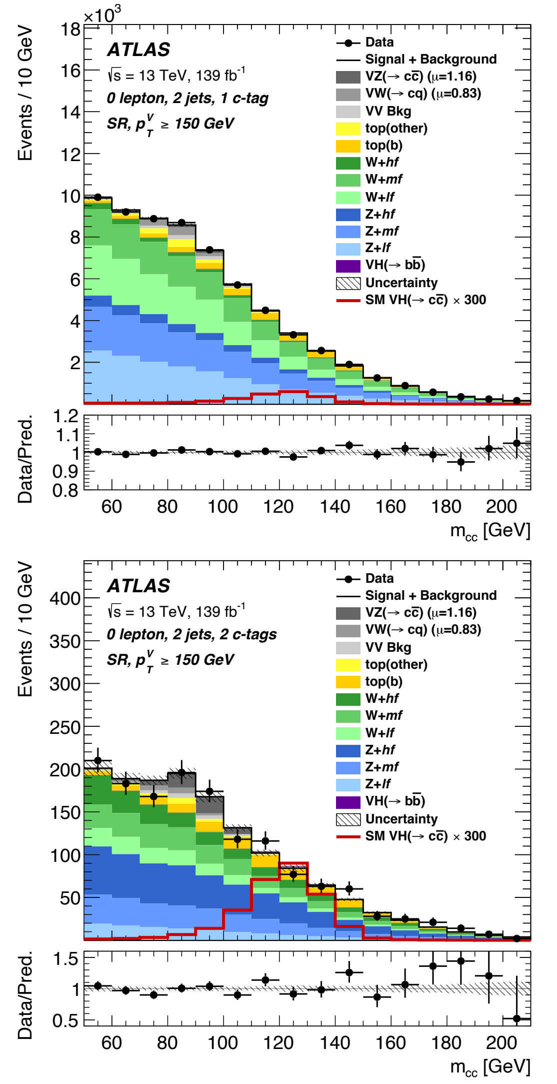
1 c-tag, 2 jets	1 c-tag, 3 jets
2 c-tags, 2 jets	2 c-tags, 3 jets

Main backgrounds

Z+jets | W+jets | Top

Subdominant backgrounds

VW and VZ production



1 Lepton Channel Signal Regions

Event Selection

- One electron or muon with $p_T > 27$ (25) GeV and satisfying tight (medium) criteria
- No additional leptons with $p_T > 7$ GeV and satisfying loose criteria
- $m_T^W < 120$ GeV
- $E_T^{miss} > 30$ (electron sub-channel only)

Four Signal Regions

1 c-tag, 2 jets	1 c-tag, 3 jets
2 c-tags, 2 jets	2 c-tags, 3 jets

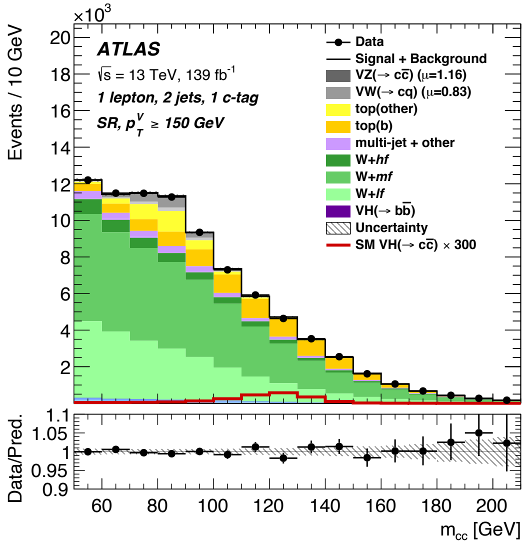
Main backgrounds

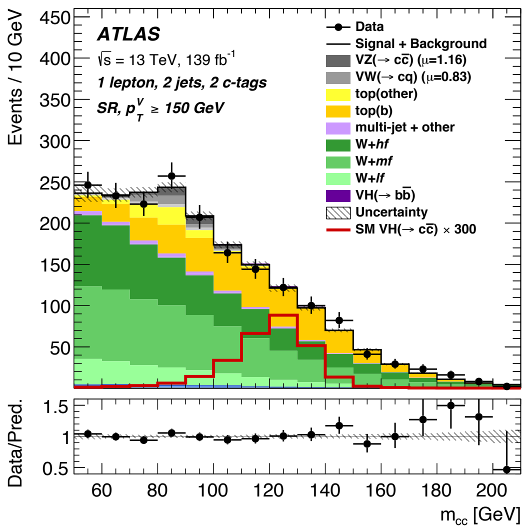
W+jets | Top

Subdominant backgrounds

VW and VZ production

Multi-jet – modelled with data-driven templates





2 Lepton Channel Signal Regions

Event Selection

- Two electrons or muons with $p_T > 7$ GeV and satisfying loose criteria
- One of the leptons must also have $p_T > 27$ GeV
- Consistency with Z boson mass: $81 < m_{ll} < 101$ GeV

Eight Signal Regions

$75 < p_T^Z < 150$ GeV – low p_T^Z		$p_T^Z > 150$ GeV – high p_T^Z	
1 c-tag, 2 jets	1 c-tag, ≥3 jets	1 c-tag, 2 jets	1 c-tag, ≥3 jets
2 c-tags, 2 jets	2 c-tags, ≥3 jets	2 c-tags, 2 jets	2 c-tags, ≥3 jets

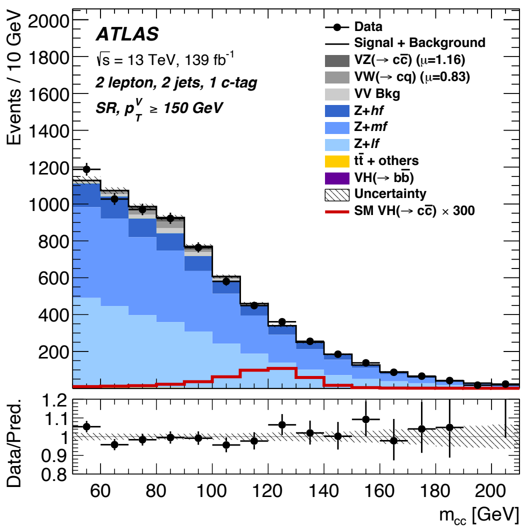
Main backgrounds

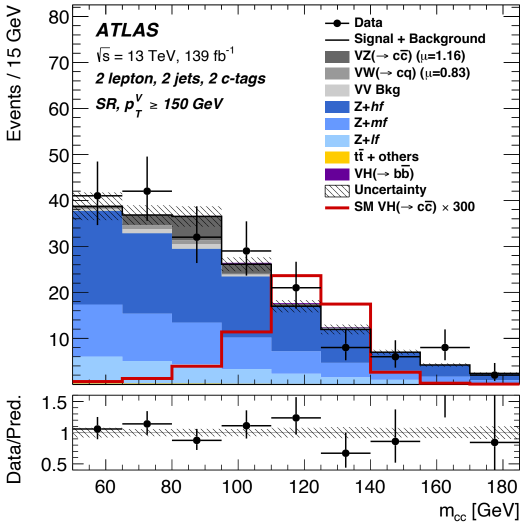
Z+jets

Subdominant backgrounds

VW and VZ production

Top quark processes in low p_T^Z regions

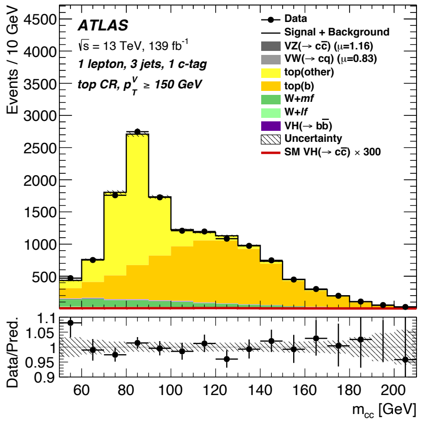




Control Regions

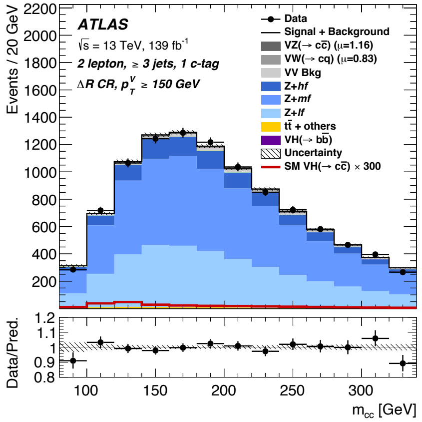
Top CRs

- **Constraining modelling of top quark processes**
- **0 and 1 lepton channels: inverted b-tag veto** in 1 c-tag, 3 jets events, ≥ 1 b-tag in these events
- **2 lepton channel: $e^{\pm}\mu^{\mp}$ events** with 1 c-tag



High ΔR CRs

- **Constraining modelling of W/Z+jets**
- Events with ΔR_{jj} > SR cuts and ΔR_{jj}< 2.5
- 0, 1 and 2 lepton channels



0 c-tag CRs – Constraining normalisations of W/Z+jets light flavour component

- 1 and 2 lepton channels: events where both of the two main jets fail the c-tag requirement and additional jets are b-vetoed

Signal and Background Modelling

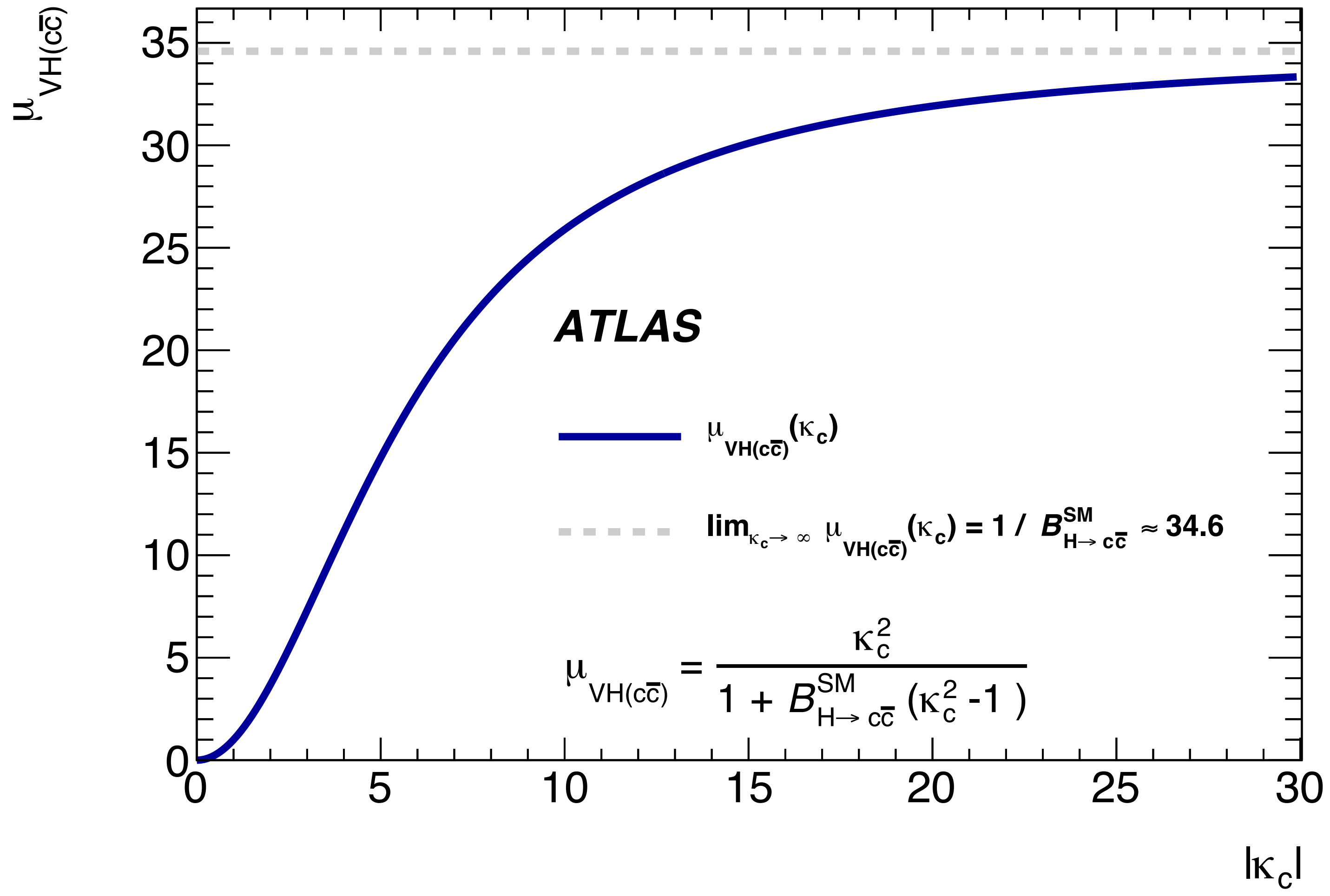
- Signal and background processes modelled using simulation (except multi-jet – templates from enriched control region)
- Same samples used for the VH (H → $b\bar{b}$) analysis
- MC statistical uncertainties mitigated through **truth tagging**
  - Apply tagging (in-)efficiency of the Higgs candidate jets as event weights
- Theory uncertainties for VH (H → $c\bar{c}$) cross-section and branching fraction

Process	ME generator	ME PDF	PS and hadronisation	Tune	Cross-section order
$qq \to VH$ $(H \to c\bar{c}/b\bar{b})$	Powheg Box v2 + GoSam + MiNLO	NNPDF3.0NLO	Pythia 8.212	AZNLO	NNLO(QCD) +NLO(EW)
$gg \to ZH$ $(H \to c\bar{c}/b\bar{b})$	Powheg Box v2	NNPDF3.0NLO	Pythia 8.212	AZNLO	NLO+NLL
$t\bar{t}$	Powheg Box v2	NNPDF3.0NLO	Pythia 8.230	A14	NNLO +NNLL
t/s-channel single top	Powheg Box v2	NNPDF3.0NLO	Pythia 8.230	A14	NLO
Wt-channel single top	Powheg Box v2	NNPDF3.0NLO	Pythia 8.230	A14	Approx. NNLO
V+jets	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
$qq \to VV$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$gg \to VV$	Sherpa 2.2.2	NNPDF3.0NNLO	Sherpa 2.2.2	Default	NLO

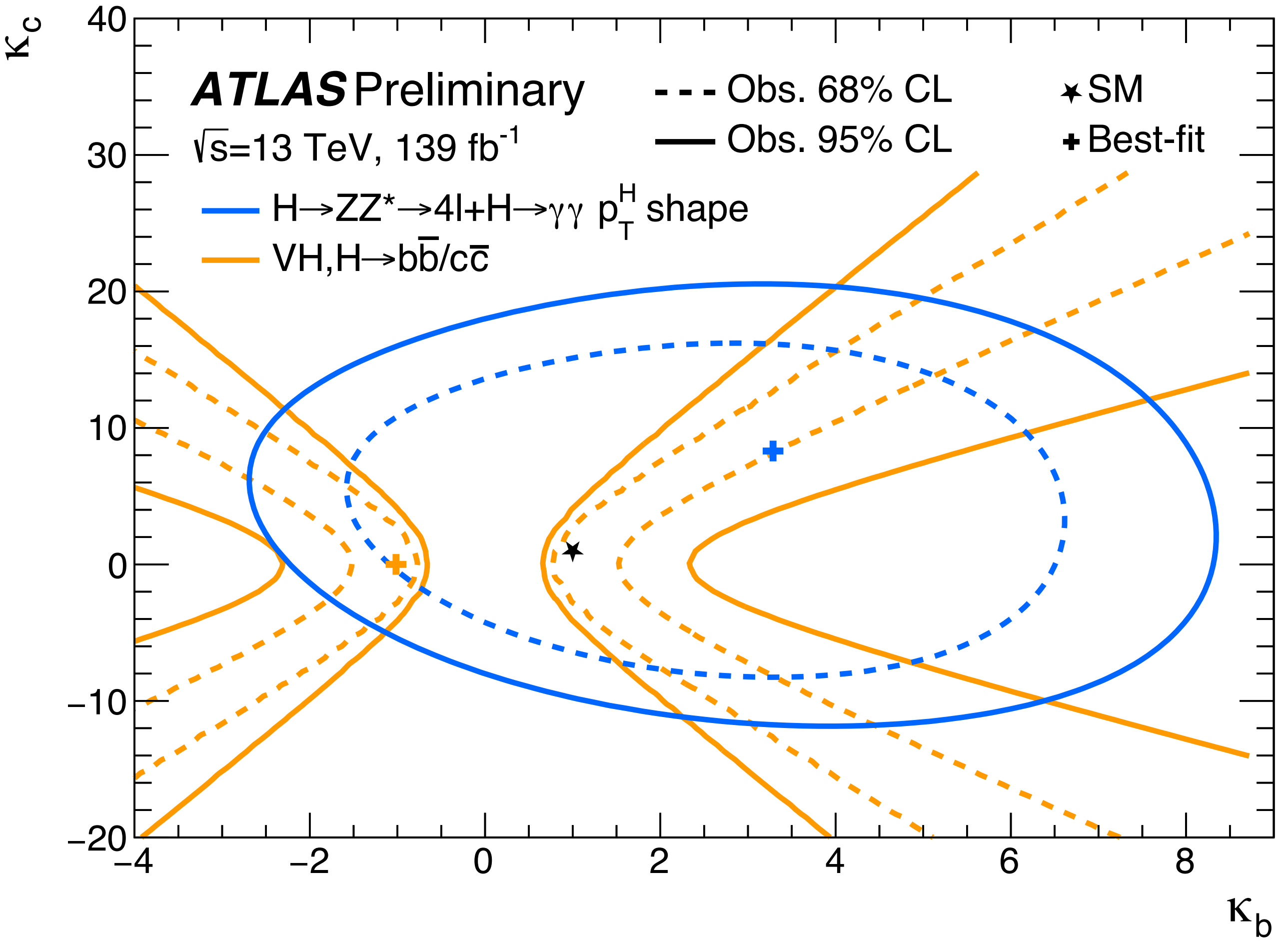
- **Modelling systematic uncertainties** - assessed using alternative generators and scale variations in nominal generators
  - **Normalisation uncertainties:** relative difference on total yield predictions
    - Applied to subdominant processes (diboson, VH): phase space acceptance
  - **Acceptance ratios:** relative differences in predictions for p_T^V and nJet categories
  - **Flavour composition ratios:** different flavour/processes predictions per categories
  - **Channel extrapolations:** different predictions per channel
  - **SR/CR extrapolation:** different predictions per region
  - **m_{cc} shape uncertainties:** account for differences in binned m_{cc} distribution prediction

Parametrisation of κ_c

- $\mu = \frac{\kappa_c^2}{[(1-BR_{Hcc})+BR_{Hcc}*\kappa_c^2]}$



Summary of κ_b vs. κ_c constraints (ATL-PHYS-PUB-2022-002)



Parametrisations of κ parameters (ATLAS-CONF-2021-053)

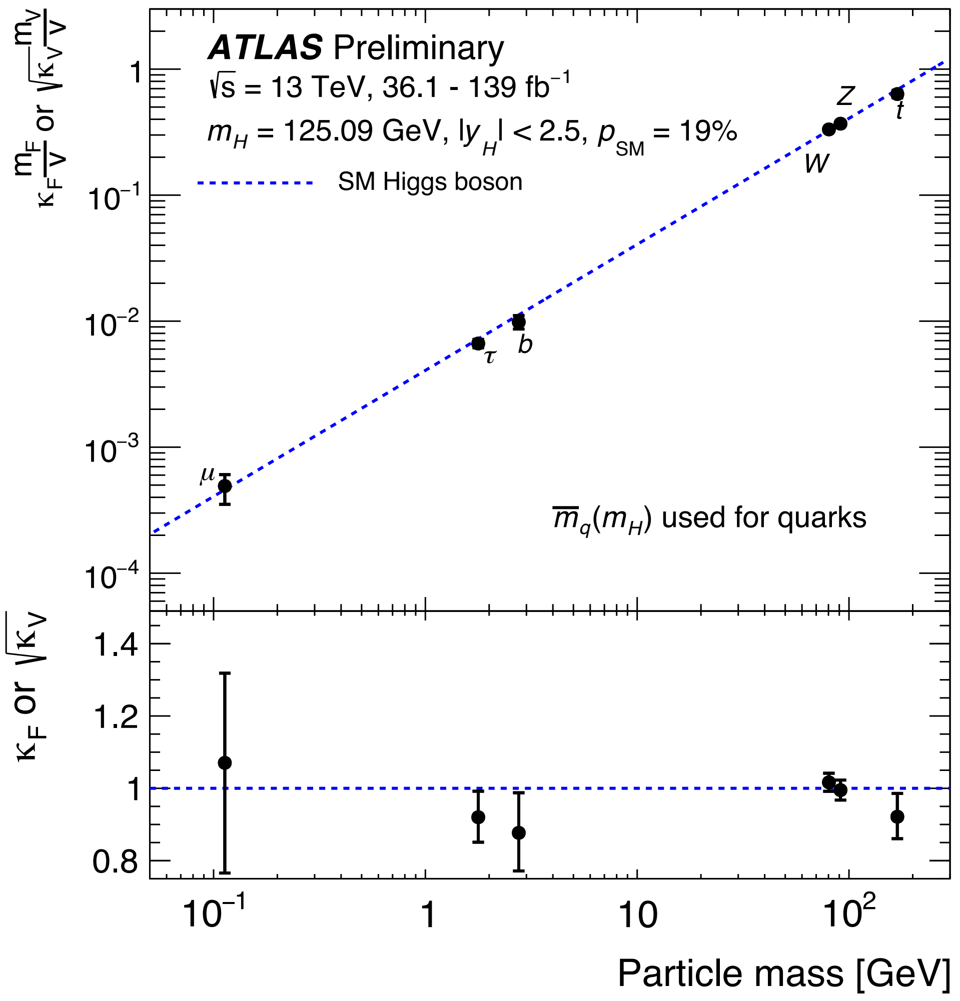
Table 6: Parametrisations of Higgs boson production cross sections σ_i, partial decay widths Γ^f, and the total width Γ_H, normalised to their SM values, as functions of the coupling-strength modifiers κ. The effect of invisible and undetected decays is not considered in the expression for Γ_H. For effective κ parameters associated with loop processes, the resolved scaling in terms of the modifications of the Higgs boson couplings to the fundamental SM particles is given. The coefficients are derived following the methodology in Ref. [37, 41].

Production cross section	Loops	Main interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	t–b	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(\text{VBF})$	-	-	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z	$\kappa_{(ggZH)}$	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t$ $- 0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t–W	-	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	t–W	-	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	t–b	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (=\kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b$ $-0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
Γ^{ss}	-	-	-	$\kappa_s^2\ (=\kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{\text{i.}} = B_{\text{u.}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

- **Invisible decays:** decays which are identified through a E_T^{miss} signature in the analyses. In the SM, the branching fraction of invisible decays is predicted to be 0.1%, exclusively from the process. **The BSM contribution to this branching fraction is denoted as B_i.**

- **Undetected decays:** decays to which none of the analyses included in this combination are sensitive, such as decays to light quarks which have not yet been resolved, or undetected BSM particles without a sizable E_T^{miss} in the final state. For the former, the SM contribution of these undetected decays is already included in Γ^{SM}, and amounts to 11%, mainly driven by the decays to gluon pairs. **The BSM contribution to the undetected branching fraction is denoted as B_u.** Note that deviations of the partial width of the input measurements of this analysis are separately included by scaling their partial width by κ_j.

Reduced coupling-strength modifiers (ATLAS-CONF-2021-053)



Reduced coupling-strength modifiers $\kappa_F m_F/v$ for fermions (F=t,b,τ,μ) and $\sqrt{[\kappa_V]} m_V/v$ for weak gauge bosons (V=W,Z) as a function of their masses m_F and m_V, respectively, and the vacuum expectation value of the Higgs field v=246 GeV. The SM prediction for both cases is also shown (dashed line). The black error bars represent 68% CL intervals for the measured parameters.

The coupling modifiers are measured assuming no BSM contributions to the Higgs boson decays, and the SM structure of loop processes such as ggF, H→γγ and H→ Zγ. The lower panel shows the ratios of the values to their SM predictions. The level of compatibility between the combined measurement and the SM prediction, estimated using the procedure outlined in the text with six degrees of freedom, corresponds to a p-value of p_{SM}=19%.

Parametrisations of κ parameters (ATLAS-CONF-2021-053)

Table 6: Parametrisations of Higgs boson production cross sections σ_i, partial decay widths Γ^f, and the total width Γ_H, normalised to their SM values, as functions of the coupling-strength modifiers κ. The effect of invisible and undetected decays is not considered in the expression for Γ_H. For effective κ parameters associated with loop processes, the resolved scaling in terms of the modifications of the Higgs boson couplings to the fundamental SM particles is given. The coefficients are derived following the methodology in Ref. [37, 41].

Production cross section	Loops	Main interference	Effective modifier	Resolved modifier
σ(ggF)	✓	t–b	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
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$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z	$\kappa_{(ggZH)}$	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t$ $- 0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t–W	-	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
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Partial decay width				
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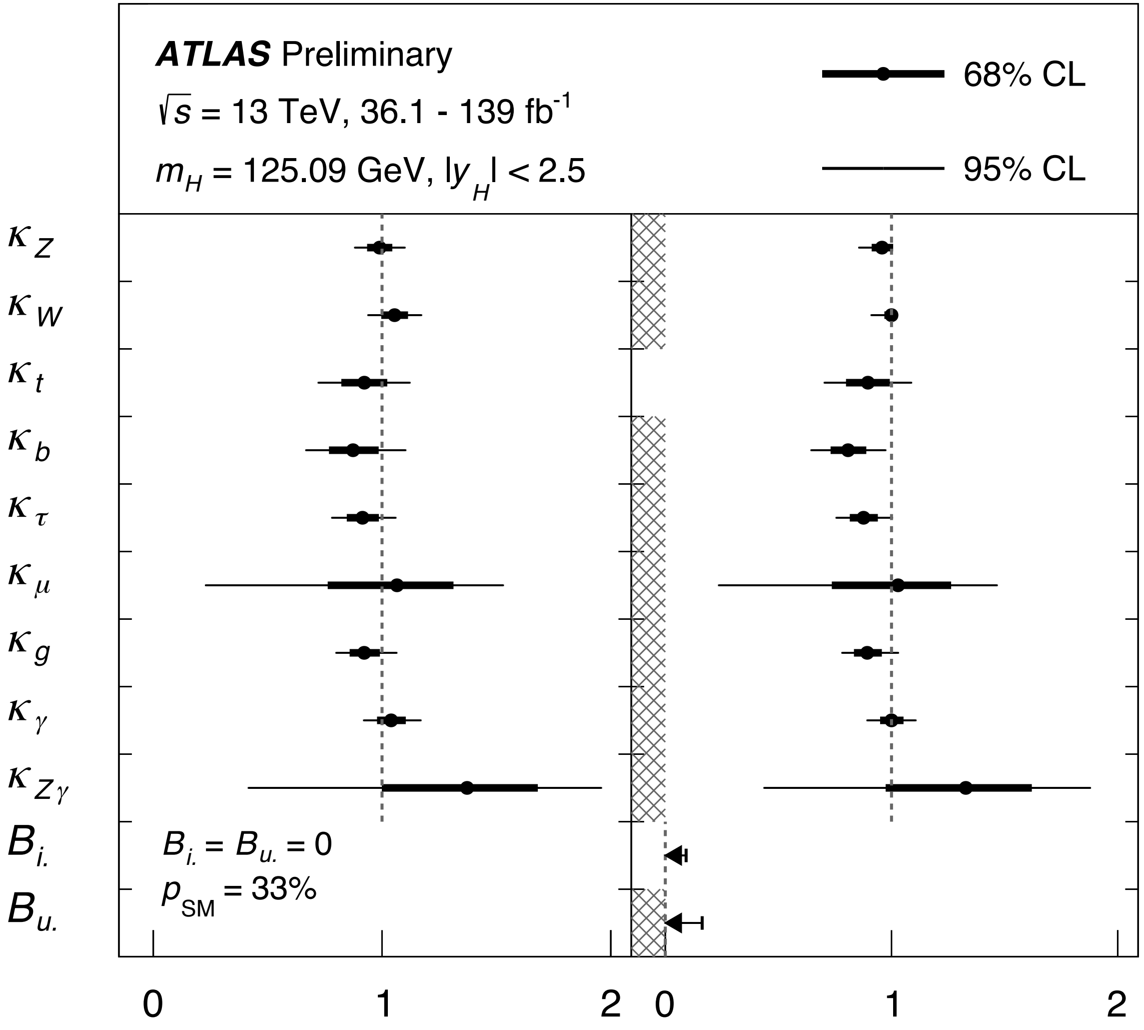
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b$ $-0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
Γ^{ss}	-	-	-	$\kappa_s^2\ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{i.} = B_{u.} = 0$)				
Γ_H	✓	-	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

- **Invisible decays:** decays which are identified through a E_T^{miss} signature in the analyses. In the SM, the branching fraction of invisible decays is predicted to be 0.1%, exclusively from the process. **The BSM contribution to this branching fraction is denoted as B_i.**

- **Undetected decays:** decays to which none of the analyses included in this combination are sensitive, such as decays to light quarks which have not yet been resolved, or undetected BSM particles without a sizable E_T^{miss} in the final state. For the former, the SM contribution of these undetected decays is already included in Γ^{SM}, and amounts to 11%, mainly driven by the decays to gluon pairs. **The BSM contribution to the undetected branching fraction is denoted as B_u.** Note that deviations of the partial width of the input measurements of this analysis are separately included by scaling their partial width by κ_j.

Combined measurements of Higgs boson production and decay: κ parameters (ATLAS-CONF-2021-053)



Best-fit values and uncertainties for Higgs boson coupling modifiers per particle type with effective photon, Zγ and gluon couplings and either $B_{i.} = B_{u.} = 0$ (left), or $B_{i.}$ and $B_{u.}$ included as free parameters with the conditions $\kappa_{W,Z} \leq 1$ imposed and the measurement of the Higgs boson decay rate into invisible final states included in the combination (right). For the $B_{i.}$ and $B_{u.}$ results, the bar with the left-facing arrow indicates an upper limit at 95% CL.

The SM corresponds to $B_{i.}=B_{u.}=0$ and all κ parameters set to unity. All parameters except κ_t and $B_{i.}$ are assumed to be positive. In the former case, the level of compatibility between the combined measurement and the SM prediction, estimated using the procedure outlined in the text with nine degrees of freedom, corresponds to a p-value of p_{SM} = 33%. In the latter scenario, p_{SM} in not provided due to the bounds on $\kappa_{W,Z}$.

Combined measurements of Higgs boson production and decay: κ parameters (ATLAS-CONF-2021-053)

Table 8: Fit results for Higgs boson coupling modifiers per particle type with effective photon, $Z\gamma$ and gluon couplings and either (a) $B_{\text{i.}} = B_{\text{u.}} = 0$, or (b) $B_{\text{i.}}$ and $B_{\text{u.}}$ included as free parameters, with the conditions $\kappa_{W,Z} \leq 1$ imposed and the measurement of the Higgs boson decay rate into invisible final states included in the combination. The SM corresponds to $B_{\text{i.}} = B_{\text{u.}} = 0$ and all κ parameters set to unity. All κ parameters except for κ_t are assumed to be positive.

Parameter	(a) $B_{\text{i.}} = B_{\text{u.}} = 0$	(b) $B_{\text{i.}}$ free, $B_{\text{u.}} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	0.99 ± 0.06	$0.96\ ^{+\,0.04}_{-\,0.05}$
κ_W	1.06 ± 0.06	$1.00\ ^{+\,0.00}_{-\,0.03}$
κ_b	0.87 ± 0.11	0.81 ± 0.08
κ_t	0.92 ± 0.10	0.90 ± 0.10
κ_μ	$1.07\ ^{+\,0.25}_{-\,0.30}$	$1.03\ ^{+\,0.23}_{-\,0.29}$
κ_τ	0.92 ± 0.07	0.88 ± 0.06
κ_γ	1.04 ± 0.06	1.00 ± 0.05
$\kappa_{Z\gamma}$	$1.37\ ^{+\,0.31}_{-\,0.37}$	$1.33\ ^{+\,0.29}_{-\,0.35}$
κ_g	$0.92\ ^{+\,0.07}_{-\,0.06}$	$0.89\ ^{+\,0.07}_{-\,0.06}$
$B_{\text{i.}}$	-	< 0.09 at 95% CL
$B_{\text{u.}}$	-	< 0.16 at 95% CL

Comparison to previous ATLAS iteration

	36.1 fb^{-1} (PRL 120 (2018) 211802)	Full Run 2 - 139 fb^{-1}
Flavour Tagging	MV2c100 (b vs c) + MV2cl100 (c vs l) (c-tag) (Working point optimisation)	DL1 (c-tag) + MV2c10 (b-veto) (Working point optimisation)
Efficiencies	c-jets (41%), b-jets (25%), light-jets (5%)	c-jets (27%), b-jets (8%), light-jets (1.6%)
FTAG Calibrations	36 fb^{-1}	140 fb^{-1}, 80 fb^{-1} for c-jets Calibrations derived by analysis team
Lepton Channels	2 lepton	0, 1 and 2 lepton
Jet Categories	2+ jets	2 and 3(+) jets
p_T^V Regimes	75 < p_T^V < 150 GeV p_T^V > 150 GeV	75 < p_T^V < 150 GeV (only in 2L) p_T^V > 150 GeV
SRs	1 and 2 c-tags	1 and 2 c-tags
CRs	-	Top emu (2L), Top (0L/1L), High dR, 0 c-tag
Main bkgs treatment	Floating Z+jets norms in each category	Common floating normalisations
VH(bb) Treatment	SM background SR overlap	SM background Orthogonality in SRs
VH(bb) Fraction in 2 c-tag	6%	0.7%
Truth Tagging	ΔR(jet$_1$,jet$_2$)	Min ΔR(tagged jet, closest jet$_2$)

- Fit to 36.1 fb^{-1} dataset with signal regions from 36.1 fb^{-1} analysis
    - Reminder: 2 lepton only
    - **36% improvement** in the expected limit
    - Mostly due to better flavour tagging performance
- + New 2 lepton channel SRs and CRs
    - **43% improvement** in the expected limit w.r.t previous iteration
        - Mainly better FTAG performance
        - Addition of diboson POIs (-7%)
        - Split in nJet categories (+6%)
        - Use of ΔR CR, 0-ctag CR, top emu CR (+10%)
- + Full Run 2 data and 0 lepton and 1 lepton channels
    - **Factor 5 improvement** in the expected limit w.r.t previous iteration