Higgs 2023, 28/11/2023, Beijing, China

Charming Yukawa Coupling of the Higgs Boson

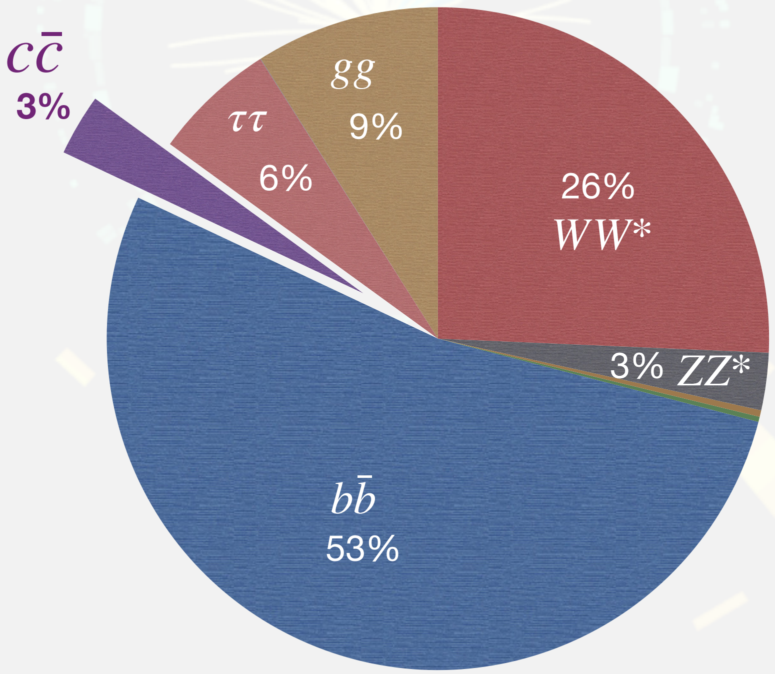
Zhuoran Feng (Nikhef)
On behalf of the ATLAS collaboration

Introduction

- Precise measurements of the Higgs Yukawa couplings to fermions are important → help understanding the mass hierarchy of fermions
- Not yet observed Higgs coupling to 1st and 2nd generation quarks can be a probe of new physics

- Higgs to charm decay ($H \to c\bar{c}$) is a promising approach
  - SM $H \to c\bar{c}$ is the most common Higgs decay mode that is not observed yet
  - Small Higgs-charm Yukawa coupling: sensitive to new physics modifications

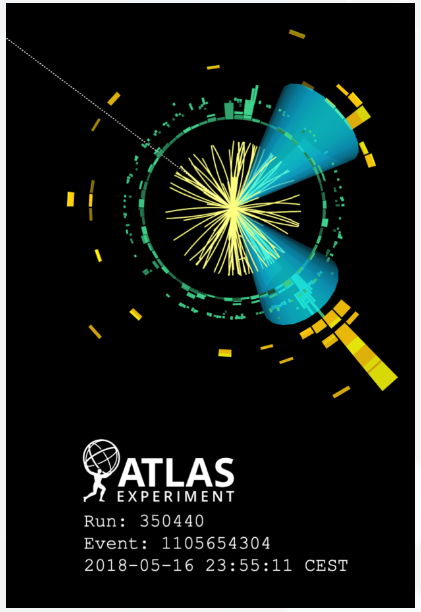
- Focus of today:
  - The ATLAS search for $H \to c\bar{c}$ with full Run 2 data [Eur. Phys. J. C 82 (2022) 717]
  - Possible improvements with state-of-the-art techniques developed by ATLAS



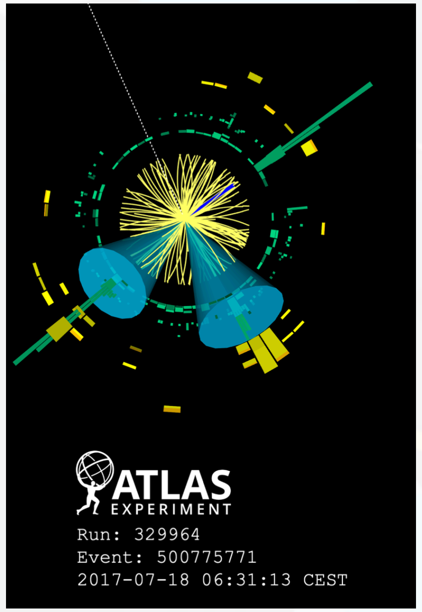
Standard Model Higgs branching ratios

$H(\to c\bar{c})$: Analysis Strategy

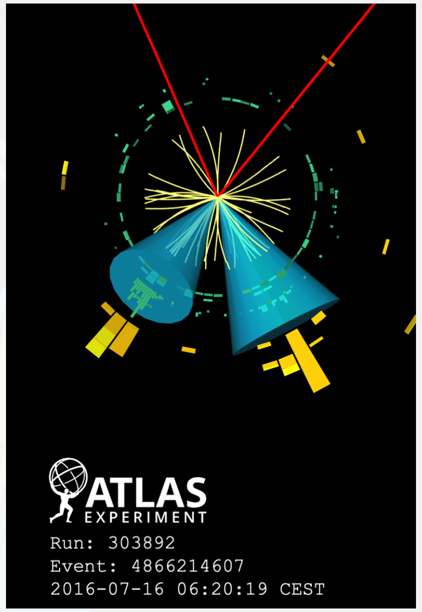
Eur. Phys. J. C 82 (2022) 717



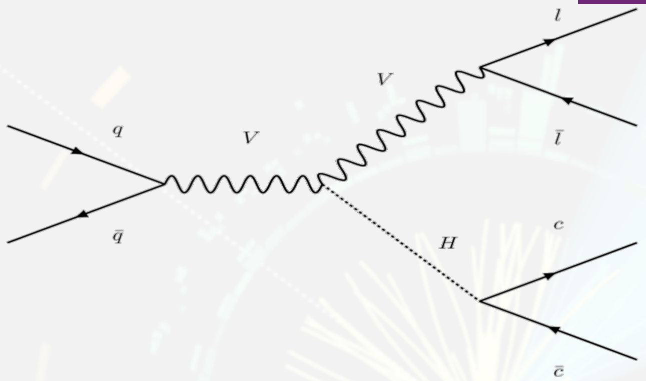
0L: Z(νν)H(cc) candidate



1L: W(lν)H(cc) candidate



2L: Z(ll)H(cc) candidate



Feynman diagram of the VH(cc) process

Categorisation in the analysis

	0-lepton	1-lepton	2-lepton
$75 < p_T^V < 150$ GeV			4 categories
$p_T^V > 150$ GeV	4 categories	4 categories	4 categories

- Production and decay modes: VH production, $Z(\nu\nu)H$ (0L), $W(l\nu)H$ (1L), $Z(ll)H$ (2L) — suppress QCD backgrounds
- Categorisation: In each lepton channel and p_T^V bin, number of c-tags (1 or 2) and number of jets (2 or 3+) divide events into 4 categories → In total 16 signal regions
- Main backgrounds: V + jets, $t\bar{t}$
- Cut-based analysis: invariant mass of the two leading jets (m_{cc}) as the discriminant
- Simultaneous binned likelihood fit to signal strength of $VH(\to c\bar{c})$, $VZ(\to c\bar{c})$ and $VW(\to cq)$

Flavour tagging

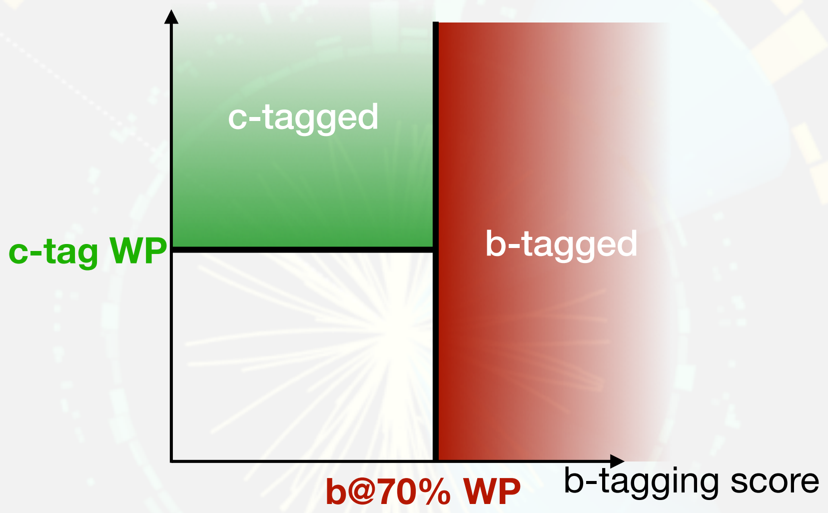
- While identifying c-jets, it makes the tagging scheme orthogonal to $VH(\to b\bar{b})$ analysis — for combination with $VH(\to b\bar{b})$

- Designs: for each jet, **c-tagging + b-veto**
  - ATLAS DL1c tagger from Run2
  - b-veto using the b-tagging working point from $VH(\to b\bar{b})$ analysis
  - Dedicated optimisation for the analysis

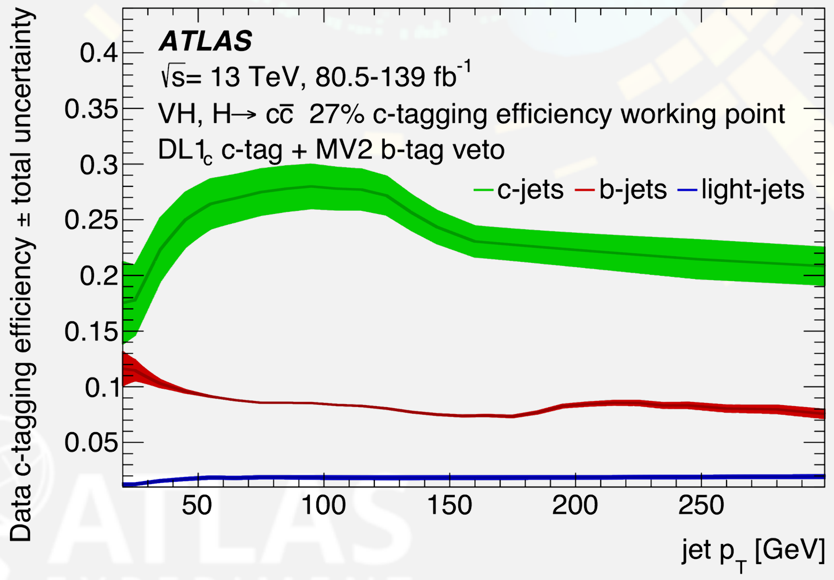
Tagging efficiency of the DL1c tagger

	b-jets	c-jets	light-jets	tau-jets
c-tagging (w/ b-veto)	8%	27%	1.6%	25%

- Event selection: at least 1 or 2 c-tags for signal region events

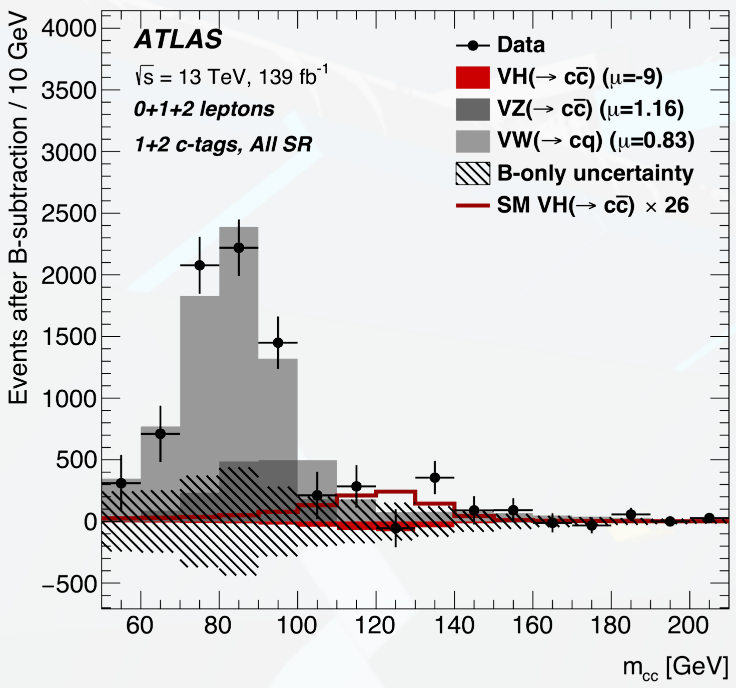


Flavour tagging scheme used in the VH(cc) analysis

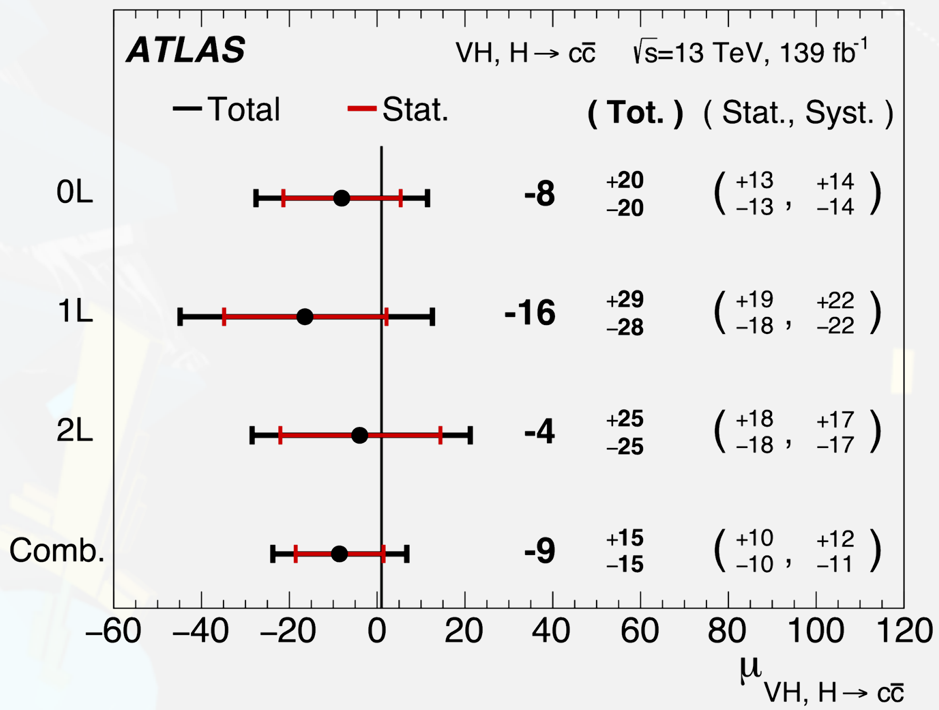


Calibrated tagging efficiency over different jet pT

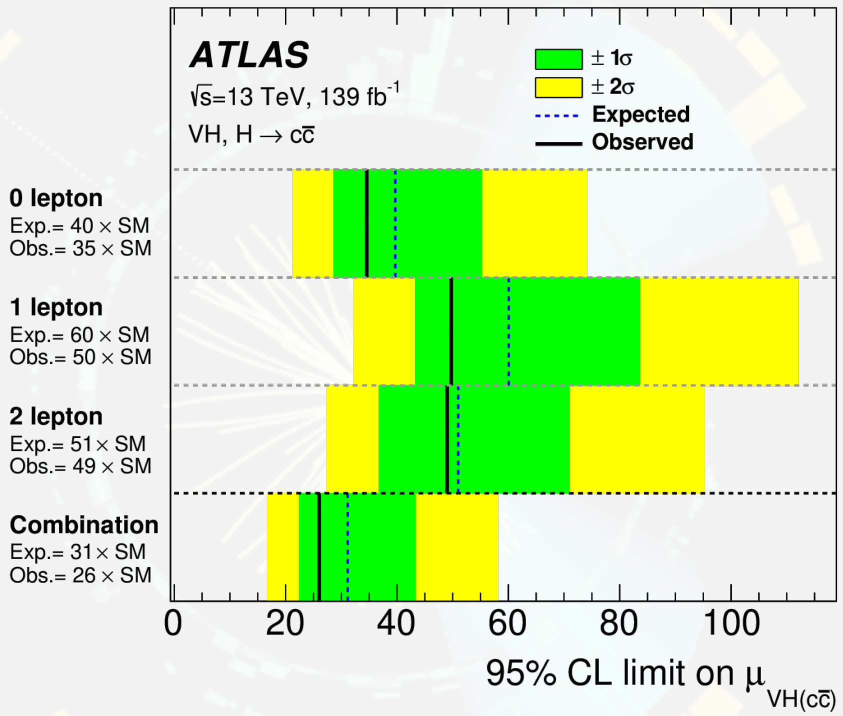
Results



Mass distributions with all backgrounds subtracted



Best fit VH(cc) signal strength



95% CL upper limits on VH(cc) signal strength

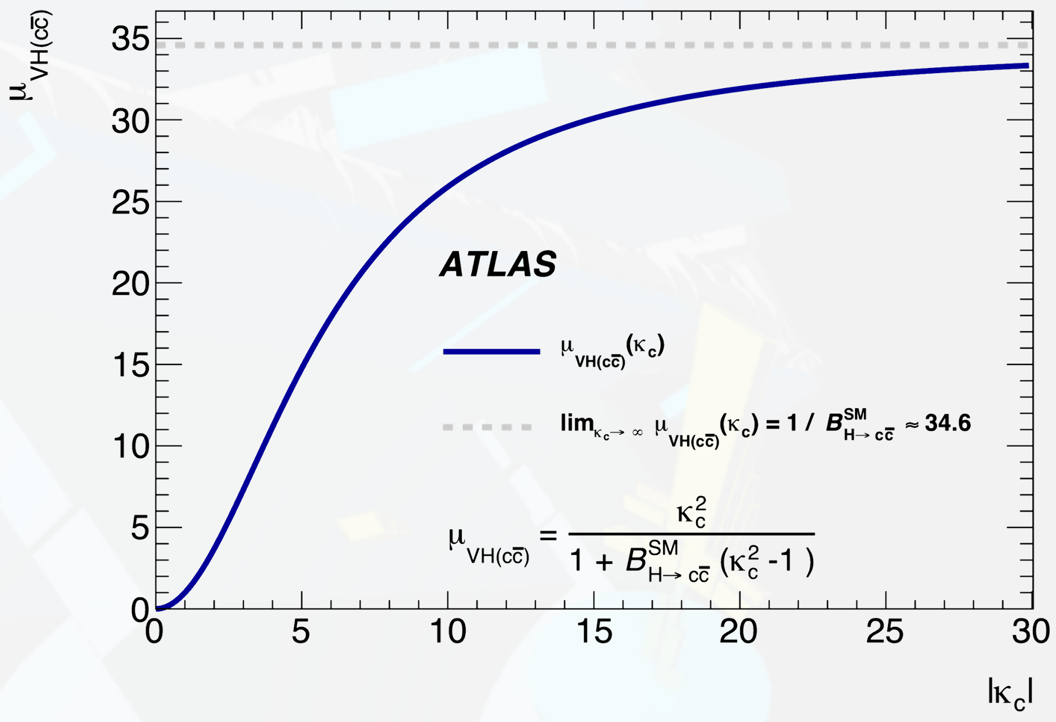
Good data/simulation agreement
VZ(cc) significance: 2.6σ (2.2σ expected)
VW(cq) significance: 3.8σ (4.6σ expected)

Best fit: $\mu_{VH(\to c\bar{c})} = -9 \pm 15$
Similar size of statistical and systematic uncertainties

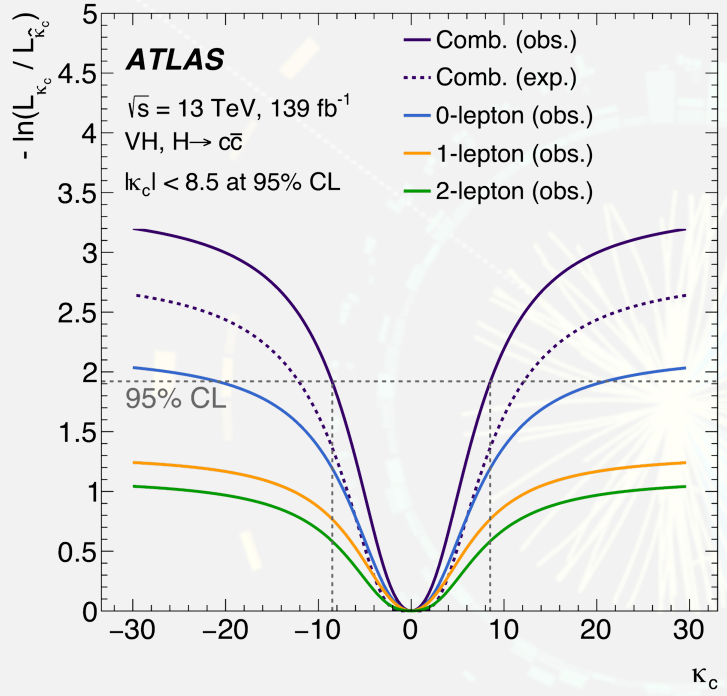
Observed $VH(\to c\bar{c})$ limit:
$26 \times SM$
($31 \times SM$ expected)

- First ATLAS measurements of $VZ(\to c\bar{c})$ and $VW(\to cq)$ using c-tagging
- Up-to-date ATLAS $VH(\to c\bar{c})$ results

Yukawa coupling strength: κ_c interpretation



Parameterisation for κ_c

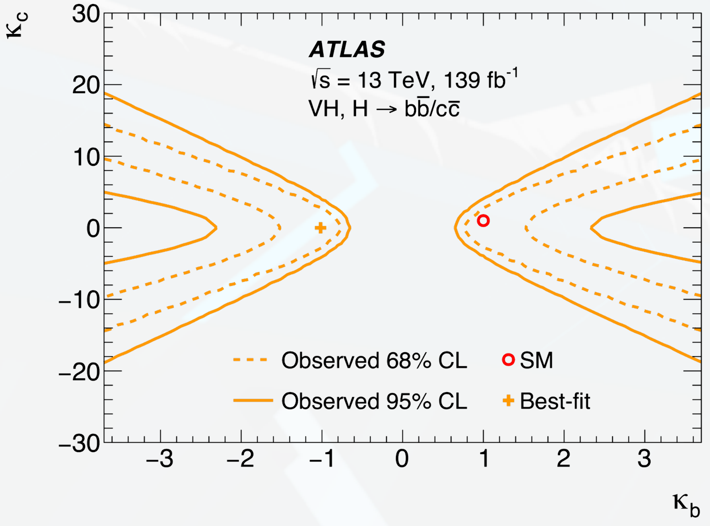


Likelihood scan for κ_c

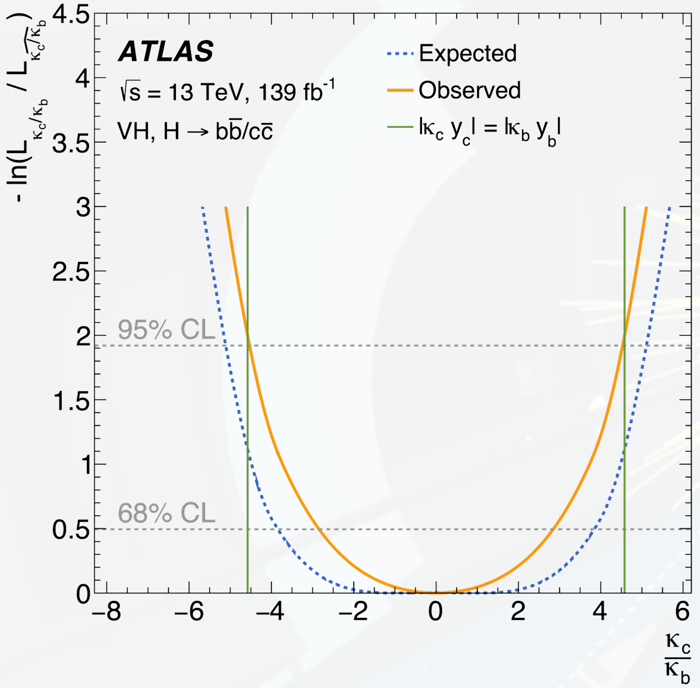
- Measured VH(cc) signal strength can be parameterised in terms of coupling modifiers (κ_i)
- Considering modifications to decay only, setting all other coupling modifiers to 1, assuming SM Higgs width:

- 95% CL limit on κ_c : [-8.5, 8.5] (expected [-12.3, 12.4])
- First direct limit on κ_c!

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



Observed constraints on κ_b and κ_c

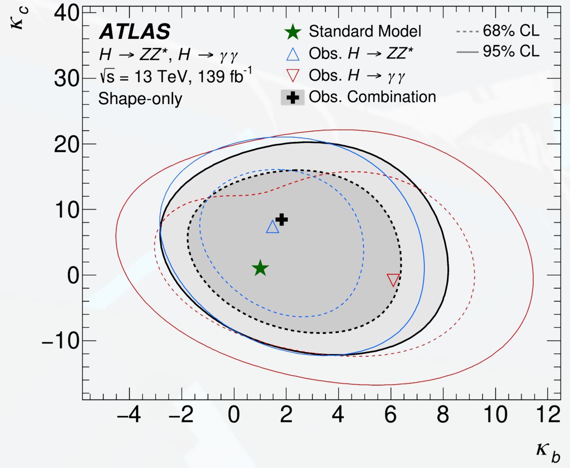


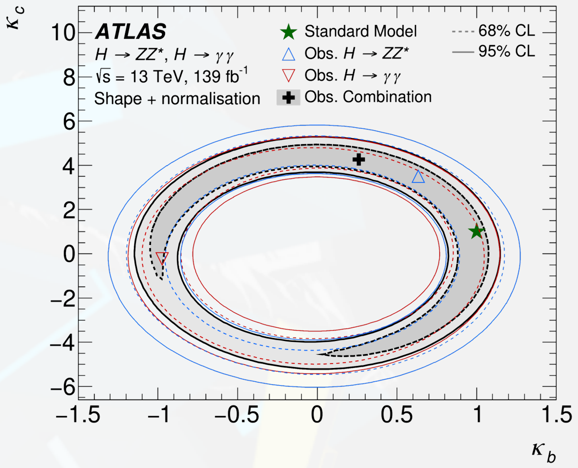
Combined $VH(\to b\bar{b})$ and $VH(\to c\bar{c})$ likelihood scan results of κ_c/κ_b. κ_b is a free parameter here.

- Designs: Combined likelihood function as the product of individual likelihood functions of $VH(\to b\bar{b})$ [Eur. Phys. J. C 81 (2021) 178] and $VH(\to c\bar{c})$
- Fitted signal strengths are in good agreement with individual analyses:
  - $\mu_{VH(\to c\bar{c})} = -9 \pm 10$ (stat.) ± 11 (syst.) (-9 ± 15 from individual $VH(\to c\bar{c})$)
  - $\mu_{VH(\to b\bar{b})} = 1.06 \pm 0.12$ (stat.) $^{+0.15}_{-0.13}$ (syst.) ($1.02^{+0.18}_{-0.17}$ from individual $VH(\to b\bar{b})$)
- κ_b and κ_c interpretation:
  - All other couplings and Higgs decays are set to SM prediction
  - 95% CL constraints on $|\kappa_c/\kappa_b| < 4.5$ (5.1 expected) — smaller than ratio between b- and c-quark masses

→ Coupling of the Higgs boson to charm quark is weaker than to bottom quark

To improve constraints on κ_c — combined with indirect searches



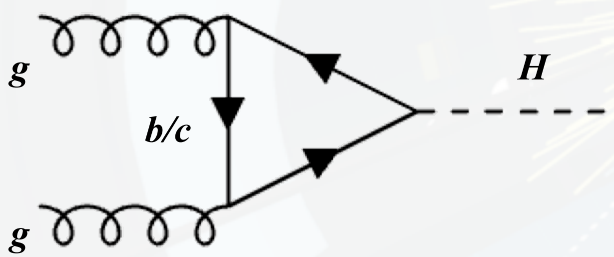


95% CL constraints on Yukawa coupling modifiers

	Observed	Expected
κ_b	[-1.09, 0.86] U [0.81, 1.09]	[-1.14, -0.92] U [0.86, 1.15]
κ_c	[-2.27, 2.27]	[-2.77, 2.75]

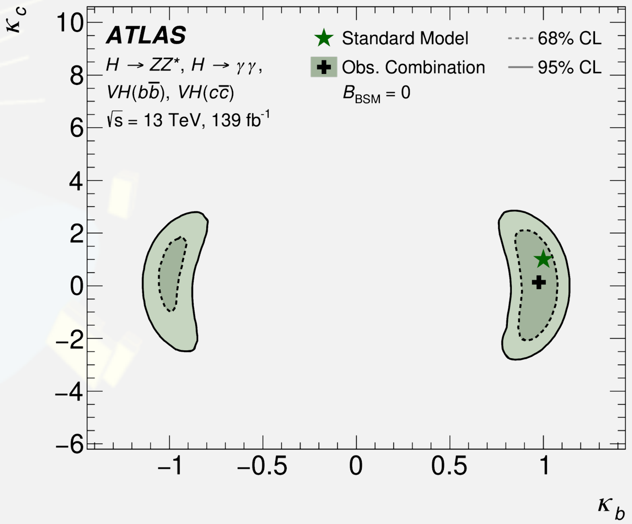
From combining $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$ measurements of total and differential Higgs production cross-sections. Both p_T^H shape and normalisation modifications are considered. Results for one modifier are obtained while fixing the other one to SM expectations.

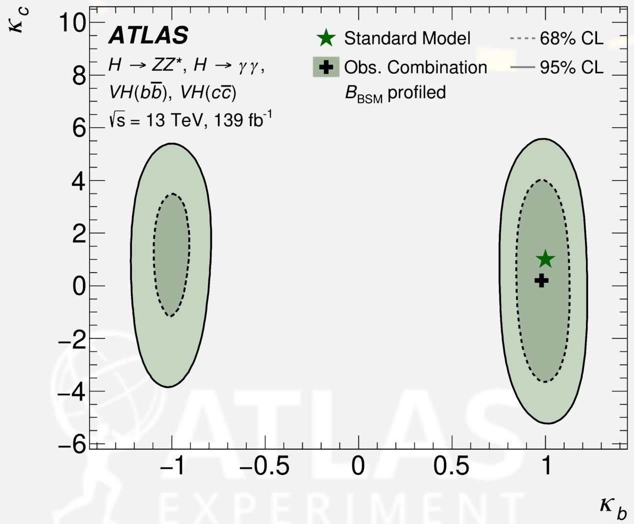
- Indirect Yukawa coupling constraints: $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$ measurements → through quark loop contributions to Higgs production
- Combining indirect and direct constraints: simultaneous fit to p_T^H ($H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$) and BDT and $m_{c\bar{c}}$ ($VH(\to b\bar{b})$ and $VH(\to c\bar{c})$) → 2D contours of κ_b and κ_c constraints



One of the loop processes that contribute to indirect searches of Higgs-charm coupling

Only allow SM Higgs decay





Also allow BSM Higgs decay

Observed 2D negative log-likelihood contours of κ_b and κ_c combining indirect and direct measurements of Higgs Yukawa coupling to bottom and charm quarks

To improve c-tagging — GN2

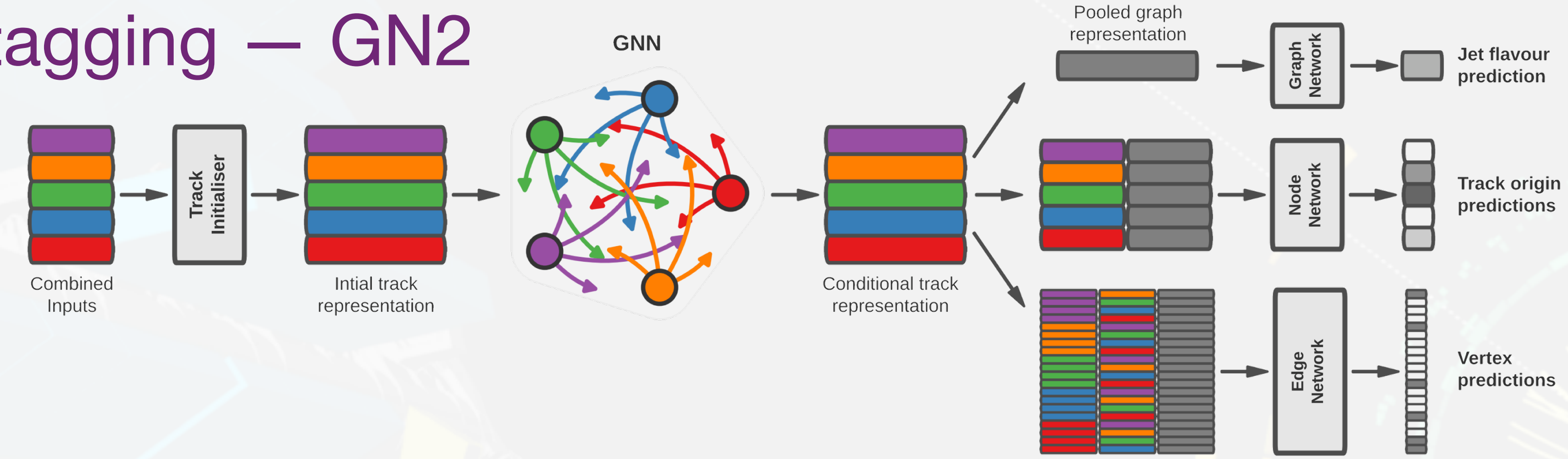
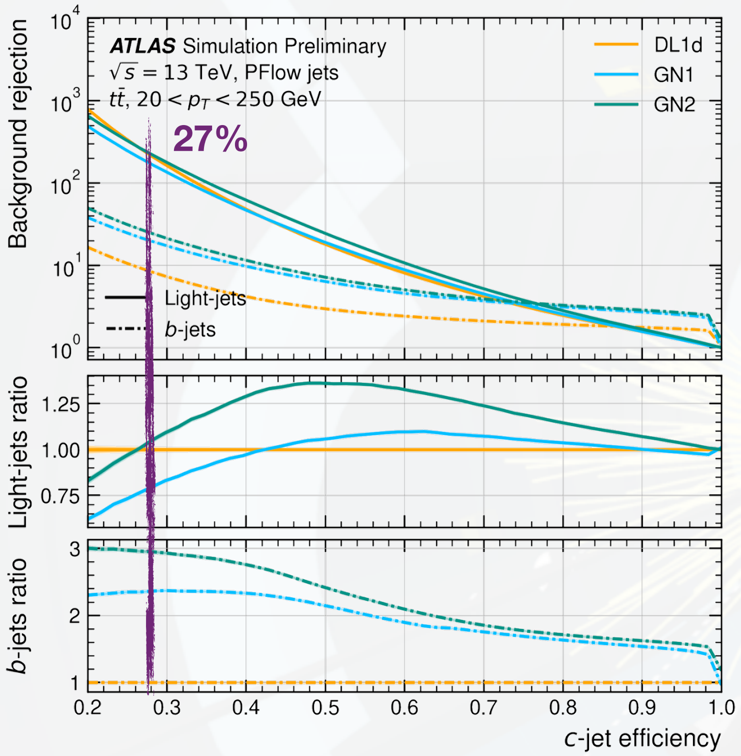


Illustration of the graph neural networks (GNN) based tagger



Background rejection of three different ATLAS taggers: DL1d (new version of DL1 series), GN1 and GN2 (graph neural network based taggers)

- Classic ATLAS Flavour Tagging procedure:
  - **Low level algorithms** investigating track information and displaced vertices associated with jets
  - Outputs fed into **high level taggers** — for Run2 and early Run3, deep neural networks are used: **DL1 series**
  - **DL1d** is the newest of this kind with the best performance
- New approach — all-in-one graph neural network based tagger: **GN series**
  - Track, jet kinematics, hit information → predict jet flavour, classify tracks, and do track-pair vertexing
  - State-of-the-art tagger **GN2**: also implementing transformer architecture [1706.03762]
  - c-tagging @27% WP, compared to DL1d: **same** light-jet rejection, **3x** b-jet rejection ($t\bar{t}$ sample)

To improve sensitivity in high p_T region: Boosted $H \to c\bar{c}$ tagger

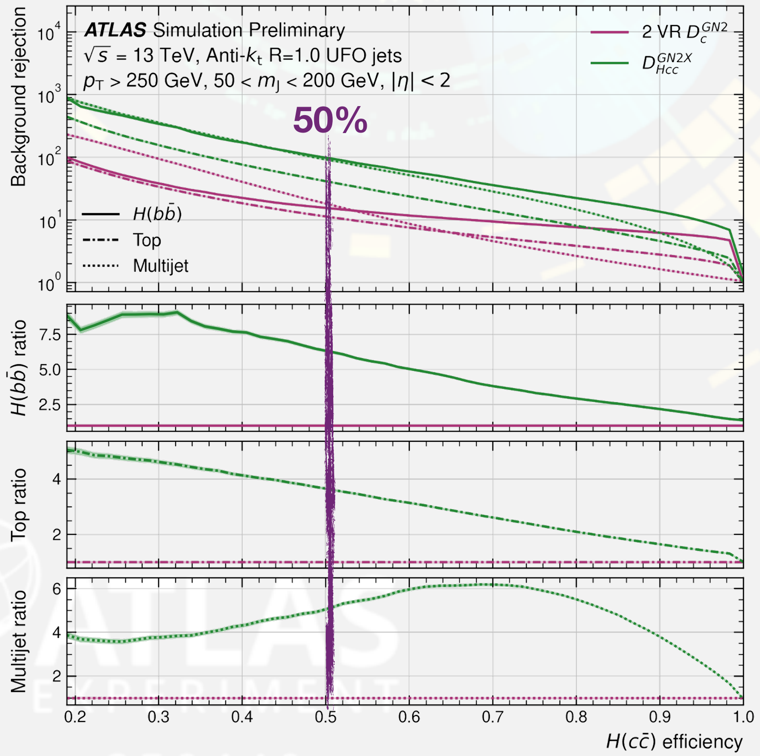
ATL-PHYS-PUB-2023-021

- High p_T regime: boosted Higgs boson decays → large-radius (large-R) jets as the final state of $H \to c\bar{c}$
- Classic techniques: tagging the sub-jets inside the large-R jet

Illustration of high-p_T Higgs decay
the single b-/c-jets are close to each other thus hard to distinguish
the Higgs candidate is reconstructed from a large-R jet

- First $H \to b\bar{b}/c\bar{c}$ tagger using GNN in ATLAS: GN2X
  - Trained to separate $H \to b\bar{b}$ and $H \to c\bar{c}$ from Top and QCD multi-jet originated large-R jets
  - Track information, large-R jet kinematics, sub-jet information (including GN2 outputs) are fed to GN2X
  - $H \to c\bar{c}$ performance compared to tagging sub-jets with GN2 (at 50% efficiency)*:
    - **6x** $H \to b\bar{b}$ rejection
    - **5x** multi-jet rejection
    - **3x** top jet rejection

2023!



GN2X: background rejections for $H \to c\bar{c}$ tagging

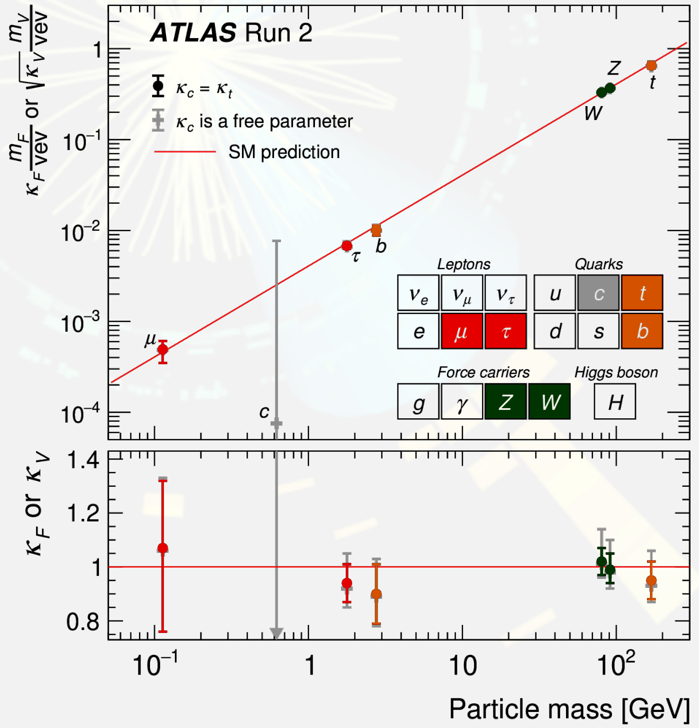
* The information used in the two strategies are not exactly the same

Conclusion

- The Yukawa coupling between charm quark and the Higgs boson is an essential probe leading to better understanding the properties of Higgs-Fermion couplings
- $H \rightarrow c\bar{c}$ is a promising channel to investigate and constrain the Higgs-charm coupling strength

- ATLAS collaboration has performed a successful $VH(\rightarrow c\bar{c})$ search with full Run 2:
  - Upper limit on signal strength: $26 \times SM$
  - First direct constraint on coupling modifier κ_c: [-8.5, 8.5]
  - Combined with ATLAS $VH(\rightarrow b\bar{b})$ measurements, the Higgs-charm Yukawa coupling strength is weaker than Higgs-bottom
  - Better constraint on coupling: combined with Higgs cross-section measurements

- Future of better understanding of Higgs-charm coupling:
  - Improved c-tagging algorithms (GN2): same light-jet rejection, 3x b-jet rejection
  - Probe higher p_T for more sensitivities with newest boosted event taggers (GN2X)

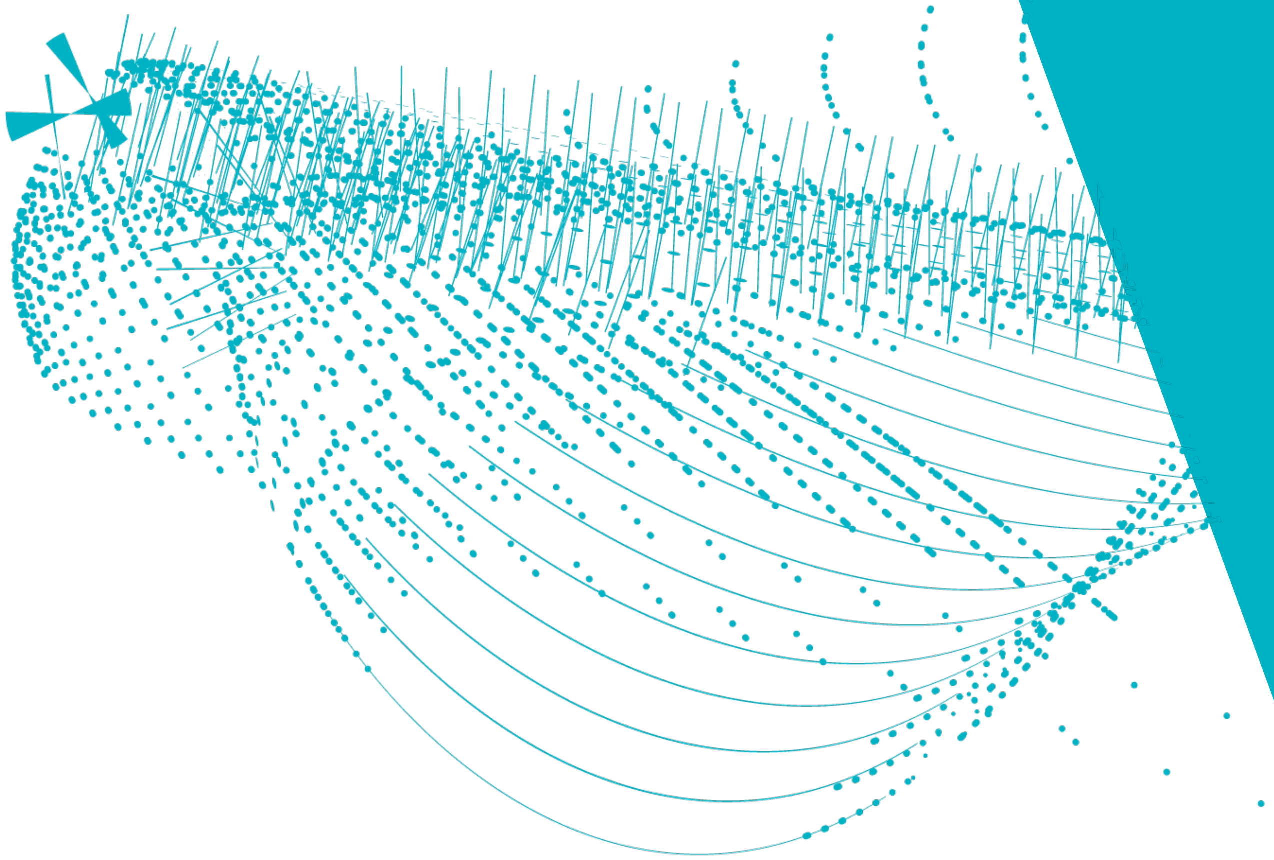


Higgs coupling strength to different particles

Thanks for Listening!

Any Questions?

Back Up



MC samples

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

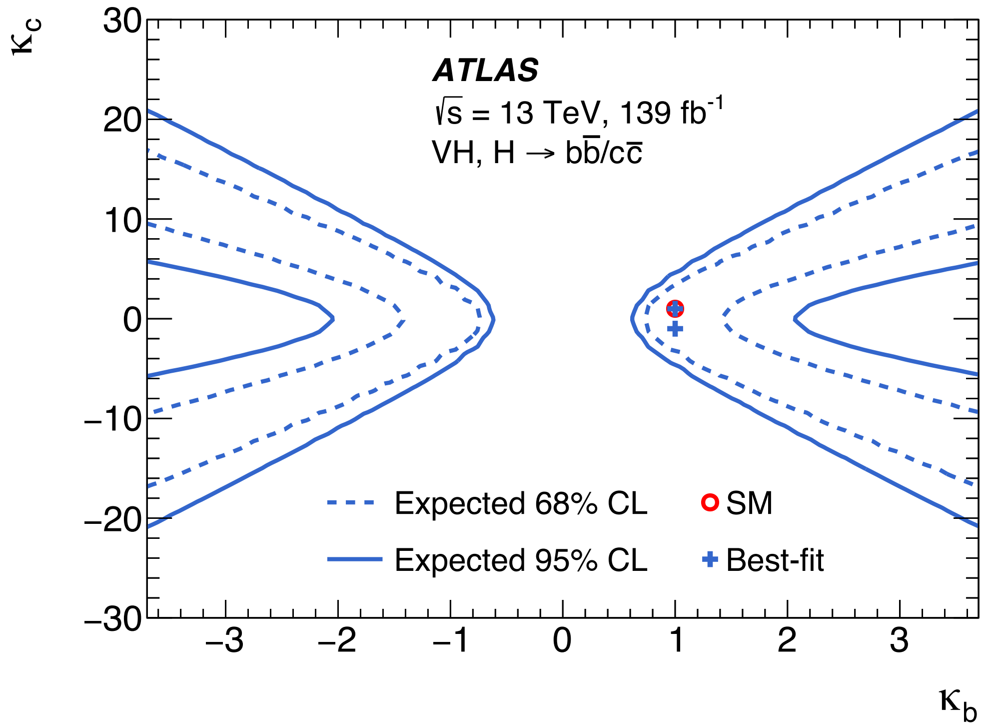
Event selections

Common Selections	
Central jets	≥ 2
Signal jet p_T	≥ 1 signal jet with $p_T > 45$ GeV
c-jets	One or two 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
$\Delta R(\mathbf{jet1},\ \mathbf{jet2})$	$75 < p_T^V < 150$ 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	No *loose* leptons
E_T^{miss}	> 150 GeV
p_T^{miss}	> 30 GeV
H_T	> 120 GeV (2 jets), > 150 GeV (3 jets)
$\min \lvert\Delta\phi(\boldsymbol{E}_T^{miss}, \mathbf{jet})\rvert$	$> 20°$ (2 jets), $> 30°$ (3 jets)
$\lvert\Delta\phi(\boldsymbol{E}_T^{miss}, \boldsymbol{H})\rvert$	$> 120°$
$\lvert\Delta\phi(\mathbf{jet1}, \mathbf{jet2})\rvert$	$< 140°$
$\lvert\Delta\phi(\boldsymbol{E}_T^{miss}, \boldsymbol{p}_T^{miss})\rvert$	$< 90°$
1 Lepton	
Trigger	e sub-channel: single electron μ sub-channel: E_T^{miss}
Leptons	One *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	Exactly two *loose* leptons Same flavour, opposite charge for $\mu\mu$
$m_{\ell\ell}$	$81 < m_{\ell\ell} < 101$ GeV

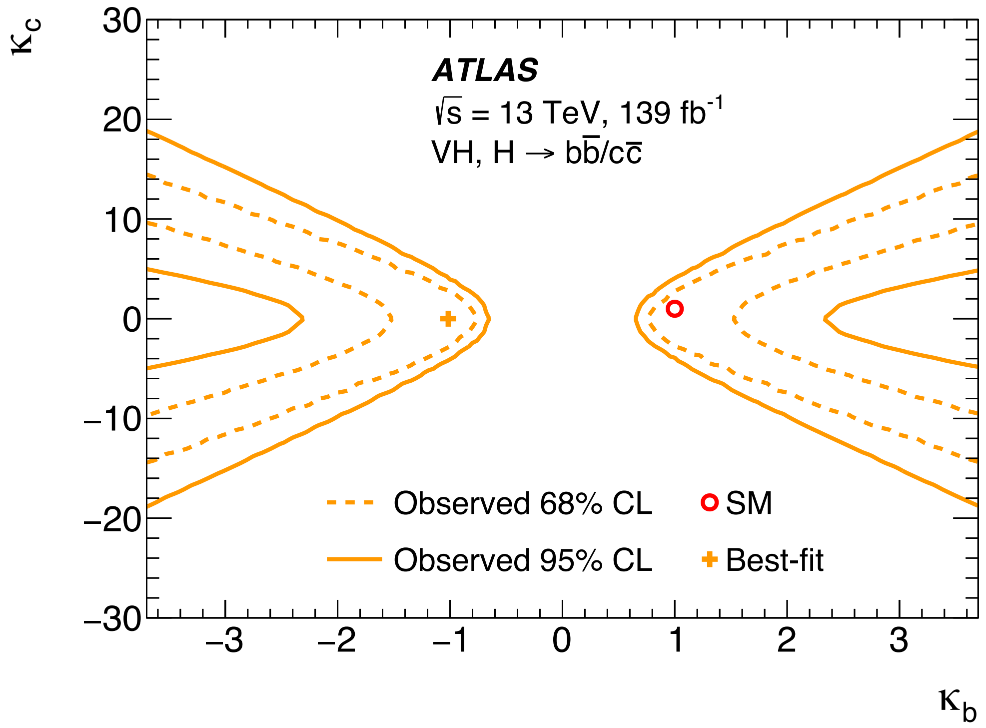
Uncertainty breakdown

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				
$VH(\to c\bar{c})$		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
$VH(\to b\bar{b})$		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_T^{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

κ_c and κ_b constraints combined with $VH(\rightarrow b\bar{b})$



Expected



Observed

Input features of GN2 and GN2X

GN2 input features

Jet Input	Description
p_T	Jet transverse momentum
η	Signed jet pseudorapidity
Track Input	**Description**
q/p	Track charge divided by momentum (measure of curvature)
$d\eta$	Pseudorapidity of the track, relative to the jet η
$d\phi$	Azimuthal angle of the track, relative to the jet ϕ
d_0	Closest distance from the track to the PV in the longitudinal plane
$z_0 \sin\theta$	Closest distance from the track to the PV in the transverse plane
$\sigma(q/p)$	Uncertainty on q/p
$\sigma(\theta)$	Uncertainty on track polar angle θ
$\sigma(\phi)$	Uncertainty on track azimuthal angle ϕ
$s(d_0)$	Lifetime signed transverse IP significance
$s(z_0)$	Lifetime signed longitudinal IP significance
nPixHits	Number of pixel hits
nSCTHits	Number of SCT hits
nIBLHits	Number of IBL hits
nBLHits	Number of B-layer hits
nIBLShared	Number of shared IBL hits
nIBLSplit	Number of split IBL hits
nPixShared	Number of shared pixel hits
nPixSplit	Number of split pixel hits
nSCTShared	Number of shared SCT hits
nPixHoles	Number of pixel holes
nSCTHoles	Number of SCT holes
leptonID	Indicates if track was used in the reconstruction of an electron or muon (only for GN1 Lep)

GN2X input features

Jet Input	Description
p_T	Large-R jet transverse momentum
η	Signed large-R jet pseudorapidity
mass	Large-R jet mass
Track Input	**Description**
q/p	Track charge divided by momentum (measure of curvature)
$d\eta$	Pseudorapidity of track relative to the large-R jet η
$d\phi$	Azimuthal angle of the track, relative to the large-R jet ϕ
d_0	Closest distance from track to primary vertex (PV) in the transverse plane
$z_0 \sin\theta$	Closest distance from track to PV in the longitudinal plane
$\sigma(q/p)$	Uncertainty on q/p
$\sigma(\theta)$	Uncertainty on track polar angle θ
$\sigma(\phi)$	Uncertainty on track azimuthal angle ϕ
$s(d_0)$	Lifetime signed transverse IP significance
$s(z_0 \sin\theta)$	Lifetime signed longitudinal IP significance
nPixHits	Number of pixel hits
nSCTHits	Number of SCT hits
nIBLHits	Number of IBL hits
nBLHits	Number of B-layer hits
nIBLShared	Number of shared IBL hits
nIBLSplit	Number of split IBL hits
nPixShared	Number of shared pixel hits
nPixSplit	Number of split pixel hits
nSCTShared	Number of shared SCT hits
subjetIndex	Integer label of which subjet track is associated to (GN2X + Subjets only)
Subjet Input	**Description** (Used only in GN2X + Subjets)
p_T	Subjet transverse momentum
η	Subjet signed pseudorapidity
mass	Subjet mass
energy	Subjet energy
$d\eta$	Pseudorapidity of subjet relative to the large-R jet η
$d\phi$	Azimuthal angle of subjet relative to the large-R jet ϕ
GN2 p_b	b-jet probability of subjet tagged using GN2
GN2 p_c	c-jet probability of subjet tagged using GN2
GN2 p_u	light flavour jet probability of subjet tagged using GN2
Flow Input	**Description** (Used only in GN2X + Flow)
p_T	Transverse momentum of flow constituent
energy	Energy of flow constituent
$d\eta$	Pseudorapidity of flow constituent relative to the large-R jet η
$d\phi$	Azimuthal angle of flow constituent relative to the large-R jet ϕ